

CHAPTER 4

A GIS-based flow model for groundwater resources management in the development areas in the eastern Sahara, Africa

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ABSTRACT: To simulate the response of the Nubian Sandstone Aquifer in the eastern Sahara to climate changes during the last 25,000 years, and modern pumping, a regional 3D groundwater flow model was developed and calibrated under steady state and transient conditions. Telescoping meshes were developed in this regional model to include the local details of development areas. The data for this model are held in a GIS database to allow for its implementation in different modeling systems. The simulations using finite element numerical modeling confirm that groundwater in this aquifer is likely to have originated from infiltration during the wet periods of approximately 20–25 ka BP and 5–10 ka BP. Modern recharge of groundwater due to regional groundwater flow from more humid areas to the south is highly unlikely. The model also indicates that the Nubian Aquifer System is a fossil aquifer system, which has been in an unsteady state condition since the end of the last wet period, approximately 5000 years ago. The telescoping modeling approach offers a good solution for the insufficient boundary conditions in the development areas. The simulation results of the large scale model, with telescoping meshes to account for current abstraction, demonstrates that the groundwater reserves of the Nubian Sandstone Aquifer in Egypt and Libya are being mined. By expanding the presently established well fields to their full capacity by year 2020, the water-levels will continuously decline and may fall below economic levels of abstraction.

1 INTRODUCTION

The integrated and sustainable management of the limited water resources in arid regions constitutes a significant issue today due to increased demand for water, water deficiency and ecological problems caused by overuse of available water. A classic example of the issues surrounding groundwater management in arid areas is the Nubian Aquifer System (NAS) in the eastern Sahara – the largest groundwater system in Africa, extending over more than 2 million square kilometers (Figure 1). The NAS is considered the only major fresh water resource in the eastern Sahara besides the River Nile which flows across its

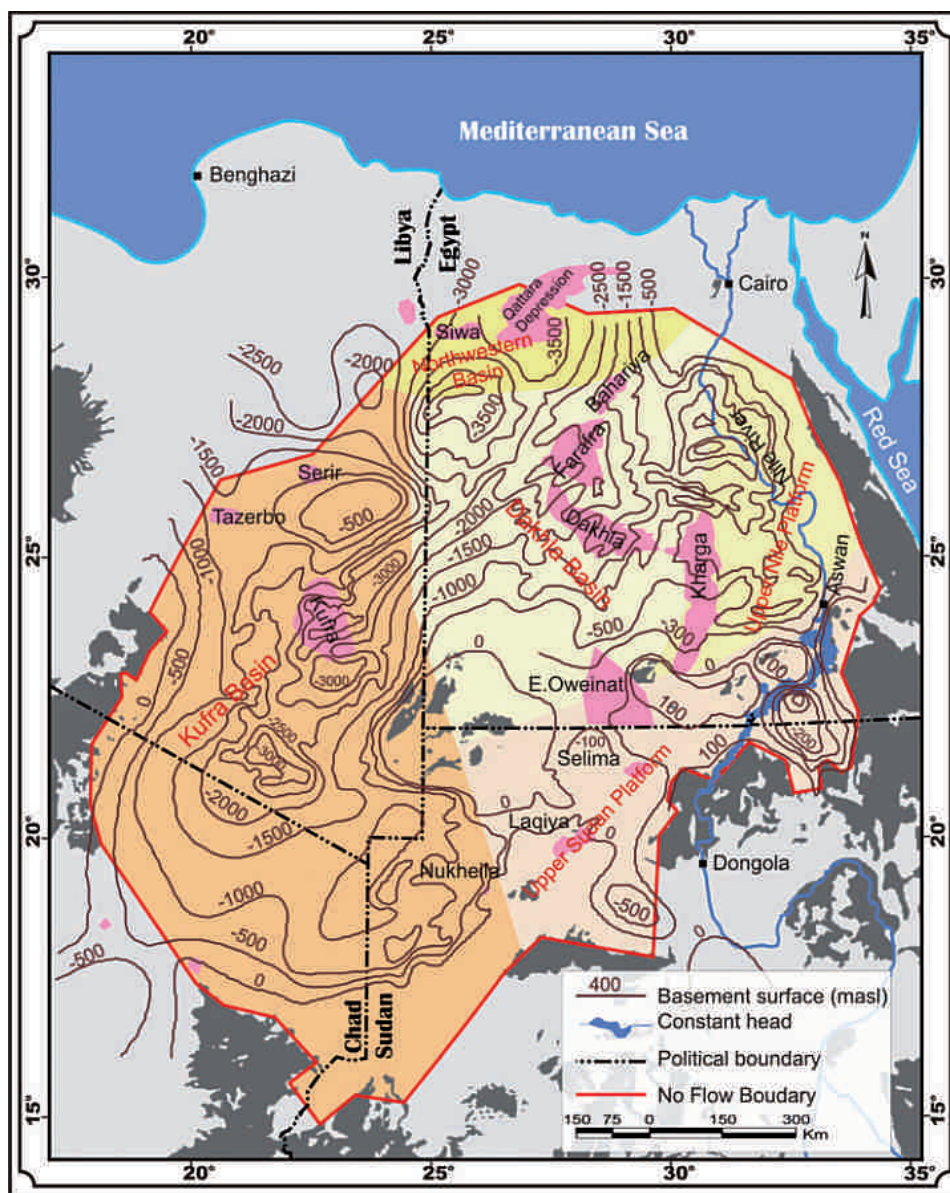


Figure 1. Extent of the Nubian Aquifer system, showing the elevation of the basement surface and the structural basins (after Klitzsch, 1983; Hissene, 1986; Hesse *et al.*, 1987). Pink areas are places of groundwater discharge.

eastern edge. Therefore, much of the population in this arid area outside the Nile valley depends totally on the NAS water for their domestic, agricultural, and industrial uses.

The NAS is formed by two major and two minor basins: (a) the Kufra Basin, which comprises the southeastern area of Libya, the northeastern area of Chad and the north-western corner of Sudan; (b) the Dakhla Basin of Egypt; (c) the northwestern basin of

Egypt; and (d) the Sudan Platform (Wycisk, 1993). In the centre and north of the system, where a hyper-arid climate prevails, the average precipitation ranges from 0 to 5 mm/a. Consequently, there is no current groundwater recharge in most parts of the system and most of the available groundwater resources were recharged during wetter periods in Saharan history approximately 20–25 ka and 5–10 ka before present (Edmunds & Wright, 1979; Heint & Thorweihe, 1993; Edmunds, 1994; Ebraheem *et al.*, 2002; Ebraheem *et al.*, 2004; Gossel *et al.*, 2004). Active recharge occurs close to the Nile, and from Wadi systems at the edge of the NAS (Edmunds, 1994).

The NAS has been the subject of hundreds of studies since the beginning of the nineteenth century. Most of the studies prior to the 1980s concluded that the aquifer had been under steady state conditions before development started in the 1960 (e.g. Sandford, 1935; Hellstrom, 1939; Ezzat, 1974; Amer *et al.*, 1981). The more recent studies e.g. (Heint & Thorweihe, 1993; Churcher *et al.*, 1999; Ebraheem *et al.*, 2002; Gossel *et al.*, 2004) recognize that the aquifer system has been in transient state condition since the current arid period began about 5000 years ago.

Several groundwater modeling studies have been carried out during the last three decades and used as groundwater management tools (e.g. Nour, 1996; Heint & Brinkmann, 1989). These models are mostly for specific small areas of the Nubian Aquifer System. In these models, the boundary conditions are poorly defined and groundwater abstraction from all other areas within the same aquifer is neglected.

Other models have been constructed covering the whole area of the Nubian Sandstone Aquifer focusing on determining the degree of non-equilibrium and time response of the aquifer to various stresses. These models ignore the local abstraction of local development areas. Only one attempt has been made by (Ebraheem *et al.*, 2002) to develop a large-scale model with refined grids on the development areas. However, the model only covered the Egyptian part of the aquifer and ignored the ongoing major groundwater extraction in Libya.

To help improve modeling and take into account both regional and local scales, Gossel *et al.* (2004) used GIS software to create a database comprising all the available hydrogeological information from the previous studies and hydrogeological data from the newly drilled water wells in Egypt and Libya up to year 2001. After constructing the GIS database, an integrated GIS-based numerical time dependent three-dimensional transient groundwater flow model for the Nubian Aquifer System in the Western Desert of Egypt and the adjacent countries was developed and used for simulating the response of the aquifer to the climatic changes that occurred in the last 25,000 years. The model calibration (discussed later) used palaeolakes that existed in this period to estimate and calibrate the groundwater recharge of this long term time horizon. Since 2004, this model has been used for:

1. Establishing a spatial and temporal prediction system for groundwater flow in whole area of NAS (the Nubian Aquifer System).
2. Developing the local scale models for the development areas by refining the grid cells of each development area in the calibrated regional model to involve the local details. In the refined grid areas, inputs from the regional model serve as boundary conditions in the refined grid. This approach allows improved analysis of pumping and the resulting drawdown (Leake & Claar, 1999) as well as taking into account the groundwater extraction from other areas in the same aquifer (which is neglected by local scale modeling studies). The resulting model is used to determine the impact of current and planned groundwater extractions.

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3. Developing solute transport models in areas where sufficient hydrogeological and hydrochemical data are available.
4. Making the necessary predictions to develop a good management scheme for the whole aquifer.

2 GEOLOGICAL AND HYDROGEOLOGICAL SETTING FOR THE MODEL

The NAS is subdivided by uplifts (Figure 1 and Figure 2). The Cairo-Bahariya arch separates the northwestern Basin of Egypt from the Dakhla Basin. The Kharga uplift forms the eastern margin of the Dakhla Basin. The Oweinat-Bir Safsaf-Aswan uplift separates the Dakhla Basin from the north Sudan platform. The Howar-Oweinat uplift forms the eastern border of the Kufra Basin. However, separation of the Kufra Basin from the Dakhla Basin caused by uplift is not evident and the basins are likely connected (Wycisk, 1993).

The dominant geological units of the Nubian Sandstone System (Figure 1 and Figure 2) are the Kufra Basin and the Dakhla Basin. The formation of the Kufra Basin began in Early Paleozoic and was completed at the end of the Cretaceous. The Dakhla Basin was presumably formed at the beginning of the Cretaceous, at least its southern part. North of the Dakhla oasis latitude, Paleozoic sediments can be found (Figure 2). The Dakhla Basin is filled with continental and marine strata of the Paleozoic to early Eocene age in the northwest and of Jurassic to early Eocene in the south. The geological and lithological information was used to set the parameters of the 3D numerical groundwater model.

The top of the basement in the Kufra oasis lies at 3500 m below mean sea level where the aquifer has its maximum thickness of 4000 m. In the area of Kharga, which represents the eastern edge of the basin, the top of the basement lies at 1000 m to <500 m below mean sea level. In Dakhla oasis, the top of the basement lies at about 2000 m below mean sea level (Figure 1). Since the sediments of the Nubian Aquifer System were deposited in a predominantly continental environment, meandering rivers and deltas were the usual transport mechanism (Wycisk, 1993).

In the east, south, and west, basement outcrops bound the system of the described basins and, therefore, the Nubian Aquifer System. In the north, the fresh water aquifer is bounded by saline water that originates either from intrusion of seawater or saline groundwater that has not flushed out since the sedimentation of marine sediments. The northwestern boundary is given by a no-flow boundary according to the overall flow conditions as observed in previous investigations (e.g. Ball, 1927; Sandford, 1935). For the model, a no flow boundary was put around the boundary of the NAS, since recharge is assumed to be negligible, and only partial seepage from the Nile. Natural discharge occurs in some locations on the Nile and in the oases.

3 DEVELOPMENT OF THE GIS DATABASE

All available information was digitized and entered into the GIS database of Gossel *et al.* (2004). This included fundamental geological, hydrogeological, and climatic data from previous studies (Ambroggi, 1966; Klitzsch *et al.*, 1979; Klitzsch & Lejal-Nicol, 1984; Hesse *et al.*, 1987; Klitzsch & Squyres, 1990; Thorweihe, 1990; Meissner & Wycisk, 1993; CEDARE, 2001); information from newly drilled boreholes in Egypt and Libya up to year 2004; information from available cross-sections of the area; and the DEM (Digital

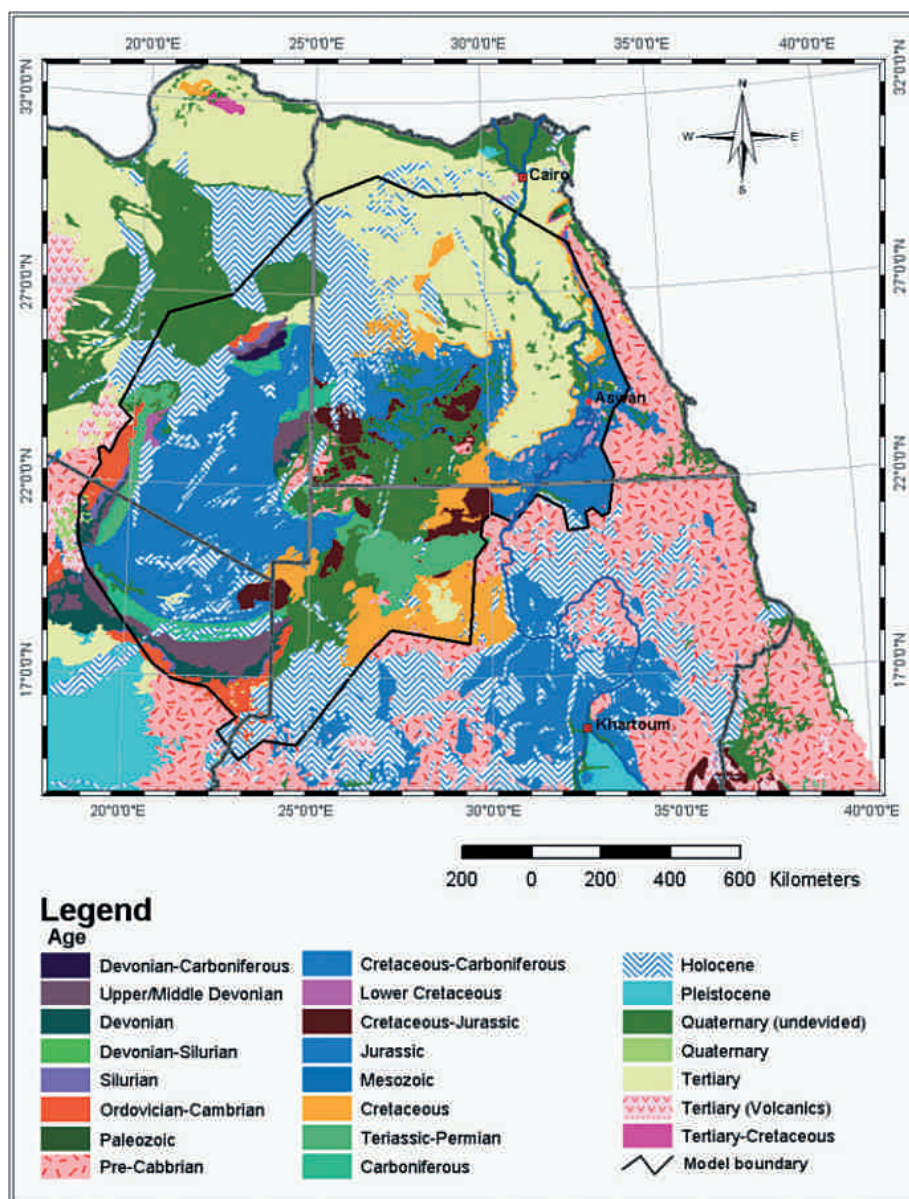


Figure 2. Map of surface geology of the Nubian Sandstone Aquifer (after Sefelnasr, 2006).

Elevation Model) distributed by SRTM-03 of Africa (NASA, 2005). Compiling the data into such coherent and logical GIS-structure helps to ensure the validity and availability of the data and provides a powerful tool for accomplishing the purposes of the study. GIS also helps in management of hydrogeological data and hydrogeological analysis, and also to provide interpreted information, such as vulnerability assessments.

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The geological database was extensively used in the modeling process to calculate the model layer bottom, top, and thickness of the aquifer structure and the formulation of parameters and boundaries of the numerical groundwater model. GIS tools were used for: the interpolation of layer surfaces; the interpolation of hydraulic conductivities; the formulation of outer and inner boundaries; and the calculation and spatial description of groundwater recharge areas.

The interpolation tools in GIS are needed to get a spatial distribution of model parameters. For geological purposes statistical and geostatistical analyses of the data have to be carried out before the interpolation. Hydrogeological data with a normal distribution (e.g. elevation data or measured groundwater levels) can be interpolated with kriging and geostatistics. The map of the basement top elevation (Figure 1) represents one example of an output from the created GIS. Data sets without normal distributions (e.g. hydraulic conductivities) first have to be log-transformed to obtain a normal distribution and then analyzed and interpolated with geostatistical tools. In GIS the data can be pre- and post-processed, proved and corrected.

GIS was also conveniently used to control the surfaces of the layers of the numerical groundwater model so that there are no intersections. Although ArcGIS (ESRI, 2005) is not fully 3D capable (only 2.5D) it is sufficient to prepare the 3D structural model for the numerical groundwater models. The GIS database was also used for the calibration of the model. It is a useful tool to visualize the deviation between modeled and interpolated measured water levels as well as statistical calculations.

4 NUMERICAL GROUNDWATER FLOW MODEL

4.1 *Model setup*

Two 3D numerical modeling systems were chosen as basic tools for the simulation of the Nubian Sandstone System: A finite difference modeling system (Modflow with the Pre- and Postprocessor Visual Modflow 3.0 (Waterloo Hydrogeologic Inc., 2002)) and a finite element modeling system Feflow 5.0 (Diersch, 2003). The grid covered an area of 2.2 million km² and the modeled area about 1.65 million km². For the finite difference solution a grid of 10 × 10 km was used. In the finite element model the area of the triangles ranged from 10 km² to 100 km². The main reasons for the choice of a 3D modeling system is to model:

- the large distance flow from Chad to the Qattara Depression;
- the climatic change from wet to semi-arid to the present arid conditions during the last 25,000 years, which is the flow time of this large distance flow;
- the possibilities to build a transport model with implementation of slices with vertically differentiated flow and transport parameters.

The model was designed as a closed system. In this way, reliable no flow boundary could be identified at the outcrops of the basement. As the saltwater-freshwater interface seems to be highly stable, it is also implemented as a no flow boundary (Neumann condition). All groundwater flow, recharge and discharge occurred within the model. Groundwater recharge was implemented on the top layer. Grid cells of the Nile River were considered as constant head cells with spatially varying time constant heads in this long-term simulation (Dirichlet condition).

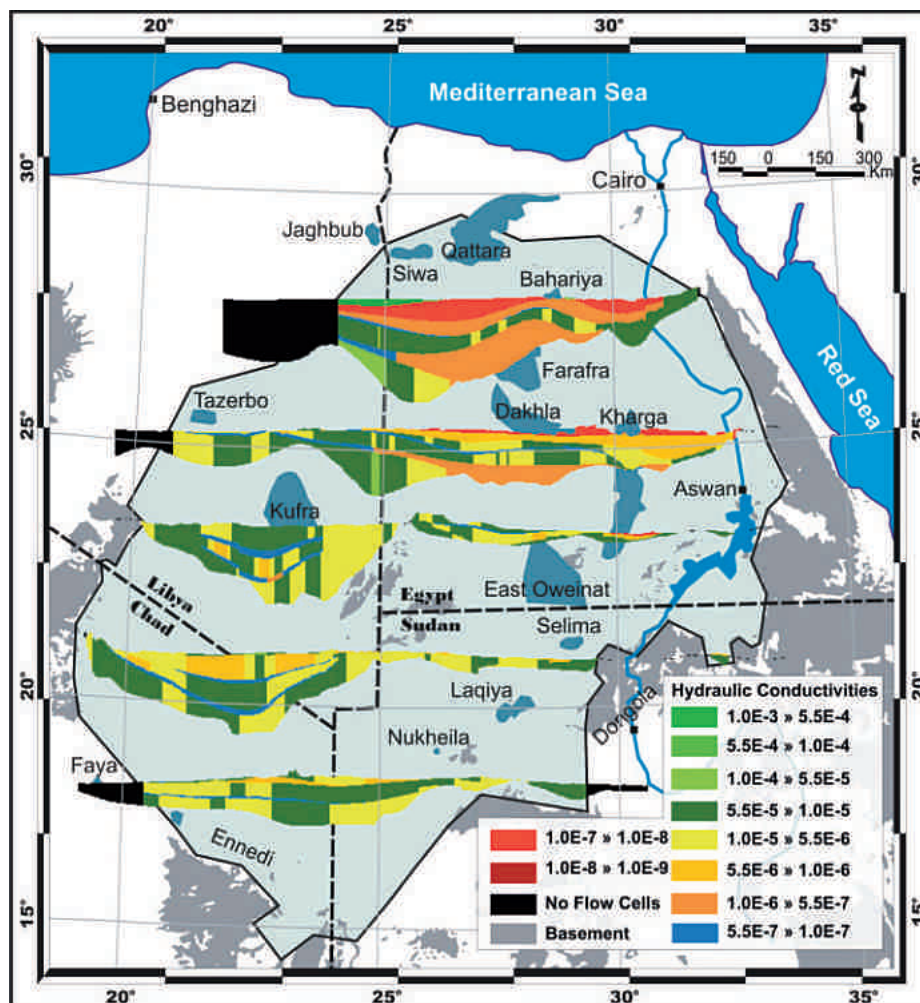


Figure 3. Cross sections of calibrated hydraulic conductivities (m/s) for the Nubian Aquifer System as they are implemented in the numerical groundwater model. Original data based on drilling information from 1960–2005 (after Sefelnasr *et al.*, 2006).

The hydraulic conductivity was evaluated for the entire area using the available drilling information up to year 2001 in the newly developed areas, e.g. Tushca (southwest of Aswan) and East Oweinat (Dahab *et al.*, 2003), as well as the results published in Thorweihe & Heintz (1999) and shown in the cross sections in Figure 3. Based on the variability of hydraulic conductivity values and the general stratigraphic setting, the Nubian Sandstone Sequence was divided into 10 layers. The layers 2 to 9 were further divided into three layers each to ensure a representative value of hydraulic conductivity and other flow parameters particularly in a local-scale solute transport model (not reported here). For the same reason, the bottom and top layer were also divided into two layers each. The confined part of the system in the north was considered as 'leaky aquifer', allowing vertical water exchange between the Nubian

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Aquifer and overlying sediments. Evapotranspiration in the large Egyptian oases was made possible and implemented as discharge (Modflow) or negative recharge (Feflow). The two different numerical groundwater modeling systems have been chosen due to the problems of the finite difference system with dry cells in the upper layers.

4.2 *Simulation Runs*

The following simulations were carried out for the regional aquifer.

1. 'Steady-state' conditions simulating the infiltration on the southern highlands and evaporation in the Egyptian oases in the last 50 years neglecting the anthropogenic abstraction.
2. A long-term transient simulation of the aquifer behavior, due to climatic change followed the steady simulation.
3. A short-term time variant simulation of the period 1960–2000 using the available hydrogeological data in 1980 and 2000 in the Egyptian part for calibration.

In subsequent simulations and prediction runs (described later), the grid cells of the development areas were refined in a manner that all local details can be included. These simulations involved the development of a local-scale model for each development area within the calibrated regional model and then using them to make the necessary prediction of the impact of the different management regimes for the next hundred years. A simulation of solute transport is planned for the future. All simulations were done with both modeling systems, first with the finite difference model and later with the finite element model.

4.2.1 *Steady-State simulation*

The steady state model was run as a 50-year simulation transient model to calibrate the hydraulic conductivities. The recharge in the model was set to the hyperarid climatic conditions of the last 100 years with a few millimeters per year of recharge on the high land at the southern edge of the model area and Gilf Kebir Plateau (at Gebel Oweinat) and an average value of 30 mm/a discharge through the Egyptian oases in the northern part of the aquifer. This model achieved a 'steady state' solution for the whole aquifer area as shown in (Figure 4). The aim of the first 'steady state' model was to match the contour map of Ball (1927) and Sandford (1935) which was created before the start of pumping of groundwater in several oases in the 1960s. The 'steady state' finite difference model (Figure 4) showed at a first glance a similar pattern as the contour lines of Ball (1927). This result was improved further by using the finite element model. The root mean square error of the finite element model was only about 4 m. For an area of about 1,000,000 km² a difference between measured and calculated groundwater levels of less than 5 m was achieved (Gossel *et al.*, 2004).

4.2.2 *Long term simulation of the aquifer system due to climatic changes*

To clearly answer the question whether the groundwater encountered today in the Nubian Aquifer System has been formed during historical humid climate periods, or if groundwater is currently recharging from more humid areas in the south, the regional model was used to simulate the aquifer response to climatic change during the last 25,000 years (using climate data recently confirmed by isotopes and paleontological studies (Thorweihe, 1986; Pachur, 1999; and Churcher *et al.*, 1999).

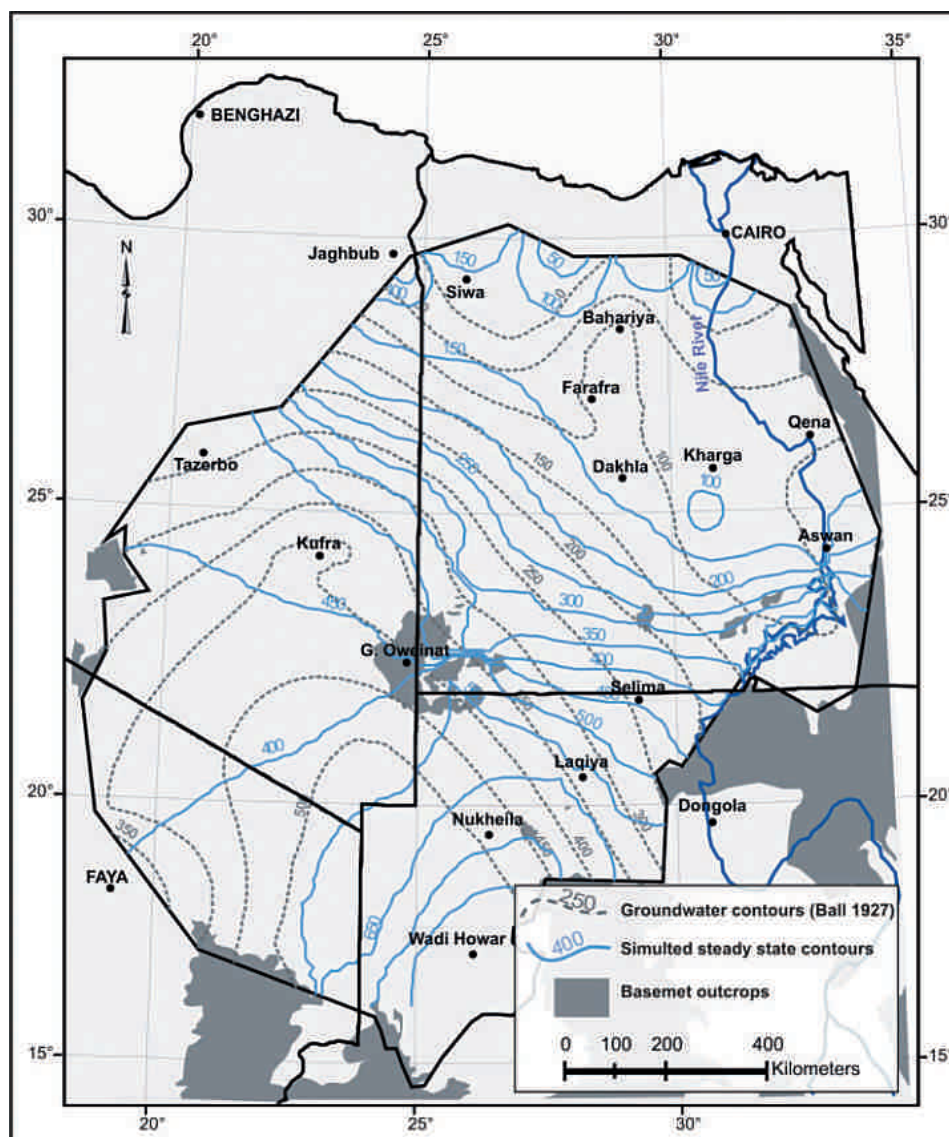


Figure 4. Simulated groundwater contours for steady state conditions with infiltration in southern highlands and discharge through the Egyptian oases (after Gossel *et al.*, 2004).

As shown in Figure 5 this long-term simulation started with a recharge period between 25–20 ka BP. In this period a 10–20 mm/a recharge rate was assumed (Pachur, 1999). Rainfall was dominated by southeast directed winds from the Mediterranean causing precipitation at the mountains in Sudan and Chad (Tibesti and Ennedi Mountains). The spatial distribution of recharge zones used in the model is shown in Figure 6. Recharge in the period between 10–5 ka BP was assumed to be up to 40 mm/a. In the periods 20–10 ka BP and 5 ka BP to present day, infiltration was set to 0 mm/a. The evaporation data for the

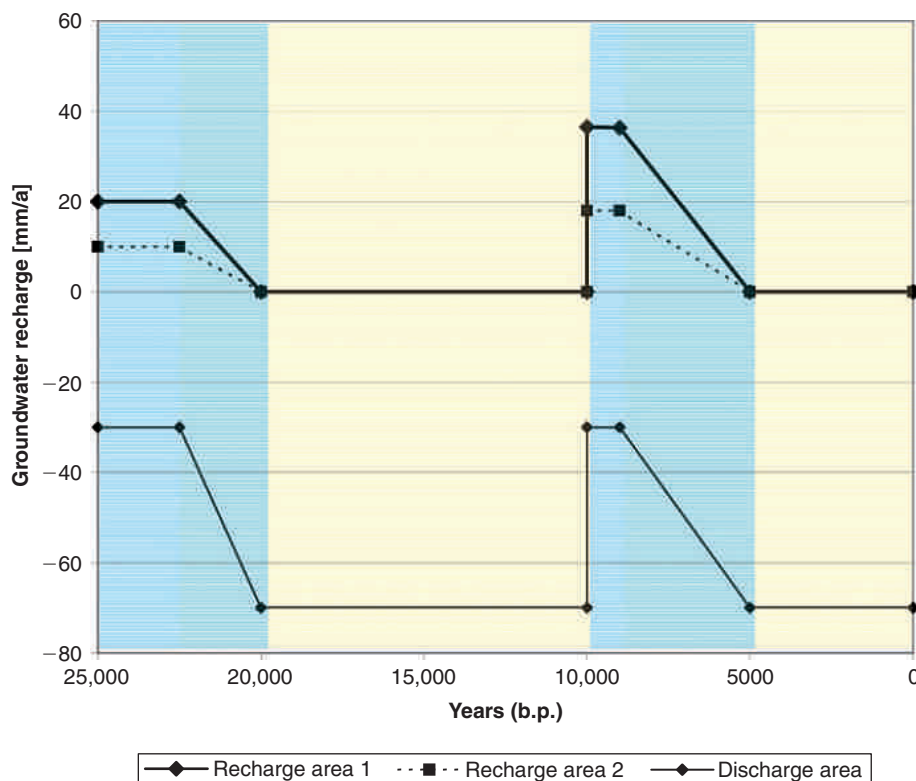
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Figure 5. Time dependent groundwater recharge in the model area (see Figure 6 for the location of the different recharge areas).

depression areas and oasis varied from 70 mm/a during the dry periods and 35 mm/a in the wet periods (Figure 5).

Simulated groundwater levels are shown in Figure 7 for the finite element model. The pattern of the measured and the calculated groundwater isolines match in largest parts of the modeled area. To verify the model results in the past, the geological and geographical analysis of Kröpelin (1993) and Pachur (1999) were used. The model successfully simulated the behavior of known paleolakes during the period and in particular the behavior of the former Lake Ptolemy (Sudan) at 560 m above sea level. For more details see Gossel *et al.* (2004).

The modeled aquifer response to climate variations confirms that groundwater in the NAS most likely recharged during the more humid climatic periods by regional infiltration. The model indicates that the decline of groundwater levels started about 19,000 years ago, but was slowed down and reversed by regional infiltration during the last wet period (of approximately 10–5 ka BP). It took about 5500 years after the start of the second wet period for the water-levels to recover and the aquifer to become almost full, and water-levels have now been declining since then. Since the last wet period, natural discharge has not been balanced by recharge (Figure 8). Natural discharge does not depend directly on the climate

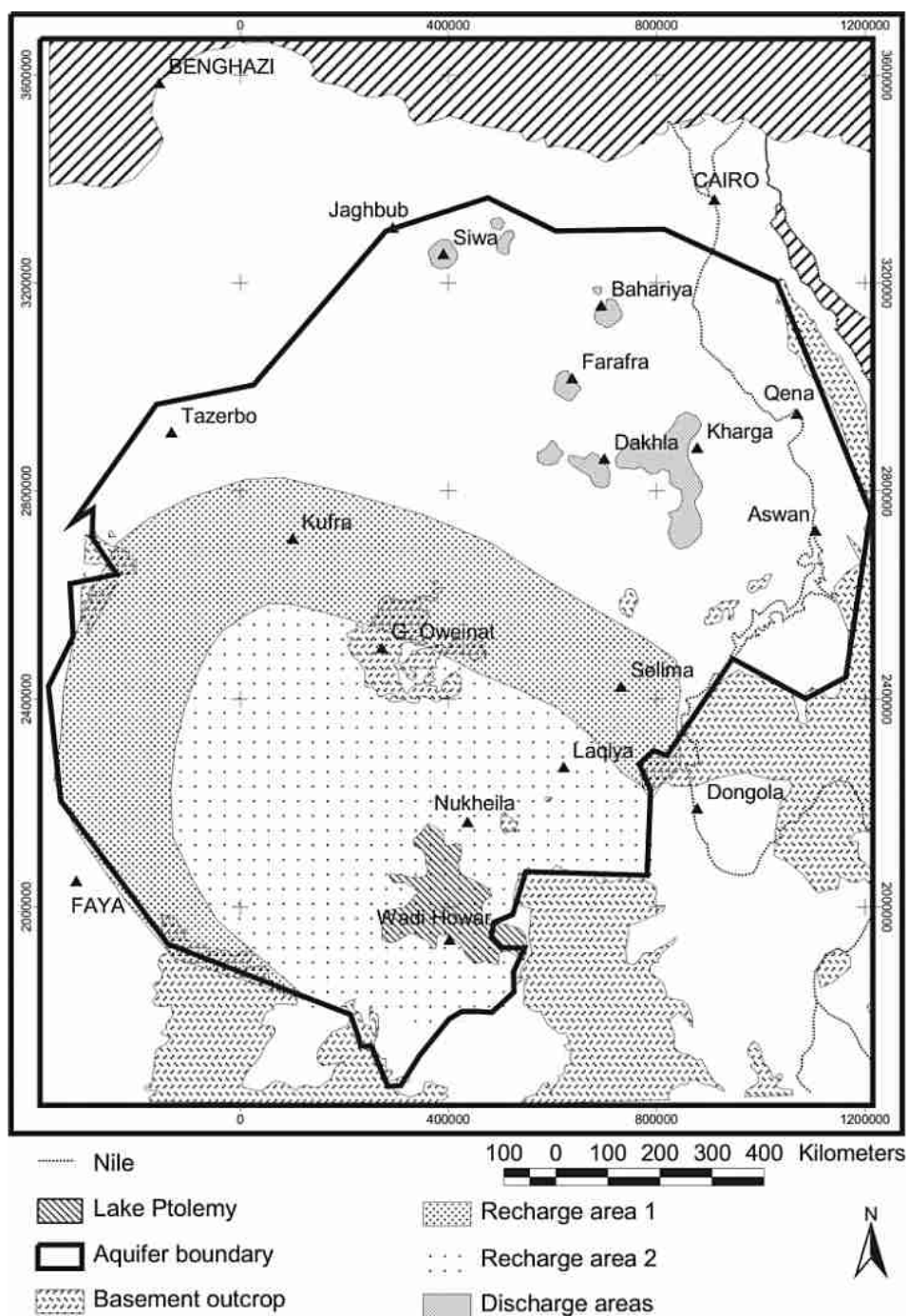


Figure 6. Recharge and discharge areas and the location of the former Lake Ptolemy (after Gossel *et al.*, 2004).

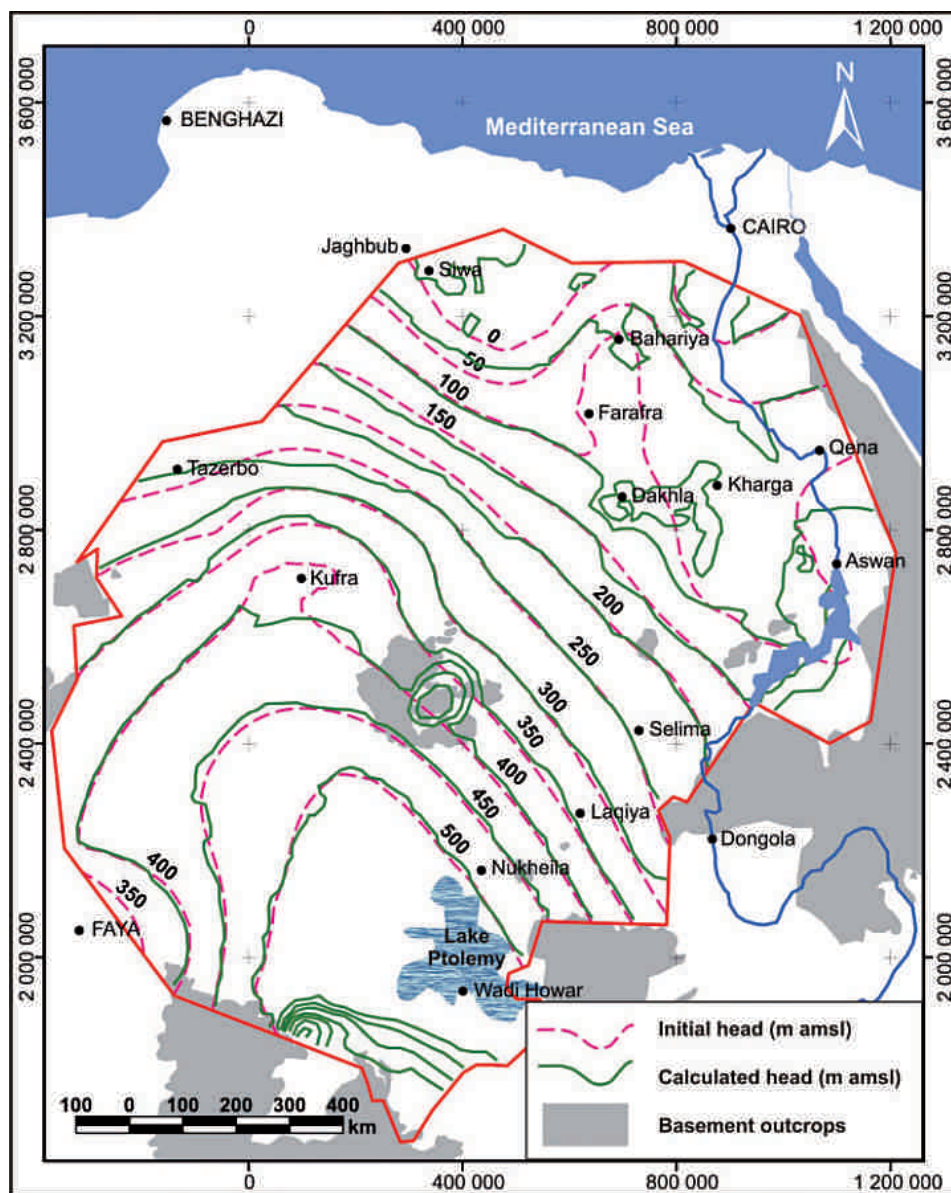


Figure 7. Simulated groundwater contours in 1960 after a simulation of climate change over the past 25,000 years. The groundwater contours of Ball's (1927) outside the Egyptian part of the aquifer were considered as the observed values for other areas (finite element model) (after Gossel *et al.*, 2004).

but rather the potential head distribution, therefore, discharge continues during the dry periods, meaning that the system is not in steady state.

Between 20–10 ka BP, infiltration stopped and the simulated groundwater contours indicate that groundwater level dropped, particularly in the higher areas. Within this time,

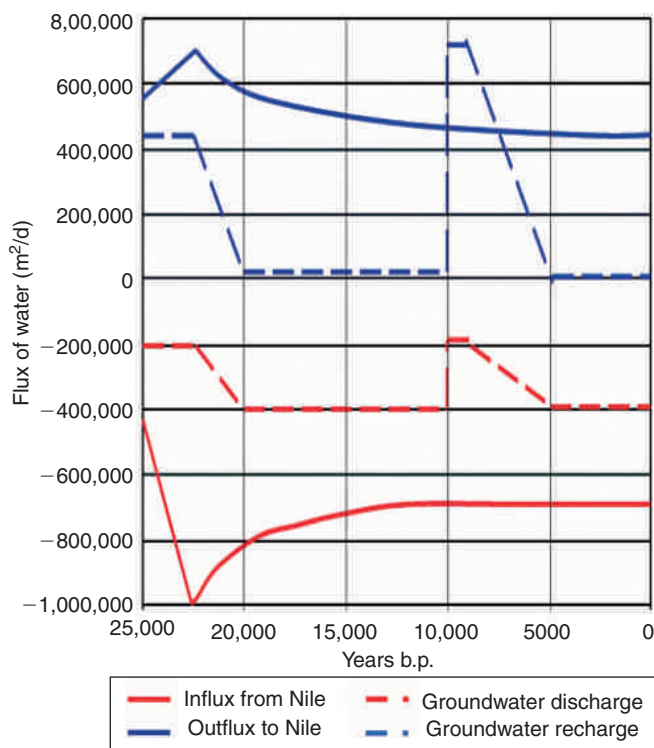


Figure 8. Groundwater balance for the Nubian Aquifer System in the last 25,000 years (finite element model). Note that groundwater discharge was imposed on the model to give evapotranspiration.

groundwater levels fell between 40 and 70 m in Gilf Kebir Plateau and about 20 to 30 m at the southern and western boundary of the model area. During the wet periods, however, the calculated depth to groundwater shows that in wide parts of the model area the aquifer comes to a nearly full condition. It is also interesting to note the time delays in the system. The highest groundwater levels are calculated about 50 to 100 years after the end of the wet periods in the southern parts of the model area. Groundwater levels have continued to decline since the end of the last wet period. Modeled depth to groundwater in 1960 is shown in Figure 10.

Even during wet periods a quasi steady state condition could have only existed for a short time for the whole aquifer area. Taking into account that the average distance between recharge areas in the south and discharge areas in the north is about 1000 km and the average groundwater velocity in sandstones is about 1 m/a, then the flow time between the recharge and development areas would be one million years. The ages of groundwater shown by (Thorweihe & Heinl, 1999) of about 20,000 to 40,000 years show that also in some northern parts recharge must have occurred in the wet periods. Older groundwater ages, found e.g. by Sturchio *et al.* (2004) can be found in deeper structures of the aquifers and in the northern parts of the NAS.

The main focus of the simulation was to decide whether or not flow in the Nubian Aquifer System was in a steady state prior to current abstraction. As shown above, the

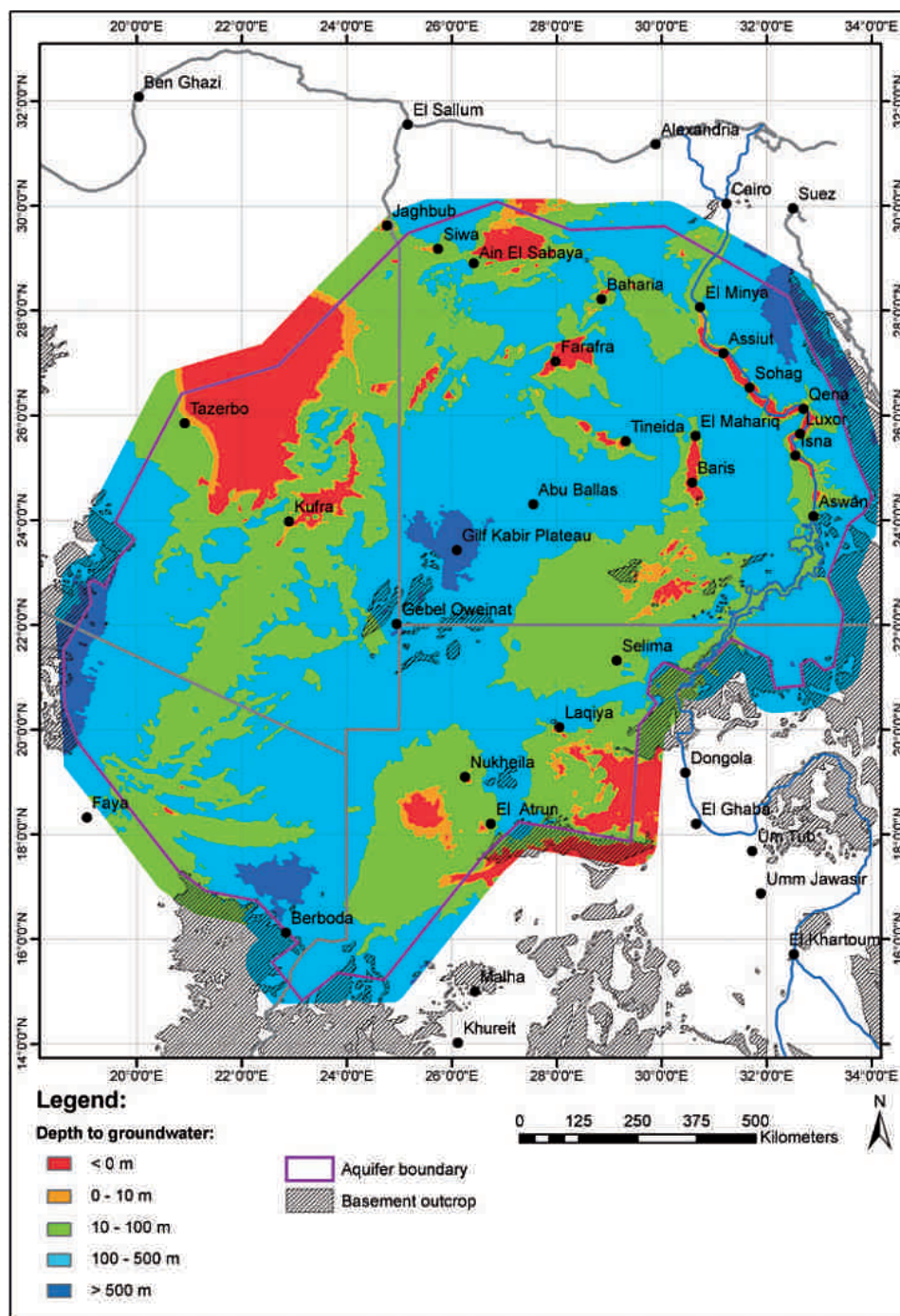


Figure 10. Depth to groundwater in 1960 (finite element model) (after Gossel *et al.*, 2004).

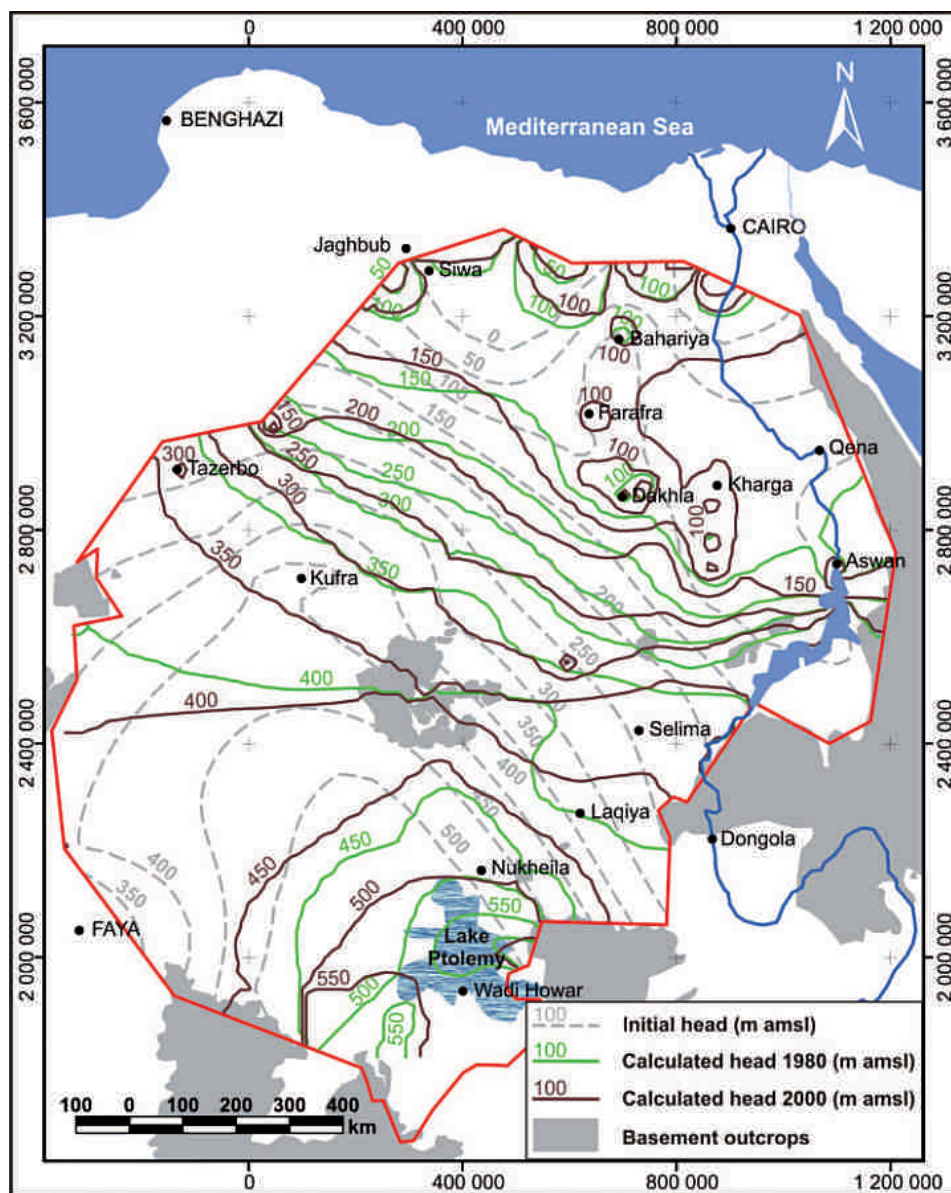


Figure 11. Simulated groundwater contours in 1980 imposing groundwater extraction in the period 1960–1980 after a very long simulation of climatic change. observed values are also shown between parentheses for the Egyptian Oasis. The groundwater contours of (Ball, 1927) outside the Egyptian part of the aquifer were considered as the observed values for other areas (finite difference model) (after Gossel *et al.*, 2004).

model indicates clearly that the water-levels were still declining since the end of the last wet period and had not reached the low levels of the time before 10,000 years BP. This indicates that the natural water-level decline ongoing and could last for another few 1000 years.

Certain aspects of the research results reported in Pachur (1999) merit further investigation. The reported former lakes could be a result of higher runoff or elevated high groundwater levels. If they were formed as a result of a high groundwater level, the recharge period must have been a little bit earlier than the formation of lakes due to the time shift between groundwater recharge and rising groundwater levels in the concerned areas. The formation of lakes in consequence of a high runoff on the other hand leads to an increased infiltration in the gathering areas and thus to higher groundwater levels. Research into these aspects is ongoing.

4.2.3 *With groundwater abstraction*

The official records of groundwater abstraction for irrigation and domestic water supply were used to calculate the abstraction for each individual pumping centre in the NAS area. The abstraction of all boreholes in each development area were applied for each year in this period and considered as the abstraction rate of a single borehole. The modeling systems allow the location of well screens in more than one layer so that there was no need to classify boreholes as shallow and deep. Due to the intensive abstraction rates in the Dakhla, Kharga, and Kufra oases, wells in each of these oases were grouped into three pumping centers. The abstraction rates shown in Figure 9 are the formally reported rates for year 2000. However, the present abstraction rates may be higher at some places (e.g. Kufra oasis in Libya and Kharga and East Oweinat in Egypt). In a proposed abstraction scenario by CEDARE (2001), the present abstraction rate will probably be reduced in some areas.

Due to the close fit between the observed groundwater contours before the development time in 1960 and the computed groundwater contours at the end of the long simulation period (for 25,000 years before 1960), the computed groundwater contours were considered as the initial heads for the short simulation periods. Thus, to model the flow in the period 1960–1980, the model ran for a simulation period of 25,020 years involving the climatic changes in the first 25,000 years and groundwater abstraction in the last twenty years (1960–1980). In the Egyptian part of the aquifer (where groundwater development started in 1960), the simulated hydraulic heads in 1980 are in good agreement with the observed hydraulic heads for that year (Figure 9). In 1980, cones of depression started to develop in Kharga and Dakhla oases and become wider and deeper with time (Figure 9). Outside the Egyptian part of the aquifer, the simulated groundwater contours are also in a good agreement with the observed groundwater contours of the predevelopment time (Figure 9).

This simulation indicates that the natural groundwater level decline, ongoing since the end of the last wet period, is small compared to the effect of modern pumping (compare with Sefelnasr *et al.* (2006)).

5 PREDICTION RUNS

With the available evidence that the Kufra Basin is not separated from Dakhla Basin by uplift and even the small basins are not completely separated, the NAS has to be looked at as one aquifer. The Nubian Aquifer System in the development areas (Egyptian oases and Kufra oasis in Libya) is only a part of the whole NAS. Groundwater flow in the main aquifer layers is governed by conditions at the boundaries of the regional system. The developed and calibrated regional model for the whole NAS (Gossel *et al.*, 2004; Sefelnasr *et al.*, 2006) was used to model groundwater flow in the development area of the Egyptian oases

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Table 1. The five possible future groundwater exploitation scenarios; abstraction in million cubic meters per year.

| Area | Scenario 1 | Scenario 2 | Scenario 3 | Scenario 4 | Scenario 5 |
|--------------|------------|------------|------------|------------|------------|
| Bahariya | 34 | 177 | 177 | 177 | 177 |
| Farafra | 283 | 471 | 471 | 471 | 471 |
| Dakhla | 439 | 625 | 625 | 625 | 625 |
| Kharga | 203 | 124 | 93 | 93 | 93 |
| East Oweinat | 164 | 300 | 600 | 900 | 1200 |
| Kufra | 200 | 300 | 400 | 400 | 500 |

and Kufra oasis in Libya by refining the grid in these areas. This modeling approach was used for the following reasons:

- it is easy and convenient to include all the local details of the development areas in the regional model by refining its grid in the development areas to the desired level (Leake & Claar, 1999);
- boundary conditions can only be well defined for these areas by using the connection to the large scale model;
- pumping from any of these development areas is affecting the whole system;
- records of hydraulic head observations needed for the model calibration procedure are only available for certain areas.

The grid cells in the regional model in these development areas were refined with a grid spacing of 5000 m in both directions. The regional model was used to calculate the fluxes across the boundary cells of the areas of the local scale model. These fluxes served as boundary conditions for the local scale model (areas with refined grid). This approach allowed precise analysis of pumping and the resulting drawdown in the development areas.

The simulation model was used to calculate five possible future exploitation/development plans (Table 1) for the NAS. The simulation was applied to the years 2000–2100. In the analysis of the simulation results, emphasis was given to the amount of decline in the hydraulic head, and consequently its effect on the depth to groundwater. The results of the modeling scenarios are summarized in Table 2. Some of the obtained results will be briefly discussed below whereas the detail is subject to ongoing research.

The simulation results of scenario 1 indicate that the major cones of depression are centered in the Kharga and Dakhla oases with maximum declines of 80, 50, and 20 m in the year 2100 for the Kharga, Dakhla, and East Oweinat areas, respectively.

In scenario 5, the consequences of expanding the groundwater abstraction rates in East Oweinat and Dakhla oasis to their planned rate (1200 and 625 Mm³/a respectively) were investigated. The resulting declines in the water-levels (Table 2) indicate that the core of the cone of depression will cover the entire planned reclaimed area in East Oweinat in Egypt. The depth to groundwater in this area will be greater than 140 m. Also, a similar negative impact, but to a lesser extent, was observed for the area around the centre of Dakhla oasis by the year 2100. This indicates that an abstraction rate of 1200 Mm³/year is not feasible for the East Oweinat area without excessive drawdown, and also it is safer if the rate in Dakhla oasis does not exceed 500 Mm³/year. Therefore, Scenario 4 is the most

Table 2. The simulated depths to groundwater under the five possible future groundwater exploitation scenarios.

| Area | Estimated economic pumping depth (m) | Scenario | Modelled depth to groundwater (m below ground surface) | | | | | | |
|--------------|--------------------------------------|------------|--|------|------|------|------|------|------|
| | | | 1980 | 2000 | 2010 | 2020 | 2030 | 2060 | 2100 |
| Bahariya | 124 | Scenario 1 | -10* | -7 | -6 | -5.5 | -5 | 0 | 3 |
| | | Scenario 2 | -7 | -5 | -3 | 0 | 2 | 7 | 10 |
| Farafra | 80 | Scenario 1 | -60 | -40 | -35 | -30 | -25 | -22 | -18 |
| | | Scenario 2 | -23 | -15 | -11 | -6 | 0 | 1 | 3 |
| Dakhla | 63 | Scenario 1 | -25 | -5 | -2 | 2 | 5 | 18 | 37 |
| | | Scenario 2 | -18 | -1 | 12 | 25 | 39 | 45 | 57 |
| Kharga | 38 | Scenario 1 | 12 | 20 | 24 | 28 | 40 | 50 | 53 |
| | | Scenario 2 | -5 | 5 | 10 | 15 | 20 | 30 | 40 |
| | | Scenario 3 | -7 | 4 | 8 | 13 | 17 | 26 | 36 |
| East Oweinat | 100 | Scenario 1 | -15 | -4 | 0 | 7 | 15 | 20 | 23 |
| | | Scenario 2 | 16 | 20 | 22 | 24 | 25 | 30 | 34 |
| | | Scenario 3 | 26 | 30 | 32 | 35 | 37 | 45 | 58 |
| | | Scenario 4 | 28 | 35 | 39 | 44 | 53 | 64 | 95 |
| | | Scenario 5 | 12 | 40 | 55 | 70 | 80 | 95 | 145 |

*negative values indicate artesian flows.

efficient option for managing groundwater resource in the Nubian Sandstone Aquifer in Egypt.

6 CONCLUSIONS

The simulation results indicated that the total groundwater storage in the NAS is about 135,000 km³, which is very close to the figure obtained by Heintz & Thorweihe (1993) by other means. The model also confirms the main recharge periods of the NAS as the wet periods at approximately 20–25 ka BP and 5–10 ka BP. Under present arid conditions, the sum of recharge from the River Nile and infiltration in the southern part is only 4% of the current discharge in the Libyan and Egyptian development areas.

A transient model simulation of the past 25,000 years shows results that correlate well with observed groundwater levels pre-development (Ball, 1927) and also a good correlation to geological research results for the lakes that existed about 6000 years BP.

To some extent, the groundwater contours from the transient model are similar to the simulated ones of a steady state condition obtained with infiltration on the highland at the southern edge and evaporation in the Egyptian oases. This similarity is caused by very slow groundwater fluctuations in the last 3000 years.

The simulation results of the regional model (without telescoping meshes) indicate that the water-levels were still declining in the aquifer in response to the end of the last wet period and had not reached the low levels of the time before 10,000 years BP. This indicates that the natural water-level decline was ongoing prior to development and could last for another few 1000 years.

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The slope of the hydraulic gradient, which has the same direction as the gradient of precipitation from south to north, should not mislead some researchers to conclude that there is continuous recharge to the Egyptian part to account for a steady state condition before 1960.

After each transition to arid climate, natural discharge continues for the entire dry period with a slow decrease with time. After this arid depletion of the aquifer, the groundwater was replenished after the climatic transition to the subsequent wet period. During wet periods, a time span of only 3000 years and a few mm/a of recharge are sufficient to keep the groundwater level near the surface (filled up condition).

The simulation results of the regional model, with telescoping meshes to account for current abstraction, demonstrates that the groundwater reserves of the Nubian Aquifer System in Egypt and Libya are being mined. By expanding the presently established well fields to their full capacity by year 2020, the water levels will continuously decline.

To avoid groundwater depletion in the shallow aquifer and to ensure sustainable development of this precious natural resource in the Kharga oasis, the present abstraction rate in this oasis has to be limited to 93 Mm³/year. The planned abstraction rate of approximately 500 and 1200 Mm³/year in the Kufra oasis (Libya) and the East Oweinat area (Egypt), respectively, is not sustainable, and will have a negative impact on water-levels not only in these two areas but also in several areas within Dakhla oasis. However, rates of 300 and 900 Mm³/year may be feasible in Kufra and East Oweinat areas respectively. The results of an ongoing detailed modeling study will provide a detailed picture about the sustainable extraction rates in these development areas.

The simulated potentiometric surface for the year 2100 for the most intensive development scenario in all development areas except Kharga oasis (scenario 5) did not drop below mean sea level in the northern part of the Nubian Aquifer System in Egypt. Therefore, the possibility of upconing of more saline water and invasion of seawater in the northern parts of the aquifer is low. However, further investigations to confirm or reject this possibility are needed.

REFERENCES

- Ambroggi, R. P. 1966. *Water under Sahara*. Scientific American, **214**, 21–49.
- Amer, A., Nour, S. & Meshriki, M. 1981. *A finite element model for the Nubian Aquifer System in Egypt*. In: Proceedings of the International Conference on Water Resources Management in Egypt, Cairo, 327–361.
- Ball, J. 1927. *Problems of the Libyan Desert*. Geographical Journal, **70**, 21–38, 105–128, 209–224.
- CEDARE 2001. *Nubian Sandstone Aquifer System Programme, Regional Maps*. CEDARE, Heliopolis, Cairo.
- Churcher, C. S., Kleindienst, M. R. & Schwarcz, H. P. 1999. *Faunal remains from a middle Pleistocene lacustrine marl in Dakhleh Oasis, Egypt: Palaeoenvironmental reconstructions*. Palaeogeography, Palaeoclimatology, Palaeoecology, **154**, 301–312.
- Dahab, K. A., Ebraheem, A. M. & El Sayed, E. 2003. *Hydrogeological and hydrogeochemical conditions of the Nubian Sandstone Aquifer in the area between Abu Simbel and Tushka depression, Western Desert, Egypt*. Neues Jahrbuch für Mineralogie, Geologie, und Paläontologie, **228**, 175–204.
- Ebraheem, A. M., Riad, S., Wycisk, P. & Seif El Nasr, A. M. 2002. *Simulation of impact of present and future groundwater extraction from the non-replenished Nubian Sandstone Aquifer in SW Egypt*. Environmental Geology, **43**, 188–196.

- Ebraheem, A. M., Riad, S., Wycisk, P. & Seif El Nasr, A. M. 2004. *A local-scale groundwater flow model for the management options in Dakhla Oasis, SW Egypt*. Hydrogeology Journal, **12**, 714–722.
- Edmunds, W. M. & Wright, E. P. 1979. *Groundwater recharge and palaeoclimate in the Sirte and Kufra basins*. Journal of Hydrology, **40**, 215–241.
- Edmunds, W. M. 1994. *Characterization of groundwaters in semi-arid and arid zones using minor elements*. In: Nash, H. and McCall, G. J. H. (eds.) Groundwater Quality, Chapman and Hall, London, 19–30.
- ESRI 2005. ArcGIS 9. <http://www.esri.com/software/arcgis/about/literature.html>
- Ezzat, M. A. 1974. *Groundwater Series in the Arab Republic of Egypt; Exploration of groundwater in El-Wadi El Gedid Project area*. Part 1 to IV, General Desert Development Authority, Ministry of Irrigation, Cairo.
- Gossel, W., Ebraheem, A. M. & Wycisk, P. 2004. *A very large scale GIS-based groundwater flow model for the Nubian Sandstone Aquifer in Eastern Sahara (Egypt, northern Sudan, and Eastern Libya)*. Hydrogeology Journal, **12**, 698–713.
- Heinl, M. & Brinkmann, P. J. 1989. *A Ground Water Model for the Nubian Aquifer System*. Hydrological Science Journal, **34**, 425–447.
- Heinl, M. & Thorweihe, U. 1993. *Groundwater Resources and Management in SW Egypt*. In: Meissner, B. & Wycisk, P. (eds.) Geopotential and Ecology, Catena Supplement, **26**, 99–121.
- Hesse, K. H., Hissene, A., Kheir, O., Schnaecker, E., Schneider, M. & Thorweihe, U. 1987. *Hydrogeological investigations of the Nubian Aquifer System, Eastern Sahara*. Berliner Geowiss. Abh (A), **75**, 397–464.
- Hellström, B. 1939. *The subterranean water in the Libyan Desert*. Geofisika Annaler, **21**.
- Klitzsch, E., Harms, J. G., Lejal-Nicol, A. & List, F. K. 1979. *Major subdivision and depositional environments of the Nubian strata, Southwest Egypt*. Bulletin American Association of Petroleum Geologists, **63**, 967–974.
- Klitzsch, E. & Lejal-Nicol, A. 1984. *Flora and fauna from strata in southern Egypt and northern Sudan*. Berliner Geowiss-Abh (A) **50**, 47–79.
- Klitzsch, E. & Squyres, H. C. 1990. *Paleozoic and Mesozoic geological history of northeastern Africa based upon new interpretation of Nubian strata*. Bulletin American Association of Petroleum Geologists, **74**, 1203–1211.
- Kröpelin, S. 1993. *Geomorphology, Landscape Evolution, and Palaeoclimates of southwest Egypt*. In: Meissner, B. & Wycisk, P. (eds.) Geopotential and Ecology. Catena Supplement **26**, 67–97.
- Leake, S. A. & Claar, D. V. 1999. *Procedures and computer programs for telescopic mesh refinement using MODFLOW*. Open file report, USGS, **53**.
- Meissner, B. & Wycisk, P. (eds.) 1993. *Geopotential and Ecology*. Catena Supplement, **26**.
- NASA 2005. SRTM03 data. <http://www2.jpl.nasa.gov/srtm>.
- Nour, S. 1996. *Groundwater potential for irrigation in the east Oweinat area, Western Desert, Egypt*. Environmental Geology, **27**, 143–154.
- Pachur, H. J. 1999. *Paläo-Environment und Drainagesysteme der Ostsahara im Spätpleistozän und Holozän*. In: Klitzsch, E. & Thorweihe, U. (eds.) Nordost-Afrika: Strukturen und Ressourcen. Deutsche Forschungsgemeinschaft, WILEY-VCH, Weinheim, 366–445.
- Sandford, K. S. 1935. *Sources of water in the northern-western Sudan*. Geographical Journal, **85**, 412–431.
- Sefelnasr, A. M., Gossel, W. & Wycisk, P. 2006. *GIS-basierte Grundwasserströmungsmodellierung des Nubischen Aquifersystems, Westliche Wüste, Ägypten*. FH-DGG-Congress, Cottbus, Germany.
- Sturchio, N. C., Du, X., Purtschert, R., Lehmann, B. E., Sultan, M., Patterson, L. J., Lu, Z. T., Müller, P., Bigler, T., Bailey, K., O'Connor, T. P., Young, L., Lorenzo, R., Becker, R., El Alfy, Z., El Kaliouby, B., Dawood, Y. & Abdallah, A. M. A. 2004. *One million year old groundwater in the Sahara revealed by krypton-81 and chlorine-36*. Geophysical Research Letters, **31** (5).

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- Thorweihe, U. 1986. *Isotopic identification and mass balance of the Nubian Aquifer System in Egypt*. In: Thorweihe, U. (ed.) *Impact of climatic variations on East Saharian Groundwaters, Modeling of large scale flow regimes*, Proceedings of "Workshop on hydrology", Berliner Geowiss. Abh. (A). **72**, 55–78.
- Thorweihe, U. 1990. *Nubian Aquifer System*. In: Said R (ed.) *The Geology of Egypt*. 2nd Edition, Balkema, Rotterdam.
- Thorweihe, U. & Heintz, M. 1999. *Grundwasserressourcen im Nubischen Aquifersystem*. In: Nordost-Afrika: Strukturen und Ressourcen. Deutsche Forschungsgemeinschaft. WILEY-VCH Verlag GmbH, D-69469 Weinheim, Germany.
- Diersch, H.-J. 2003. *Feflow reference manual*. WASY GmbH, Berlin.
- Waterloo Hydrogeologic Inc. 2002. *Visual Modflow Pro User's Manual*. Waterloo, Canada.
- Wycisk, P. 1993. *Geology and Mineral Resources, Dakhla Basin, SW Egypt*. In: Meissner, B. & Wycisk, P. (eds.): *Geopotential and Ecology*. Catena Supplement, **26**, 67–97.