Groundwater Lowering in Multi-layer Aquifer Systems: Case Study of Esna City – Egypt

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Abstract

The city of Esna is an ancient city dating back to the Pharaoh Era. It is located on the western bank of the Nile River in South Egypt. The city houses the Esna temple, which is a major tourist attraction in the region. At present, Esna is composed of residential areas, with scattered spots of agricultural areas. Neither a complete sanitary drainage system nor an agricultural drainage system have been provided for the city.

The high groundwater table in Esna City was cited as a problem resulting from the construction of the New Esna Barrage across the Nile River. Although the Esna Temple is located in the highest location of the city, it is strongly affected by elevated groundwater since the temple structure is immersed in the ground well below the ground surface.

The main objectives of this study are to perform a baseline study of the groundwater situation in Esna City, study some alternatives for mitigating the groundwater problems, study the interaction between the existing groundwater problem and the proposed sewerage system design in Esna, and present the optimum mitigation plan.

The analysis of the reasons for elevated groundwater table in the city was complicated by several factors (high difference in permeability between upper and lower layers, anisotropy of upper layer, and limited amount of field data. Hence, field investigations, including drilling of piezometers, water level measurements, pumping tests were undertaken.

A multi-layer finite element groundwater model has been employed to assess the groundwater situation in Esna and to evaluate proposed mitigation measures.

Assessed alternatives include lowering the piezometric head of the lower aquifer, lining Ramady Canal, constructing a cutoff drain, and constructing a tile drainage system in the upper layer

1. Introduction

The city of Esna is an ancient city in Upper Egypt, located on the western bank of the Nile River as shown in figure (1). The city is composed of residential areas, with scattered spots of agricultural areas as shown in figure (2).

Since no solid information was available about the main sources of increased groundwater levels, or to which extent the groundwater has been affected by the current situation, the main objectives of the study include:

- Performing a baseline study of the groundwater situation within Esna City.
- Propose and evaluate alternatives for mitigating the groundwater problems.
- Study the interaction between the existing groundwater problem and the proposed sewerage system design in Esna.
- Present the optimum mitigation plan.
- Provide conceptual designs and cost estimates for the optimum groundwater mitigation plan.

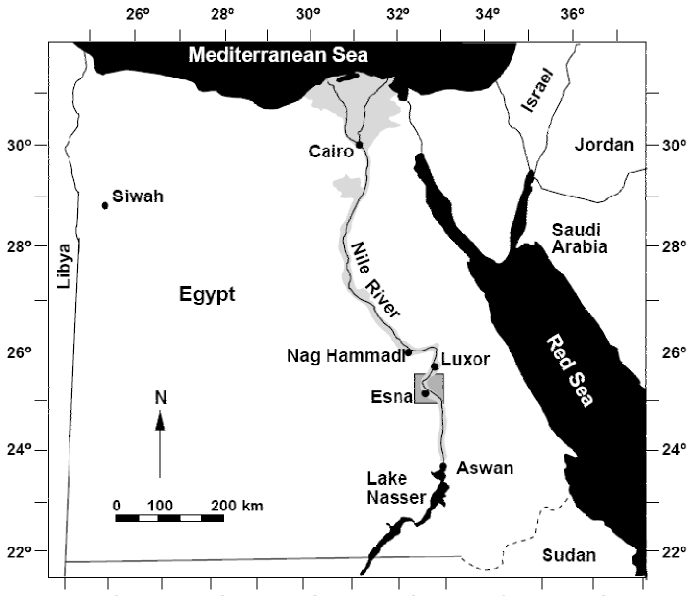


Figure (1) Location map of Esna City in Upper Egypt

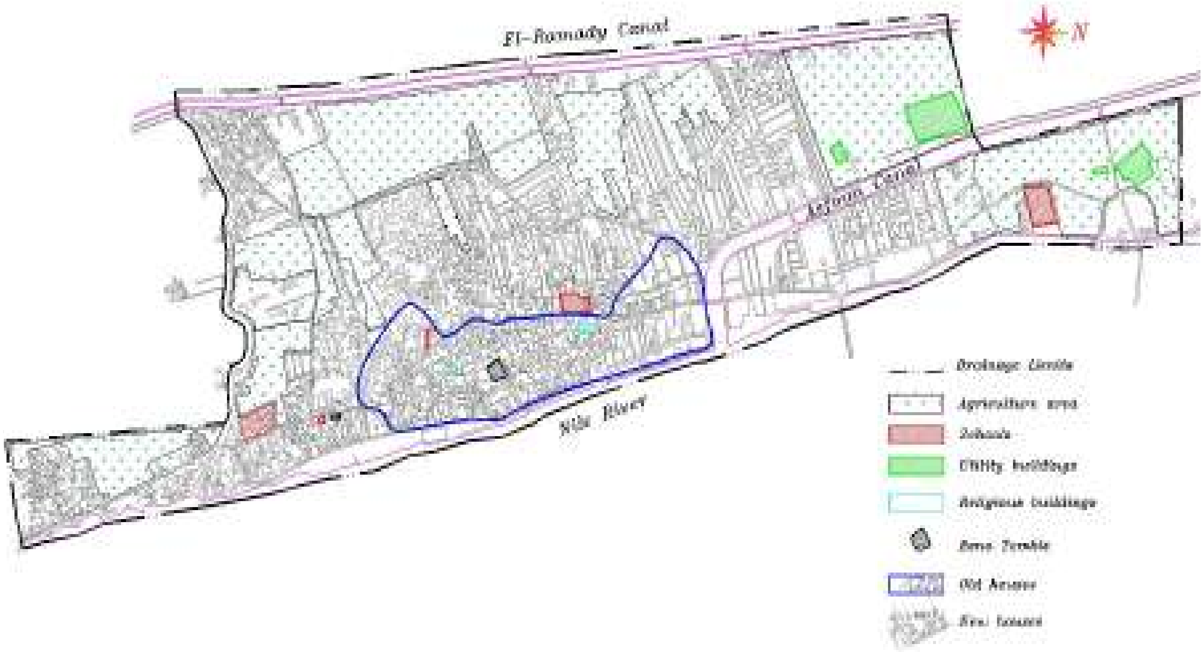


Figure (2) Land use pattern in Esna City

This study focuses on groundwater investigations in the region within the boundaries of the city. Land use in the city has been identified broadly as either agricultural area or residential area. The number and spacing of piezometers has been selected to suit the purpose of preparing the feasibility study. Soil investigations have been designed to identify thickness and type of hydro-geological unit. A depth to groundwater of 1.0m or less has been considered as critical. This is due to the fact that most of the houses in the affected areas are small houses with shallow foundations. This is also in congruence with the critical limit assumed in similar studies (Lahmeyer, Electrowatt, Sogreah, 1996).

Further, presented designs of groundwater lowering alternatives are conceptual designs, with the purpose of evaluating feasibility and preliminary cost estimates.

2. Hydro-geological Data

2.1 Regional data

Regional hydro-geological data has relied on field measurements and a number of articles, reports and thesis as Hashem et al 1966 and 1967, RIGW 1980, Abdelaziz 1984 and Allam 1993. These references were also used to verify and compare obtained field data regarding aquifer characteristics. These references represent mainly hydro-geological studies in Upper Egypt. However, no detailed groundwater studies have been found specifically in the study domain (City of Esna), and no existing piezometers were found.

The valley width on the reach extending from Esna to Naga Hammadi is in the range of 8 to 15km, with the alluvium thickness ranging between 80 to 110m. The geological succession of the rocks in contact with the valley alluvium is as shown in table (1) and Figure (3).

Table (1) Geological Succession of the Rocks in Contact With the Valley Alluvium

Nile valley alluvium	Unconsolidated, graded sands which are overlain by a silty-clay layer in most of the area of the valley
Tertiary sediments	Limestone and shale with some sandstone and gravel in the upper part of the sequence
Cretaceous sediments	Limestone and shale
Nubian sandstone	Alternation of sandstone, shale and clay, predominantly shale or sandy shale in the upper part.

2.2 Data of the Nile Valley Alluvium

The alluvium underlying the Nile Valley may be sub-divided into two units, a clay-silt layer underlain by a graded sand layer. The graded sand layer ranges in thickness along the valley from a minimum of 20m to a maximum of 300m. It wedges out laterally at the escarpments, which mark the limits of the valley. Its width ranges from about 2km at Aswan, up to about 20km in some reaches. The layer consists almost exclusively of sand and includes lenses of both predominantly coarse and fine sand. The clay-silt layer overlies the graded sand layer. It consists predominantly of silt and clay, though some lenses of fine sand also occur, Figure (3).

Characteristics of an aquifer section just north of New Esna Barrage are as follows:

- Width of graded sand layer = 8.5 km
- Maximum thickness of graded sand layer = 90 m
- Average thickness of graded sand layer = 50 m
- Width of clay-silt layer = 2.3 km
- Average thickness of clay-silt layer = 10 m

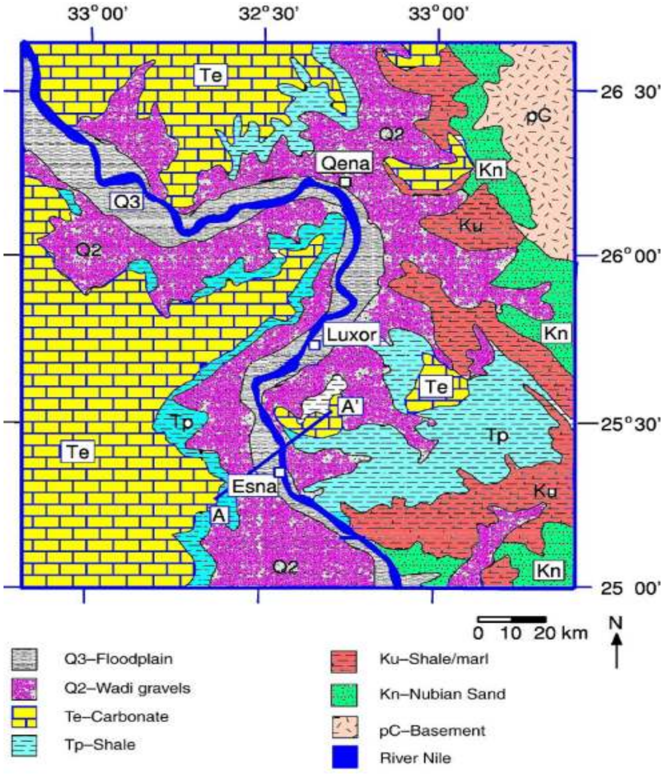


Figure (3) The Nile Valley alluvium at Esna

2.3 Extent of the Study Area

The boundaries of the study area are shown in Figure (2). The eastern boundary is represented by the Nile River upstream and downstream of the New Esna Barrage. The western boundary is represented by Ramady Canal. Ramady Canal is a main canal feeding from the Nile River some 15km upstream the study area through a major pumping station and running towards north for several hundred kilometers. The canal discharge is in excess of 4 million m^3/day serving more than 120,000 acres of agricultural lands in Upper Egypt. The canal is running full all year round. The canal has a top width of about 22m and the depth is about 3m. No sealing or lining has been provided for the canal, and the canal is dredged regularly, which can increase its impact on the groundwater. The southern boundary is represented by El-Mekssar canal. This is a minor irrigation canal, operated on a rotation basis. It represents the southern end of the city's residential areas. The northern boundary is represented by the northern end of the city's boundary. For the purpose of computational modeling, the southern and northern boundaries have been extended for about 500 meters to reduce any inaccuracies resulting from assumptions relating to these boundaries.

3. Field Investigations

Field investigations, including drilling of piezometers, water level measurements, pumping tests were performed.

Measurement points were located along the water bodies. Measured water levels were taken during the late summer and early fall season, which represents the time of maximum water levels, due to maximum irrigation requirements and the annual flooding season of the Nile River. These levels were taken as input for the computational model, as they represent the worst case with regard to studying the groundwater situation and groundwater lowering alternatives.

3.1 Drilling of Piezometers

Sixteen locations have been selected for drilling piezometers, as shown in Figure (4). The locations were selected to cover the extent of the study area and to give a good representation of aquifer characteristics and groundwater variations. At each of the sixteen locations, two piezometers were drilled. One deep piezometer, which was designed to penetrate the whole thickness of the silt-clay cap and tap the lower aquifer, and one shallow piezometer, which was drilled inside the silt-clay cap to show the piezometric head in the upper layer. Actual drilled depths of the piezometers are shown in Table (2).

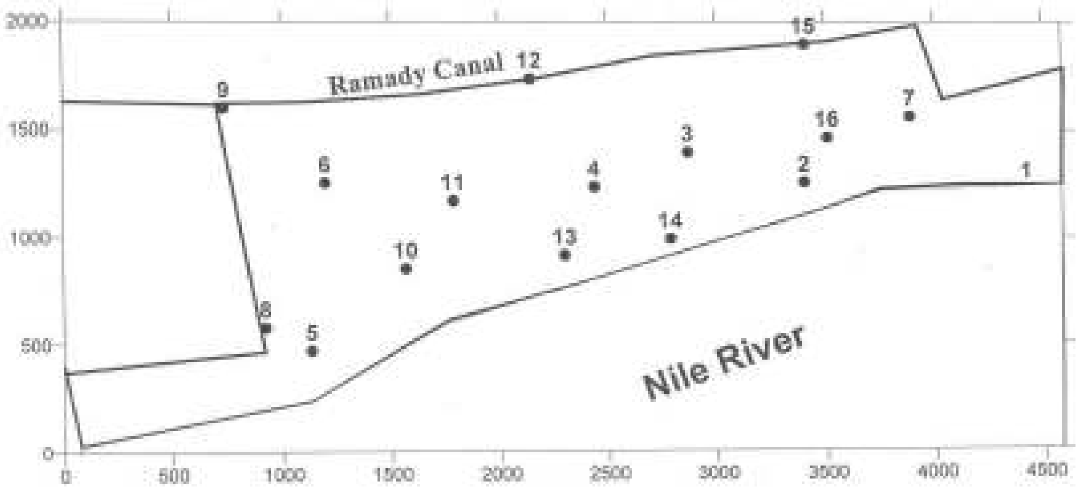


Figure (4) Selected locations for drilling piezometers and collecting samples

Table (2) Actual Drilled Depths of Piezometers

Site Number	1	2	3	4	5	6	7	8	9	10	11	12	13	14	15	16
Deep Piezometer Depth (m)	20	20	15	16	20	20	15	16	16	12	12	15	13	15	16	15
Shallow Piezometer Depth (m)	5	5	3.3	5	5	7	4	5	5	3	2.8	5	3.5	5	5	4

3.2 Water Level Measurements

Depth to water was measured in shallow and deep piezometers once a week during the period of July 24th to September 15th. Further, water levels at selected points in all open water bodies (Nile River upstream and downstream of New Esna Barrage, Asfoun Canal, Al-Ramadi Canal, and Secondary Canals) were measured at the same time.

3.3 Auger Hole Tests

Hydraulic permeability of the aquifer was evaluated through application of the auger hole test. In this test, a volume of water is removed instantly from the aquifer, and the recovery observed. Hydraulic permeability is then evaluated from Van Beers and Oosterbaan (1983) equation:

$$K = \frac{C}{864}\frac{dy}{dt}$$

where dy/dt is the measured rate of rise in cm/sec and the factor 864 yields K values in m/day. The factor C is a dimensionless parameter, which can be obtained from tables. The value of C depends on the drawdown depth y at which dy/dt is measured, the penetration depth L_w of the auger hole in the saturated thickness of the aquifer, and the depth H, which represents the saturated thickness of the aquifer under consideration above the relatively high-permeability sand layer.

In order to quantify the hydraulic permeability of the upper layer, auger holes have been drilled at three locations within Esna, locations 1, 4 and 5 in Figure (4). The auger hole diameter was chosen as 42 cm, while the depth was 2.88m, 2.80m and 2.70m at sites 1, 4 and 5, respectively. Obtained values of permeability were as shown in table (3).

Table (3) Obtained Values of Permeability

Site Number	1	4	5
Horizontal Permeability K (m/day)	0.0280	0.0565	0.0329

These results are in agreement with results of previous studies in Upper Egypt as Hashem et al 1966. These studies had concluded that the variations in hydraulic characteristics of the layers in Upper Egypt are generally small, due to the similarity of process of developing the Nile alluvium over thousands of years through annual flooding of the Nile prior to construction of the High Aswan Dam. It should be noted that the obtained values for K are predominantly values for the horizontal permeability of the upper aquifer. Due to the depository nature of this layer, vertical permeabilities are typically about 10 to 20% of the horizontal. This ratio has been obtained and verified in some of the above-cited references. Value of permeability for the lower sand aquifer in the previous studies was found to be around 40 m/day (Hashem, et al, 1966; RIGW, 1980; Hashem, et al, 1967; and Abdel Aziz, 1984).

4. Analysis of Field Data

4.1 Flow Directions and Areas of Discharge and Recharge

Figures (5) and (6) depict contour lines of piezometric head in the shallow and deep aquifer layers, respectively. For the upper silt-clay layer, contour lines were produced based on water level measurements inside the shallow piezometers, as well as measured water levels of the water bodies around and within the study area (Nile River upstream and downstream of New Esna Barrage, Ramady Canal, Asfoun Canal, secondary canals network). For the lower sandy aquifer layer, contours were produced solely from measured water levels inside deep piezometers. The figures reveal the following:

- Generally, there is very little difference between piezometric heads in the shallow and deep aquifers. This can indicate that the two aquifers are hydraulically interconnected and/or the aquifers are in a state of steady (equilibrium) condition.
- Variations in groundwater levels were minimal during the period of observation. It is expected that variations would be greater if different seasons (summer and winter) were included. However, the presented levels represent the most critical as the levels are usually higher in summer and early fall due to the annual flooding season of the Nile, which leads to elevated water levels in the Nile and canals, and thus in groundwater levels.
- Around piezometer 6 a lowering of contour lines can be observed. However, no pumping out of the aquifer could be located. Thus, this could be due to error in measurement.
- With regard to the lower aquifer, contour lines indicate that groundwater flow in the southern region of the study area is somehow parallel to the Nile, with a northward to north-west gradient. A lowering of the contours can be observed in the vicinity of piezometer 6. With the raised doubts about the leveling of that piezometer, if the measurement of piezometer 6 is removed, contour lines appear to flow close to parallel to the Nile, with slight inclination towards the Nile. It appears that water levels in that region are maintained by the Nile from the east and, perhaps to a less extent, Ramady Canal from the west. Towards the middle of the study area, it can be seen that contour lines turn towards the east, with increasing gradient. This can be explained through the water level in the Nile downstream New Esna Barrage, which is about 4m lower than the upstream levels.
- Asfoun Canal has its intake about 1km upstream of the New Esna Barrage. A regulator exists about 150m downstream of the intake, where the canal water level drops by about 75cm. From the flow lines in the shallow layer it can be concluded that Asfoun Canal acts mainly as a sink (drain) for groundwater in the reach lying within Esna City, especially downstream of the regulator. However, in the northern-most portion (in the vicinity of the New Esna Barrage), the canal acts as a source of groundwater flowing towards the much lower Nile reach downstream of Esna Barrage.

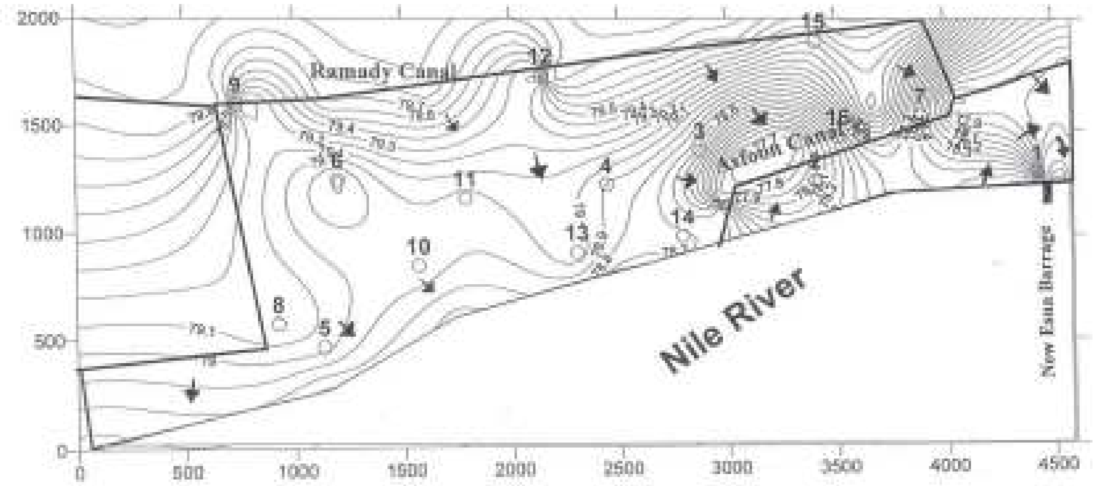


Figure (5) Shallow Wells Water Levels

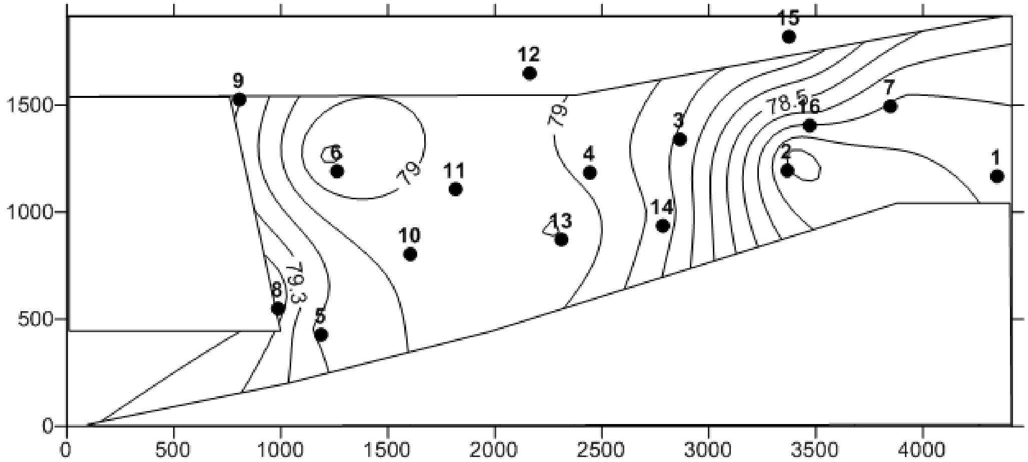


Figure (6) Deep Wells Water Levels

4.2 Areas Affected by High Groundwater Table

The analysis of the reasons for elevated groundwater table in the city is complicated by several factors as the high difference in permeability between upper and lower layers, anisotropy of upper layer, and limited amount of field data. Figure (7) depicts the contours of depth to water within the city. It can be seen that the area mostly affected by elevated groundwater is in the western and southwestern region of the city bordering the Ramady Canal, and extending to more than half the city's width to the east. The map shows contours of depth to groundwater of 1.0m, 2.0m, 3.0m, etc.

The critical area (depth to groundwater table less than one meter) has been hatched. It can be seen that about half of the city area lies in the critical area. Figure (7) reveals that the critical area consists mainly of agricultural areas with scattered residential settlements. Further, it could be noted that although the Esna Temple is located in the highest location of the city, it is strongly affected by elevated groundwater since the temple structure is immersed in the ground well below the ground surface.

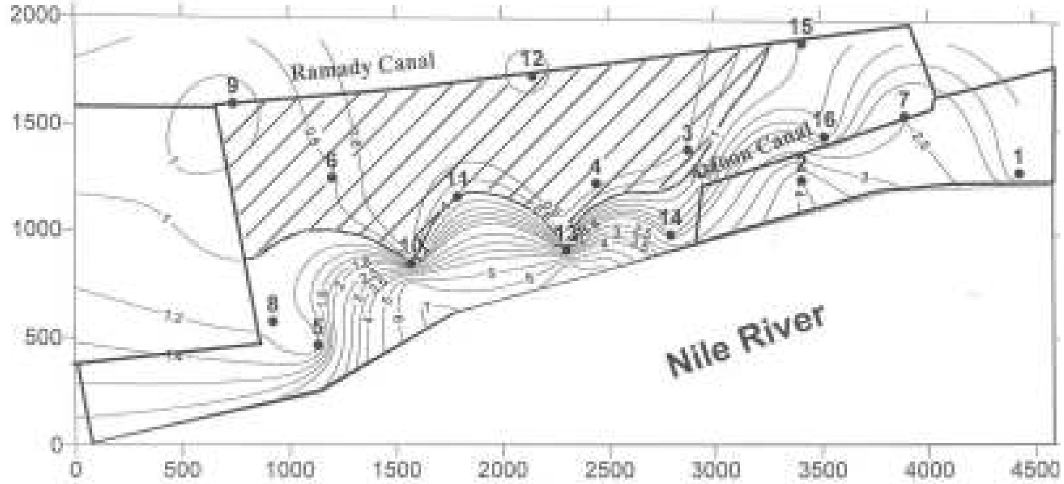


Figure (7) Critical Area (depth to water less than 1.0 m) based on measured depth to water in piezometers

5. Computational Groundwater Model

This section describes the development and calibration of a finite element multi-layer aquifer model to simulate groundwater conditions in Esna. First, the model characteristics and main underlying assumptions and capabilities are discussed. Then, the model is used to predict measured groundwater levels, given measured aquifer characteristics and boundary conditions (model calibration). Differences between measured and predicted water levels are presented.

5.1 Model Type and Capabilities

The approach adopted for simulation of groundwater conditions within Esna City is a quasi three-dimensional approach, which simulates horizontal flow in each layer as two-dimensional flow, in addition to vertical flow between the layers. To achieve this, a multi-layer finite element model has been utilized for the study area. The computational model selected for this study is MicroFEM version 3.6, 2004. Confined, semi-confined, phreatic, stratified and leaky multi-aquifer systems can be simulated with a maximum of 20 aquifer layers. Heterogeneous aquifers, aquitards and spatially varying anisotropic aquifers can be simulated under steady-state and transient flow conditions. The model can simulate spatially and temporally varying wells and boundary conditions, precipitation, evaporation, drains, rivers and wadi top systems.

5.2 Application of the Computational Model to Esna City

A groundwater model has been developed to represent the hydrogeological conditions of Esna City. The following summarizes the adopted approach and underlying assumptions:

5.2.1 Surface conditions

The city of Esna consists mainly of two different types of surface cover. The first type is the main city, covered with residential and public buildings, streets, etc. The second type of cover is agricultural lands. These agricultural lands contain scattered areas of residential settlements. Figure (2) shows the extent of the two types of surface cover.

5.2.2 Aquifer characteristics of Esna

The aquifer underlying Esna have been simulated as two layers. The upper layer is represented by the silty-clay cap, while the lower aquifer is represented by the sand aquifer. Interchange between the two aquifers has been simulated through the specification of a leaky layer, having a vertical permeability of one tenth the horizontal permeability of the upper layer.

Field data obtained from shallow and deep piezometers as well as from tests have been entered to the model at well locations and used to interpolate field data for other locations of the study domain. The following parameters were used in the model.

In the upper clay/silt cap, horizontal permeability from Auger hole tests was estimated between 3 and 6 cm/day. An average value of 4 cm/day was applied to the study domain. Vertical permeability was taken as 1/10 of this value, based on previous studies in the Nile Valley alluvium in Upper Egypt (Abdelaziz, 1984). The thickness of the layer was obtained from piezometer well logs, and interpolated over the study domain.

In the lower sand layer, values of aquifer characteristics were obtained from the above-cited references, as little variability was found among these references in values for that layer. The horizontal permeability was taken as 40m/day. The "hydraulically active" aquifer thickness of that layer was taken as 10m.

For the leaky layer, the flow was assumed to be essentially vertical, and the vertical permeability value of 4 mm/day was chosen. The thickness was based on the "active" thickness of the upper clay/silt layer through which vertical exchange occurs, and averaged around 5m.

5.3 Finite Element mesh of the study domain

A finite element mesh has been developed for the City of Esna region. The boundary conditions for the city of Esna are shown on Figure (2). A triangular finite element mesh has been developed to represent the study domain, Figure (8). The mesh contains 2304 nodes and 4344 elements for each aquifer layer.

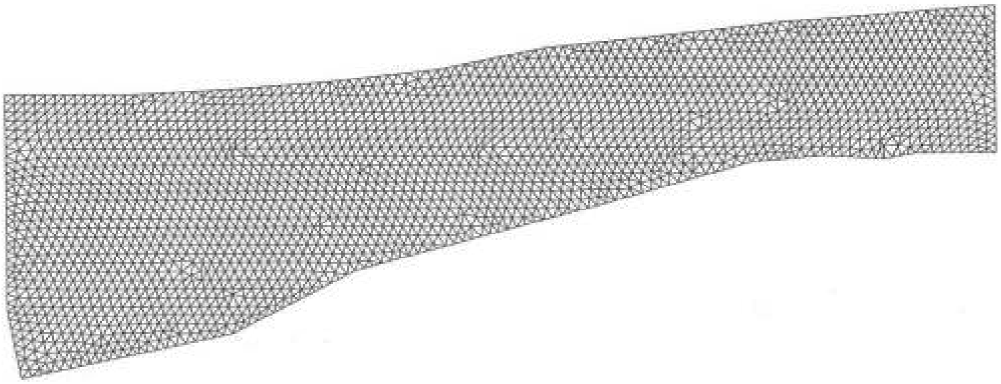


Figure (8) Finite Element Mesh of the Study Area

5.4 Boundary Conditions

The eastern boundary has been specified as a first type (specified head) boundary condition for both aquifer layers, represented by the water levels in the Nile River. Water levels of the Nile in the vicinity of the study domain range between 78.80 and 78.60 m upstream of New Esna Barrage, and 74.66 and 74.59 m downstream of New Esna Barrage.

The western boundary condition is represented by Ramady Canal. The canal has been specified as a first type (specified head) boundary condition for the upper aquifer layer, and as a third type (leaky) boundary condition for the lower layer. Measured water levels in Ramady Canal have been entered for this boundary. Water levels along this boundary vary from 80.00 m in the south to 79.50 m in the north of the study domain. The land use west of the city consists of graveyards, military areas, as well as some agricultural activities, mainly fed from Ramady Canal through minor ditches. To the west of this starts the Western Desert. Ramady Canal has been considered to provide a groundwater divide, due to its relatively large size and elevated water level.

The southern and northern boundary conditions have been specified as no-flow boundaries. This has been based on the observation that the flow of groundwater at the southern and northern extremities of the study domain are essentially from west to south (i.e. from the Ramady canal to the Nile in the south and from the Ramady canal to Asfoun canal and from Asfoun canal to the Nile in the north). Further, to minimize any inaccuracies resulting from this assumption, the study domain has been extended about 500m towards the south and towards the north.

Further, a first type internal boundary condition has been specified for Asfoun Canal, which passes through the study region in the upper aquifer layer. For the lower layer, Asfoun Canal has been represented as a third type (leaky) boundary condition. Asfoun Canal is supplied by gravity from the Nile upstream of new Esna barrage. About 150 m downstream this intake, a regulator across the canal creates a drop of about 0.75m in the water level. Thus, water levels for Asfoun Canal have been specified as 78.67m upstream the regulator, and 77.94 to 77.74m downstream the regulator.

A secondary irrigation canal, El-Mekssar Canal, cuts through the southern part of the study area. This canal is a small canal (depth about 1.20m) operated on a rotation basis. It has been included as a third type boundary in the model. It has been simulated as running full when simulating groundwater lowering alternatives, as this represents the most critical case.

5.5 Model Calibration

The ability of the model to reproduce measured data is tested. This is performed through the specification of all aquifer parameters (permeability, geometric data, storativities, etc.) and boundary conditions. Arbitrary (but physically reasonable) piezometric head values are supplied to all internal nodes. This might be an average constant value somewhere between the minimum and maximum values of the boundary conditions. Then the model is applied to calculate the piezometric levels in the study domain, given the measured boundary conditions. Simulated piezometric levels are then compared with average measured levels. If a discrepancy exists in certain regions, the reasons behind such discrepancy are investigated, and model assumptions are revised to improve simulation results. Upon completion of the calibration process, the model was ready to predict the impact of any future excitations to the aquifer domain (such as changes in boundary conditions, effect of sewer system, effect of land drainage system, etc.).

Figure (9) shows the computed piezometric heads for the shallow aquifer. These computed heads have been compared with the average measured values, Table (4). In Figure (9) there is an area with groundwater level slightly higher than the surrounding areas (around 79.1 m against 78.8 m in the area around). This area represents a densely populated area of the old city. While calibrating the model, it was observed that this area shows somehow elevated groundwater. This has been interpreted as leakage from the septic tanks of this area. Thus a surcharge of about 0.5 mm/day has been added to that area to simulate this effect. This surcharge has then been removed when modeling the situation with sanitary drainage system in operation.

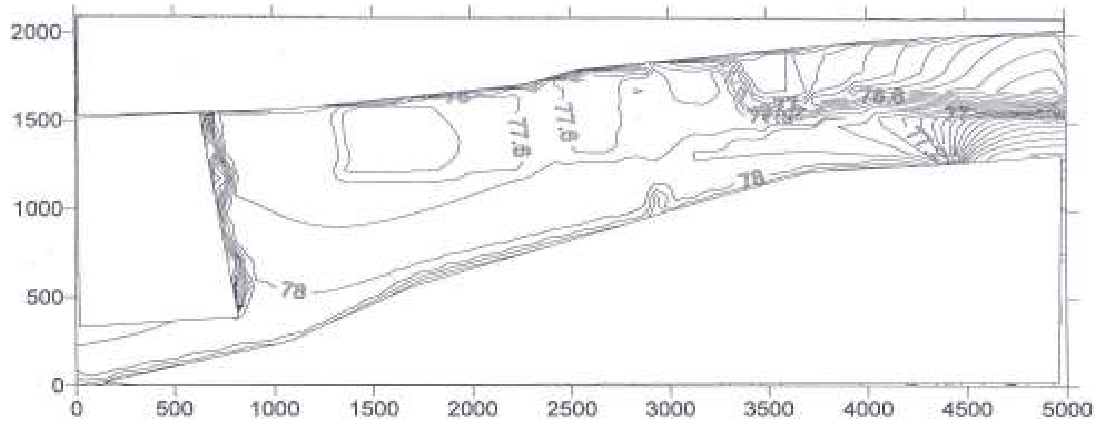


Figure (9) Predicted depth to water table with sanitary drainage system in operation

The average values have been based on the days of complete inventory of piezometers reading of the 32 piezometers (16 shallow and 16 deep). The complete inventory has been performed 4 times at the following dates: August 12; August 21; September 4 and September 15. Table (4) shows that the difference between measured and simulated values is within acceptable limits. The minimum difference is 4cm at Piezometer No. 8, while the maximum difference is 20cm at piezometers No. 6. Further, it can be observed that the difference is positive at some locations, and negative at others. This can be attributed to irrigation of agricultural lands and/or seepage from septic tanks, for which no concrete data is available.

Table (4) Comparison between Measured and Computed Water Levels for Shallow Aquifer

Shallow	Measured Groundwater Levels (m)					Computed	Difference
piez #	12-Aug	21-Aug	4-Sep	15-Sep	Average	Levels (m)	(m)
1	78.10	78.33	78.20	78.26	78.22	78.28	-0.06
2	78.02	78.11	78.23	78.19	78.14	78.19	-0.05
3	78.60	78.80	78.90	78.94	78.81	78.72	0.09
4	78.88	79.05	78.93	78.91	78.94	78.81	0.13
5	79.05	79.10	78.98	78.94	79.02	78.85	0.17
6	78.76	78.80	78.80	78.80	78.79	78.99	-0.20
7	78.40	78.43	78.39	77.17	78.10	78.22	-0.12
8	79.21	79.37	78.61	79.61	79.20	79.16	0.04
9	78.94	79.00	79.95	78.96	79.21	79.22	-0.01
10	79.00	79.13	79.10	79.08	79.08	78.97	0.11
11	78.95	79.07	79.03	79.00	79.01	78.90	0.11
12	79.11	79.18	79.16	79.15	79.15	79.07	0.08
13	79.10	79.17	79.16	79.13	79.14	79.07	0.07
14	78.72	78.86	78.81	78.82	78.80	78.69	0.11
15	79.40	79.46	79.16	79.11	79.28	79.24	0.04
16	78.42	78.56	78.38	78.35	78.43	78.37	0.06

Table (5) Comparison between Measured and Computed Water Levels for Deep Aquifer

Deep	Measured Groundwater Levels (m)					Computed	Difference
piez #	12-Aug	21-Aug	04-Sep	15-Sep	Average	Levels (m)	(m)
1	78.10	78.31	78.28	78.32	78.25	78.29	-0.04
2	77.90	77.99	78.15	78.12	78.04	78.36	-0.32
3	78.59	78.78	78.90	78.93	78.80	78.77	0.03
4	78.84	79.04	78.97	78.92	78.94	78.89	0.05
5	79.26	79.21	79.14	79.19	79.20	79.00	0.20
6	78.80	78.95	78.87	78.87	78.87	79.15	-0.28
7	78.24	78.33	78.34	78.35	78.32	78.30	0.02
8	79.55	79.53	79.58	79.58	79.56	79.14	0.42
9	79.43	79.36	79.32	79.40	79.38	79.30	0.08
10	79.00	79.20	79.00	79.08	79.07	78.98	0.09
11	78.96	79.07	79.10	78.99	79.03	79.00	0.03
12	78.93	79.15	79.01	79.14	79.06	79.08	-0.02
13	79.01	79.16	79.16	79.11	79.11	78.85	0.26
14	78.67	78.80	79.14	78.83	78.86	78.77	0.09
15	78.51	78.81	79.82	78.71	78.96	78.73	0.23
16	78.39	78.55	78.75	78.05	78.44	78.53	-0.09

6. Alternatives for Groundwater Lowering System

The developed finite element model serves as a tool to predict the expected effect of any water lowering alternatives on the groundwater table (and consequently on the critical area) in the city.

The main idea behind water lowering alternatives comes from the identification of the reasons behind elevated groundwater levels in the city. It is important to consider the effect of the complex hydrogeology of the region. Due to the relatively low permeability of the upper silt-clay layer, horizontal flow is mainly governed by the lower sand aquifer. From the above analysis it has been concluded that piezometric heads in the lower layer are mainly governed by the major water bodies (i.e. the Nile and Ramady Canal to a less extent). However, the area of interest for lowering water table is the upper layer. Water table in this layer is governed generally by the piezometric head in the lower layer, as well as by other factors such as irrigation canals, infiltration from agricultural lands, possible leakage from septic tanks and municipal water supply pipes, etc. Although the water level in this layer is directly affected by the existing water bodies, the effect is limited to a zone adjacent to the respective water bodies and dies off further away from that body, as has been verified by computer simulations in Figure (7), leaving the lower layer to control water levels. The city of Esna is composed of two distinct types of land use, residential areas (to be covered by sanitary drainage system) and agricultural areas. As has been mentioned above, no agricultural drainage system has been provided. Further, the critical area (depth to groundwater less or equal 1.0m) lies mainly in the agricultural areas, affecting scattered residential settlements within agricultural areas. First, the effect of the proposed sanitary drainage system on the groundwater situation is assessed. Then, additional measures needed to lower the water table to acceptable limits shall be considered.

6.1 Effect of Proposed Sanitary Drainage System on the Groundwater Situation within Esna City

The sanitary drainage system has been entered to the model. According to the Egyptian code of practice, infiltration into the system from groundwater amounts up to 20% of the design flow of the sanitary drainage system. Here different values for the percentage have been assumed. The sanitary drainage system has been designed to cover all of the built-up areas in the city (an area of about 5 square km). This is achieved through 6 drainage zones, each containing a pump station. The total design discharge for the six pump stations is about 24.000 m^3/day for the year 2020. Amounts 5% and 10% of the design discharge (1,200 and 2,400 m^3/day, respectively) of groundwater was assumed to be allowed to enter the sanitary drainage system. This amount of discharge has been distributed equally among all built-up areas to model the scenario of groundwater levels with sanitary drainage system in operation. Further, it has been assumed that leakage from septic tanks will seize. Figure (9) shows the predicted depth to groundwater table for the case of 10% infiltration. It can be seen that the sanitary drainage system has an overall beneficial effect on lowering the groundwater table in the city. However, some locations of critical areas (depth to water table less or equal 1.0m) still exist, especially in the vicinity of agricultural areas. Thus, it can be concluded that additional groundwater lowering measures are needed. These measures are further described below.

6.2 Investigation of possible groundwater lowering alternatives

To reach the selection of the optimum water lowering system, several alternatives have been considered and analyzed as follows;

6.2.1 Lowering the piezometric head of the lower aquifer

This alternative has been considered due to the influence of the lower layer on controlling the groundwater table in the city. This could be achieved through the design of pumping wells tapping the lower aquifer in critical areas. Although this could yield a solution to the groundwater problem, this alternative has been rejected due to the following reasons:

- The need to pump substantial amounts of water from the lower aquifer due to its relatively high permeability in order to achieve the required lowering.
- The need for continuous operation around the clock.
- Maintenance requirements.
- Possibility of creating differential settlement in buildings of the city due to the depression cones of pumping wells. This could lead to damage to buildings, especially medium and large-size buildings such as schools and hospitals, some of which were found to be located in the critical area adjacent to Ramady Canal.

6.2.2 Lining Ramady Canal

As the canal is a major canal as described above bordering the critical area, it was identified of being a main cause for elevated water levels in the critical area, on one hand through direct contact with the upper layer, and on the other through recharge to the lower layer. Although the canal is not in direct contact with the lower aquifer, throughout its course, at some regions the clay cap is thin enough to validate such assumption (e.g. in the vicinity of piezometer 12). Further, continuous dredging activities further lead to increased amounts of seepage. However, this solution has been rejected for the following reasons:

- There exists uncertainty regarding the degree of control of the water table by the canal.
- The canal extends for several hundreds of kilometers, and sealing the reach adjacent to the city of Esna might not solve the problem due to the possibility of leakage from the upstream reach affecting the study area.
- The alternative would at best provide a partial solution, as this does not mitigate other affects in the critical area such as infiltration from agricultural lands. Further, if the regional affects other than the canal lead to increased piezometric head in the lower aquifer, this would result in raising the water table of the upper layer.
- As this canal is running full year-round, the execution of any lining would require substantial construction works such as creating a bypass of similar size, the technical difficulties and financial burdens of which would be prohibitive.

6.2.3 Constructing a cutoff drain

Simulation runs with a cutoff drain indicated that the drain serves only a limited strip of land on both sides of the drain. This is due to upward flow from the lower layer feeding the upper layer.

6.2.4 Constructing a tile drainage system in open areas

Due to the hydrogeological conditions of the city, it was conceived that the problem of the city must rely on two conjunct solutions. As has been indicated above, the proposed sanitary drainage system is expected to solve the problem of elevated water table in the city residential areas. A solution is required that solves the problem in the agricultural areas. Thus, the following system is proposed for analysis:

- A system of secondary tile drains (4-inch PVC pipes with gravel filter) to be distributed in the agricultural areas within the city, to collect any excess irrigation water and/or upward groundwater flow, and to discharge the water to the main covered drain. The area to be covered by tile drains represents all agricultural

areas within the city (an area of about 300 feddans i.e. about 1.25 square km). The drain spacing for tile drains has been assumed to be around 30-50m on average. Tile drain depths have been assumed to vary from 1.20 to 1.80m.
- A main covered drain (perforated PVC pipe with gravel filter, diameter varying from 8 inch to 14 inch) to be constructed parallel to Ramadi Canal.

It is important to take consideration of the high level of iron and manganese found in the groundwater samples in the final design of the drain. The drain should be designed to run full to prolong life and minimize maintenance requirements.

Based on computer simulations of the drainage system, the expected flows from the drainage system are about 2000 m3/day. With regards to discharging (disposing off) the drainage water, two alternatives have been considered:

Alternative 1: Discharge to Asfoun Canal

The water levels in Asfoun Canal are about 2m lower than Ramady Canal. In this case, a pumping station would be required at Asfoun Canal, as the main drain shall be around 2.5m below the canal water level at its confluence to the canal. A sump (ground reservoir) would need to be constructed to collect the flow of about 8 hours (i.e. storage volume around 800 m^3).

Alternative 2: Discharge to the Nile downstream of the New Esna Barrage

The water level of the Nile downstream of the barrage is quite low, on the average 74.50m. Thus, it is possible to discharge the flows by gravity to the Nile.

6.2.5 Effect of proposed groundwater drainage system on the groundwater situation within Esna City

To predict the expected effect of the proposed groundwater drainage system (main covered drain and tile drainage system) on the groundwater situation in Esna City, the calibrated groundwater model has been used and the following scenarios have been simulated:

1. Effect of groundwater drainage system on the groundwater levels in Esna: This phase represents the expected groundwater situation after construction of the groundwater lowering system and prior to the construction of the sanitary drainage system.
2. Combined effect of the groundwater lowering system and the sanitary drainage system on groundwater levels in Esna: This phase represents the expected groundwater situation after completion and operation of the groundwater lowering system together with the sanitary drainage system.

a. Effect of groundwater drainage system on the groundwater levels in Esna

The groundwater drainage system (main covered drain and tile drainage system in agricultural areas) has been entered to the calibrated model of Esna City. Figure (10) shows the predicted groundwater levels in the upper aquifer layer, figure (11) shows the predicted depth to water, and figure (12) shows simulated Groundwater Levels with Groundwater Drainage System Only. It can be seen from figure (11) that a minor critical area still exists in the residential region of the city. However, a comparison between figures (7) and (11) shows that the critical area in the city has been reduced to about 10% of its original size.

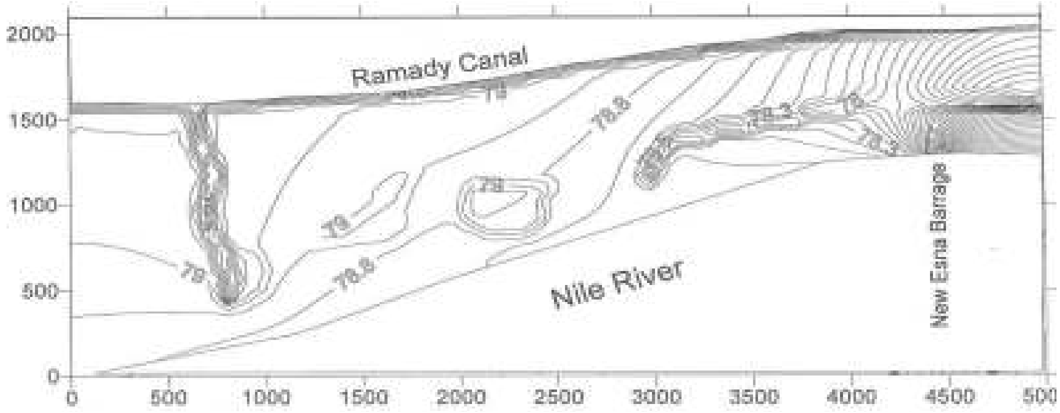


Figure (10) Contour Lines of Computed Groundwater Levels in Upper Layer

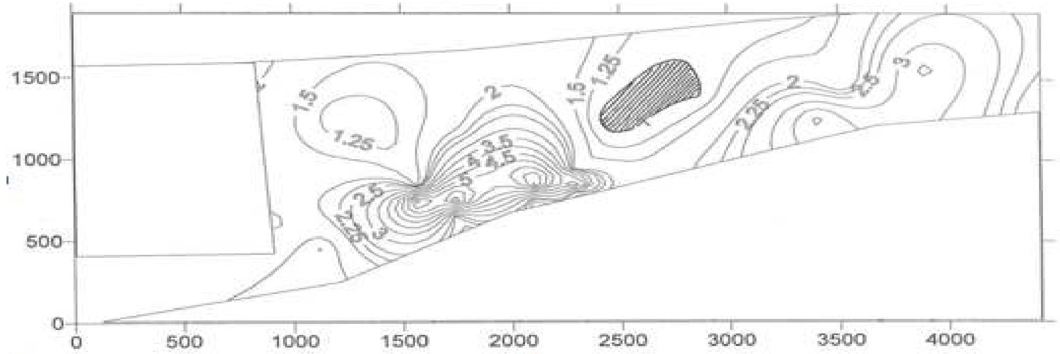


Figure (11) Depth to Ground and Critical Area with Groundwater Drainage System

b- Combined effect of the groundwater lowering system and the sanitary drainage system on groundwater levels in Esna

Figure (13) shows the predicted groundwater levels in the upper aquifer layer, and Figure (14) shows the predicted depth to water. Figure (14) reveals that the critical area has disappeared completely and that the minimum depth to groundwater table shall be not less than 1.50m. Table (6) compares between the initial averages measured groundwater levels at piezometers locations and simulated groundwater levels after the construction of the groundwater drainage system and Sanitary Drainage system. The final expected lowering from the initial values due to the construction of both systems ranges between 0.6 and 1.70m.

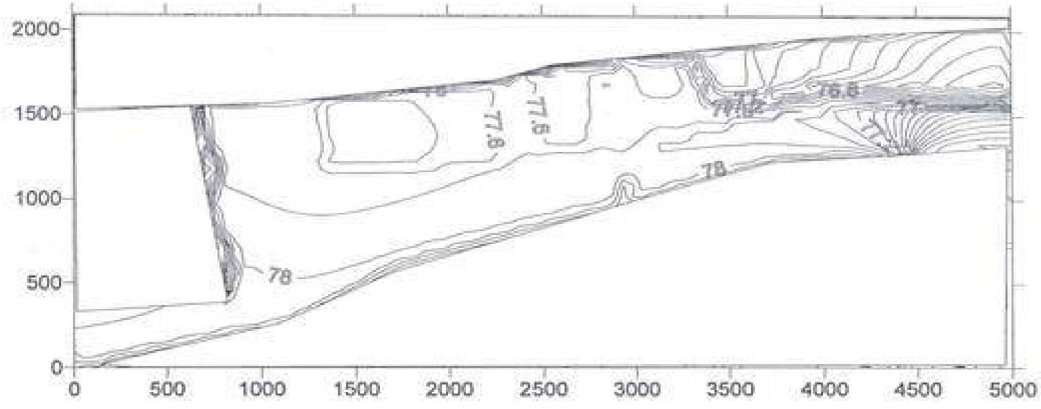


Figure (12) Simulated Groundwater Levels with Groundwater Drainage System Only

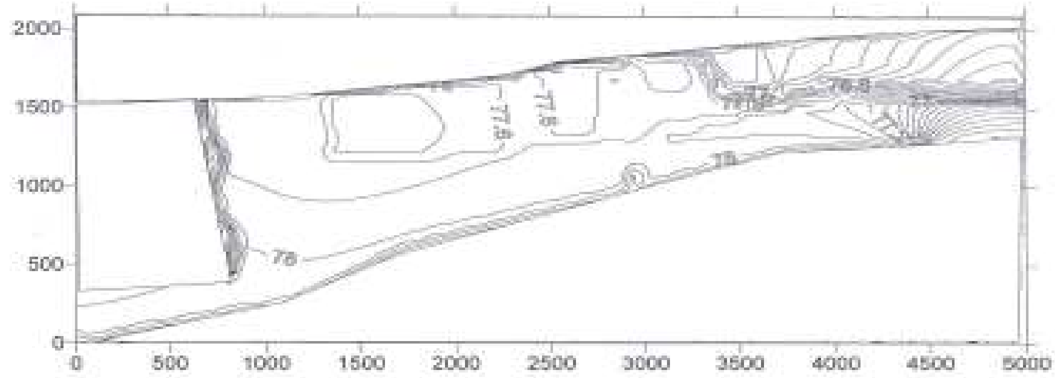


Figure (13) Simulated Ground Levels with both Proposed Groundwater Drainage System and Sanitary Drainage System in Operation

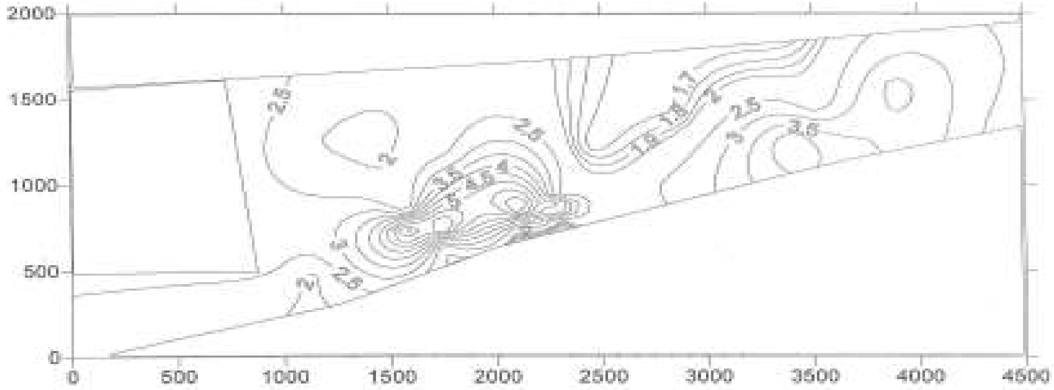
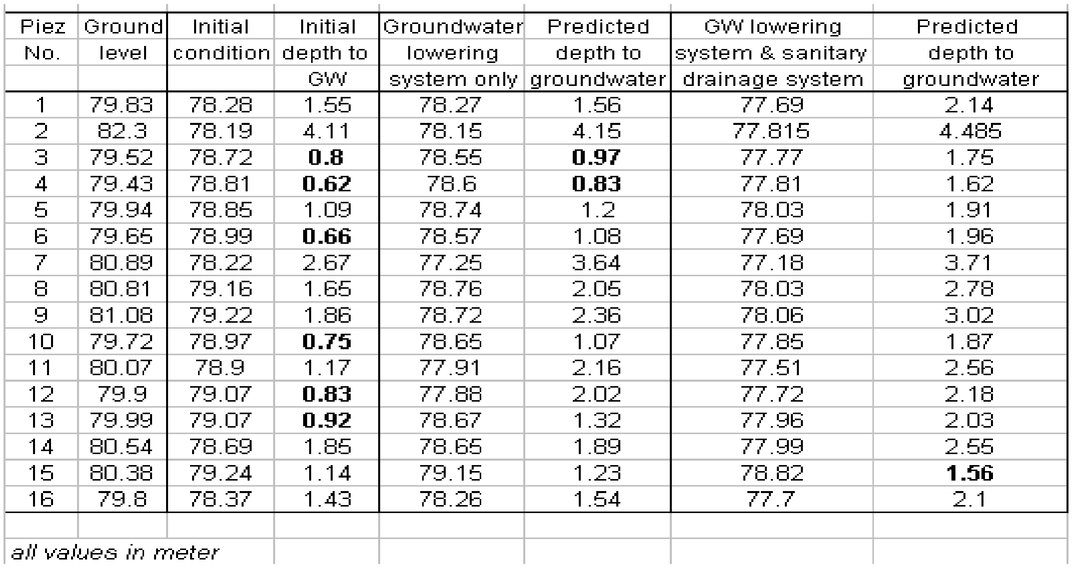


Figure (14) Depth to Groundwater with both Land Drainage System and Sanitary Drainage System in Operation

Table (6) Predicted levels and depth to groundwater at piezometer locations due to groundwater lowering system and sanitary drainage system



Piez No.	Ground level	Initial condition	Initial depth to GW	Groundwater lowering system only	Predicted depth to groundwater	GW lowering system & sanitary drainage system	Predicted depth to groundwater
1	79.83	78.28	1.55	78.27	1.56	77.69	2.14
2	82.3	78.19	4.11	78.15	4.15	77.815	4.485
3	79.52	78.72	**0.8**	78.55	**0.97**	77.77	1.75
4	79.43	78.81	**0.62**	78.6	**0.83**	77.81	1.62
5	79.94	78.85	1.09	78.74	1.2	78.03	1.91
6	79.65	78.99	**0.66**	78.57	1.08	77.69	1.96
7	80.89	78.22	2.67	77.25	3.64	77.18	3.71
8	80.81	79.16	1.65	78.76	2.05	78.03	2.78
9	81.08	79.22	1.86	78.72	2.36	78.06	3.02
10	79.72	78.97	**0.75**	78.65	1.07	77.85	1.87
11	80.07	78.9	1.17	77.91	2.16	77.51	2.56
12	79.9	79.07	**0.83**	77.88	2.02	77.72	2.18
13	79.99	79.07	**0.92**	78.67	1.32	77.96	2.03
14	80.54	78.69	1.85	78.65	1.89	77.99	2.55
15	80.38	79.24	1.14	79.15	1.23	78.82	**1.56**
16	79.8	78.37	1.43	78.26	1.54	77.7	2.1

all values in meter

6.2.6 Cost estimate of proposed groundwater drainage system

A preliminary cost estimate for the two alternatives is provided below.

Alternative 1: Discharge to Asfoun Canal

Item	**Cost, $ US**
Main covered drain up to Asfoun Canal (including manholes)	404,600*
Secondary tile drainage system	142,300
Pump station	202,300
Total	749,200

Alternative 2: Discharge to the Nile downstream of the New Esna Barrage

Item	**Cost, $ US**
Main covered drain up to Nile (including manholes and valves)	476,000*
Secondary tile drainage system	142,800
Crossing with Asfoun Canal and adjacent road	54,740
Crossing the Corniche (main road) at the Nile and civil outlet structure	28,560
Total	702,100

* A spacing of manholes of 50m has been assumed along the main drain.

In addition, the cost of operating the pump station should be considered in the first alternative.

6.2.7 Comparison between alternatives

Two alternatives have been presented above for the discharge of the drainage effluent. Both alternatives shall have the same effect on the lowering of groundwater table. Further, no big difference exists with regards to cost.

However, the second alternative has the following advantages:

- It requires less time for construction (estimated execution time is around 2.5 months). Thus, the alternative can be constructed prior to the construction of the sewer network, which will make construction of the sewer network easier at some locations of the city.
- It has no running cost. The first alternative requires running cost for the pump station.
- It has no operation requirement. The water flows by gravity to the Nile. In the first alternative, some operation requirements exist for the pump station.
- Maintenance requirements are minimal. If the drainage network is properly designed, it will operate with virtually no maintenance requirements. However, the pump station will require continuous maintenance.
- In the first alternative it will be necessary to secure a site for the pump station and reservoir. This land might have to be purchased (price of land has not been included in the cost estimate of the first alternative). No such requirement exists in the second alternative.

7. Conclusions and Recommendations

Field investigations for the groundwater study of Esna City have been carried out. Critical areas within the city of Esna and sources of groundwater recharge have been identified. A finite element multi layer aquifer model has been developed for the city of Esna. The model has been tested on measured values and produced satisfactory results. The major findings are summarized below:

a) Esna City is underlain by two layers. A shallow silty-clay layer and a deep sand aquifer. Both layers are hydraulically interconnected.

b) About half of the city's area is subjected to a high groundwater level, 1m or less below ground surface. The areas strongly affected by elevated groundwater levels lie in the western and southwestern parts of the city.

c) Results of the simulation model showed that the sanitary drainage system will have a positive impact on the groundwater situation of the city, but some locations will remain with elevated groundwater table. Thus, a groundwater lowering system consisting of a secondary tile drainage system and a main covered drain is recommended. The expected lowering of groundwater levels in the critical areas of the city with the groundwater lowering system in operation range between 0.5 and 1.4m. The critical area (depth to groundwater less than 1.0m) is expected to be reduced to about 10% of its present area.

d) The simulation of the combined effect of the groundwater drainage system and the sanitary drainage system showed that expected lowering of groundwater levels ranges between 0.6 and 1.7m, with a minimum depth to groundwater table of 1.50m.

e) With regard to discharge of the effluent, two alternatives have been proposed, either discharge to Asfoun Canal via a pump station or discharge to the Nile River by gravity. The second alternative is recommended.

f) The proposed groundwater drainage system is expected to have a positive impact on the groundwater situation of the City of Esna. The following advantages can be expected:

    - It will provide an agricultural drainage system for an area of about 300 feddans. This will have a positive effect on the productivity of these areas, thus raising the standard of living and family income.

    - The drainage effluent will be discharged to the Nile (about 2000 m^3/day), and thus contributes positively to the water balance of the river.

g) Esna Temple is at present affected seriously by the elevated groundwater levels. It is recommended that the comprehensive solution of the groundwater problems of the temple consists of two components, a regional and a local component. The regional component shall be provided by the execution of the proposed groundwater lowering system as well as by the proposed sanitary drainage system. Although saving the temple from deterioration, and possibly destruction, through elevated groundwater levels shall have a direct impact on the inhabitants of Esna due to increased tourist activities, creation of jobs, etc., the benefits are far more important as the temple should not be regarded as the property of the Egyptian people but a heritage of the whole humanity.

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