

Optimal Well Locations using Genetic Algorithm for Tushki Project, Western Desert, Egypt

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Abstract— The well location problem is challenging due to the non-linear, discrete and often multi-modal objective function. The optimal distribution of productive well locations mitigates the groundwater productivity problem that threatens the national projects in arid countries like Egypt. In this paper, a trial to mitigate this problem in Tushki National Project, south western desert, Egypt is supposed via delineating the optimal well locations and optimal pumping rates. The methodology of combination between simulation and optimization techniques is applied. The simulation outputs of groundwater flow system by Visual MODFLOW model is linked by the constructed Fortran Code for Optimal well Location using Genetic Algorithm (OLGA Code) for obtaining the optimum management of groundwater resources in this project. Two management cases are considered by running the model domain with adopted steady and transit calibrated parameters. The first management case deals with the present well locations and predicts the optimal value of the objective function (maximum pumping rate). In the second case, the optimal new well locations resulted from the OLGA Code is predicted from flexible well location with the moving well option. Also, the prediction of the future changes in both head and flow are studied in steady and transient states.

Keywords— Groundwater, Optimization, Genetic Algorithm, Tushki project.

I. INTRODUCTION

Selecting optimal well sites is a valuable problem to solve; maximizing groundwater recovery increases oil reserves and minimizing costs improves profitability. One of the best methods of selecting optimal sites is the combined use of simulation and optimization (S/O) models. While simulation models basically provide solutions of the governing equations of groundwater flow, optimization models identify an optimal management and planning strategy from a set of feasible alternative strategies. The genetic algorithm (GA) is 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). Rana et al, (2008) conducted a study on a spatio-temporal optimization of agricultural drainage, using groundwater model and GA. Guan et al. (2008) proposed an improved genetic algorithm (IGA) to solve optimization problems with equality and inequality constraints. Hamid et al. (2009) presented a paper focusing on the S/O for conjunctive use of surface water and groundwater on a basin-wide scale, the Najafabad plain in west-central Iran. Gad et al., (2011), and Moharram et al., (2012) used an optimization model based on the combination of MODFLOW simulation with GA to maximize the total pumping rate from the Nubian sandstone aquifer in El-Dakhla and El-Farafra depressions, Egypt. Saafan et al., (2011) applied multi-objective genetic algorithm (MOGA) Code in El-Farafra depression, Egypt to study the maximum pumping rate and minimum operation cost. Gad and Khalaf, (2013) used MOGA model to develop the maximum pumping rate and minimum operation cost in the Miocene aquifer of Wadi El-Farigh, West Delta, Egypt.

In the other side, there are limited studies for the determination of optimal operating strategy, including unknown well locations and pumping rates, for groundwater systems to the best of our knowledge (Wang and Ahlfeld, 1994, Karahan and Ayvaz, 2005, and Ayvaz and Karahan, 2008). Saffi and Cheddadi (2007) developed an algebraic expression which gave the matrix of transient influence coefficients for one-dimensional semi-confined aquifer model and solved the governing equation by using a mixed compartment model. Tung and Chou (2004) integrated pattern classification and tabu search to optimize the average zonal groundwater pumping for an aquifer. As a general, the research conducted in this field dealt with the identification of locations and released histories of unknown groundwater pollution sources (Mahar and Datta, 2000, 2001; Aral et al., 2001; Ruperti, 2002; Singh et al., 2004; Sun et al., 2006), pumping well optimization for optimum remediation design (Wang and Ahlfeld, 1994; Huang and Mayer, 1997; Guan and Aral, 1999; Zheng and Wang, 1999; Mantoglou and Kourakos, 2007; Chang et al., 2007), and optimum well locations and pumping rates in the coastal sides (Park and Aral, 2004; Ferreira da Silva and Haie, 2007). Meira, et al. (2016) proposed technique for decision-making process in optimal well location including a step of risk analysis associated with the uncertainties present in the variables of the

Due to the few of scientific researches related to optimal well locations especially in our national governmental and investment agricultural projects, a trial was carried out in this paper to through a light on the optimal location for new fourteen production wells in Tushki project required for irrigation of 25 thousand acres which will drill under the strategy of reclamation of 1.5 million acres project.

E-W and NE-SW folds, the Ring forms and the structural lineation. The fault systems play an important role in recharging the NSAASA from Lake Nasser especially the NW-SE. They act as conduits and help in transmitting the groundwater within the NSAASA supporting the hydraulic connection between the aquifer units (Aggour et al., 2012).

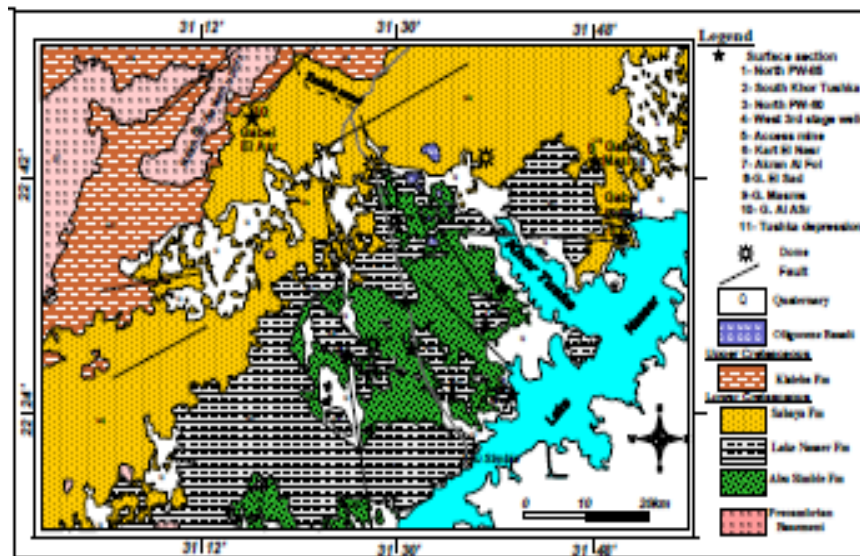


FIGURE 2: GEOLOGICAL MAP OF THE STUDY AREA (AFTER

2.3 Hydrogeological aspects

The NSAASA is mainly composed of three successive water-bearing units, namely; the Gifl, Abu Simbel and Lake Nasser. The middle unit is an aquiclude that extends under the lake and the lower unit overlying the granitic basement is a confined aquifer of fluvial sandstones (Figure 3). The groundwater of NSAASA exists under unconfined to semi-confined conditions. The NSAASA maximum thickness reaches 400 m and decreases towards north and NW. The transmissivity of the NSAASA ranges between 389 and 1322 m²/day (Table 2), and increases from SW to NE. The constructed equipotential contour maps (Figure 4) show that the local recharge of the NSAASA depends upon the leakage from the Lake Nasser due west direction. The estimated groundwater flow rate based on these contour maps (Figure 4) reaches 0.054 m/day near Nasser Lake and decreases to 0.044 m/day towards northwestern parts.

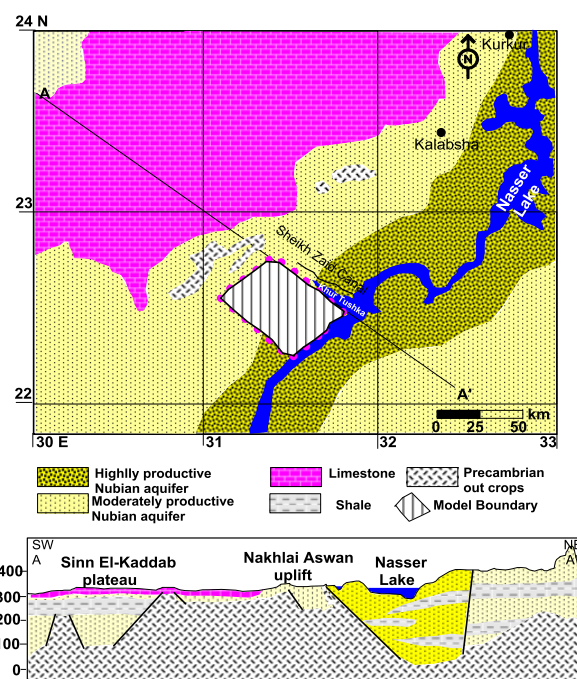


FIGURE 3: NSAASA POTENTIALITY MAP AND SW-NE CROSS-SECTION SHOWING AQUIFER THICKNESS

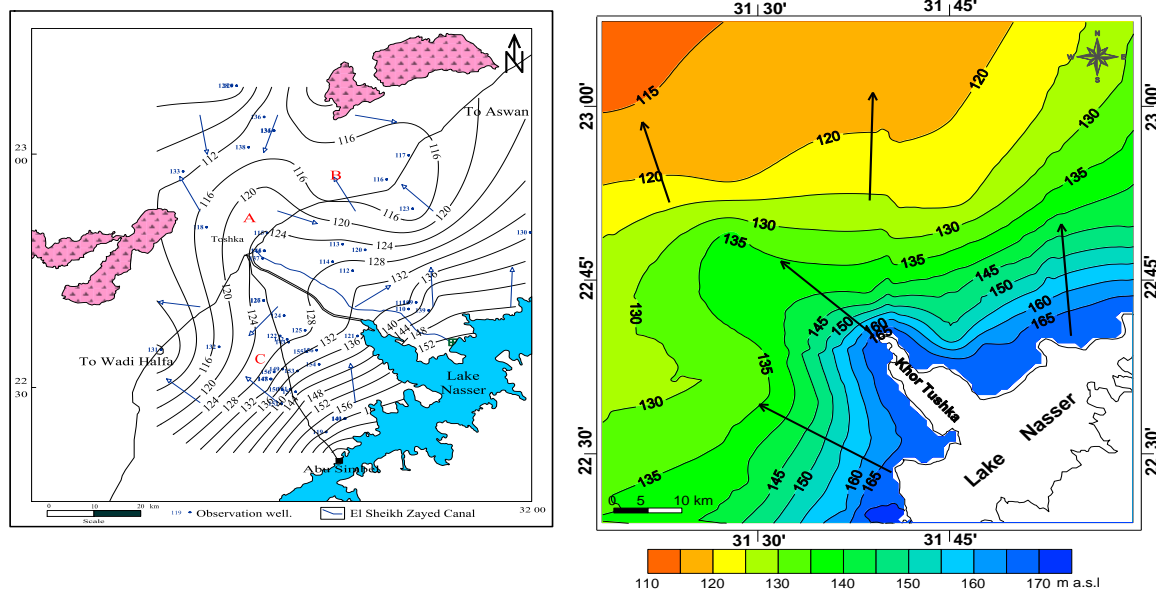


FIGURE 4: THE GROUNDWATER EQUIPOTENTIAL MAPS OF NSAASA DURING 2008 (LEFT MAP AFTER EL-SABRI ET. AL., 2010) AND DURING 2010 (RIGHT MAP-AFTER AGGOUR ET. AL., 2012)

III. MATERIALS AND METHODS

3.1 Field trip and data collection

The materials used in this paper are collected through carrying out four field trips in Abu Simbel area during the period 2010-12. The basic hydraulic parameters of NSAASA are estimated based on carrying out one step test and 13 long duration pumping tests (Tables 1 and 2). The different hydrologic data are obtained during the field trips. These materials also include collection of archival data (well drilling reports, WRI 2002), 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.

TABLE 1
RESULTS OF STEP DRAWDOWN TEST ANALYSIS IN NSAASA

Step No	Step time Duration (hour)	Well discharge Q (m ³ /day)	Total DD (s) (m)	s/ Q (day/m ²)
I	1.5	1080	8.32	0.008666667
II	1.5	1200	11.8	0.009833333
III	1.5	1368	13.38	0.009291667
IV	1.5	1488	15.82	0.01063172

TABLE 2
RESULTS OF LONG DURATION PUMPING TESTS ANALYSIS IN NSAASA

Well No	Pumping rate (m ³ /h)	Depth to water (m)	Total DD (m)	Screen (m)	Hydraulic parameters		
					K (regional) (m/day)	K (local) (m/day)	T (m ² /day)
W27	105	79.4	5.67	80.5	6.88	12.45	1003
W30	120	76.79	7.89	80.5	4.9	9.09	732
W38	173	60.88	11.81	80.5	4.94	10.07	812
W40	120	62.59	10.01	80.5	9.21	16.42	1322
W43	112	71.26	-	80.5	-	-	878
W45	160	55.6	16.28	80.5	5.19	10.41	839
W50	172	30.64	17.53	74.75	2.19	5.64	422
W55	123	58.6	24.87	57.5	-	9.28	534
W 57	110	63.15	20.84	57.5	-	8.06	464
W 60	100	74.07	13.17	135	-	7.11	389
W75	107	72.7	14.5	57.5	-	10.01	576
W80	110	68.8	11.25	57.5	-	-	912
W85	130	58.2	-	57.5	-	-	340

The methodological approach used in this paper is based on the mathematical modeling techniques which combines between simulation and optimization model. A computer programming with FORTRAN language has been originally established to apply the principles of the genetic algorithm for studying the optimal location of the groundwater productive wells as a principal tool for groundwater resources management. The Optimal well Location applying Genetic Algorithm (OLGA Code) links MODFLOW with genetic algorithm technique to establish a simulation optimization groundwater model.

3.2 Simulation technique

Groundwater flow simulation is carried out applying MODFLOW software. It describes 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).

3.2.1 Conceptual Model

The conceptual model of the NSAASA is based on the geology of the study area which is comprised of Nubian sandstone sediments. The hydrogeologic system is concerned two hydraulically connected through fault planes layers. The top hydrostratigraphic unit (Gulf Formation) is considered to be a sandy unconfined aquifer zone up to 95 meters maximum thick. The second confined aquifer zone of fluvial sandstones is separated from the sandy unconfined aquifer zone by aquiclude, and had maximum thickness of 79 meters. The scattered new communities around the asphaltic road in the N-S direction of the Abu Simbel area are primarily planned for agriculture.

3.2.2 Model domain

The model domain of NSAASA is selected to cover 3315 km² (51x65 Km-Figure 3). It is discretized using 130 rows × 102 columns rectangular cells. This discrimination produces 13260 cells in the model layer. The width of the cells along rows (in x-direction) is 500m and along columns (in y-direction) is 500 m. The grid geometry is shown in (Figure 5).

3.2.3 Boundary conditions

The hydraulic conditions at the boundaries of the model domain are specified (Figure 5). Based on the groundwater flow pattern of the NSAASA (Figure 4) and the field measurements of the groundwater head in the present productive wells (Table 2), the initial and boundary conditions of the local model is defined. The lower boundary (water body of Lake Nasser) is considered a time-constant head at level of 175 m asl (DRC 2012). The equipotential contour line of 130m asl characterizing to the upper boundary (Figure 5) is far enough from the well fields to be general head boundary condition. The left and right boundaries are assumed to be no flow boundaries due to the regional flow direction from SE to the NW.

The impermeable Basement rock is assumed to be the bottom boundary of the model domain with no flow and maximum depth 236.45m (Table 3 and Figure 6). The hydraulic heads and hydraulic conductance are assigned to boundary cells. These heads vary during the simulation process according to different stresses applied on the modeled area.

3.2.4 Aquifer properties

The aquifer material properties of the NSAASA include the transmissivity, the storage coefficient and the hydraulic conductivity. The transmissivity ranges from 389 and 1322 m²/day (Table 2) and the storage coefficient from 1.2×10^{-4} to 5×10^{-4} (El-Sabri et. Al., 2010). Vertical heterogeneity is assumed adequate to allow treatment as multi layered aquifer. The vertical hydraulic conductivity, estimated from the aquifer thickness (Figure 6-left) and aquifer transmissivity values, is varied from 5.64 to 16.42 m/day. Furthermore, the availability of a relatively complete database of 75 groundwater drilled wells and 9 observation wells in the NSAASA help in constructing the present model. In addition, the initial piezometric heads are computed from the absolute ground elevation values of the model domain extracted from the Digital Elevation Model (DEM) of the study area (Figure 6-right).

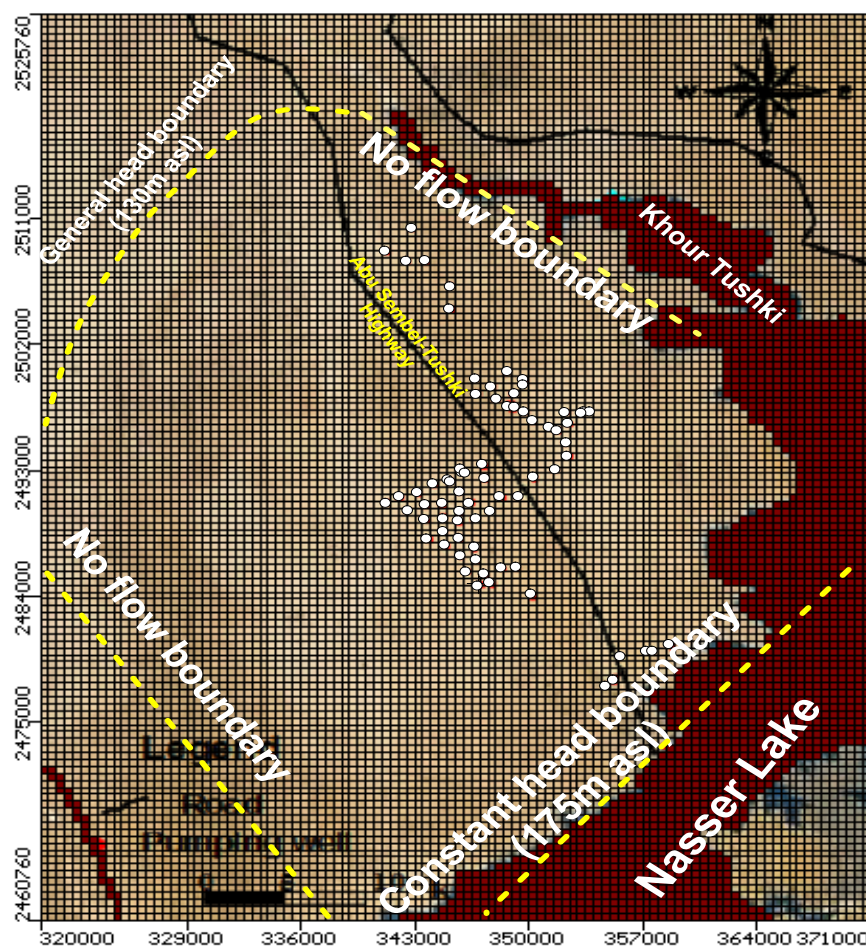


FIGURE 5. FLOW MODEL DOMAIN GRID AND THE BOUNDARY CONDITIONS OF THE NSAASA

TABLE 3
UPPER SURFACE OF BASEMENT ROCK (AMSL) IN ABU SIMBEL AREA

Well name	Ground elevation (m)	Basement level (m)	Well name	Ground elev. (m)	Basement level (m)
Akaria well	185.07	-34	O.B No11	85	-236.45
Well No 4	193.57	-176	O.B No 3	225	+107
Well No 5	204.72	-176	O.B No 3	225	0.0
Well No 13	194.05	+10	O.B No 6"	201	-129
Well No 21	195	-4	O.B No 7	165	-86
KADCO No 1	230	-2	O.B No 8	215	-9
KADCO No 2	233	+8	O.B No 10"	165	+75
KADCO No 3	233	+15	O.B No 18	190	-42
El Masria well	164	+92	O.B No 18"	190	-116
Akaria well 2	198.06	-124	O.B No 19	193	0.0
O.B No 4	193.05	-168	O.B No 20	165	+51
O.B No 10	186.07	-45	O.B No 25	183	-41

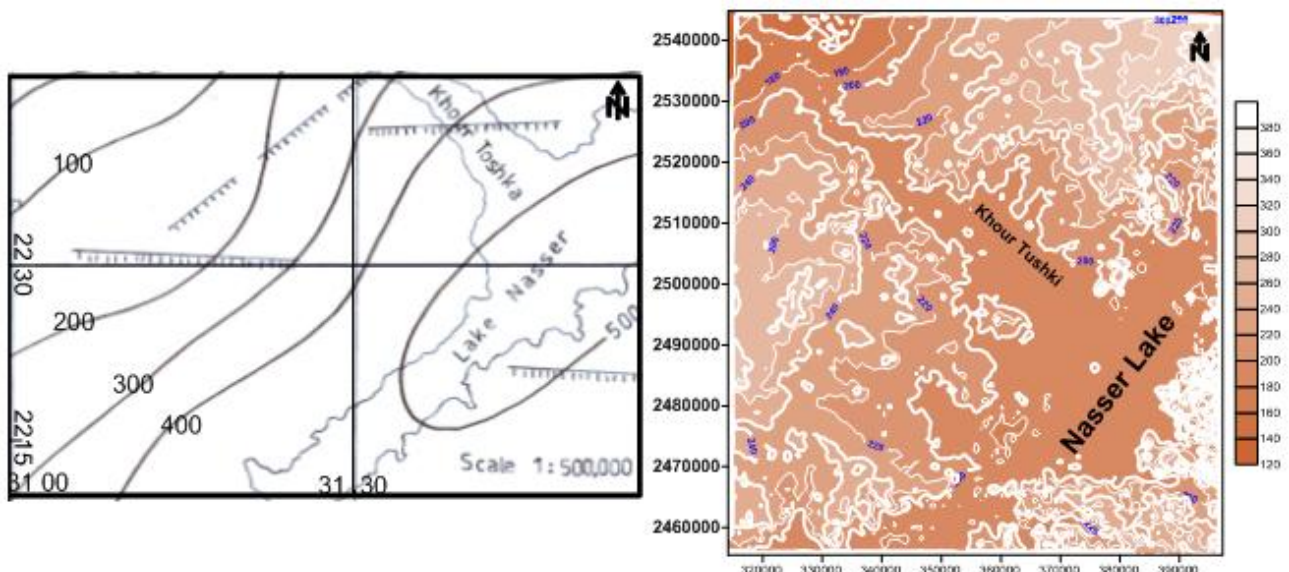


FIGURE 6: AQUIFER THICKNESS CONTOUR MAP (LEFT MAP) AND GROUND ELEVATION EXTRACTED FROM DEM (RIGHT MAP)

3.2.5 Model calibration

Calibration involves modification of the parameters, and forcing functions in the model in such a way as to assure that the model reproduced observed-head values (Hill, 1998 & 2000). The calibration process typically involves calibrating to steady-state and unsteady state conditions. The performed steady state calibration permits the adjustment of the hydraulic conductivity, where NSAASA storage changes are not significant. The relation between the calculated and observed heads is checked from the calculated-observed head curve and the variance appears as 45.966 % (Figure 8). This large value indicates great difference between the heads calculated by the model and actual measured heads. After many times of changing the k values, the variance between the observed and calculated heads is minimized to 3.61 % and the calculated head values is very closely related to the field-measured head values (Figure 7). Based on the calibrated model, the estimated hydraulic conductivity values are ranging from 4.33 to 7.60 m/day. These values are generally more slightly than the values calculated from the field data. The difference may relate to the benchmarks, uncertainty and grid refinement.

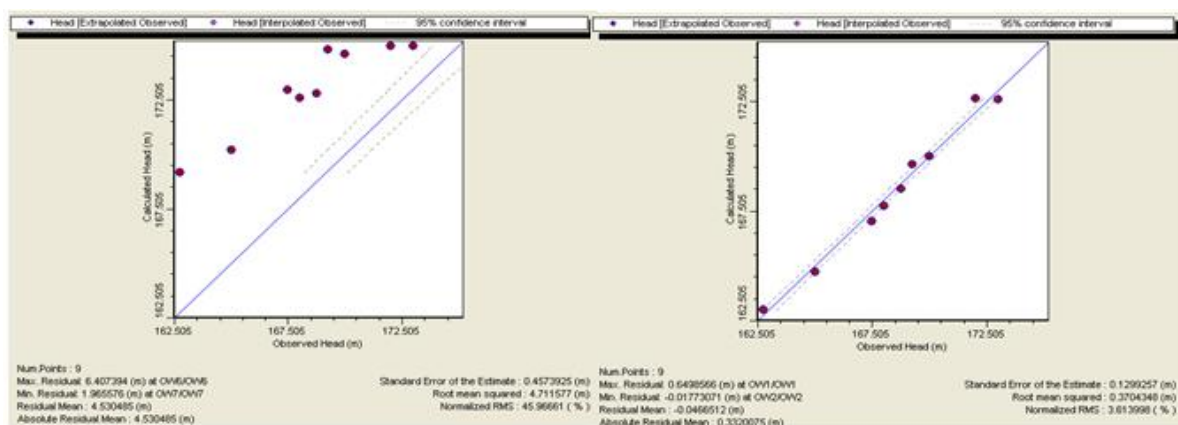


FIGURE 7: THE CALCULATED AND OBSERVED HEADS OF THE MODEL DOMAIN OF NSAASA FOR STEADY STATE

Transient state, specific yield values are modified on a trial and errors basis, until a good match between the observed heads in the years 2002 and 2012 (sited in Kim and Sultan, 2002 and Aggour et. Al., 2012) and the calculated heads are achieved. The range of the resulted specific yield after the final calibration of the transient state is found to be varying from 0.14 to 0.34 (Fig. 8). It can be seen that, in general, there is a good agreement between the observed and simulated head values.

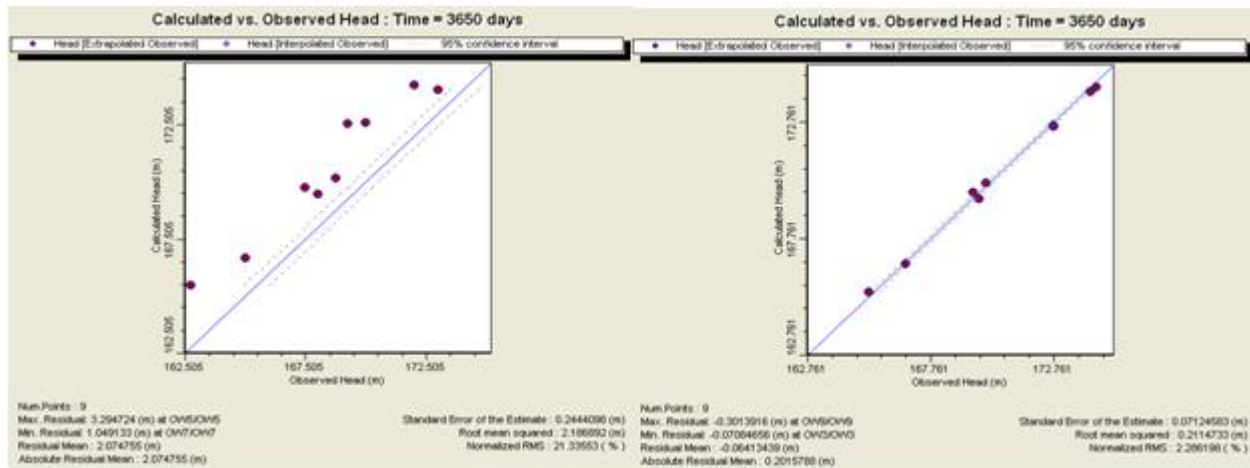


FIG. 8: THE CALCULATED AND OBSERVED HEADS OF THE MODEL DOMAIN OF NSAASA FOR UNSTEADY STATE

3.3 Optimization Technique

Genetic Algorithms (GA) are adaptive heuristic search algorithm premised on the evolutionary ideas of natural selection and genetic. The basic concept of GA is designed to simulate processes in natural system necessary for evolution. 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 evolutionary 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 to obtain optimal location of wells, Q_j as design variable, where:

$$\text{Max} \quad Z = \sum_{j=1}^{N_w} Q_j - P_j \quad (2)$$

in which: N_w is the total number of pumping wells and P_j is penalty.

Moreover, the management objectives must be achieved within a set of constraints. The constraints may be decision variables. The objective function is subjected to the following constrains:

3.3.1 Objective function constraints

3.3.1.1 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:

$$Q_j^{\min} \leq Q_j \leq Q_j^{\max} \quad j = \dots, N_w \quad (3)$$

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

3.3.1.2 Drawdown constraint

This constraint normally means to protect the ecosystem by avoiding excessive drawdown. In this work, the drawdown constraints were formulated to avoid mining and formulated as follows:-

at arbitrary point 1, Drawdown constraint = $r_{w1} + r_{w2} + r_{w3} + r_{w4} + r_{w5} + \dots + r_{w68}$

at arbitrary point 2, Drawdown constraint = $r_{w1} + r_{w2} + r_{w3} + r_{w4} + r_{w5} + \dots + r_{w68}$

at arbitrary point 3, Drawdown constraint = $r_{w1} + r_{w2} + r_{w3} + r_{w4} + r_{w5} + \dots + r_{w68}$

at arbitrary point N_c , Drawdown constraint = $r_{w1} + r_{w2} + r_{w3} + r_{w4} + r_{w5} + \dots + r_{w68}$

Accordingly, it postulates the relation;

$$\sum_{j=1}^{N_w} r_j \leq d_i \quad (4)$$

In which: r_{w1} is drawdown at point 1 due to pumping well no 1, r_{w2} is drawdown at point 1 due to pumping well no 2, r_{w3} is drawdown at point 1 due to pumping well no 3, N_c no of control points, r_j is the drawdown at control point i caused by a pumping rate from pumping well j (value of r_j in Table 4 to 6), d_i is the permissible drawdown at control point i equals to 30 m.

3.3.1.3 Water demand constraint

The NSAASA 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:

$$\sum_{j=1}^{N_w} Q_j \geq Q_D \quad (5)$$

In which Q_D is water demand.

3.3.1.4 Distance between wells constraint

This constraint obeys the relation:

$$D_i \geq D_{all} \quad (6)$$

Where D_i is actual distance between wells and D_{all} is minimum distance between wells.

3.3.1.5 Location of wells

The locations of wells constraint is to be decided by the model itself within a user defined region of the model grid until the optimal location is reached (Figure 9).

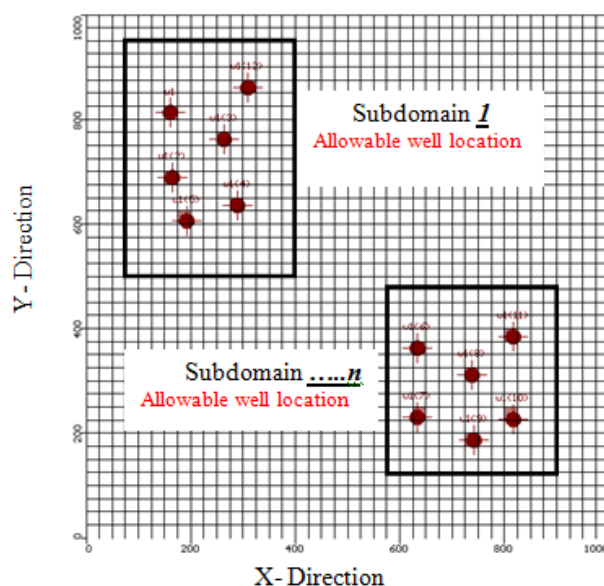


FIG. 9: PLAN VIEW SHOWING FINITE DIFFERENCE GRID WITH SUB-DOMAIN FOR WELL LOCATIONS

3.4 Optimization Procedure of the Simulation-Optimization model

In groundwater management problems, there are two sets of variables, decision variables and state variables, where the decision variable is the pumping and injection rates of wells. Also other decision variables include well locations and the on/off status of a well. By optimization techniques the decision variables can be managed to identify the best combination of them. Moreover, hydraulic head is the state variable. The simulation model updates the state variables, and the optimization model determines the optimal values for all decision variables. In this work, MODFLOW FORTRAN code is used as the simulation of groundwater flow which links with GA optimization (OLGA Code). The flowchart for simulation-optimization model is given in (Fig. 10).

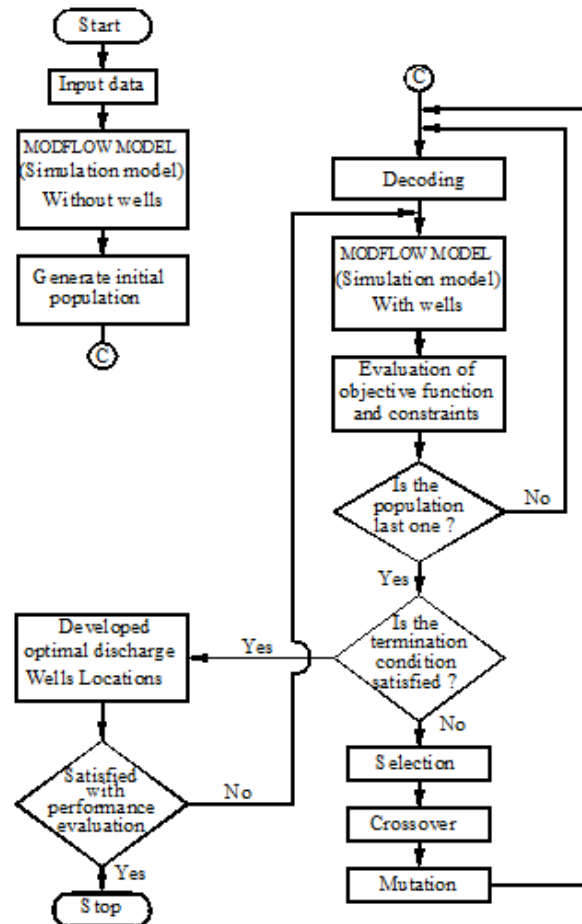


FIGURE 10: FLOWCHART FOR THE SIMULATION/OPTIMIZATION MODEL

It must refer that MODFLOW simulation without wells is used to generate the initial head, but initial population is generated from GA via random number for each well according to constraints and number of chromosome.

3.4.1 Checking the termination criterion

The optimization algorithm continues to be executed by iterating until the given termination criteria are satisfied (Fig. 10). 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,

$$\frac{f_1 - f_0}{f_0} \leq \varepsilon \quad (7)$$

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

3.5 Testing scenarios

The testing scenarios include three proposed pumping rates and well locations policies. The first scenario estimates the pumping rates from 75 productive wells with their present locations. The second scenario checks the present locations for these 75 productive wells and the optimality of their pumping rates. The third one proposes water exploitation policy aimed at increasing the present productive wells by 14 wells, as a result of the increase in reclamation activities (new 25 thousand acres), and delineates the optimal locations of these new wells and keeping the present locations of the other 75 present wells besides estimating the optimal pumping rates for all.

IV. RESULTS AND DISCUSSIONS

The expected interference between cones of depression of the present productive wells due to their configurations around the highway roads of the Abu Simbel area will affect the groundwater productivity of the NSAASA. Accordingly, the need to determine optimal well location strategy for the new drilled wells required for future expansion of the project (1.5 million acres national project) is essential.

In addition, applying the constructed OLGA Code for solving the optimization problems related to the optimal pumping rates and the optimal well locations, the initial pumping rates are assigned to each well as more than 700 m³/day and less than 1000 m³/day and then the optimization procedure explained before is used. The GA parameters used in the optimization problem are given in Table 4. The optimal well location and pumping rate are determined, based on OLGA Code, from one feasible solution to the other according to the calculated residual errors values where they improve quickly in the early iterations and change slowly in subsequent iterations till satisfying the constraints.

TABLE 4
THE GA SOLUTION PARAMETERS APPLYING OLGA CODE

Continuous GA Parameter	Value
Population size	200
Mutation ratio	0.006
Type of crossover	uniform crossover
Crossover probability	0.7
Tolerance for the convergence of iterations	0.01

On the other side, the results of the three testing optimal policies applying OLGA Code show the future predictions in the optimal pumping rates after 5, 10, 15, 20, 25, 30, 40 and 50 years. The first scenario investigates the proposed pumping rates from the 75 productive wells penetrating the NSAASA under their current locations. The OLGA simulation results show that the optimal pumping rates, under the present conditions of water demand Q_D of 60000 m³/day, range from 57585 to 50144 m³/day with corresponding total drawdown ranges from 3.42 to 13.73 m during the simulation period of 50 years (Table 5).

TABLE 5
OPTIMAL PUMPING RATE FOR FIRST SCENARIO

Year	5	10	15	20	25	30	40	50
N	75	75	75	75	75	75	75	75
r (m)	3.42	5.62	6.78	7.88	8.93	9.96	11.85	13.73
$Q_{min}/well$	746.8	726.4	708.6	695.6	645.2	629.2	613.8	605.7
$Q_{max}/well$	1000	1000	1000	1000	1000	1000	1000	1000
Q_{opt} (m ³ /day)	57585	56033	54511	53021	52292	51568	50852	50144

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.

Moreover, by running the developed OLGA Code for time step of 5 years, the predicted head distribution maps of the NSAASA under the current pumping rates at years 2015, 2025, 2035 and 2060 are shown in (Figure 11). It is noticed from (Figure 11) that the groundwater levels change from 164.5 masl to 161.3 masl in the center of the cone of depression. Few productive wells in the southwestern part of the model domain show relatively slight drawdown amounts to 13 m at East El-Emaratiah Company well field. This is mainly attributed to the effect of increasing the thickness of water bearing formation towards the northwestern and western parts. In addition, one large cone of depression will develop in the cultivated areas.

This cone is in the central part of Abu Simbel-Tushki road and may attribute to the present extraction rates from the reclaimed areas.

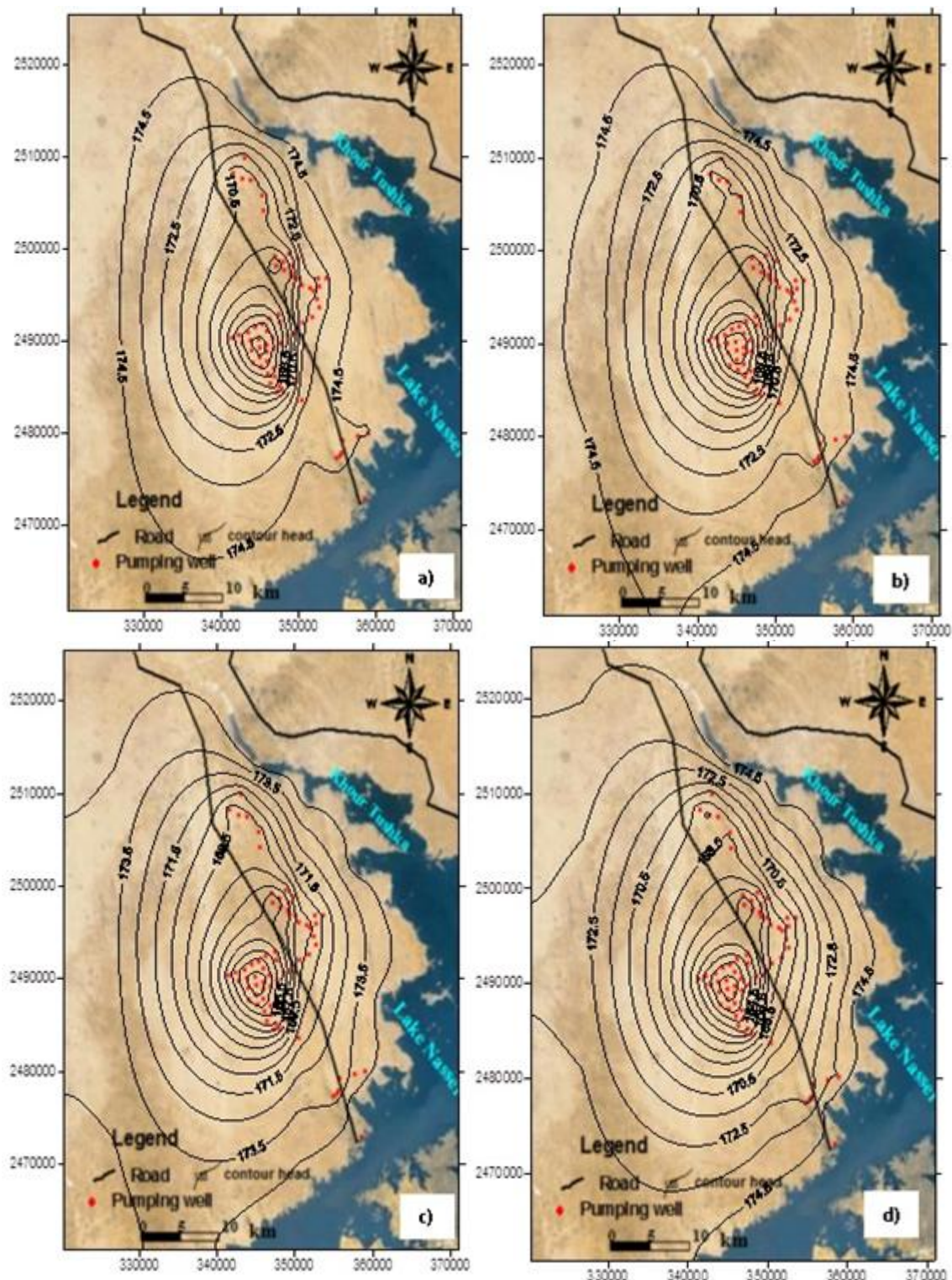


FIGURE 11: PREDICTED HEAD DISTRIBUTION MAP OF THE NSAASA FOR OPTIMAL PUMPING RATES APPLYING 1ST SCENARIO a) at 2015, b) at 2025, c) at 2035, and d) at 2060

Otherwise, the second scenario seems to be theoretical more than practical since it studies the optimal locations of already 75 present productive wells under the present constraint of water demand Q_D of 120000 m^3/day and predict their optimal pumping rates. The GA parameters used in this optimization case are given in (Table 6). The initial pumping rates are assigned to each well as less than 1500 m^3/day and the optimal pumping rates after 5, 10, 15, 20, 25, 30, 40 and 50 years are

predicted (Table 6). It is noticed from (Table 6) that the number of the total operating wells N is still constant (75 wells), and the maximum drawdown (r) ranges from 2.22 to 12.13 m while Q_{\min}/well begins with 1460.6 and ends by 1053.2 m^3/day for the simulation period. The total optimal pumping rate for all wells (Q_{opt}) ranges between 102038 and 100773 m^3/day (Table 6).

TABLE 6
OPTIMAL PUMPING RATE FOR THE 2ND SCENARIO APPLYING OLGA CODE

Year	5	10	15	20	25	30	40	50
N	75	75	75	75	75	75	75	75
r (m)	2.22	4.32	5.43	6.63	7.73	8.64	10.53	12.13
Q_{\min}/well	1460.6	1369.5	1301.6	1286.4	1201.3	1183.2	1102.4	1053.2
Q_{\max}/well	1500	1500	1500	1500	1500	1500	1500	1500
Q_{opt} (m^3/day)	102038	101797	101561	101330	101103	100992	100882	100773

In the same side, the results of the OLGA Code based on this scenario show that the predicted optimal location of the productive wells differ more or less from the present location (Figure 12). Although the proposed OLGA approach successfully identified all the well locations and pumping rates of the present numerical study, identification of all the well locations and pumping rates may not be feasible for real-world applications since the number of pumping wells is usually very high. Instead, the proposed procedure may be applied to the suspected illegal pumping areas as noticed in the field trips. As an extension of this study, the performance of the proposed OLGA Code should be tested on a real field system in a future study.

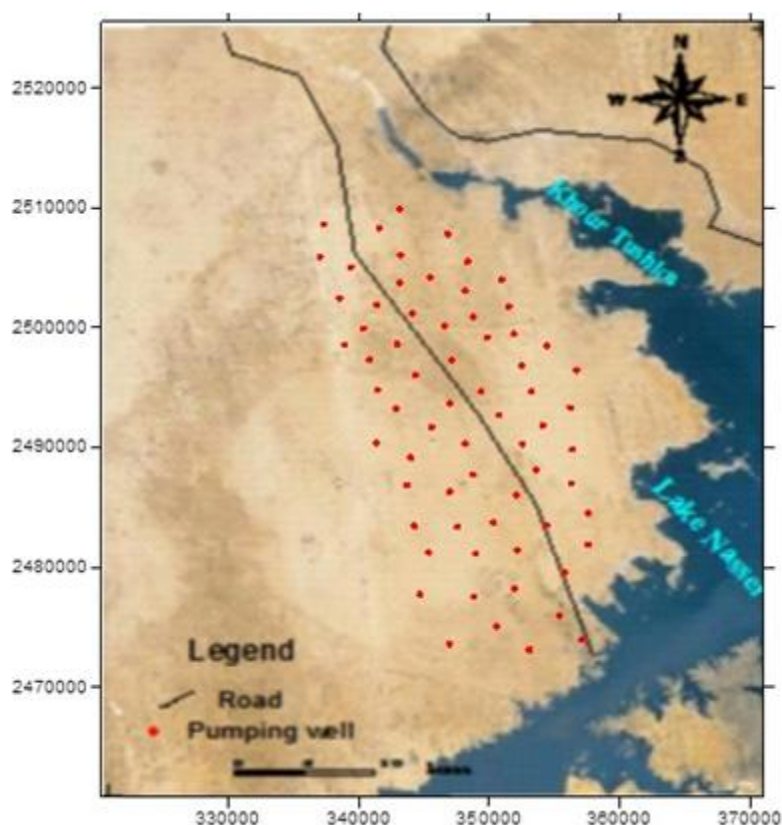


FIGURE 12: OPTIMAL LOCATION OF PRESENT WELLS (2ND SCENARIO)

Otherwise, the predicted head distribution maps of the NSAASA under the 2nd scenario (Figure 13) show groundwater levels change from 165.5 masl to 162.5 masl in the center of the cone of depression. It is noticed from (Figure 13) that the normal decline in the groundwater levels (3 m) may attribute to the small thickness and low hydraulic conductivity of the NSAASA in these localities. Moreover, the cone of depression will appear in the cultivated areas during the simulation time (with diameter of 2.5 to 4 km approximately). 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.

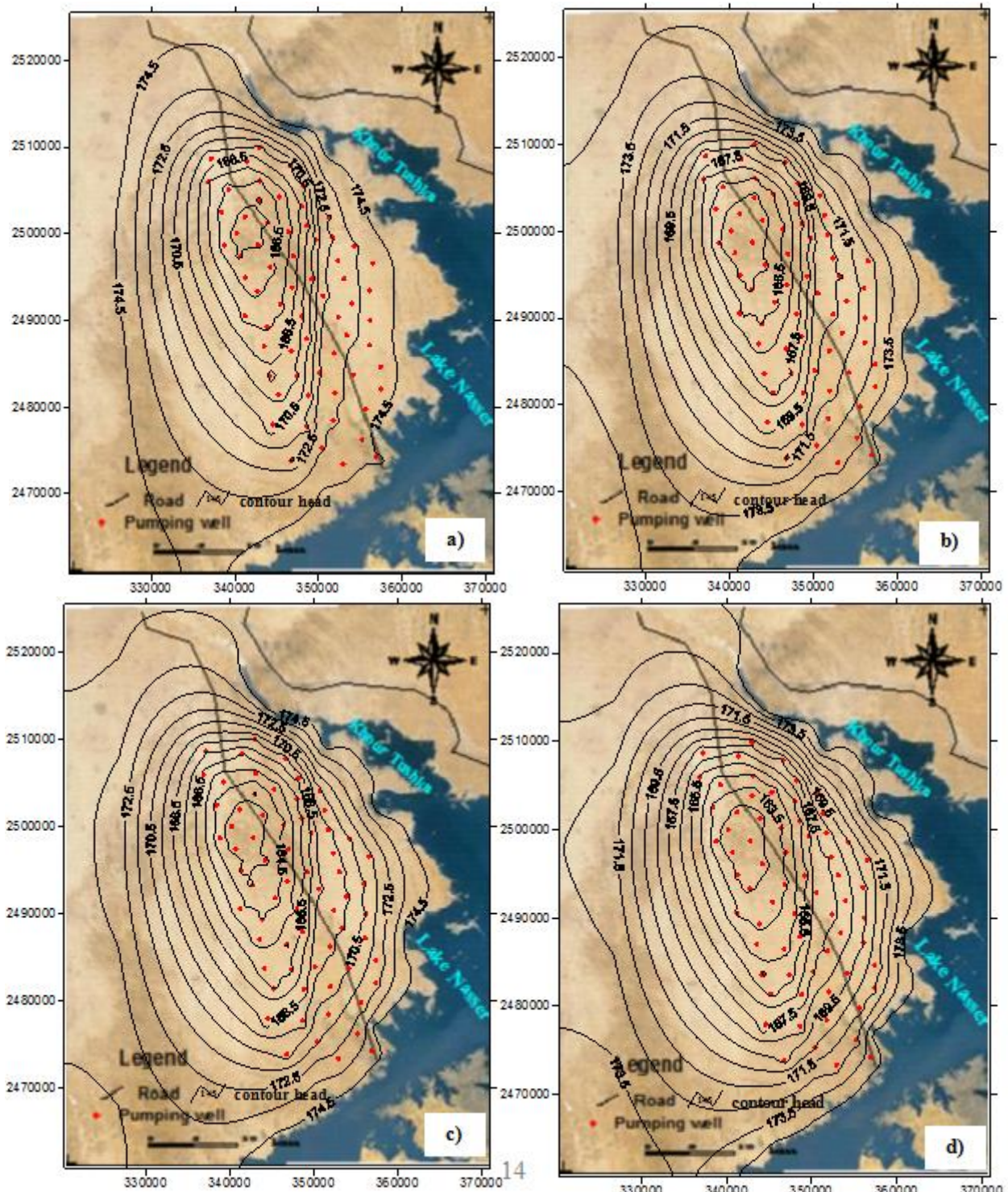


FIGURE 13: PREDICTED HEAD DISTRIBUTION MAPS OF THE NSAASA FOR OPTIMAL WELL LOCATIONS APPLYING 2ND SCENARIO A) AT 2015, B) AT 2025, C) AT 2035, AND D) AT 2060

The third scenario proposes water exploitation policy aimed at increasing the present productive wells by 14 wells, as a result of the increase in reclamation activities, under the constraints of 500 m as minimum distance between wells and 900000 m^3/day as water demand Q_D , and delineates the optimal locations of these new productive wells and keeping the present locations of the other 75 present productive wells, besides estimating the optimal pumping rates for all. The GA parameters

used in this optimization case are given in (Table 7). The OLGA Code runs for time step of 5 years. The predicted optimal location of the new productive wells is checked (Figure 14) and the predicted head distribution maps of the NSAASA for the optimal pumping rates at years 2015, 2025, 2035 and 2060 are shown in (Figure 15).

TABLE 7
OPTIMAL PUMPING RATE FOR THIRD SCENARIO

Year	5	10	15	20	25	30	40	50
N	89	89	89	89	89	89	89	89
r (m)	4.27	6.47	7.63	8.72	9.77	10.80	12.68	14.56
$Q_{min}/well$	923.2	913.3	902.8	879.6	823.6	813.2	800	800
$Q_{max}/well$	1500	1500	1500	1500	1500	1500	1500	1500
$Q_{opt} (m^3/day)$	87187	85635	84114	82623	81894	81171	80454	79747

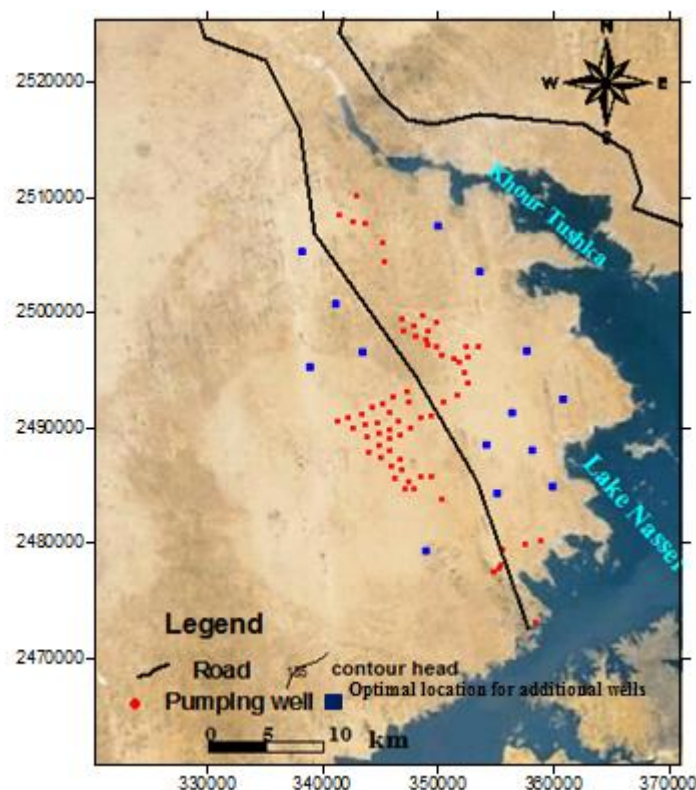


FIG. 14: OPTIMAL LOCATION OF THE NEW PRODUCTIVE WELLS (BLUE COLORED) (3RD SCENARIO)

It is noticed from (Table 7) that the maximum drawdown r ranges from 4.27 to 14.56 m while $Q_{min}/well$ begins with 923.2 and ends by 800 m^3/day in case of number of total operating wells N of 91 productive wells. Moreover, $Q_{min}/well$ begins with 923.2 and ends by 800 m^3/day during the simulation period. The total optimal pumping rate for all wells (Q_{opt}) ranges between 87187 and 79747 m^3/day .

However, it is noticed from the predicted head distribution maps (Figure 15) that the groundwater level decreases from 163m asl in the beginning of the simulation period (the year 2015) to 158m asl in the end of the simulation period (the year 2060). 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 optimal pumping rates of the productive groundwater wells beside its optimal locations in the reclaimed areas. Accordingly, it is preferred to extend the future reclamation activities parallel to the western side of the Khour Tushki area. Although the results of this scenario provide more or less good degree of confidence in the optimal location of the new productive wells and optimal pumping rates, the expected sharp decline in groundwater levels in the concerned area assumes more applied studies. The Q_{opt} in the 3rd scenario is actually lower than that in the 2nd scenario because the second scenario studies the optimal locations for these 75 productive wells and their optimal pumping rates. The third one proposes water exploitation policy aimed at increasing the present productive wells by 14 wells. The predicted value of (r) based on the 3rd scenario is more or less similar to the results of the other two scenarios although the number of the operating wells is increased by 19%. This reflects the great importance to apply the optimal well location concept in any

new reclamation projects. As a result of the above discussion of the OLGA Code optimal well location and pumping rates results, it can be concluded that the groundwater withdrawal from the NSAASA under this optimization study could be safely conducted.

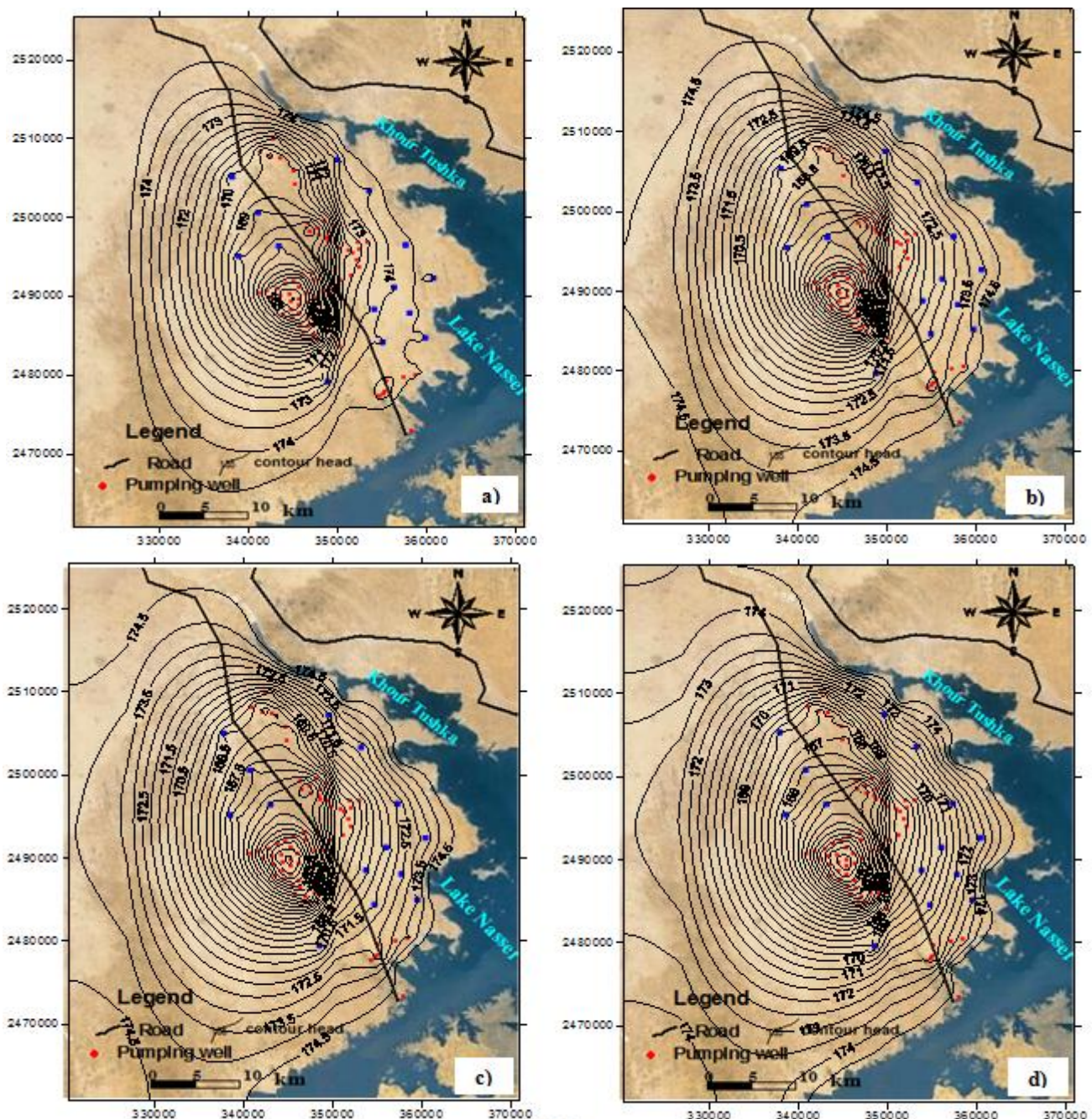


FIGURE 15: PREDICTED HEAD DISTRIBUTION MAPS OF THE NSAASA FOR OPTIMAL WELL LOCATIONS APPLYING 3RD SCENARIO a) at 2015, b) at 2025, c) at 2035, and d) at 2060

V. CONCLUSION AND RECOMMENDATION

This paper is devoted to propose an assisted methodology to identify representative models for optimal well locations. To do so, first a mathematical equations were developed to model the representativeness of a subset of constrains with respect to the full set that characterizes the well location problem. Then, an optimization tool was implemented to identify the representative constrains of any problem, considering not only the main output variables, but also the probability distribution of the attribute-levels of the problem. Accordingly, OLGA Code was linked MODFLOW with genetic algorithm technique to establish a simulation optimization groundwater model. This model was applied for NSAASA to develop the optimal location of the groundwater productive wells with maximum pumping rate. Three scenarios were tested to choose the proper

water exploitation policy. For the first scenario, the predicted groundwater drawdown after simulation period of 50 years ranged from 3.42 to 13.73 m while the corresponding optimal pumping rates ranged from 57585 to 50144 m³/day. Under the second proposed scenario, the predicted drawdown (r) and the corresponding total optimal pumping rate for all wells (Q_{opt}) ranged from 2.22 to 12.13 m and between 102038 and 100773 m³/day, respectively. Moreover, the predicted value of (r) based on the 3rd scenario was more or less similar to the results of the other two scenarios although the number of the operating wells was increased by 19%. Computational restrictions were common and likely the cause of the systemic lack of algorithm benchmarking for well location optimization. Still, some valuable insight can be gained from these results that could guide further investigation.

Based on the results of the OLGA model, it is highly recommended to choose the new productive well locations in staggered system parallel to the western side of the Khour Tushki area. More applied studies are needed for verification the results of this optimal well location model. Also, this study should be extended to contain more test cases and more comprehensive selection of algorithms including interpolation methods, ad joint methods and hybrid methods.

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