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Sustainable Groundwater Management in El-Moghra Aquifer

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Abstract

The population in Egypt is increased by a very high rate during the last decades, and in order to face this increase, new areas are being reclaimed. Normally the reclamation is mainly depends on groundwater as water resource due to the shortage of any surface water network at this remote areas. In Wadi El-Farigh in Western Desert, thegroundwater is considered the single water resource for the irrigation purposes. Sustainable Water management of this resource is of vital importance for Wadi El-Farigh. Theslight morphologic features of Wadi El-Farigh embolden the development of many reclamation projects in the area. In order to sustain the groundwater in this area, some approaches should be deliberated, such as the demand and supply managing, the efficiency of groundwater usage, reducing the unused water and sustainability of the water usage. For forecasting the fluctuation of the groundwater in El-Moghra Aquifer in the study area(Wadi El-Farigh)due to random reclamation projects, a quasi-three dimensional groundwater flow model was applied in this studyusing the Visual MODFLOW package for planning and managing the groundwater.

The studyresults will show the water usage style in the area either it will be threatened the sustainability of the developmentor not. The maximum groundwater decline will be presented under different proposed policies.

Keywords: Sustainable Groundwater Management, El-Moghra Aquifer, Miocene aquifer, Visual MODFLOW, Wadi El-Farigh, West Delta Egypt.

1. Introduction

In the limited surface water resources areas, the potential of water from rivers or lakes is not sufficient to cover the demand for fresh water. Consequently, the groundwater resources exploitation has greatly increased worldwide in the 2ndhalf of the 20thcentury. Due to the surplus groundwater utilization, its levels have spatially declined all over the world. This fact indicates the misuse of the groundwater. And it has many results for example the water tables induce rising provision costs due to increased energy requirements for water lift. Also, it causes the contamination of the groundwater either natural contamination or due to manmade effects such as the sea water intrusion in the coastal aquifers. These undesired and negative effects resulting from resource exploitation indicated the need for careful management of groundwater systems.

Due to the water scarcity in the MENA region,thegroundwaterin Egypt, especially in the Western Desert, is considered a strategic water resource. The study area located in the western bounds of the Nile Delta occupied an area of about 3600Km^2 (800,000 feddan). After the National Water Resources Plan 2017, the horizontal expansion projects based on the groundwater fromEl-Moghra Aquifer isabout 60,000 feddan the total cultivated area completed by 2004 reaches about 15,000 feddan in the same time the areas under reclamation is about 45,000 feddan.

The purpose of this study is to sense the effect of the previous reclamation projects on the groundwater potentiality in El-Moghra Aquifer, and develop some future policies byapplying a groundwater mathematical model (Visual MODFLOW) to forecast the impacts of these policieson the sustainability of El-Moghra Aquifer.

1.1 Location and climate of the study area

The study area lies between longitudes 30º 00' and 30º 50' E and latitudes 30º 00' and 30º 33' N (Fig. 1)in the western bounds of the Nile Delta, Egypt. It extends from El-Alamin Desert Road at km 126 to the north to km 62 (Cairo-Alex. Desert Highway) in the south, it covers an area of 800,000 Fadden.

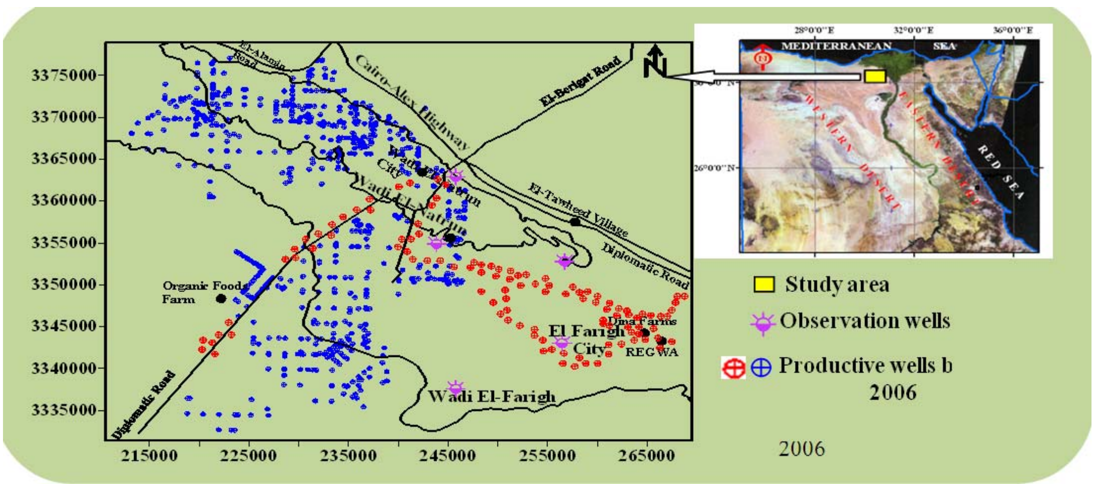

Fig. 1: the Study Area.

It encompasses Wadi El-Farigh, Wadi El-Natrun and adjacent areas. The climate is characterized by a long hot summer and a short warm winter, the amount of rainfall is significant through the year.It can be noticed that most of the rainfall is precipitated during winter time. The mean annual rainfall reaches its maximum values (80.96 mm) while its minimum value is 30.94. While the minimum air temperature is recorded during February with value 6° C, and the maximum air temperature is recorded in August with value 35.7° C.

1.2 The Geomorphological and geological setting of the study area

Many researchers along the past decades discovered the geomorphology and geology of the study area. They concluded that it comprises three geomorphological units namely the Alluvial plains(young and old alluvial plains) which are characterized by an average gradient of 0.l m/km. The elevation varies from +12 m to +14 m for the young alluvial plains, and between 60 m and 20 m for the old alluvial plains. The lowest point in Wadi El-Natrun and Wadi El-Farigh depressions are (-23m and -4m) respectively. The Structural plains (depressions, folded ridges and structural plateaux) which have an elevation ranges between 110 m at Gebal Hamza and 200 m at Abu Roash (the ridges bounding Wadi El-Farigh). The Tablelands which are differentiated into Maryut tableland and marginal tableland. The sedimentary succession in the study area ranges in age from Late Tertiary which is differentiated into Oligocene at 400 m, Miocene at 200 m and Pliocene at 150 m to Quaternary at 300m. The study area also is affected by a number of faults having NW-SE and NE-SW trends (Fig. 2).

1.3 The subsurface hydrology of the study area

The study area consists of three main aquifers namely; The Nilotic sand and gravel (Pleistocene aquifer), Wadi El-Natrun sand and clay (Pliocene aquifer) and El-Moghra quartizitic sand.The present study will focus on El-Moghra Aquifer, according to its high transmisivity and water quality.

The Horizontal and Vertical distributions of the encountered aquifers as well as their inter-relationships are well clarifiedby two cross sections as shown in Fig. 3. Regarding thisFigure, the Pleistocene aquifer exists at the northeast part of the study area to the east of Wadi El-Natrun with thickness range of 65 m to 75 m. The Pliocene aquifer exists at Wadi El-Natrun depression with thickness of 50 m to 70 m. El-Moghra Aquifer exists at Wadi El-Farigh depression to the south and west of Wadi El-Natrun having a thickness of about 100m. The basaltic sheets were detected along the southeastern part of the study area and is considered as the base of El-Moghra Aquifer and as a marker bed separating the overlying Miocene aquifer and the underlying Oligocene aquifer. The faults play an important role in the connections between the different aquifers as well as the direct effect on the saturated zones. The depth to water ranges between zero at the ground surface at Wadi El-Natrun lakes to 180 m from the ground surface to the west of Wadi El-Natrun. Generally, the depth to water increases from Wadi El-Natrun to the other directions. The general trends of the groundwater movement are from east to west, from northeast to southwest, from south to north and from southwest to northwest. The contour lines make a closer around Wadi El-Natrun and reach its minimum level -22 m. This means Wadi El-Natrun depression is recharged from the surrounding aquifers, in other words it acts as a drain for these aquifers.

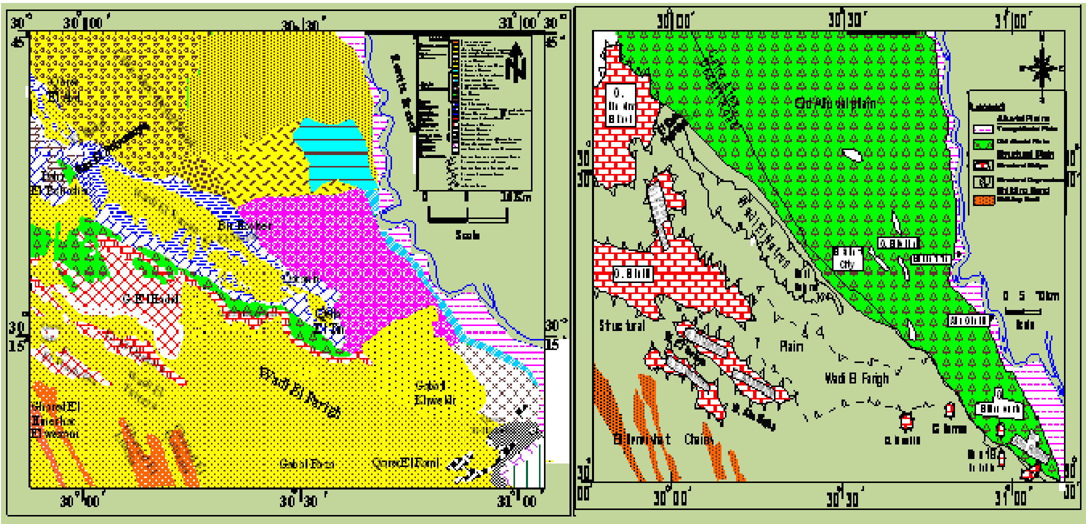

Fig. 2: The different geomorphologic units (right map) and geologic setting (left map) in the study area

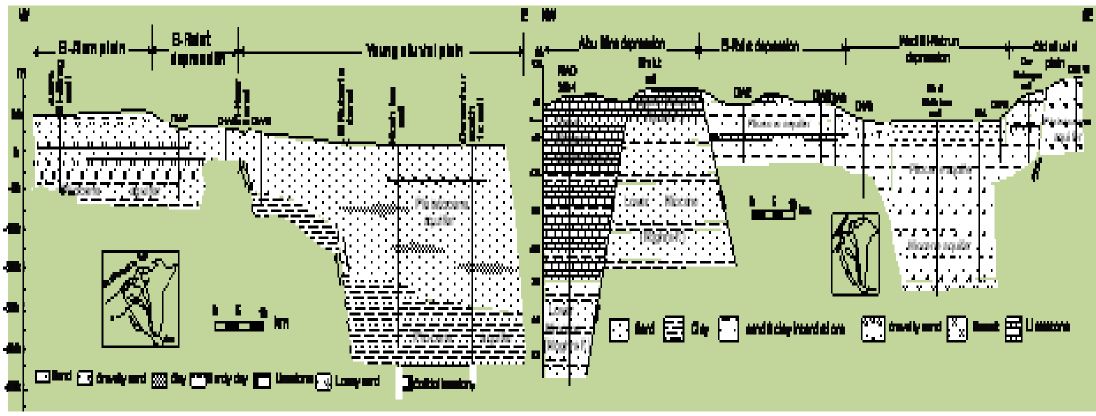

Fig. 3: Hydrogeological cross sections in the E-W and NW-SE directions of the study area

2. Collected Data and Methodology

The data used in this study *were collected from previous studies based on carrying out field trips in West Delta area during the period 2009-2010. Two field trips were achieved by the team work of the Desert Research Center (DRC) to monitor seasonally periodic groundwater level records. The hydrologic data of some of the groundwater wells' sites were obtained during these field trips. In addition, the* archival data such as long term groundwater level records were collected from the DRC library beside the recent records from the team work of the Ground Water Research Institute (GWRI). *The basic hydrologic data of the studied wells were obtained from these field trips databasebeside the data from two data loggers were installed by REGWA team work in the observation wells in north and south of the reclaimed area of Wadi El-Farigh (Table1).*These materials include collection of archival data (well drilling reports, REGWA 2006), 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.

The methodological approach used in this study is based on the mathematical modeling techniques applying visual MODFLOW computer program. Visual *MODFLOWversion 3 is a 3D finite difference based groundwater simulation system. It is initially written by McDonald and Harbaugh (1988).The model is capable of modeling time-dependent flow as well as mass and heat transport problems. The time-dependent data that should be included into the FDM model has to be stored outside in database or GIS systems.* The model describes groundwater flow of constant density under non-equilibrium conditions in a heterogeneous and anisotropic medium according to the following equation (Bear, 1979):

$$\frac{\partial}{\partial x}(k_{xx}\frac{\partial h}{\partial x}) + \frac{\partial}{\partial y}(k_{yy}\frac{\partial h}{\partial y}) + \frac{\partial}{\partial z}(k_{zz}\frac{\partial h}{\partial z}) - w = SS\frac{\partial h}{\partial t} \quad \ldots \qquad 1$$

Where

K_{XX}, K_{yy} and K_{zz} are the hydraulic conductivity along the x, y, and z coordinate axes, (Lt^{-1}); h is the potentiometric head (L); W is a 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). In general, S_S, K_{XX}, K_{yy}, and K_{ZZ} may be functions of space ($S_S = S_s(x,y,z)$, $K_{xx} = K_{XX}(x,y,z)$, etc.) and *W* may be a function of space and time ($W = W(x,y,z,t)$). Equation 1 describes ground-water flow under non-equilibrium conditions in a heterogeneous and anisotropic medium and provided the principal axes of hydraulic conductivity are aligned with the coordinate directions.

This equation was solved using the Adams-Bashforth/Trapezoid rule (AB/TR) predictor-corrector time stepping scheme and best-accurate Galerkin-based formulation no upwinding method and the finite difference technique (Warner, 1987). The budget analyzer in the numerical MODFLOW model computes quantities of fluid masses entering or exiting the simulated region, sub-regions or boundary sections. The balance computation takes into account only gridcells occupied by values for areal recharge or boundary conditions. Under steady state conditions when the total balancing for the entire region is calculated, the imbalance represents a measure for the accuracy of the computations. Characteristics of the groundwater flow mechanism and its spatial and temporal variation, as well as its future behavior, were thoroughly investigated by means of the mentioned numerical model.

3. Construction of the Groundwater Flow Model

The construction of the groundwater flow model of El-Moghra Aquiferrequires the definition of the conceptual model, the model domain with flow boundary conditions and the aquifer material properties.

3.1 Conceptual model of El-Moghra Aquifer

To enable studying groundwater potentiality in Wadi El-Farigh area,the conceptual model of El-Moghra Aquiferhas been constructed as shown in Fig. 4.Based on the geology and the petro physics of the Moghra Formation. Its thickness is about 75 m in the northern portion, 150 m in some localities at Wadi El Farigh, 250 m in Wadi El Natrun and gradually increases northwestward with a maximum thickness of about 900 m at El Qattara Depression. The basaltic sheets are separating the overlying El-Moghra Aquifer and the Daba'a shale Formation, it has variable thickness ranging between 20 to 30 meters and located at different vertical levels.

The hydrogeological system was concerned unconfined and confined of one layer type. The variations of the hydraulic conductivity are resulting from the variation in the saturated thickness through the flow section as well as the variation in the transmisivity resulting from the change in the Potentiometric level.

3.2 Model domain and boundary conditions

The simulation procedure was started by dividing El-Moghra Aquifer domain into a suitable grid pattern on which all the input items are performed via input menus. The total surface area of the model domain reaches 3600 km^2 (60 km in length and 60 km in width). The computational grid for the aquifer domain in the study area is dividedinto 3600 cells (60 columns and 60 rows). The dimension of the cell nodes reaches 1000m for the cultivated and reclaimed areas (Fig. 5).

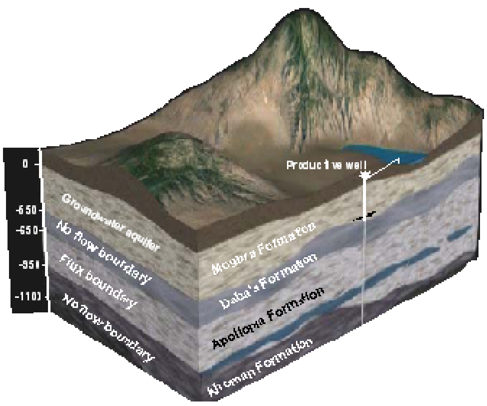

Fig. 4: Conceptual model of El-Moghra Aquifer

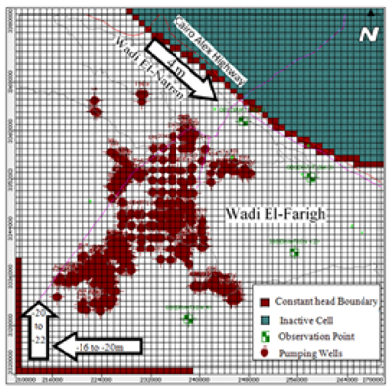

Fig. 5: the model domain grid and the boundary conditions of El-Moghra Aquifer.

The boundary conditions are represented by the outer boundaries which are chosen to be natural boundaries to the system taking into account that the boundaries should be taken remote enough from the effect of wells field to be considered as constant head boundaries. This constant head boundary is assigned in the NW-SE direction parallel to the general fault (F6) which separates El-Moghra from the adjacent Pleistocene aquifer with constant value of 4m a.m.s.l and in the SW direction with variable values ranged between -16 to -22m a.m.s.l. as shown in Fig. 5. 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.

3.3 Aquifer characteristics

The input parameters for El-Moghra Aquifer simulation include aquifer hydraulic parameters (permeability and storage coefficients), aquifer geometry (vertical and areal extent of the aquifer) and aquifer stresses (recharge and discharge). Based on the previous studies and field investigation done by many researchers since the 1960' up-to-date the transmisivity (T) in the study area ranged from 95.04 to 3033.96 m^2/day, while the Hydraulic Conductivity (K) ranged from 9.8 to 77.76 m/day, and the Storativity (S) ranged from $1.2x10^{-4}$ to $7x10^{-3}$

According to the Digital Elevation Model (DEM) files generated by the United States Geological Survey (USGS) based on the topographic maps of Egypt, these files represent the land surface as a matrix (grid) of elevation values at a given space (resolution) apart. The 1:250,000 map series has been converted into 3 arc-second (approximately 90 m) resolution DEMs.DEM data is used in WMS to automatically delineate topography and ground elevation of the model domain (Fig. 6). The depth to impermeable bed (bottom of the aquifer) is used to estimate the aquifer thickness of every cell in the modeled area (Fig. 6).

3.4 Initial hydraulic head distribution

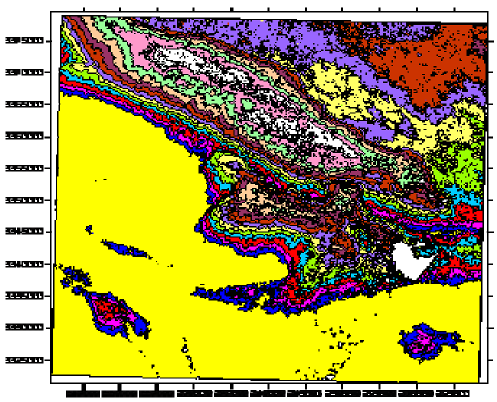

Fig. 6: The topographic contour map of the model domain extracted from Digital Elevation Model (left map) and the depth to aquifer bottom map in msl (right map)

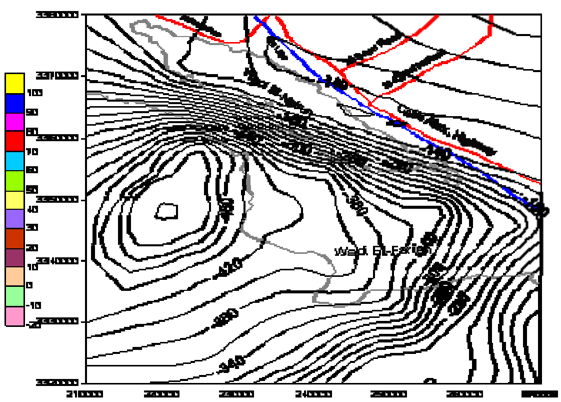

Fig. 7: Initial piezometric head contour map of El-Moghra Aquifer {17}

The water level measurements through thebore hole piezometers in the model domain during March 1991.The pre-development stage) are used to construct a contour map for the initial piezometric head distribution as shown in Fig. 7. The flow field is not particularly complex and denotes to the general trend towards the center of model domain as mentioned before. Gradients are largest along the northern peripheries due to the high pumping stresses and great number of productive wells which are more than in the southern low production areas (almost stagnant).

3.5 Aquifer stresses

The recharge to the modeled aquifer system may be from the Nile Delta area in the East and the Tahrir Province in the north as well as rainfall. The annual estimated rainfall in this arid area can be neglected.The discharge from the aquifer may be from natural discharge represented in the evapotranspiration from Wadi El-Natrun depression and it is neglected. Artificial discharge is mainly through water extraction for the development projects and this is the source of discharge in the model domain.The total annual losses due pumping reaches 569020 m^3/day, from number of wells reached 443 wells.

3.6Calibration and verification of the model

The initial hydraulic parameters such as hydraulic conductivity (K) and specific yield (S) were entered to the model with initial values based on pumping test results from previous studies. These data have very wide different ranges over the modeled area.

3.6.1 Steady state calibration

Once these data entered the model, it was allowed to run. If there is convergence between observed heads and calculated heads, an input data error is present and should be repaired time after time until running process goes successfully.

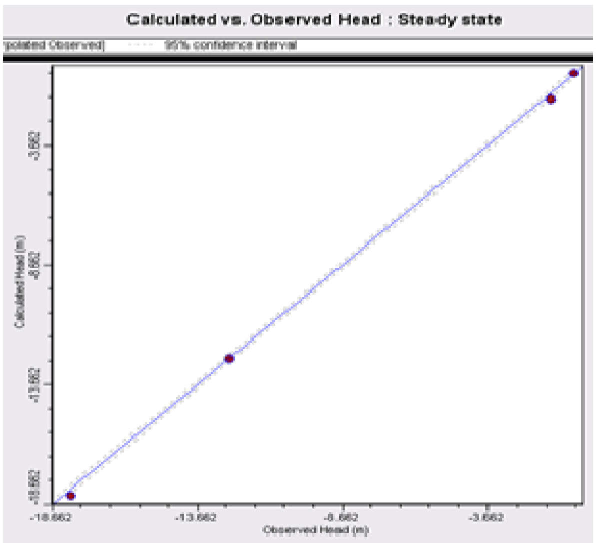

Fig. 8: The calculated vs the observed head for the steady state calibration in El-Moghra Aquifer.

This means that the model succeeds in computing the heads of the aquifer at every cell. As a result, a water level contour map namely calibrated head map is constructed by using these calculated heads. It differs from the map plotted from the actual field head measurements namely observed head map. The relation between the calculated and observed heads is checked every run from the calculated-observed head curve. The variance appears as 19.92 %. This large value indicates great difference between the heads calculated by the model and actually measured heads, thus the calibration process is very essential to minimize this variance to a lower possible value. After many times of changing the K values, the variance between the observed and the calculated heads was minimized to 1.186% as shown in Fig. 8.

3.6.2 Transient state calibration

Transient calibration depends mainly on the good estimation of hydraulic conductivities obtained from the steady state condition. Generally, specific storage for confined aquifer is the main parameter that is changed during the transient calibration. In the process of transient state calibration, specific storage values are modified on a trial and errors basis, until a good match between the observed heads of years 2006 and 2009 and the calculated heads are achieved as shown in Fig. 9. The range of the resulted specific storage after the final calibration of the transient state is found to be varying from 0.027 to 0.135. In general it can be found that, there is good agreement between the observed and simulated head.

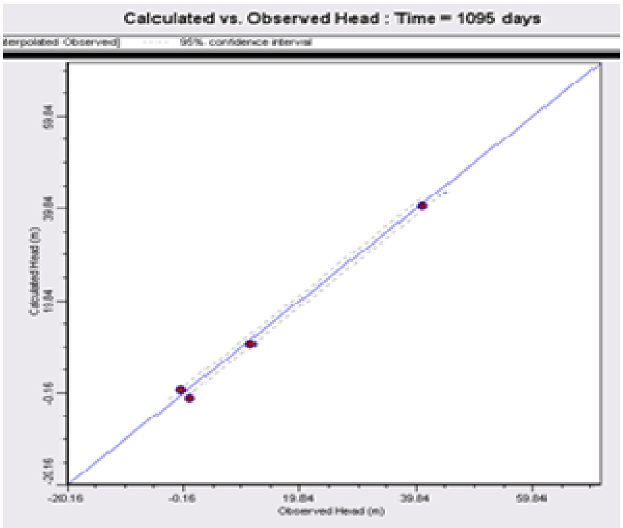

Fig. 9: Calculated versus observed head after transient calibration in El-Moghra Aquifer.

4. The Proposed Policies

After completing the calibration process, the model is ready to simulate the aquifer under different pumping policies. It worth to mentioned that the total number of wells in the study area based on the inventory at year 2006 was 953 wells, but in order to be adequate with grid capacities, and ensuring that discharge is only from El-Moghra Aquifer, the total number of wells were reduced to 443 discharge wells. The developed model is run for every year during the stress period (2006-2050). Evaluation of a development plan represented in certain scenario depends essentially on predicting the groundwater hydraulic heads resulting from presumed discharging rates from existing productive wells. Assuming that the groundwater recharge is variable with values equal to the quantities computed by the predicted run and the groundwater flow through the boundariesof the modeled area remains constant as well,i.e., the neighboring areas to the flow boundary receive an identical development scheme. In case these neighboring areas have intensive discharge from the huge number of wells as in the present condition, the groundwater level will decline and accordingly, the hydraulic gradient will increase, which makes the boundary flow increases towards the modeled area. Several management policies are considered using different discharge rates due to the increasing trend of the reclamation in the modeled area. Taking into account the last assumptions, the following policies are computed to show the predicted groundwater flow conditions till the year 2050. A summary of the different policies applied on the study area to predict the behavior of the groundwater flow in El-Moghra Aquiferpresented in table 1.

Table 1: Policies based on different extraction rates.

Presented Policy	**Extraction Rates (m^3/day)**		
	Policy 1	**Policy 2**	**Policy 3**
Total pumping rate from model domain	569020	0	0
Increasing pumping rate by 20%	0	682824	0
Decrease of pumping rate by 10% (Groundwater depletion or deterioration)	0	0	512119

5. Results and Discussions

The results of the simulation process expose that the implementation impacts of the current development policy have serious impacts on the storage of El-Moghra aquifer. This is detected through the arbitrary five observation points in the model domain as shown in the output maps.

5.1 Results of first Policy

Under the exploitation strategy represented in the first proposed policy with total pumping rate of 569020 m^3/day, the predicted hydraulic head maps for El-Moghra aquifer at year 2015 and 2050 is shown in Fig. 10.

From the output maps of the hydraulic head in the El-Moghra aquifer under existing policy, it is found that; one cone of depression appears in the center of the study area south of Wadi El-Natrun and matches almost the center of the wells distribution in the area with hydraulic head value of about 30m below sea level at 2015. This cone of depression appears in all simulation periods but, the hydraulic head values decrease gradually to reach about 36m below sea level at 2050. This reflects the critical situation that faces the aquifer represented in its quantitative deterioration as a result of the present high pumping rates.

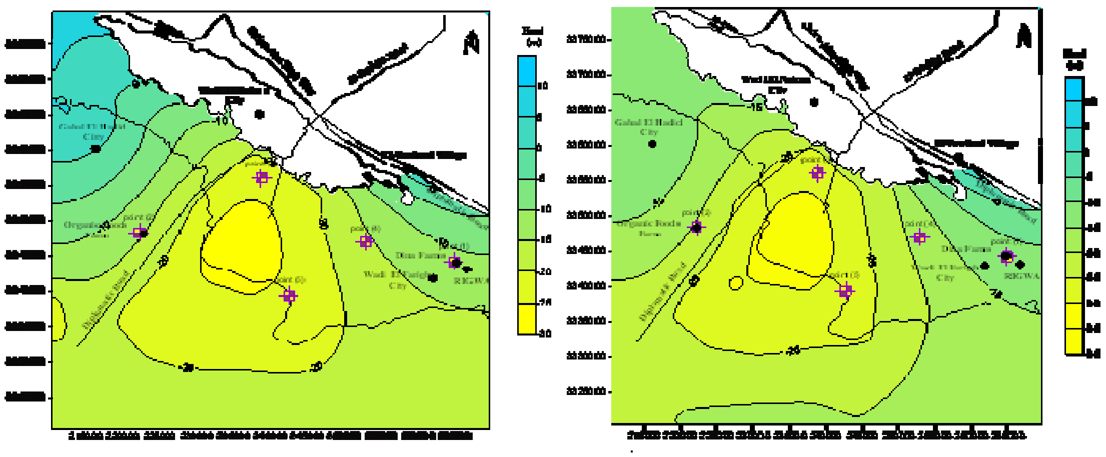

Fig. 10: Predicted hydraulic head applying the 1st policy at 2015(left) and 2050 (right)

From the above figures and from the recorded results at the five observation points, it can be concluded that the hydraulic head decreases with high rate till 2015, then it starts to decline gradually until the end of the simulation period, regarding point 1 Eastern part (Dina Farms) the difference between the hydraulic heads at the beginning of the simulation period and year 2050 is less than 5m this may attribute to being close to the boundary condition which is assumed to be a recharge boundary. Due to its location with respect to the center of cone of depression and in the area of high hydraulic conductivity the hydraulic head in point 5 (central part) reaches its lowest value at the end of the simulation period that means the maximum drawdown value occurred at that point with value 17.23m.

5.2 Results of second policy

Under the exploitation strategy represented in the second proposed policy due to increase of the daily pumping rates for all operating wells by 20%; where the total pumping rate reaches m3/day; the predicted hydraulic head maps for the El-Moghra aquifer are shown in Fig. 11.

From the output maps of the hydraulic head distribution in El-Moghra aquifer under this policy, it is obvious that the same cone of depression occurred in the first policy appeared also in this one, with hydraulic head value of about 32m below sea level at 2015. This cone of depression appears in all simulation periods but the hydraulic head values reduce gradually to reach about 38m below sea level at 2050. This reflects the effect of increasing the pumping rate on the hydraulic head, if it is compared to the first policy.

From the following figures and from the recorded results at the five observation points, it can be concluded that the hydraulic head decreases rapidly at the first nine years then it starts to decrease gradually until the end of the simulation period. Due to the policy of this scenario (increasing discharge with 20%) the decrease in hydraulic head at point 1 Eastern part (Dina Farms) reaches less than 6m which is the minimum drawdown from the whole points, this can be attributed to the same reason as explained in the 1st policy. While the maximum drawdown value occurred at point 5 (central part) with value 21.33m that means the increase in discharge with 20% increases the drawdown with about 4m.

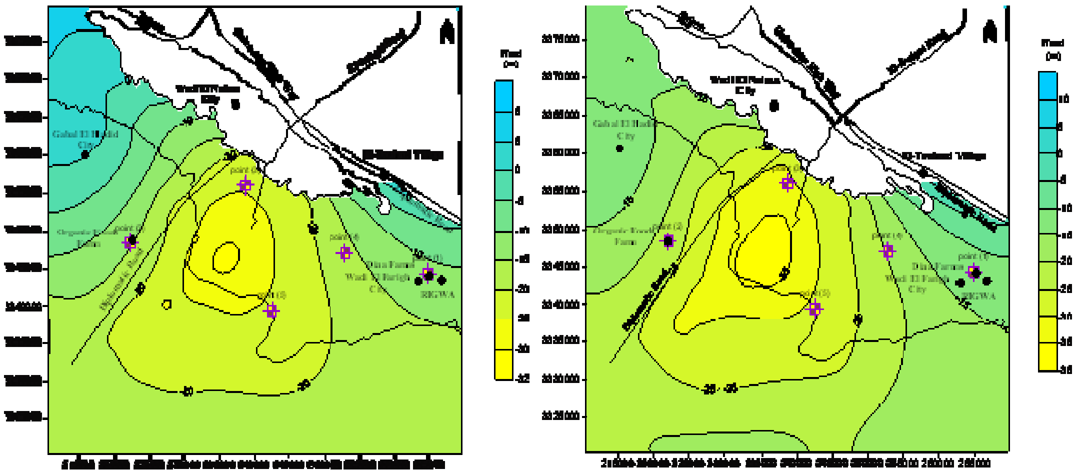

Fig. 11: Predicted hydraulic head applying the 2ndpolicy at 2015(left) and 2050 (right)

5.3 Results of third policy

Under the exploitation strategy represented in this policy by decreasing the daily pumping rate for all operating wells by 10%; i.e. the total pumping rate reaches 540756m3/day; then the predicted hydraulic head maps for El-Moghra aquifer are shown in Fig. 12.

From the output maps of the hydraulic head in El-Moghra aquifer under this third policy, it is evident that the same cone of depression appears as in the previous two policies. The hydraulic head reaches 29m below sea level at year 2015. This cone of depression appears in all simulation periods but, hydraulic head values reduce gradually to reach 32m below sea level at year 2050, which reflects the effect of decreasing the pumping rate on the hydraulic head.

From the above figures and from the recorded results at the five observation points table, it can be concluded that the hydraulic head at all observation points have the same attitude of the 1st and 2nd policy, and the effect of decreasing the discharge resulted in decreasing the drawdown value at point 1 Eastern part (Dina Farms) reach 6.4m which is the lowest value, While the highest drawdown value reach 12.35m at point 5 (central part) due to its location with respect to the center of the cone of depression,that means the decrease in discharge with 10% decreases the drawdown with about 4.88m.

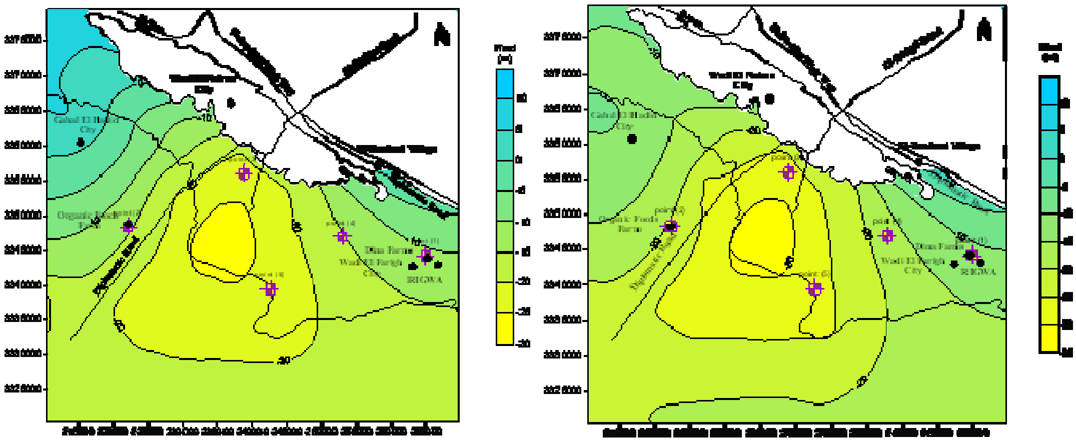

Fig. 12: Predicted hydraulic head applying the 3rd policy at 2015(left) and 2050 (right)

6. Conclusions and Recommendations

From the results obtained from this study it can be concluded that;

- Their direct proportional between the increases of agricultural development depending on groundwater resources and the depletion of El-Moghra aquifer in the study area with the time.
- The problem of over exploitation from the El-Moghra aquifer dominated in the study area resulted in progressive decline of groundwater hydraulic head with value of 21.33m as a worst case scenario in this study, which means that within the simulation period (44years), the average saturated thickness which is less than 100m will decrease by more than 20%. i.e. The hydraulic head in the study area decreases by about 0.5m/year.
- The decreases of groundwater exploitation will definitely lead to the sustainable development of the study areaas a result of the decreases of the drawdown in El-Moghra aquifer.

To conserve the storage of the El-Moghra aquifer for sustainable development from the ground water Resources in the study area, it is recommended that;

- It highly recommended that the decision makers in Egypt, who take care about the ground water potentiality, issue some restricted rules to avoid the depletion of this important source of water in this important area. These rules could include that any intended plan for drilling new productive wells should satisfy the sustainability of the groundwater resources plan in the study area.
- A daily Monitoring system for pumping rate in the area should take place.
- In order to improve the sustainable development in the study area more studies should be implemented regarding the effect of a surface canal in the area on the ground water from the recharge point of view also aiming to decrease the stress on the groundwater in the area.

- In order to detect the critical localities that must be controlled, more detailed local studies should be implemented on the study area after dividing it into small areas in order to determine their individual effect on the aquifer.
- Study the vulnerability of the Miocene aquifer of the study area.
- Study the effect of uncertainty and sensitivity analysis in aquifer hydraulic parameters estimate for groundwater quality management

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