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Restoring Water and Salt Balance of Qarun Lake, Fayoum, Egypt.

استعادة الاتزان المائي والملحي لبحيرة قارون، الفيوم، مصر

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KEYWORDS:
Fayoum, Qarun Lake, Water Balance, Salt Balance, Water Management.

الملخص العربي: -يهدف هذا البحث إلى دراسة الاتزان المائي والملحي لبحيرة قارون بمنخفض الفيوم، للوقوف على أسباب زيادة منسوب البحيرة وارتفاع ملوحتها، ولذلك تم الدمج بين البيانات الحقلية والجغرافية والمناخية وخرائط الارتفاعات الرقمية وصور الأقمار الصناعية، لبناء نموذج رقمي باستخدام برنامج (SOBEK-1D2D)، مع عمل مقترح بإضافة أحواض بخر جديدة، لسحب كمية من المياه المالحة من البحيرة، للتخلص من كمية المياه الزائدة عن سعة البحيرة وكذلك خفض المحتوي الملحي للبحيرة. تم أيضاً افتراض عدة سيناريوهات للميزان المائي والملحي للبحيرة. أظهرت النتائج فعالية أحواض البخر الجديدة في تخفيض منسوب بحيرة قارون وخفض معدل الملوحة، وزيادة قدرة البحيرة على استيعاب كميات جديدة من مياه الصرف الزراعي مما يتيح الفرصة لزيادة المخصصات المائية لمحافظة الفيوم واستصلاح أرض زراعية جديدة.

***Abstract*— The current paper aims to study the water and salt balance of Qarun Lake in Fayoum, to find out the causes of the increase of water levels and salinity of the lake. Therefore, the field data, geographic data, climatic data, digital elevation maps and satellite images were combined to produce data for developing SOBEK- 1D2D model. With the new approach of adding new evaporation ponds to withdraw saltwater from the lake, to eliminate excess water from the lake, as well as to reduce the salt content of the lake. Several water and salt balance scenarios were designed. The results showed that the effectiveness of the new evaporation ponds in reduction of the water levels of Qarun Lake and reducing the salinity. Moreover, leading to increase the capacity of the lake to receive new quantities of the agricultural drainages, which provide the opportunity to increase the water share for Fayoum Governorate and reclaim new agricultural lands.**

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I. INTRODUCTION

FAYOUM or as they call it "small Egypt " because it represents a miniature geographical image of the Egyptian country where Bahr Yusuf is the lifeline of Fayoum as the Nile River for Egypt, and its northern coast on Qarun Lake as the coast of Egypt on the Mediterranean Sea. Fayoum is located at 90 kilometers southwest of Cairo as in Fig. 1, with a total area of 1800 square kilometers, and a population of 3 million, most of them working in agriculture and fishing. After transformation of the agriculture system from seasonal flooding to permanent irrigation, modern irrigation and drainage systems were established in Fayoum. The Fayoum depression is a closed basin, which receives irrigation water from one source, Bahr Yusuf, to drain the agricultural drainage into Qarun Lake, which is located at the bottom of the depression. As shown in Fig. 2, the land at the city of Fayoum is (+25.00m), which decreases gradually to reach (-43.00m) at the level of the water surface in the lake with an average slope of 2.0 m / km.

Fig. 1. Fayoum governorate, (Google Earth, 2017).

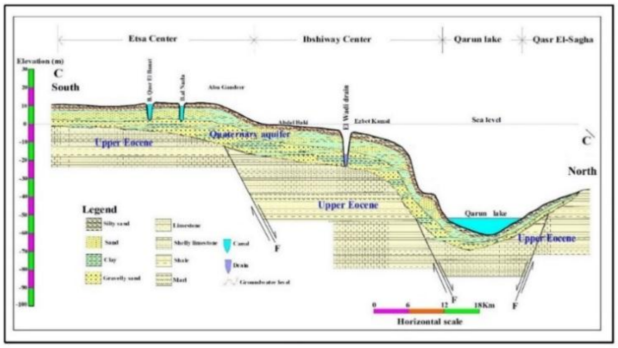

Fig. 2. Geological section of El-Fayoum depression.

II. QARUN LAKE

Qarun Lake is the main feature of Fayoum Governorate, it is a closed lake, located in the north of Fayoum depression between longitudes (30.40°to30.83°E), and latitudes (29.404°to 29.537° N). Qarun Lake is one of the historic lakes, a remnant of ancient Lake Morris, located on the northwestern part of the province of Fayoum, which is one of the largest natural lakes in the country. Lake Moeris Fig. 3, that sheet of water famous in classical antiquity, and regarded by the modern Egyptian engineer as the earliest of the great irrigation works of the Nile Valley, [1]],[[2]. Qarun Lake is currently saline, turbid (Secchi disc transparency less than 40 cm), and without surface outflow. It has a rectangular shape with length of 43 km, 5.6 km width, and considered as a shallow lake, where the average depth of about 4.20 meters, while the maximum depth is 9.0 meters in the north side near the horn island. Satellite images were used in 2015 to determine the area of Qarun Lake, which is estimated at 244.80 km^2. Previous studies since 1930 have indicated that the lake has been transformed from fresh water into salty water, Its salinity has exceeded seawater salinity [3]. The surface of Qarun Lake (200-250 km) is exposed to high evaporation rate, approaching 2.0 m/y, Table. I shows climate of Fayoum and Qarun Lake. Agricultural drainage water compensates for the loss of evaporation to keep the lake level almost constant at the end of the year. Until the early seventies, Qarun Lake was the only place to receive Fayoum drainage. After the water level exceeded the risk level, one third of the governorate's drainage was diverted to Wadi El Rayyan [4].

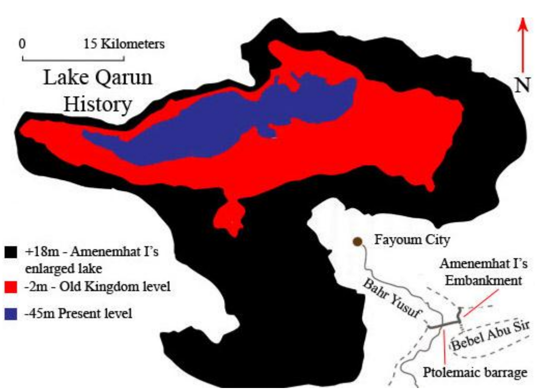

Fig. 3. Long-term changes of Qarun Lakearea [5].

TABLE .I:
THE CLIMATE OF FAYOUM (ANNUL AVERAGE VALUES) [6]

	Qarun Lake	Fayoum city
Mean Temperature	22.10 C°	22.00 C°
Max. Temperature	28.60 C°	26.50 C°
Min. Temperature	15.70 C°	14.50 C°
Mean relative humidity(RH)	61%	51%
Relative sunshine	82%	82%
Annual rainfall	9.20 mm	13.70 mm
Annual evaporation	1980 mm	2090 mm

The evaporation rate of Qarun Lake has estimated using the measured data of Shakshouk Evaporation Experimental Station of Water Management Research Institute (WMRI). Table. II represents the evaporation rate of the lakes during the period (2006-2012).

TABLE .II.
AVERAGE EVAPORATION RATE, (WMRI).

Month	Date	Average Evaporation Rate [mm/day] (2006-2012)
Jan.	1st half	2.16
	2nd half	2.21
Feb.	1st half	2.58
	2nd half	3.28
Mar.	1st half	3.43
	2nd half	5.70
Apr.	1st half	6.02
	2nd half	6.37
May	1st half	6.25
	2nd half	7.19
Jun.	1st half	7.66
	2nd half	7.99
Jul.	1st half	8.14
	2nd half	8.04
Aug.	1st half	8.05
	2nd half	7.83
Sep.	1st half	7.11
	2nd half	6.36
Oct.	1st half	5.89
	2nd half	4.93
Nov.	1st half	3.60
	2nd half	2.80
Dec.	1st half	2.25
	2nd half	1.90

Water levels of the lake surface was assembled for the past years, especially in years of very high water level, such as in 2009, where the level of the lake rose to (-42.28), a great value exceed the dangerous level of the lake, Fig. 4 shows the sequence of increase in lake level with time.

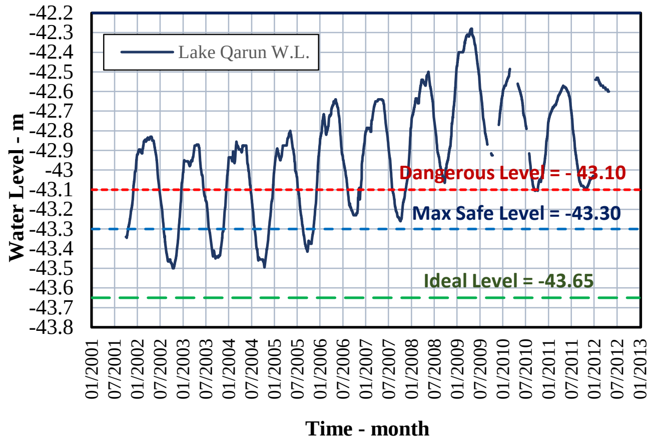

Fig. 4. Qarun Lake measured water levels (WMRI).

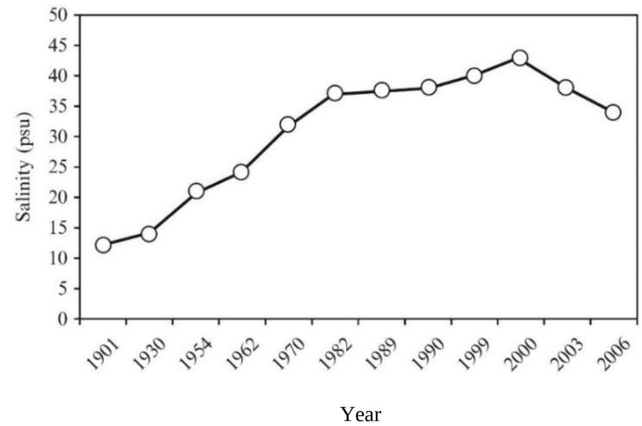

Fig. 5. Salinity of Qarun Lakeduring the last century [11].

The ANN based model was developed by Ali [7], a tool to assist in the management of Qarun Lake and salinity control. The input data required to run the model are monthly drainage water rates, monthly evaporation rates and initial storage of the lake at the start of the simulation period. Since the groundwater levels nearby the lake are not available, the seepage from and to the lake is not taken into account.

Sedimentary samples of Qarun Lake provided descriptions of the climatic changes that occurred in the late Eocene era in North and East Africa in addition to the environmental changes resulting from the activities of the ancient Egyptians. Baioumy [8] conducted geochemical and sedimentary analyzes of samples from the vicinity of Qarun Lake to explore the long-term changes of lake levels resulting from changing hydrological inputs

The level of Qarun Lake increased significantly in the late 1970s, causing extensive damage to agricultural lands, adjacent buildings and tourist facilities, which required the study of the water and salt balance of the lake [6]. In 1984, an irrigation water and salt management project was initiated in Fayoum (FWSBM), to control water levels and salinity of Qarun Lake. This project is being implemented in collaboration between the Fayoum Irrigation Department and the Drainage Research Institute of the National Water Research Institute. To achieve this work, a water monitoring network was installed in the main and subsidiary channels as well as in Qarun Lake [9].

Qarun Lake receives agricultural drainage salt water from the drains of Fayoum. The amount of water evaporates from the lake's surface almost equal the quantity of drainage water, resulting in the deposition of salts in the lake and increased salinity [10]. Body of Qarun Lake contains almost 40 million tons of dissolved salts in over one billion cubic meters of water. The salinity of the lake has greatly increased through the twentieth century as shown in Fig. 5 [11].

In 1906, salinity was 10.5 gm/lit; it was reached 18.0 gm/lit in 1925. Naguib [12] reported 17.8 gm/lit in 1953, and 25.50 gm/lit in 1955. The reason behind the increased salinity rate is high evaporation rate with no outflow of the lake [13]. Salinity increased further, to 30.9 gm/lit, 38.7 gm/lit and 42.8 gm/lit in the 1971, 1995 and 1999-2000, respectively [14], [15].

Al-Nasr Salt Company measured the salinity of Qarun Lake in 1979, the average salinity of 650 samples was 37.60 gm/lit, [16]. Increased salinity caused the disappearance of Nile fish species from the lake and have been replaced by marine fish to adapt to the salinity of the lake.

Soliman [17] predicted that the lake would become a "dead water body" if the salinity of the lake continued to increase in the current century. In 2003, lake salinity recorded a temporary decline to 32.40 gm/lit [18]. Table. III represents the saline water components of Qarun Lake and compares them with seawater [19].

TABLE. III.

COMPONENTS OF QARUN LAKE WATER AND COMPARISON WITH SEA WATER, [19].

component	$CaCO_3$	$Ca(HCO_3)_2$	$CaSO_4$	$MgSO_4$	Na_2SO_4	NaC1	KCI	$MgCl_2$
	gm/lit	*gm/lit*	*gm/lit*	*gm/lit*	*gm/lit*	*gm/lit*	*gm/lit*	*gm/lit*
Seawater	-	0.19	1.20	2.18	-	27.7	0.50	3.25
Lake Qarun	0.15	0.32	1.68	6.14	3.42	21.8	0.60	-

The annual increase in salinity of the lake range from 0.35 gm/lit/y to 0.38 gm/lit/y. Abdel-Wahed et al, [20] , collected water samples from canals and drains as well as from Lake Qarun, so he could study the salt distribution on the entire depression. Fig. 6 represents the distribution of salinity on the Fayoum depression showing that salinity rate increases towards Qarun Lake.

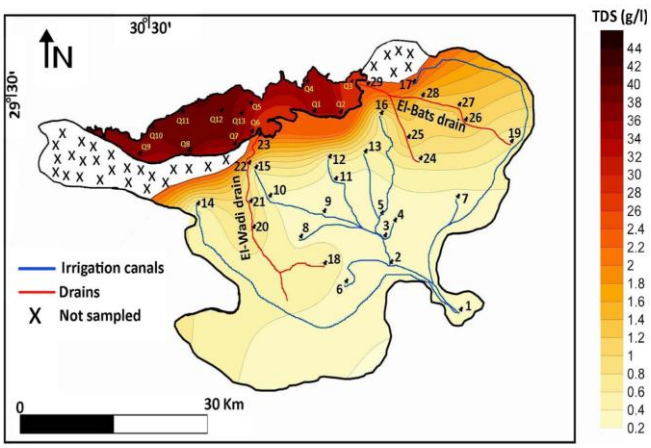

Fig. 6. Distribution of salinity on the Fayoum Basin.[20]

A. Salts Extraction Projects.

Qarun Lake receives about half a billion of agricultural wastewater per year with average salt level of 1.60 gm /lit., the salt load reaching the lake is about 800 thousand tons per year. Deposition of this quantity in the lake has caused high salinity rate. This was the reason for the establishment of a project to extract salts in order to reduce the salt load of the lake

1) The Egyptian Salt and Minerals Company (EMISAL).

The Egyptian Company for Salts and Minerals (EMISAL), constructed according to the Law No. 43/1974 and its amendment No. 230/1989 of “The Arab and Foreign Investment and Free Zones” [21].

2) EMISAL Evaporation Ponds.

EMISAL was established on the southern shore of the lake as in Fig. 7, where part of the lake was cut off to construct evaporation basins to raise the concentration of salt water to ten times and then withdraw the solution to the factory for salt extraction. The amount of water drawn to the plant is estimated at 20 mcm/y [11].

Fig. 7. EMISAL location (Google Earth, 2017).

Evaporation ponds occupy an area of about 1,200 feddans, separated from the lake by a 3.0 km long earth bank, which rely on solar evaporation to concentrate saline solution. It is the cheapest method used to extract salts [22]. As mentioned earlier that the amount of salt entering the lake equivalent to 800 thousand tons per year, the extracted salt by EMISAL company is about 350 thousand tons per year, and the remaining 450 thousand tons added to the salt load of the lake [23].

III. Water Balance.

The first issue that needs to achieve sustainable water development is to understand the annual water balance of the basin. This means knowing inflow water entering the basin and the quantity that comes out. As well as the amount of water infiltrated to the groundwater reservoir, surface runoff to the sea, and the amount of evaporation again destined to the atmosphere [24].

A. Water Balance Objectives.

- Water balance estimates are important to assess the current situation and the availability of water resources in a particular area for a specific period.
- It is a strong support for decision making in water resources management by improving and clarifying vision to build scenarios and develop management strategies.

B. Balance Estimation.

Water in nature is in a permanent movement and has the ability to switch from liquid state to solid or steam and vice versa depending on surrounding environmental conditions. In order to obtain a state of equilibrium, the amount of water entering a given area in a specific period is equal to the quantity exiting it, plus or minus the change in the storage rate of the area under study. This is a simplified form of water equilibrium equation as follows:

$$P = R + E \pm \Delta S \tag{1}$$

Where, P =precipitation, R =runoff, E =evaporation and ΔS =change of the storage in the soil, aquifers or reservoirs.

The techniques used in water balance calculations range from very simple operations to operations requiring complex computer models. Good advance knowledge of hydrological processes is required as a pre-requisite for water balance calculations.

IV. Water Salinity.

Salinity is an important determinant of many chemical properties of natural water and biological processes within it. Conceptually salinity is the (quantity of dissolved salt in the water). Salts are compounds like sodium chloride, magnesium sulfate, potassium nitrate, and sodium bicarbonate, which dissolve into ions, Rhoades [25] represented a classification of water according to its salinity Table. IV.

TABLE. IV.

CLASSIFICATION OF WATERS ACCORDING TO SALINITY [25].

Types of water	EC (dS/m)	TDS (gm/lit)	Water class
Drinking and irrigation water	< 0.70	<0.50	Non-saline
Irrigation water	0.70-2.0	0.50-1.50	Slightly saline
Primary drainage water and groundwater	2.0-10.0	1.50-7.0	Moderately saline
Secondary drainage water and groundwater	10.0-20.5	7.0-15.0	Highly saline
Very saline groundwater	20.5-45.0	15.0-35.0	Very highly saline
Seawater	> 45.0	> 35.0	Brine

The Food and Agriculture Organization of the United Nation's guidelines proposed that the irrigation water salinity of 0.45 gm/lit will not cause any problems; 0.45–2.0 gm/lit gm/lit ay cause slight to moderate problems; and over 2.0 gm/lit will cause intensive problems [26].

Average salinity in the main drains in Egypt, is 0.565 gm/lit , while it can reach 6.0 gm/lit in northern parts of the delta [27]. It is possible to irrigate with salt water and maintain a good level of production "biosaline-agriculture"; this requires precise practices for irrigated land management. Biosaline-agriculture has tried in Egypt, but has not commonly used [28], [29]. In studies conducted by the ministry, irrigation with the salt water of salinity (1.0 gm/lit) produced yields up to 29% lower than irrigation by freshwater [30].

V. DRAINAGE BASINS

In the natural world, without the interference of humankind, rivers play the role of drains; oceans, seas, and lakes play the role of salt sinks. Salt content in water is generated by continuous weathering of soil minerals [7]. Saline drainage water is disposed of either by discharging into another water body, such as a river or lake, or into a nearby depression. Drainage water can be disposed of without seriously affecting the water quality of the receiving water body. However, in some cases, the resulting mixture is unsatisfactory for future use.

Dead Sea (401 meters below sea level), Great Salt Lake (1280 meters above sea level), and Aral Sea (41 meters above sea level) are examples of areas where large scale disposal of drainage water by evaporation process [31]. Where large quantities of fresh water (containing salts at relatively low concentration) are disposed to a basin with a limited natural drainage capacity, the imported salts will accumulate in soil, in groundwater and in the surface water. An example is the Salton Sea in the Imperial Valley of California, created and maintained by surface runoff, subsurface seepage and drainage from imported irrigation water. The Salton Sea, which appeared in 1902 when fresh water first ran into a geological depression, is now more salty than seawater and is accumulating salt at a rate of 9000 tons per day [32].

VI. FAYOUM DRAINAGE SYSTEM.

In Egypt, the disposal of saline drainage water takes different forms. Disposal into the Mediterranean Sea and coastal lakes occurs from main drains in the Nile Delta. With the exception of the Fayoum region, all drainage water produced in the Nile Valley until the south of Cairo returns to the river's main course. In the Fayoum region, the saline drainage water is disposed into Qarun Lake and the Wadi El Rayyan depression. In 1996, the total disposal volume has been estimated to be 650 MCM [8].

The natural drainage system in Fayoum depression discharges the drainage water into Qarun Lake. The main drains of Fayoum are Bats drain in the eastern part, and Wadi drain in the western part of Fayoum, together with several minor drains, all these drains discharge into Qarun Lake as in Fig. 8. Since 1973, part of the water in the Wadi drain is diverted in the Wadi El Rayyan depression through a tunnel in the limestone ridge between these two depressions. This represents about 30-40% of the total drainage water [33]. Drainage in Fayoum works on gravity, except for a low laying area of some 12,000 feddans, bordering on Lake Qarun, which requires pumped drainage.

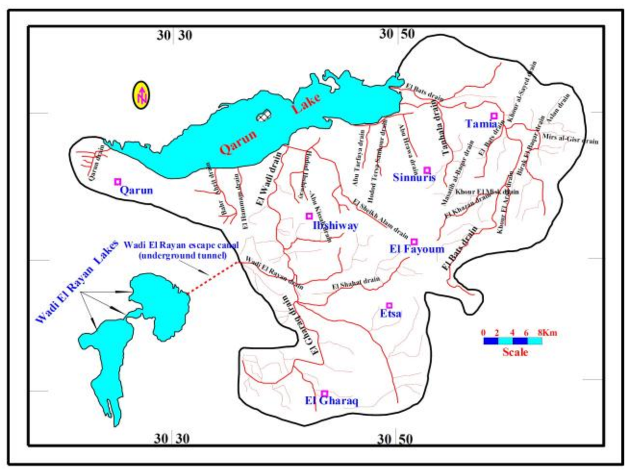

Fig. 8. Drainage network of Fayoum basin. Lake Qarun.

VII. RESEARCH METHODOLOGY.

Use of hydraulic modeling in the present time is one of the most important methods of studying hydraulic system in water channels and shallow lakes. Over the years, many mathematical simulation models have been developed to study flow behavior through channels. Numerical models are the most common means of representing and solving expressions that describe the natural phenomenon. These models need to collect sufficient and reliable field data to achieve model calibration leading to successful application.

Since 1970s, digital computers became available; Finite-difference models have been developed to simulate hydraulic systems, which have been applied to looped and branched canal networks. The unsteady-flow simulation models thereafter developed for either upstream or downstream-control, to deal with the different ways of water delivery, [34]. There are several examples of hydraulic systems simulation programs such as, FLO-2D, CANALMAN, CARIMA, SOBEK, DUFLOW, MODIS, and USM.

Models of irrigation canal simulation are tools for conducting research on the hydraulic behaviors of main canal system under different water management scenarios. Most models combine efficient numerical algorithms and up- to-date user-friendly interfaces [35].

El-Belasi, et al, [33] study the water balance for Wadi El Rayan Lakes area using (SOBEK-1D2D). El-Belasi [36] used a mathematical model (SOBEK-1D) for the two channels of Tahwila and Makshofa to study the effect of the trash rack in front of the Rayyan tunnel on the water levels in the two channels. Liew [37] Presented a simulation on the (SOBEK-urban v.2.09) to study the effects of urbanization on runoff and catchment flooding in Singapore. Prinsen [38] pointed out that, the Netherlands Hydrological modelling Instrument (NHI) currently uses the 1D hydraulic SOBEK model as a pre-processor to produce chloride concentrations predictions at the critical locations in the Rhine–Meuse estuary. Betrie [39] was linked the SOBEK model to the modified SWAT model and applied to simulate the sediment transport of the Blue Nile River basin. Abdelhaleem [40] applied (SOBEK Rural-1D2D v.2.10) to study the water and saline balance of Rayyan lakes. Balica [41] built (SOBEK Rural-1D2D) hydrodynamic model of the Budalangi River, using topographical information from (SRTM) with resolution of 90*90 m, to assess flood impact and evaluate damages.

A. Model Description.

SOBEK program has developed by (WL| Delft Hydraulics) in corporation with Inland Water Management and Wastewater Treatment Institute) [42]. SOBEK program includes three main products covering all water situations in both rural and urban areas. Each product consists of different units covering certain area of water systems. These units can work individually or in- combination. The data can transfer between the different units automatically, and the units can work sequentially or in parallel to facilitate the physical interaction.

In the present study, SOBEK Rural-1D combined with SOBEK-2D, has used for simulating drains as 1D and lake area as 2D. SOBEK Rural-1D Flow is a one-dimensional model that can simulate the flow and water quality in canals, river and estuary systems. SOBEK-2D (Overland flow) is a two-dimensional modeling system, which supports hydrologists' research on flood study, where the program can simulate flood progress, water depths, velocities and directions in the flood zone. The flow module has the ability of simulating unsteady flow in drains, while overland module is capable of simulating the water surface and the depth in the lakes area. SOBEK is based on highly performance computing technology, enabling it to handle water networks, from simple networks to highly complex networks [42].

The combined 1D 2D model has been built in order to:
• determine the water level of the Qarun lake under different scenarios;
• determine the volume of the lakes at different elevations and
• determine the salinity of Qarun Lake.

B. Model Setup.

The topographical identification was extracted from the index map of the Nile River System that is stored in SOBEK model. The (DEM) and (GIS) software has used during the development of the model in the present study. Qarun Lake area has simulated through a grid of vertical and horizontal gridlines 56.0 m apart. The simulated area has divided into a mesh of 743 x 250 cells. In addition, EMISAL pump stations were simulated. Fig. 9 shows the model schematization of Qarun Lake. The internal and external boundary conditions are determined during the creation of the model. These conditions can be entered into the program in the form of a file or table that contains data such as water depths, discharges, evaporation rate and rain. Other conditions can be defined through the program interface such as initial water levels, salinity rates, and structures locations.

After completion of the model, some parameters can be identified such as the simulation period, which starts from several minutes, and it can reach large number of years, as well as specifying the time step. The program then reads data files and period, and performs a check to ensure that there are no errors in the simulation.

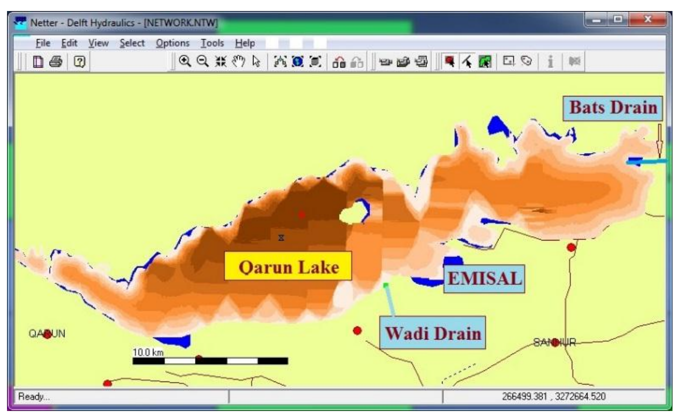

Fig. 9. Qarun Lake simulation, SOBEK program 2D.

C. Model Calibration.

Qarun Lake model has been calibrated for hydraulic resistance number of 35 using the average daily measured discharge, water withdrawn to EMISAL, evaporation and water levels of year 2002. The simulation period is one year, and the simulation time step of one day has selected. Fig. 10 shows the simulation results and Fig. 11 shows the relation between water levels calculated by SOBEK and measured water level of Qarun Lake.

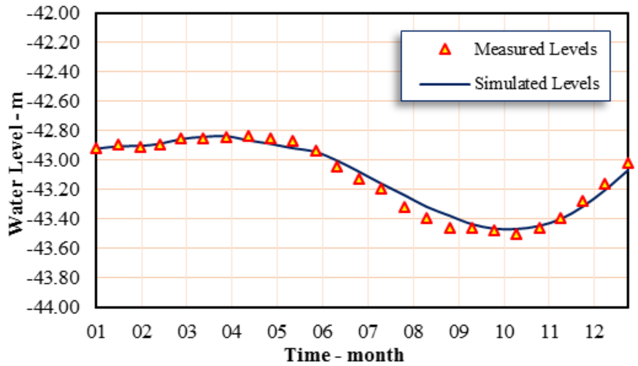

Fig. 10. Model calibration, comparison between observed and simulated water levels of Lake Qarun.

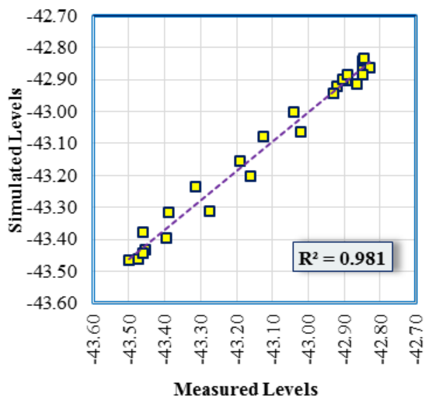

Fig. 11. Relationship between simulated and measured water levels of Lake Qarun.

By observing the results and previous figures, Values derived from simulations show good agreement with the measured values in the field. This gives confidence in the efficiency of the model on simulating Qarun Lake as well as trust in simulation results.

D. Scenarios Building.

There are some constraints that affect the management process of the Fayoum depression area, these are:

- Water quantity;
- Water levels;
- Water salinity;
- Future planning.

The process of building scenarios is to study the current situation to find out the actual causes of water and environmental problems in Fayoum depression, propose effective solutions to these problems and study the possibility of future expansions in agriculture and fisheries. The following Table .V summarizes the proposed scenarios for Lake Qarun.

TABLE. V.

BUILDING SCENARIOS FOR QARUN LAKE BALANCE.

Scenario	Balance type	Status Description
1	Water Balance	Simulating the current state of Qarun Lake by SOBEK program, using drainage water inflow to the lake, the amount of water withdrawn EMISAL, and the evaporation rate, to Calculate the annual variation of the lake's level, (Reference case).
	Salt Balance	Applying the salt balance equation between the amount of salt entering with the agricultural drainage water and the amount of salts extracted by the EMISAL, to estimate the change in lake's salinity, (Reference case).
2	Water Balance	Simulate water balance as scenario-1, after adding the minimum area of the new evaporation ponds.
	Salt Balance	Calculate salinity rate after adding the minimum area of the new evaporation ponds.
3	Water Balance	Same as scenario-2, with the maximum area of the new evaporation ponds.
	Salt Balance	Calculate salinity rate after adding the maximum area of the new evaporation ponds.
4	Salt Balance	Calculation of salinity in the case of the minimum area of the new evaporation ponds with the additional quantity of agricultural drainage water to stabilize the water volume of the lake
5	Salt Balance	Same as Scenario-4 with the case of maximum area of the new evaporation ponds and the addition of a quantity of agricultural drainage water to stabilize the water volume of the lake

E. Initial Conditions.

It is important to mention the initial conditions used in the different scenarios.

- Drainage water salinity 1.60 gm/lit.
- The initial water level is (-43.00) m.
- The initial water salinity is 35 gm/lit.
- The amount of water withdrawn EMISAL 20 mcm/year

VIII. RESULTS AND DISCUSSION

This part presents the equations for water balance of Qarun Lake and the data tables used in the process of simulation of the lake. As well as the production of digital and contour maps, also shape of the surface of the earth to help in reaching the best solutions to address the problem of water and salinity. Then comment on the results and choose the appropriate solutions for the application in practice.

A. Qarun Lake Water Balance.

In order to reach solutions to the problem of Lake Qarun, we had to study the water and salt balance of the lake and find out the causes of these problems so that we can develop possible scenarios and solutions, not only to eliminate the current problem but also to face the expected effects of future expansions in agriculture.

1) Qarun Lake Water Budget.

The equation of the water budget of Qarun Lake can be written as follows:

$$I - O + P \times A \pm G - E \times A = \Delta S \quad (2)$$

Where: I= inflow of drainage water to the lake (mcm), O= outflow, water withdrawn to the extraction of salts project (mcm/month), P= precipitation (mm/year), A= lake's surface area (km^2), G= seepage, the seepage can neglect or considered as equal to zero, depending on the previous studies as mentioned in [43], E= evaporation (mm/day), and ΔS=change of storage volume (mcm).

Since the lake has Precipitation less than 10 mm/year, and the seepage can be neglected, Eq. (2) can be reduced to:

$$I - O - E \times A = \Delta S \quad (3)$$

Table. VI shows average monthly amounts of drainage water, water withdrawn to the company of extracted salts (EMISAL), and Qarun Lake evaporation rate.

TABLE. VI.
DRAINAGE WATER, OUTFLOW TO EMISAL, AND EVAPORATION RATE, *(WMRI & FID).*

Month	Drainage	EMISAL	Evap.
	mcm	*mcm*	
1	26.09	0.31	2.185
2	30.3	0.39	2.93
3	42.25	0.9	4.565
4	43.73	1.19	6.195
5	35.39	2.11	6.72
6	25.34	2.58	7.825
7	29.69	3.03	8.09
8	39.83	2.73	7.94
9	51.14	2.33	6.735
10	50.06	2.25	5.41
11	58.62	0.81	3.2
12	60.98	0.47	2.075

To summarize the equation of the water balance of Qarun Lake in a clear and simplified manner, Fig. 12 shows the curves of incoming discharges, outgoing discharges from Qarun Lake, evaporation losses and the fluctuation of the water level in the lake throughout the year.

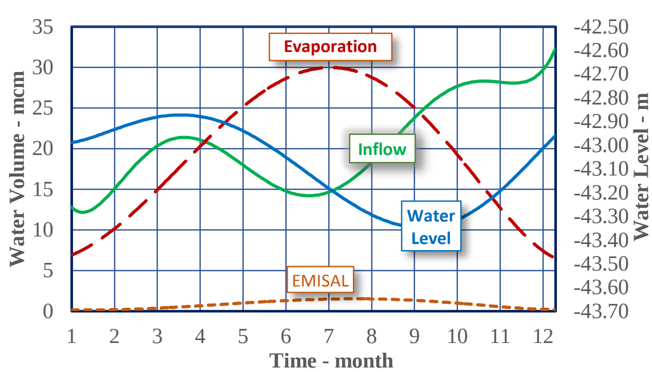

Fig. 12. Relationship between inflow and outflow of Qarun Lake with the resulted water level.

- Surface Area and Capacity of Qarun Lake.

In order to manage the water and salt balance, the relationship between water levels, surface area and the volumes of Qarun Lake was determined, as shown in Fig. 13 and Fig. 14 respectively.

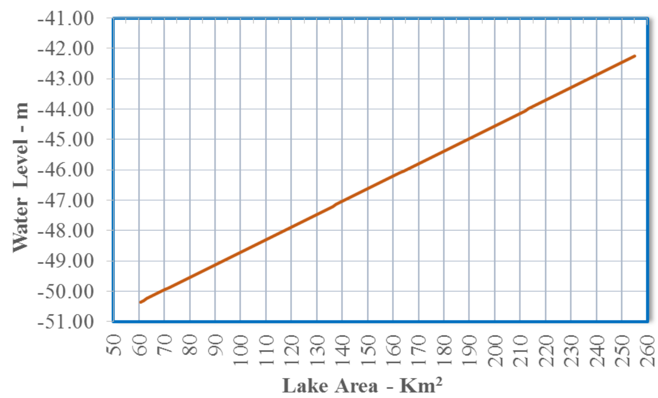

Fig. 13. Relationship between surface area of Qarun Lake and water level.

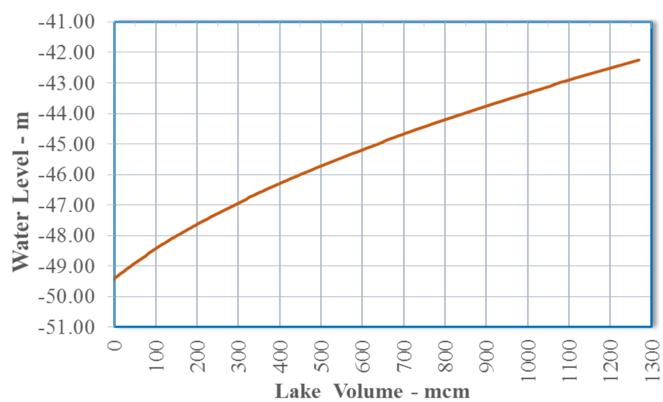

Fig. 14. Qarun Lake volume at different water levels.

The water volume of lake is 1078 mcm at corresponding water level of (-43.00) m and the water surface area 237.2 km^2 at the same level, This value corresponds to the measured value of surface area of aerial photography.

2) Scenario-1, Simulation of Qarun Lake at Current Status.

A simulation was conducted on the SOBEK program for the past years discharges. Water level fluctuation during the year as shown in the next Fig. 15. The level of the lake at the beginning of the year was (-43.00) and the level of the lake reached the maximum value (-42.88) in March and April, while the lowest value reached (-43.33). The lake reached (-42.956) at the end of the year, recording an increase in the lake level by about 4.4 cm from the beginning of the year.

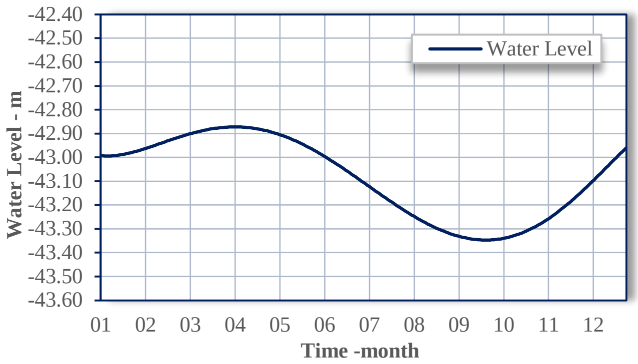

Fig. 15. Fluctuation of Qarun Lake water level during the year.

Since the ideal level of Qarun Lake is (-43.65), the maximum safe level is (-43.30), and the dangerous level is (-43.10). It is clear from the above figure that the level of the lake exceeds the danger from February to May, which is a threat for residential, tourist and agricultural land adjacent to the lake.

After the above study, there are two proposed solutions to the problems of Lake Qarun:

- Reducing the amount of drainage water flowing to Qarun Lake and redirect it to the Wadi El Rayyan lakes, but this solution contributes to high salinity levels in the lake.
- The second solution is best suited to the water level inrceasing and salinity problems, is the establishment of new evaporation areas added to the surface area of the lake.

3) *Searching for New Evaporation Ponds.*

It was necessary to find a solution to the problem of water level increasing and salinity accumulated by looking for a place for a new evaporation plant to evaporate the excessive water from the lake so as not to interfere with the activities of agriculture, fisheries and housing alike.

A map of the digital elevation model has downloaded from the site (https://earthexplorer.usgs.gov/) of the U.S. Geological Survey (USGS) in order to show land levels around lake, to determine the new evaporation areas. After obtaining the map of the study area, a three-dimensional model of the Earth's surface (3D Surface) has created, as shown in Fig. 16, using, (Surfer v.14.0.599) and (ArcGIS v.10.4.1) programs.

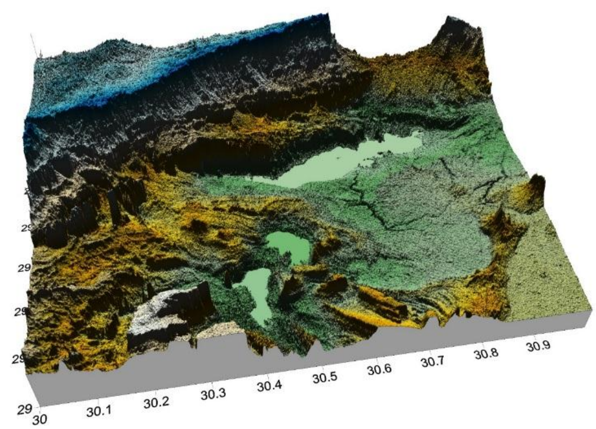

Fig. 16. Fayoum 3D surface as extracted from the Digital Elevation Model (DEM).

Using aerial maps and digital elevation maps extracted from satellite images, a comprehensive survey of the surrounding areas of the lake was conducted resulting the following observations.

- Through the 3D Digital Elevation Model (DEM) image, it is clear that the northern rocky area is very inclined towards the lake and is not suitable for the required evaporation ponds, except for small areas that do not meet the needs Fig. 16.
- The eastern, southern and western regions are full of agricultural activity and some areas have fish farms, particularly at the mouth of Al-Bats drain and Al-Wadi drain on the lake, as shown in Fig. 17.
- The suitable area for the new evaporation areas located in the northeast of the lake, which is approximately 36 square kilometers between the level (-42.00) and (-34.00), which is mostly flat except for some high places.

Fig. 17. Aerial map for Qarun Lake and surrounds, (Google Earth 2017).

In order to focus on the selected area for the new evaporation ponds, a part of the total map of Fayoum Governorate has cut off; and the digital elevation map has processed on ARGIS-v.10.4.1 program to convert the map into heights, in order to facilitate the determination of land levels and mapping the contour lines. The digital elevation map has converted to contour map with 2.0 m intervals as represented in Fig. 18.

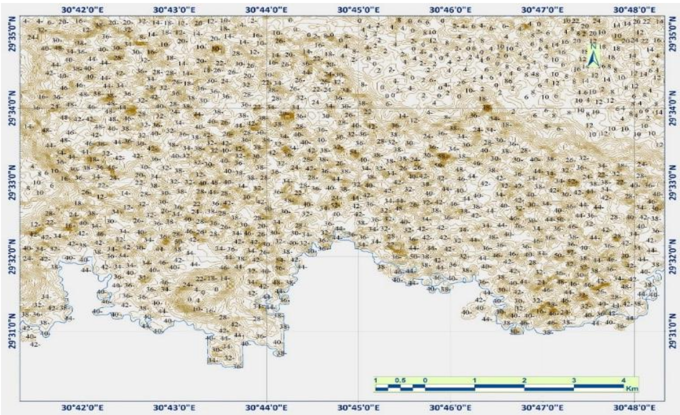

Fig. 18. Contour map of the study place in the northeastern part of Lake Qarun.

- Proposal to Divide the Selected Area into Separate Ponds.

The proposed area has been divided into four separate basins according to land levels, and at the lowest possible cost as in Fig. 19. Some ponds need a construction of a number of earth banks separating the basins from the ridge of Lake Qarun. Calculations results of the new ponds areas, levels, and the amount of evaporation of each basin were summarized in Table. VII.

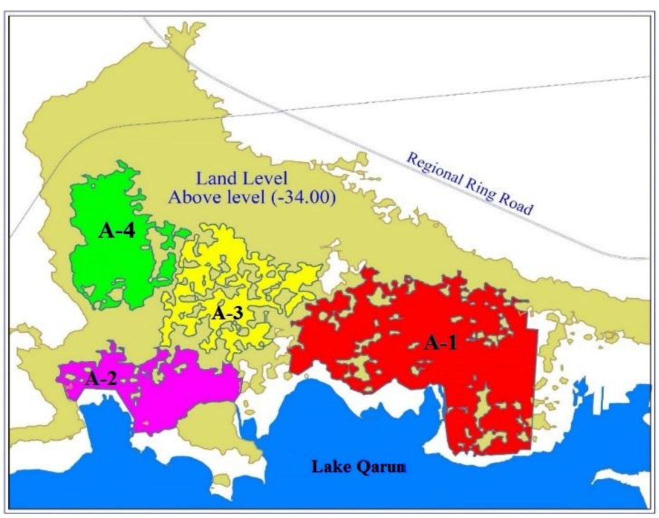

Fig. 19. New proposed evaporation ponds.

TABLE.

VII. EVAPORATION PONDS DETAILS.

Pond	Min. Level	Max. .Level	Area	Earth Bank		
	(m)	(m)	km^2	Level -m	Length-km	Height-m
A-1	(-44.00)	(-36.00)	12.67	-(40.00)	7.50	4.30
	(-44.00)	(-38.00)	8.43	-(40.00)	7.50	2.30
A-2	(-44.00)	(-36.00)	4.03	-(40.00)	3.33	4.30
	(-44.00)	(-38.00)	2.66	-(40.00)	3.33	2.30
A-3	(-38.00)	(-34.00)	4.50	-	-	-
A-4	(-48.00)	(-32.00)	6.02	-(34.00)	0.56	2.3
	(-48.00)	(-34.00)	4.88	-	-	-

From the previous table, the sum of the evaporation area can be calculated as follows:

- The Maximum evaporation area with earth bank of 2.30 m = 27.24 km^2,
- The Minimum evaporation area with earth bank of 4.3 m = 20.48 km^2.

4) Evaporation Ponds Simulation for Scenarios 2 and 3.

A simulation was carried out on SOBEK to measure the fluctuation of water levels in Qarun Lake in the following cases:

- Scenario-2: Study the balance between the current discharges entering Qarun Lake, the amount of water withdrawn to Emisal, evaporation rate, and the quantity of water withdrawn to the new evaporation ponds with minimum area.
- -Scenario-3: same as sxenario-2 with the amount of water withdrawn for the evaporation ponds with the maximum capacity. Simulation results appear in Fig. 20.

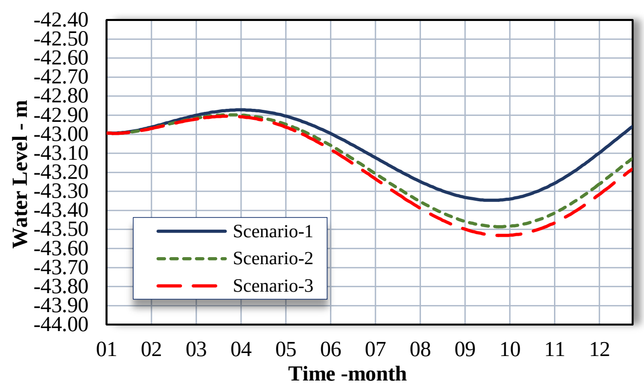

Fig.20. Fluctuation of water levels in Qarun Lake in the case of new evaporation ponds.

For easy comparison of the results of the previous three cases, simulation results were summarized in Table. VIII, it is included scenario-2 and scenario-3, comparing the two scenarios with the original state results in scenario-1.

TABLE. VIII.
EVAPORATION PONDS SIMULATION RESULTS.

Simulation cases	Start level (m)	Max. level (m)	Min. level (m)	End level (m)	Level change Δh (m)
Scenario-1	(-43.00)	(-42.88)	(-43.33)	(-42.956)	+ 0.044
Scenario-2	(-43.00)	(-42.90)	(-43.47)	(-43.124)	-0.124
Scenario-3	(-43.00)	(-42.91)	(-43.51)	(-43.179)	-0.179

After adding the minimum area of new evaporation ponds, the lake level dropped by 12.40 cm/year, while in the case of maximum evaporation area, the lake level decreased by 17.90 cm/year. We conclude from this that we need to establish new evaporation ponds to extract excess water from Qarun Lake, in order to reduce the water level of the lake and restore the safe water levels. As well as the establishment of evaporation ponds, increase the ability of Qarun Lake to receive new quantities of drainage water, which estimated at approximately 42 million cubic meters of water, giving a great hope for future expansions and increasing agricultural land by about 18000 feddans.

5) Future View of Qarun Lake Water Levels.

A simulation of water balance scenarios 1, 2 and 3 of Qarun Lake carried out for a future period of 6 years to identify the effects of adding a new evaporation surfaces to the lake.
The following Fig. 21 shows the comparison of the three cases with the clarification of the levels of the lake at safe, extreme and dangerous state.

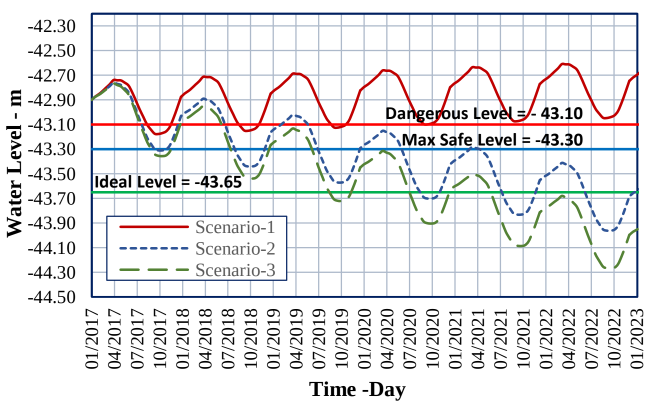

Fig.21. Water levels in Qarun Lake at future period of 6 years.

The previous figure shows the following:

- The level of the lake with the current discharges exceeds the danger level. This is causing future disasters.
- In the case of addition of evaporation surfaces at a minimum area, the maximum lake level drops to the safe level at the beginning of the fifth year from the beginning of the addition of evaporation areas.
- In the case of addition of evaporation surfaces at a maximum area, the maximum lake level drops to the safe maximum level at the beginning of the fourth year.
- It is clear that there is no way to solve the problem of Qarun Lake other than to add new evaporation areas.

B. Qarun Lake Salt Balance.

The salinity balance of Qarun Lake is a relationship between the amount of salt entering the lake with the drainage water, the amount of salt extracted by the salt plant, and the amount of salt precipitated in the lake.

1) Qarun Lake Salt Budget.

Salt budget equation can be written as:

$$C_i \times I - C_o \times O = \Delta C \times (V - \Delta V) \qquad (4)$$

Where: C_i =salinity of inflow (gm/lit), I =inflow of drainage water from El-Bats, El-Wadi, and minor drains (mcm), C_o=salinity of outflow (gm/lit), O=outflow, water withdrawn for the extraction of salts project, and new evaporation ponds (mcm), ΔC=change of lake salinity (gm/lit), V = Qarun Lake volume (mcm), ΔV =change in lake volume in the specified period, (mcm).

- Application of Salt Balance Equation to Scenarios (1 to 3).

This equation (4) will apply to the previous water balance scenarios 1, 2 and 3 as follow:

- The first scenario: salt balance between the amount of salt entering with agricultural drainage water, and the amount of salt extracted by EMISAL Company, and calculate the change of the salinity of lake.
- The second scenario: the same as the first scenario with the addition of salt water that withdrawn through the new evaporation pond at minimum capacity.
- The third scenario: is the same as first scenario with the addition of salt water withdrawn through the new evaporation pond at maximum capacity.

As the size of the lake changes daily due to incoming, outgoing discharges and evaporation, which affect the rate of salinity. Therefore, the size of the lake calculated daily to ensure correct salinity calculations. The figure below Fig. 22 shows the daily variation of the size of Lake Qarun, and results of salinity equation represented in Fig. 23. All of these results are tabulated in the following Table. IX .

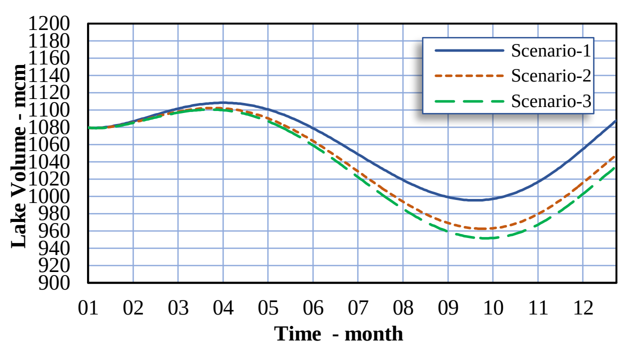

Fig. 22. Qarun Lake volume at current state, and after adding the proposed evaporation ponds.

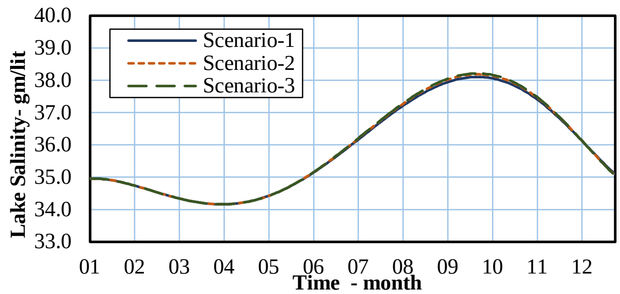

Fig. 23. Qarun Lake salinity fluctuation after adding evaporation ponds.

TABLE.
IX. QARUN LAKE SALT BALANCE RESULTS.

Simulation cases	Start volume	End Volume	Volume Change	Start salinity	End salinity	Salinity change
	mcm	*mcm*	*mcm*	*gm/lit*	*gm/lit*	*gm/lit*
Scenario-1	1078.0	1088.41	+10.41	35.0	35.069	+ 0.069
Scenario-2	1078.0	1048.51	-29.49	35.0	35.033	+ 0.033
Scenario-3	1078.0	1035.35	-42.65	35.0	35.020	+ 0.020

The result derived from previous scenarios, there has been little change in the rate of salinity since the amount of salt extracted from the lake is accompanied by a large amount of water, resulting in a decrease in the size of the lake. Reducing the saline load of the lake with the reduction of the water volume of the lake in the same proportion leads to the stability of the salinity ratio. To reduce the salinity of the lake, it is necessary to add a quantity of agricultural drainage water to equal the amount withdrawn by the evaporation ponds. This means maintaining constant lake's water level and volume.

-Application of Salt Balance Equation to Scenarios (4 and 5).

In this section, new quantities of agricultural wastewater will add to the lake, equivalent to the quantities withdrawn for the new evaporation ponds, in order to study the resulted salinity rate of the lake.

- In the fourth scenario, the amount of water added to Qarun Lake 29.50 million cubic meters per year to maintain the stability of lake's size.
- In the fifth scenario, the additional quantity is 42.7 million cubic meters per year.

The figure below Fig. 24 shows the daily variation of the size of Qarun Lake, and results of salinity equation were represented in Fig. 25.

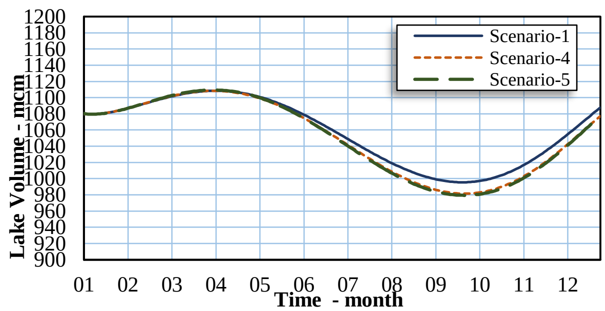

Fig. 24. Fixing Qarun Lake volume by adding new quantities of drainage water.

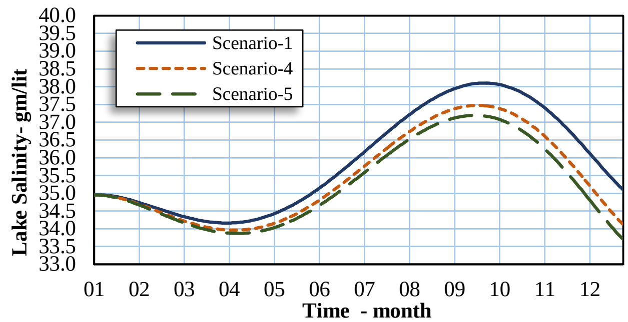

Fig. 25. Qarun Lake salinity after adding the new drainage water.

After adding a new quantity of agricultural drainage water, the effect of the addition of new evaporation ponds on the salinity rate of Qarun Lake was clearly emerged. All results are summarized in Table. X.

TABLE. X.
SALT BALANCE RESULTS AFTER ADDING NEW QUANTITIES OF DRAINAGE WATER.

Simulation cases	Start volume	End volume	Volume Change	Start salinity	End salinity	Salinity change
	mcm	*mcm*	*mcm*	*gm/lit*	*gm/lit*	*gm/lit*
Scenario-4	1078	1078	0.00	35.0	34.091	- 0.91
Scenario-5	1078	1078	0.00	35.0	33.665	- 1.335

- When the minimum evaporation areas were used, salinity decreased by 0.91 gm/lit/year. In this case, the amount of salt extracted from the lake is approximately 1437 tons per year.
- In the case of maximum evaporation volume, salinity decreased by 1.335 gm/lit/year, and salt extracted from the lake is approximately 1911 tons per year.
- It is concluded that we need to create additional evaporation areas to Qarun Lake to restore water and salt balance.

C. Advantages of the New Evaporation Ponds.

The advantages of establishing the new evaporation ponds could be summarized in the following points:

- The advantages of establishing the new evaporation ponds could be summarized in the following points:
- The proposed land for the new project is uninhabited and there are no costs of expropriation and there is no conflict with the residential areas either.
- According to the exploratory maps of the area, the soil in this place is not suitable for agriculture, and there is no conflict between the project and the current or future agricultural activities.
- Proposed land with a slight slope of 1 m / km, enabling the formation of evaporation basins in the form of terraces.
- Access to the stage of water balance of Qarun Lake, due to the amount of water withdrawn to the project.
- Exploit new evaporation basins in the establishment of a factory to extract salts like EMISAL.
- From previous studies, it is clear that the concentration of salinity on the northern side of the lake is higher than the

southern side, which enhances the economic feasibility of the project.

- The amount of salt extracted from evaporation ponds is 4 to 5 times the amount extracted by EMISAL.
- The proposed area is very close to the regional ring road and Cairo-Fayoum road, which can facilitates product commercialization.
- Maintaining salinity of the cumulative increase and turn it into gradual decline.
- Providing the opportunity to increase the water share of Fayoum governorate to cultivate new areas, this is due to increased capacity of the lake to receive more amounts of agricultural drainage water.

CONCLUSIONS.

- The discharges coming to Qarun Lake, and the amount of water withdrawn to the EMISAL plant has collected, as well as the volume of evaporation of the lake. A simulation was conducted on the SOBEK 1D2D program for the past years discharges. The drainage water discharged into Qarun Lake exceeds the outflow of the lake and the quantity of evaporation by about 10.40 MCM annually, which means increasing the level of the lake by about 4.40 cm /year
- With the help of digital elevation maps and satellite images, a place has been set up to allow the construction of new evaporation ponds, to discharge the amount of water that exceeds the capacity of the lake. The proposed areas for evaporation ponds, Divided into four basins according to the contour lines.
- In the case of establishment of an earth bank between Qarun Lake and evaporation ponds with a height of 2.30 m, the area available to the area of basins is 20.48 km^2. When added to the lake, the withdrawn water helps reduce the level of the lake by 12.40 cm/year, the maximum lake level drops to the safe maximum level at the beginning of the fifth year from the beginning of the addition of evaporation areas.
- When the bank level rises to 4.30 meters, the area of the evaporation ponds is 27.24 km^2. This area contributes to reducing the lake level by 17.90 cm/year. The maximum lake level drops to the safe maximum level at the beginning of the fourth year from the beginning of the addition of evaporation areas.
- The establishment of evaporation ponds increase the ability of Qarun Lake to receive new quantities of drainage water, which estimated at approximately 42 MCM of water per year, which gives great hope for future expansions and increasing agricultural land.
- The equation of salt balance of Qarun Lake applied after addition of the new evaporation ponds. After adding the minimum evaporation area of 20.48 km^2, there is an increase in salinity rate by 0.033 gm/lit/year. As well as for the evaporation area of 27.24 km^2, salinity rate has increased by 0.020 gm/lit/year.
- Due to the salinity of Qarun Lake has not affected by the added evaporation ponds, a simulation of the lake has performed after adding a new quantity of agricultural drainage water in the fourth and fifth scenario. The result of the fourth scenario show a decrease in the salinity rate by 0.910 gm/lit, moreover salinity of the lake has decreased from 35.00 to 30.03 gm/ lit in the next six years. In the fifth scenario, salinity rate has reduced by 1.335 gm/lit per year, as well as salinity of the lake has decreased to 27.92 at the end of the six years.

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NOTATION

A	Lake surface area
C	Chezy coefficient
C_i	Salinity concentration of inflow
C_o	Salinity concentration of outflow
E	Evaporation
G	Seepage from the lakes
I	Inflow
O	Outflow
P	Precipitation
Q	Discharge
R	Runoff
S	Salinity
V	Lake volume
ΔC	Change of lake salinity
ΔS	Change of the storage
ΔV	Change in lake volume

ABBREVIATIONS

BCM	Billion Cubic Meters
DEM	Digital Elevation Model
DN	Digital Number
DRI	Drainage Research Institute
EC	Electrical Conductivity
EEAA	Egyptian Environmental Affairs Agency
EMISAL	Egyptian Salt and Minerals Company
FAO	Food and Agriculture Organization
FID	Fayoum Irrigation Department
FWSBM	Fayoum Water and Salt Balance Model Project
GIS	Geographic Information Systems
HRI	Hydraulic Research Institute
MCM	Million Cubic Meters
MSL	Mean Sea Level
MWRI	Ministry of Water Resources and Irrigation
NASA	National Aeronautics and Space Administration
NHI	Netherlands Hydrological modelling Instrument
NWRC	National Water Research Center
SWAT	Soil and Water Assessment Tool
TDS	Total Dissolved Solids
USGS	United States Geological Survey
WHO	World Health Organization, United Nations
WMRI	Water Management Research Institute