Egy. J. Pure & Appl. Sci. 2020; 58(1):51-61

Egyptian Journal of Pure and Applied Science

Groundwater flow model of the quaternary aquifer in El Khatatba area for water resources management

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ARTICLE INFO

Article history:
Received 2 December 2020
Accepted 2 February 2021

Keywords:
El Khatatba area;
Numerical mathematical model;
North west Cairo.

ABSTRACT

El Khatataba area is considered one of the most important areas of agricultural reclamation area at North West Cairo, Egypt. It depends on the groundwater of the Quaternary aquifer as a major source for human activities and agricultural development. However due to lack of good management of the Quaternary aquifer in the studied area it led to the salinization of groundwater in the wells and drop of groundwater levels in some of wells. The main target of the current research is to construct a numerical mathematical model to represents the present hydrological conditions in the area, and to predict the hydrological situation in the next ten years.The obtained results indicate that the values of hydraulic conductivity vary from 0.5 m/day to 25 m/day, the values of transmissivity coefficient vary between 200m^2/day to 1800 m^2/day, the values of specific yield vary from 0.10 to 0.15, and the values of diffusivity coefficient vary between 1000 m^2/day to 14000 m^2/day. The current model indicates an amount of the extracted groundwater reaches to 97 million cubic meters. The result of water budget indicate a loss in groundwater storage increases up to about 75 million cubic meters for the hydrological year 2019. The seepage from El Rayyah El Nasiri to the Quaternary aquifer in the area reaches about 34 million cubic meters. The leakage from the Quaternary aquifer in the studied area to Wadi El Natrun reaches about 12 million cubic meters through the crossing steep faults. The groundwater levels decrease and increase in the studied area through the ten years water level prediction map.

Introduction

The main purpose of the current study is to construct a numerical mathematical model for the Quaternary aquifer in El Khatatba area aiming a water resources management. Modeling represents a logical approach for assessment of the internal and external hydrological stresses on the groundwater aquifers, as well as the identifying water balance at the time of modeling.

The studied area is located, at North west Cairo **Fig. 1**. It is bounded by longitudes 30° 15' E and 31° 00' E and latitudes 30° 10' N and 30° 30' N. It occupies an area of about 2628 km^2. An inventory of 265 water wells tapping the Quaternary aquifer for El Khatatba area is conducted by the present author **Fig. 2**. The studied area is characterized by over exploitation of groundwater for domestic and agricultural uses. Over exploitation of groundwater in the studied area is leading to continuous quantitative and qualitative deterioration.

Geological and Hydrological Aspects

The Quaternary aquifer extends from Rosetta branch to the east of Wadi El Natrun. It is composed of fluviatile graded sand and gravel intercalated with thin clays. The Quaternary aquifer comprises a structural subsidence area **Fig. 3** [1].

The Pleistocene sediments in the western fringes of the Nile Delta are classified into the following six rock units from older to younger:[2]

1- *El Mansouria gravels*; cover Gebel El Mansouria and Qaret El Haddadin tableland. It consists of ravel intercalated with coarse sands.
2- *El Khtatatba gravels*; lie in the area to the north of El Mansouria gravels till El Sadat City.
3- El Khatatba sands; lie to the east of Gebel El Mansouria, where the unit is directly overlooking the cultivated land facing Manshia Radwan – El Khatatba.
4- El Natrun channel deposits; lie at the northern edge of Wadi El Natrun.
5- El Debba gravels; extend from El Sadat City to the southern border of the stabilized dunes.
6- El Debba sands and muds; situated to the east of El Debba gravel close to El Tahrir province.

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In the current study, two longitudinal and traversal hydrogeological cross-sections (B – B') and (A – A') are constructed **Fig. 4** and **Fig. 5**. They are constructed to include the studied area in order to delineate the different hydrogeologic rock units, the lateral and vertical extensions of the Quaternary aquifer and fancies changes. Such cross sections are constructed according to the lithological logs of some wells tapping the Quaternary aquifer. From the hydrogeological cross-sections **Fig. 4** and **Fig. 5** and the saturated thickness map **Fig. 6**, The following remarks can be identified:

1- The main water bearing formation in the studied area is the Quaternary rock units. The groundwater in the aquifer exists under unconfined conditions.

2-The Quaternary aquifer rests unconformably on the clay sheets of the Pliocene tme. Quaternary deposits consist of gravels and sands intercalated with clays.

3- Different steep faults are defined as (F_1, F_2, F_3 and F_4). They have prominent effect on the hydrological regime of the Quaternary aquifer in the studied area.

4- The saturated thickness of the Quaternary aquifer ranges from 20 m to 60 m in the western part and from 20 m to 40 m in the eastern part. While it ranges from 20 m to 70 m in the middle area.

Materials and Methods

- Data were measured directly during field investigation in June 2018 and June 2019, in addition to other complementary data from last studies. MODFLOW software was used to develop the numerical model and SURFER software was used for preparing model input data and visualizing output data.
- Theoretical identification for the water flow in unsteady state presented by equation (1), numerical solution especially (finite difference methods) is used to state flow problems.
- SIP (Strongly Implicit Procedure) was chosen as a solver for this model.
- Try and error method for calibration was used.
- Liner correlation coefficient was used to verity the calibration results.
- Equation (6) was used for calculating error percentage of the water balance.

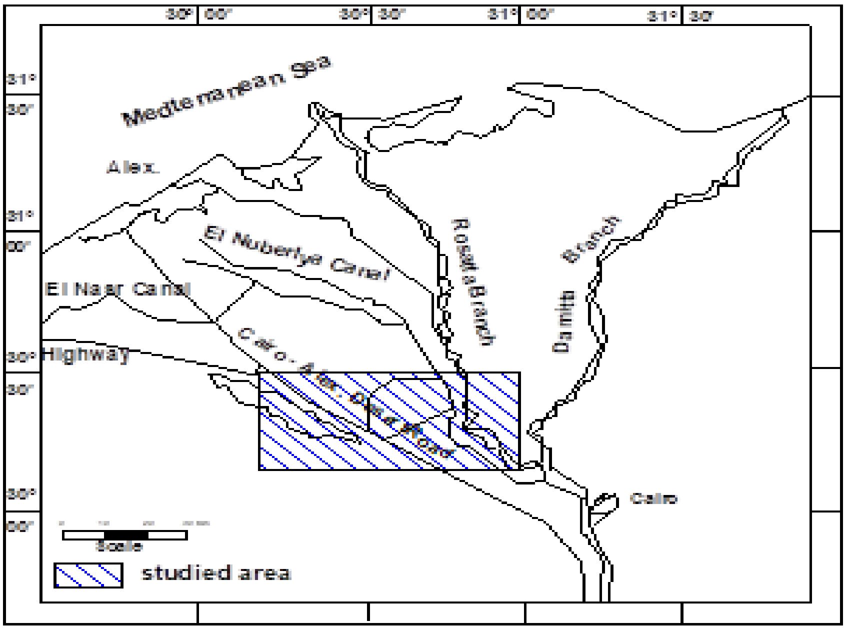

Fig. (1): Location Map of El Khatatba area, Egypt

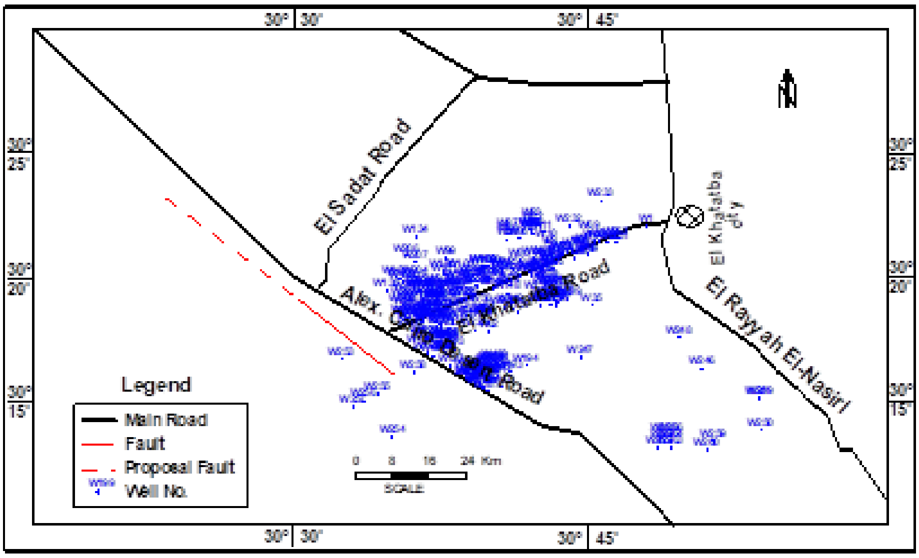

Fig. (2): Well Location Map of Quaternary aquifer, El Khatatba area, Egypt.

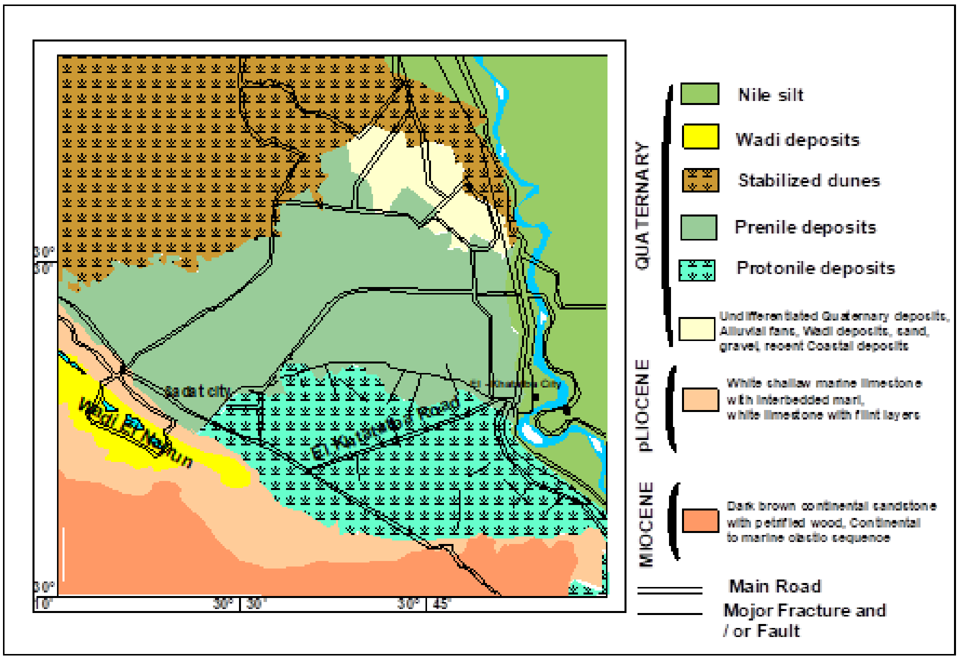

Fig. (3): Geological Map of the study area, (after[3])

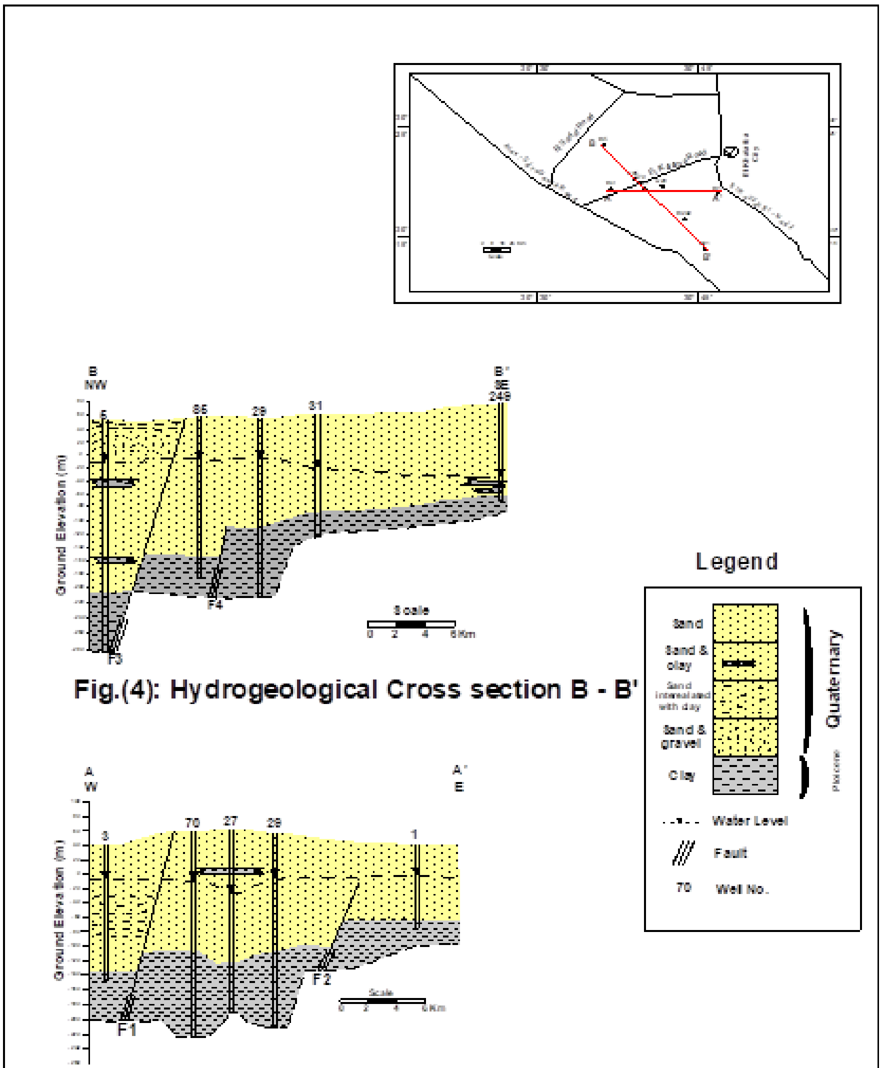

Fig.(4): Hydrogeological Cross section B - B'

Fig.(5): Hydrogeological Cross section A - A'

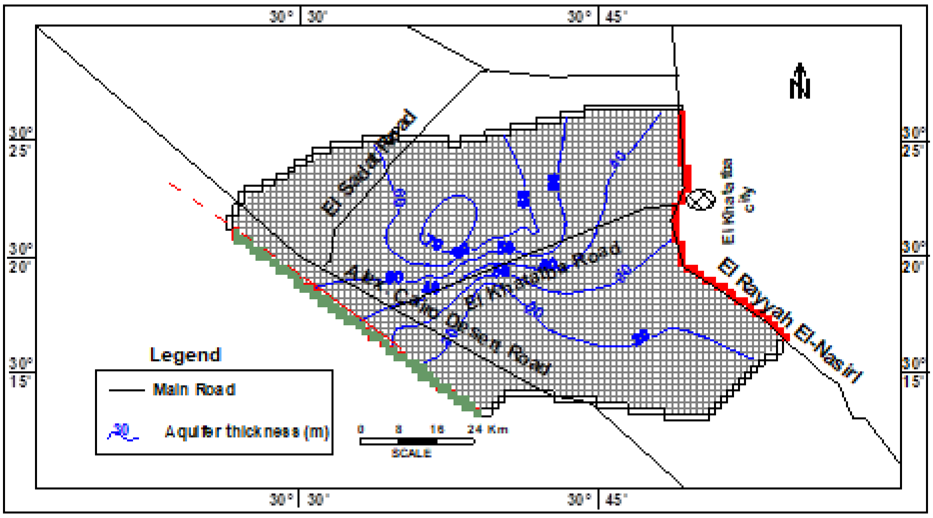

Fig. (6): Isopach Map of the saturated thickness of the Quaternary Water Bearing Rock Unit, El Khatatba area, Egypt.

Results and Discussion

Description of the Constructed Numerical Model

The current model is a sort of hydrological flow model. It is constructed by appling Modflow software [4]. The model is applied for the area of 655 Km^2 with regular square cells grid (140 columns and 73 rows).

Conceptual Model.

The conceptual model is developed to define the hydrogeological and hydrological stresses and boundary conditions of the Quaternary aquifer in the studied area. Such model is designed to represent the following conditions **Fig. 7**:

- The local recharge of the Quaternary aquifer takes place through lateral seepage of water from El Rayyah El Nasiri in the eastern part and discharges by lateral flow to Wadi El Natrun in the western part. No flows are adopted in the northern and southern parts.
- The Quaternary aquifer consists of gravels and sands with interclations of clays, and rests on the Pliocene clay layer.
- The boundary conditions in the studied area can be reported as follows:

The Quaternary aquifer extends downward from land surface and rests on the Pliocene clays layers. A constant head boundary exists in the eastern parts of El Rayyah El Nasiri, no flow boundaries are existed at the southern and the northern parts. A general head boundary exists at Wadi El Natrun in the western part.

Design and Preparation of Groundwater Flow Model

The construction of the groundwater flow model was carried out by applying MODFLOW software program [4]. It is governed by three dimensional parabolic partial differential equations for transient state (non equilibrium equation):

$$\frac{\partial}{\partial x}(Kxx\frac{\partial h}{\partial X})+\frac{\partial}{\partial y}(Kyy\frac{\partial h}{\partial y})+\frac{\partial}{\partial z}(Kzz\frac{\partial h}{\partial z})\pm W=Ss\frac{\partial h}{\partial t} \quad (1)$$

Where:-

Kxx, Kyy and Kzz are the values of hydraulic conductivities along the x, y and z coordinate axes, which are assumed to be parallel to the major axes of hydraulic conductivity (m/day).

h : is the potentiometric head (m).

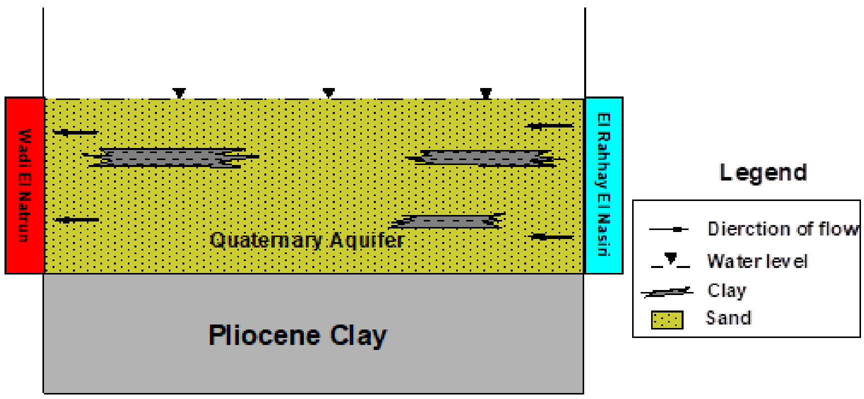

Fig.(7): Conceptual Model for the Quaternary Aqufifer, El Khatatba area, Egypt.

W: is a volumetric flux per unit volume and represents sources and or sink of water (m^3/day).
Ss: is the specific storage of the porous material (dimensionless).
t : is the time (day).
The groundwater flow model is designed with regular square cells grid, where the dimensions of each cell is 500 m x 500 m for an area of 655km^2 **Fig. 8**. The requied data for the numerical model for the studied area are collected from the field. It is prepared by appling the following:

1- SURFER software is used for compiling the mapps and model input preparation.
2- MODFLOW software is used for modeling and running the model.

Calibration and Running Groundwater Folw Model

The groundwater flow model was calibrated for steady and transient time states. As for the steady state, the groundwater levels (as depicted at June 2018) **Fig. 9** are used for the initial conditions and the groundwater levels (for June 2019) are used for the final conditions. Different runs are carried out for adjusting the values of the hydraulic conductivity in order to approximate the calibrated data of groundwater levels of the water bearing formations in the studied area to the measured field data (observation data).
Twenty water points are selected at different locations for the calibration of the model **Fig. 10** and **Table 1**. The model was run using such data. It has been found that there are discrepancies between the measured field data and the computed ones for the water levels (for June 2019). Some changes in the values of the hydraulic conductivity were performed in order to attain better coincidence of groundwater levels.
In the transient simulation, the model is calibrated using specific yield and the data of 12 months for water level, discharge of wells, and general head boundary for the year 2019.

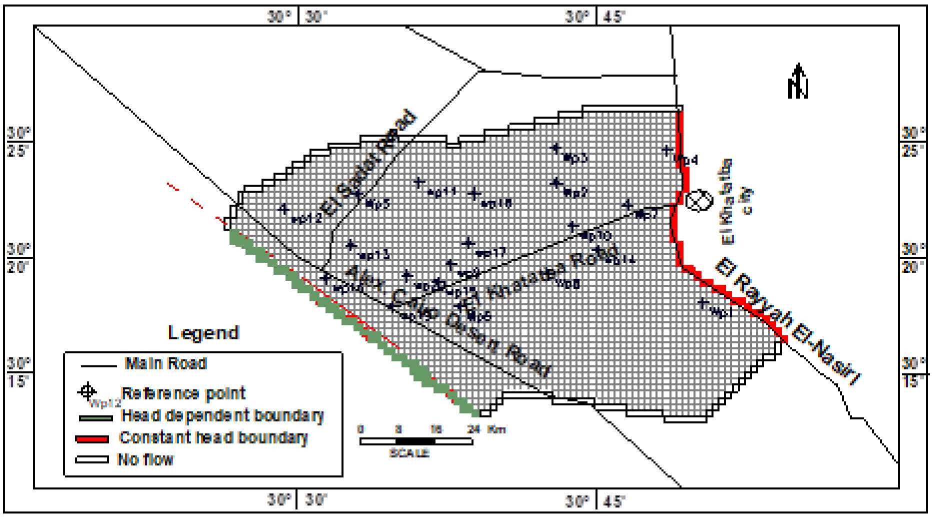

Fig. (8): Mathematical Model Network and Boundary conditions of the Quaternary aquifer, El Khatatba area, Egypt.

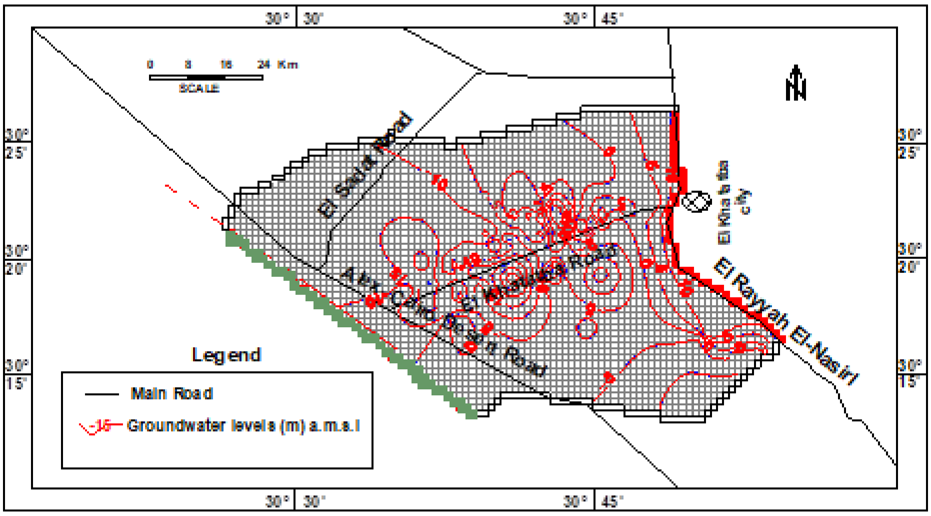

Fig. (9): Water Table Contour Map of the Quaternary aquifer (June 2018), El Khatatba area, Egypt.

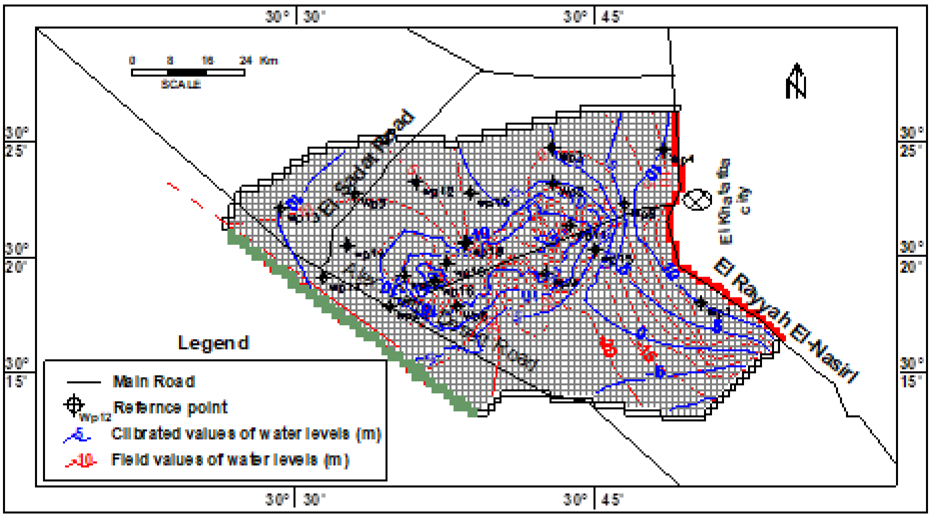

Fig. (10): Groundwater Level Contour Map of the Qautemary aquifer (June 2019), Unsteady State Calibrated Run, El Khatatba area, Egypt.

Table 1: Field measurements and predicted groundwater level (June 2019) El Khatatba area, Egypt

Water Points	***Model Row***	***Model Column***	***Observed head (H_0)***	***Calculated head (H_c)***	***Residual (H_0 - H_c)***
Wp1	107	45	10.47	11.27	**-0.80**
Wp2	83	26	-5.13	-5.40	**0.28**
Wp3	83	20	-0.15	0.13	**-0.27**
Wp4	101	21	10.26	9.25	**1.00**
Wp5	51	28	-9.01	-10.11	**1.10**
Wp6	68	46	-14.71	-15.60	**0.89**
Wp7	95	30	6.82	6.97	**-0.15**
Wp8	82	40	-16.39	-15.10367	**-1.29**
Wp9	66	39	-16.45	-16.69	**0.24**
Wp10	86	33	-16.94	-13.98	**-2.96**
Wp11	61	26	-7.23	-7.54	**0.31**
Wp12	39	30	-10.01	-9.87	**-0.14**
Wp13	50	36	-9.15	-12.45	**3.30**
Wp14	90	37	-4.99	-5.72	**0.73**
Wp15	64	42	-21.03	-20.11	**-0.93**
Wp16	46	41	-9.60	-11.55	**1.95**
Wp17	70	36	-9.03	-7.44	**-1.59**
Wp18	70	28	-5.45	0.46	**-5.91**
Wp19	57	46	-8.74	-11.26	**2.52**
Wp20	59	41	-15.78	-14.00	**-1.78**

In general head boundary, the hydraulic conduction is calculated from the following equation:

$$CR = T\frac{\emptyset}{\text{Ꞔ}} \qquad (2) \text{ (modified after[5])}$$

Where:

T: Transmissivity coefficient (m^2/day)

CR: Is the hydraulic conductance (m^2/day)

Ø: Is the effective porosity of the sedimentary or any rock materials
(dimensionless)

Ꞔ: Is the tortuosity (dimensionless)

The match between the model responses and field observations may be examined qualitatively in the preliminary stages of the calibration process using contour maps of calculated head and observed head. However, after the initial runs are completed, some statistical measure of goodness of fit should in general be used for more quantitative comparison and assessment. Several basic statistical measures of goodness of fit are used such as linear correlation coefficient [6]:

The linear correlation coefficient (r), is defined by the following equation:

$$r = \frac{\sum_{i=1}^{N}\left(Cal_i - \widetilde{Cal}\right)\left(Obs_i - \widetilde{Obs}\right)}{\sqrt{\sum_{i=1}^{N}\left(Cal_i - \widetilde{Cal}\right)2\sqrt{\sum_{1=1}^{N}\left(Obs_i > \widetilde{Obs}\right)2}}} \qquad (3)$$

Where, $\widetilde{Cal}$ & $\widetilde{Obs}$ are the means of calculated and observed values respectively. In the current study, the linear correlation coefficient (r) equals 0.974, which means a strong significant correlation.

As a result of such calibration, the hydraulic parameters of the Quaternary aquifer in the studied area were depicted as follows:

1- Hydraulic conductivity (K)

Hydraulic conductivity distribution map **Fig. 11** is plotted based on the model calibrated data. It indicates that the value of hydraulic conductivity of the Quaternary aquifer in the studied area ranges from 0.5 m/day in the middle area to 25 m/day in the North western part of the area.

2- Transmissivity coefficient (T)

The values of transmissivity coefficient (T) are also computed by multiplying saturated thickness of the Quaternary aquifer for each cell and the hydraulic conductivity. **Fig. 12** shows the distribution map of the transmissivity coefficient values of the Quaternary aquifer. They range from 200m^2/day to 1800m^2/day.

3- Specific Yield (Sy)

The Specific Yield distribution map **Fig.13** is plotted based on the values obtained from the unsteady state calibrated run. The values range from 0.10 to 0.15.

4- Diffusivity coefficient (A)

The diffusivity coefficient is computed as a function of the transmissivity and specific yield by the following equation;

$$A = T / Sy \qquad (4)$$

The values of the diffusivity coefficient are obtained from the unsteady state calibrated run. The values of this parameter range from 1000 m^2/day to14000 m^2/day **Fig. 14**.

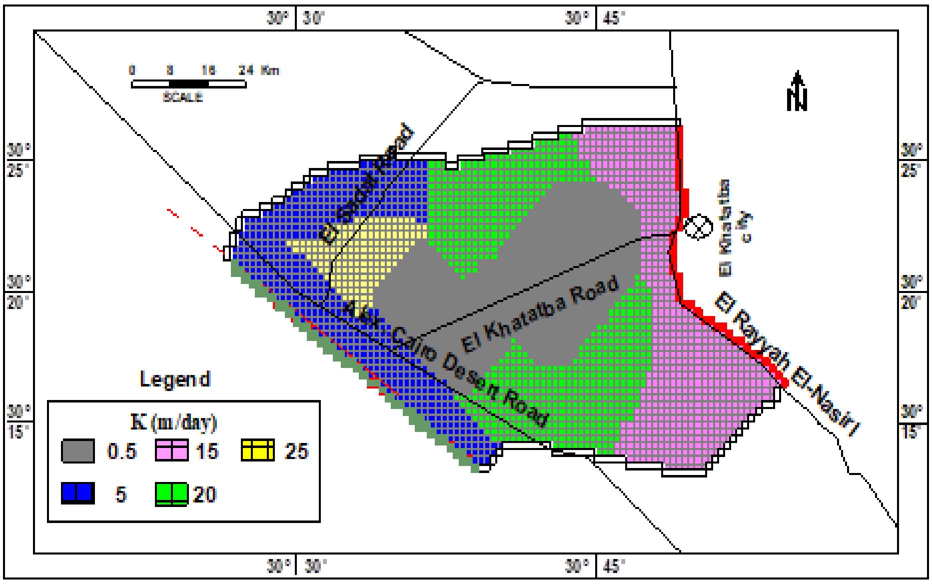

Fig. (11): Hydraulic Conductivity Coefficient Distribution Map of the Quaternary aquifer, (Unsteady State Calibrated Run), El Khatatba area, Egypt.

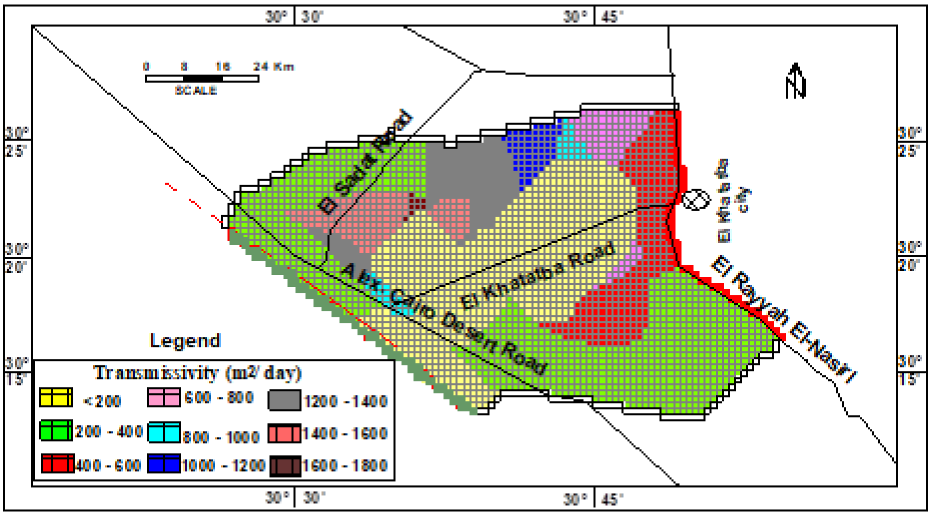

Fig. (12): Transmissivity Distribution Map of the Quaternary aquifer, (Unsteady State Calibrated Run), El Khatatba area, Egypt.

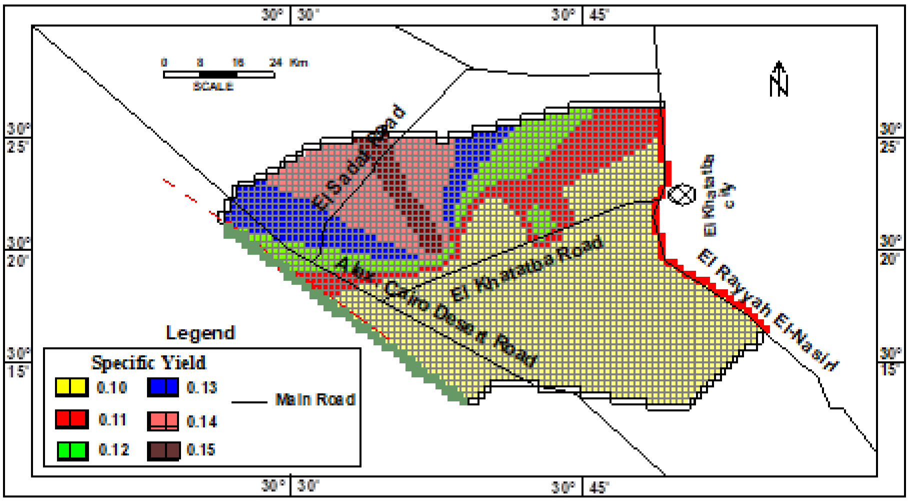

Fig. (13): Specifi Yield Distribution Map of the Quaternary aquifer, (Unsteady State Calibrated Run), El Khatatba area, Egypt.

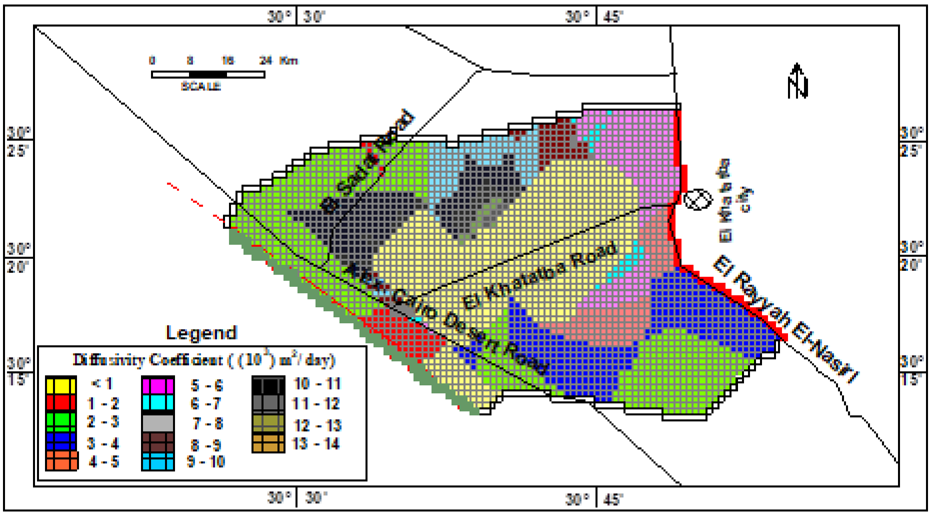

Fig. (14): Diffusivity Coefficient Distribution Map of the Quaternary aquifer, (Unsteady State Calibrated Run), El Khatatba area, Egypt.

Water Balance

The water balance of the Quaternary aquifer in the studied area is calculated by applying MODFLOW software. In this stage of work, the term "discharge" means "pumped water from the Quaternary aquifer". Where,

The change in the groundwater storage = subsurface water flow from boundaries + discharge. (5)

The percentage error (D) of water balance is calculated according to the following equation[7];

$$D=\frac{100(In-Out)}{(In+Out)/2} \qquad (6)$$

Where;

In : is the total inflow to the system.

Out : is the total outflow from the system.

D : is the percentage error term.

Considerably, if the model equations are correctly solved, an error around 1% is usually considered acceptable [8].

Present Situation

Water budget for the hydrological year (June 2019) is computed as follows in **Table 2**.

$\sum$Input elements - $\sum$output elements = $\pm\Delta$ storage

(34.13×10^6(in)) - (109.61×10^6(out)) = $75.49 \times (10)^6$ m^3/year (storage).

An expected Loss of 75.49 million cubic meters per year in the groundwater storage is recorded, while an amount of 96.87 million cubic meters per year of groundwater is extracted. El Rayyah El Nasiri contributes to the groundwater storage by about 33.61 million cubic meters into the Quaternary aquifer. A leakage of about 12.23 million cubic meters from the Quaternary aquifer to Wadi El Natrun during the hydrological year 2019 is computed. From equation (6) the percentage error for the current scenario equals 1%.

Prediction of The Hydrological Situation

Two scenarios were assumed for determining possible management policies of the Quaternary aquifer.

First Scenario:

The groundwater flow model, which have been built for the studied area was run yearly for ten years prediction period in order to detect the future hydrological situation. **Table 3** and **Fig. 15** represent the results of the prediction.

Table 2 : The Water Balance of the Quaternary Aquifer (June 2019) ($(10)^6$ m^3 / year), the present scenario, El Khatatba area, Egypt.

Elements	Inflow	Outflow	Resultant
Constant head	33.98	0.37	33.61
Pumped Water		96.87	-96.87
Head dependent boundary	0.14	12.37	-12.23
Sum	34.13	109.61	-75.49
Loss in the groundwater storage =			***75.49***

Table 3 : The Water Balance of the Quaternary Aquifer for ten years prediction ($(10)^6$ m^3 / year), the second scenario, El Khatatba area, Egypt.

	Inflow	Outflow	Resultant
Constant head	31.22	0.35	30.87
Pumped Water		91.84	-91.84
Head dependent boundary	0.11	8.90	-8.79
Sum	31.33	101.09	-69.76
Loss in the groundwater storage =			***69.76***

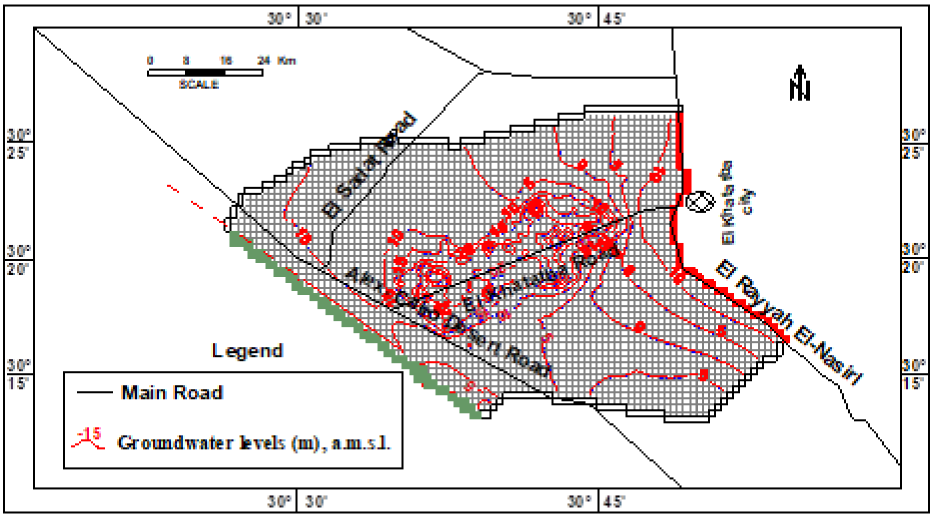

Fig. (15): Water Table of the Quaternary aquifer (June 2029),the first scenario, El Khatatba area, Egypt.

∑Input elements - ∑output elements = ± Δ storage

$(31.33\times10^{6}(in)) - (101.09\times10^{6}(out)) = -69.76\times(10)^{6}\ m^{3}/year\ (storage)$.

The result of ten years prediction for this scenario indicate a loss in the groundwater storage of about 69.76 million cubic meters per year with an amount of groundwater extraction equals 91.84 million cubic meters per year. Droping and rising of groundwater levels through these ten years prediction are represented in **Fig. 16**. From equation (6) the percentage error for the current scenario equals 1%.

Second Scenario:

In this scenario the amount of groundwater extracted were assumed to decrease by about 47.7million cubic meter per year. This scenario is illustrated by **Table 4** and **Fig. 17**.

∑Input elements - ∑output elements = ± Δ storage

$(33.46\times10^{6}(in)) - (60.42\times10^{6}(out)) = -26.96\times(10)^{6}\ m^{3}/year\ (storage)$.

According to this scenario, a loss of the groundwater storage for about 26.96 million cubic meters per year in the studied area was expected.

Conclusion

El Khatatba area is built up of sedimentary rocks belonging to the Quaternary time. The main water bearing formation in the studied area is the Quaternary aquifer. The groundwater exists under unconfined conditions. The Quaternary aquifer rests unconformably on the clay sheets of the Pliocene time. Quaternary deposits consist of gravels and sands intercalated with clays, and the saturated thickness ranges from 15 m to 70 m. The local recharge of the Quaternary aquifer takes place through lateral seepage of water from El Rayyah El Nasiri in the eastern part. A lateral leakage from the Quaternary aquifer to Wadi El Natrun in the western part is recorded. No flow is adopted in the northern and southern parts. The results of a numerical mathematical model indicates that the hydraulic conductivity values vary from 0.5 m/day to 25 m/day, the transmissivity coefficient values vary between $200m^{2}$/day to 1800 m^{2}/day, the specific yield values vary from 0.10 to 0.15, and the diffusivity coefficient values vary between 1000 m^{2}/day to 14000 m^{2}/day. Two scenarios were proposed using the groundwater flow model. The second scenario is recommended.

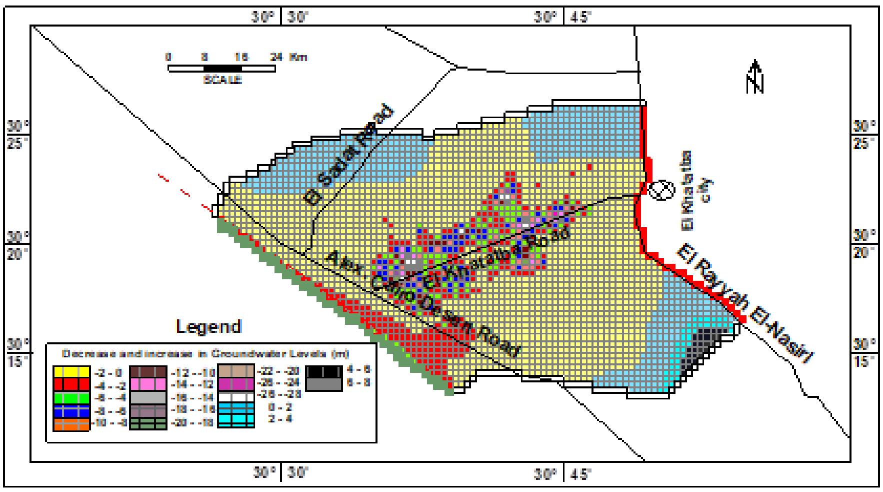

Fig. (16); Decrease and increase in Groundwater Levels of the Quaternary Aquifer for ten years prediction (Unsteady State Prediction), El Khatatba area, Egypt.

Table 4: The Water Balance of the Quaternary Aquifer for the hydrological year $((10)^6\ m^3/year)$, the second scenario, El Khatatba area, Egypt.

Elements	Inflow	Outflow	Resultant
Constant head	33.32	0.42	32.90
Pumped Water		47.70	-47.70
Head dependent boundary	0.14	12.31	-12.16
Sum	33.46	60.42	-26.96
Loss in the groundwater storage =			***26.96***

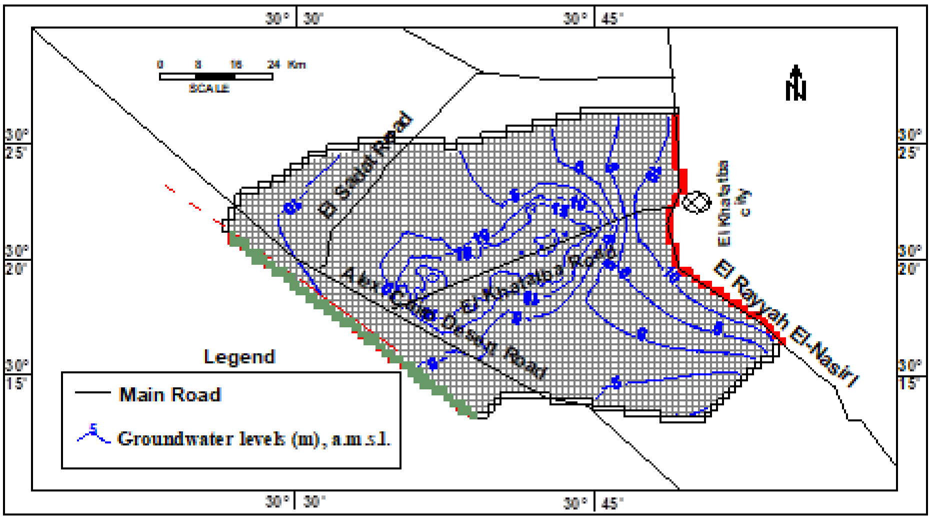

Fig (17): Water Table Map of the Quaternary aquifer, the second scenario, El Khatatba area, Egypt.

Recommendations

1- Drilling more wells should be prevented in the studied area especially in middle area.

2- Salts transport model is suggested depicting the deterioration in the groundwater quality in the area.

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