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A GROUNDWATER FLOW MODEL FOR WATER RELATED DAMAGES ON HISTORIC MONUMENTS – CASE STUDY WEST LUXOR, EGYPT

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Abstract

Shallow groundwater is an important factor contributing to the deterioration of the Pharaonic monuments in Egypt. The capillary zone of the soil layers reaches the ground surface, and constant transport of salts and water takes place in an upward direction due to evaporation. The result of this is a concentration of salts in the upper soil layers under and near the surface of the temple walls.

The main objectives of this research were to investigate the hydrogeological conditions at the West bank temples, and to propose measures to lower the groundwater levels by at least 2.5 m, avoiding in this manner deterioration of the monuments caused by evaporation driven salt transport.

Results show that a reduction of irrigation rates over the model area is not sufficient to lower groundwater levels and it has to be combined with other measures, such as pumping and a better management of the internal canals and drainage flows. The fundamental problem is the raised groundwater table due to increased irrigation and reduced water level variations in the Nile. Therefore, the most sustainable solution is to change or improve the irrigation systems in the area.

Key words – Groundwater, conceptual model, hydrogeology, irrigation, GMS 6.0, World Heritage, Luxor, Egypt.

1. Introduction

Due to the continuous growth of population and the needs for food security, the reclamation of new lands for agriculture has started within the desert fringes of the Nile Valley and Delta. This, combined with excessive irrigation, contributes for extensive areas of traditionally cultivated lands in the Nile Valley to become affected by waterlogging and soil salinity (see, for example, Shamrukh, 2001). Since ancient times, the Nile has deposited layers of fine-grained alluvial soil several meters thick in the valley. The capillary zone normally reaches the ground surface and continuous transport of salts takes place in an upward direction when water is available from the saturated zone (Høybe, 2002). These facts combined with the water capillary forces, make that shallow groundwater moves upwards where the driving force is the high rate of evaporation at the ground surface and at the surfaces of the monuments themselves. Salts are dissolved in the water and enriched at surfaces, where they crystallize. This causes discolouring, and owed to the expansion during crystallization, the building material can be crashed and the surfaces deteriorated.

The temples of Medinet Habu, Ramesseum and Sethos I are located in the western side of the Nile and the city of Luxor (Figure 1).

2. Previous studies in the area

According to the general information available, the hydrological regime in the Nile valley was changed considerably after the construction of the High Aswan Dam (HAD) in 1970 (Abu-Zeid, 1997). The construction of the dam made it possible to control the water levels of the river and the canals, and in this way achieve the most

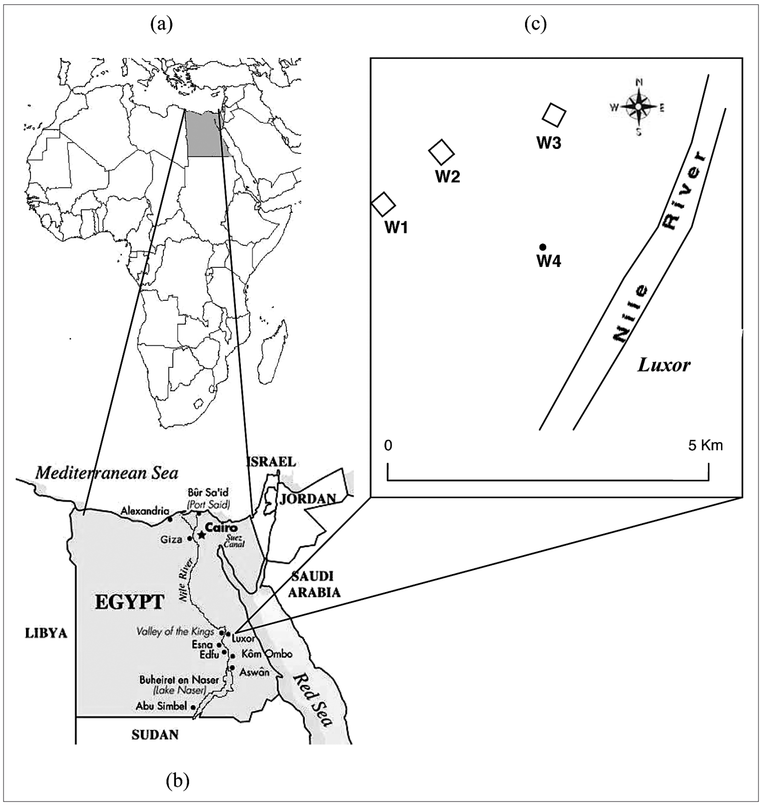

Figure 1. *Situation Maps of (a) Africa, (b) Egypt: showing the location of the city of Luxor; and (c) the study area and the observation wells (W) at the three temples, and the fourth one closer to the Nile.*

favourable conditions for irrigation. Høybe (2002), presents in the figure 2 how the groundwater regime in the area has changed during time.

The difference between the groundwater level before and after the intensive regulation and irrigation is indicated in figure 2, meaning that the water level was increased considerably (2–3 m) in the period March to September, providing a surplus of water which in turn is evaporated during warm seasons.

Traunecker (1970, 1971 and 1975) installed approximately 20 groundwater observation wells at Karnak and measured groundwater levels in these and some old wells for a total time of more than 2 years. This information was utilized in the project for the Salvation of Karnak and Luxor Temples executed by SWECO INTERNATIONAL (2002). The Salvation project included several field investigations similar to water level observations, pumping tests, water quality analysis, settlement observations, surveying and mapping, groundwater modelling including calibration and validation processes.

In 1997 the Egyptian Research Institute for Ground Water (RIGW, 1997) performed a study of the problem with shallow groundwater at Karnak. This study included field investigations (surveying, drilling of groundwater observation wells, geoelectrical investigations and water samples). The RIGW produced Topographical and Hydrogeological Maps for Luxor.

In 2001 Shamrukh and others, presented a study with some of the hydrogeological conditions in Tahta, a region situated about 200 km north from Luxor. These conditions were basically based on the studies executed by the RIGW.

3. Methodology

The principal objective in the methodology was to use the available and useful data to simulate the groundwater flow system in the specific area, with the aid of the computer program GMS (Groundwater Modelling System), version 6.0.

In studying a ground water flow system, we develop a conceptual model which is static. It describes the present condition of a system. To make predictions of future behaviour, it is necessary to have some kind of dynamic model. There are many types of dynamic models of ground water flow; they include physical scale models, analogue models, and mathematical models (see, for example, Fetter 2001).

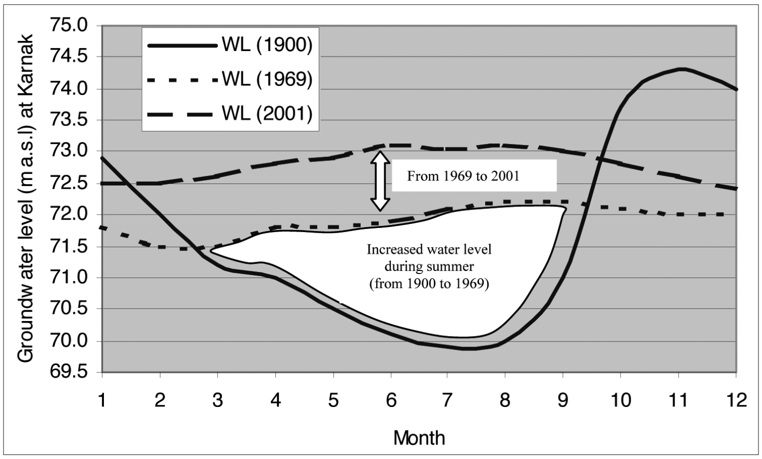

Figure 2. *Change in groundwater regime (well 31 at Karnak).*

3.1. Field investigation

The objectives of the supplementary field investigations were to collect more information about the stratigraphy of the area, get a better understanding of the groundwater flow and groundwater levels, analyze the groundwater quality and relate it to possible recharge sources and salt concentrations, localize groundwater observation point wells and monitor groundwater level fluctuations for the analysis and presentation of the results. The activities performed included laboratory work, execution of borings, collection of water elevation readings for all piezometers and collection of soil samples for testing.

The groundwater monitoring works started on the 25th of September 2005 and the readings were taken every 10 to 15 days, for a period of approximately 6 months.

For an average terrain elevation of 78 m for the piezometers, the depth of the groundwater fluctuated between 4 m for well number 4 (near Nile River) and 0.80 m for well number 2 (Ramesseum Temple), respectively. Piezometer readings were left out at Ramesseum Temple from December 2005 until the end of the monitoring, due to unknown reasons (Figure 3).

3.2. Location and Topography

The area is located in west Luxor, between latitude 25.44' and longitude 32.37', approximately 4 Km North West from Karnak Temple (RIGW, sheet NG 36F6a, Al-Uqsur, Luxor).

The cultivated area extends from the Nile River to the temples of Medinet Habu and Ramesseum, where the area is divided principally by the Asfün Canal.

The stratigraphy in the Nile valley begins at the bottom with the Nubian Sandstone; secondly the Lower Eocene limestone that forms the hills at the sides of the valley, underlying the Pliocene Clay that extends to the slope of the limestone. Next we find the sand and gravel deposits of the Late Pleistocene, with a thickness of

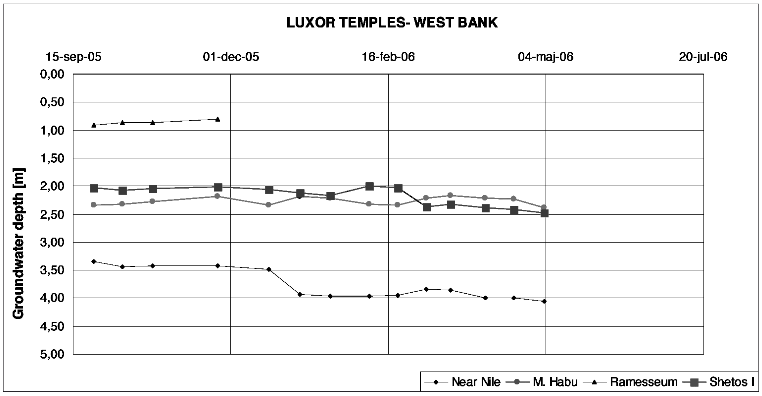

Figure 3. *Water Levels for piezometers from September 2005 to May 2006 (A&A Report, March, 2006).*

approximately 40 m in the study area (RIGW, 1997). At the bottom there are Holocene deposits consisting of silt and clay with inter-bedded layers of sand and gravel. The thickness of these deposits varies between 0 (they disappear at the outer fringes of the valley) and 20 m.

According to the hydrogeological map of Luxor, the aquifers are classified as highly productive, highly to moderated, and low and non -productive aquifers. The main aquifer is formed by the Late Pleistocene sand and gravel. The over-laying Holocene silt and clay deposits have a variable permeability and acts at many locations as a semi-confining layer (SWECO Report, 2002). On the outside fringes, where the silty and clayey deposits disappear, the main aquifer becomes unconfined. The Pliocene Clay below the Late Pleistocene sand and gravel deposits is considered an aquiclude.

For the present study, the Pliocene Clay is considered to form a tight impermeable bottom layer, limiting the groundwater system to the Holocene and Late Pleistocene.

4. Groundwater model set up

The main objectives of the groundwater modelling were to identify the area where detailed field data are criteria to the success of the model, and to analyze the effect of groundwater levels for different measures similar to drainage, local pumping, and restriction of some irrigation areas. With the groundwater model it was possible to:

- Analyze the effect of pumping from wells located in the temples areas
- Analyze the effect of limiting the irrigation recharge rate over the modelling area during specific stress periods, in order to reduce the groundwater flow.

The geological framework is characterized by two alluvial unconsolidated layers composed by clays, silts, sands and gravels. The uppermost alluvial layer varies in thickness and is in the model approximated 7 to 20 meters. The greater layer thickness is found closer to the Nile, mainly consisting of silt and clay (Figure 4).

The second layer is also alluvial and has a thickness of approximately 30 m. This layer consists mainly of sand and is more permeable than the first layer. There is a third layer composed of clay that acts as a low-permeable bottom layer in the model.

Precipitation is insignificant. Instead, the levels in the Nile and crop irrigation recharge govern the overall hydrology of the study area. From upstream intakes, water from the Nile is led into irrigation canals and distributed to the fields.

According to the local authorities, water is led into the fields in a regulated pattern governed by the crop rotation and seasonal changes. Under the prevailing climatic conditions much of the irrigated water is lost through evaporation.

Surplus irrigation water percolates and flows either to the drainage system or forms groundwater. The quantitative relation between these two flow paths in the study area is not known. However, the groundwater model is used to illustrate and analyze different scenarios presented in section 5.

The Nile water level shows a seasonal pattern where the amplitude is approximately 3.5 m. The Nile level variations affect groundwater levels on a considerable distance from the Nile, but it does not have much influence in the area where the temples are situated.

No pumping tests were conducted to quantify transmissivity values for the model area. However, the values used in the groundwater model for the salvation project

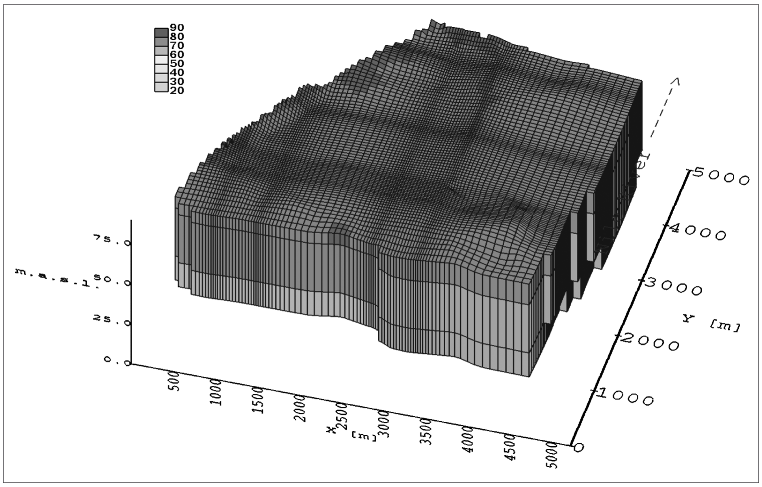

Figure 4. *Graphical representation of the model area showing the three principal layers and the top elevation (from GMS 6.0).*

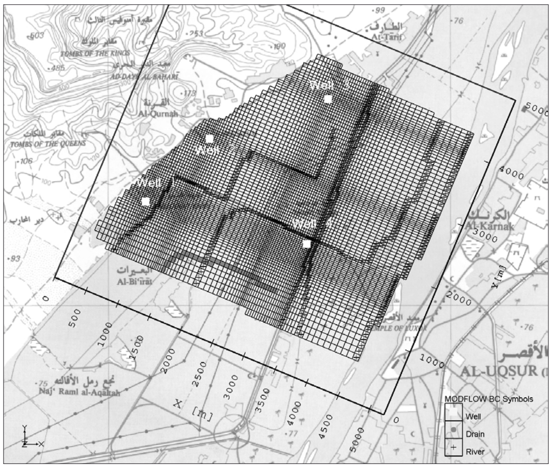

Figure 5. *Modelling area with grid showing the location of Wells 1 to 4, the internal canals and drainage, (Graphic aid, GMS 6.0).*

at Luxor and Karnak temples, executed by the Swedish company SWECO International (2002) were selected for the model calibration.

The most complex and dominating boundary is the Nile River, situated at the eastern side of the model area. This boundary was entered with falling river stages along the cells representing it, for the river gradient falling from the south to the north. The river stages were entered as time series, meaning that the model can be run transient with respect to the varying river stages. The length of the Nile River in the model is about 3,6 km and the perimeter of the entire model area is 14,6 km (Figure 5).

As it is internally described in GMS, a river boundary can both receive outflowing groundwater or contribute with induced recharge, depending on the relative level of the river and the groundwater table. A parameter known as Conductance in m^2/day, specifies the internal flow resistance through the river bottom sediments of that respective cell.

The conductance along the Nile is difficult to calculate and is one of the principal unknown parameters for the present study. The northern, southern and western sides of the model area were considered as no-flow boundaries. Since the rainfall is negligible, there is no groundwater recharge outside the irrigated land that can generate a groundwater flow across this boundary.

The hydraulic heads inside the model area are supposed to be affected to a great degree by internal hydraulic boundaries; irrigation, canals and drains, and groundwater extraction from local wells.

The irrigation canals are specified in the model as internal river boundaries in a similar way as the cells representing the Nile with falling river stages corresponding to the gradient of the canal. The difference comparing to the Nile, is that the values for the water level of the irrigation canals are unknown and have been specified as constant over time, with an average value of 76 m.

According to the hydrogeological map of the region, an average extraction of about 1000 m^3/day is present close to the west corner of the model area, represented as one constant extraction well during all the groundwater model runs.

4.1. Calibration

Most of the calibration was done for a steady-state case, with the Nile flow at a low level and with the average value for the four piezometers during the period of March to May of 2001.

An adequate calibration can be reached when there is access to consistent data of at least two or more hydraulic parameters during relatively long periods (for example the internal flows and river stages data of a few years). In that way, unknown parameters such as conductance, irrigation recharge and hydraulic conductivity can be changed in a trial-and-error manner until acceptable groundwater levels are calculated. However, the calibration of the model was prepared with an average of 69.5 m for the Nile level with bottom elevations of 50 m at both extremes north and south, and an average value of 75.7 m for each of the piezometers.

The water balance was important to analyze during the calibration of the model. Nevertheless, because of the lack of data for the internal canals and the drainage flows, the values presented in table 1 are considered as highly sensitive.

The table indicates both daily flow rates for respective hydraulic boundary and the annual recharge in mm, calculated dividing by the total model area of 12.3 km^2.

Table 1. *Water balance for a steady-state case with the Nile River at a low level (level from March 19th). These net values were automatically calculated by MODFLOW.*

	IN from irrigation recharge	IN from irrigation canals	OUT through drains	OUT through the Nile
m^3/day	14884	83758	55813	42829
mm/year	441	2486	1656	1271

Table 2. *Hydraulic properties applied to the model (values selected from SWECO report, 2002).*

Layer Number	Horizontal K (m/d)	Vertical anisotropy.	Specific. Yield
Layer 1 A	1.55	10.0	0.05
B	**35.0**	**10.0**	**0.15**
C	1.55	10.0	0.05
Layer 2	**35.0**	**10.0**	**0.15**
Layer 3	0.00016	10.0	0.05

The groundwater flow occurs mainly in the second layer. Tests were performed by multiplying and dividing the K-values of layer 1 both horizontal and vertical, by a factor of 5. The modelling results were not sensitive to these changes. The final parameters for the calibration process are presented in table 2.

4.2. Transient modelling

The values from table 2 with the Nile at a low level were used for further steady-state runs for high stages of the Nile. The residuals (the difference between calculated and observed values) of these runs were greater at well number 4 (the one closer to the Nile), comparing to the other wells located at the temples fairly distant from the Nile river (see Figure 1).

A transient model was applied using the Nile river stages of 2001 to analyze the groundwater level changes at the temples of Ramesseum and Sethos I (W2 and W3 in Figure 1, respectively). The river stage of the Nile was allowed to vary over the entire period, according to the recordings obtained from the Egyptian Company A&A (Herbas, 2009).

A first transient model was set up with the same hydraulic parameters and boundary conditions that were used in the steady-state modelling. It showed a good correlation between observed and calculated heads and the response to the change of the river stages in the Nile was satisfactory with respect to the amplitude. In the following runs, the K-value of the second layer was changed from 35 to 43 m/day, given that this last value was finally selected during the simulations for the Salvation project at Luxor and Karnak temples, and they were based on pumping tests (SWECO report, 2002). The response of the calculated hydraulic heads to variations of river stages and stresses applied under the transient simulations for the temples of Ramesseum and Sethos was satisfactorily increased.

Figure 6. *Division of the uppermost Layer 1: Areas A and C mostly consist of silty clay with a low K-value of 1.55 m/day. Area B contains sands and gravels, with a K-value of 35 m/day.*

5. Development and testing of scenarios

The simulations of alternatives for lowering the groundwater levels were based on a combination of drains, centrally located pumping wells, and reduction of recharge rates of irrigation.

5.1. Scenario 1

The first scenario includes reducing the irrigation recharge rate to 50 % over the total area with a continuous withdrawal of 25 l/s during the entire simulation period at both temples of Ramesseum and Sethos I. The run shows groundwater levels lowered by approximately 90 cm at both temples.

Another simulation was performed maintaining 500 mm/year for irrigation net recharge and continuous withdrawal of 25 l/s at both temples. The results showed the groundwater levels lowered by 80 cm, almost the same values as when reducing by 50 % the irrigation rate.

5.2. Scenario 2

These simulations take into account the possible variations of the constant head adopted for the internal irrigation canals inside the model area.

One of the assumptions regarding the boundary conditions for running the model was the constant heads for the internal canals for irrigation. The water level of the canal which is closer to the temples area (see Figure 5) plays a very important role during the transient runs. This was clear when the selected water level of 75.5 m was changed to 74 m, and simulations were performed

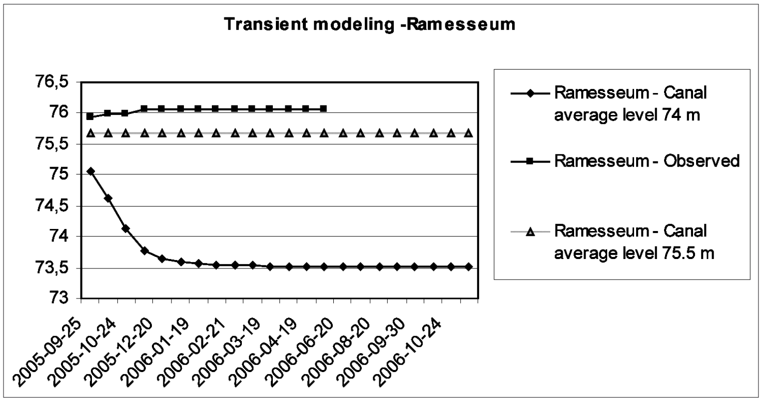

Figure 7. *Transient runs at Ramesseum. Observed and calculated heads after reducing the selected water level of the canal closer to the temples, by 1.5 meters (from 75.5 to 74 m).*

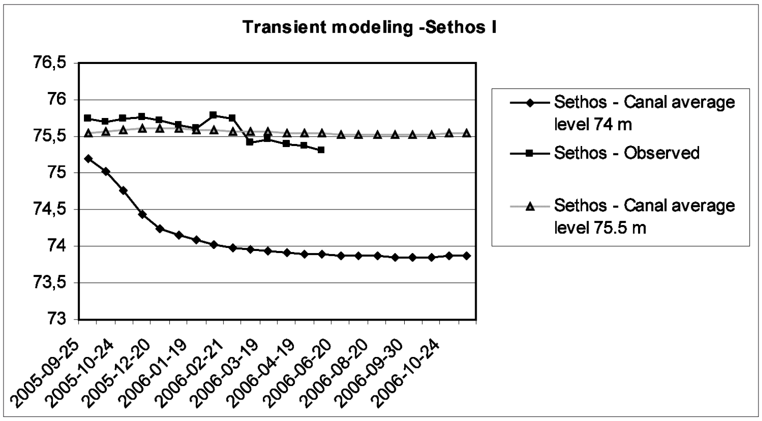

Figure 8. *Transient runs at Sethos I. Observed and calculated heads after reducing the selected water level of the canal closer to the temples, by 1.5 meters (from 75.5 to 74 m).*

with the same conditions as in the first scenario. The figures 7 and 8 show the results of both temples for observed and calculated groundwater levels.

6. Conclusion

To improve the calibration and validation estimates of the model, the access to reliable data related to inflows and outflows for some of the principal internal canals is required. This would give us the possibility to simulate drainage and pumping flow solutions at the temple areas. If there is a second set of field data, for example head changes during a pumping test in one of the temples, a second stage of calibration (verification) will increase the level of confidence in the model (Anderson and Woessner, 1992).

The reduction of irrigation rates is not sufficient to diminish groundwater levels and it has to be combined with other measures. According to some representatives in Luxor, some of the canals work as drainages during certain periods of the year, making the overall hydrology of the area more complex to analyze.

However, the option to construct a greater "regional model", including the Luxor and Karnak temples with the observation wells and hydraulic parameters used in the Salvation project executed by SWECO, together with the data obtained from A&A for the present project could be implemented. Subsequently, with the use of the GMS tools, a conversion to a "local model" could be approached, and in this way it would be possible to analyze in more detail the hydrogeological conditions and other measures inside the areas of the temples.

The Nile River water level reaches its highest elevation point (76 m) during September, and probably the groundwater levels at the temples have more or less the same value. Even so, during the rest of the year, the Nile acts as a gaining river, due to the excessive irrigation and the topography of the area. However, the highest elevation point value of the Nile level for the year 2001 differs by more than 3 m between the data from A&A and the SWECO project.

Høybe (2002), insinuates that using simplified hydraulic properties in a model reduces the validity of the simulation results. The calculation of groundwater levels could be improved if coordination between different agencies and authorities also improved. This means that the success of engineering methods will rely on basic and key design data which is not available generally because of political concerns.

The fundamental problem is the raised groundwater table due to increased irrigation and reduced water level variations in the Nile. This can be solved in various ways, but probably the most sustainable solution is a combination of improvement of the irrigation management in the area; restricting crop types, water uses and reduction of urban and agricultural development impact. Cooperation between local authorities, agencies and ministries is essential to find solutions for groundwater problems in the area.

A first reconnaissance study was conducted in 1982, showing that already at that time, water related problems as salt actions, settling and increased groundwater level were present at many heritage sites (SWECO, 1982). It is interesting to see the high rate of urban and agricultural development, and the limited protection and management of cultural heritage after more than 20 years of knowledge.

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