A very large scale GIS-based groundwater flow model for the Nubian sandstone aquifer in Eastern Sahara (Egypt, northern Sudan and eastern Libya)

W. Gossel · A. M. Ebraheem · P. Wycisk

Abstract A three-dimensional GIS-based groundwater flow model for the Nubian Sandstone Aquifer in the eastern Sahara was developed and calibrated under steady-state and transient conditions. The model was used to simulate the response of the aquifer to climatic changes that occurred during the last 25,000 years. The simulation results indicated that the groundwater in this aquifer was formed by infiltration during the wet periods 20,000 and 5,000 years B.P. The recharge of groundwater due to regional groundwater flow from more humid areas in the south was excluded. It also indicates that the Nubian Aquifer System is a fossil aquifer, which had been in an unsteady state condition for the last 3,000 years.

Résumé Pour l'aquifère gréseux Nubien de Sahara -Est on a mis au points un modèle tridimensionnel, basé sur GIS. Le modèle a été calibré tant pour l'écoulement stationnaire que pour l'écoulement transitoire. On a simulé après la réponse de l'aquifère aux changements climatiques des derniers 25000 ans. Les résultats des simulations indiquent que la nappe a été rechargée par des infiltrations pendant une période humide qui s'étend 5000 et 20000 ans, dès temps actuel. On n'a pas pris en compte la recharge de l'aquifère par la zone plus humide située dans sa partie sud. Le modèle indique aussi que l'eau de l'aquifère Nubien est une eau fossile qui a eu un écoulement transitoire pendant les derniers 3000 ans.

Resumen Fue desarrollado un modelo de flujo de agua subterránea en tres dimensiones, basado en un SIG, para el Acuífero Arenisca Nubian en el Sahara Oriental, el cual fue calibrado para condiciones de estado estacionario y transitorio. El modelo se usó para simular la respuesta del acuífero a los cambios climáticos que ocurrieron durante los últimos 25000 años. Los resultados de esta simulación indicaron que el agua subterránea en este acuífero, se formó por infiltración, durante los períodos húmedos que hubo hace 20000 y 5000 años, antes del presente. Fue excluida la recarga del acuífero debida a un flujo regional de agua subterránea proveniente de áreas con un clima más húmedo en el sur. El modelo también muestra, que el Sistema Acuífero Nubian es un acuífero fósil, el cual ha permanecido en una condición de estado no estacionario, durante los últimos tres mil años.

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Introduction

The problem of water resources is most critical for the development in the area of the Eastern Sahara, the most arid region in the world. In this area, the only available water resource is the Nubian Sandstone Aquifer, which consists of an immense sedimentary basin (Fig. 1) and holds an enormous water reserve.

This aquifer has been the subject of hundreds of studies since the beginning of the 19th century. All of the studies until the beginning of the 1980s (e.g. Sandford 1935; Hellström 1939; Ezzat 1974; Amer et al. 1981) have concluded that this aquifer has been under steady-state conditions before 1960. Groundwater flow is driven from areas with precipitation which is sufficient for groundwater recharge. The recent studies (e.g. Heinl and Thorweihe 1993; Ebraheem et al. 2002a) indicate that this aquifer has been in an unsteady state condition for thousands of years before 1960, and the climatic changes including wet periods supplied plenty of precipitation to suffice for local groundwater formation.

Most of these studies had big problems in defining their model boundaries. They always had to define hydrogeological boundaries at national borders and here the estimations about influx or water levels can only be a more or less bad approximation. Only supranational research as in the German "Sonderforschungsbereich Nor-

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dost Afrika" can solve such outstanding problems, because the groundwater recharge for this aquifer system occurs in Sudan and Chad and the natural discharge in the Egyptian oasis. Thus steady-state models only for the Egyptian part of the aquifer lead to wrong conclusions because the varying recharge conditions of the whole system are neglected.

Actually, there is a general agreement that the aquifer is under a non-steady condition since the beginning of the development in Egyptian and Libyan oases in 1960. The current groundwater extraction is approximately ten times the maximum present recharge for this aquifer in the Egyptian part, even if the internal flux from the adjacent areas of the same aquifer is considered as a recharge. This clearly indicates that good groundwater management of this water resource on a multinational level is crucial for the sustainable development of the whole area of East Sahara.

Several groundwater flow-model studies were carried out during the last three decades and used as groundwater management tools (e.g. Nour 1996; Heinl and Brinkmann 1989). However, these models are mostly local-scale models for specific small areas of the Nubian Sandstone Aquifer. In these models, the boundary conditions are ill defined and the groundwater extraction from all the other areas within the same aquifer is neglected as if it does not exist (e.g. Nour 1996). Most of the time, these models are only satisfying a consultancy job without any scientific interest. Other models are very large scale models covering the whole area of the Nubian Sandstone Aquifer focusing on the determination of the degree of non-equilibrium and time response of the whole aquifer to various physical stresses. Despite the fact that these large-scale models have resulted in databases (e.g. Heinl and Thorweihe 1993) which are used by subsequent models (e.g. the present model), they completely ignored the local details and did not take into account the possible updating as more new data become available with time. Only one incomplete attempt has been made by Ebraheem et al. (2002b) to develop a large-scale model with refined grids on the development areas. However, the models only covered the Egyptian part of the aquifer and hence ignored the ongoing major groundwater extraction in Libya.

The aim of the present study is to develop an integrated GIS-based groundwater flow model. The GIS software was used to create the necessary input database, which involves all the available hydrogeological information from the previous models and the hydrogeological data from the newly drilled water wells in Egypt and Libya up to the year 2001. After formalizing the GIS database, a large-scale flow model covering the whole area was developed and calibrated under both steady-state and transient simulations. This model was then used to determine the impact of the present and planned groundwater potentiality of this aquifer. The preliminary results are presented here, while the further development of the model is ongoing to:

1. refine 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 precise analyses of pumping and the resulting drawdown (Leake and Claar 1999) as well as taking into account the groundwater extraction from other areas in the same aquifer which was always neglected during local scale modeling studies.
2. develop solute transport models in the local areas where detailed hydrogeological data are available to study the solute transport hydrodynamics.
3. produce the necessary predictions to develop a good management scheme for the whole aquifer.

Geological and Hydrogeological Settings

The geological setting of the study area as well as the hydrogeology of the Nubian Sandstone Aquifer are discussed in detail in Ambroggi (1966), Klitzsch et al. (1979), Klitzsch and Lejal-Nicol (1984), Klitzsch and Squyres (1990), Thorweihe (1990), Meissner and Wycisk (1993), and CEDARE (2001). The major outline is given below.

The available drilling information up to the year 2001 of the fully penetrated wells as well as the available geological cross sections (e.g. Hesse et al. 1987) were digitized and entered into a formulated GIS database. The USGS digital elevation model (DEM) of Africa was used to determine the ground surface elevation.

The top of the basement in Kufra Oasis lies at 3,500 m below mean sea level and the aquifer has its maximum thickness of 4,000 m. In the area of Kharga, which represents the eastern edge of the basin, the top of the basement lies at 1,000 m to <500 m below mean sea level. In Dakhla Oasis, the top of the basement lies at about 2,000 m below mean sea level (Fig. 1). Since the sediments of the Nubian Sandstone Aquifer System were deposited in a predominantly continental environment, meandering rivers and deltas were the usual transport mechanism.

The Nubian aquifer system is subdivided by uplifts (Fig. 1): The Cairo-Bahariya arch separates the northwestern Basin of Egypt from Dakhla Basin. The Kharga uplift forms the eastern margin of Dakhla Basin. The Oweinat-Bir Safsaf-Aswan uplift separates the Dakhla Basin from north Sudan platform. The Howar-Oweinat uplift forms the eastern border of Kufra Basin. A separation of Kufra Basin from Dakhla Basin caused by uplift is not evident (Wycisk 1993).

The dominant geological units of the Nubian Sandstone System as shown in Figs. 1, 2 are the Kufra Basin and the Dakhla Basin. The formation of the Kufra Basin began in the 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 (Fig. 2). The Dakhla Basin is filled with

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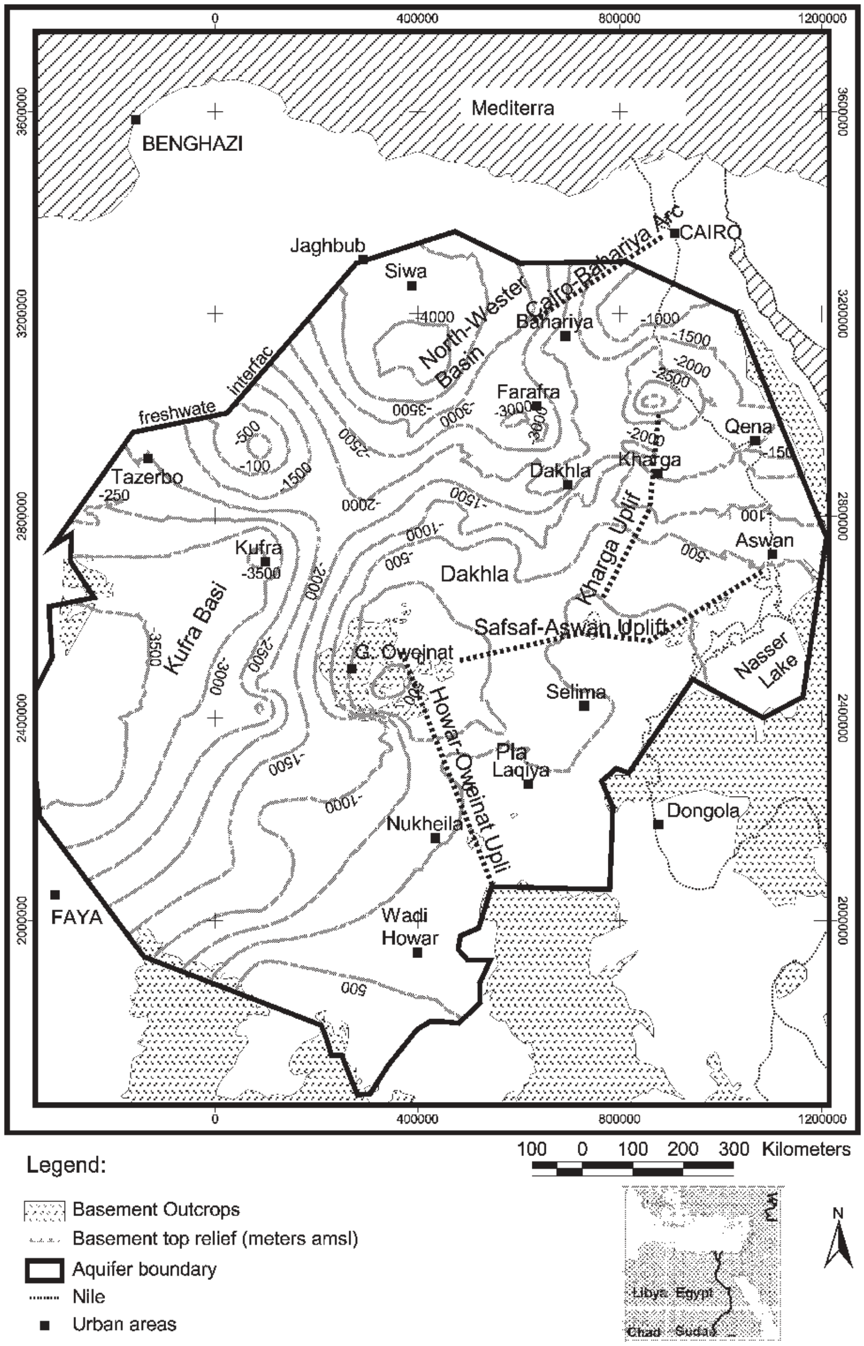
Fig. 1 Contour map of the basement top relief



continental and marine strata of the Paleozoic to early Eocene age in the northwest and of Jurassic to early Eocene in the south. The thickness of the Nubian Sandstone succession varies from one area to another, depending on the relief at the top of the basement and the controlling geological structures. The paleozoic to permotriassic sediments are thick continental sandstones. In the upper Cretaceous and in the Tertiary, transgressions from the north caused intercalations of shales and limestones. In the northern part of the Dakhla Basin, these sediments with low hydraulic conductivities are dominat in the upper Cretaceous and Tertiary sediments (Wycisk 1993). In the southern part, continental sandstones are dominant.

In the east, south, and southeast, basement outcrops bound the system of the described basins and thereby the Nubian Aquifer System as well. In the north and northwest, the pore volume of sediments is filled with saline water that enters the system either via an intrusion of Mediterranean Sea water or saline groundwater that has not flushed out since the sedimentation of marine sediments. The saline-freshwater interface can be considered spatially stable and hence forms the system margin in the north and northwest. Estimations of the groundwater resources of the Nubian Sandstone Aquifer System have been published by Ambroggi (1966:15,000 km^3), Gischler (1976:60,000 km^3), and Heinl and Thorweihe

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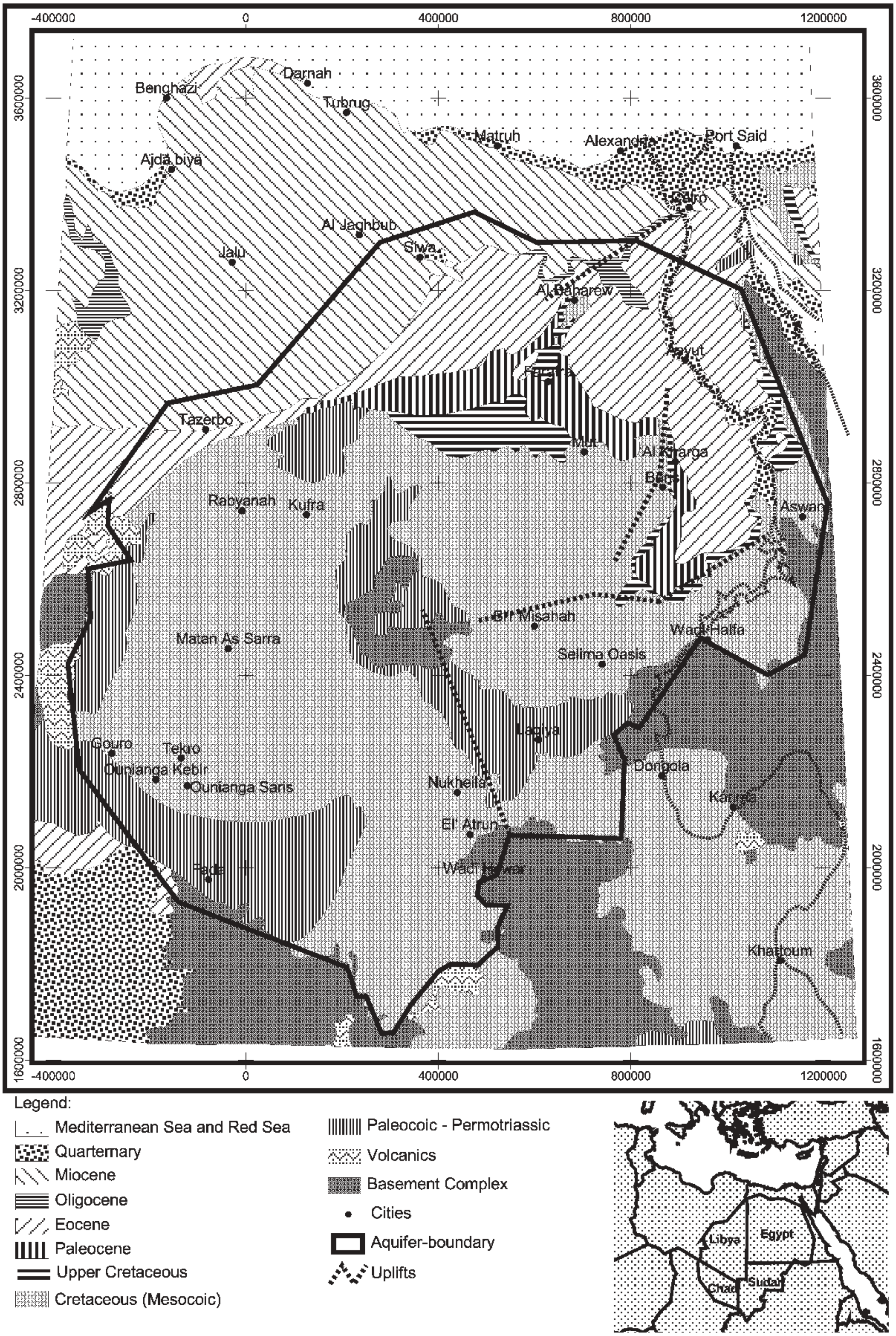

Fig. 2 Geological map of the Nubian Sandstone Aquifer (modified after CEDARE, 2001). Outlines of lithologies are explained in the text

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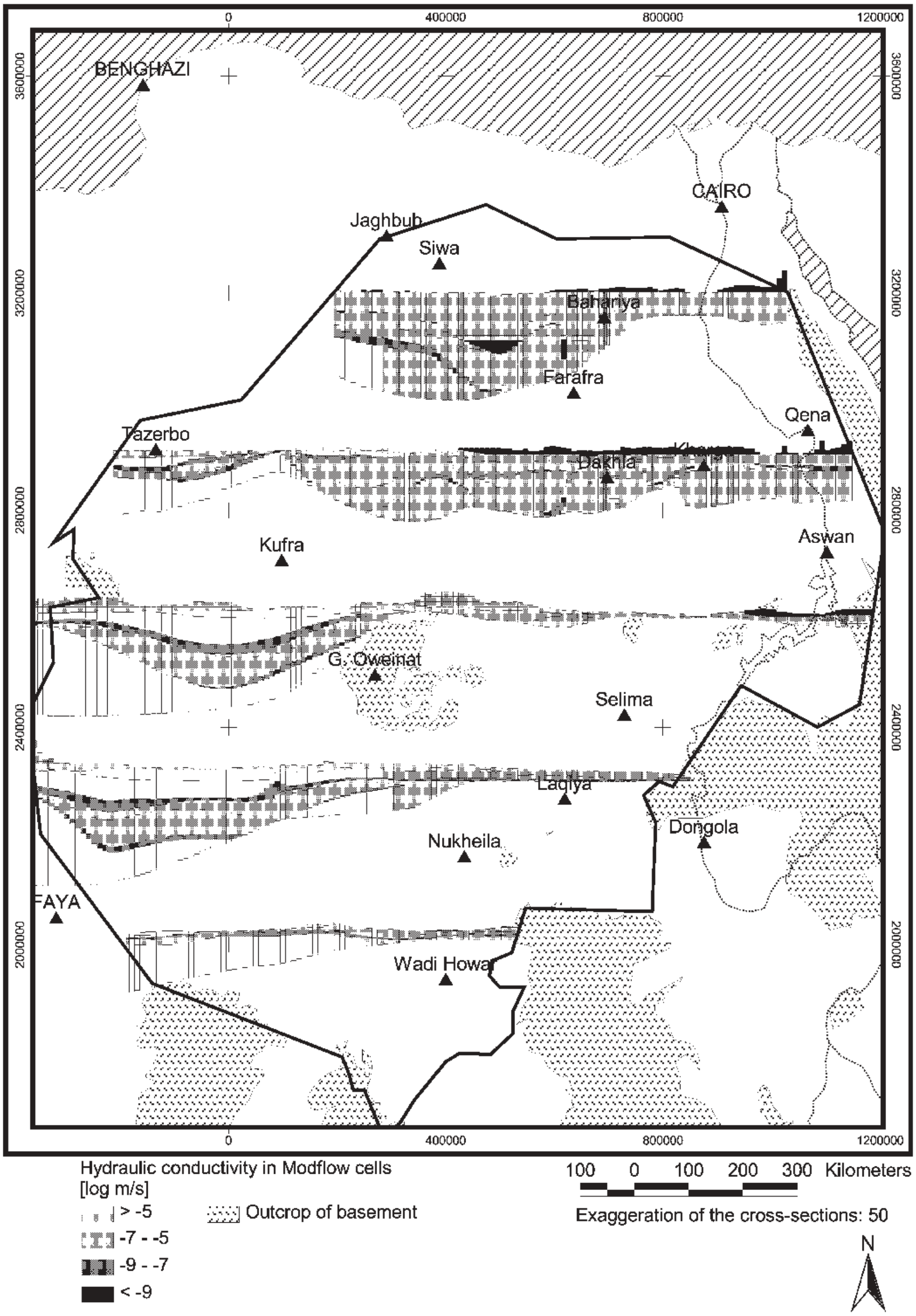

Fig. 3 Cross sections of hydraulic conductivities for the Nubian Aquifer System as they are implemented in the numerical groundwater model

(1993:150,000 km^3). It is only economically and infrastructurally possible to exploit a small portion of this quantity.

Development of the GIS Database

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 surfaces,
- the interpolation of hydraulic conductivities,
- the formulation of outer and inner boundaries and
- the calculation and spatial description of groundwater recharge areas.

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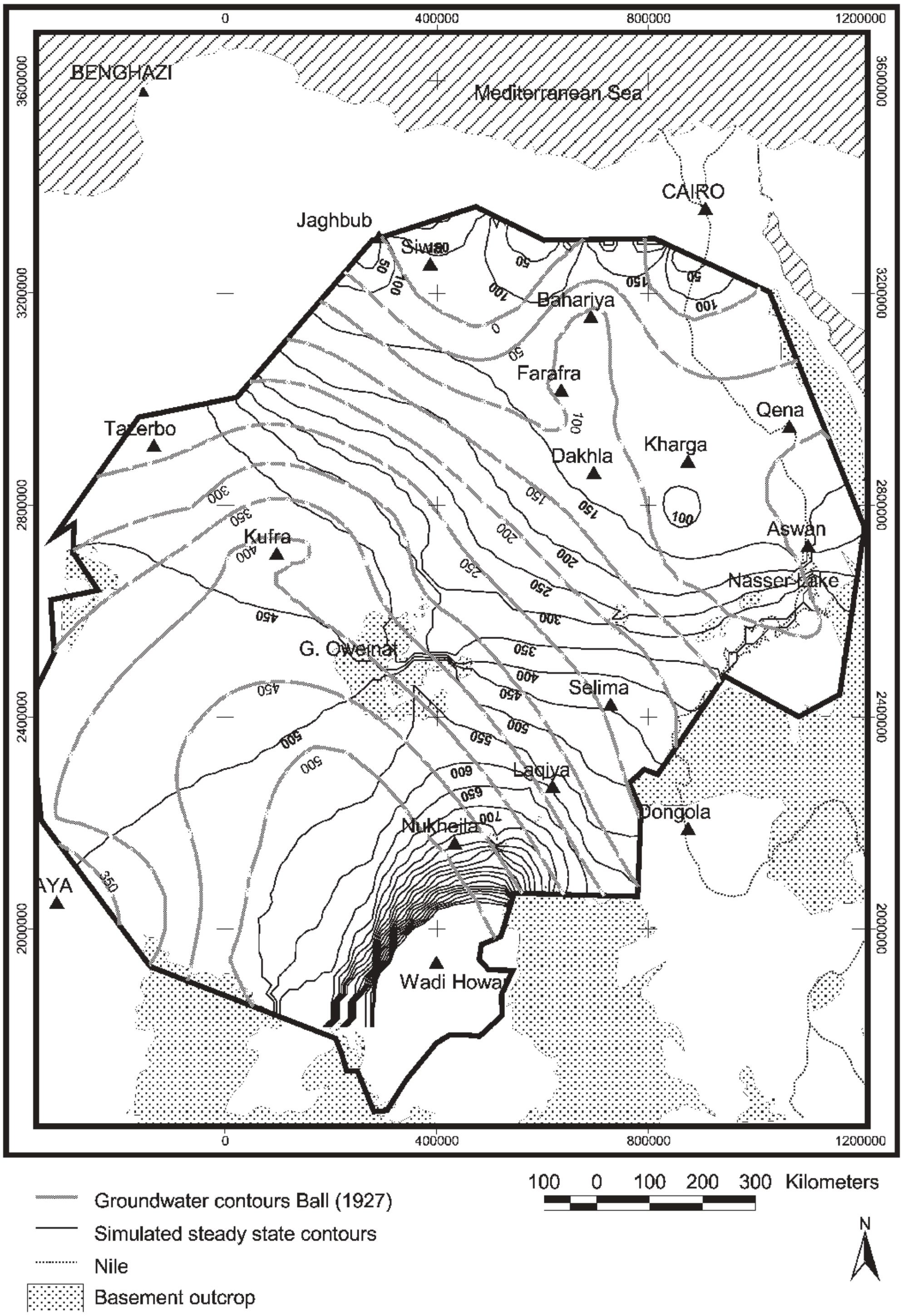

Fig. 4 Simulated groundwater contours for steady-state conditions with infiltration in the southern highlands and exfiltration in the Egyptian oases (finite difference model)

The interpolation tools in GIS are very important. For geological purposes, statistical and geostatistical analysis of the data have to be carried out. Hydrogeological data with a normal distribution (e.g. elevation data or measured groundwater levels) can be interpolated directly. Data sets without normal distributions (e.g. hydraulic conductivities) first have to be logarithmized to get a normal distribution and then interpolated with geostatistical tools. In GIS, the data can be pre- and post-processed, proved and corrected.

One important application is that GIS was conveniently used to control the surfaces of the layers of the numerical groundwater model so that there are no intersections. Although GIS is not really 3D capable (only 2.5D), it can thus be used to prepare the 3D structural model because the numerical groundwater models need a structure with layers that cover the whole area. Other

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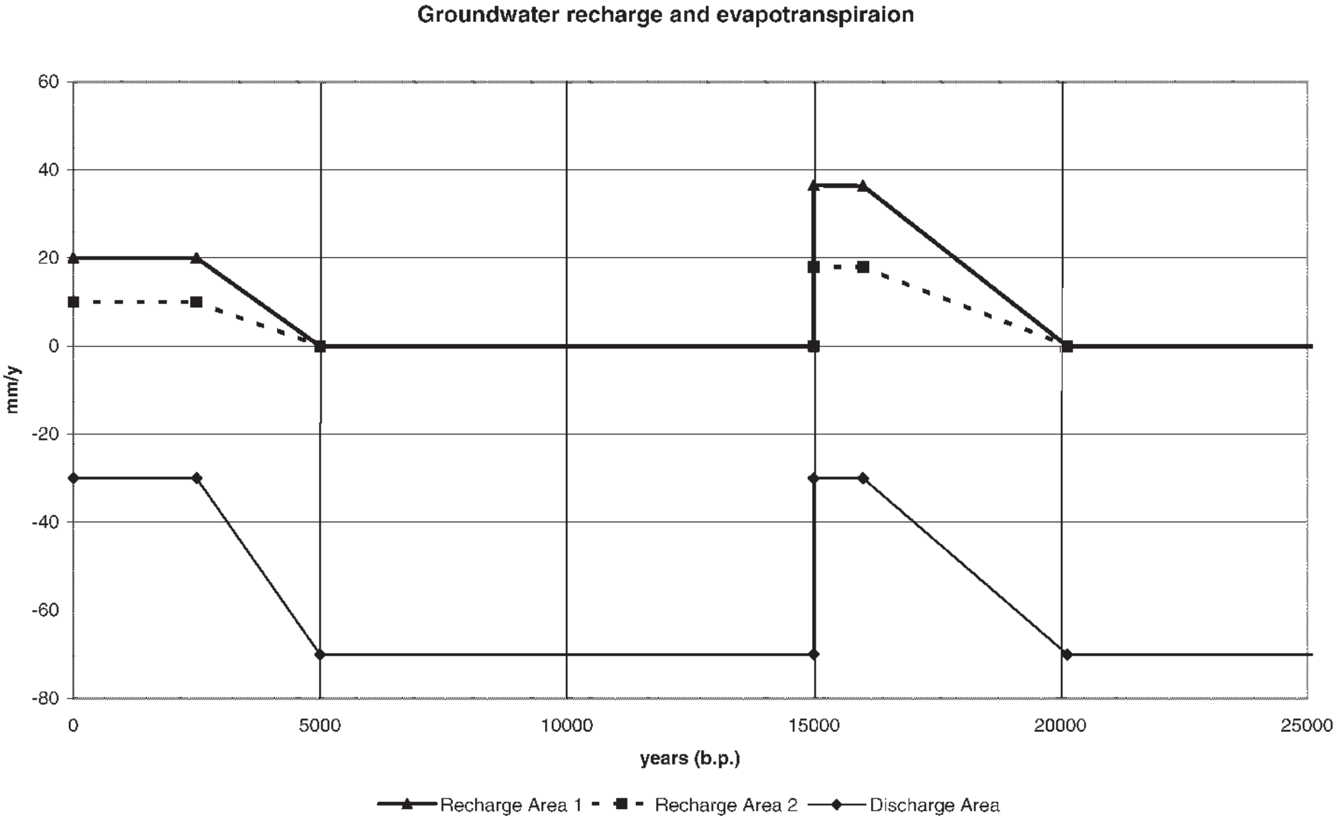

Fig. 5 Time-dependent groundwater recharge in the model area

advantages of the use of GIS as the most important database for the numerical groundwater model are the multi purpose use for

- transparency of the model (i.e. creation of maps and cross sections) and
- the use of the database in various groundwater modelling systems (finite difference and finite element modeling systems).

The map of the basement top elevation (Fig. 1) serves as one example for the created database.

A GIS database is also most important for the calibration of the model. It can be used to visualize the deviation between modeled and interpolated and measured water levels as well as statistical calculations.

Numerical Groundwater Flow Model

Two three-dimensional numerical modeling systems were chosen as basic tools for the simulation of the Nubian Sandstone System: A finite difference modeling system that had some problems with dry cells in the upper layers, and a finite element modeling system that had no such problems. The grid covered an area of 2.2 million km^2 and the modeled area about 1.65 million km^2. For the finite difference solution, a grid of 10×10 km^2 was used. In the finite element model, the area of the triangles ranged from 10 to 100 km^2. The main reasons for the choice of a three-dimensional modelling system are to model:

1. large distance flow from Chad to the Qattara Depression,
2. 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 and,
3. the possibilities to build a transport model with implementation of slices with vertically differentiated flow and transport parameters.

The model was designed to be a closed system. In this way, a reliable no-flow boundary could be identified at the outcrops of the basement. As the saltwater-freshwater line seems to be very constant, it is also concerned as a no-flow boundary (v. 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 varying heads in this long-term simulation (Dirichlet condition).

The hydraulic conductivity was evaluated for the entire area using the available drilling information up to the year 2001 in the newly developed areas, e.g. Tushca (southwest of Aswan) and East Oweinat (Dahab et al. 2003), as

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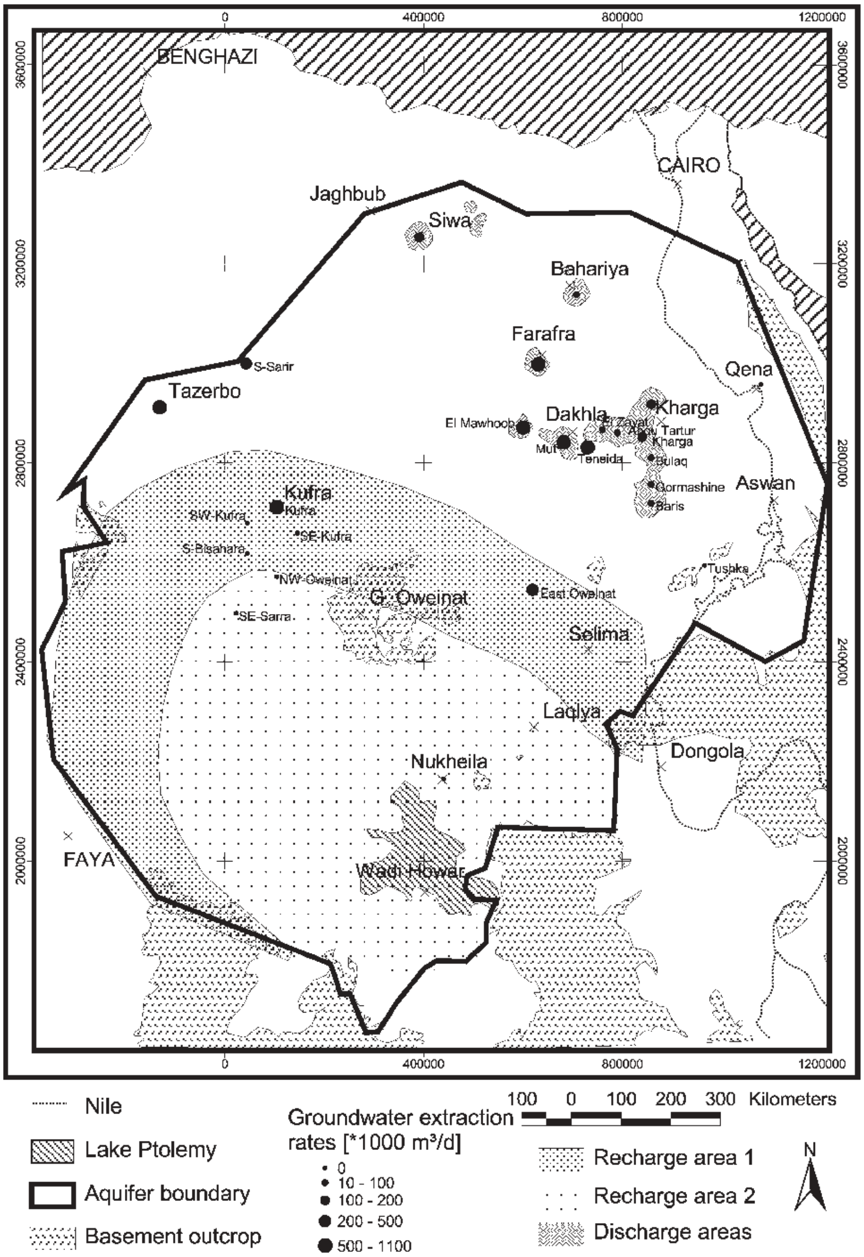

Fig. 6 Recharge and discharge areas, position of former Lake Ptolemy

well as the results published in Thorweihe and Heinl (1999) and shown in the cross sections in Fig. 3. Based on the variability of hydraulic conductivity values and the general stratigraphic setting, the Nubian Sandstone Sequence was divided into 10 layers in the vertical direction. 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 Aquifer and overlying sediments. Evapotranspiration in the large Egyptian Oases was made possible.

Simulation Runs

The following simulations were carried out:

– “Steady-state” conditions simulating the infiltration on the southern highlands and evaporation in the Egyptian oases in the last 50 years neglecting the anthropogenic discharge.
– A long-term transient simulation of the aquifer behavior, due to climatic change followed the steady simulation.

A short-term simulation of the year 1960–2100 using the available hydrogeological data in 1980 and 2000 in the Egyptian part for calibration.

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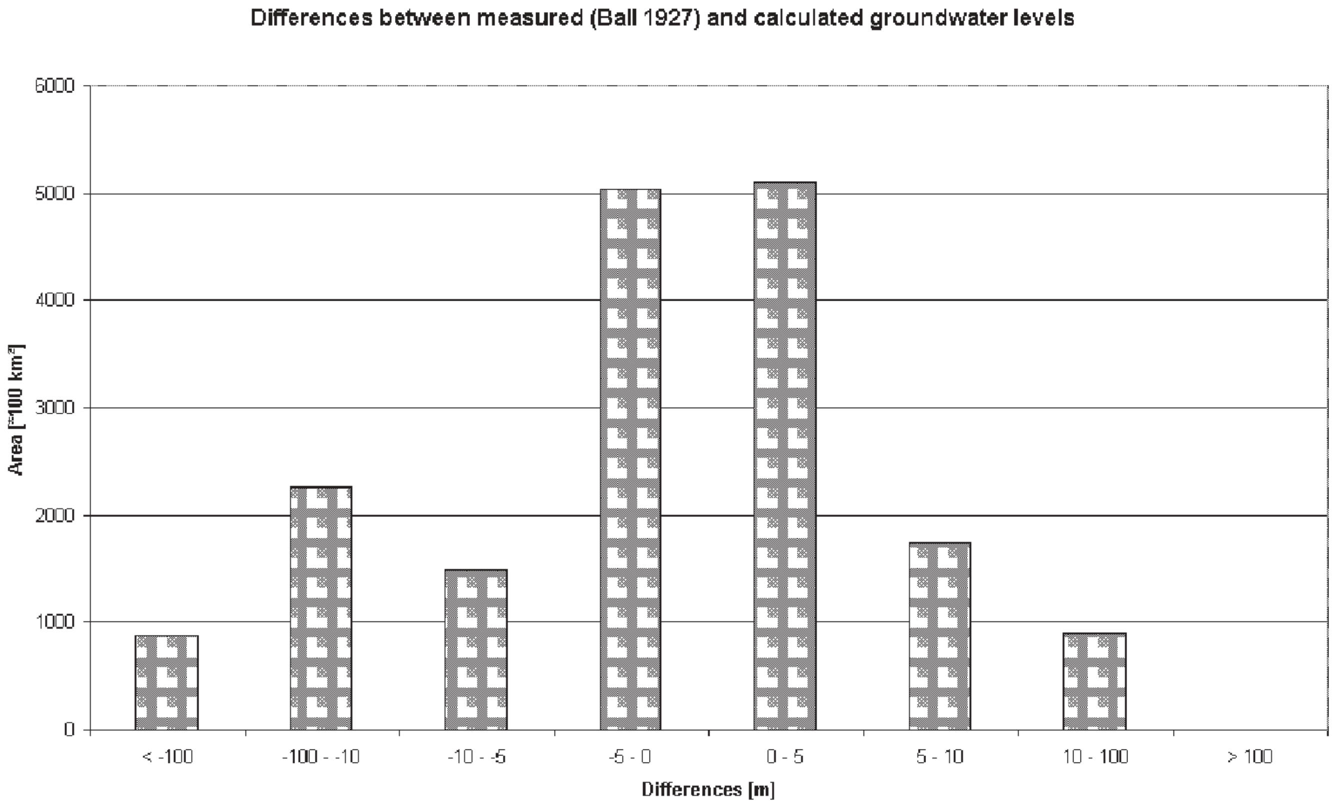

Fig. 7 Differences between measured and calculated groundwater levels (finite element model)

It is planned to refine the grid cells of the development areas in a manner that all local details can be included. These simulations are going to involve:

– the development of a local-scale model for each development area within this 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.
– the simulation of solute transport.

All simulations were done with both modeling systems: First with the finite difference model and later with the finite element model.

"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 millimetres per year of recharge on the highland at the southern edge of the model area and Gilf Kebir Plateau (at G. Oweinat) and an average value of 30 mm/year exfiltration of the Egyptian oases in the northern part of the aquifer, it was possible to obtain the "steady-state" solution for the whole aquifer area as shown in Fig. 4. The most striking feature of the simulated groundwater contours is their similar pattern to the observed groundwater water contours before 1960 published in Ball (1927) at least in the Egyptian part of the aquifer. The regional groundwater flow is also from southwest to northeast. The problem is that there were no real steady-state conditions during the last 25,000 years due to the dramatic climatic changes. Therefore the transient approach was taken.

Long-term Simulation of the Aquifer System due to Climatic Change

To clearly answer the question of whether the groundwater encountered today in the Nubian Aquifer System has been formed during former more humid climatic periods by local infiltration or if it is still flowing 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, which was recently confirmed by isotope studies (Thorweihe 1986; Pachur 1999).

As shown in Fig. 5, this long-term simulation started with a recharge period between 25,000 and 20,000 years B.P.As described in Pachur (1999) in this period a 10–20 mm/year recharge rate can be assumed, that was dominated by southeast directed winds from the Mediterranean causing precipitation at the mountains in Sudan and Chad (Tibesti and Ennedi Mountains). The precipitation during this period was not as high as in a later period between 10,000 and 5,000 years B.P.The spatial

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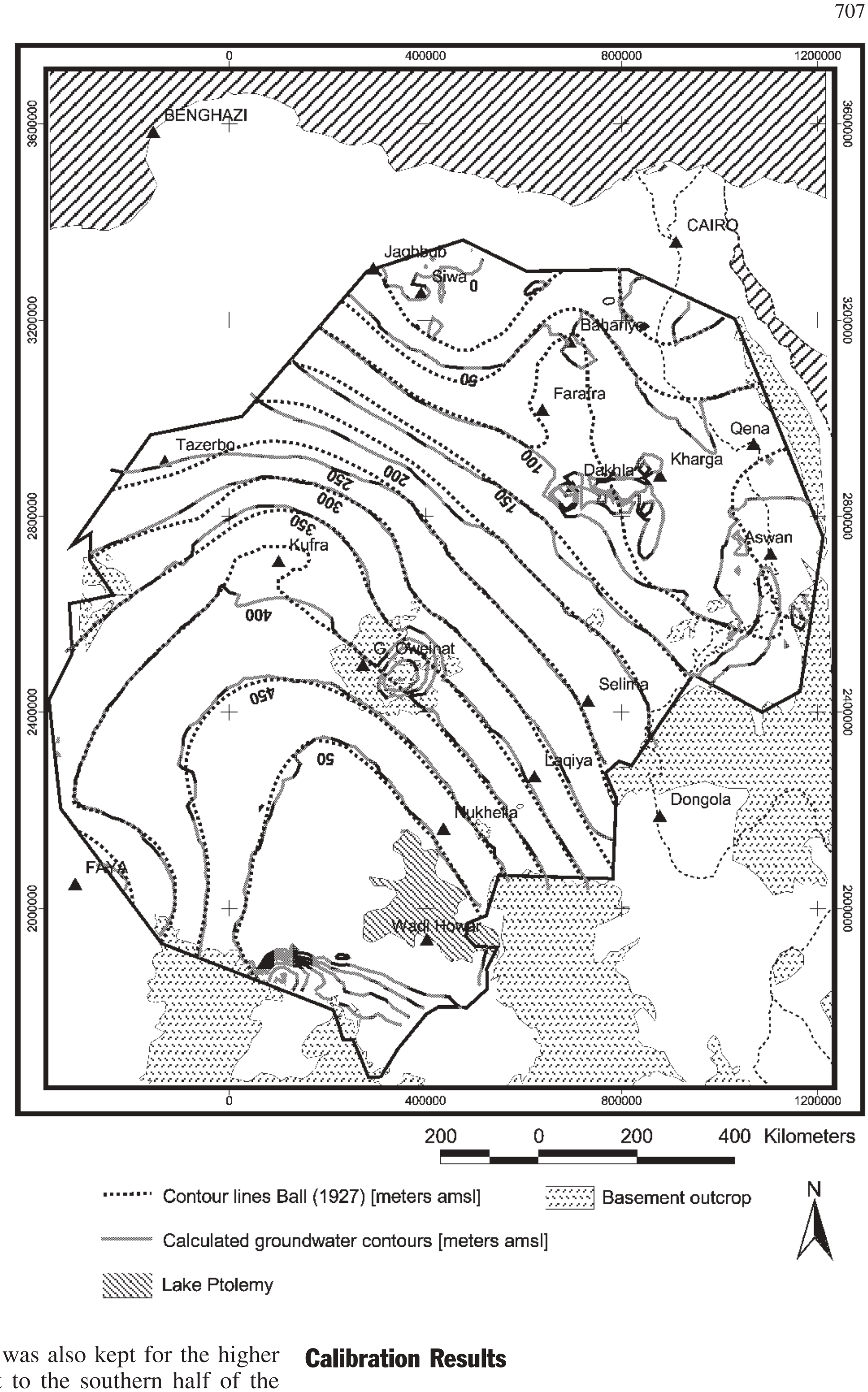

Fig. 8 Simulated groundwater contours in 1960 after a very long simulation of the climatic change. The groundwater contours of Ball's (1927) outside the Egyptian part of the aquifer were considered as the observed values for other areas (finite element model)

distribution shown in Fig. 6 was also kept for the higher recharge period and was set to the southern half of the area. In the periods 20,000 to 10,000 B.P. and 5,000 B.P. to present infiltration stopped and was set to 0 mm/year.

The evaporation data for the depression areas and oasis on the other hand varied from –70 mm/year during the dry periods and –35 mm/year in the wet periods, which is shown in Fig. 5.

Calibration Results

The aim of the "steady-state" model was to match the isolines of Ball (1927), which were measured before the human withdrawal of groundwater in several oasis. The "steady-state" finite difference model (Fig. 4) at first glance showed a similar pattern to the contour lines of Ball (1927). This result could be improved in the finite element model. The root mean square error of the finite

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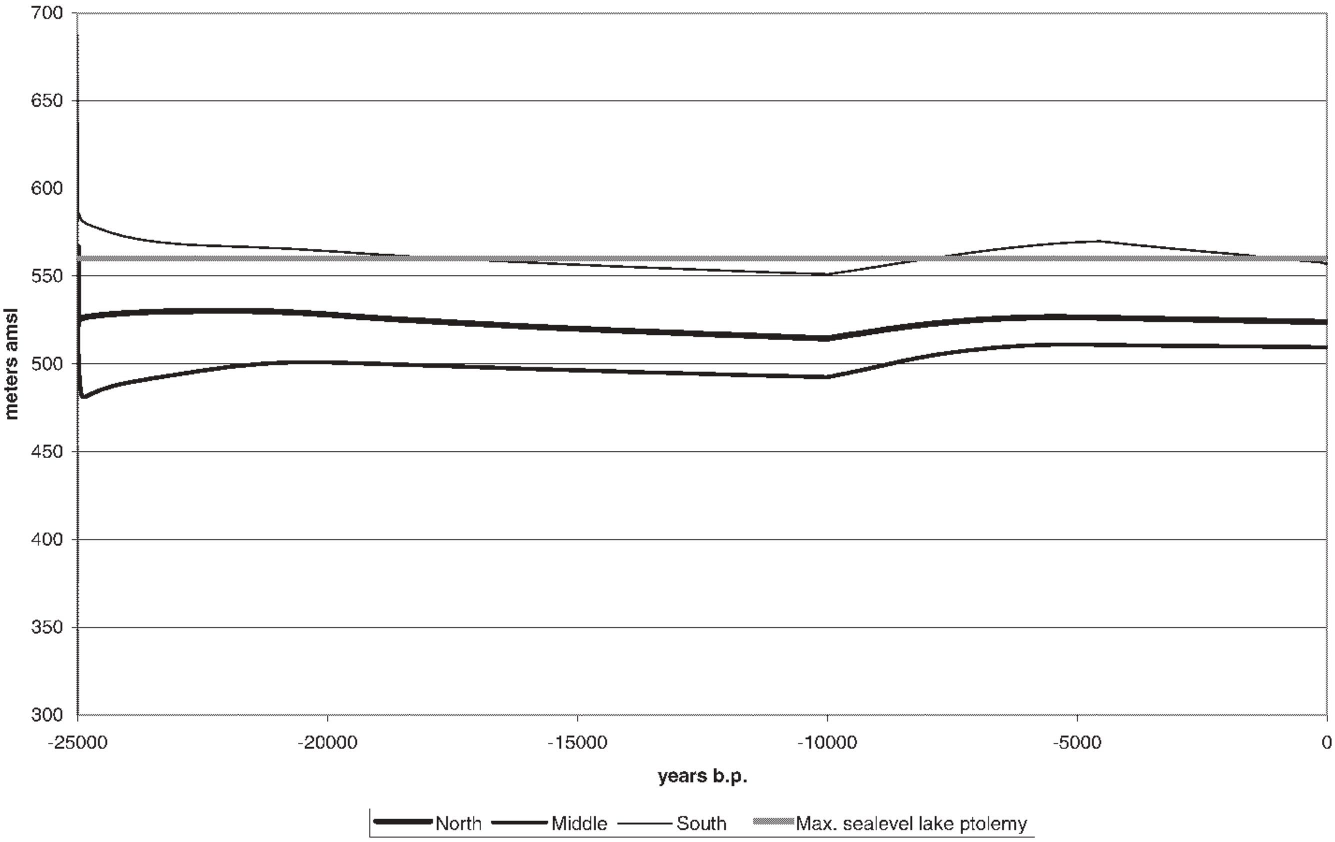

Fig. 9 Water levels in the region of the former Lake Ptolemy (finite element model)

element model was only about 4 m, and an area of about 1,000,000 km^2 had a difference between measured and calculated groundwater levels of less than 5 m; see also Fig. 7.

These good results couldn't be held in the transient model after the adjustment of recharge, evaporation and porosity parameters and the errors reached only about 30 m. The pattern of the measured and the calculated groundwater isolines match in big parts of the model area. With the finite element model the results were improved as shown in Fig. 8.

During the wet periods the results of Pachur (1999) could be verified. For the area of the former "Lake Ptolemy" (Sudan) the maximum level of 560 m a.s.l. was reached for a few thousand years; see Fig. 9.

Simulation Results

In general, the aquifer response to climatic variations suggests that groundwater was formed during former more-humid climatic periods by regional infiltration (Kröpelin 1993). The decline of the groundwater surface started about 19,000 years ago, but it was slowed down and completely interrupted by regional infiltration during the last wet period (ended 2,500 years ago). It took about 5,500 years after the start of the second wet period to return to the nearly filled up condition, and since then the groundwater levels receded for more than 4,000 years (Fig. 10). In this period, natural discharge was not completely balanced by recharge.

Between 20,000 and 10,000 B.P., infiltration stopped, and the simulated groundwater contours indicate that the groundwater level particularly dropped in the elevated areas. Within this time, the drawdown ranged 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. Even in this long dry period, the groundwater levels didn't return to the low levels before the recharge period. This may indicate that the porosity parameters are too high, but for the sandstone values of 0.01 to 0.1 have been proven (total porosity of about 0.25 to 0.3). During the wet periods, on the other hand, the calculated depth to groundwater shows that in wide parts of the model area the aquifer comes to a nearly filled up condition. It is also remarkable that there is a time shift between the recharge and evaporation data and the groundwater levels. The highest groundwater levels are calculated about 50 to 100 years after the end of the wet periods.

It seems that natural discharge during the second wet period did not depend on the climatic condition and rather depended on the potential head distribution and therefore continued during this period. Only after the decline of groundwater level in the present arid conditions, did natural discharge start to diminish (Fig. 10). The depth to groundwater in 1960 is shown in Fig. 11.

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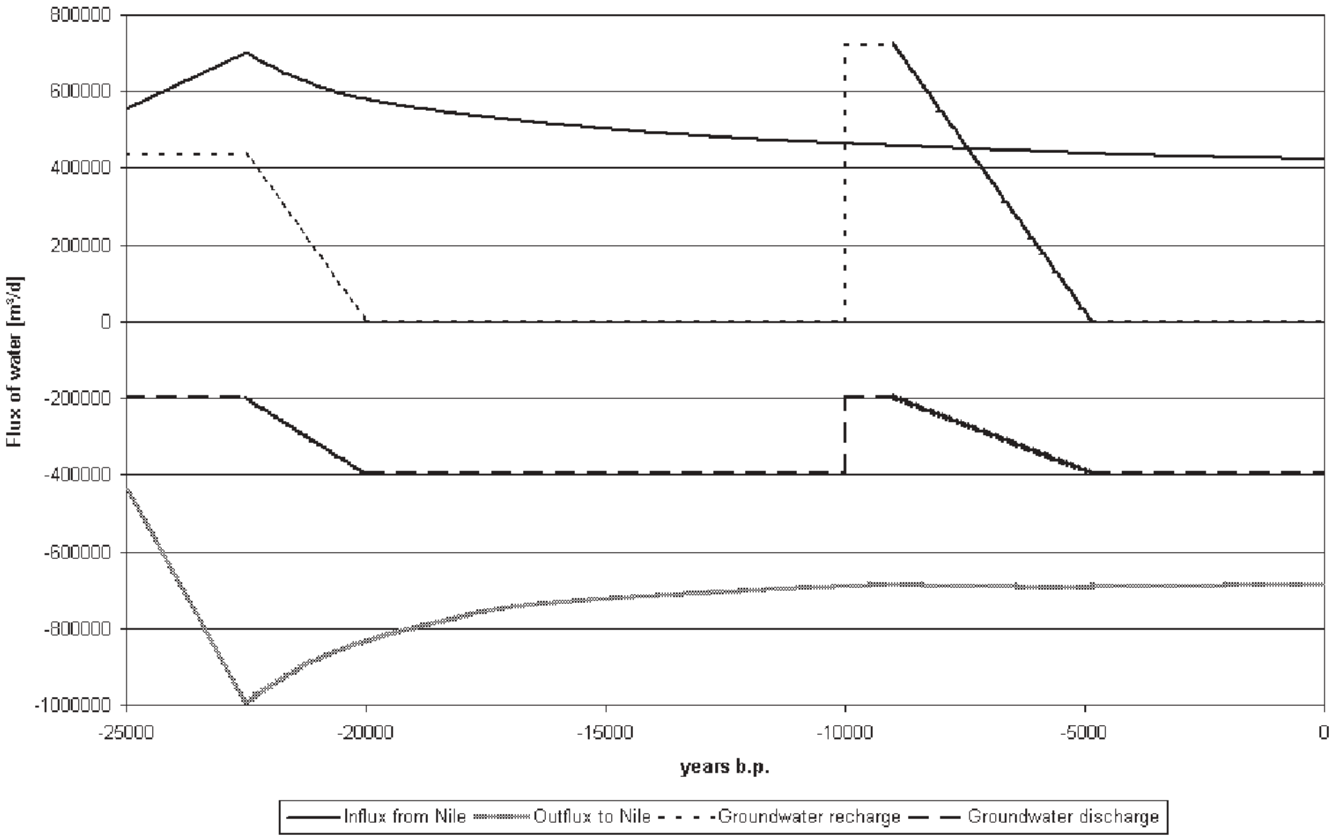

Fig. 10 Groundwater balance for the Nubian Sandstone Aquifer in the last 25,000 years (finite element model)

However, the simulated groundwater contours are located at the ground surface or slightly below at the end of both recharge periods indicating a nearly "filled up condition". Because of the drawdown in the last 3,000 years, due to the prevailing arid condition as well as the insufficient transmissivity distribution to maintain it, this filled up condition has not existed since the end (+100 years) of the last wet period.

Even during wet periods this filled up status as a certain kind of steady-state condition could have only existed for the whole aquifer area (1.6×10^6 km^2). Taking into account that the average distance between recharge areas in the south and discharge areas in the north are 1,000 km, and the average groundwater velocity in sandstones is about 1 m/year, then the flow time between the recharge and development areas would be 1 million years. The ages of groundwater shown by Thorweihe and Heinl (1999) of about 20,000 to 40,000 show that also in some northern parts recharge must have occurred in the wet periods.

The research results reported in Pachur (1999) must be investigated concerning two aspects:

The reported former lakes could be a result of high groundwater levels or a high runoff. 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. These aspects can't be decided now but the research on this topic is going on.

In order to calibrate the regional model and thus make it reliable for the development of local scale flow and transport models, data of extraction and drawdown of a new development area in the Egyptian part of the aquifer for the period 1960–2000 were used. No major extractions and drawdown in the other parts were reported before 1980 and therefore the observed groundwater contour lines of Ball (1927) were used as the observed groundwater contours in these areas.

The official records of groundwater extraction for irrigation and domestic water supply were used to calculate the annual artificial discharge for each individual well pumping center in the study area. The extraction rates of all wells in each development area were added for each year in this period and considered as the extraction rate of a single well. As the modelling system allows locating well screen in more than one layer, there was no need to classify the wells into shallow and deep wells. Due to the intensive extraction rates in Dakhla, Kharga, and Kufra oases, wells in each of these oases were grouped into three pumping centers. The extraction rates shown in Fig. 12 are the formally reported rates for year 2000. However, the present extraction rates could be higher at

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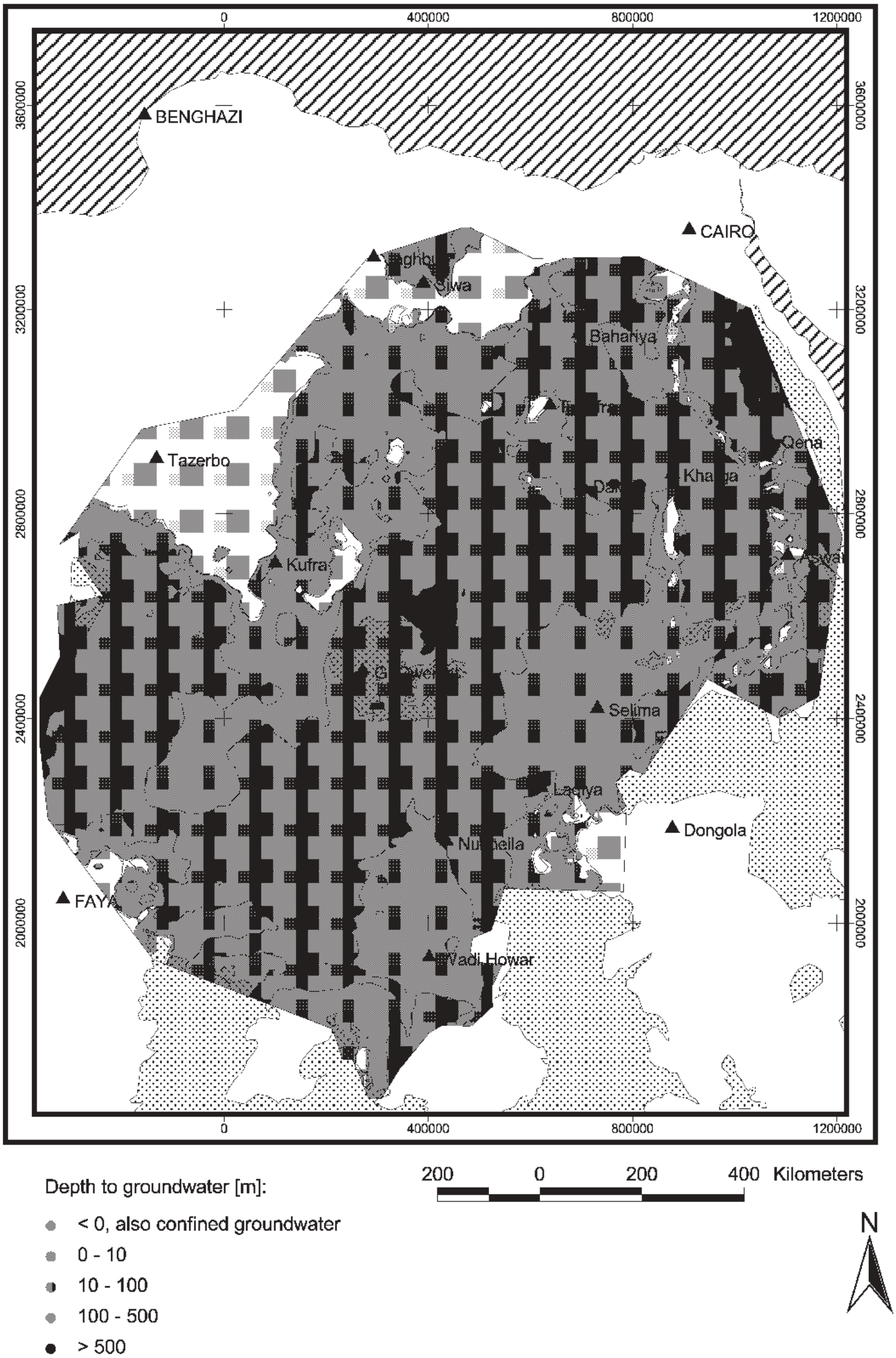
Fig. 11 Depth to groundwater in 1960 (finite element model)



some places (e.g. Kufra Oasis in Libya and Kharga and East Oweinat in Egypt). In a proposed extraction scenario by CEDARE (2001), the present extraction 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 a very 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 extraction in the last twenty years (1960–1980). In

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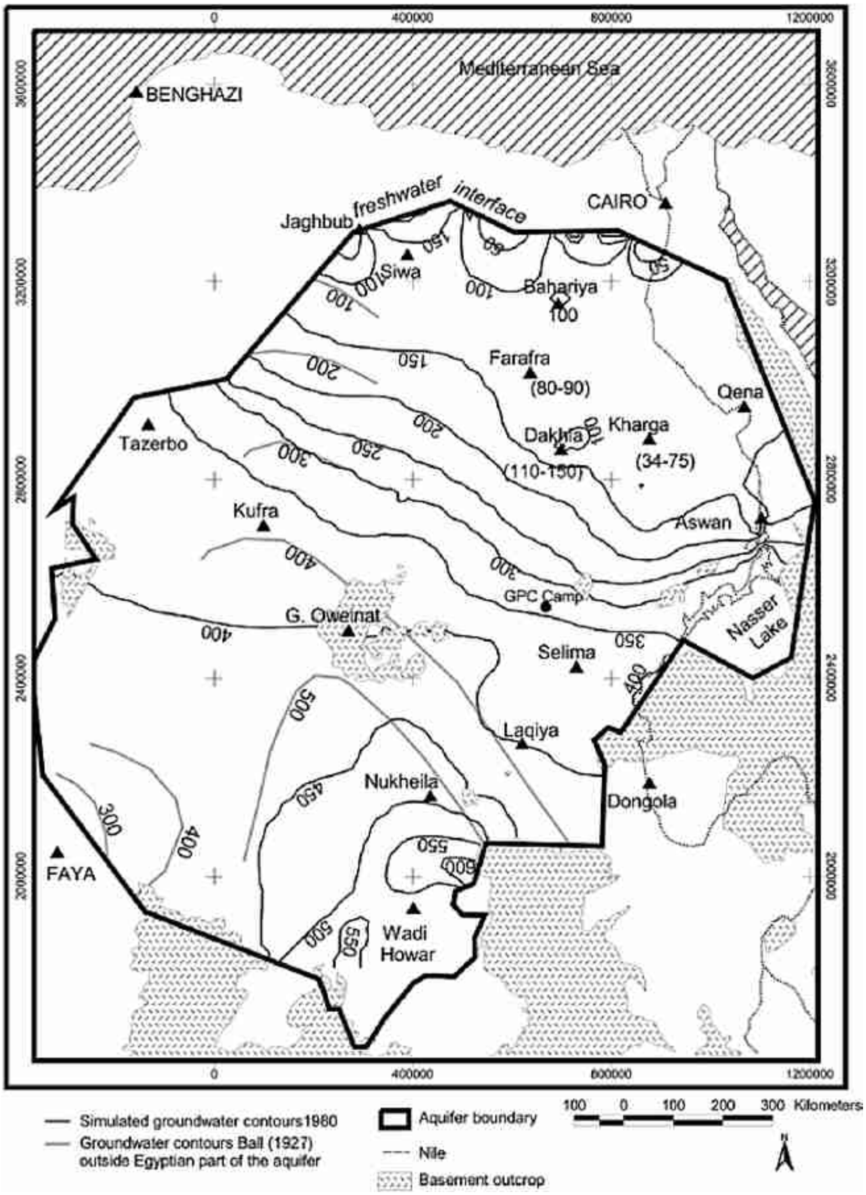

Fig. 12 Simulated groundwater contours in 1980 imposing groundwater extraction in the period 1960–1980 after a very long simulation of climatic change. Observed values are also shown between parentheses for the Egyptian Oasis. The groundwater contours of Ball's (1927) outside the Egyptian part of the aquifer were considered as the observed values for other areas (finite difference model)

the Egyptian part of the aquifer (where groundwater development started in 1960), the simulated hydraulic heads in 1980 is in good agreement with the observed hydraulic heads for that year (Fig. 12). In 1980, cones of depression started to develop in Kharaga and Dakhla Oasis and became wider and deeper with time (Fig. 13). 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 (Fig. 12).

The focus of the simulation was to decide whether or not flow in the Nubian Aquifer System was in a steady state. The simulation results of the transient model showed clearly that the water levels were receding since the last wet period and they didn't reach the low levels of the time before 10,000 B.P. This indicates that the drawdown is going on and will last even for another few 1,000 years. The second argument for this interpretation of the modelling results is the balance: As Fig. 9 shows, the water levels (as well as the balances) recede in the dry periods. The second drawdown hasn't reached the low values of the first dry period (20,000 to 10,000 B.P.). So if the circumstances of recharge and evaporation will continue, the loss in the balance will also continue.

Conclusion

With the available evidence that Kufra Basin is not separated from Dakhla Basin by uplift and even the small basins are not completely separated, the system has to be looked at as one aquifer. The simulation results indicated that the total groundwater storage is about 135,000 km^3, which is very close to the figure obtained by Heinl and Thorweihe (1993). Simulation results also indicated that

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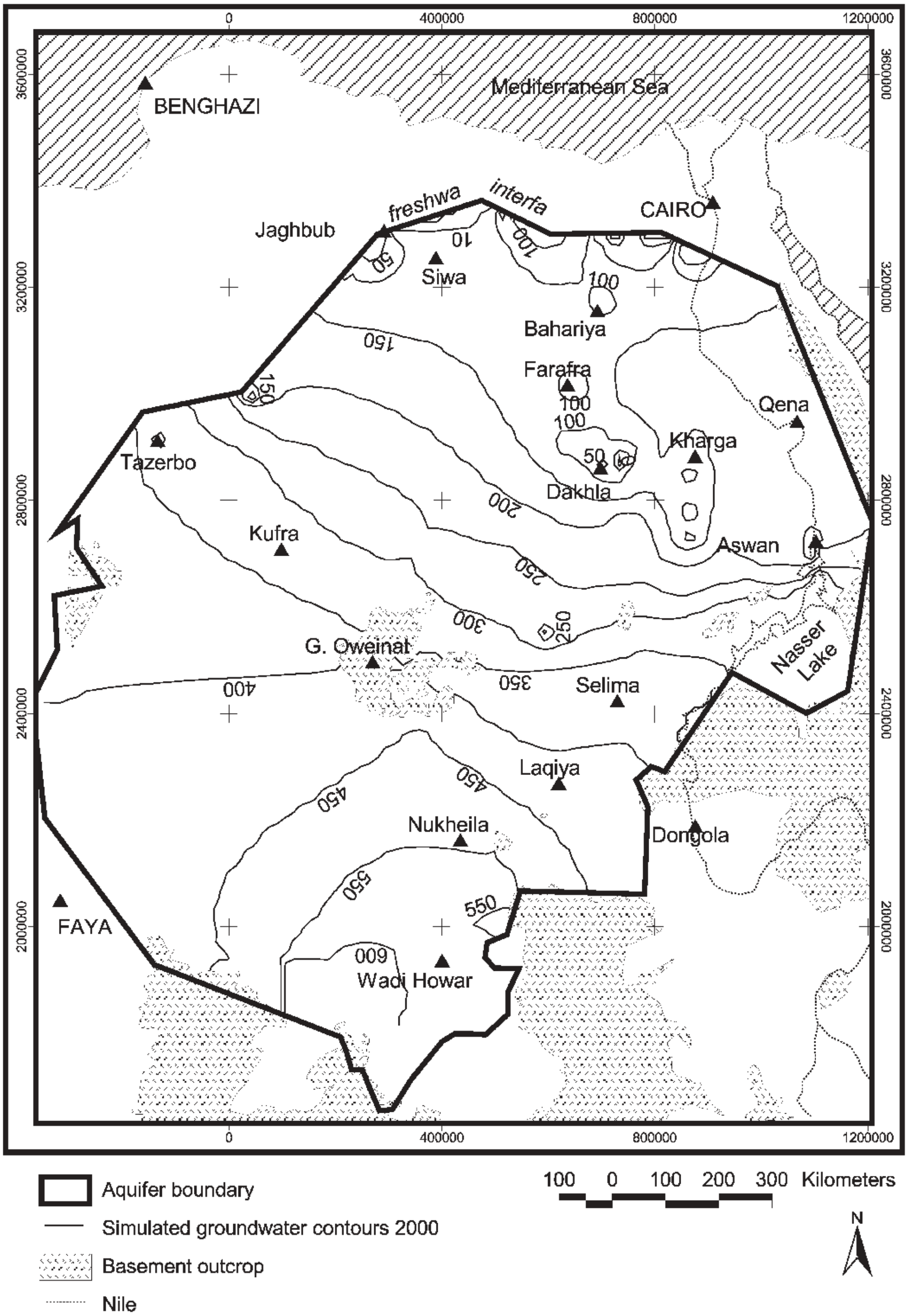

Fig. 13 Simulated groundwater contours in year 2000 imposing groundwater extraction in the period 1960–1980 after a very long simulation of the climatic change for 25,000 years before 1960 (finite difference model)

in both wet and dry periods, groundwater flow from the aquifer to the Nile River has occurred in the area between Dongola and Aswan where the hydraulic conditions were favourable before the construction of Aswan High Dam. The amount of Nile water seepage into the aquifer was very low and only possible in the area south of Dongola. However, after the construction of the dam, rising water level in Nasser Lake increased Nile water seepage into the aquifer. The exchange of groundwater (flux in and out of this boundary condition) is about 500,000 m^3/day over the whole course of the river in the model area (about 1,200 km).

The simulation results indicate that the Nubian Aquifer System had been in an transient state for the last three thousand years due to the following reasons:

1. The groundwater contours observed by Ball (1927) and the simulated contours at the end of a very long transient simulation period are very similar. The simulation results show also a good correlation to geo-

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logical research results for lakes that existed about 6,000 years B.P.

2. To some extent, these groundwater contours are also 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 3,000 years.
3. During wet periods, a time span of only 3,000 years and a few millimetres per year of infiltration are sufficient to keep the groundwater level near the surface (filled up condition).
4. The imbalance in the dry period indicates that there is a remarkable outflow of the system that leads to decreasing groundwater levels.
5. On the other hand, the groundwater levels haven't decreased to the levels they had before the last wet period, so that it must be foreseen that, also without any human impact, they would decrease in the next few thousand years.
6. The slope of the ground level 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 increased from its minimum to its maximum and continued at this rate with a slow decrease with time for the whole dry period. After this arid depletion of the aquifer, the groundwater was quickly replenished after the climatic transition to the subsequent wet period.

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