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RESERVOIR HYDROLOGIC ROUTING FOR THE HYDRODYNAMIC OF AL-MANZALA LAKE, EGYPT

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ABSTRACT: Al-Manzala lake receives most of the agricultural drainage water of the east Nile Delta region in Egypt. As a consequence, hydrological status of the lake has been changed due to this process. Accordingly, knowing the interaction between Mediterranean Sea water and lake's water was desired. Under these circumstances, reservoir hydrologic routing procedure was implemented to investigate the lake's hydrodynamic. In this context, the lake hydrodynamic is represented by water level and flow direction. To implement the flood routing process, meteorological data and lake's water resources were investigated, collected, and analyzed. The study developed an auxiliary diagram that relates storage change within the lake and outflow to the sea. Reservoir hydrologic routing results estimated lake's water level, outflow, and storage change in the lake for the study period. In addition, an inflow-outflow hydrograph was developed. Furthermore, the water budget of the lake was investigated. Results analysis indicated that water level fluctuates between 17.5 and 56 cm with an average value of 37 cm above mean sea level. This fluctuation maintains a continuous flow from the lake to the sea. In addition, water budget results defined evaporation losses (27.8%), outflow (64.5%), and change in storage (7.7%). It is recommended to study the effect of climate change induced sea-level rise and the Mediterranean Sea tide on the hydrodynamic and hydrologic status of the lake.

Keywords: Hydrologic routing, Al Manzala lake, Hydrodynamics, Outflow, Storage change.

1. INTRODUCTION

Egypt northern coast hosts five coastal lakes named, from east to west, Al Bardaweel lake, Al Manzala lake, Al Burulus lake, Edku lake, and Mariut lake. Except for Al Bardaweel lake located in the North Sinai coastal zone, all other four lakes are situated in the Nile Delta coastal zones. The Nile Delta coastal lakes have an important environmental role for Egypt because they receive most of the drainage waters through the drainage system. These lakes used to contribute about 50% of Egypt's total fish production before the year 2014 [1].

Economically, Al Manzala lake is considered one of the most valuable fish sources in Egypt. It contributed about 35% of the total country yield during the 1980s [2]. At the present, it is the most productive lake in Egypt and contributes about 30% of the total annual production of the Egyptian lakes, which contribute about 12.5% of Egypt's total fish production [3]. In fact, the production reduction is due to several reasons resulted from human activities.

The lake's hydrological status has been changed as a result of receiving drainage water. This process resulted in changes in fish production as well as fish catch composition. Accordingly, the lake has been under intensive environmental investigations.

Water pollution has been one of the most important issues concerning the environment. Not only in large oceans but also in rivers and lakes which are closely related to daily life. Few studies on lake-water pollution have been taken in countries such as Egypt, Iran, and the USA. The study in Egypt was carried out by [4], [5].

Similar studies on numerical models for lake environments have also been conducted by [6], [7], and [8]. This was stated by [9].

In fact, degradation of the hydrological function is caused by exploitation of water and land resources exceeding their bearing capacity [10]. In this respect and due to lack of hydrological data, Al Manzala lake's hydrodynamic was rarely modeled in previous studies [11].

Regarding Al Manzala lake water budget, previous studies implemented simple inflow-outflow equation to estimate outflow from the lake to the sea [12], [13]. Furthermore, previous studies did not implement the hydrologic routing technique to investigate Al Manzala lake's hydrodynamic or to define its water budget. Accordingly, the reservoir hydrologic routing method was implemented in the current study to investigate lakes' hydrodynamic in terms of lake's water level and flow conditions. In addition, water budget of the lake's hydrologic system is investigated.

To implement the reservoir hydrologic routing method, lake's water resources (known as inflow or gains) and losses were defined. Historical data for annual inflows to the lake from the agricultural drainage system, rainfall, and evaporation data were investigated, collected, and analyzed.

2. STUDY AREA

Al-Manzala Lake is the largest Egyptian coastal lakes situated along the Mediterranean Sea coast. It is located at the north-eastern side of the Nile Delta between longitudes (31º45`-32º15`E) and latitudes (31º00` – 31º30` N), fig.1. It covers an area of about 750 km^2. A sandy bar separates the lake from the Mediterranean Sea in the north except at three openings where the interaction of water occurs between the lake and the Mediterranean Sea. These openings are El-Gamil, El-Boughdady, and the new El-Gamil. The eastern border for the lake is the Suez Canal. To the west, the Damietta branch of the Nile River borders the lake while the southern side of the lake is bordered by cultivated land.

The lake receives agricultural, industrial, and domestic effluents through Faraskor, El-Serw, Mataria, Haddus, and Bahr El-Baqar drains. These five drains are considered the main drains in the eastern Nile Delta.

The lake has been gradually transformed from a marine estuary environment to a brackish water environment. Exchange processes between the Mediterranean Sea and the lake water enhance water quality in the vicinity of the openings only.

Human activities and development programs such as the construction of Aswan High Dam, land cultivation activities, human settlements, and wastewater discharge to the lake have impacted water quality status in the lake [14]. Before the construction of Aswan High Dam, fresh Nile water used to flow into the lake through Nile Damietta branch. Recently and due to freshwater deficit in Egypt, little quantities of freshwater reaches the lake.

Water salinity in the lake fluctuates spatially. Salinity is low in the south and west, brackish over most of its area, and saline in the extreme northeast.

The lake is shallow with depths vary between 0.7 to 1.3 m with an average depth of one meter. The lake is composed of about 30 interconnected basins which vary in their hydrological and water quality characteristics.

Water resources (inflows or gains) of the lake are limited to drainage water and little rainfall quantities, while the lake's hydrology is affected by evaporation losses as well as outflows of water to the sea.

Mediterranean Sea tide has little influence (through the openings) on the water exchange process. In the vicinity of lakes' openings, the water environment is more strongly influenced by sea water due to tide action.

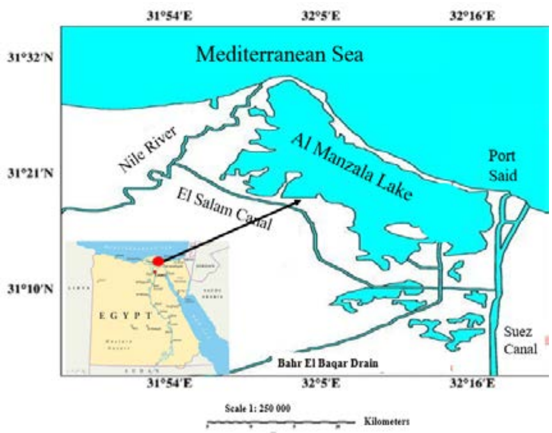

Fig .1 Layout of Al-Manzala Lake

3. MATERIALS AND METHODS

The reservoir hydrologic routing procedure is the passage of an inflow hydrograph through a reservoir as an unsteady-flow phenomenon. It requires investigation of gains and losses of the hydrologic system of the lake. Gains are represented by drains discharges and rainfall whereas losses are dominated by outflows from the lake to the Mediterranean Sea as well as evaporation from lakes' surface water and transpiration from vegetation cover.

3.1 Water Resources (Inflows or Gains)

3.1.1 Drains Discharges

Historical data for drainage discharges into the lake indicate that the drainage system discharged an average annual volume of about 3882 million cubic meters during years 1984-2002.

The maximum rate of water is discharged in July and August while the lake receives minimum rate in February as presented in table 1, figure.2.

Bahr El Baqar drain contributed about 36% of drainage water into the lake over the historical data. Haddus Drain is the second-largest source of drainage water. It contributed about 31 % for the same period. Both drains (Bahr El Baqar and Haddus drains contributed about 66% of total inflows discharged into the lake over years 1984 - 2002. On the other hand, low average (8.3, 11.25, and 13.45%) were contributed by Faraskor, Mataria, and Lower Serw drains, respectively.

The same conclusion was drawn by other researchers. They found that Bahr El Baqar and Haddus drains contributed about 67% of drainage discharges to Al Manzala lake. On the other hand, the less percentages were contributed through Faraskor, Matarria, and Lower Serw (10, 11, and 14%), respectively [15].

Table 1 Average drainage water discharged into Al-Manzala lake (Eastern Delta, 1984-2002), [16].

Drain	Lower Serw	Mataria	Farsqur	Haddus	Bahr El-Baqar	Total
Year	Q 10^6 (m^3/mo.)	Q 10^6 (m^3/mo.)	Q 10^6 (m^3/mo.)	Q 10^6 (m^3/mo.)	Q 10^6 (m^3/mo.)	Q 10^6 (m^3/mo.)
84/85	620	263	274	2051	1182	4390
85/86	611	280	287	2005	1035	4218
86/87	631	288	284	1567	1035	3805
87/88	578	282	302	1480	868	3510
88/89	564	296	321	1155	845	3181
89/90	570	366	305	1526	884	3651
90/91	628	417	294	1240	965	3544
91/92	556	425	321	1381	1110	3793
92/93	678	552	308	1433	1122	4093
93/94	646	521	316	1578	1156	4217
94/95	436	549	261	1042	1540	3828
95/96	509	566	329	761	1623	3788
96/97	402	581	316	806	1782	3887
97/98	282	583	314	805	1827	3811
98/99	134	540	366	935	2079	4054
99/00	575	447	425	865	1818	4130
00/01	482	323	372	746	1893	3816
01/02	494	563	427	592	2091	4167
Aver.	522	436	323	1220	1380	3882
%	13.4	11.2	8.33	31.44	35.57	100

Q: Drainage Water Discharge (million m3 / month)

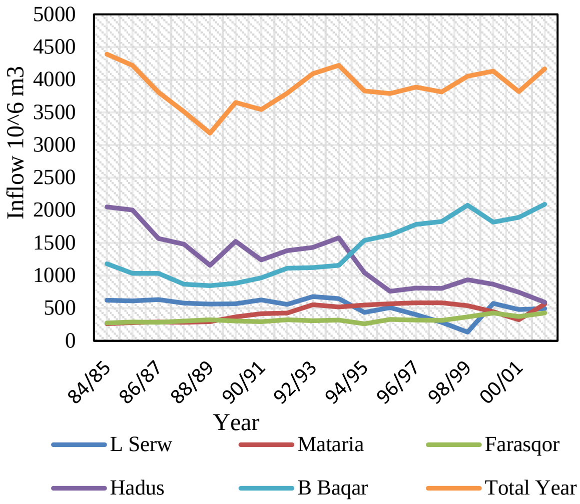

Fig.2 Annual Discharges of Drainage Water into Al Manzala Lake (1984-2002), after [16].

To indicate the monthly variation of agricultural discharges into the lake by each drain, available monthly data for the year 1999-2000 is presented in figure.3. Recent data indicated that discharges have increased over the years 2012–2015 with an average annual rate of about 4507.667 million cubic meter, table 2. Data for monthly inflows in table 2 were implemented in the study as it represents the most recent data available

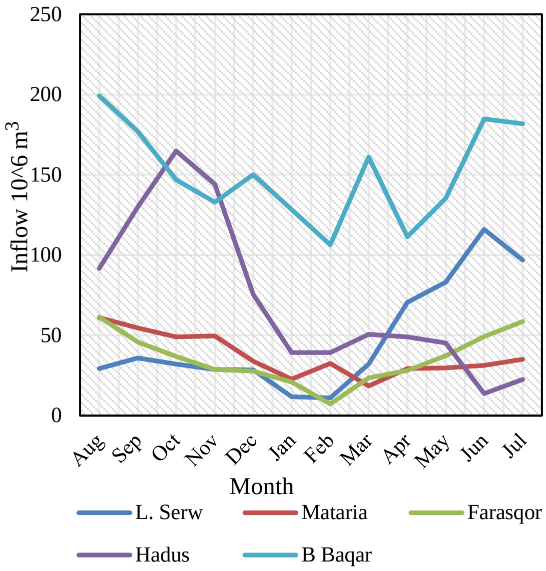

Fig.3 Monthly Drains Discharges (1999-2000)

Table 2 Monthly inflows to Al Manzala lake in years (2012-2015) (Million m^3), after [17].

Month	2013-2013	2013-2014	2014-2015	Aver. Monthly
January	490.4	482.3	476.4	483.
February	491.3	483.2	477.3	484
March	476.3	468.5	462.8	469
April	425.5	418.5	413.4	419
May	350.0	344.3	340.1	345
June	247.1	243.1	240.1	243
July	217.6	214.0	211.4	215
August	316.5	311.4	307.5	312
September	319.6	314.4	310.6	315
October	366.4	360.4	356.0	361
November	437.9	430.8	425.5	432
December	436.7	429.5	424.2	430
Annual Discharges	4576	4501	4446	4507

3.1.2. Rainfall

Rainfall measurements in three meteorological stations close to Al Manzala lake were collected and statically analyzed to define the average monthly rainfall over the lake for the last 30 years. These stations are located in Port Said (northeastern corner), Damietta (northwestern corner), and

Ismailia (southeastern corner). Average values of rainfall depth measurements are tabulated in table 3 and illustrated in fig.4.

Table 3 Average monthly rainfall depth over Al Manzala lake (mm)

Month	Average	Ismailia	Damietta	P. Said
Jan.	17	7	29	15
Feb.	11.3	4	18	12
Mar.	10.4	4	17	10
Apr.	4.3	2	6	5
May	1.4	1	1	2
June	0	0	0	0
July	0	0	0	0
Aug	0	0	0	0
Sep	0	0	0	0
Oct	5.6	1	10	6
Nov	9.7	4	14	11
Dec	15	6	22	17

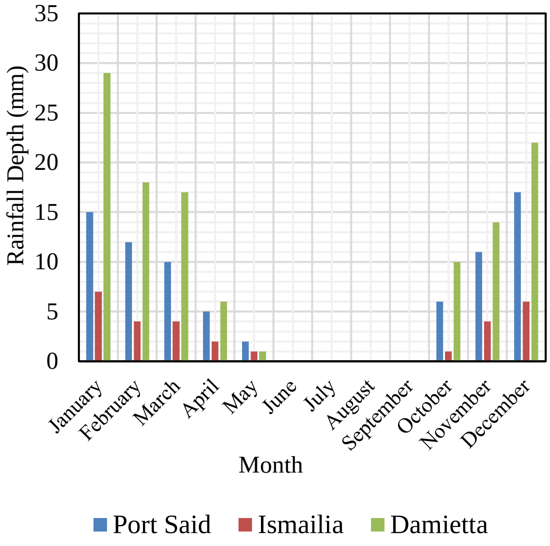

Fig.4 Rainfall Depth at Al Manzala Lake

Rainfall analysis indicated that the lake receives about 75 mm of rainfall annually. Most of the rainfall is received in November, December, January, February, and March. The area, as an arid zone, does not receive any rainfall in the summer months (June through September).

To estimate the rainfall monthly quantities, the average values in table 3 were multiplied by the surface area of the lake (750 km2), table 4.

Table 4 Rainfall inflows into Al Manzala Lake

Month	Rainfall Vol. (10^6 m^3)	Rainfall Depth (mm)
Jan	12.75	17
Feb	8.5	11.3
Mar	7.75	10.3
Apr	3.25	4.3
May	1	1.3
Jun	0	0
July	0	0
Aug	0	0
Sep	0	0
Oct	4.25	5.7
Nov	7.25	9.7
Dec	11.25	15
Total	56	74.6

3.2 Lak's Losses

3.2.1 Evaporation

A standard class "A" pan was installed to measure pan evaporation in a constructed wetland in the vicinity of Bahr El Bakar drain discharging area [18], [19]. In fact, pan evaporation represents evaporation from the free water surface as well as transpiration from aquatic weeds spread over the lake. Data were collected continuously on hourly basis through electronic sensors and stored on a data logger [20]. Measured data were analyzed to define average daily evaporation for each month. Monthly evaporation was estimated by multiplying the average daily value by the number of days in each month. Monthly evaporation losses were obtained by considering lake's surface area, table 5.

Fig.5 illustrates a simple presentation of drains discharges into Al Manzala lake, rainfall quantities, and evaporation losses.

Table 5: Average Daily and Monthly Evaporation Losses from Al Manzala Lake

Month	Volume (10^6*m^3)	Monthly (mm)	Daily (mm)
Jan	44.64	59.52	1.92
Feb	77.07	102.76	3.67
Mar	77.19	102.92	3.32
Apr	106.2	141.6	4.72
May	123.2	164.3	5.3
Jun	174.6	232.8	7.76
July	157.9	210.5	6.79
Aug	157.9	210.5	6.79
Sep	127.8	170.4	5.68
Oct	106.7	142.3	4.59
Nov	68.2	90.9	3.03
Dec	45.8	61.1	1.97
Tot.	1267.2	1690	

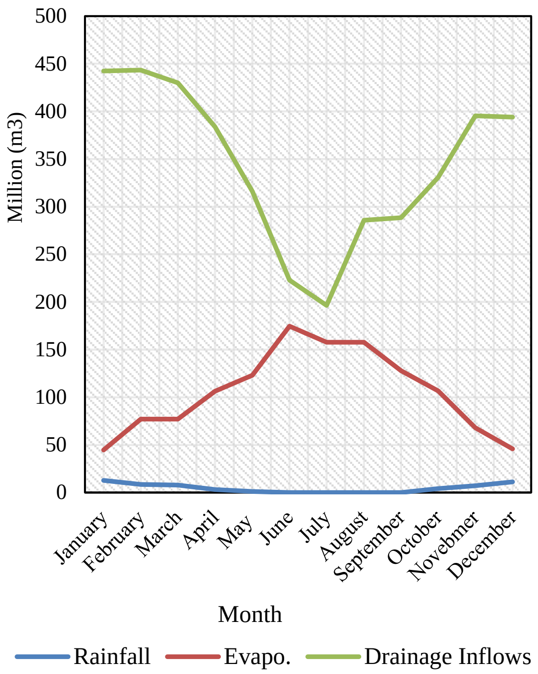

Fig.5 Quantities of Monthly Drains Inflows, Rainfall, and Evaporation, Al Manzala Lake

3.2.2 Outflow to Mediterranean Sea

The reservoir hydrologic routing procedure was discussed and presented previously [21]. Reservoir flood routing is the passage of an inflow hydrograph through a reservoir as an unsteady-flow phenomenon. The continuity equation is used in all hydrologic routing as the primary equation. It states that the difference between the inflow and outflow rate is equal to the rate of change in storage as follows:

$$I - O = (S/\Delta T)$$

The continuity equation could be rewritten as follows:

$$\frac{(I_1 + I_2)\Delta T}{2} - \frac{(O_1 + O_2)\Delta T}{2} = S_2 - S_1 \quad (1)$$

Where I and O represent rates of inflow and outflow while S refers to the storage. ΔT is a suitable time interval for the routing period. The subscripts 1 and 2 refer to the start and end of any time step ΔT.

The routing problem consists of finding outflow "O" as a function of time, given inflow "I" as a function of time, and having information or making assumptions about storage "S".

Any procedure for routing an inflow hydrograph generally has to adopt a finite difference technique and choosing a suitable time interval for the routing period ΔT. In the current study, the routing period ΔT has been set as a month.

At the beginning of the first time step, all values in Eq.1 are known except O_2 and S_2. Thus with two unknowns, a second equation is needed to be solved for O_2 at the end of a time step. A second equation was obtained by relating S to O alone. The two equations are then used recursively to find sequential values of O through the necessary number of ΔT intervals until the outflow hydrograph can be fully defined.

In this context, it is convenient to rearrange Eq.1 to get the unknowns S_2 and O_2 on one side of the equation and to adjust the O_1 term to produce Eq.2 as follow:

$$\left(\frac{S_2}{\Delta T} + \frac{O_2}{2}\right) = \left(\frac{S_1}{\Delta T} + \frac{O_1}{2}\right) + \frac{I_1 + I_2}{2} - O_1 \quad (2)$$

Since S is a function of O, [(S/ΔT) + (O/2)] is also a specific function of O (for a given ΔT), replacing [(S/ΔT) + (O/2)] by G, for simplification, Eq.3 can be rewritten as:

$$G_2 = G_1 + I_m - O_1 \quad (3)$$

Where $I_m = (I_1+I_2)/2$.

In order to estimate G_2, G_1 would be estimated by assuming O_1 and calculating $S_1/\Delta T$ as the surface area of the lake is known.

To estimate outflows, an auxiliary curve was developed to Al Manzala lake assuming that the lake water at the beginning of the process has zero levels. This means that the water level in the lake has the same level as the sea.

4. RESULTS AND ANALYSIS

For a lake connected to the sea (as the study case), the temporary storage, S, is directly and uniquely related to water level (H) above mean sea level. The outflow from the lake to the sea is also directly and uniquely related to H. Hence S is indirectly a function of outflow O. Accordingly, an auxiliary curve that would help in estimating outflow and change in lake storage as a function in water level was developed for the study area. Derivation of the auxiliary curve is tabulated in table 6. The outflow is plotted against G and a curve was developed for the study area to define the relationship between O and G, fig.6. Eq.3 and the auxiliary curve in fig.6 provide an elegant and rapid step-by-step solution. At the beginning of any time step, G2 would be G1 for the following step.

Table 6 Derivation of the auxiliary curve of O versus G.

dH (cm)	S/ΔT (m^3/s)	Outflow (m^3/s)	G (m3/s)
0.05	14.4675	5	16.9675
0.1	28.935	28.935	43.4025
0.15	43.4025	57.87	72.3375
0.2	57.87	86.805	101.272
0.25	72.3375	115.74	130.207
0.3	86.805	144.675	159.142
0.35	101.2725	173.61	188.077
0.4	115.74	202.545	217.012
0.45	130.2075	231.48	245.947
0.5	144.675	260.415	274.882
0.55	159.1425	289.35	303.817
0.6	173.61	318.285	332.752

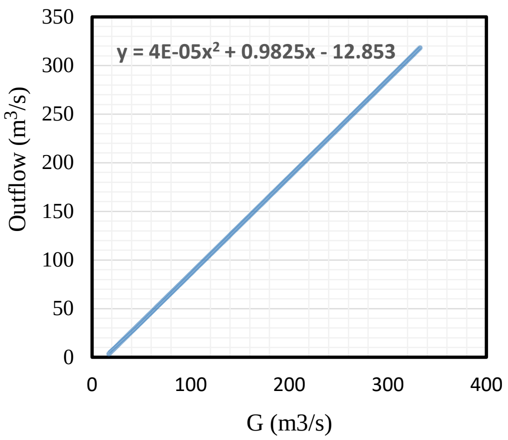

Fig.6 Developed auxiliary curve for Al Manzala Lake.

For the study period, 2012-2015, flood routing results are presented in table 7. It is worth mentioning that the study assumed that drainage waters have a spatial and temporal uniform distribution over the month. Results that describe the fluctuation in lake's water level related to the storage change in the lake are presented in the table as well as in fig. 7.

As the hydrologic system of the lake is a dynamic and cumulative processes, water gains (drainage discharges and rainfall) and water losses (evaporation and outflows) change from one month to another. This process results in a continuous change in lake's water storage all over the year. Accordingly, water stored in the lake increases or decreases due to the difference between inflow and outflow. In other words, the minus sign in the dS column in the table refers to more outflow than inflow in that time step. In addition, results indicated that reservoir water level fluctuated between 17.5 and 56 cm for the study period. The minus sign in (dH) column in table 7 refers to less storage in that month than in the previous month.

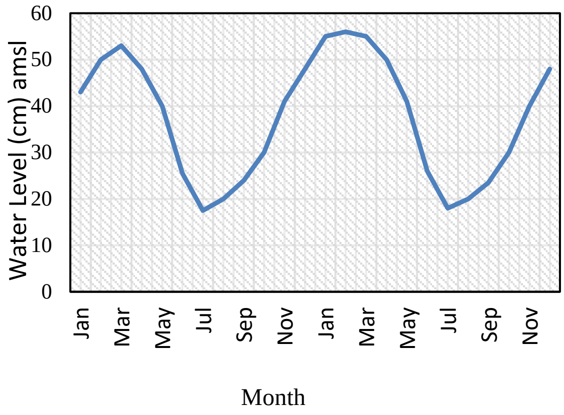

Fig.7 Water level in Al Manzala Lake, 2012-2015.

Furthermore, the inflow-outflow hydrograph is illustrated in fig.8. The figure shows a typical inflow/outflow hydrograph resulted from the reservoir flood routing procedure.

Results indicated that the lake received about 4507.667 million cubic meters from the drainage system during the study period (2012-2015) while its capacity is about 750 million cubic meters. This means that the lake received as much as six times its capacity. Accordingly, results indicated that the water level of the lake is always above sea level and water flows from the lake to the sea all over the year.

Results indicated that the net inflow (drainage discharges plus rainfall minus evaporation) varies from about 21 to about 174 m3/s without any trend but according to the climatic conditions and water requirements in the catchment area of the lake. On the other hand, outflow changes from about 43 to 153 m3/s as presented in table 7 and illustrated in fig.8. Accordingly, storage change is in a dynamic and continuous process as it represents the difference between inflow and outflow.

For simplification, a simple test was made for the lake water budget, table 8. Results demonstrated that the hydrological system of the lake is influenced by drainage discharges which represent about 98.77% of the water resources while rainfall represents a very tinny ratio. As the surface area of the lake is huge (750 km^2), evaporation losses share about 27.8% and outflow represents about 64.5%. The change in storage accounts for 7.7% with an average water level of about 37 cm above mean sea level. This average level maintains continuous flow from the lake towards the Mediterranean Sea.

Table 7: Results of the reservoir hydrologic flood routing for Al Manzala Lake.

Month	Inflow*	Im	O*	dS*	(Im –O)*	G*	dH (cm)	Water Level H (cm)
	0							
Jan.	174.08	174.08	50	124.08	124.08	149.08	43	43
Feb.	160.3	167.19	139.43	20.866	14.806	273.16	7.2	50
Mar.	154.24	157.27	146.81	7.4227	-24.81	287.96	2.7	53
April	122	138.1	134.4	-12.44	-48.54	263.1	-4.3	48
May	85.9	103.95	110.23	-24.33	-83.66	214.60	-8.4	40
June	26.57	56.23	68.51	-41.94	-47.00	130.9	-14.5	25.5
July	21.51	24.04	45.071	-23.56	16.278	83.94	-8.15	17.5
Aug.	61.35	41.43	53.189	8.1604	19.000	100.22	2.82	20.2
Sept.	72.19	66.77	62.66	9.524	37.08	119.2	3.29	23.5
Oct.	99.75	85.97	81.159	18.590	61.800	156.30	6.42	30
Nov.	142.9	121.3	111.9	30.98	40.65	218.1	10.7	41
Dec.	152.6	147.7	132.2	20.37	41.82	258.7	7.04	48
Jan.	174.08	163.355	153.11	20.968	-136.81	300.58	7.25	55
Feb.	16.3	95.19	84.88	-68.58	69.35	163.7	1.25	56

Table 7 continued

Mar.	154.24	85.27	119.471	34.7683	2.52835	233.133	-.42	55
April	122	138.1	120.7	1.267	-34.83	235.6	-5.8	50
May	85.9	103.9	103.3	-17.46	-76.79	200.8	-9.16	41
June	26.57	56.23	65.06	-38.49	-43.55	124.0	14.87	26
July	21.51	24.04	43.34	-21.83	18.00	80.48	-8.33	18
Aug.	61.35	41.43	52.3238	9.026195	19.8662	98.48728	2.7	20
Sep.	72.19	66.77	62.23	9.958	37.51	118.3	3.44	23.3
Oct.	99.75	85.97	80.94	18.80	62.01	155.8	6.5	30
Nov.	142.9	121.3	111.8	31.08	40.75	217.8	10.74	40.5
Dec.	152.63	147.795	132.19	20.432	41.882	258.65	7.06	48.5
Jan.	174.0	163.3	153.0	20.99	-153.0	300.5	7.25	55

*Units in (m^3/s)

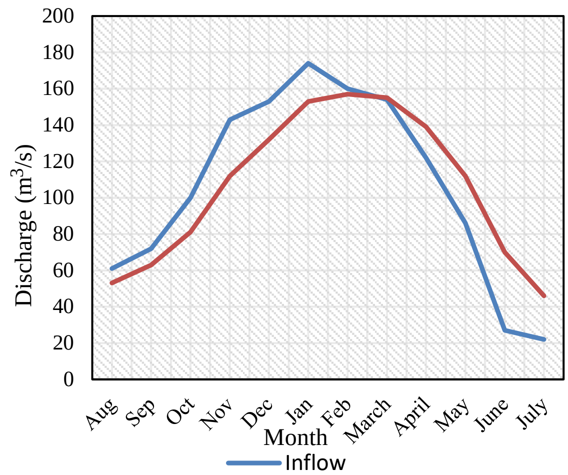

Fig.8 Inflow – Outflow Hydrograph for average inflows, 2012-2015

Table 8 Water budget for Al Manzala Lake, average of (2012-2015)

Water Budget	Item	Quantity (10^6 m^3)	Percent age
Gains	Drainage Discharges	4507.7	98.77 %
	Total Rain	56	1.23%
Losses	Total Evaporation	1267.15	27.77 %
	Total Outflow	2943.888	64.50 %
Storage Change	Total Storage	357	7.73%

5. CONCLUSIONS AND RECOMMENDATIONS

Al-Manzala lake receives most of the agricultural drainage water of the East Nile Delta region in Egypt. Recently, lakes' hydrological status has been changed due to the continuous discharging of agricultural drainage into the lake. To study the hydrodynamic of the lake, the reservoir hydrologic routing method was implemented.

To define inflows and outflows of the lake's hydrologic system, historical data of rainfall, drainage discharges, and evaporation measurements were collected and analyzed.

The current study concluded the following:

- Al Manzala lake receives about 75 mm of rainfall annually which accounts for about 56 million cubic meter.
- The annual lake losses are about 1690 mm due to evaporation which accounts for about 1267.15 million cubic meter. Besides, the lake received about 4507 million cubic meter of drainage water during the study period (2012-2015).
- An auxiliary curve was initiated for the lake.
- An inflow-outflow hydrograph was developed for the Lake.
- The water level fluctuated between 17.5 and 56 cm above mean sea level. This level fluctuation maintains a continuous flow from the lake toward the Mediterranean Sea.
- The hydrological system of the lake is influenced by agricultural drainage discharges which represent about 98.77% of the water resources while rainfall represents a very tinny ratio.
- Agricultural drainage waters dominate the hydrologic behavior and the fluctuation of water level in the lake.
- As the surface area of the lake is huge (750 km^2), evaporation losses are about 27.8% and outflows account for about 64.5%.
- The change in storage accounts for 7.7% with an average water level of about 37 cm above mean sea level. This average level maintains a continuous outflow towards the Mediterranean Sea.
- Water inflow to the hydrologic system of the lake makes water level in the lake during the whole year above mean sea level. Accordingly, the hydrologic environment of the lake has been changed in terms of quality and quantity.
- To re-establish the lake's hydrologic status, it is recommended to reuse drainage water (4507.7 million m3) in the development projects in Sinai, Egypt.
- If the government of Egypt has to discharge quantities of drainage water into the lake, the monthly net evaporation (evaporation minus rainfall) could be discharged into the lake.
- It is recommended to study the effect of climate change induced sea-level rise and the Mediterranean Sea tide on the hydrodynamic and the hydrologic status of the lake.

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