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Full Length Research Paper

Optimal management for groundwater of Nubian aquifer in El Dakhla depression, Western Desert, Egypt

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El Dakhla depression occupies a structurally localized depression at 100 to140 m (amsl), below a 400 m escarpment bordering the Libyan Plateau, Western Desert of Egypt. In this area, groundwater of the Nubian Sandstone aquifer is the unique source of fresh water. The increasing demand of groundwater in El Dakhla depression has resulted in an indiscriminate exploitation of this source causing environmental hazards such as decline of groundwater levels. In this paper, the study of this problem is conducted. The methodology introduced in this paper includes application of mathematical and genetic algorithm (GA) techniques. The proposed model of optimization is based on the combination of the MODFLOW simulation with GA. The performance of the proposed model is tested on groundwater management problem (maximization of total pumping rate from Nubian aquifer at steady-state). The results of the simulation show that the present groundwater extractions (511783 m^3/day) will affect the groundwater flow patterns in the northeastern areas of El Dakhla depression causing a significant head decline of about 26 m in some wells at the year 2050. The increase of the groundwater extractions from the concerned aquifer by 25% (126355 m^3/day) will cause a great head decline of about 60 m in some wells and accordingly a cone of depression around the wells in the year 2050. In addition, the GA solutions solve these management problems in the groundwater of Nubian aquifer. The results show that under the increasing of pumping rate by 25% (which equalizes an increase in the cultivated area by 6000 ha), the optimal pumping rate and drawdown range from 638137.9 m^3/day to 595977.9 m^3/day and from 4.292 m to 10.36 m respectively. This result seems to be the best for optimal management of groundwater.

Key words: Hydrogeology, Nubian Sandstone aquifer, optimal management, genetic algorithm, MODFLOW, Dakhla depression, Egypt.

INTRODUCTION

Groundwater is not only an important component of water resources but also a reliable source of fresh water for a variety of purposes including domestic, industrial and irrigational uses. Nowadays, with increasing population and life standards, there is a growing need for the utilization of groundwater resources. Therefore, sustainable management strategies should be developed by decision makers to optimally utilize the groundwater resources.

Optimization methods were used in the field of hydrogeology with the development of study on the optimization control and management of groundwater system. The genetic algorithm (GA) was widely used to modify the parameters of groundwater flow models (Yan et al., 2003; Yao et al., 2003) and to solve the management models of groundwater resources (Mckinney and Lin, 1994; Liu et al., 2002; Zhu et al., 2003). Numerical models have been used in combination with optimization techniques to design optimal strategies. Moreover, Aquifer management models that combine simulation with optimization help in understanding how social and economic forces interact with the water resource allocation. A simulation model is a tool to understand the physical behavior of an aquifer system, a management model can be thought of as a tool, which provides insight into the economic and social

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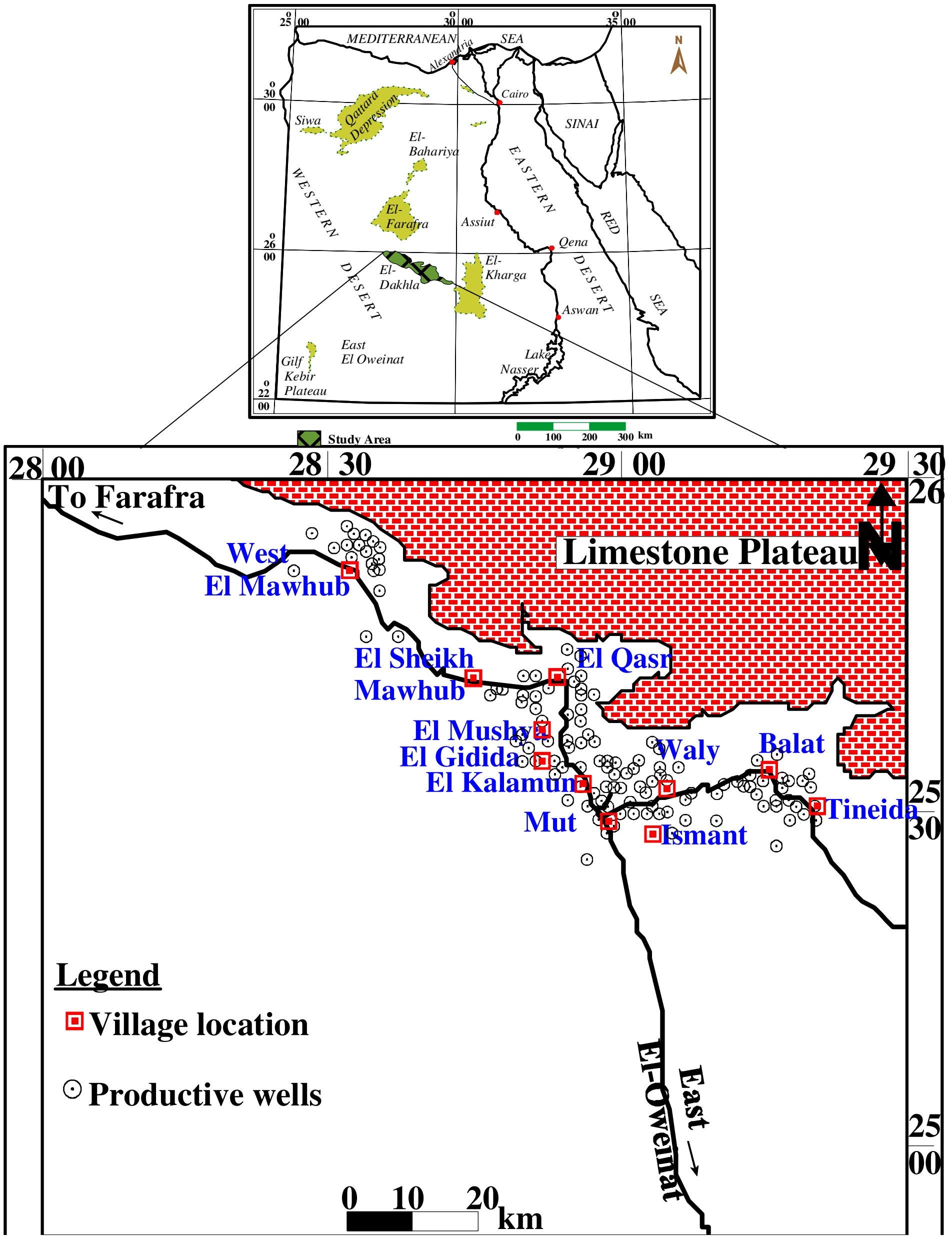

Figure 1. Base map of El Dakhla depression, Western Desert, Egypt.

consequences of institutional changes. Mahinthakumar et al. (2005) used hybrid genetic algorithm-local search optimization approaches to solve inverse problem of groundwater source identification problem. Singh and Datta (2006) used (GA) to solve the problem of identification of unknown groundwater pollution sources. Guan et al. (2008) proposed an improved (GA) to solve optimization problems with equality and inequality constraints. Moreover, Moharram et al. (2011) used the combination between MODFLOW and optimization techniques to solve the optimization problem of groundwater management in El-Farafra Oasis, Western Desert, Egypt with equality constraints.

Site description

El Dakhla depression is a closed basin located in the hyper arid region of western Desert, Egypt. It lies at 1100 km south of the Mediterranean shoreline and at 265 km east of the Libyan borders. It lies between longitudes 28˚ 00´ and 29˚ 30´ E and latitudes 25˚ 25´ and 26˚ 00´ N with a total area of about 4000 km^2 (Figure 1).

It is characterized by desert climate. The average temperature ranges between 6ºC in January and 38ºC in July. The precipitation is scarce and does not exceed 6 mm/year (Sadek, 1996). The lowest point is 100 masl near Tineida Village and the surface of the depression

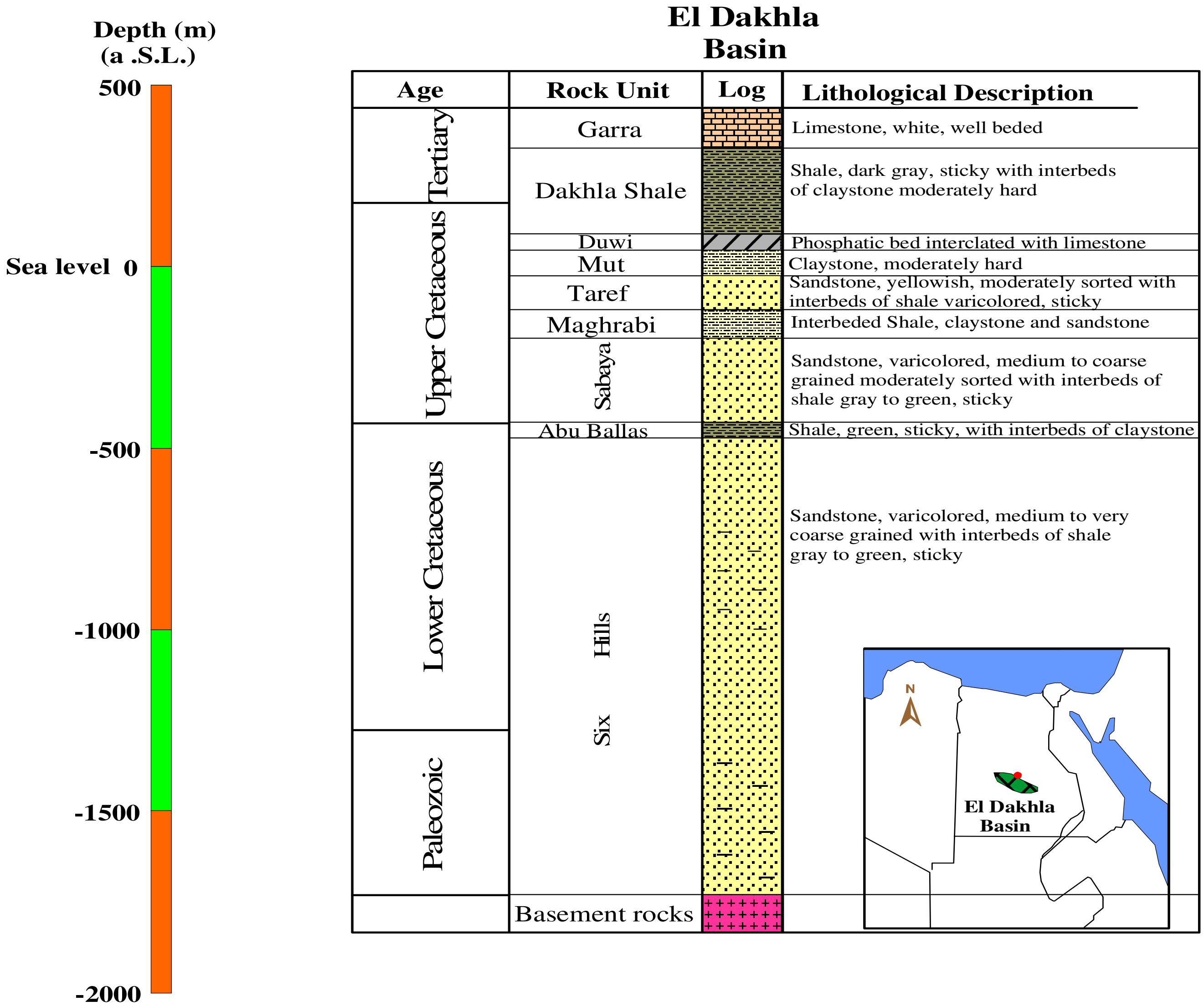

Figure 2. Generalized section of the Nubian sandstone aquifer system units in El Dakhla depression (Modified after Heinl and Thorweihe, 1993).

rises gradually toward the north. The edges of El Dakhla depression are not conspicuous except in the north where the calcareous plateau and a precipitous escarpment of 400 m lie above the level of the depression floor. In the east, there are a low lands covered with sand dunes while in the west some dunes trace the western boundary of the depression. In the south, the depression is completely open.

Geologically, the exposed surface is entirely composed of sedimentary rocks ranging from Upper Cretaceous to Quaternary (CONOCO, 1987). While in the subsurface, the sedimentary succession is divided into several lithologic units (Figure 2). The Late Jurassic-Campanian sequence includes the sandstone and clay succession overlain by Nubia sandstone. The Nubia sandstone is subdivided into six formations (six hills formation with thickness 1082 m, Abu Ballas formation with thickness 45 m, Sabaya formation with thickness 344 m, Maghrabi formation with thickness 79 m, Taref formation with 144 m thick and Mut formation with 105 m thickness). The second sequence belongs to Campanian-Lower Eocene sequence. It overlies the Nubia sandstone formations and consists of shale, marl, claystone interbeds with limestone at top. It is subdivided into four formations (Duwi formation with 40 m thick, Dakhla formation with 304 m thick, Tarawan formation with thickness 20 m and Garra formation with 42 m thick). The third sequence is the Quaternary deposits. They vary from fresh water deposits to aeolian. They include Sand dunes, alluvial deposits, Playa deposits and Inland sabkha (Issawi et al., 1978, Mansour et al., 1982, Diab, 1984, Heinl and Thorweihe, 1993, Ghoubachi, 2001, Koraney et al., 2001, and Ebraheem et al., 2004; DRC, 2005). A shallow synclinal basin oriented N.NW-S.SE occupies El-Dakhla

Table 1. Productive wells in El Dakhla depression, Western Desert, Egypt (Data source: Ministry of Water Resources and Irrigation, Groundwater sector, El Wadi El Gidid area).

Area name	Aquifer	Number of productive wells	Discharge from wells (m^3/day)	Cultivated area (acres)
Tineida	Nubian sandstone aquifer (Taref, Sabaya and Six Hills formations)	13	21336	971
Balat		27	42312	1922
Ismant		7	12672	577
El Masara		15	27303	1243
El Sheikh Waly		6	8779	400
Mut		31	58039	2640
El Rashda		13	30703	1397
El Hindaw		10	22206	1010
El Owina		5	10374	470
Bedakhluila		10	15762	717
El Gidida		14	22987	1045
El Mushya		6	10653	485
El Kalamun		10	18924	860
El Qasr		29	49262	2194
El Sheikh Mawhub		9	13677	622
East El Mawhub		33	146794	6673
Total		238	511783	23226

area. Budkhulu, and Tawil anticlines and Teneida and Mawhoub synclines are the local structural undulations. The best represented faults lie between Teneida-El Zayat and between El Qasr-El Mawhub (Attia, 1970).

Hydrogeologically, the Nubian Aquifer in El-Dakhla Depression (NADD) includes three water bearing formations (Figure 2). Figure 2 shows that, groundwater is available from these three successive water bearing units (Taref, Sabaya and Six Hills). These three formations are capped by water confining chalk, El Dakhla shale, phosphatic beds, variegated shales and underlain by the basement complex giving a confining condition. The average thickness of the NADD is 1386 m (111 m for Taref Formation, 275 m for Sabaya formation and more than 1000 m for Six Hills formation) with a general increase due west and south (Koraney et al., 2001). This situation is mainly attributed to the effect of faulting which throws towards the south and west directions. The groundwater from NADD is exploited through 238 shallow and deep wells (Figure 1 and Table 1). These wells are pumped with a total discharge rate 511783 m^3/day (the irrigation water requirements of 23226 ha). The groundwater flow direction is generally from southwest to northeast. The estimated transmissivity of NADD ranges between 494 m^2/day (well No. 11) in El Masara locality and 2350 m^2/day (well No. 38) in El Qasr locality (Table 2). This wide variation may be attributed to the rapid lateral facies changes as well as the variation in the thickness of the productive water bearing units.

The problem is that the groundwater of the NADD is heavily exploited since the year 1960. This led to continuous decline in the piezometric heads of the non-renewable NADD (more than 30 m). The main objective of this study is to develop the optimal pumping rate under the expected increase in the irrigation water requirements covering the new reclaimed areas of 6000 ha

Table 2. Hydrogeological data in El Dakhla depression, Western Desert, Egypt (WRRI, 2007).

Well No.	Area name	Total depth (m)	Formation	Ground elevation (m) (a.m.s.l.)	Piezometric surface (2005) (m) (a.m.s.l.)	Piezometric surface (2008) (m) (a.m.s.l.)	Transmissivity (m^2/day)
1	Tineida	885	Six Hills	126.2	-	114.84	-
2		1150		126.37	-	116.67	1987
3		750		125	-	115.5	-
4		760		126	-	118	-
5	Balat	703	Six Hills	121.53	-	117.83	-
6		444	Sabaya	121.5	-	116.7	-
7		755	Six Hills	126.2	-	119	1658
8	Ismant	745	Six Hills	112	112	103.6	-
9		412	Sabaya	115	-	104.7	-
10	El Masara	1231	Six Hills	111	-	111	1192
11		470	Sabaya	125.6	125.6	120.7	494
12	Mut	1020	Six Hills	107.5	-	100.5	1650
13		748		122.5	116.6	110.6	-
14		233	Taref	114.5	-	110.7	-
15		744	Six Hills	113.5	-	104.8	-
16		507	Sabaya	110.4	-	110.4	-
17		505		111	-	111	1450
18		844	Six Hills	121	-	110.7	-
19	El Hindaw	765		109.3	107.9	104.2	908
20		517	Sabaya	103	-	103	-
21		985	Six Hills	106	-	104.7	-
22		495	Sabaya	106.9	-	106.9	-
23		545		107	-	105	670
24		460		105.8	-	105.8	-
25	El Owina	514	Six Hills	107.8	107.5	105	-
26		872		106.8	-	103.85	850
27		1123		108.85	106.85	104.75	-

Table 2. Contd.

28	Budkhluila	687		108	-	103.2	1775
29		520	Sabaya	107.8	107.8	106.1	811
30	El Gidida	1174	Six Hills	122.5	-	116.6	1890
31		518		116	-	113	-
32	El Mushya	472	Sabaya	121	119.5	115.7	670
33	El Kalamun	1175		129	-	113.1	1850
34		972	Six Hills	129.33	-	116.33	-
35	El Qasr	931		115	-	107.5	847
36		483	Sabaya	110	-	106	-
37		839	Six Hills	115	114.2	110.3	1160
38		1127		115.6	-	111.5	2350
39		460	Sabaya	121	-	107.5	860
40		480		115	113.25	109.7	-
41	El Sheikh Mawhub	1085	Six Hills	118.5	117.89	115.25	2260
42		1201		118.5	-	118.5	-
43		605	Sabaya	117	-	115.3	-
P1	Tineida	839.5	Six Hills	264.72	135.14	134.7	-
P2		205	Taref	163.26	118.16	117.96	-
P3	Road Mut – El Oweinat	1199		169	-	121.26	-
P4		950	Six Hills	158	-	109.91	-
P5		715		375.2	145	143.2	-
P6		675		135	135	134.7	-
P7	East El Mawhub	511		155	140	139.4	-
P8		366	Sabaya	225.5	138.5	138.2	-
P9		924	Six Hills	226	137.1	137	-

depending on the future development policy. A mathematical model that combines MODFLOW and GA was developed to achieve this goal.

MATERIALS AND METHODS

The materials used in this paper were collected through carrying out two field trips in El-Dakhla depression during the period 2005 to2008. The two field trips were achieved with the team work of the desert research center. The

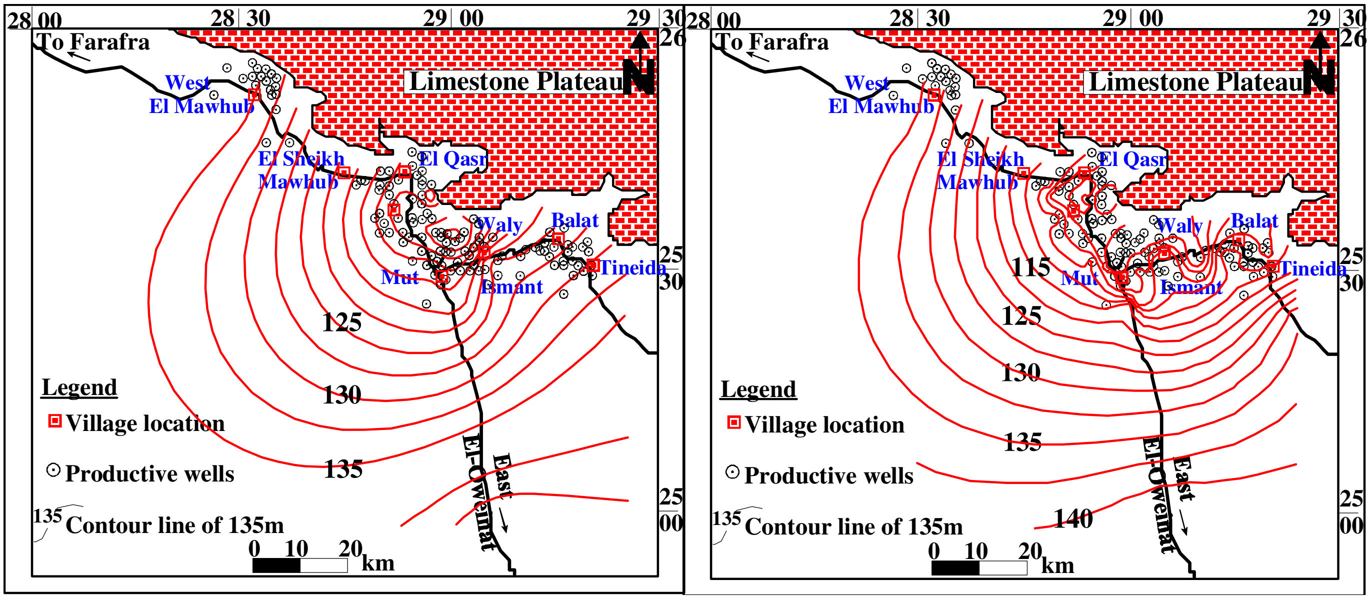

Figure 3. Piezometric surface contour map of the NADD during the year 2005 (left map) and during the year 2008 (right map).

basic hydrologic data of the present flowing wells were obtained from the Groundwater Sector, WRRI during these field trips. These materials include collection of archival data (well drilling reports, registration of discharge, distribution of wells, proposed operating systems for both groundwater supply and reclaimed area beside recording depth to water for groundwater level changes) were gathered from groundwater sector-WRRI (Table 2). These data were used in constructing Piezometric surface contour maps (Figure 3).

In addition, the methodologies applied in this work include the combination between the groundwater flow simulation and optimization model using GA techniques.

Groundwater flow simulation

During the past thirty years, simulation of the whole Nubian Sandstone Aquifer System was made by several authors such as Heinl and Brinkmann (1989) to predict the probable changes in groundwater levels with extensive exploitation of water from this aquifer. In this way, large numbers of wells in the different depressions such as El Dakhla, El Kharga, El Farafra, Siwa, and El Bahariya were represented by center of gravity. Accordingly local scale flow models became very important when boundaries are clearly defined. A three dimension finite difference MODFLOW program (MacDonald and Harbough, 1988) is applied for the simulation of the NADD. The model described groundwater flow of constant density under non-equilibrium conditions in three-dimensional heterogeneous and anisotropic medium according to the following equation (Bear, 1979):

$$\frac{\partial}{\partial x}\left(K_{XX}\frac{\partial h}{\partial x}\right)+\frac{\partial}{\partial y}\left(K_{YY}\frac{\partial h}{\partial y}\right)+\frac{\partial}{\partial Z}\left(K_{ZZ}\frac{\partial h}{\partial Z}\right)-W=S_s\frac{\partial h}{\partial t} \quad (1)$$

In which; K_{XX}, K_{yy} and K_{zz} are values of hydraulic conductivity ($L\,T^{-1}$); along the x, y, and z coordinate axes; h is the potentiometric head (L); W is the volumetric flux per unit volume and represents sources and/or sinks of water (T^{-1}); S_s is the specific storage of the porous material (L^{-1}); and t is time (T).

The model was used the finite difference approach to solve the groundwater flow equation. Moreover, the availability of a relatively complete database of 238 groundwater wells and 9 observation wells in El Dakhla depression enabled to develop the local scale flow model through the building of the grid, identification the model boundaries, initial conditions, calibration of the model over a three years period (2005-2008) and using the calibrated model to display the impacts on the aquifer in the next 42 years (till the year 2050).

Conceptual model

On the light of the hydrogeologic properties of the NADD (Figures 2 and 3), a pictorial representation (conceptual model) of the water flow system is constructed to this aquifer. The constructed conceptual model depends on the facts that the NADD consists of one complex layer that is composed mainly of coarse to fine sand with dominance of clay units. A thick Dakhla shale layer and sometimes sandy clay layer covers the aquifer all over the depression. The NADD is characterized by lateral and vertical facies changes. The aquifer thickness varies from one place to another. The groundwater flows locally from SW to NE direction. There is no any recent recharging source while the main discharging source is the present productive wells (154 deep and 84 shallow wells in NADD). The NADD groundwater occurs under the confining conditions. The base of the aquifer is detected.

Model grid and boundary conditions

The constructed finite difference grid to represent the whole concerned area was refined to formulate a local-scale model involving the area of wells where detailed information on the aquifer properties is available (Figure 4). The model domain is bounded in the southeastern and northwestern parts by open flow boundaries. On the other hand, general head boundaries are applied in the extreme southwestern and northeastern parts by +207 m head and +149 m head respectively. These boundaries are chosen far enough from the well field effect (Figure 4). The model geometry is simulated by inputting the hydrogeological parameters

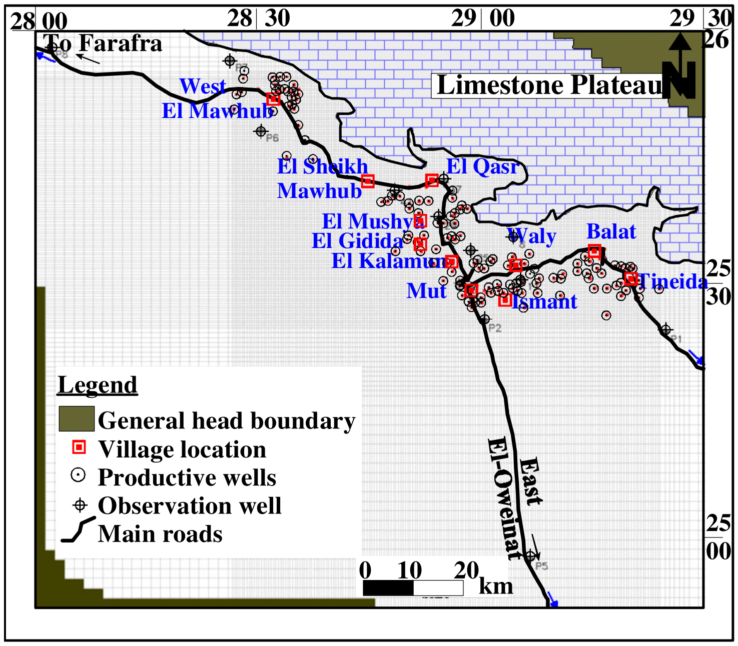

Figure 4. Grid and boundary conditions of the model domain in the NADD.

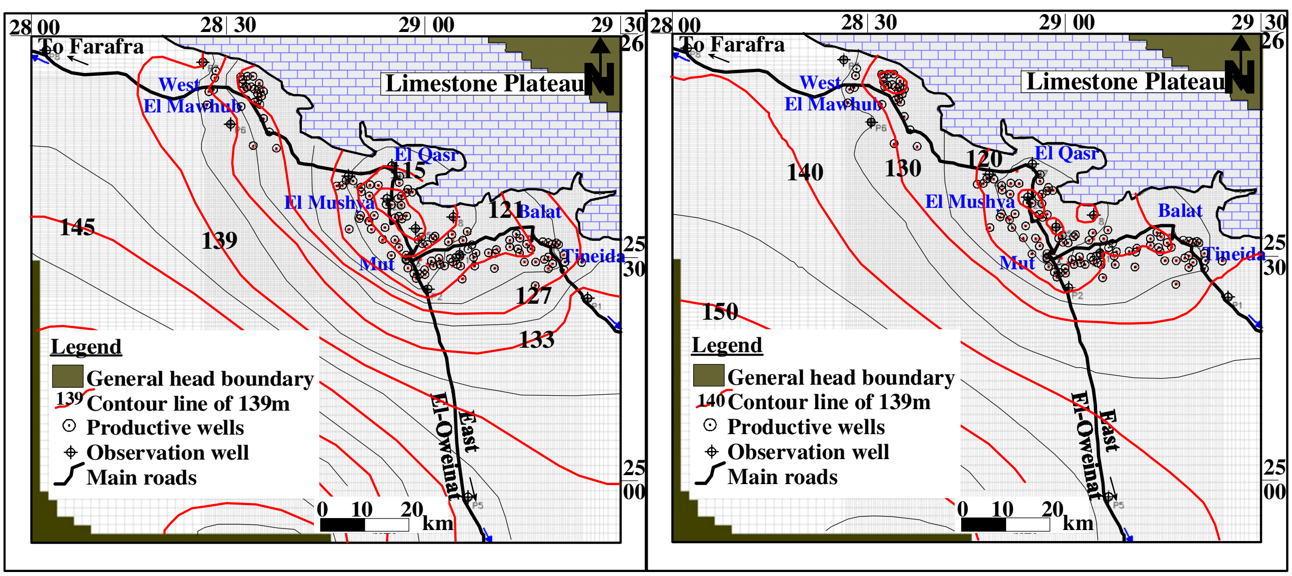

Figure 5. Steady state calibrated water level contour map of the model domain (left map- the year 2005) and unsteady state calibrated water level contour map (right map- the year 2008).

(transmissivity T, hydraulic conductivity K, and storage coefficient S), values of the NADD top and bottom levels, groundwater abstraction and boundary conditions to the grid cells. Each of these phenomena is simulated in MODFLOW by a separate package.

Model calibration

The calibration process typically involves calibrating both steady-state and transient conditions. 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 by trial and error method (Doherty, 1990) until the contours of the calculated heads match the observed heads of the year 2005 (Figure 5).

To calibrate the model under transient conditions, heads resulted from the steady state simulation (year 2005) are used as initial hydraulic heads in the transient analysis. The storage coefficient, the specific yield and the discharging rate of wells (511783 m^3/day) are assigned to the model grid. The model is run under these new conditions. The head is checked in the 3^{th} time step where twelve of wells (8, 13, 25, 29, 37, 41, P1, P2, P5, P6, P7 and P8) are actually measured (year 2008). The storage coefficient and specific storage are changed until the observed and calibrated heads are become comparable low variance value of about 0.873 (Figure 5). The calibrated model over a three years period (2005-2008) was used to display the impacts on the NADD in the next 42 years (till the year 2050) under different scenarios.

Optimization model

The genetic algorithm (GA) is the most extended group of methods representing the application of evolutionary algorithms. GA technique is developed based on the Darwinian principle of the 'survival of the fittest' and the natural process of evolution through reproduction. A solution for a given problem is represented in the form of a string, called "chromosome", consisting of a set of elements, called "genes", that hold a set of values for the optimization variables (the decision variables). The fitness of each chromosome is determined by evaluating it against an objective function. The chromosome represents a feasible solution for the problem under study. The length of the chromosome equals the number of variables. A Gene value is real coding (actual values). The concept of GA is based on the initial selection of a relatively small population. Each individual in the population represents a possible solution in the parameter space. The fitness of each individual is determined by the value of the objective function, calculated from a set of parameters. The natural evolutional processes of reproduction, selection, crossover, and mutation are applied using probability rules to evolve the new and better generations. The probabilistic rules allow some less fit individuals to survive. The objective of this study is to maximize the benefit function Z with respect to pumping rate, Q_j as design variable.

$$\text{Max} \qquad Z = \sum_{j=1}^{N_w} Q_j - P_j \tag{2}$$

In which N_w is the total number of pumping wells and P_j is penalty. The pumping rates are subjected to the pumping constraint, drawdown constraint and water demand constraint.

1- Pumping constraint: the pumping rates at potential pumping wells in the water demand are constrained to values between some minimum (Q_j^{min}) and maximum (Q_j^{max}) permissible pumping rates as the following:

$$Q_i^{min} \le Q_i \le Q_i^{max} \qquad j = 1\ldots\ldots.,N_w \tag{3}$$

In the GA simulation, this constraint can be easily satisfied by restricting the population space of the design variables to be within the above limits. Hence, no special treatment is needed for this constraint.

2- Drawdown constraint: this constraint normally meant to protect the ecosystem by avoiding excessive drawdown. In this work, the drawdown constraints are formulated to avoid mining and formulated as follows:

$$\sum_{j=1}^{Nw} r_j \le d_i \tag{4}$$

In which: $r_{,j}$ is the drawdown at control point *i* caused by a pumping from pumping well *j*, d_i is the permissible drawdown at control point *i*.

3- Water demand constraint: the Nubian sandstone aquifer is considered as the sole source of water. This, therefore, means that the designed optimal pumping strategy must supply at least the minimum water demand. It is formulated as follows:

$$\sum_{j=1}^{Nw} Q_j \ge Q_D \tag{5}$$

In which: Q_D is water demand.

Optimization procedure of the simulation-optimization (S/O) model

In this study, a groundwater resources management model is proposed the solution performed through a linked simulation-optimization model. MODFLOW FORTRAN code is used as the simulation of groundwater flow. This model is linked with genetic algorithm optimization. Figure 6 shows the flowchart for simulation-optimization model where FORTRAN program is used to link between the simulation code and genetic algorithm.

Checking the termination criterion

The optimization algorithm continues to be executed by iterating until the given termination criteria are satisfied. Note that different termination criteria can be used to stop the computation. These may be: Stopping the computation after a given number of iterations; reaching a specific objective function value; no improvement in the objective function value for a specified number of passed iterations; or after limited time. In this study, the relative error definition is used to check the convergence of iterations. Thus, the convergence criterion is defined as,

$$\frac{f_1 - f_0}{f_0} \le \varepsilon \tag{6}$$

Where **ε** is a tolerance for the convergence of iterations, if two consecutive objective values (f_1, f_0) satisfy the criterion.

Testing scenarios

In addition to the present annual pumping rate of 186.8 million cubic meters per year (MCM), (511783 m^3/day for all wells x 365 days = 186.8 MCM/year), three proposed pumping scenarios were simulated based on the potentiality of the NADD to predict the head and optimal pumping rate during the period 2008 to 2050.

The first scenario keeps the present pumping rate from 238 productive wells in the model domain without change (511783 m^3/day). The second scenario assumes increasing pumping rates from the deep wells only (154 wells) by 25% (126355 m^3/day) as a response to the increase in groundwater demands covering the irrigation water requirements of the new reclaimed areas of 6000 ha depending on the future development policy. Otherwise, the third scenario accounts for decreasing the annual pumping rate from the modeled area by 20% of the current pumping rate to reach 409426 m^3/day. This condition is expected as a result of the decrease in aquifer storage related to climate change. With the third scenario, the total annual extraction rate from the NSDD reaches 149.4

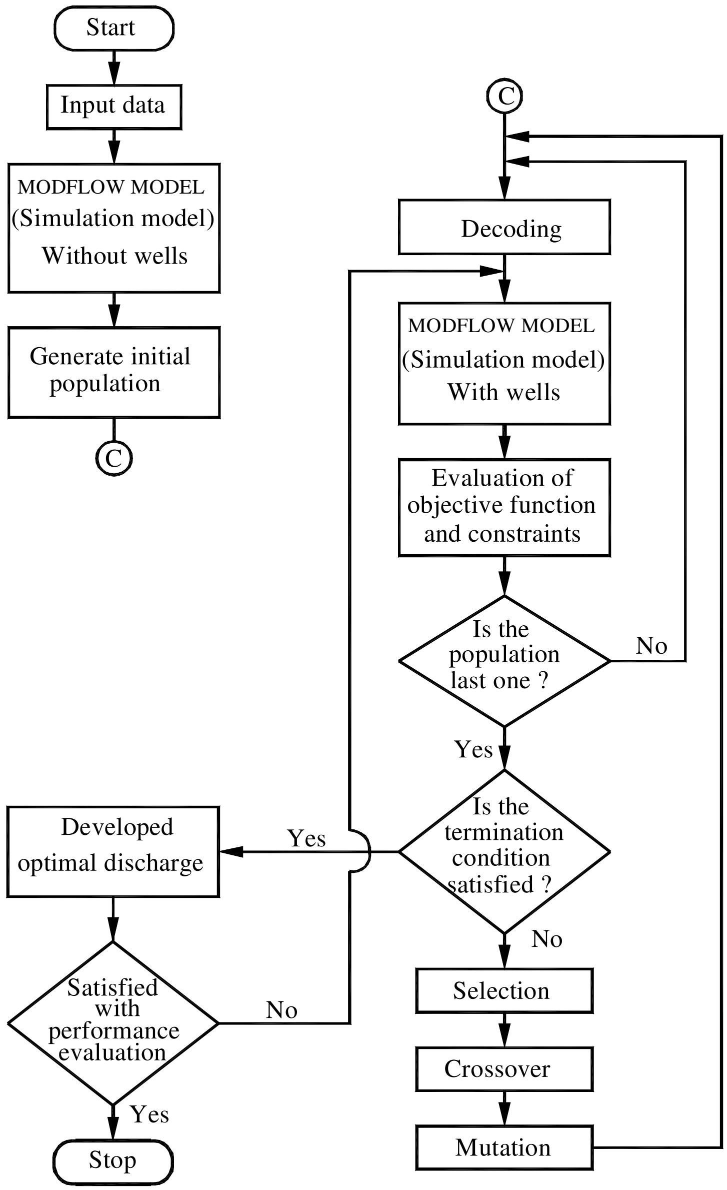

Figure 6. Flowchart for the simulation/optimization model.

MCM/year. A summary of the proposed extraction for the three scenarios is shown in Table 3.

RESULTS AND DISCUSSIONS

The recorded data in Table 2 and Figure 3 show relatively decline in the measured piezometric surface of groundwater between 0.1 m and 6 m (P9 at East El Mawhub village, west of El Dakhla depression, and well No. 13 at Mut village in the central part of the Depression respectively) within the interval from 2005 to 2008. This relatively wide decline may attribute to the intensive irrigation activities with hydraulic stresses in the NADD.

On the other side, the results of the three applied management scenarios show the future predictions in groundwater levels after 2, 12, 22 and 42 years under the probable stresses. The first scenario investigates optimal pumping rate from the current 238 productive wells penetrating the NADD with total discharge of 511783 m^3/day and its drawdown. The model developed was run for time step of 1 year. The predicted head distribution maps of the NADD for the current pumping rate at years 2010, 2020, 2030 and 2050 are shown in Figure 7.

It is noticed from Figure 7 that groundwater levels will decline by about 26 m especially in the central part of El Dakhla depression around El Qasr, Bedakhluila and El Rashda villages. Few wells in the northwestern part show

Table 3. Scenario descriptions based on the different extraction plans from the model domain in the NADD (Master Plan of the Ministry of Agriculture and Land Reclamation till 2030).

Scenario description	(Scenario 1) (million m^3/year)	Extraction change (million m^3/year)	
		Scenario 2	Scenario 3
Current pumping rate from model domain	186.8	186.8	0
Increasing pumping rate by 25% (126354.9 m^3/day) as a result of reclamation of 6000 acres	0	46.1	0
Climate change condition (Decrease pumping rate by 20%)	0	0	149.4
Total	186.8	232.9	149.4

relatively slight drawdown amounts to 13 m at East El Mawhub village. This is mainly attributed to the effect of increasing the thickness of water bearing formation towards the northwestern part. In addition, two large cones of depression will develop in the cultivated areas. The first cone is in the central part of El-Dakhla depression as a result of the present extraction rates from the old reclaimed areas, while the second cone is near the northwestern portion which may attribute to the interference between the adjacent productive wells.

The second scenario proposes an increase in the cultivated area by 6000 ha in the new reclaimed areas in West El-Mawhub village (or covers the water stresses due to the decrease in Egypt Quota from Nile River). The required discharge assumes drilling of new productive wells in West El-Mawhub village with an increase in the total pumping rate by 25%. In this scenario, the total irrigation water demand reaches 638138 m^3/day for both new reclaimed and current cultivated areas. The predicted drawdown ranges from 60 m (El Qasr, El Mushya, Bedakhluila, El Masara, Ismant and El Rashda villages) to 30 m at East El Mawhub village. Also, The predicted head distribution maps of the NADD for proposed pumping rate for years 2010, 2020, 2030 and 2050 are shown in Figure 8.

It is noticed from Figure 8 that the sharp decline in groundwater levels (60 m) may attribute to the small thickness and low hydraulic conductivity of the NADD in these villages. Moreover, two cones of depression will appear in the cultivated areas during the simulation time (with diameter of 2.5 and 4 km respectively). While the southern and western cultivated parts of the model domain does not be affected with this scenario. This may attribute to the effect of the great aquifer thickness and the presence of thin clay layers in the southern and western parts rather than the geologic structure impact. Accordingly, this reflects the low potentiality of the northern cultivated parts for positive response to this scenario.

Otherwise, the third scenario assumes a decrease in the cultivated area by 5000 ha (that is, due to desertification, or a change in crop unit with high tolerant crops due to climate change). This means numerically a decrease in pumping rate by 20%. The water demand in this case requires 409426 m^3/day. The predicted head distribution maps according to this scenario are shown in Figure 9. It is noticed from Figure 9 that the maximum drawdown recorded in the reclamation areas is about 15 m while many productive wells located in the southern and the northwestern parts of the model domain show slight decrease in the groundwater levels at the end of simulation period (year 2050). The depression cones related to the first and the second scenarios are mitigated in the northern part of the model domain. Moreover, limits are placed on the total amount of groundwater withdrawn in the reclaimed areas. Accordingly, it is preferred to extend the future reclamation activities southward away from the depression (along El Dakhla – El Oweinat road). Although the results of this scenario provide more or less good degree of confidence in mitigating the expected sharp decline in groundwater levels in the concerned area but it is not realistic.

As a result of the above discussion of the aquifer response to both the current and new pumping scenarios, it can be concluded that the groundwater withdrawal from the NADD in the reclamation areas could not be safely conducted. The alternative pumping system is essential for sustainability development of these new reclaimed areas. Accordingly, this situation may be relatively critical and needs to be optimized. In addition, it is

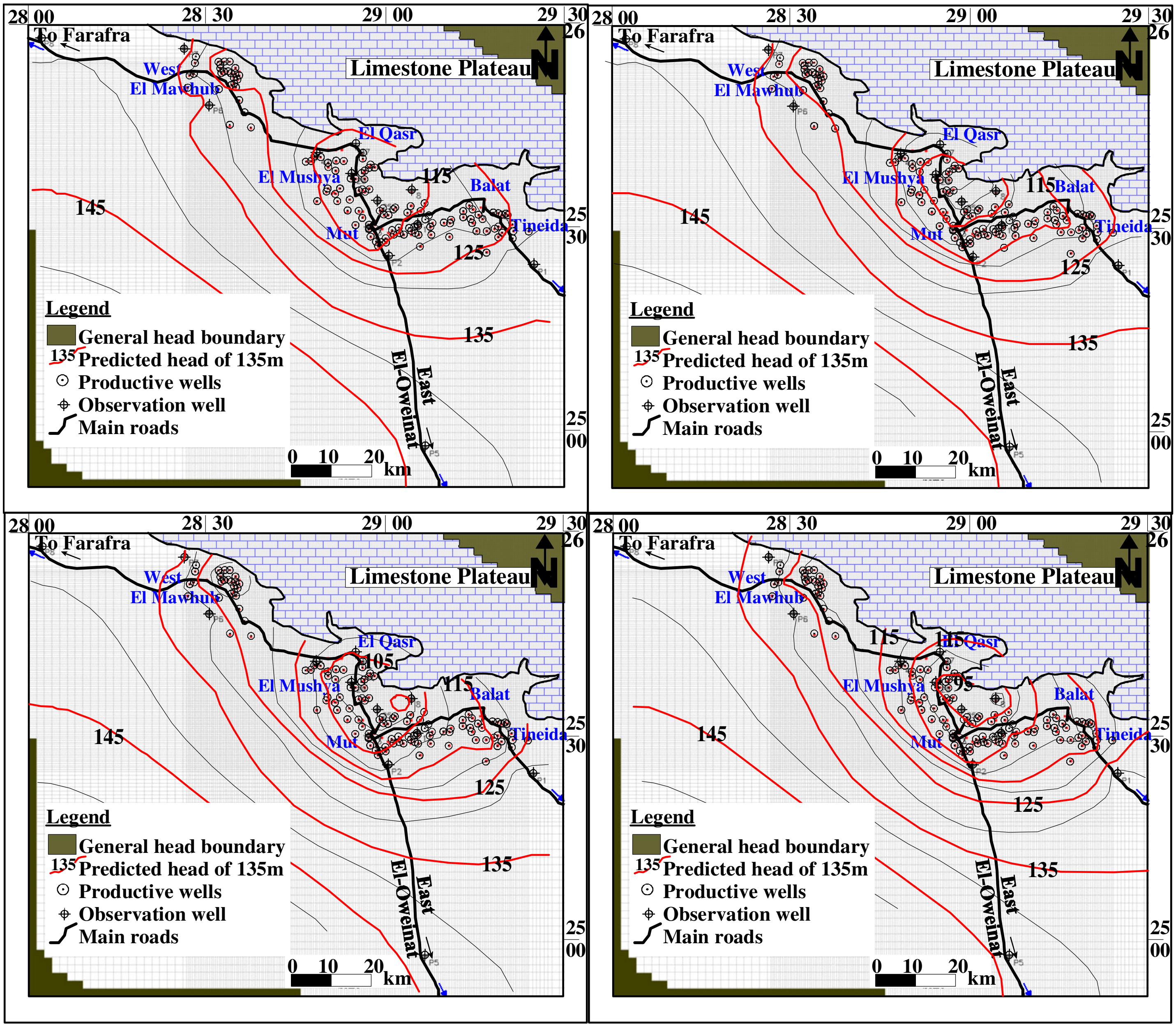

Figure 7. Predicted head distribution maps in the model domain of the NADD at 2010 (upper left), at 2020 (upper right), at 2030 (lower left), and at 2050 (lower right) applying 1st proposed scenario.

noticed that the cultivated area will be affected since the drawdown is maximized depending on the second scenario (from 30 to 60 m). This reflects that the deep productive wells, under this condition, are violated the drawdown constraint and pumping constraint. A trial was carried out to optimize this second scenario depending on the results of the simulation (Figure 10 and Table 4).

N is number of operation wells, r is maximum drawdown, Q_{min}/well is min optimal pumping rate for well, Q_{max}/well is max optimal pumping rate for well and Q_{opt} total optimal pumping rate for all wells.

For optimal solution, the optimal pumping rate and drawdown range from 638137.9 m^3/day to 595977.9 m^3/day and from 4.292 to 10.36 m respectively (Table 4). Also, the predicted head distribution map of the NADD for optimal pumping rate for years 2010, 2015, 2020, 2025, 2030, 2035, 2040 and 2050 is shown in Figure 10. It is noticed from Figure 10 that the diameter of both two cone of depressions will increase by the end of the simulation time. Moreover, the increase in the cultivated area by 6000 ha in the new reclaimed areas in West El-Mawhub village will decline the piezometric head in the wells of El Qasr, El Mushya, Bedakhluila, El Masara, Ismant and El Rashda villages more than that of East El Mawhub

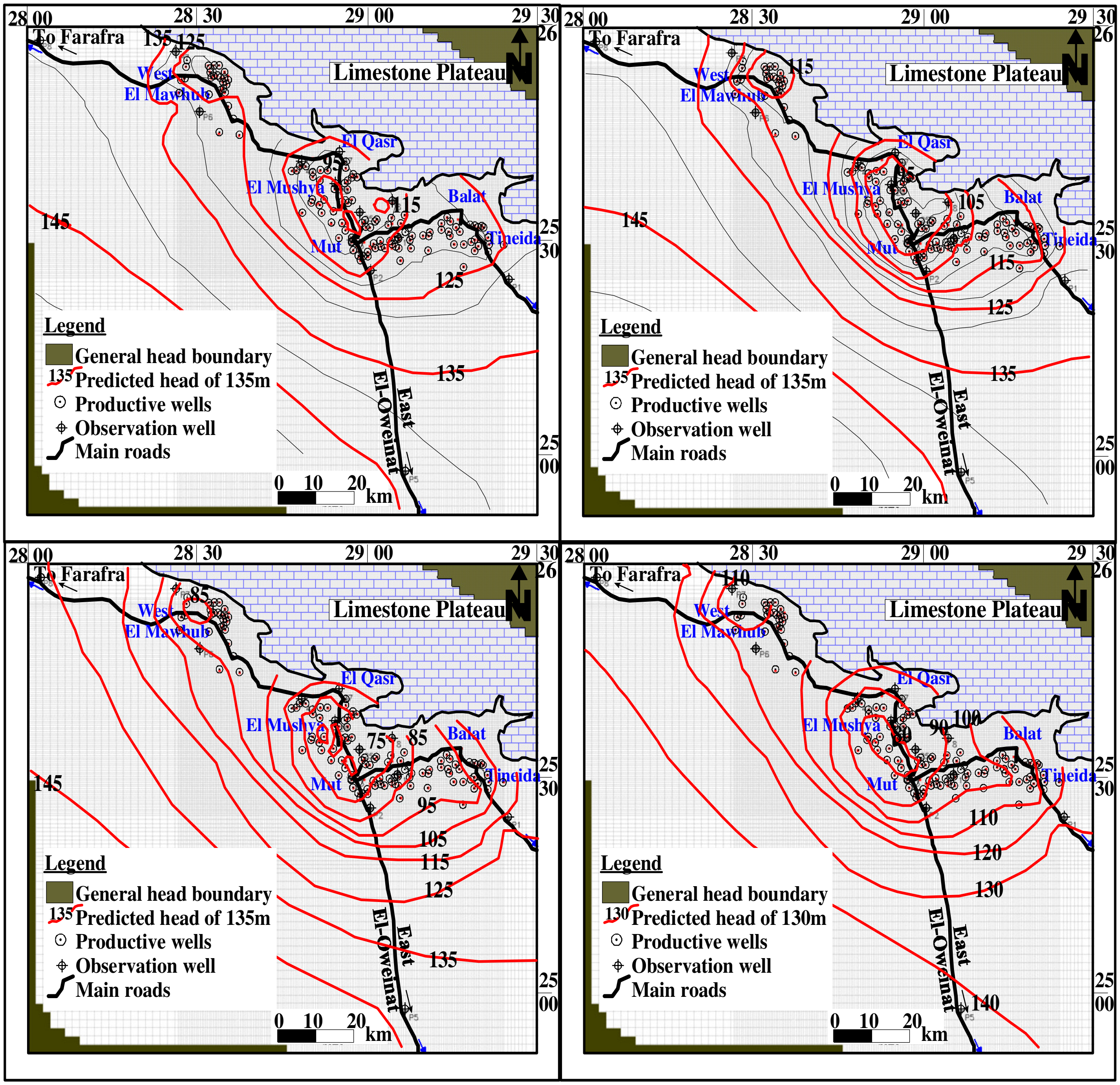

Figure 8. Predicted head distribution maps in the model domain of the NADD at 2010 (upper left), at 2020 (upper right), at 2030 (lower left), and at 2050 (lower right) applying 2nd proposed scenario.

village. A cone of depression of diameter length less than 2.5 km will cover the reclaimed areas beside the cultivated areas in the middle part of the model domain. This may reflect the structure control of this locality (negative barrier). The groundwater flow in this locality may be affected by the aquifer porosity. This reflects the need of alternative pumping system in this new reclaimed area to minimize the effect of the resulted cone of depression.

Performance evaluation optimization criteria

Performance of the proposed model for the groundwater management is evaluated on the basis of some GA criteria. These criteria are mutation ratio, crossover type and crossover ratio. The sensitivity analysis was carried out for mutation ratio at 0.005, 0.009, 0.05 and 0.01 (Figure 11). The mutation ratio 0.005 was found to be the most suitable for model sensitivity at number of

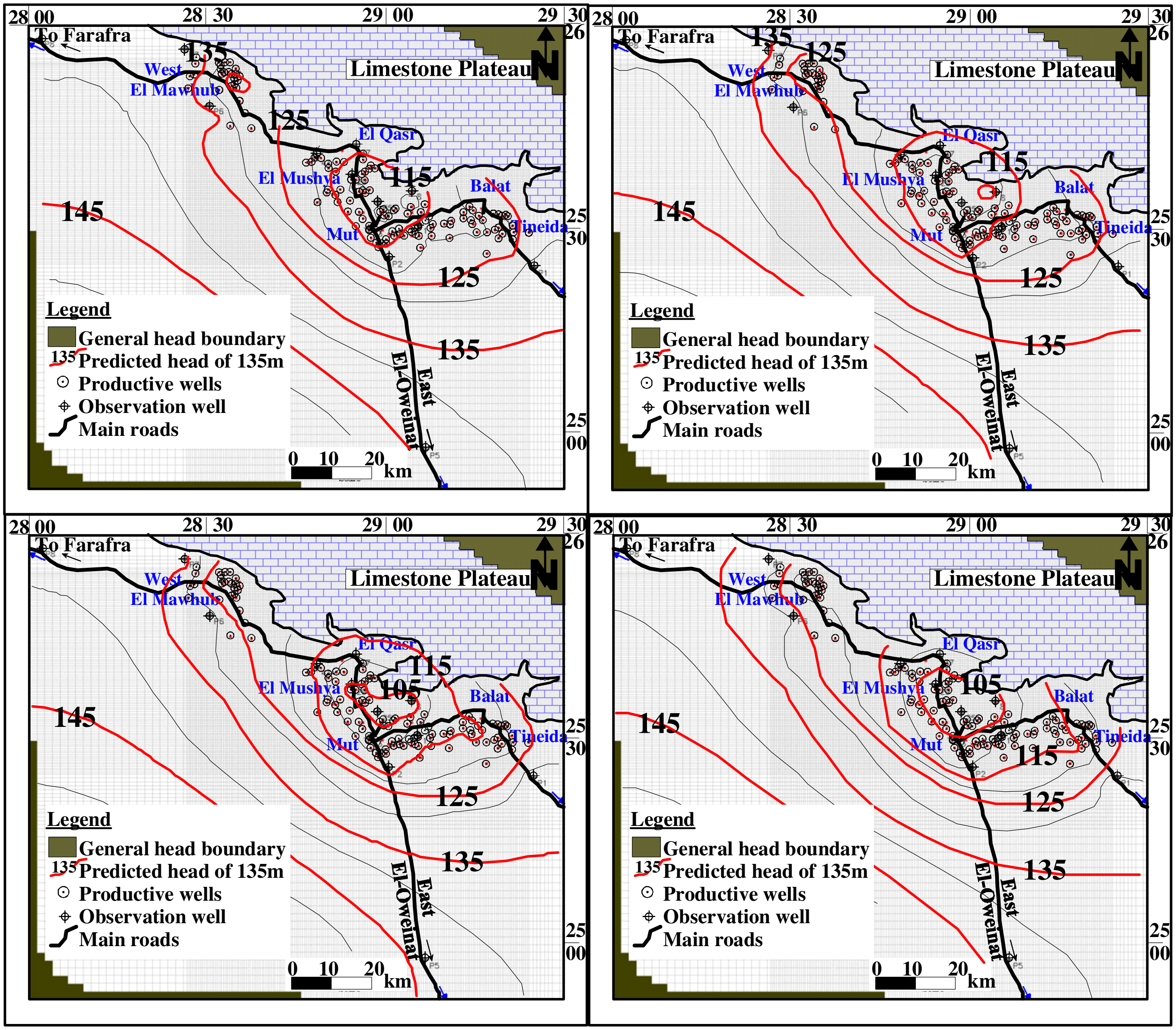

Figure 9. Expected head distribution maps in the model domain of the NADD at 2010 (upper left), at 2020 (upper right), at 2030 (lower left), and at 2050 (lower right) applying 3rd proposed scenario.

generation 225 as shown in (Figure 11). In addition, population size of 200 was taken from the previous works as it is the most preferable population for groundwater optimization. Figure 11, demonstrates convergence rate to optimal solution (total pumping rate). The figure indicates a slow convergence of the GA for mutation ratio 0.005, uniform crossover probability 0.60, tolerance for the convergence of iterations 0.001, and a population size of 200.

Conclusion

In this study, the groundwater resources management model is proposed based on the combined use of simulation-optimization models. In the proposed management model, MODFLOW is used as the simulation tool to model groundwater flow in the NADD and GA is used as the optimization tool. The performance of the proposed model is tested on groundwater management problem (maximization of total pumping rate from an aquifer at steady state). The results show that GA yields better solutions than the simulation methods and may be used to solve management problems in groundwater modeling. This model makes it feasible to solve the groundwater problems for three dimensions complex aquifer, complicated boundary conditions, steady and transient state. The performance

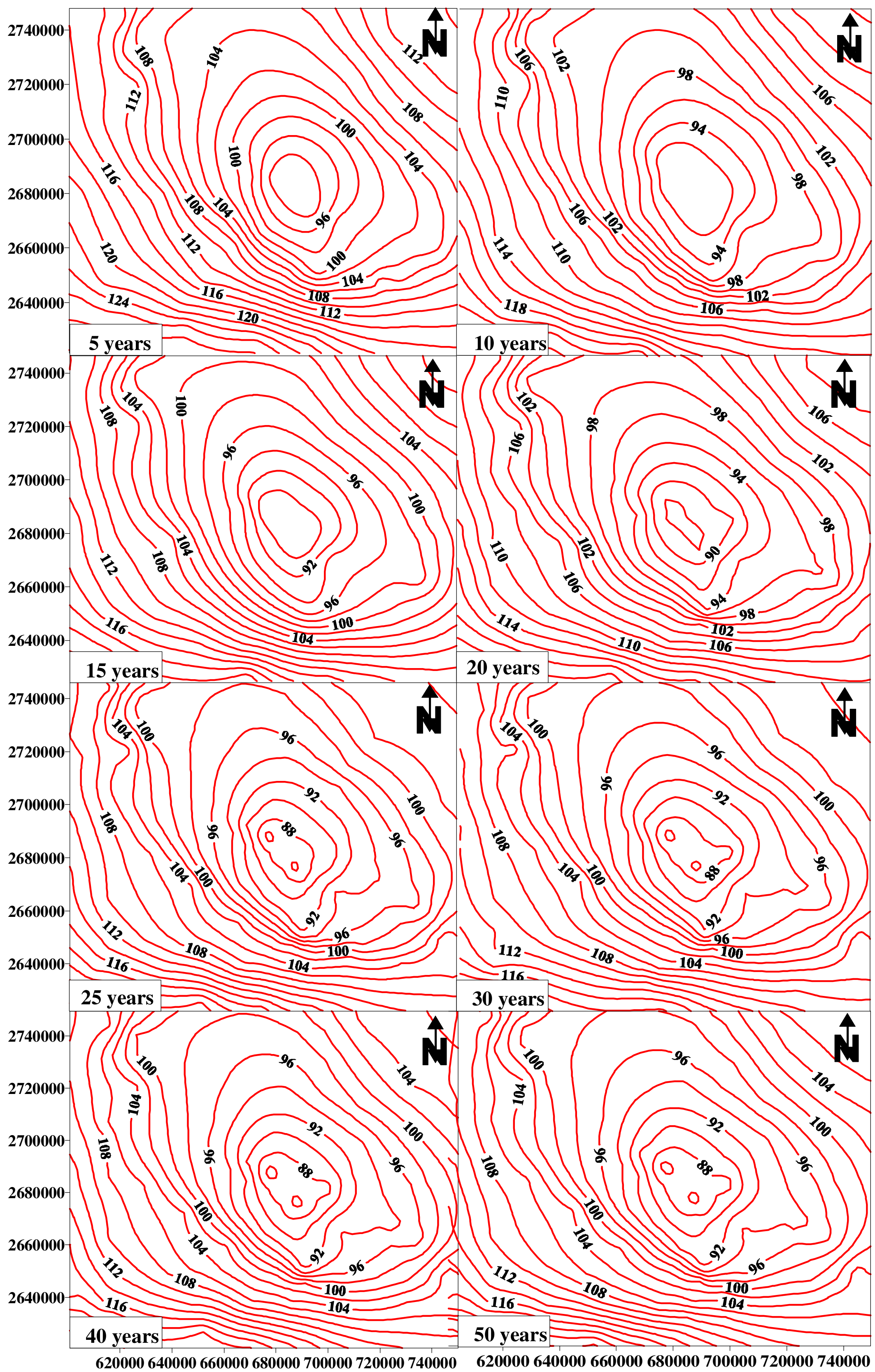

Figure 10. Predicted head distribution map of the Nubian sandstone aquifer in El-Dakhla depression for optimal pumping rate for 2nd scenario.

Table 4. Optimal pumping rate for Nubian sandstone aquifer in El-Dakhla depression.

Year	5	10	15	20	25	30	40	50
N	154	154	154	154	154	154	154	154
r (m)	4.292	7.012	8.167	9.065	9.962	10.219	10.347	10.360
Q_{min}/well	3351.38	3267.56	3026.62	2966.12	2906.77	2863.13	2776.34	2806.19
Q_{max}/well	5000	5000	5000	5000	5000	5000	5000	5000
Q_{opt} (m^3/day)	638137.9	615948.4	609062	603706	598349.9	596819.6	596054.4	595977.9

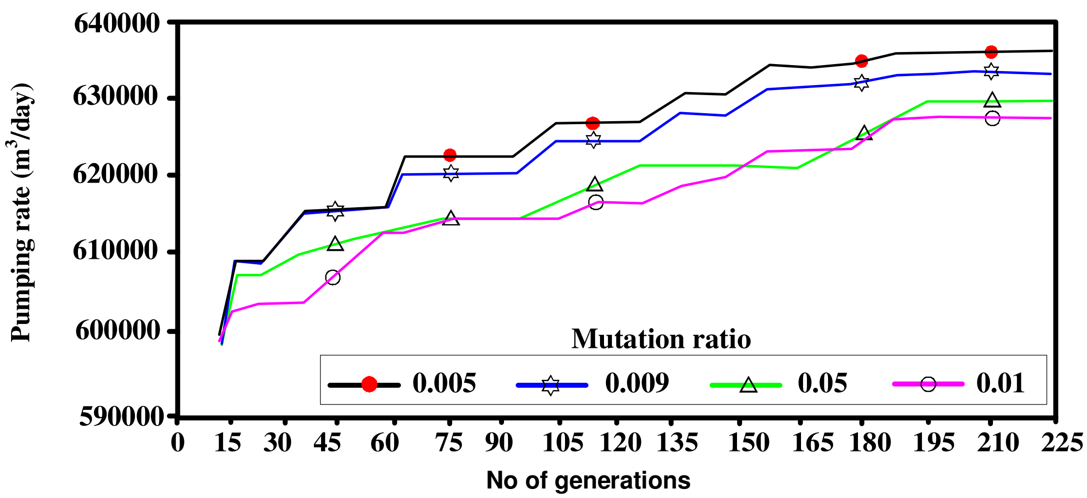

Figure 11. Pumping rate versus number of generations for the 2nd scenario.

of the proposed model when applied in the NADD to develop the optimal pumping rate under different scenarios establish the optimal pumping rate 595977.9 m^3/day under the current reclamation activity beside new reclamation of 6000 ha with total number of 154 deep productive wells. Therefore, this model gives a feasible solution to optimize the number of wells according to the optimal pumping rate.

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