Journal of African Earth Sciences 85 (2013) 115–124

Contents lists available at SciVerse ScienceDirect

Journal of African Earth Sciences

journal homepage: www.elsevier.com/locate/jafrearsci

Recharge flux to the Nubian Sandstone aquifer and its impact on the present development in southwest Egypt

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ARTICLE INFO

Article history:
Received 22 August 2012
Received in revised form 16 March 2013
Accepted 28 March 2013
Available online 12 April 2013

Keywords:
East El Oweinat
Nubian Sandstone aquifer
FEFLOW model
Recharge flux
Simulation
Groundwater

ABSTRACT

The southwestern part of Egypt (East El Oweinat) is an arid area with no surface water and only one resource of useable groundwater in the well-known Nubian Sandstone aquifer. This resource has been heavily exploited since 1990, which has led to a continuous decline in the potentiometric surface of this aquifer. The groundwater recharge in the concerned area depends exclusively on the subsurface inflow across the Egyptian/Sudanese borders. A FEFLOW, finite element groundwater model, has been used to investigate the length of the recharge window and to predict the hydrodynamic impacts of different groundwater extractions on the potentiometry of this aquifer. A complete database of the hydrogeological and drilling information of about 600 water wells drilled in the period 1985–2010 was evaluated and used for the model parameter input as well as for its simulation. The results of steady-state simulation indicate that the length of the southwest flux boundary is about 170 km with angle flow direction about 52°NW with a groundwater flow rate about 0.018 m/day. A calibrated regional numerical model with refined grid on the pumping centres, hydraulic properties and flux boundary in the southwest is used to simulate the impacts of the present and planned groundwater extraction on the potentiometry of the aquifer. The results show a real danger of increasing the water depth to uneconomic lifting depth. Through implementation of 135 pumping wells in time 2002–2008, the lowering of water table ranges from 1 to 1.5 m in the reclamation areas. On the other hand, the distribution of 1600 proposed wells with distance between every two adjacent wells not less than 2700 m indicates that the lowering of water table ranges from 5 m away of the reclamation areas to 15 m in the reclamation areas in time period of 27 years (2008–2035). This result seems to be the better for the present irrigation project in East El Oweinat area.

1. Introduction

The study area is located in the southwestern part of the Western Desert of Egypt at the Egyptian/Sudanese border. The area is located between latitudes 22°00′–23°00′N and longitudes 28°00′–29°00′E (Fig. 1). As Egypt is essentially a desert land (about 94%), great consideration is given to desert reclamation and to the exploration of groundwater, which is the sole resource to be used for different purposes such as domestic and irrigation uses, spatially in the areas outside of the Nile valley. The East El Oweinat area has attracted considerable attention with respect to the exploration and exploitation of the Nubian Sandstone aquifer system. The natural resources of this area cover the demands for the continuing reclamation and housing projects, where the good soil quality and groundwater resources are important factors. In the last few decades, intensive drilling for groundwater has been performed; there are now about 600 wells, while the total proposed wells in this area of about 1884 wells will be finished in 2017 for reclamation the full capacity of the project (220,000 feddan) in 22 plots with 10,000 feddan/plot (Fig. 1). The principal goal of this national project is to drill 83 wells within each plot with an average discharge of about 200 m^3/h/well and for a pumping period of 12.5 h/day/well (Ministry of Agriculture, 1999). Several rural villages have been established, which depend on the newly explored and exploited groundwater resources. The area concerned could be taken as an example of poverty alleviation through migration of people from overpopulated areas in the Nile Valley towards the newly initiated settlements in this far southern area of Egypt but it is dependent on the available water resources. From the climatic point of view, the area is located in an arid region, being warm in winter and rather hot in summer with wide diurnal varia-

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http://dx.doi.org/10.1016/j.jafrearsci.2013.03.009

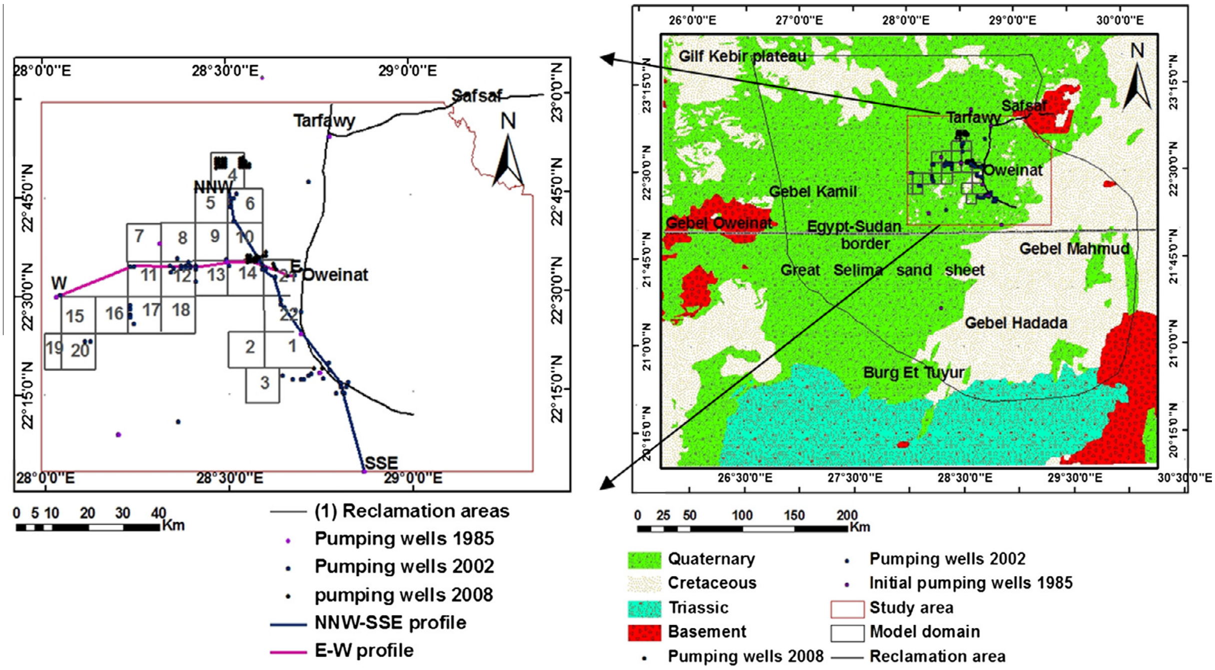


Fig. 1. Map showing the new reclaimed plots and geology of the study area.

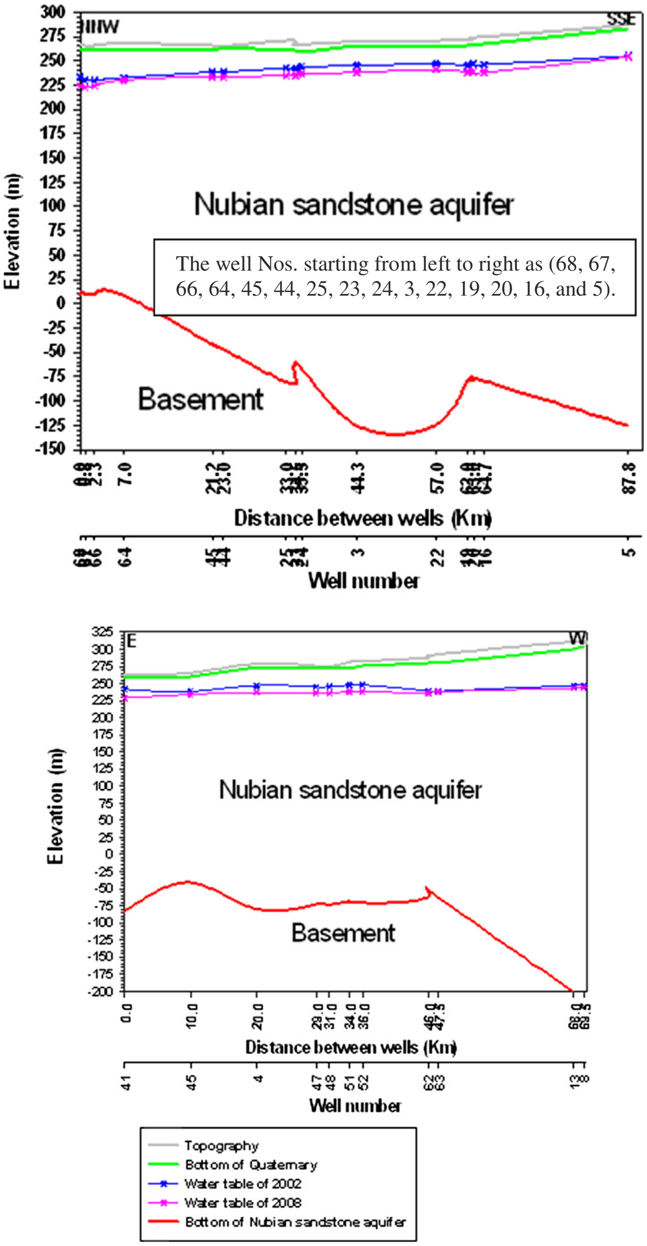
tions and almost no precipitation, where the maximum air temperature is 39.3 °C in July and the minimum is 13.1 °C in January. The prevailing wind direction in the study area is generally from northwest to north–northeast. Natural evaporation rate ranges between 10.1 mm/day during January to 32.8 mm/day during June with an annual average of 22.2 mm/day.

2. Geologic and hydrogeologic settings

Geologically, the rock formations occupying the South Western Desert of Egypt belong to the Precambrian, Triassic, Upper Jurassic–Lower Cretaceous (Nubian Sandstone), and Quaternary (Table 1) (CONOCO, 1987). In East El Oweinat area, the

Table 1
Composite litho – stratigraphic succession in the South Western Desert of Egypt (compiled after CONOCO, 1987).

Age		Formation	Lithologic description	Available maximum thickness (m)
Quaternary	Pleistocene to Recent		Chalcedony, lake deposits, eolian deposits (sand dunes and sand sheets) and Wadi deposits	Variable
Oligocene			Basaltic rocks	
Eocene	Early Eocene	Thebes	Earthy-brown reefal limestone with shale interbeds	127
Paleocene	Late Paleocene to Early Eocene	Esna	Green shale and marl enclosing carbonate, more calcareous ingredients towards top of marine environment	104
		Garra	Well-bedded, white limestone and chalk with minor shale and marl intercalations	111
	Late Paleocene	Tarawan	Chalky limestone: white, containing bands of marl, of outer shelf depositional environment	50
	Early Paleocene	Kurkur	Limestone brown; siliceous and sandy in parts with intercalations of shale	110
Upper Cretaceous	Mastrichtian to Early Paleocene	Dakhla	Shale and marl intercalated by siltstone, sandstone and limestone	230
	Campanian–Mastrichtian	Kiseiba	Sandstone: fine grained with shale intercalations. Bone and phosphate beds are also recorded	150–340
	Late Campanian	Duwi	Phosphate bearing unit; a sequence of alternating beds of claystone, sandstone, siltstone and oyster limestone including phosphatic limestone interbeds	65
	Early Campanian–Late Campanian	Quseir	Varicolored pelites, ferruginous and glauconitic, the lower part of this formation is made up of alternating claystone, siltstone, sandstone and conglomerate	80
	Turonian to Santonian	Taref	Sandstone: white, yellow fine to coarse grained, tabular cross bedded with conglomerate and marine intercalations	115 – 150
	Late Cenomanian to Early Turonian	Maghrabi	Massive grey claystone; with siltstone, sandstone and conglomerate intercalations	60
Lower Cretaceous	Albian	Sabaya	Sandstone: white, grey, yellowish, brown and red, fine to coarse grained with conglomerate intercalations	160
	Aptian to Early Cenomanian	Abu–Ballas	Shale: silty shale and siltstone, with thin intercalations of sandstone of shallow marine environment.	30–44
	Pre-Aptian	Six Hills	Sandstone: fine to mainly medium to coarse grained sandstone having different colour. compaction ranges from friable to highly consolidated, tabular cross bedded	450
Carboniferous		Gilf	Sandstone: fine to coarse grained, yellowish white to brown, with intercalations of clay and clay beds	20–85
Precambrian			Older granitiods, granodiorite and Younger granites	Base is not reached



The well Nos. starting from left to right as (68, 67, 66, 64, 45, 44, 25, 23, 24, 3, 22, 19, 20, 16, and 5).

Fig. 2. Profiles show the variations in water table of Nubian Sandstone aquifer in East El Oweinat area in period between 2002 and 2008.

sedimentary succession in subsurface represents the filling of Misaha Graben, a NNW–SSE – striking structure east of Gebel Kamil which attains a maximum thickness of about 720 m (Himida et al., 2007). It belongs to Upper Jurassic–Lower Cretaceous and Quaternary (Fig. 1). The Precambrian basement rocks are composed of granite, gneisses, and granodiorite, and are exposed in Qaret El Mayit (the northeastern part of the studied area), Gabel Oweinat (in the west) and east Sudan. The Upper Jurassic–Lower Cretaceous Nubian Sandstone occupies the majority of the surface forming isolated hills with a height ranging from 3 m to about 10 m above the surrounding sand sheet. It is built up of sandstone beds, ranging from very fine to medium grained with different colour gradation (Six Hills Formation). It is considered the main water bearing formation in East El Oweinat area. The Nubian Sandstone Sequence is extensively covered by the Quaternary aeolian sand sheets of the southward-extending Great Selima Sand Sheet, stretching into the northern Sudan. In the eastern part it is overlain by an Upper Cretaceous–Lower Tertiary rock complex (Kamel et al. (1984).

The Nubian Sandstone is the main exploitable water bearing formation in the studied area. This aquifer is used for the agricultural and socio-economical development of the whole southern Western Desert of Egypt (CEDARE, 2002). It was formed by the local infiltration during the past wet periods (pluvial periods), which ended in the northeastern Sahara about 8000 years ago, while it ended in the south about 4000 years ago (Hesse et al., 1987; Heinl and Thorweihe, 1993). Regionally speaking, the Nubian Sandstone aquifer system is the Sahara's most important easterly groundwater province. It covers southeast Libya, Egypt, northeast Chad, and northern Sudan with a total area of about 2.4 million km^2. From the data derived from 300 drilled wells in the East El Oweinat area, it is concluded that the hydrogeological framework consists of one water bearing unit known as Six Hills Formation which is built up of fine to medium grained sand and sandstone intercalated by water confining beds of clay and silt. The presence of these semi-permeable sediments is discontinuous due to rapid lateral changes of facies. This situation has lead to hydraulic interconnection between upper and lower water bearing sandy and sandstone layers. Therefore, the Nubian Sandstone in the investigated area acts as one hydraulic unit of unconfined type. The inflow to this aquifer includes recharge by underground inflow through the southwest boundary of the system.

2.1. Problem identification and objectives

From the monitoring of the water table of the drilled wells in the study area, it was found that a noticeable lowering of the water table started after condenses of well drilling in the reclaimed area. Two profiles (NNW–SSE and E–W) were constructed for the period between 2002 and 2008 (Fig. 2). These profiles show that the water table lowered about 1.5–2 m/year. This lowering is very serious, since it was as result of pumping groundwater only from about 200 pumped wells, while the total proposed wells in this area about 1884 wells will be finished in 2017. So, this is the question of the present study, if the water table has been lowered as result of pumping of 200 wells with 2 m/year, how is the situation of water table after pumping the proposed 1884 wells? And what is the recharge flux and groundwater flow rate?

3. Materials and methodology

The methodology adopted in this work is described briefly as:

1. Compiling the available well logs of most new and old water wells drilled in the area, groundwater depths recorded between 1985 and 2008 and pumping tests.
2. Digital Elevation Model (DEM) of Shuttle Radar Topography Mission (SRTM) 30 m resolution and geological maps processing and interpretation for extracting linear features (geological and hydrogeological fractures and/or faults) and planning for future possible groundwater artificial recharging and aquifer development planning.
3. On-screen digitizing with the aid of ArcGIS (version 9.x) and ArcView softwares, where various hardcopy maps were converted into digital formats.
4. Building up a groundwater flow model using FEFLOW which provide an advanced 2D and 3D graphically based modelling environment with the purpose to meet water needs, and to avoid groundwater depletion and/or groundwater depth increase.

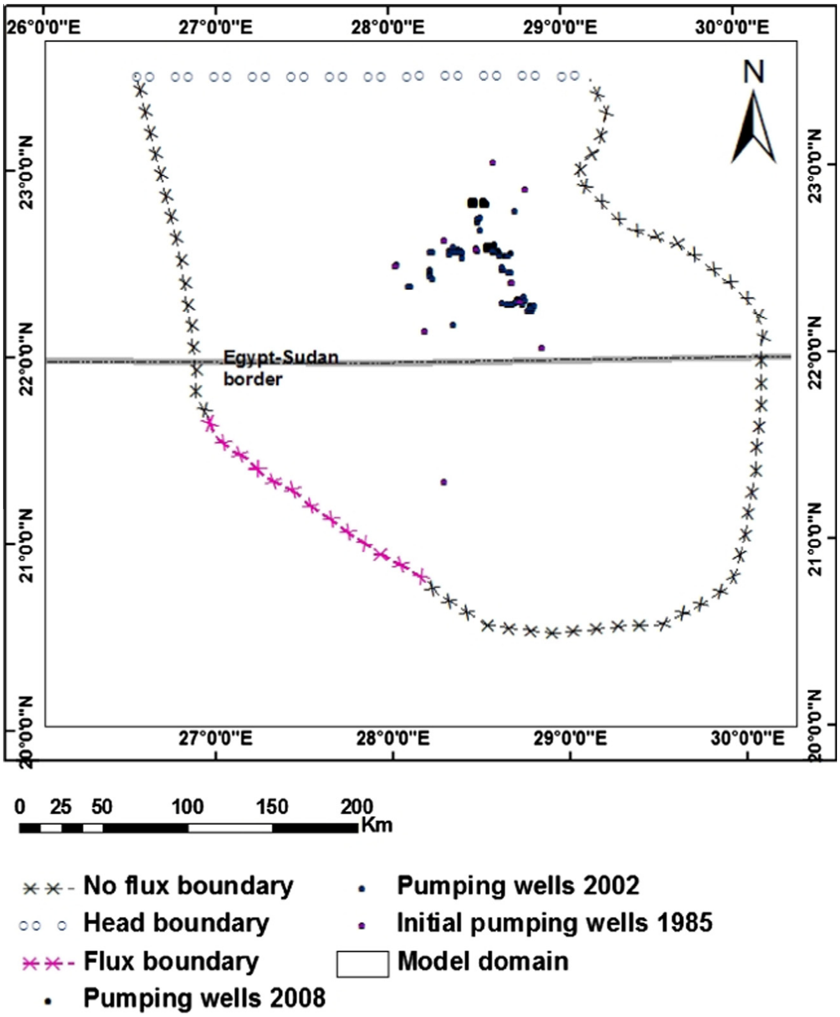


Fig. 3. The boundary conditions of the model area.

4. Implementation of a large scale groundwater flow model

To answer the raised questions of the impact of the planned groundwater extraction from the concerned aquifer on the local aquifer a finite element groundwater model was established.

The study area of about 14,000 km^2 is located East of Gebel Oweinat and Gilf Kabir Plateau close to the Egyptian/Sudanese borders. The model area is extended into north Sudan to the natural hydrogeological boundary of the Nubian aquifer (Fig. 3).

4.1. Setting up the numerical model

4.1.1. The 3rd dimension and 3D slice elevation

The model of the study area consists of three slices or two layers namely (Table 2 and Fig. 4):

- Quaternary layer.
- Nubian Sandstone aquifer (NSA) layer.

4.1.2. Stratigraphical model using FEFLOW

FEFLOW allows the user to choose which interpolation technique suites the available data best. Because of the present well logs only restricted for the study area not for all the model area. Therefore, an interpolation for the thickness of the Quaternary and Nubian layers was made using ArcView and FEFLOW techniques with kriging and Akima methods to produce some assumed wells to make an improvement for the hydrogeological cross sections. Two hydrogeological cross sections are constructed crossing the model area to study the geographical extension of the Quaternary and Nubian aquifers (Fig. 5). From this figure the following can be concluded:

- The thickness of the Nubian Sandstone aquifer increases towards the south and west directions with the greatest thickness in the southwestern part of the study area.
- The study area is affected by many step faults striking in NW–SE and NE–SW which causes at the same time the increase of thickness of the Nubian aquifer to the southwest and west directions (Dahab et al., 2006).

4.2. Problem classes

The specifications of all model attributes in a given finite element mesh are completed in the FEFLOW problem classifier menu which allows to define model physics, specify problem classes, control data and time characteristics and manipulate mesh data. In the problem, class window it should be defined the principal type of the FEFLOW Model. The problem class in the study model area is defined into the following classes:

Table 2
Allocation of geological units to slice and layer concepts of the numerical groundwater model in the study area.

Slice name	Slice no.	Layer no.	Layer name	Geological characteristics	Hydraulic conductivity (m/s)	Effective porosity %
DEM.trp	1					
Bottom quaternary	2	1	Quaternary	Quaternary	1.6×10^{-4}	27
Bottom of NSA	3	2	Nubian Sandstone Aquifer (NSA)	Aquifer	0.968×10^{-4}	8

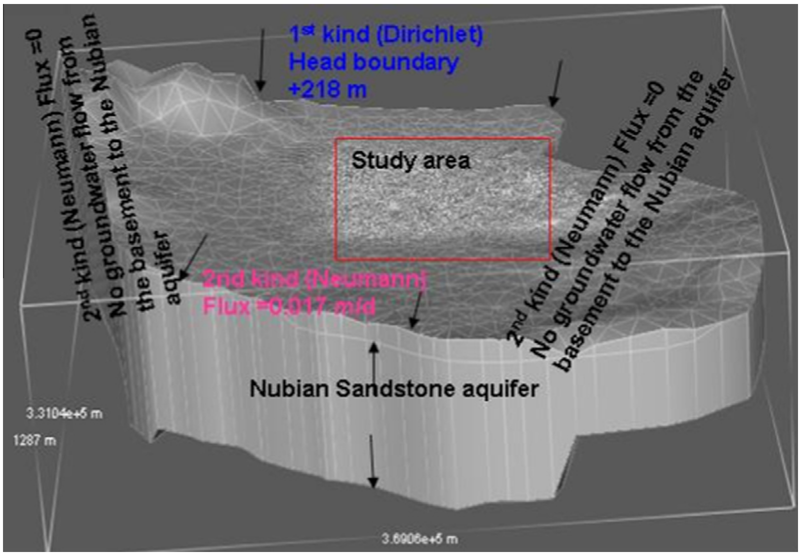


Fig. 4. Hydraulic boundaries of the Nubian Sandstone aquifer with layer elevations (3D) and the finite element mesh.

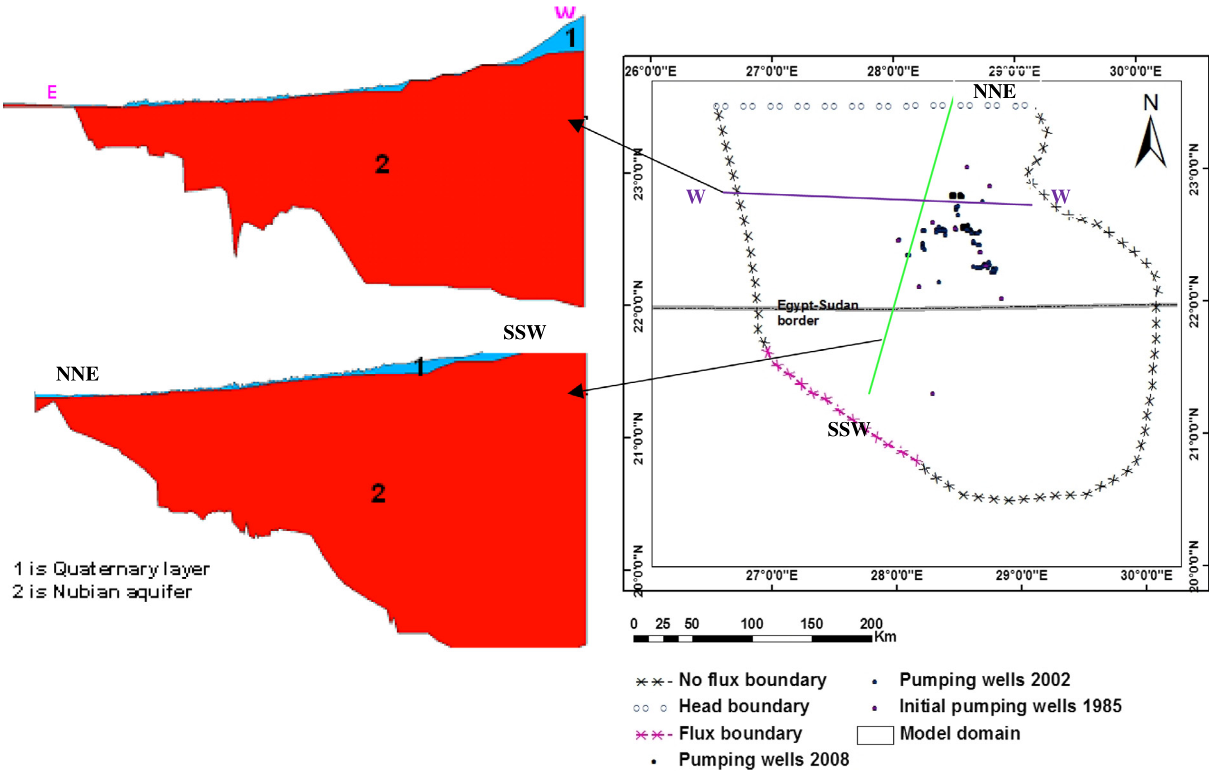


Fig. 5. Longitudinal hydrogeological cross sections E–W and NNE–SSW in the model area.

Table 3
The categories of the model area properties.

Flow attributes
• Flow boundaries; head (1st type) in the north, flux (2nd type) in the Northeast, southeast and north west where there is no flux and in the southwest where there is flux about 0.018 m/d, well in the study area (4th type)
• Flow initials; initial hydraulic head in the north (+218 m)
• Flow materials; conductivity (*Kx*,*Ky*,*Kz*), storativity (7%)

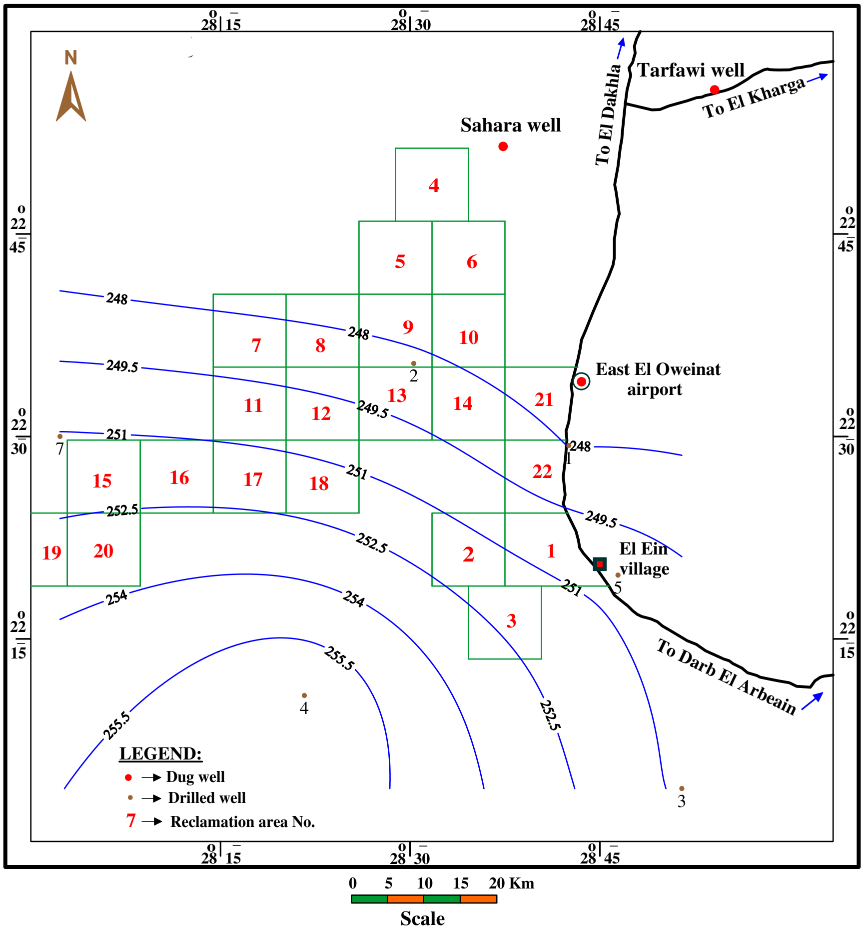


Fig. 6. Initial hydraulic head for the Nubian Sandstone aquifer in the study area (1985).

1. *Steady state calibration:* Variable saturated media, unconfined aquifer with steady flow.
2. *Un-steady state calibration:* Variable saturated media, unconfined aquifer with transient flow (with average pumping rate about 200,000 m^3/day).
3. *First scenario:* Variable saturated media, unconfined aquifer with transient flow (with average pumping rate about 337,500 m^3/day).
4. *Second scenario:* Variable saturated media, unconfined aquifer with transient flow (with average pumping rate about 4,000,000 m^3/day).

4.3. Model properties

FEFLOW has a comprehensive selection of graphical tools for assigning and modifying model properties like flow, mass and heat transport properties. The FEFLOW tools allow assigning properties using:

- A global-uniform value for the entire model.
- Element-specific values for selected elements.
- Node-specific values for selected nodes.
- Uniform values to an area defined by a box.
- Stored values from an external database (*X*, *Y*, *Z*) or ARC/INFO GIS file.

Imported model properties can be regionalized with respect to a local model area or extrapolated to the entire area model domain. FEFLOW model properties are divided into three major categories that define various characteristics and conditions of both flow and transport models as shown in Table 3 as follows:

4.3.1. Flow boundaries

The flow boundaries of the Nubian aquifer are shown in Fig. 4 and Table 3, where the north boundary is of the first kind boundary (hydraulic fixed head or Dirichlet boundary), which

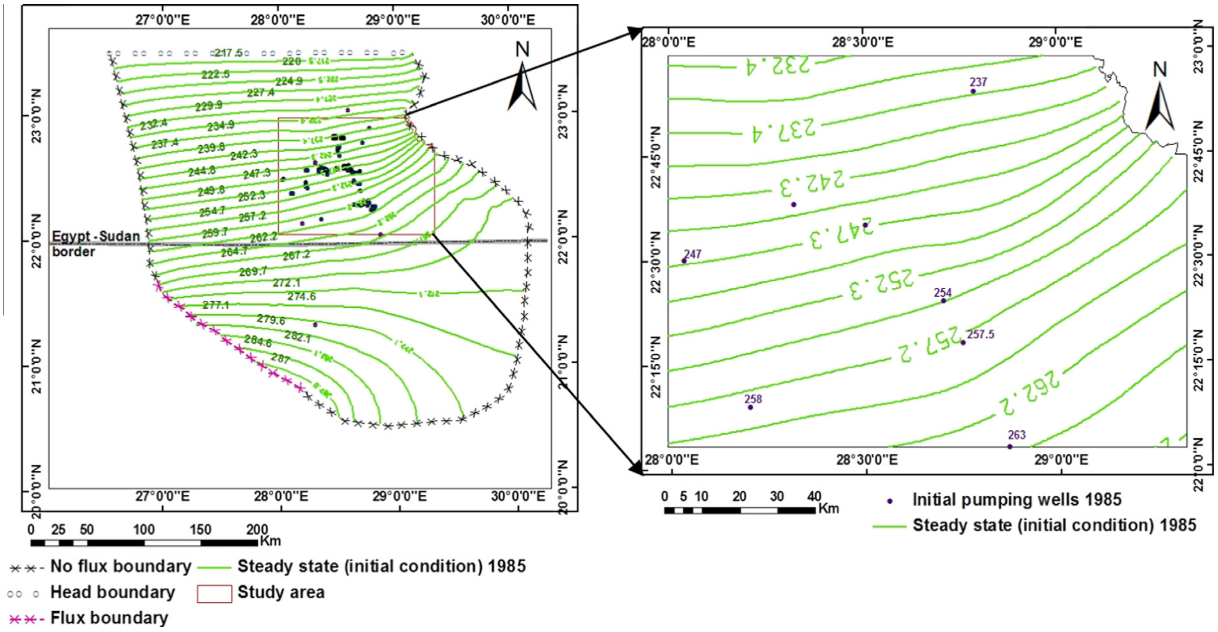


Fig. 7. Steady state calibrated water level contour map of the modelled aquifer (year 1985).

equals +218 m in the North. The northeast, southeast and northwest boundaries are of 2nd type where there are no fluxes since the basement rocks act as barrier which prevent the water flux. The southwest boundary is of 2nd type, where there is flux water which varies directly with the hydraulic conductivity and hydraulic gradient. It estimated through the modulus contour map by applying the equation of Darcy's law; $V = K\ dh/dl$ to be equal 0.018 m/day (El Osta, 2006).

4.3.2. Initial hydraulic head

The hydraulic head has been defined as the water level above a zero datum (mean sea level) of water in a well tapping an aquifer that is open to the atmosphere (unconfined aquifer). The initial hydraulic head in this study (Fig. 6) depends on the measured water table for 10 wells that drilled in the concerned area by G.P.C. (1985) and are tapped the Nubian Sandstone aquifer (Schneider, 1986). It can be noticed that the initial hydraulic levels mainly incline towards northeast, i.e. the water flows from southwest to northeast. It is also noticed that the initial hydraulic gradient is, generally, from south to north.

4.3.3. Flow materials

Flow materials include; hydraulic conductivity and effective porosity of the two layers (Table 1), as well as storativity, storage compressibility, and density ratio.

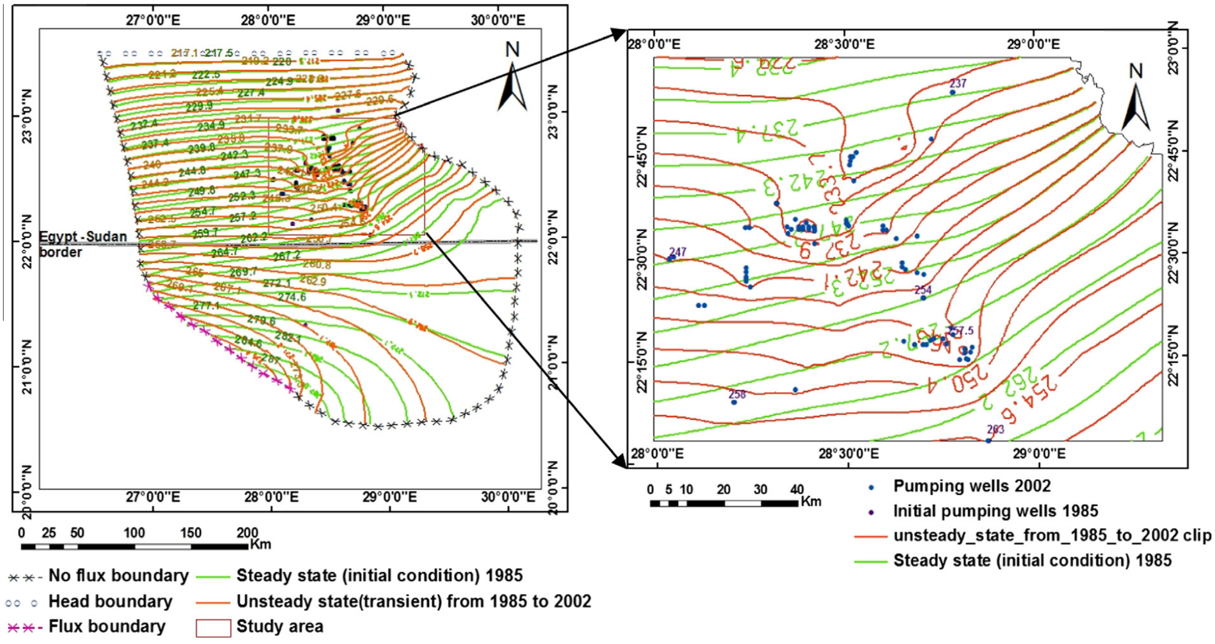


Fig. 8. Unsteady state calibrated water level contour map of the modelled aquifer in year 1985–2002.

4.4. Simulation results and discussion

4.4.1. Steady state calibration

The model is firstly run under steady state flow conditions. Head calculations of the first run showed great difference between the calculated and the observed heads, so the hydraulic conductivity and transmissivity are changed until the contours of the calculated heads match the observed heads of the year 1985. According to the mentioned model properties, the results of the first simulation with FEFLOW for the water table map of the initial flow condition of Nubian aquifer as shown in Fig. 7 is based on linear Akima (1975) interpolation with three neighbouring points. They indicate that the water flows from the southwest to the northeast and from south to north. The gradient of water table is steep in the southwest where the recharge window and northeast direction where the thickness of the aquifer in this area is thin than the southwest aquifer thickness. But the gradient is gentle in the southeast direction where there is no recharge (no flux) and the thickness is great. The resulted initial condition of the water flow depends on the actual hydraulic properties that measured and the calibration of the flux boundary from the southwest.

Many scenarios were attempted to set the flux boundary in the southwest, the best assume was with the length of southwest boundary about 170 km with angle flow direction about 52°NW (Fig. 7). With these boundary conditions the simulated water table is compatible with the initial hydraulic heads of the drilled wells. Eventually, both the length of recharge flux (170 km) to the Nubian Sandstone aquifer and the groundwater flow rate (0.018 m/day) are small to support a future large scale of agricultural expansion if comparison with the future requirements from this aquifer. Therefore, the groundwater levels expected to suffer from continuous depletion due to that the major part of groundwater withdrawal will be taken from the aquifer static reserved. The impact of recharge flux on the present and future groundwater extraction from this aquifer is simulated under unsteady state conditions as follows:

4.4.2. Unsteady state calibration

To calibrate the model under transient conditions, heads resulted from the steady state simulation of time 1985 (Fig. 7) are used as initial hydraulic heads in the transient analysis with implementation of the 80 pumping wells in year 2002 (transient state), with average pumping rate about 200,000 m^3/day. The resulted water table map (Fig. 8) was compatible with the contour water table map of El Osta (2006). From this simulation it is found that sudden drop of water table is occurred specially in the reclaimed area where the condense of pumping wells, with range between 0.40 and 0.55 m/year.

4.4.3. First scenario: implementation of discharging rate as 337,500 m^3/day for 7 years (year 2008)

The resulted water table map (Fig. 8) is used as base for the this simulation, with keeping all the model parameters, only the change is with the fourth kind boundary conditions through implementation of 135 pumping well (337,500 m^3/day). The resulted water table map show considerable lowering only in the reclamation area (Fig. 9). This lowering of the water table ranges from 1.0 to 1.5 m/year. This is compatible with the hydrological profile of actual measured water table variation in time between 2002 and 2008 (Fig. 2). This lowering is very serious; it may result from low aquifer recharge, parameters and closeness of wells, where at the north of the reclamation areas the distance between the drilled wells less than 1000 m. So, the question is what about the water table if the proposed 1884 wells were implemented? The better for the present irrigation project in East El Oweinat area will be in the next second scenario.

4.4.4. Second scenario: implementation of discharging rate as 4,000,000 m^3/day for 27 years (year 2035)

This scenario tries to control the fast head decline (from 1.0 to 1.5 m/year) recorded in the first scenario with keeping all the model parameters, only the change was with the fourth kind boundary

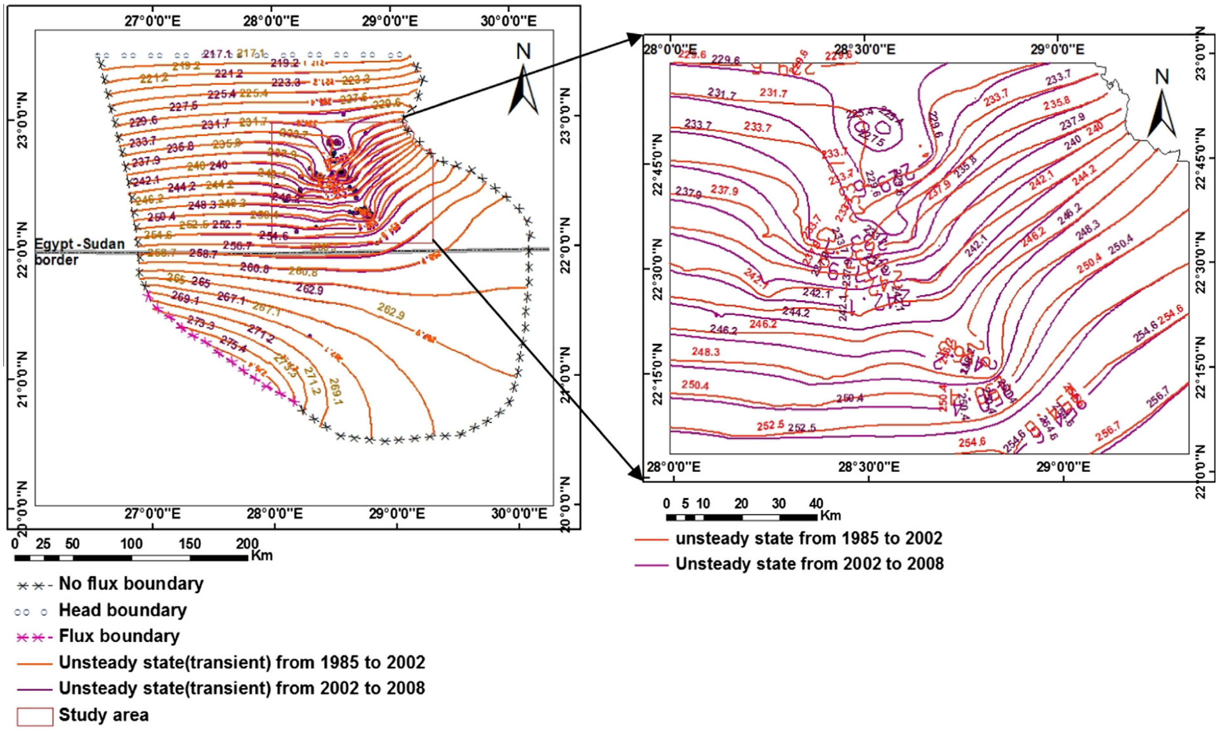


Fig. 9. Predicted head distribution map of the first scenario for the Nubian Sandstone aquifer in year 2002–2008.

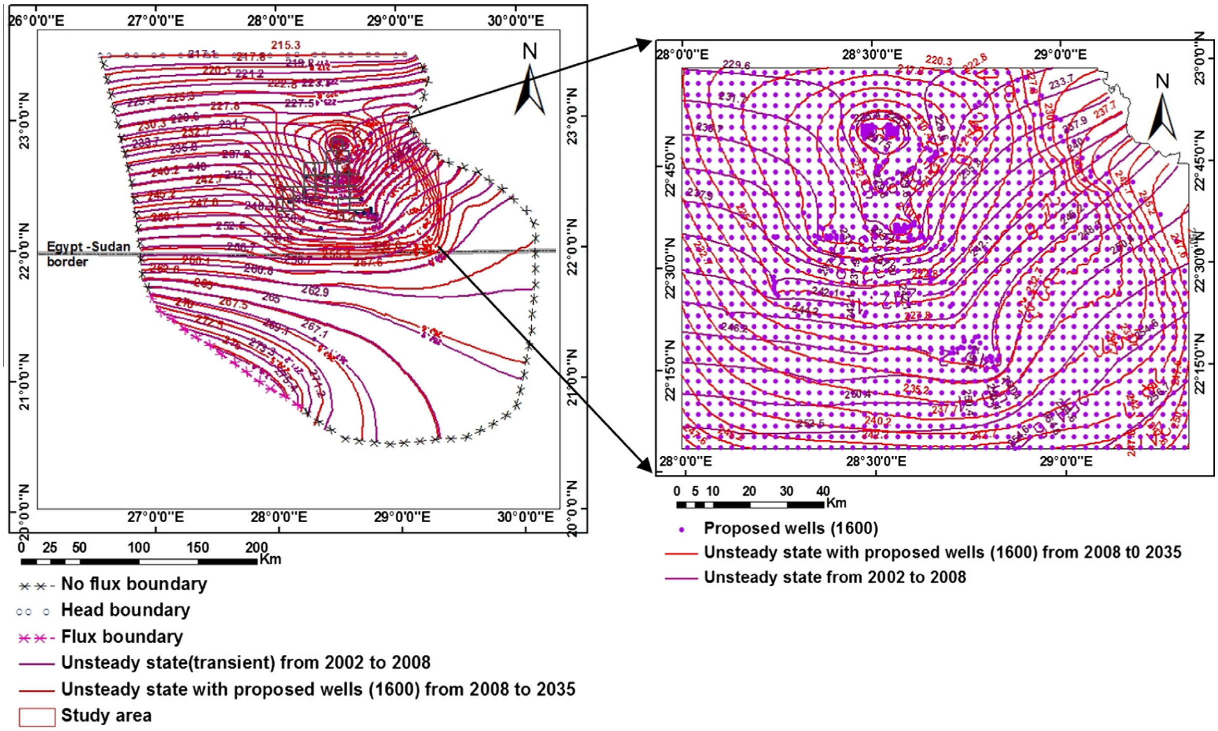


Fig. 10. Predicted head distribution map of the second scenario for the Nubian Sandstone aquifer in year 2008–2035 with 1600 proposed pumping wells.

conditions through implementation of 1600 proposed pumping well (4,000,000 m^3/day). Many scenarios were applied to set the proposed 1600 wells. The better scenario was the distribution of all proposed wells with distance between every two adjacent wells not less than 2500 m. In this Scenario the distance between wells is 2700 m, and the declining of heads ranges from 5 m outside of the

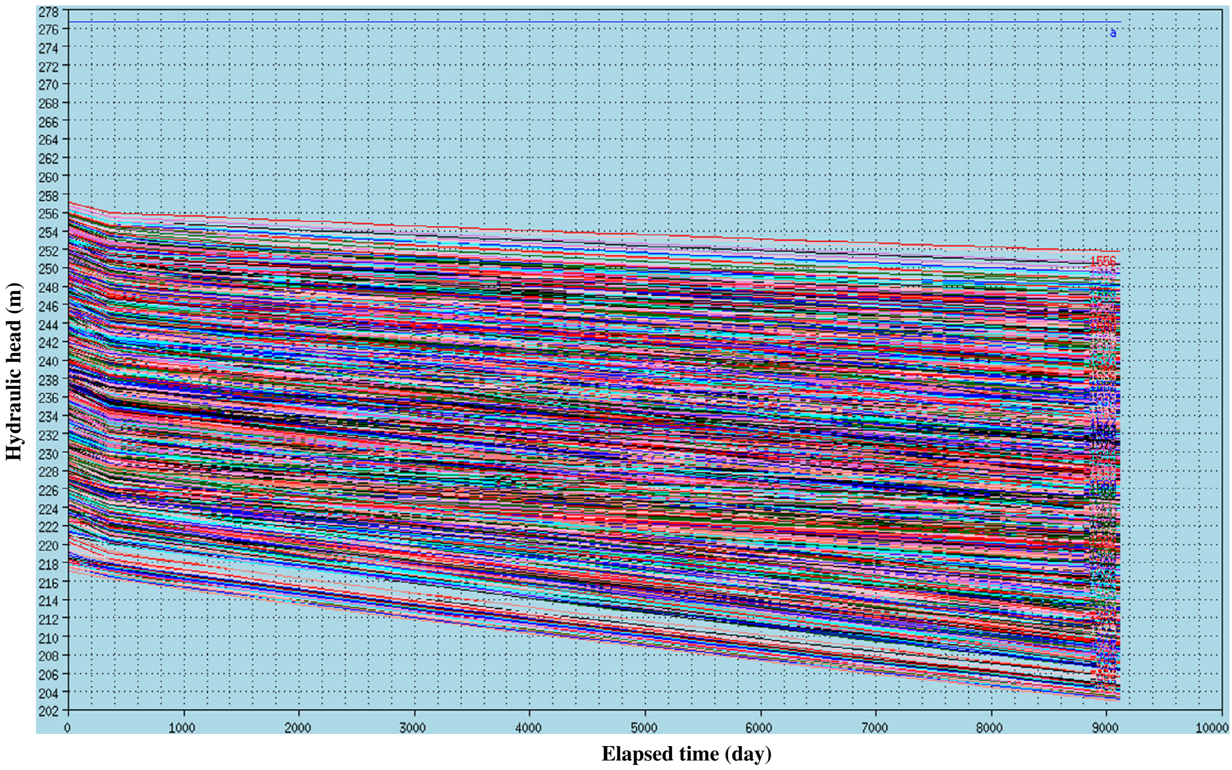


Fig. 11. Hydrograph showing the head–time relationship at the reclamation areas based on the second scenario as result of implantation of 1600 pumping wells with 4,000,000 m^3/day.

reclamation area to 15 m in the reclamation areas in time period of 27 years (Fig. 10). In all parts of the proposed development areas, the rate of decline in head of the Nubian Sandstone Aquifer is about 0.6 m/year (Fig. 11). It will not exceed half of the saturated thickness within a pumping time of 27 years. In conclusion, the results of the Nubian Sandstone Aquifer response to extraction rate of 4 million m^3/day at the different reclamation areas provide this scenario a degree of acceptance in mitigating the drawdown in groundwater levels.

5. Conclusions

According to results of the present work the following concluding remarks are of particular interest:

1. The main recharging source of the Nubian Sandstone aquifer in East El Oweinat area is the underground inflow reaching the aquifer across the southwestern boundary of the system.

The length of the southwest recharge flux is about 170 km with angle flow direction about 52°NW with a groundwater flow rate about 0.018 m/day.

2. The groundwater flows in one main direction from southwest to northeast and in other parts from south to north directions.
3. The water abstraction from the middle parts in the Nubian aquifer in the reclamation areas is estimated for 135 pumped wells to be 337,500 m^3/day in year 2008. Such water abstraction affects the water level in the central areas causing a kind of trough in the water body extended to the adjacent area of the pumping wells with water lowering about 1.5 m per year for the distance between the pumping wells less than 1000 m.
4. The pumping rate (4,000,000 m^3/day) for proposed 1600 pumping wells but with distance between every two adjacent well not less than 2500 m (second scenario) causing water table lowering about 0.6 m/year at the different reclamation areas. This result provides this simulation a degree of acceptance in mitigating the drawdown in groundwater levels due to the following reasons; no complete depletion of the Nubian Sandstone aquifer at any part of the proposed reclamation areas by the end of simulation period (year 2035), not increasing the water depth to uneconomic lifting depth (more than 100 m) and the decline in head of the Nubian Sandstone aquifer in all proposed development areas will not exceed half of the saturated thickness within a pumping time 27 years.

Acknowledgements

Authors are highly thankful and appreciate to Katholische Akademischer Ausländer-Dienst (KAAD) for financial support. Gratitude extends to DHI WASY in Berlin office for supporting license of FEFLOW software. Thanks and appreciation to Hydrogeology Group of Freie Universität Berlin (FUB) for technical support.

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