Qattara Depression and its Hydropower Potential

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Abstract
The Qattara Depression in Egypt has been suggested to be used for hydropower production. This paper investigates the possibility of having a Hydropower plant in this location to solve the current energy problem in the region, by providing the most updated results that would be used in such a project compared to previous studies. Hydrological elements affecting the water balance of the Qattara Depression region are studied, as by predicting the level of the water with time, the nature of the operation of the station can be chosen efficiently. Salinity concentration, evaporation rate of the formed lake, and the water channel formed that leads to the lake, and inward and outward seepage are all factors that had either been neglected in previous studies or not studied in the level of detail necessary for an accurate estimation of the lifetime, energy and economic feasibility of the plant. Metrological data obtained from weather stations surrounding the region were used in the calculations. Also we needed information about the nature of the region's soil and the hydraulic conductivity and studied the surrounding aquifers to obtain the best estimates when modelling the seepage values along with the years. The detailed calculation of the seepage and salinity have never been done and incorporated in the results making the results in this paper the most updated results. The results showed the lifetime of the Qattara Depression and the increase in the level of the water level with time.

Keywords: Qattara Depression; Hydropower; Energy

Introduction

Qattara Depression was first investigated by Professor Ball in 1927. Table 1 shows information about the routs offered by Ball. By the 1950s after Ball's study and proposal the subject was reopened, were Siemens proposed a scheme that would have provided a power potential of 100 MW, with turbines only operating six hours per day (Martino, 1973). A commission led by Bassler in 1964 with results showing that the Qattara Depression, alternatively to what had previously been said, can be used for pumped-hydro-storage for peak load energy production. Bassler offered several configurations some including a canal that would deliver water to the depression as well as being a shipping route towards the Qattara Lake with a harbor and fishing grounds in the depression [Ezz El Din, 2004]. The depression was to be filled to a height of 60 m below sea level, which would correspond to an area of 12000 km^2. The volume removed due to evaporation would be 19000 million cubic meters annually. A flow of 600 m^3/s would be used for the compensation of the evaporation (Martino, 1973). The tunnels carrying the discharge would be about 80 km long and it would reach an underground power plant at level -54 m (Martino, 1973). The operation Bassler proposed was that during hours of low network load demand, the energy produced by the project turbines would be used to pump the water into a high-level natural reservoir that has a capacity of 50 million cubic meters (Martino, 1973). Water located in this zone would offer a valuable head during peak load hours. Therefore, during the peak load periods pumps would not be allowed to work and the extra head obtained would be able to generate a huge amount of power (Ezz El Din, 2004). This system would be able to produce 4000 MW during the peak period and would be adaptable to handle varying demand patterns [Ezz El Din, 2004]. The results of this paper would greatly help in choosing from the different options offered for operation of the Qattara Depression plant. Also Magdi Ragheb (Ragheb, 2012) proposed a power plant that would have wind turbines used in its operation by driving the pumps that would pump the water up to the storage reservoir. And his analysis showed that the plant could produce up to 1,500 MW (Ragheb, 2012).

But, what was lacking the previous studies is that they did not put in to the consideration the channel flow, the effect of salinity on the evaporation rate, and the outward seepage flow. Each of these factors would be investigated to understand their effect on the plant lifetime and operation. And having these results the best method of operation would be chosen.

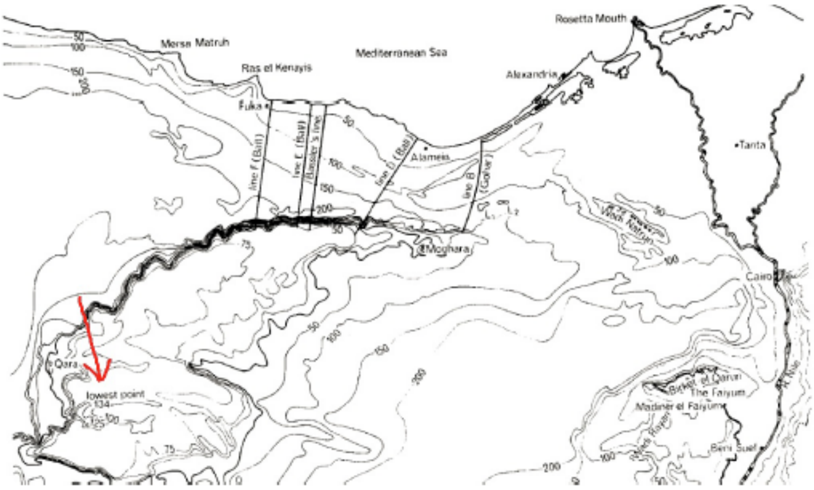

Figure 1: Qattara Depression (Martino, 1973)

Table 1: Routs offered by Dr. Ball

Routs	D	E	F
Lake level below sea-level (m)	50	60	70
Flow rate (m^3/sec)	656	546	348
Amounts of power developable (kwh)	200,000	200,000	150,000
Length of conduit from sea to contour (km)	72	76	80
Open channel from sea to tunnels (km)	20	———	———
Diameter of tunnels (m) for 200,000 kwh	12	11	———
Diameter of tunnels (m) for 175,000 kwh	11	10	———
Diameter of tunnels (m) for 150,000 kwh	10.3	9.5	9.2
Diameter of tunnels (m) for 125,000 kwh	9.8	9	8.2

Mathematical Model

Hydrology

Evaporation is one of many factors that affect the governing hydrological equation below:

$$\Delta S = \{P*A + Q_s + Q_{in} - Q_{out} - E*A\}*dt \quad (1)$$

Where:
ΔS=monthly change in storage (m^3)
P=monthly mean precipitation (m^3/day)
Q_s=monthly mean subsurface inflow (m^3/day)
Q_{in}=monthly mean discharge to be conveyed (m^3/day)
Q_{out}=monthly mean discharge to be pumped (m^3/day)
E=monthly mean evaporation rate from sea surface (m^3/day)
A=Qattara Depression surface area at corresponding level (m^2)
dt =Time interval equals a month

The subsurface inflow was estimated to be (Q_s) 57.5 million m3=year (Ezz El Din, 2004). While (Q_{out}) represents the discharge to be pumped back to the sea. The latter term was based on a proposal by Ezz El Din (Ezz El Din, 2004) to pump water from the depression back to the Mediterranean Sea since his calculations showed that the evaporation rate at some point is negligible due to the increase in salinity, this point will be investigated in details in this paper. This is in direct contrast to what Ball and Bassler deduced, which is that the evaporation would continue and would balance with the inflow. (Q_{ou}t) is not considered by the author in his model due to its high cost, therefore the term is taken as zero. As will be shown, even the calculations produced in regards to the salinity by Ezz El Din where simple and a more detailed calculation would produce a less aggressive increase in salinity that would affect the evaporation rate and in turn the final level of the lake. Add to that the effect of the outward seepage to the final results.

Topography

A very important section in the model is the calculation of the area and the volume of the lake at each level in each time step. Topographic data about Qattara Depression is desperately needed for such a project. Data produced from the Shuttle Radar Topographic Mission elevation data product

(SRTM) was used in mapping Qattara Depression (Hafiez, 2014). The following procedure was followed to produce the volume and area of Qattara Depression at different altitudes which is necessary for our model. Using the SRTM data a digital elevation model (DEM) file is produced which is imported to Golden Software Surfer that produces the volume and surface area data at different levels (Hafiez, 2014). The below equations were produced and are used in our Model at each time step to obtain the area.

$$A = 117.5 * S.L + 1950 \qquad For\ (-40 \le S.L \le 0) \quad (2)$$

$$A = 0.0085 * S.L^4 + 2.1211 * S.L^3 + 188.6 * S.L^2 + 7286.7 * S.L + 118522 \qquad For\ (-90 \le S.L \le -40) \quad (3)$$

$$A = 463073 * e^{0.0682*L} \qquad For\ (-120 \le S.L \le -90) \quad (4)$$

Where:
A = Total area of the Qattara Depression surface (m^2)
S.L= Surface level of the Qattara Depression (m)

Channel Flow

After examining the topography of the Qattara Depression it became clear that there was another factor that would affect the model which is the channel flow. As the area of the channel formed at the entrance of the sea water to the depression can be included in the evaporation calculation in addition to the area formed by the lake.

The slope at the borders of the depression is aggressive which would provide inertia for the seawater at the entrance. The study shows that the maximum width from north to south is 145 km at longitude 27_30’E (Hafiez, 2014). While the maximum length from east to west is 300 km at approximately latitude 29_45’N. The deepest point is at 134 below sea level. (Hafiez, 2014), and is located at the depression’s western corner (29_23’33”N. latitude by 26_43’57”E. longitude) (Hafiez, 2014). In our model the sea water flowing out of the turbines is assumed to follow a channel like flow towards the lowest point in the depression. Analysis of the topography of the depression indicates a slope of approximately 0.4 m/km. Moreover the terrain is assumed to have a manning coefficient n=0.035 based on comparison with similar terrains. The effect caused by this channel on the filling scenario has never been studied before. Manning's formula for channel flow was used as shown below.

$$Q = \frac{1}{n} * A * R\frac{2}{3} * \sqrt{S} \tag{5}$$

Where:
Q = Flow Rate, (m3/sec)
v = Velocity, (m/s)
A = Flow Area, (m2)
n = Manning's Roughness Coefficient
R = Hydraulic Radius, (m)
S = Channel Slope, (m/m)

$$R = \frac{A}{P} = \frac{b*h}{2h+b} \tag{6}$$

Therefore:

$$V = \frac{1}{n} * R^{\frac{2}{3}} * \sqrt{S} \tag{7}$$

From the topography obtained from Qattara Depression (h) can be considered in the range of 0.5 to 2 m, with (b) ranging from 378 to 3810 m. And in equation 6 b is the breadth h is the height and P is the perimeter. These values are used in the model to see if the channel would have an effect on the filling scenario and the evaporation rate and also to estimate the time the journey would take to reach the lowest point in the Qattara Depression, the latter was found to be of the order of 2 days.

Evaporation

An extensive study was done by Ezz El Din (Ezz El Din, 2004) who calculated the evaporation rate using Penman's equation (Peel, 2013) predicted the changes of the Qattara Depression surface level and analyzed the economics of the project at that time. Ezz El Din's usage of Penman's equation (Peel, 2013) was also incorporated in our Model, but the increase of salinity concentration is where our Model differs. There are many formulas available to be used for the estimation of evaporation. Most of them are based on Dalton's fundamental law, which states that evaporation will take place if the actual vapor pressure of the air above the water surface is less than the actual vapor pressure at the water surface. Penman's equation has given very good results especially in humid regions from all the regions that it has been checked around the world (Ezz El Din, 2004). Therefore this part was also used in our Model with confidence. Ezz El Din (Ezz El Din, 2004) modeled the change in the surface level with time using the meteorological data for 360 months (1970-2000). Once using the evaporation rates measured and once using the evaporation rates calculated using Penman's equation, the results showed that the equation is applicable to the monthly average. In Ezz El Din's model, each run had a random year chosen from the

30 years available. The same meteorological data was used in our Model. Different schemes where studied by Ezz El Din as shown below:

- Base-load scheme 24 hours production
- Peak-load scheme for some hours of production per day for developing hydro power during the peak load period
- Mixed pumped storage scheme which is used to develop the hydro power at peak-load period and pumping at the off-peak period, and the pumping power coming from the grid during off peak period

Ezz El Din concluded from his results of the three alternative schemes that salinity would have a severe effect on the lifetime of the project. As increasing the salinity will severely decrease the evaporation rate and lead to the water level increasing much more rapidly and not leveling out, as will be seen in the results, contrary to what Ball and Bassler deduced. Our model studied the effect of salinity in greater detail. The following form of Penman formula (Peel, 2013) is used in the model to obtain the evaporation rate in mm/day:

$$E = \frac{\Delta * H + \gamma * E_a}{\Delta + \gamma} \qquad (8)$$

Where:
E= Evaporation in mm/day
Δ= The slope of vapor pressure vs temperature curve
E_a=Evaporation rate using Dalton's equation (Jensen, 2008) of the boundary layer above the water surface in mm/day
γ= psychomotor constant = 0.66 if temp in ℃ and e in millibar or 0.485 if e is in mm Hg.
Hence using equation (1) the variations in the monthly water storage are obtained but an important factor that needs to be studied is salinity and its effect on the plant's lifetime.

Salinity

The salinity would increase due to the sea water continuously pouring and evaporation occurring. This would lead to a decrease of the evaporation rate, which in turn would lead to a rise in water level and consequent decrease in head available and therefore power output and lifetime of the plant. Specific gravity of the sea water entering Qattara Depression (S.G) is taken as 1.025 as this represents the (S.G) of the Mediterranean Sea. Variations in the specific gravity of the Qattara Depression Lake (g_s), were considered in Ezz El Din's calculations using the general equation shown below:

$$S.G = \frac{\Delta S * g_s + V_o * S.G_O}{V_o + \Delta S} \qquad (9)$$

Where:
$S.G_o$ = Initial value of specific gravity
V_o = Initial volume of sea water
g_s = The specific gravity for the differential volume
ΔS = Change in contents of water

The Equation used in Ezz El Din's model was found to be very approximate so for more accuracy in our model the following equations are used.

$$C = \frac{mass\ of\ salt}{volume\ of\ water} \tag{10}$$

Where:
C: Instantaneous salt concentration in reservoir

$$\delta C = \frac{dC}{dm_{salt}} * \delta m_{salt} + \frac{dC}{dV} * \delta V \tag{11}$$

$$\delta m_{salt} = [V_{sea} * C_{sea} + \sum V_{si} C_{si} - (V_{so} + V_{pumped})C] \tag{12}$$

$$\frac{dc}{dt} = \frac{1}{V}[V_{sea} * C_{sea} + \sum V_{si} C_{si} - (V_{so} + V_{pumped})C] - \frac{m_{salt}}{V^2}[V_{sea} + V_{rain} + \sum V_{si} - V_{so} - V_{evap} - V_{pump}] \tag{13}$$

Where:
$\frac{dc}{dt}$=Rate of change of salinity
V=Volume of water (m^3)
V_{sea}=Flow rate of sea water entering the depression (m^3/month)
C_{sea}=Salinity of the sea in kg/m^3
V_{si} =Flow rate of water entering the depression through seepage (m^3/month)
C_{si} =Salinity of the inward seepage in kg/m^3
V_{so} =Flow rate of water leaving the depression through seepage (m^3/month)
V_{pumped} =Flow rate of sea water pumped out of the depression (m^3/month)
C=Salinity kg/m^3
m_{salt} =Mass of salt in kg
V_{rain} =Flow rate of water entering the depression through rain (m_3=month)
Vevap =Flow rate of water leaving the depression through evaporation (m3=month)

The predictor corrector method is then used in matlab for equation to obtain accurate values for the salinity (C) in every time step which is then converted to specific gravity to find the effect of salinity on the evaporation rate. The evaporation factor is derived as shown below. This factor is multiplied in the model to the value of evaporation calculated and it can reach zero if the salinity of the water reaches a certain threshold. Es represents the value of evaporation at the salinity reached.

$$\frac{E_s}{E_o} = 8.23 * S.G^3 - 32.5 * S.G^2 + 39.8 * S.G - 14.5 \tag{14}$$

$$\frac{E_s}{E_o} = 5.6 * S.G^2 - 16.58 * S.G \quad + 12.273 \tag{15}$$

Seepage

Seepage is also another very important factor that was neglected in all previous studies. This is a factor that when included in the calculation was assumed by all previous studies to have a positive effect on the plant life, which is true. But, that positive impact needs to be calculated as it would affect the economic study of such a project significantly. Dr. Fredlund (Fredlund, 2001) presents a three dimensional partial differential equation for seepage through a heterogenous, anisotropic, saturated-unsaturated soil and satisfies conservation of mass for a representative elemental volume. The equation shown below assumes that the total stress remains constant during a transient process (Fredlund, 2001).

$$\frac{d}{dz}\left(k\frac{dh}{dz}\right) = m\gamma\frac{dh}{dt} \tag{16}$$

Where:
k=Coefficient of permeability of the soil in the z direction
m=The slope of the soil water characteristic curve (water storage)
γ=Unit weight of water

The one dimensional form of the above equation is used in our matlab code to model Qattara Depression; the justification being that the lateral extent of the seepage flow is much larger than its depth, leading to vertical gradients being much larger than lateral ones. The value of the coefficient of permeability or also called hydraulic conductivity for this region is obtained from S. Rizk (Rizk, 1991) as 0.00025 m/sec as an average value for the Qattara Depression. The hydraulic conductivity varies from one region to another in the depression for that a sensitivity analysis was performed to determine the effect of the hydraulic conductivity changes on the model and the plant life. The tables below show values for the hydraulic conductivity and storage coefficient for many locations including Kharga,Dakhla, and Moghera which are close to the Qattara Depression. Definitely a site survey preformed on the exact nature of soil in the Qattara Depression would present more accurate results. But, using this study the model is run using different specific yields and for sand classified as fine or coarse and the results are compared. The value of the storage coefficient will be taken as an average of $2.84*10^{-4}$ and a sensitivity analysis performed. Equation (16) is going to be solved in the model by employing the finite volume method.

Initial conditions:

At t=0 $(\frac{dz}{dz})_t = 0$

Boundary conditions:

h=ρgH

$\frac{dh}{dz}$=0

$$\int_t^{t+\Delta t}\int_z^{z+\Delta z}\frac{d}{dz}(k*\frac{dh}{dz})dz.dt = m\gamma\int_z^{z+\Delta z}\int_t^{t+\Delta t}\frac{dt}{dt}dt.dz$$

Taking x=$\frac{k}{m\gamma}$ integrating the DE over a finite volume extending between z and z+ Δz, and time t to t+Δ t yields:

$$xh_{j+1}^{t} + (1-2x)h_j^t + xh_{j-1}^t = (1+2x)h_j^{t+\Delta t} - xh_{j+1}^{t+\Delta t} - xh_{j+1}^{t+\Delta t} - xh_{j-1}^{t+\Delta t} \tag{17}$$

Equation (17) expressed at all nodes across the domain constitute a set of linear algebraic equations displaying a tri-diagonal matrix of coefficients. The time steps are taken as daily steps, and the space steps are taken as 1 m. An assumption is made that there are no rocks underneath the surface and that the seepage will continue. So for each time step the head is calculated for all the nodes. The head is then used to obtain the velocity at each node as it is the difference between the head between two nodes multiplied by the hydraulic conductivity. The velocity at the first node is then multiplied by the instantaneous area being solved for and that presents the outward seepage m^3/month.

Display of Results

The results that would offer a contribution to the planning of the project. As will be shown in the figures below the inclusion of the Chanel Flow in all the models and results did not have any effect on the life cycle or power production of the Plant. And that was the case no matter the breadth of the Chanel taken. The figures below show the effect of salinity on the surface level of the water in the Qattara Depression. We have three alternatives to compare between when assessing the effect of salinity on the plant life. First, we have salinity affect not included, second we have Ezz El Din's calculation explained above, and third there is the new detailed salinity calculation included in our Model. As seen from the results having no salinity the level of the lake levels out by incorporating Ezz El Din's method for salinity calculation the evaporation rate progressively decreases with the passage of time leading to the level of the lake to keep increasing. The new detailed method for Salinity showed the same affect but the results were less aggressive leading to a longer life. In the salinity comparison between all three different options for a fair comparison the same conditions were used in the model, same hydraulic conductivity and seepage and water inflow from the sea.

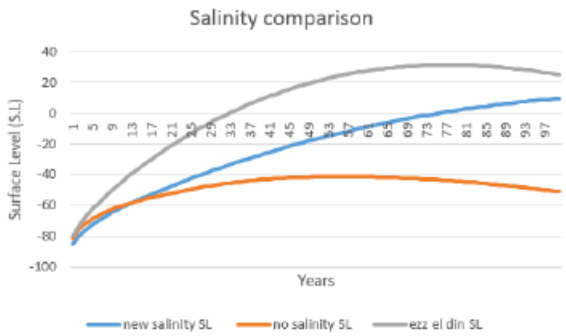

Figure 2: Salinity Comparison

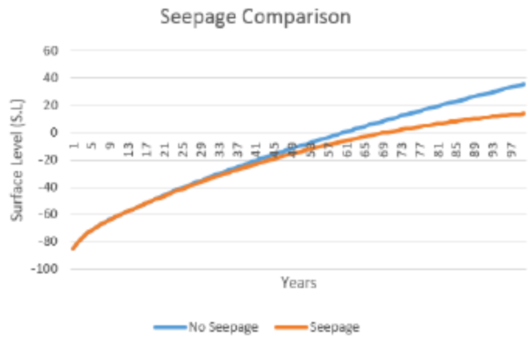

Figure 3: Seepage Comparison

Also, the effect of seepage was studied to show the effect of having this factor in the model. And it showed that after 100 years the level of the lake would be 14 m when seepage is included and 36 m when seepage is not included and in both cases salinity is calculated with the most updated method explained in this paper. The results show that the effect of increasing the hydraulic conductivity from 0.00025 m/sec to 0.0025 m/sec has a great effect on the overall results. Surface level (S.L) decreases to a lower level when hydraulic conductivity increases. And the surface level increases faster when hydraulic conductivity of the soil decreases.

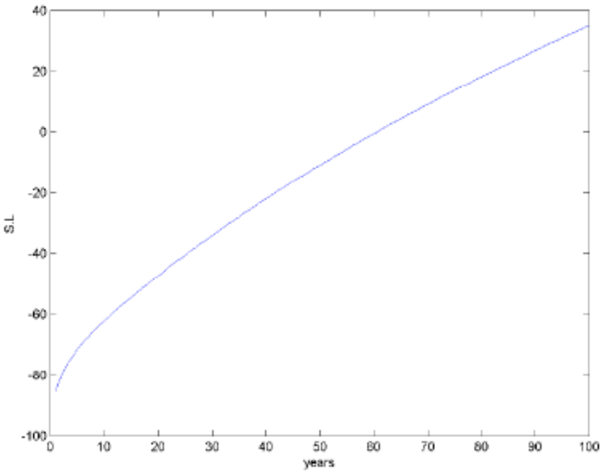

Figure 4: Effect of keeping the hydraulic conductivity at 0.00025 m/sec

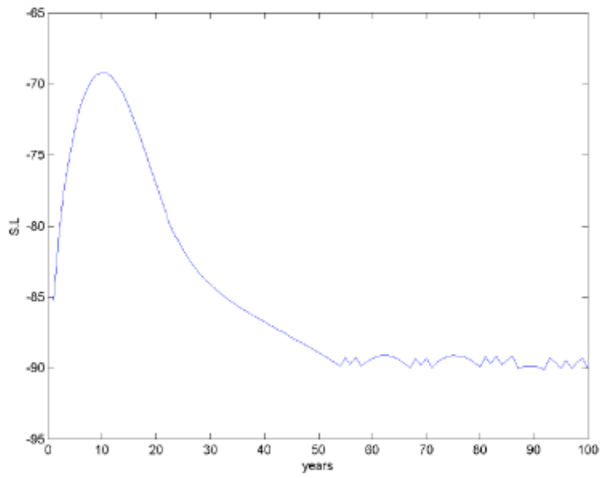

Figure 5: Effect of increasing the hydraulic conductivity

Summary and Conclusion

Therefore, as seen from the results Channel Flow has no effect on the plant life. But the effect of the new salinity calculation showed different results as the lake reached 10 m above sea level in the new salinity calculation while it reached 25 m above sea level using Ezz El Din's method after 100 years. And in both cases a 656 m^3/s flow was used and outwards seepage was incorporated in the models.

While outward seepage also showed a considerable effect on the results as the lake would last longer with outwards seepage calculated in the model. The manner of operation is flexible so it must not necessarily be 656 m^3/s. Different flow rates can be used and the plant does not have to be operational 24 hours/day it can be pumped hydro storage operation. All these new results would have great effects on the economic study preformed on such a project and the method of operation chosen which should be pumped hydro storage to prolong the plant's life time.

References

G. Martino. (1973), The qattara depression. Water Power.

M. F. N.T.M. Thieu. (2001), Seepage modelling in a saturaed/unsaturated soil system.

M. E. E. Din. (2004), Evaluation of potential hydropower of qattara depression.

M. E. Jensen. (2008), Estimating evaporation from water surfaces.

M. Ragheb. (2012), Integrated wind and solar qattara depression project with pumped storage as part of desertec. *G-Animal's Journal*.

R. Hafiez. (2014), Mapping of the qattara depression,egypt, using srtm elevation data for possible hydropower and climate change macro projects, *International Journal of Water Resources and Environmental Engineering*.

L. L. R. S. T. R. M. Thomas A McMahon, Murray C Peel. (2013), Estimating actual, potential, reference crop and pan evaporation using standard meteorological data: a pragmatic synthesis.

Z. S.Rizk. (1991), Impact of the proposed qattara reservoir on the moghra aquifer of northwestern Egypt.