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Ensuring sustainable development through groundwater management, area one, south western desert, Egypt

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Article Info	ABSTRACT
	Darb El-Arbeain area lies between long. 29o 00/ and 31o 00/ E and lat. 22o 00/ and 24o 30/ N. It is divided into three separate areas; The northern part extends 90 km to the south from Paris town and has an area of 90 km2. In this study four suggested scenarios of pumping rates have been explored to fit with the Egyptian ministry of irrigation using the three dimensional finite difference flow model (MODFLOW) to simulate the flow system. These scenarios include: first, model will run with abstraction from the aquifers equal 110 %, 180%, 280%, and 370% of calculated initial recharge. Results indicate that the second scenario has the most economic scenario on the area. The fourth scenario caused the highest increase of drawdown values which should be avoided.

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1. INTRODUCTION

The groundwater represents the main resource of water in an arid region for farmers along about 400 km from Paris town towards the Egypt–Sudan border. The annual rainfall is less than 1.1mm. The aquifer thickness in northern parts ranges between 211 m and 294 m, the aquifer thickness increases to the northern part. The Nubian sandstone aquifer in the area of study is capped by a confining bed (Dakhla Formation) and underlain by basement rocks. The hydraulic conductivity ranges between 2.76 m/day and 1.99 m/day, and transmissivity ranges between 233 m^2/day and 652 m^2/day.

2. METHODOLOGY
2.1. Description of the Study Area

In [1] is subdivided into three geomorphologic units, the southern Naklai-Shebpene-plain; the western at murpene plain; and a plateau surface [2]. The litho-stratigraphic successions are divided into seven units, from base to top [3-7]: 1) Pre-Cambrian basement 2) Paleozoic-Mesozoic sandstone; 3) Lower Cretaceous; 4) Upper Cretaceous; 5) Paleocene; 6) Eocene; and 7) Quaternary. Darb El-Arbaein area is related structurally to the Red Sea and south western regions (EGSMA 1987a and b). [1] has identified the faults in E-W, NE-SW and NW-SE and three anticlines) [8, 9]. The stored water in Nubian sandstone is mainly fossilized water and ranges from20000 to 40000 y. Darb El Arbeain map is shown in Figure 1.
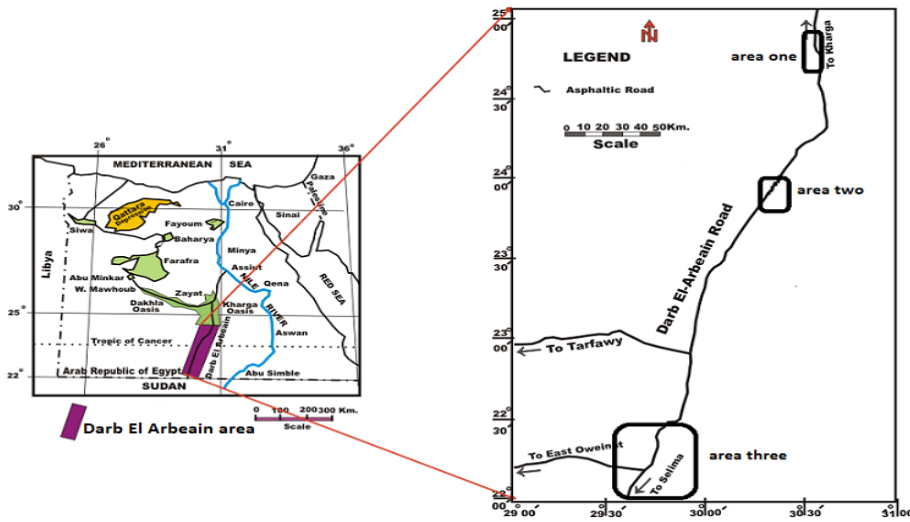
Figure 1. Darb El Arbeain map

2.2. Model Description and Calibration for Northern Area

The Governing Partial Differential Equation, for a confined aquifer used in MODFLOW is (WHI):

$$\frac{\partial}{\partial x}\left[K_{xx}\frac{\partial h}{\partial x}\right] + \frac{\partial}{\partial y}\left[K_{yy}\frac{\partial h}{\partial y}\right] + \frac{\partial}{\partial z}\left[K_{zz}\frac{\partial h}{\partial z}\right] + W = S_S\frac{\partial h}{\partial t} \tag{1}$$

Where; K_{xx}, K_{yy} and K_{zz} are the values of hydraulic conductivity along the x, y, and z coordinate axes (L/T), h is the potentiometric head (L), W is a volumetric flux per unit volume representing sources and/or sinks of water, where negative values are extractions, and positive values are injections (L^3T^{-1}), S_S is the specific storage of the porous material (M^{-1}); and t is time (T).

For The Steady Flow InPorous Anistropic Saturated Medium, subsitution of Darcy law for v in x, y and z direction yields to;

$$_x\ (\mathbf{K_x}\ \partial\mathbf{h}/\partial\mathbf{x}\ ) + \partial/\partial_y\ (\mathbf{K_y}\ \partial\mathbf{h}/\partial\mathbf{y}\ ) + \partial/\partial\mathbf{z}\ (\mathbf{K_z}\ \partial\mathbf{h}/\partial\mathbf{z}\ ) = 0\qquad \partial/\partial \tag{2}$$

for the isotropic medium ; $K_x = K_y = K_z$ and for homogenious medium K (x,y,z) = constant.

Trsnsit Flow Conservation Law In Asaturated Porous Medium, The net rate of fluid mass into any element control volume = the changes time rate in the stored fluid mass within the element, and continuity equation will be;

$$(\ \text{-}\ \partial\ (\boldsymbol{\rho}\ \mathbf{vx})/\ \partial\ \mathbf{x}\ ) - (\partial\ (\boldsymbol{\rho}\ \mathbf{vy}\ )/\ \partial\ \mathbf{y}\ ) \text{-}\ (\partial\ (\boldsymbol{\rho}\ \mathbf{vz})/\ \partial\ \mathbf{z}\ ) = \mathbf{n}\ (\ \partial\boldsymbol{\rho}/\partial\mathbf{t}\ ) + \boldsymbol{\rho}\ (\ \partial\ \mathbf{n}/\partial\mathbf{t}\ ) \tag{3}$$

Where; n ($\partial\rho/\partial$t); the effect of density (ρ) chages on the expansion of the produced water mass rate, which is controlled by fluid compressibility β. And ρ (∂ n/∂t) ; the effect of the porous medium compaction due to changes of porosity n, which is controlled be the aquifer compressibility α.

2.3. Initial Model Input (First Assumption);

The hydraulic conductivity; Kx = Ky = 3.07 m/day Kz = 0.307 m/day, no of aquifers; 1 divided into 4 layers), no of rows = 100, no of columns = 183 (each cell is 60*60 mt), Average Specific storativity= 0.0001 m-1, Average total porosity = 0.3, average effective porosity = 0.15, Piezometric level; (Figure 2), currently average pumping rates of the wells is 1700 m3/ day. Boundary conditions (Figure 3); the western boundary; consist 2 segments, line a-b represent constant head 73 mt, mean while line from b-c represents 88 mt. the eastern boundary; line d-e represent constant head 58 mt, and line e-f represent Constant head 70 mt. the northern and southern parts represent no flow boundary. calibration (Figure 4) involved comparison of the model results and observed heads at 22 observation points (taken from pumping wells) from a piezometric head map to run in a steady state simulation, once the model calibrated, the calculated hydraulic heads were used as initial heads for the transient flow scenarios.
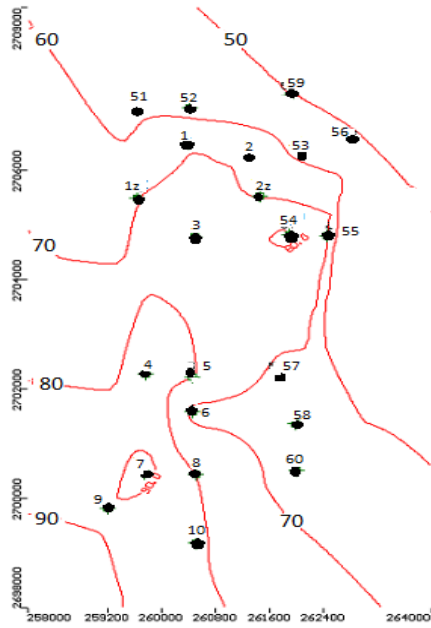
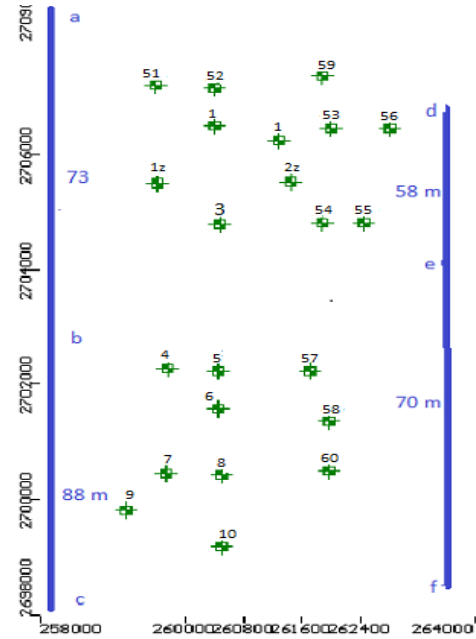Figure 2. Piezometric levels in area one, Darb El Arbeain

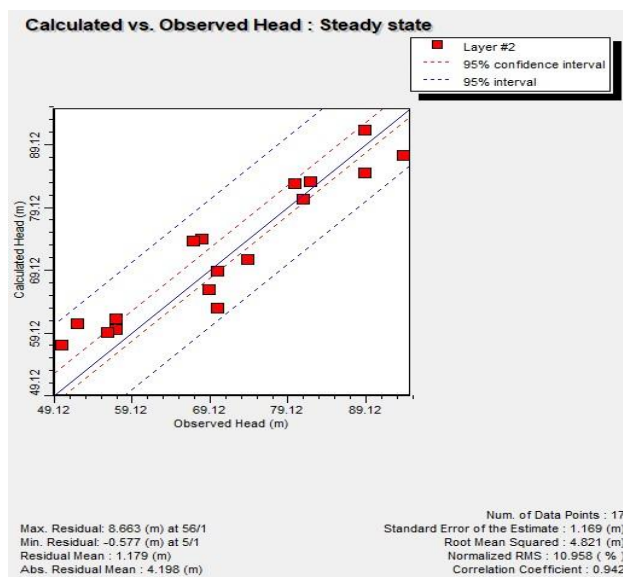Figure 3. Boundary condition heads in area one, Darb El Arbeain

Figure 4. Calibration result to area one, Darb El Arbeain

3.   RESULTS

Managing water supply in any area depends on reaching the equilibrium state where maximum drawdown achieved [10-16]. Introducing new concept called; the aquifer respond, which could be defined as the average maximum drawdown in the aquifer when reach the equilibrium state and drawdown stay without any change under pumping conditions. The drawdown stabilizing means the volume of water exploited equal the recharge rate or $Q_{out} = Q_{recharge}$. The average maximum expected drawdown in confined aquifer achieved through;

a) Assumptions represent the current conditions of the aquifer.

b) Ccollected the field data and interpreted to predict maximum drawdown and maximum time required to achieve the equilibrium (maximum drawdown).

c) Run modflow under different pumping rates, correlate the data with actual field data and interpret the results.

The proposed assumptions were more or less satisfied with the prevailed natural conditions of the aquifer, these conditions comprise the following:
a) The aquifer has a seemingly infinite areal extent. With 15 % effective porosity.
b) The aquifer is more or less homogenous, isotropic and uniform in thickness.
c) The wells are out of cone of depression from other wells and almost equally distributed in the area.
d) Prior to pumping, the piezometric surface is (nearly) horizontal over the area.
e) The diameter of well is small, and the flow to the well in unsteady state.
f) The aquifer is pumped at a constant rate; the aquifer is confined or semi-confined.
g) The pumped well penetrated the entire aquifer and thus receives water from entire thickness of the aquifer by horizontal flow.
h) Introduce 4 managing systems and introduce the performance of confined aquifer;
   1) all wells pumping out = 1.1 of initial recharge (run all wells 1700 m^3/day)
   2) all wells pumping out = 1.8 of initial recharge (run all wells 2800 m^3/day)
   3) all wells pumping out = 2.8 of initial recharge (run all wells 4300m^3/day)
   4) all wells pumping out = 3.7 of initial recharge (run all wells 5700m^3/day)

3.1. Pumping Out=1.1 of Initial Recharge (Currently, Each Well 1700 m^3/d)
3.1.1. From the Field Data
From the data of 2 observation wells; the maximum average expected (interpolated) drawdown is 8 mt and expected time for stability or equilibrium is around 25 years. Observed well drawdown M vs years as shown in Figure 5.
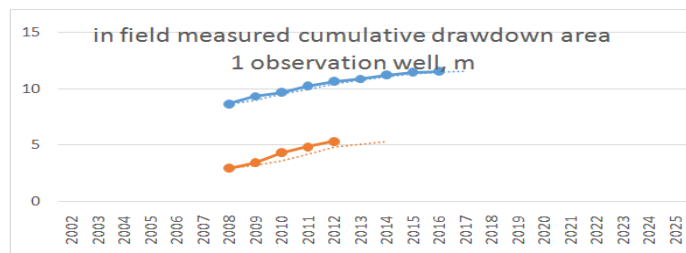

Figure 5. Observed well drawdown M vs years, in area one, Darb El Arbeain

3.1.2. Results from the Modelling
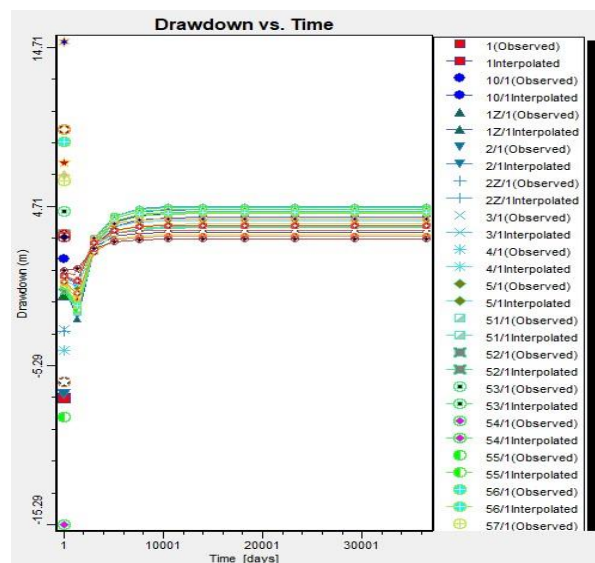Observed well drawdown M vs years as shown in Figure 6.

Figure 6. The modelling results; Drawdown Vs time at Q_{out}/Q_{in} = 110 %, area one

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3.1.3. The Maximum Average Expected (Interpolated) Drawdown
Is 4 MT and expected time for stability or equilibrium is around 20 years.

3.1.4. Results of Managing System When Q
out (1700m3/day each well) $=1.1$ Q in (initial recharge)

3.1.5. after correlation between modelling results and field observation wells;
a)   The average maximum expected drawdown is around 6 mt.
b)   The years required for equilibrium is around 22 years.

3.1.6. The Drawdown Prediction in 2100 (Figure 7) Shows That
The southern boundaries of the area has the lowest drawdown in the area, where the lowest value of drawdown is 2 mt of well no 9 in the western southern parts [17, 18]. The northern middle parts have the highest values of drawdown where it reaches 4.3 MT in wells 2 and well 2 Z. The rate of change of drawdown is going smooth which reveals more stability of the area or gradual changes of the geologic structure.
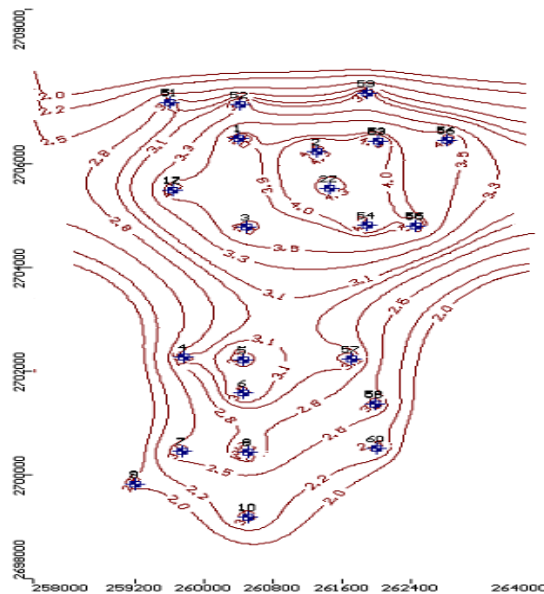

Figure 7. Expected drawdown in 2100, m. area one, Q out/Q initial recharge = 110 %

3.2. Pumping Out=1.8 of Initial Recharge (Each Well 2800 m^3/d)
3.2.1. From Modelling;
a)   The average maximum expected drawdown is around 6.5 mt.
b)   The years required for equilibrium is around 22 years.

3.2.2. After Correlation
Between modelling results and field observation wells;
a)   The average maximum expected drawdown is around 10 mt.
b)   The years required for equilibrium is around 24 years.
The drawdown prediction in 2100 Figures 8 and 9 shows that; the southern boundaries of the area has the lowest drawdown in the area, where the lowest value of drawdown is 3.1 mt of well no 9 in the western southern parts. The northern middle parts have the highest values of drawdown where it reaches 7.3 MT in well 2 Z [19-24].
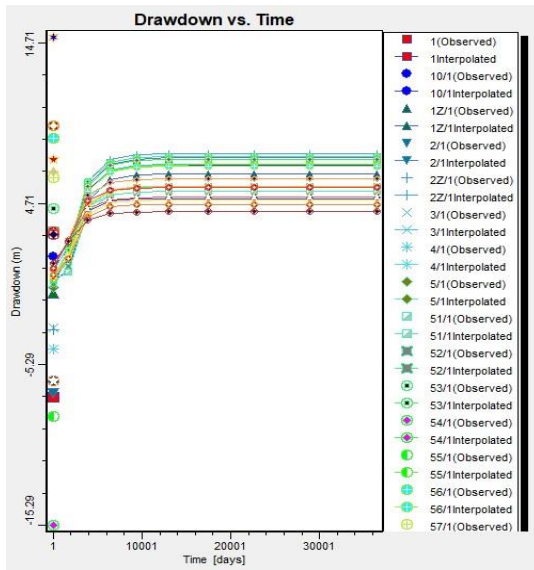
Figure 8. The modelling results Drawdown Vs time at Q_{out}/Q_{in} = 180 %, area one
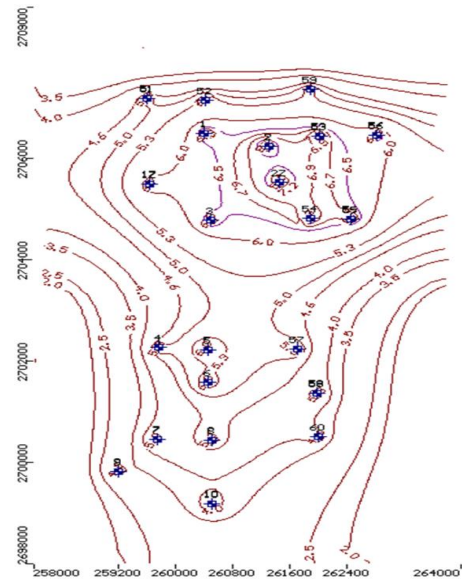
Figure 9. Expected drawdown in 2100, m. area one, $Q_{out}/Q_{initial\ recharge}$ = 180 %

3.3. Pumping Out=2.8 of Recharge (each well 4300 m³/d)

3.3.1. Results from Modelling of Managing System when $Q_{out\ (4300\ m3/day\ each\ well)}$ =2.8 Q_{in}

The maximum average drawdown (Figure 10) is 10.5 mt, with 24 years for equilibrium.

3.3.2. After Correlation between Modelling Results and Field Observation Wells;

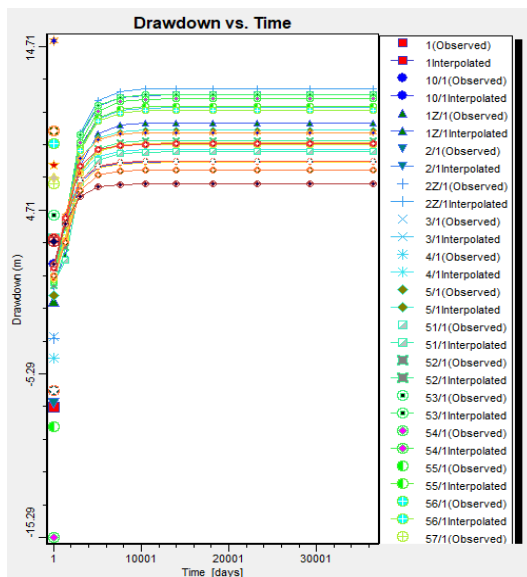The average maximum expected drawdown (Figure 11) is around 16 mt, and 26 years for equilibrium.

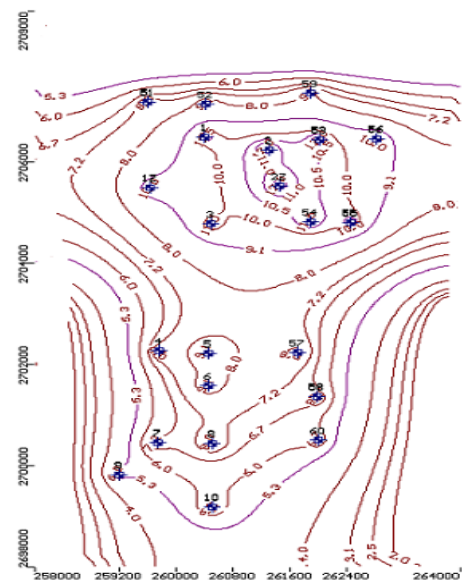Figure 10. The modelling results drawdown vs time at Q out/Q in = 280 %, area one

Figure 11. Expected drawdown in 2050, m. area one, $Q_{out}/Q_{initial\ recharge}$ = 280 %

3.3.3. The Drawdown Prediction in 2100 Shows That

The southern boundaries of the area has the lowest drawdown in the area, where the lowest value of drawdown is 4.9 MT of well no 9 in the western southern parts. The northern middle parts have the highest values of drawdown where it reaches 11 MT in well 2 Z.

3.4.   Pumping Out = 3.7 of Initial Recharge (Run All Wells 5700m³/day)
3.4.1. Results of Managing System When Q $_{out\ (5700\ m3/day\ each\ well)}$ =3.7 Q$_{in}$
When using pumping out = 3.7 of initial recharge;
The maximum average drawdown is 12 MT with 25 years for equilibrium.

3.4.2. After Correlation between Modelling Results and Field Observation Wells;
The average maximum expected drawdown (Figure 12) is around 18 mt, with 28 years for equilibrium.
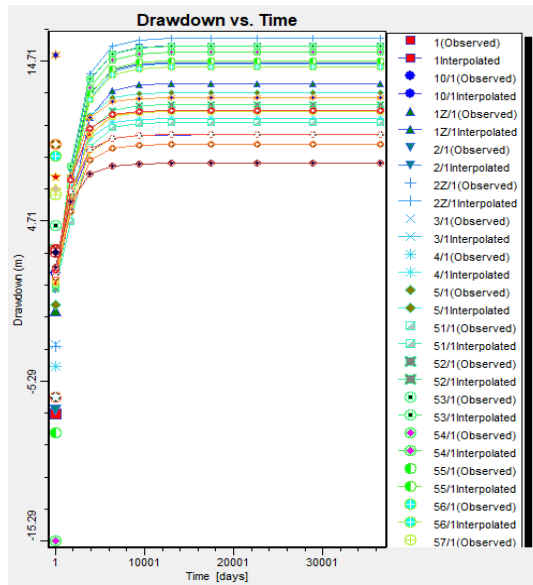

Figure 12. The modelling results drawdown vs time at Q out/Q in = 110 %, area one

3.4.3. The Drawdown Prediction in 2025 Shows (Figure 13)
That the southern boundaries of the area has the lowest drawdown in the area, where the lowest value of drawdown is 6.7 MT of well no 9 in the western southern parts. The northern middle parts have the highest values of drawdown where it reaches 15 MT in well 2 Z [25, 26].
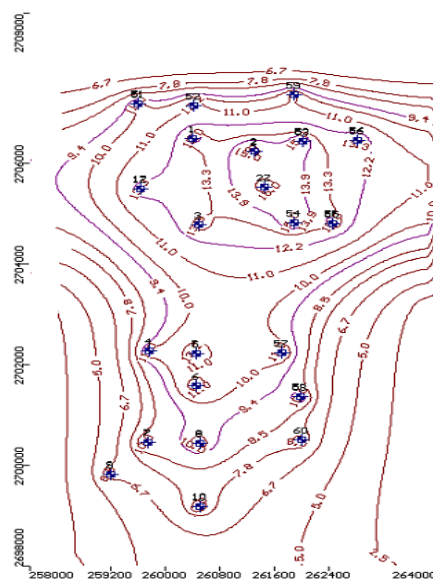

Figure 13. Expected drawdown in 2050, m. area one, Q $_{out}$/Q $_{initial\ recharge}$ = 370 %.

3.5 Managing Plan for Northern Part of Darb El Arbeain

Managing plans for area one (northern part) are tabulated in Table 1.

Table 1. For Confined Aquifers under Previous Assumptions, Can Choose for Managing Plan

$Q_{out}/Q_{in(initial)}$	Average drawdown (after correlation with field results), m	Time for equilibrium (after correlation with field results), years
1.1	6	22
1.8	10	24
2.8	16	26
3.7	18	28

4. DISCUSSION

The tabulated values of min and maximum values of drawdown under different pumping rates as shown in Table 2.

Table 2. Min and Maximum Values of Drawdown under Different Pumping Rates

$Q_{out}/Q_{initial\ recharge}$	Min –drawdown, m	Max- Drawdown, M
110 %	2	4.3
180 %	3.1	7.3
280 %	4.9	11
370 %	6.7	15

a) The southern area represents less drawdown which means high potentiality and more stability. It's recommend to drill more wells in this part of the area.

b) The northern centre represents more drawdown which not recommended places to drill more wells for horizontal extension of the project.

Under different managing plans we can observe that the first ($Q_{out}/Q_{initial\ recharge} = 1.1$), and the second ($Q_{out}/Q_{initial\ recharge} = 1.8$) are highly recommended where; drawdown is not too much, not too much changes to ground water quality due to moderate flowrate in the aquifer which reduce the dissolving rate of the minerals and extending the life time of the well itself. Using Figure 14 to interpolate the average maximum drawdown versus pumping rate.
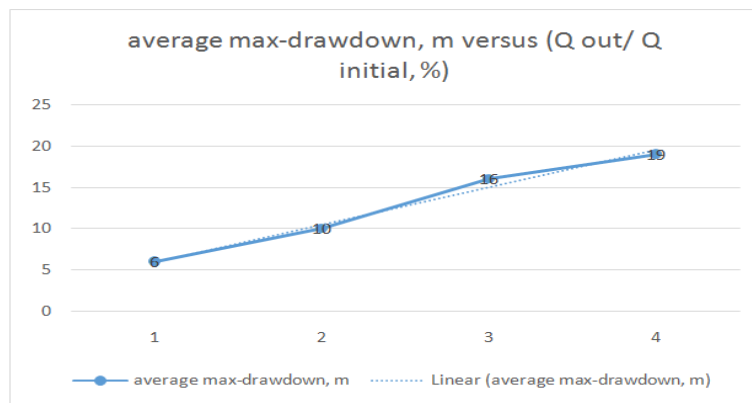

Figure 14. Average max- drawdown, mt VS $Q_{out}/Q_{recharge}$

For Moderate Aquifer Potentiality (K = 3.07 M/Day)
Average maximum drawdown, m = ($Q_{out}/Q_{initial\ recharge}$) * constant
From the curve the constant equal 5
Average maximum drawdown, m = ($Q_{out}/Q_{initial\ recharge}$) * 5
The constant depends on;
    a) Transmissivity, T, M^2/day
    b) Hydraulic gradient, I, dimensionless

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c) Width of aquifer surface field, W, M
d) Heterogeneity of the aquifer, depends on the formation nature and structure geology.
e) Pumping rate M^3/day

5. CONCLUSIONS

The study area occupies the northern part of Darb El Arbeain. It is characterized by arid climatic conditions. Four different pumping scenarios were applied for 25, 50, and 100 years. Through applying visual mod flow and correlation with field data. The results indicated that the best pumping rate for the confined aquifer in the northern part of Darb El Arbeain is 180 % of initial calculated recharge rate. Pumping rate has huge effect on groundwater drawdown, where scenario No.4 has the bigger amount of pumping rate, so this scenario worst scenario in increasing drawdown. Increasing pumping rate decreases the head in both aquifers, and vice versa. In all scenarios the middle northern part of area one has the maximum drawdown.

5.1. Recommendations

For any management plan to be successful for northern area of Darb El Arbeain, pumping from all wells must be addressed. This is due to the fact that it has high impacts on water table drawdown and heads. More studies are required for increasing the validity of the new introduced equation to be used worldwide for any groundwater confined aquifer project.

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