NUMERICAL MODELLING ON WATER FLOW IN MANZALA LAKE, NILE DELTA, NORTHERN EGYPT

N.A. El-Naggar*, A.E. Rifaat and M. Kh. Khalil
National Institute of Oceanography and Fisheries, Al-Anfushi 21556, Alexandria, EGYPT
*Correspondence Author E-mail: Naglaa.elnaggar@gmail.com

Abstract

This paper presents the preliminary results of the application of the hydrodynamic of water flow model experienced within Lake El-Manzala, Egypt. Lake Manzala is the largest of the Egyptian shallow coastal lakes on the fringe of the Mediterranean Sea and currently supports 30% of the fresh water fish farm production of Egypt. In recent years the aquatic health of the lake has significantly deteriorated due to an increase in the contamination of the lake by polluted inflows and over intensive aquaculture. The focus of this study is to develop a model that shows the effects of hydrodynamics on pollutant dispersion from drains and examine a potential mitigation alternative by decreasing the pollutant loads that enter the Lake. A hydrodynamic model using AQUASEA software was used to solve the shallow water flow equations using the Galerkin finite element method. This hydrodynamic model on the Lake can act as an effective decision support tool for improving the environmental conditions in the surroundings, contamination prevention efforts for the sustainable use of the Lake, crucial for future planning and solution of engineering problems.

Keywords: Lake Manzala, Nile Delta, AQUASEA, flow modelling

1. Introduction

Economically, Lake Manzala is one of the most important Egyptian farmed fish resources; it was contributing about 35% of the total country yield during 1980's (Khalil 1999). Nowadays, the lake contributes by about 30% from the total annual production of the Egyptian lakes, which is about 12.5% of Egypt total fish production (Mehanna 2014). The physical, chemical and biological quality of the lake water has been observed to be deteriorated dramatically over the last few decades.

This has been documented in numerous field studies [3,4,5,6,1] (Abdel-Star and Geneid 2009, Shakweer 2005, Khedr 1997, Wahaab and Badway 1997, Khalil 1999). The maintenance of the aquatic health of Lake Manzala is a high priority for the Egyptian government (UNDP 1997). Several physical factors combine to make the coastal systems complex and unique in their hydrodynamics and the associated physical transport and dispersal processes of the coastal flow field are equally complex (Rao and Schwab 2007). Modeling the circulation inside the lake is an essential tool in order to investigate the Lake water balance and its flushing rate.

Some studies recently discussed the hydrodynamics of the coastal lakes in Egypt. Bek *et al.* (2010) applied the ocean model (FVCOM) to replicate the hydrodynamic flows experienced within Lake Manzala. However, 2D water quality and eutrophication screening models were developed for the Lake Edku system (Azab 2012). Rasmussen *et al.* (2009) investigated the influence that a reduced inflow nutrient load may have on water quality of Lake Manzala through hydrodynamic- ecological modelling.

The complex flow model at coastal inlets often induces patterns of accumulation in and around the opening that causes a wide range of engineering problems. The current study deals with the water flow hydrodynamics of Lake Manzala that will enhance our understanding of the hydrodynamic behavior of the Lake. The expected outcomes of the study are:

1. To represent the general circulations inside the lake.
2. To simulate the effect of hydrodynamics on pollutants dispersion from Bahr El-Baqar drain that is discharging directly into the Lake then into the Mediterranean Sea.

2. Materials and methods

2.1 Area of Study

Lake Manzala, situated in the north-eastern Nile Delta, is a shallow, rhombohedra-shaped wetland (Fig. 1) formed in the actively subsiding delta plain (Stanley 1988, 1990). It is the largest of the northern Egyptian lakes. The surface area of the lake is 700 km^2, and has an average depth of 1 m (Bek and Lowndes, 2010). The Lake is connected to the Mediterranean Sea through narrow outlets of El-Gamil and the New El-Gamil. It is bounded from East by the Suez Canal (there is a very narrow canal (El-Qabuty Canal) connecting the lake to Suez Canal).

Damietta Branch of the River Nile borders the lake from west (the lake is connected to Damietta Branch by Enanya Canal). Numerous drains (urban, industrial wastewater and agricultural runoff) are the main source of water inflow to the lake. Six major drains (Fareskour, Elserw, Mataria, Hadous, Ramsis and Bahr El-Baqar) contribute a flow flux of 4170 million cubic meters annually (Bek and Lowndes, 2010).

The largest of these is the Bahr El-Baqar drain which carries domestic and industrial wastewater from the eastern part of Cairo city (Taha *et al* 2004, Thompson *et al*. 2009). Total discharge into Bahr El-Baqar drain is 2,049,030 m^3/d and this drain splits into two branches before it opens into the lake (Saad 1997).

The low tides of the Mediterranean Sea are observed to produce little hydrodynamic effect on the lake, other than to increase the relative salinity of the lake in the vicinity of the coastal discharge channels. A characteristic feature of Lake is the presence of a large number of islets, of sand and mud, created by a combination of natural sedimentation and dredging operations to facilitate the construction of fish pens.

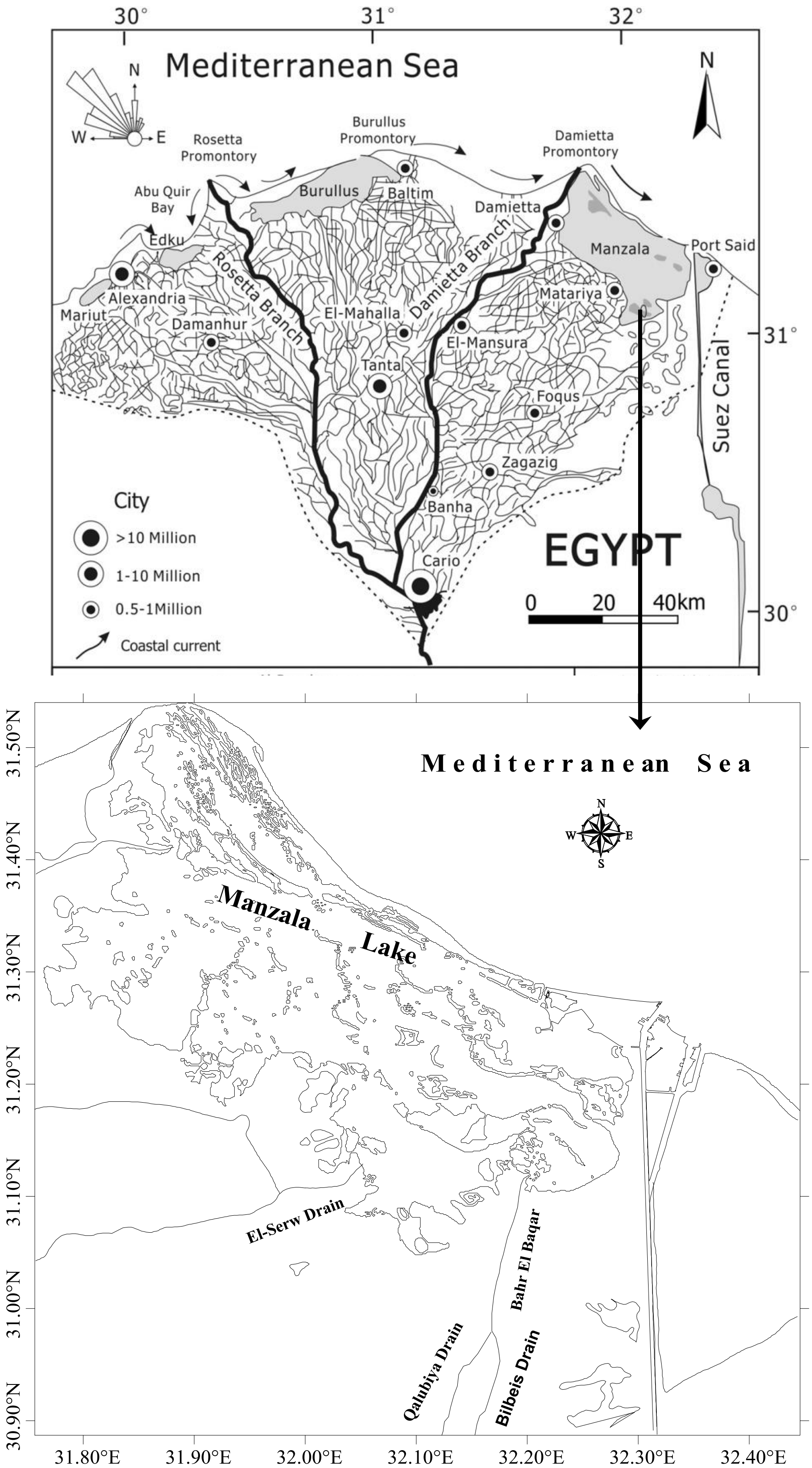


Fig. (1) A map showing the study area

These islets divide the Lake into about 30 interconnected basins. Most of these islets are inhabited by fishermen and farmers. Due to land reclamation, the surface area of the lake has been decreasing steadily over the past few decades (Bek and Lowndes 2010). So, the ecosystem of the lake is under intensive pressure from human activities which are rapidly changing its water quality and environmental health. The major challenges being faced are the increase in illegal land reclamation and construction of new fish enclosures. These practices reduce the available lake volume and restrict the free hydrodynamic flows within the lake.

2.2 Hydrodynamic flow model

2.2.1 Model description

The flow model can simulate water level variations and flows in response to various forcing functions in lakes, estuaries, bays and coastal areas. The water levels and flows are approximated in a numerical finite element grid and calculated on the basis of information on the bathymetry, bed resistance coefficients, wind field and boundary conditions. The basic equations of flow model that are used in this study are given below as:

The equation of continuity is given by Kolar et al. (1994):

$$\frac{\partial}{\partial x}(uH) + \frac{\partial}{\partial y}(vH) + \frac{\partial \eta}{\partial t} = Q$$

where
$H = h + \eta$
h is mean water depth, m
η is change in water level, m
H is total water depth, m
u is velocity component in x-direction, ms^{-1}
v is velocity component in y-direction, ms^{-1}
T is time, s
Q is injected water, m^3s^{-1}

As the continuity equation includes three unknown variables u, v, and h, thus two more equations are needed to complete the solution of the problem. These are given by the momentum equations in two directions:

$$\frac{\partial u}{\partial x} + u\frac{\partial u}{\partial x} + v\frac{\partial u}{\partial y} = -g\frac{\partial \eta}{\partial x} + fv - \frac{g}{HC^2}(u^2+v^2)^{1/2}u + \frac{k}{H}W_x\,|W| - \frac{Q}{H}(u-u_0)$$

$$\frac{\partial v}{\partial t} + u\frac{\partial v}{\partial x} + v\frac{\partial v}{\partial y} = -g\frac{\partial \eta}{\partial y} + fu - \frac{g}{HC^2}(u^2+v^2)^{1/2}v + \frac{k}{H}W_y\,|W| - \frac{Q}{H}(v-v_0)$$

The Coriolis parameter f, is defined as follows:

$$f = \phi\ \omega \sin 2$$

φ is the latitude and ω is the Earth's rate of rotation equal to 7.2722×10^{-5} s^{-1}. The wind shear stress parameter, k, is defined as follows:

$$k = \frac{\rho_a C_D}{\rho}$$

η is change in water level, m
H is total water depth, m
u is velocity in x-direction, ms^{-1}
v is velocity in y-direction, ms^{-1}
t is time, s
g is acceleration of gravity, ms^{-2}
ω is the Earth's rate of rotation, s^{-1}
φ is latitude, deg
C is Chezy bottom friction coefficient, $m^{1/2}s^{-1}$
ρa is density of air, kgm^{-3}
C_D is wind drag coefficient
ρ is fluid density, kgm^{-3}
W_x is wind velocity in x-direction, ms^{-1}
W_y is wind velocity in y-direction, ms^{-1}
W is wind speed, ms-1
u_o is velocity of injected water in x-direction, ms^{-1}
v_o is velocity of injected water in y-direction, ms^{-1}

The momentum equations together with the equation of continuity complete the specification of the shallow water flow problem.

2.2.2 Model grid and forcing factors

The complex bathymetry of Manzala Lake, with many islands and narrow passages between islands and connections with the sea, requires a bathymetric set up with a flexible grid size. Therefore, GEBCO Digital Atlas, DXF files, which produced by CAD packages and contouring programs (Surfer program) were selected. The program AQUASEA 7.2 developed by Vatnaskil Consulting Engineers is used to calculate the shallow water flow equations using the Galerkin finite element method. The area of study is divided into small regions of finite elements consisting of 1518 nodes (Fig. 2).

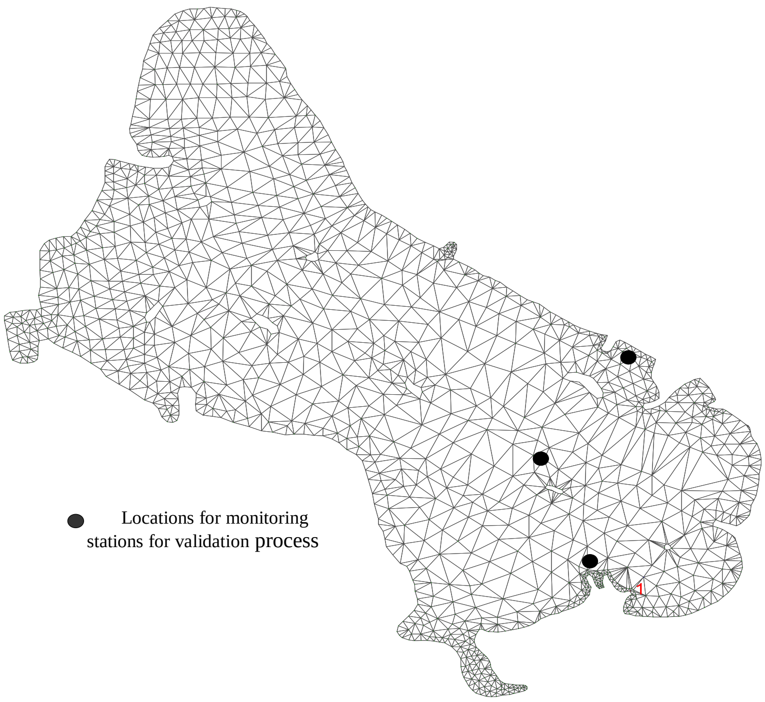
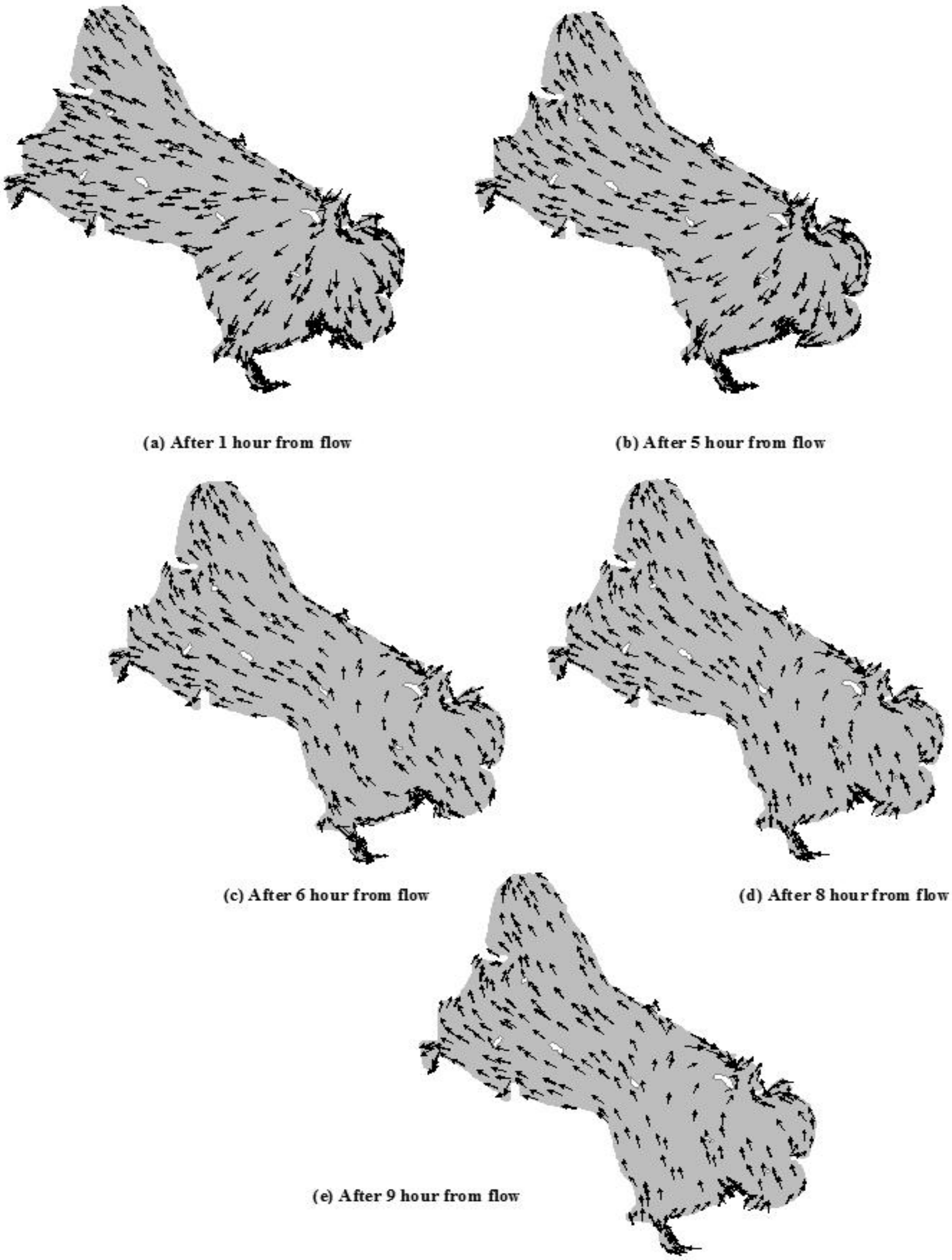


Fig. (2) Grid used in the model
(The measurement stations used to validate the model are marked with a red dot)

The mesh was generated on triangular formation by inserting nodes manually using the AQUASEA program. The mesh is composed of triangles, the edges of which are defined by model nodes. Each triangle is an element, and calculations are carried out for each element. Boundary conditions on closed internal boundaries are also generated (Fig. 2). In order to generate correct bathymetry, additional nodes were inserted at fast-varied depth sections. The mesh density was also greater inner parts of region than open external boundary. The conditions defined in external boundaries are 'no slip'u = v = 0 for solid surfaces and time-dependent values for the open external boundary (Fig. 2). The input parameters were, water depth average of the lake is 1 m, the direction of the injected plume (311°), period of sinusoidal forcing (12 hours), the most common wind direction (222°), average wind speed (3.9 m/sec), the discharge average flow rate (24 m^3/sec) (Saad 1997), the cross-section area of the outlet (61.5 m^2), the Chézy coeffiecient (23 $m^{1/2}$/sec). Water levels were obtained from Port Said station beside the Lake and total phosphorous was undertaken at three stations within the lake (Fig. 2). The hydrodynamic accuracy of the model was validated with data from these locations. The output of the AQUASEA application is presented using the computer application Surfer 11 from Golden software Company.

3. Results and discussions

Hydrodynamic flow model simulation for Manzala Lake showed that it depends mostly on wind direction and geometry of the region. Flow takes 13 hour to reach its original state at the boundary conditions. The velocity magnitude and direction pattern of outflow around the main coastal outlet at 1 hour are shown in Fig. (3). It should be noticed that positive value of velocity indicates that the discharge is from sea to lake and vise-versa. Simulated exchange between Lake and Sea at cross section in outlet indicates that near the open boundary, the velocity vector is affected mainly by the tidal forces. Inside the channel links the sea and the Lake can reach 1.69 m/s. Inside the Lake where the velocity vector is mainly affected by wind direction, the velocity is different between 0.02 and 1.9 m/s. Clockwise and anti-clockwise eddies are generated at different positions inside the Lake and they are independent of tides. It also should be noticed that the effect of Bahr El Baqar drain discharge on velocity vectors is high to the areas near its inlet, reaching 2.69 m/s.



(a) After 1 hour from flow

(b) After 5 hour from flow

(c) After 6 hour from flow

(d) After 8 hour from flow

(e) After 9 hour from flow

Fig. (3) Water flow patterns in El-Manzala Lake thought out simulation time
(The arrows define the directions of the flow)

The occurrence of high velocity at the lake outlet after 5 hours is due to the confluence of the various exiting flows. In the northern upper part of the lake, the water movement comes from the west where the water inflow occurs towards the east where the main coastal outlet exists. Water flow patterns changes in the lake from 6 hours till reach maximum velocity towards outlet after 8 hours (good mixing with the sea) (Fig. 3). At 9 hours, velocity inside the lake is faded or reaches to zero. At this time, the discharge is from lake to sea and water movement comes from the south at Bahr El-Baqar towards the main coastal outlet. In this region the water flows parallel to the shoreline. This movement is motivated by the wind shear stress which is responsible for the water circulation inside the lake annually (Bek and Lowndes 2010). After 10 hours velocity gradually increases at outlet and inside the lake. At this time the velocity value becomes negative that the discharge is from the lake to the sea. After 13 hour, flow pattern reach its original state, water flow occurs from the sea towards the main coastal outlet into the lake as after 1 hour.

To study model results in more details, we picked up some nodes to study their elevation and velocity; and we track some nodes on how they move in our area of study. This can be seen in the Fig. (4).

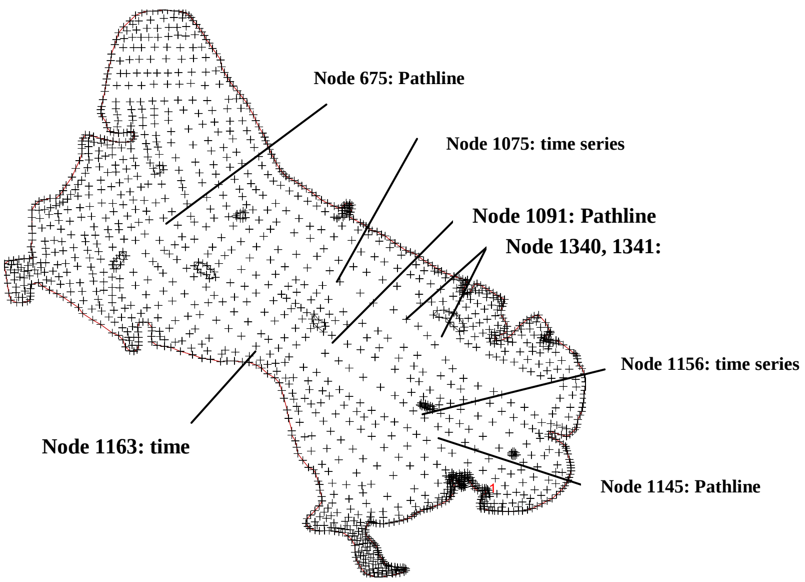


Fig (4) Some nodes and their type in nodal inputs for flow model

Time series nodes are to study their elevation and velocity at node 1156 (Fig. 5a-b) whereas pathline nodes are to study their movement at nodes 1340, 1341, 1091, 675, 1163 (Fig. 5c).

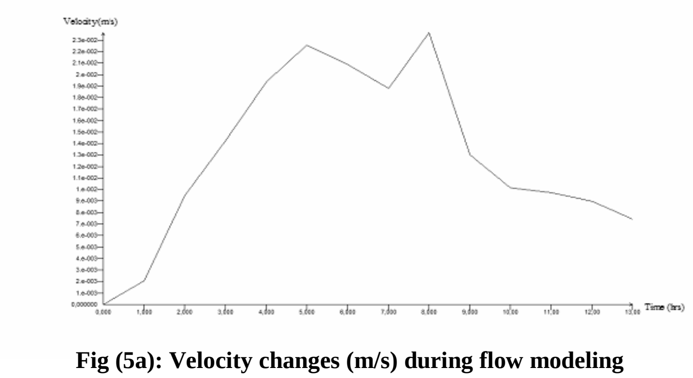


Fig (5a): Velocity changes (m/s) during flow modeling through out the entire simulation period at node 1156.

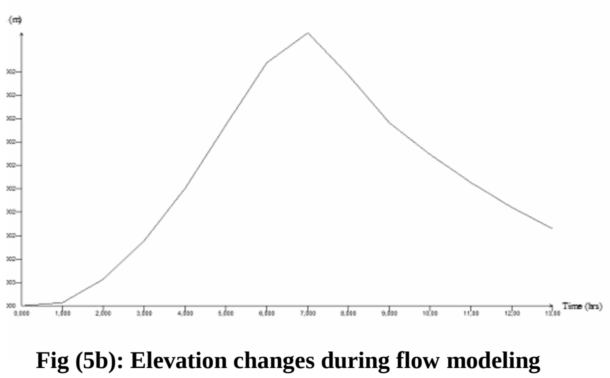


Fig (5b): Elevation changes during flow modeling through out the entire simulation period at node 1156.

Fig (5c): Water particle pathlines from different points in the Lake.

From the above figures, we can see that the similar results are obtained, which is consistent with general idea that a "good" mixing zone occurs inside the inlet through out 6 hour, and flow takes 13 hour to reach its original state at the boundary conditions. Velocity varies from low (0.02-1.9 m/s) inside the Lake to high (1.69 m/s) inside the coastal outlet. Further, some water particles does not succeed to move outside the channel, which means we can or not obtain renewable water and hence good water quality parameters. Flow direction also effected mostly by island inside the Lake as can be seen from vector velocities in the above figures. Finally, some practices should be made to ensure that water inside the channel is mixed entirely with water outside the channel and this is confirmed by pollutant dispersion within the lake.

To simulate the effects of pollutant dispersion within the lake domain, total phosphorous concentrations of 776.71 μg/l were measured inside Bahr El-Baqar drain. Total phosphorous patterns took 6 hours to spread all over the lake till reach the main coastal outlet, so we can conclude that pollutants dispersion from Bahr El-Baqar drain can affect water quality of the Lake (Fig. 6).

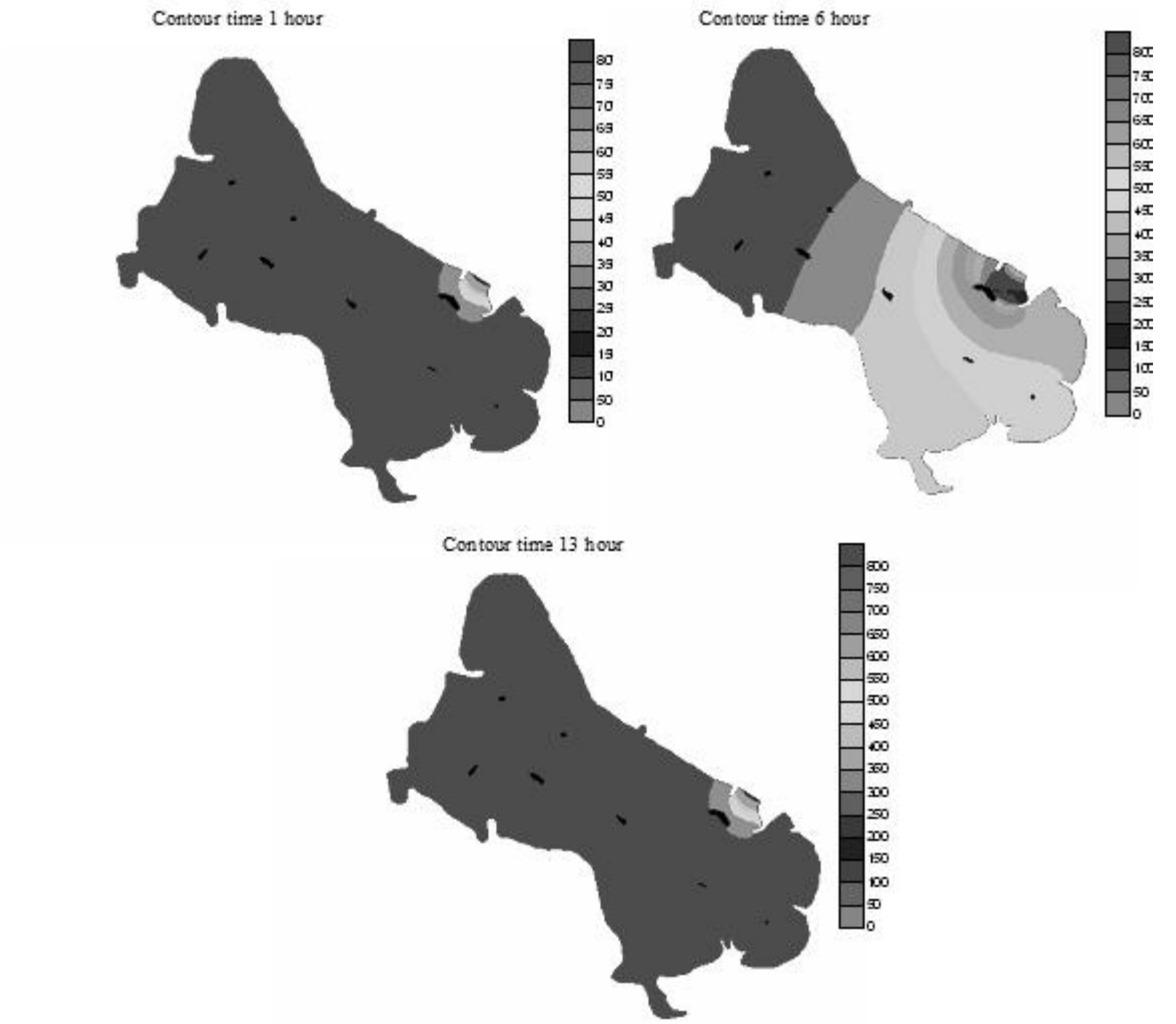


Fig (6): Total phosphorous concentrations plume at 1, 2, and 13 hours after it was released from Bahr El-Baqar drain.

The model was calibrated using the data available of daily averaged water levels and Total phosphorous. The simulated water levels are compared to water levels data used from Port Said station beside the Lake (Fig. 7a). The variations between the measured and predicted date are caused by lack of continuous recording of water levels and the error and uncertainty in the manually measured data. In addition the water level used in the simulation is from Port Said station beside the Lake not well distributed stations all over the Lake.

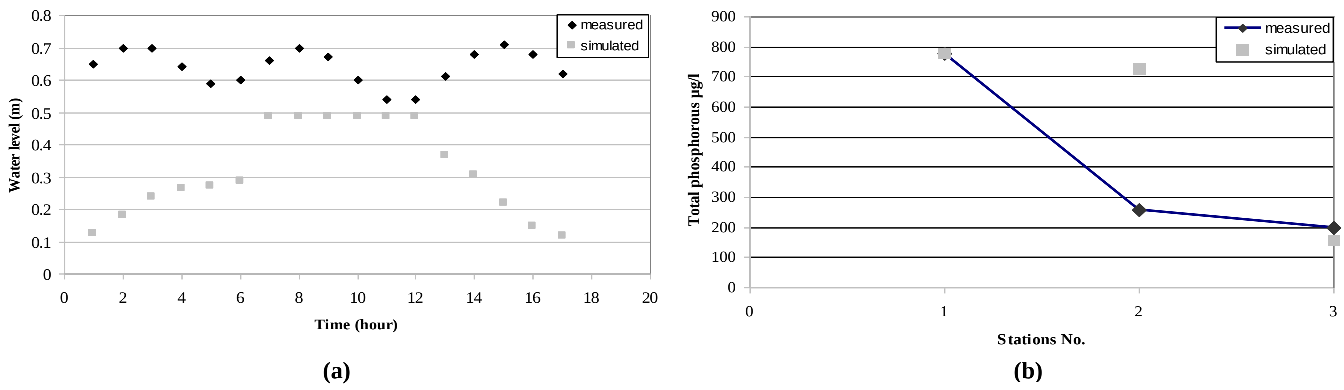


Fig. (7): Simulated and measured water levels (a) and total phosphorous at three stations (b).

The predicted model lake total phosphorous distributions were validated against the measured data. Fig. (7b) represents a comparison between the measured and predicted total phosphorous at the 3 sampling stations. The predicted total phosphorous is in a good agreement with the measured data. The complex geometry of the central zone makes accurate total phosphorous prediction for station 2 is hard to achieve.

4. Conclusion

Based upon the flow model presented in this research, it may be concluded that the results are useful to asses any proposed engineering solution for preserving the aquatic system of the Lake and stop the continuous deterioration of the water quality. The simulation results revealed that the main driving forces that are responsible for the circulation patterns inside the Lake is wind and drains' discharges. The direction of flow is from the Lake to the sea and vise versa and a pollutant coming from Bahr El-Baqar drain affects the whole area of the Lake. A permanent monitoring system should be established to get continuous records of both hydrodynamic and water quality parameters and should cover all parts of the Lake. Therefore, the results of this study would be an important input in the contamination prevention efforts for the sustainable use of the Lake.

References

Khalil, M.T., 1990, The physical and chemical environment of Lake Manzala, Egypt, *Hydrobiologia,* **169,** 193-199.

Mehanna, S.F., 2014, Impacts of excessive fishing effort and heavy metals pollution on the Tilapia production from Lake Manzala. 4th Conference of Central Laboratory for Aquaculture Research, 57-74.

Abdel-Star, A.Y. Geneid, 2009, Evaluation of heavy metal status in ecosystem of Lake Manzalah, Egypt, *Global Journal Of Environmental Research,* **3,** 194-204.

Shakweer, L., 2005, Ecological and fisheries development of Lake Manzalah (Egypt) hydrography and Chemistry of Lake Manzalah. *Egyptian Journal of Aquatic Research,* **31,** 251-270.

Khedr A.H.A., 1997, Aquatic macrophytes distribution in Lake Manzala, Egypt, *International Journal of Salt Lake Research,* **5**, 221-239.

Wahaab, R. A. and M.I. Badway, 1997, Environmental impact of some chemical pollutants on Lake Manzala *Int. Journal of Environmental Health Research,* **7,** 161-170.

UNDP (1997) Lake Manzala Engineering wetland, United Nations Development program,` project number: EGY/93/G31.

Rao, Y.R. and Schwab D.J., 2007, Transport and mixing between the coastal and offshore waters in the Great Lakes: a review, *J. Great Lakes Res,* **33**, pp. 202–218.

Bek, A.M. and I.S. Lowndes, 2010, The application of a validated hydrodynamic model to improve the water management of an Egyptian shallow water coastal lake. Available online at: www.googl/xkl2e.

Azab, A.M., 2012, Integrated gis, remote sensing and mathematical modeling for surface water quality management in irrigated watersheds, Available online at: www.googl/BaUb3.

Kock Rasmussen E., Svenstrup Petersen O., Thompson, J.R., Flower, R.J. and Ahmed, M.H., 2009, Hydrodynamic-ecological model analyses of the water quality of Lake Manzala (Nile Delta, Northern Egypt). **622 (1)**, pp. 195-220, Available online at: www.googl/6DZUy.

Stanley, D.J., 1988. Subsidence in the northeastern Nile Delta: Rapid rates, possible causes, and consequences. *Science*, **240**, 495–500.

Stanley, D.J., 1990, Recent subsidence in the northeast tilting of the Nile Delta: Egypt. Marine Geology 94, 147–154.

Taha, A.A., El-Mahoudi A.S. and El-Haddad I.M., 2004, Pollution sources and related environmental impacts in the new communities southeast Nile Delta, Egypt. Emirates *Journal for Engineering Research*, **9**: 35–49.

Thompson, J. R., Flower, R. J. Ramdani, M. Ayache, F., Ahmed M.H., Rasmussen E. K. and Petersen O.S., 2009. Hydrological characteristics of three North African coastal lagoons: insights from the MELMARINA project. Hydrobiologia. doi:10.1007/s10750-008-9680-x.

Saad, A.K (1997). Environmental hydrogeologic impacts groundwater withdrawal in the eastern Nile Delta region with emphasis on groundwater pollution potential. Ph.D. Thesis, Institute of Environmental Studies. Ain Shams Univ. p. 232.

Kolar L.R., Westerink J.J. Cantekin M.E. and Blain C.A., 1994, Aspects of Nonlinear Simulations Using Shallow Water Models Based on the Wave Continuity Equation, *Computers and Fluids*, **23**, No. 3, pp. 523-538.