Investigating the Impacts of Dredging on Improving the Water Quality and Circulation of Lake Mariout via Hydrodynamics

Noha Donia

Abstract A two-dimensional hydrodynamic and water quality numerical flow model has been developed for Lake Mariout to simulate the flow pattern in the lake vicinity of the study area, the discharges and pollution loadings coming from the agricultural drains, and the point sources discharged directly to the lake. After the model development and calibration, different potential model scenarios were suggested for increasing the storage capacity of the lake's basins and its impact on lake hydraulics, and therefore water quality conditions have been implemented.

The first scenario was to study the deepening one or more basin and the effect of this deepening on water levels on different basins and the effect on the performance of El Mex pumping station and whether the pump station can lift the new lifting head or not. If there is an effect on the water surface of the lake, the model studied the optimum operation scenario for operating the El Mex pumping station. Also, different scenarios for high flood events have been studied and how shall flood water be stored in the basins and be lifted to the sea. Also, a study was carried on the possibility of using the Wadi Mariout as an emergency storage basin by connecting it to the current lake's basins and its capacity to accumulate future floods. Finally, a scenario has been conducted on the diversion of inflowing drains for agriculture reuse and the inflow into the lake with evaporation compensation. The results indicated that 1 m dredging works in the northern, western, and southern basin would improve the circulation in the lake. Moreover, it will increase the storage capacity and will improve the water quality. Also, a connection between the south-western basins with the salt basin will improve the water circulation and storage capacity of the lake.

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Contents

1 Introduction

Lake Mariout is a salt lake, and it is considered a major coastal lagoon, which forms the southern border of Alexandria city. Lake Mariout lies between latitude 31° 07′ N and longitude 29° 57′ E along the Mediterranean coast of Egypt. It is separated from the Mediterranean Sea by the narrow isthmus on which the city of Alexandria was built. The lakeshore is home to fisheries and salt industry. Some of the marshy areas around the lake have been reclaimed for the new building as the city grows. Human pressure, as well as land reclamation, causes' quality degradation in the lake environment as well as a reduction in lake area. In 1801, the original area was probably more than 700 km^2. Due to the construction of railway and road, parts of the lake were isolated. The cessation of the annual Nile flood after building the Aswan High Dam, and land reclamation the area of the lake, is now less than 65 km^2 and ranges in depth from 1 to 3 m [1]. The land reclamation started early in the twentieth century and became state policy in its second half. Currently, the lake is divided artificially into four main basins as shown in Fig. 1, namely, 6,000 feddan basin (main basin), 5,000 feddan basin (southern basin), 3,000 feddan basin (western basin), and 1,000 feddan basin (aquaculture basin). Roads and embankments dissect these ponds. The water depth and area of each basin are the following.

The main basin is about 14.77 km^2 with an average depth of 0.8 m. This basin receives water from the El-Nubariya canal and El-Omoum drain; the heavily polluted water by industrial wastes and untreated sewage from municipal and industrial outfalls of El-Qalaa drain had been diverted through the new Risha drain. West wastewater treatment plant effluent had been discharged along the north of the basin. One minor inflow is a discharge of waste from a textile plant into a ditch which crossed Qabarry district, Alexandria. The main basin is bisected by the El-Nubariya canal, and the triangular area between this canal and the El-Omoum drain is also considered as part of the main basin.

Fig. 1 General layout of Mariout Lake basins

The western basin is about 11.59 km^2 with average water depths of 0.7 m. Adjacent to the basin, salt marshes are located and producing 1,000,000 kg of unrefined salt per year. Many industrial and petrochemical companies surround them.

The southern basin area is 33.77 km^2. The basin average water depths are 0.68 m. El-Omoum drain and El-Nubariya canal are the main source of water to this basin. This basin consists of densely vegetated areas and fish farms. Also, considerable wetland loss in this portion of the basin was recorded. Many petrochemical and petroleum companies such Amria and Misr Petroleum companies discharge their wastes into the north part of this basin [2].

The (fisheries) aquaculture basin covers 9.44 km^2 (849 feddans); it consists of a series of small basins separated by earthen berms. This facility is a research center for fish farming and is operated by Alexandria Governorate. There are two sources of water for this facility. One is small pump stations which pump 400,000 m^3/day from Abis drain and which run parallel to the basin. The other is small opening from El-Omoum drain [2].

The water column of the lake has a change in level throughout the time; this is because it was under the high influence of the Nile's flood season. During the Middle Ages, the lake was ignored and became a massive salt marsh. After modernization of irrigation system in Egypt, the lake body was utilized as a receptor for agricultural drainage as well as a source of irrigation water to the nearby cultivated lands.

This chapter represents the hydrodynamic and water quality modeling studies that are carried out to investigate the improvement of the water circulation and water quality parameters of Lake Mariout in response to some proposed scenarios.

2 Model Development

Many modeling studies have been conducted to simulate the hydrodynamics of shallow lakes such as [3] studied Lake Pontchartrain circulation by using different types of models. In Haralampides et al. [4], EFDC model was used to simulate the hydrodynamic and transport processes in Lake Pontchartrain. Lake Okeechobee water circulation was simulated by Jin et al. [5]. The final step toward the ultimate goal of developing a 3D hydrodynamic-sediment-water quality model was achieved by adding a water quality module [6]. The developed model was applied to a study of water quality parameters in the lake. The results indicated that algal growth mainly depended on the nitrogen, limited in the summer, and nitrogen and light co-limited in the winter [6]. Chung et al. [6] implemented sediment resuspension models with a hydrodynamic and water quality model, to create a dynamic lake and water quality (DLM-WQ) model, based on DYRESM and DYRESM-WQ [7, 8]. They investigated the effect of the resuspension model's existence in the prediction of water quality. Their results stressed the importance of including the sedimentation process when studying the water quality.

Delft3D Software Package of Deltares in the Netherlands will be used to develop the hydrodynamic and water quality numerical flow model which simulates the flow pattern in Lake Mariout. Delft3D is an integrated, powerful, and flexible software. It can carry out simulations of two- (either in the horizontal or a vertical plane) and three-dimensional flows, sediment transports, waves, water quality, morphological developments, and ecology. The Delft3D package is used for the modeling of coastal, river, and estuarine areas. It encompasses a number of well-tested and validated modules, which are linked to and integrated with one another. These modules are flow, waves, water quality, ecology, particle tracking, and sediment transport.

The model will help in improving the understanding of flow circulation, transport, and advection of the substances and the cross flow.

Since this study focuses on hydrodynamic and water quality simulations including the transport and advection of the pollutants, the hydrodynamic module (flow module) linked with water quality module (WAQ module) of Delft 3D will be used. The flow module of Delft 3D is used for far-field modeling in which the simulations are accurate enough. For more details on the Delft3D-Flow module, reference is made to Delft3D Manual. The Delft 3D Software Package is supported by two other modules, the computational grid generation (Delft-RGFGRID) and bathymetric schematization at the grid points (Delft-QUICKIN) [9].

The numerical model will simulate the water circulation including both dispersion and diffusion of substances processes. The model will use computational grid with high resolution to maximize the accuracy in representing and simulating the area of interest. Hydrodynamic simulations in this study will consider small time step to fulfill the accuracy requirements representing in Courant number. This will lead to increasing the total simulation time. The hydrodynamic simulation will simulate the flow pattern, which will be used as an input for the water quality substances transport.

2.1 Hydrodynamic Simulation

The current or hydrodynamic module will compute the current field based on the flow forces which are the dominant driving forces in the lake. Wind-driven flow will be computed and compared with the measured values for the sake of model calibration.

In the calibration phase, various model parameters may be adjusted within the limits of their uncertainties to achieve the best model results compared with available measurement data.

Calibration is based upon the comparison of model results against (preprocessed) measurement data. A good agreement between the model predicted data and measurements indicates that the model adequately represents the water hydrodynamics of the system under study.

For the present application, calibration will focus on currents. If the model can adequately represent these quantities, it is reasonable to assume that flow-driven transport is adequately resolved by the model dynamics. This is relevant to obtain an adequate representation of the effluent transport.

In the calibration process, the model open boundaries (discharge and water level boundaries) and all other sources of water were obtained from the measurement data. These data were collected by the National Institute of Oceanography and Fisheries (NIOF). These data were collected for 2 weeks in the period from May 16, 2016 to May 30, 2016 in the framework of the study. In the calibration phase, the model was run in its 2D mode (depth-averaged mode). The model was calibrated at four different locations; the first was located in the main basin (31° 08′ 59.41″ lat, 29° 53′ 51.6″ long), the second was located at El Mex pumping station (31° 08′ 33.5″ lat, 29° 51′ 05.8″ long), the third one was located in the southwest basin (31° 07′ 12.6″ lat, 29° 53′ 43″ long), and the last one was located in the northwest basin (31° 08′ 10.8″ lat, 29° 51′ 37.3″ long).

During the model calibration, the measured averaged water levels were compared with the model results. Tuning of the roughness parameter in the model was carried out to obtain the best match between the model and the field measurements. Manning roughness coefficient was varied from 0.02 at the non-vegetated area to 0.038 at the heavy vegetated area along the model area to give the best match between the measurements and model computations. Figures 2, 3, 4, 5, and 6 present

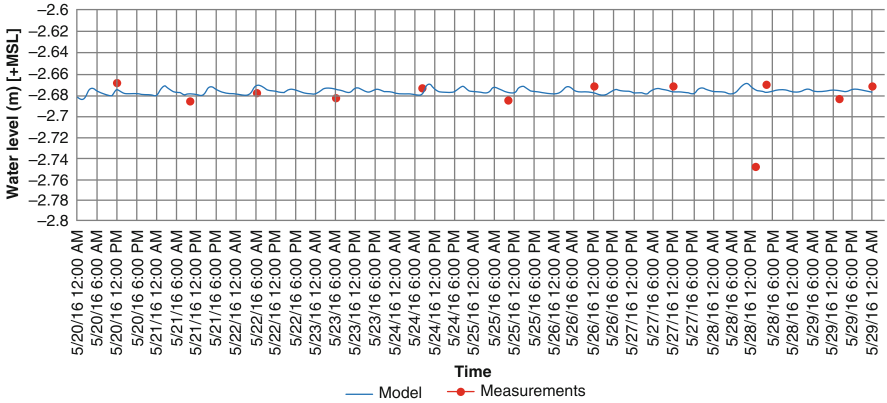


Fig. 2 Water level comparisons at main basin

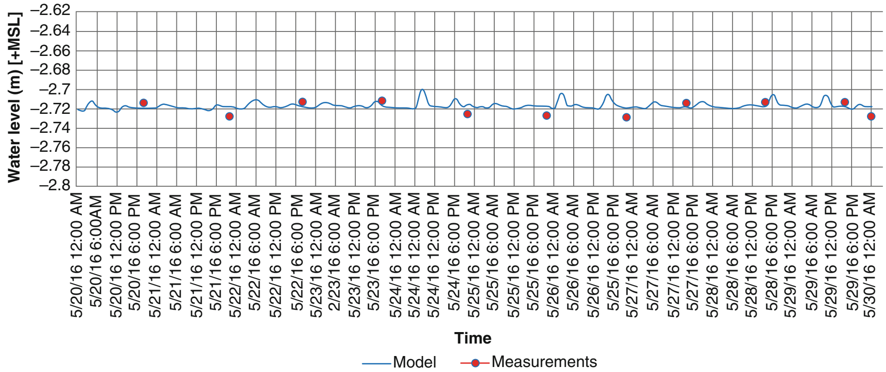


Fig. 3 Water level comparisons before El Mex

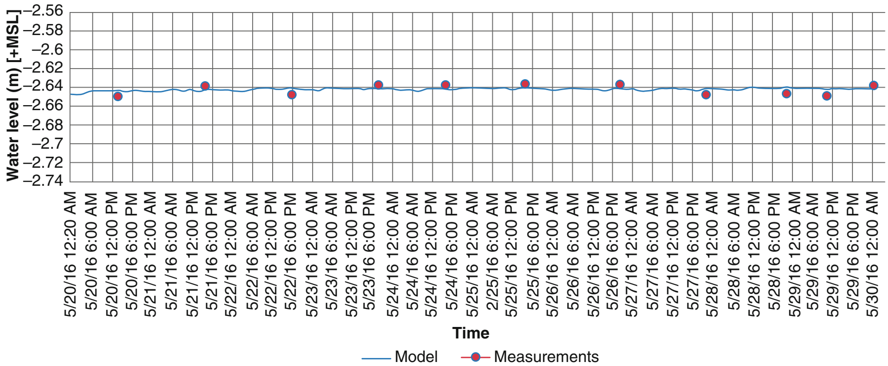


Fig. 4 Water level comparison at south basin

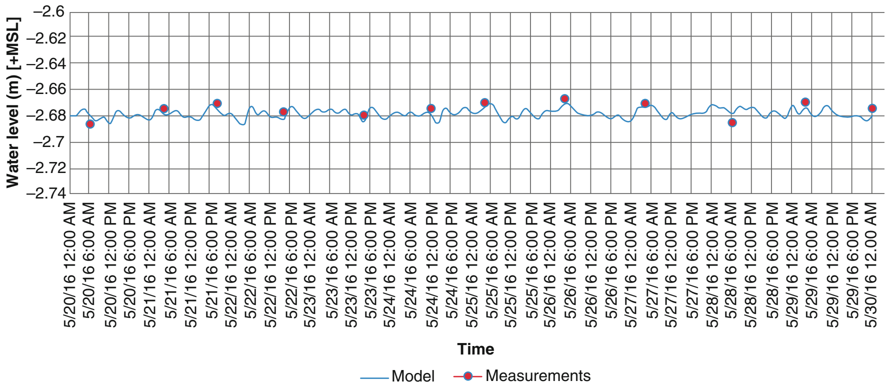


Fig. 5 Water level comparisons at the middle of western basin

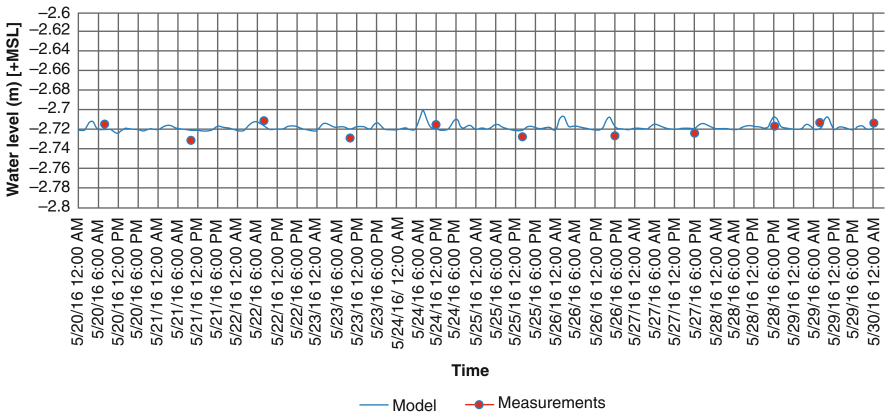


Fig. 6 Water level comparison at the north of western basin

the comparison between the measured and computed water level values after the calibration process. The predicted results were in good agreement with the measured data. This confirms that the model simulates the flow pattern in the main basin of Lake Mariout with a good accuracy.

2.2 *Water Quality Simulations*

The Delft3D-WAQ module [10] is used for the water quality modeling component coupled with the hydrodynamic module. Delft3D-WAQ is a two-dimensional water quality modeling framework within the Delft3D modeling package. It solves the advection-diffusion-reaction equation on a predefined computational grid for a wide range of model determined. Delft3D-WAQ allows a good level of flexibility in the substances to be modeled, as well as in the processes to be considered. It is important to note that Delft3D-WAQ is not a hydrodynamic model, so information on flow fields has to be provided by the hydrodynamic module. Among the full range of model substances that are available in Delft3D-WAQ, the following ones are of high interest to this study:

- Conservative substances (salinity, chloride, and up to five tracers)
- Decayable substances (up to five decayable tracers)
- Suspended sediment (up to three fractions)
- Nutrients (ammonia, nitrate, phosphate, silicate)
- Organic matter (subdivided into a carbon, nitrogen, phosphorus, and silicon fraction)
- Dissolved oxygen
- BOD and COD (respectively, biological and chemical oxygen demand)
- Algae
- Bacteria
- Heavy metals
- Organic micro-pollutants

Delft3D-WAQ allows the specification of an even wider range of physical, (bio) chemical, and biological processes. These processes are stored in the so-called Process Library from which any subset of substances and processes can be selected. These processes include, for example, sedimentation and suspension, reaeration of oxygen, algae growth and mortality, mineralization of organic substances, (De) nitrification, and adsorption of heavy metals and volatilization of organic micro-pollutants.

The following section discusses the model calibration procedures in details. The objective of model calibration is to adjust the input parameters so that there will be a closer agreement between the simulated values and observed data. There are several methodologies and techniques applied for water quality model calibration. In the current study, the water quality model calibration is conducted on the conventional water quality parameters or oxygen group (DO, COD, BOD), nutrients group (NH4, detN, and NO3), and coliform group (fecal and total) and their associated model process parameters. The calibration was based on a comparison between simulations and measurements through calculating the mean relative error (MRE) and the root mean square error (RMSE).

Due to the scarcity of the lake parameters data, the comparison and calibration were done by comparing concentrations on a spatial basis between predicted and measured values.

The model was calibrated through visual comparison between the simulations and measurements. The overall performance of the model was examined with the calculation of the statistical error values such as mean relative error (MRE) as well. The output variables of the model such as DO, COD, and BOD were compared with the observations data of Lake Mariout. “Besides, MRE was used to quantify the agreement of the model, by dividing the residuals by the observed values. In this study the calculation of RE and MRE was based on the following Equations" [2]:

$$RE = \frac{(Csim - Cobs) \times 100}{Cobs} \tag{1}$$

$$MRE = Sum|RE|/n \tag{2}$$

where Csim and Cobs are the simulated and observed values, respectively, and n is the number of cases. The MRE denotes the mean relative difference between simulations and observations. Table 1 shows the different values of RE and MRE for the modeled parameters at this level.

"It is noted that at the entrance of the El-Qalaa drain to the lake, the DO has the lowest values; in general, the DO measurements are close to the simulated results with an RME value" of 7.59% [2]. The simulated BOD and COD results are very close to the measured values at most locations within the lake, and the MRE values are around 3% for BOD5 and 3.6% for COD. In general, we can conclude that the calibration of the oxygen group parameters shows that there is good agreement between the simulated values and observed data, with an acceptable range of error since the model performance is very much dependent on the sufficiency and accuracy of the measured data. For eutrophication group parameters, the values show agreement between measured and modeled parameters with mean relative error 0.79% for DetN and 6% for NH4 values which are considered acceptable for this kind of water quality modeling. The inorganic matter shows relatively high relative error of 10% especially very high values at fishery south basin due to low velocity and setting of inorganic matter.

Table 1 Relative error for the calibrated model parameters

Location/ parameter	DetN (RE%)	NH4 (RE%)	CBOD5 (RE%)	COD (RE%)	DO (RE%)	IM
Main basin middle	0.07	0.16	3.59	3.92	7.59	3.54
Fishery basin north	3.13	0.12	0.018	3.71	24.24	16.29
Fishery basin south	1.17	10.14	11.25	1.89	23.59	28.79
Southwest basin north	0.15	15.89	6.21	3.15	9.9	12.82
Southwest basin south	1.01	8.58	0.27	4.31	14.75	1.2
Northwest basin north	0.14	6.6	0.11	2	11.95	6.99
Northwest basin south	0.45	1.81	0.019	5.79	15.1	5.46
MRE	0.79	6.18	3.07	3.53	7.59	10.73

3 Model Scenarios

Using the calibrated hydrodynamic model as described in previous sections, proposed scenarios were performed. The goal of these scenarios is to study different management plans to increase the storage capacity in the lake against the anticipated storm flooding events and, also, to assess the effect on lake water quality.

The model scenarios are described as follows:

Scenario-0 (Baseline): This scenario is considered the baseline scenario which simulate the current situation of the main basin of Lake Mariout as existed now. This model scenario will be as a guide to evaluate different alternatives to reduce the pollution problem.

Scenario-01: The first scenario is a reduction in the water level of the main basin by 0.5 m to avoid the impact on the aquatic environment. In this case, the lake water depth will be reduced by increasing the discharged water through El Mex pumping station to be about 122 m^3/s. After the implementation of this scenario, the size of the acquired capacity of the lake will be about 13,020,000 m^3.

Scenario-02: This scenario aims to increase the capacity of the discharged water to this part of the lake. The dredging works will be done in both of northern, western basin, and the southern basin where the reduction in bed level is proposed to be 1 m below the existing bed levels.

Scenario-03: The third scenario is the same as the second scenario except for a connection between the main basin and the northern, western basin as a first phase, and then the connection between the northwestern basin and southwestern basin as a second phase will be made. In the first phase, the water will be moved from the main basin (in case of storm events) to the northern, western basin until the water level reaches -3.42 m; then the water from the northwestern basin will be moved toward the southwestern basin. After the implementation of this scenario, the size of the acquired capacity of the lake for the first phase is 1,960,000 m^3, and the second phase is 9,800,000 m^3.

Scenario-04: This scenario simulates the lake where a connection between the southwestern basin and the salt basin will be made. The aim of this model scenario is to reduce the water level inside the southwestern basin by 0.5 m to increase the water capacity by 18,000,000 m^3.

Scenario-05: This scenario simulates the case of diverting the discharge of El-Qalaa drain to discharge into El-Omoum drain via El-Mouheet drain. El-Mouheet drain will easily convey the incoming discharge by gravity because the bed level of El-Mouheet drain is lower than the bed level in El-Qalaa drain and then the discharge will be pumped into El-Omoum drain. This scenario will show the impact of mixing between the two types of the waste on reducing the pollution load. The amount of 1,000,000 m^3 of El-Omoum drain after mixing process will be delivered to be used for irrigation purpose; the mixed water product will be analyzed to determine the suitable types of trees and the method of application. As a result, the hydraulic load on Mariout Lake will be reduced. The amount of 270,000 m^3 of the mixed water will dispose to Lake Mariout to compensate for evaporation, and the rest of water will be pumped to El-Nahda district to be used in irrigation after mixing with the existing freshwater as seen in Table 2.

The discharges and water levels used for all model scenarios are considered the dominant values that recorded and analyzed through some previous studies. The discharges used in the model are shown in Table 3. The water level data related to the averaged discharges used in the model was not available; the water level was considered varying from −2.8 m at the El Mex pumping station to −2.7 at the lake basins (USAID Project 263-0100, 1996). In all model scenarios, the wind condition was taken into account; the predominant wind condition is 22.5° NW with a wind speed of approximately 3.75 m/s. These values of wind speed and direction were used in the model. The total simulation time for each model scenario was taken to be 15 days.

Table 2 Scenario-05 water flow and quality description

Element	El-Qalaa drain	El-Omoum drain	Mixture	Egyptian law (48/1982)
Flow rate (m^3/day)	915,790	4,200,000	5,115,790	–
BOD	124	16	35.3	60
COD	214	68	94	100
NH4	18.62	1.22	4.3	3
NO2	8.16	0.06	1.51	–
NO3	2.09	0.79	1.02	9
T.D.S	853	2,200	1,958	2,000
S.S	487	–	–	60
DO	0.33	4.3	3.58	–

Note: In all model scenarios except the baseline case (Scenario-0), a rehabilitation of all banks of the existing drains and canals inside the lake will be done to close all opening and connections that hinders the water level control

Table 3 Flow discharge input to the model

Location	Discharge (m^3/s)
El-Nubariya canal	29.28
El-Omoum drain	48.61
El-Qalaa drain	10.60
West Nubariya drain	3.5
Waste water treatment plant	5.75

4 Model Results

The two-dimensional model results are presented in this chapter. The following sections discuss the results of the model scenarios including the hydrodynamic results and the water quality results.

4.1 Hydrodynamic Modeling Results

The hydrodynamic results show the water level variation inside the lake basins in addition to the flow circulation inside the lake.

4.1.1 Scenario-0 (Baseline)

Scenario-0 simulates the current situation of the Lake Mariout with the average flow conditions effluents from the different water sources. Figure 7 shows the flow velocity values at the end of the simulation period (2 weeks). The figure shows that the velocity values varied from 0 to 0.35 m/s overall the simulated area. The highest flow velocity values were found in the restricted water areas like inside the drains of Risha and El-Omoum and at the area close to El Mex pumping station. The variation in water levels at the lake basins is shown in Fig. 8.

4.1.2 Scenario-01

Scenario-01 simulates the effect of increasing the capacity of El Mex pumping station to be 122 m^3/s for 8 days continuously to reduce the water level at the main basin of Lake Mariout in addition to rehabilitation of the drains and canal banks inside the lake. The result of velocity distribution is presented in Fig. 9. The figure shows that the flow velocity increased only at the main basin and at the canal and drains because of closing all opening along the banks of the drains and canal. The water level at the lake basins is shown in Fig. 10. The figure shows that the water level was reduced after 8 days to be −3.25 m, which means saving about 0.45 m in water depth to be used as a storage area for storm events.

4.1.3 Scenario-02

Scenario-02 simulates the effect of 1 m dredging works that proposed to be done in both of northern, western basin and the southern basin. Also, this scenario will include rehabilitation of the drains and canal banks inside the lake. The result of velocity distribution is presented in Fig. 11 which shows that the flow velocity

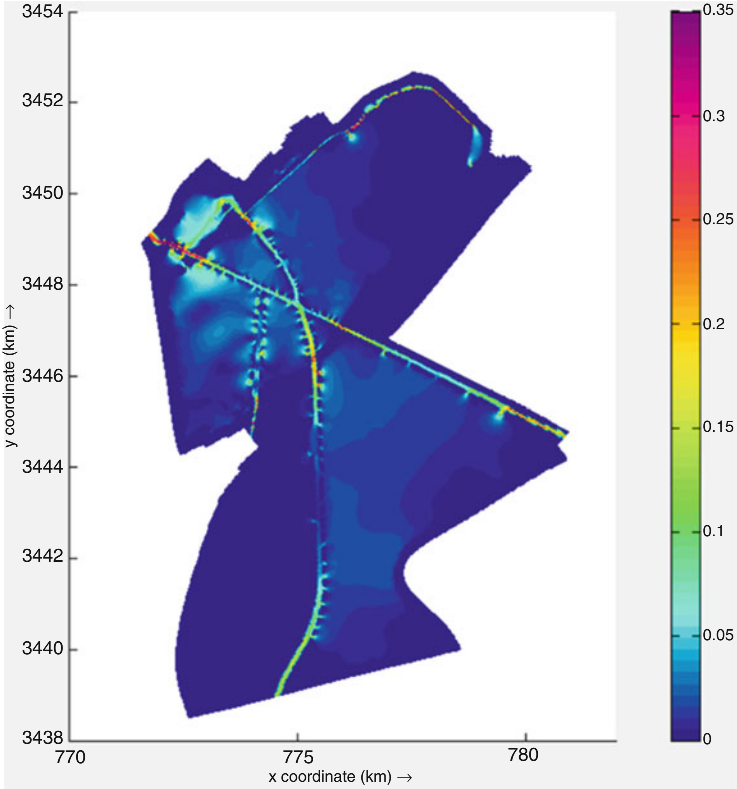


Fig. 7 The flow velocity map "Scenario-0"

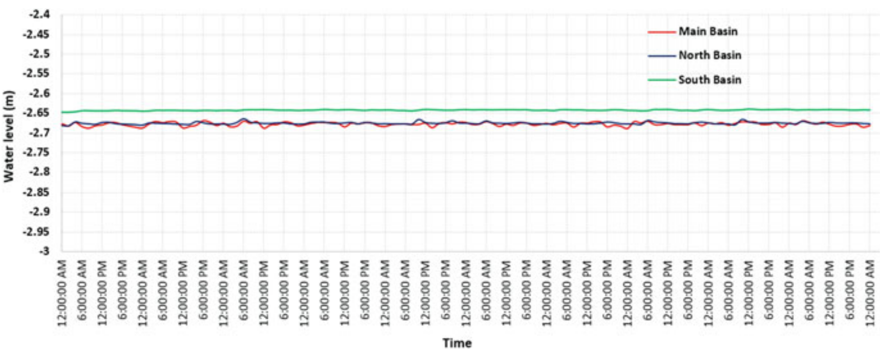


Fig. 8 The water level at the lake basins "Scenario-0"

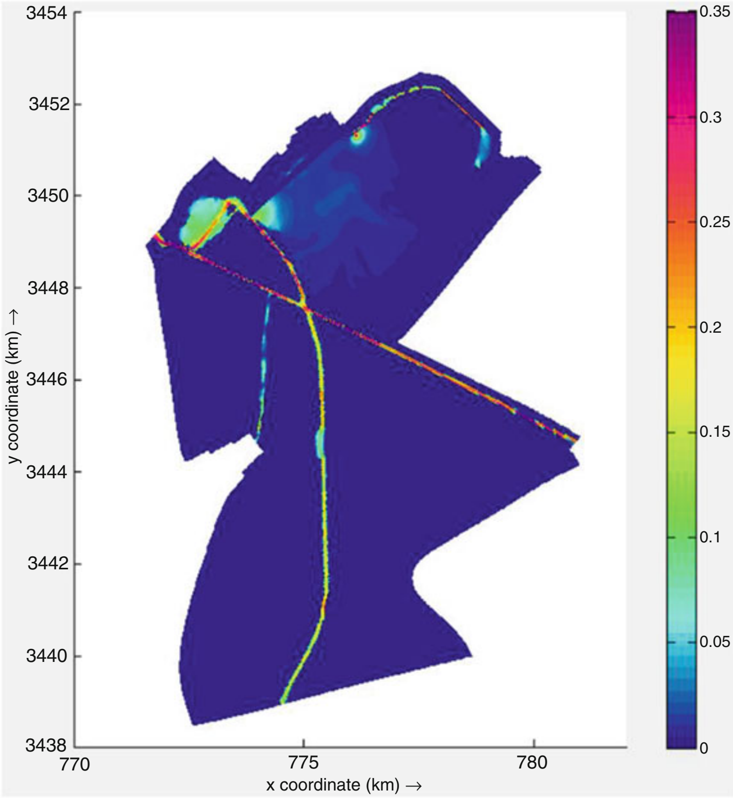


Fig. 9 The flow velocity map "Scenario-01"

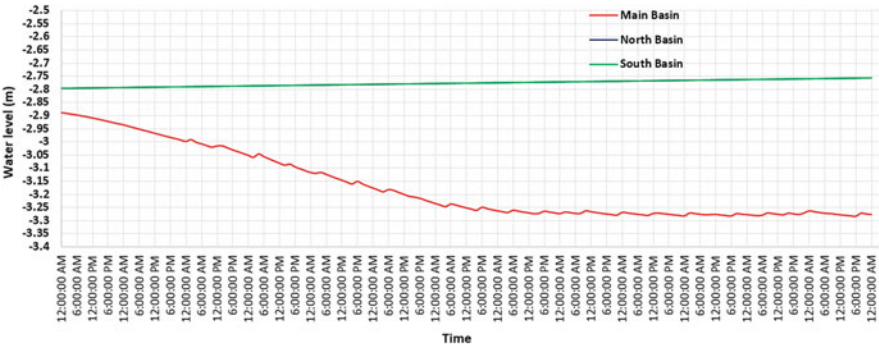


Fig. 10 The water level at the lake basins "Scenario-01"

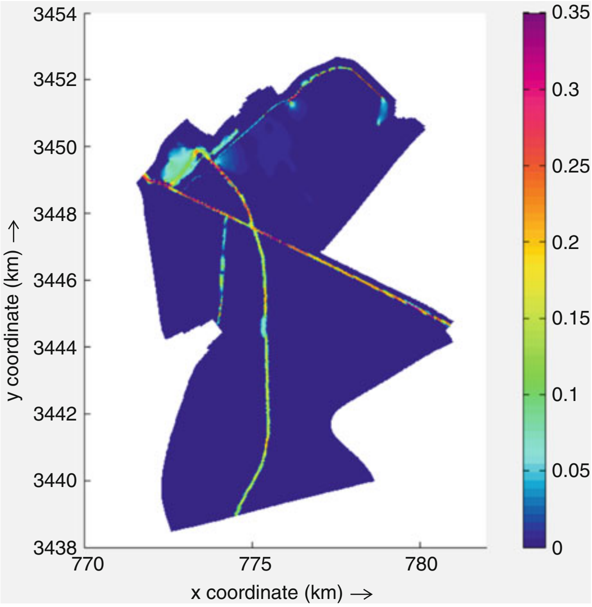


Fig. 11 The flow velocity map "Scenario-02"

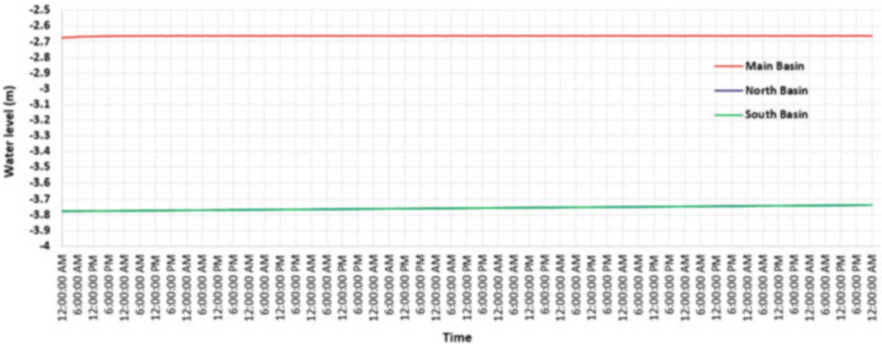


Fig. 12 The water level at the lake basins "Scenario-02"

increased only at the main basin and at the canal and drains because of closing all opening along the banks of the drains and canal. The water level at the lake basins is shown in Fig. 12 which shows that the water level was reduced at both of northern and southern basins about 1 m below the mean original water level at the main basin.

4.1.4 Scenario-03

Scenario-03 simulates the effect of dredging works and the banks rehabilitation to drains and canal as the same as in Scenario-01. Also, this scenario simulates the movement of the water from the main basin (in case of storm events) to the northern, western basin until the water level reaches to −3.42 m, then the moving water from the northern, western basin toward the southwestern basin. The result of velocity distribution is presented in Fig. 13 which shows that the flow velocity increased only at the main basin and at the canal and drains because closing all opening along the banks of the drains and canal, the flow velocity in the northern basin had a bit increased. The water level at the lake basins is shown in Fig. 14. The figure shows that the water level was reduced at both of northern and south basins about 1 m below the mean original water level at the main basin to be −3.8 m. During the simulation run, the water level was increased at the northern basin to reach −3.42 m after 6 days due to the discharged water from the main basin during storm events with a discharge rate of 7 m^3/s to the northern basin. This water level in the northern basin became constant along the remaining simulation time; at the same time, the water was discharged to the southern basin for the remaining simulation period. The results of water level also show that after 15 days the water level inside the south basin will not reach to level −3.42 m, which means that the southern basin will be ready to have a capacity of water coming from storm events continuously more than 15 days.

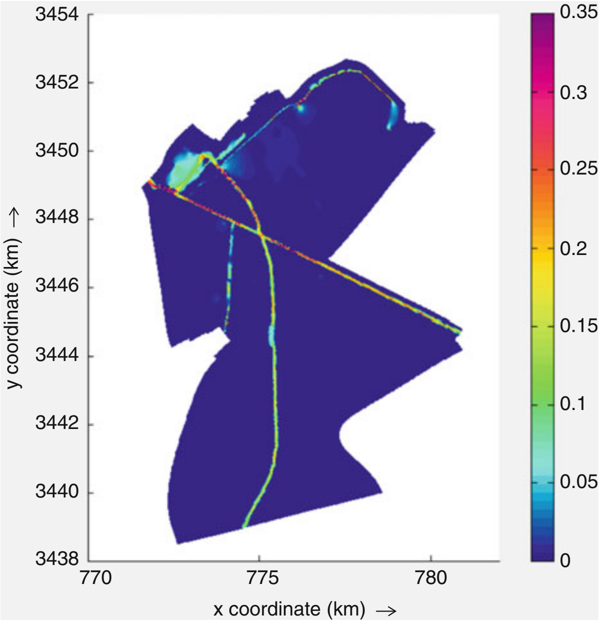


Fig. 13 The flow velocity map "Scenario-03"

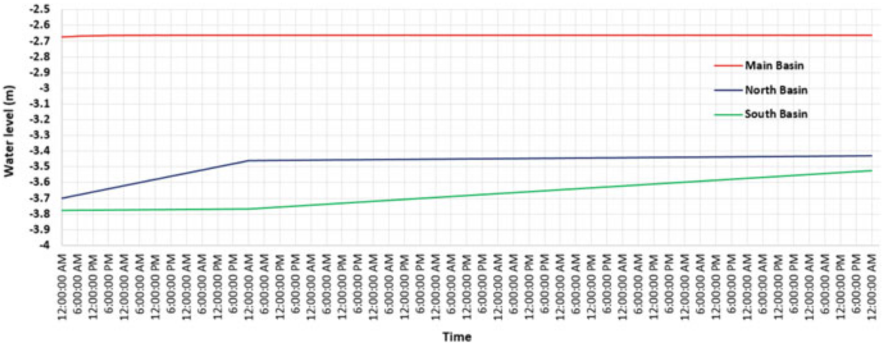


Fig. 14 The water level at the lake basins "Scenario-03"

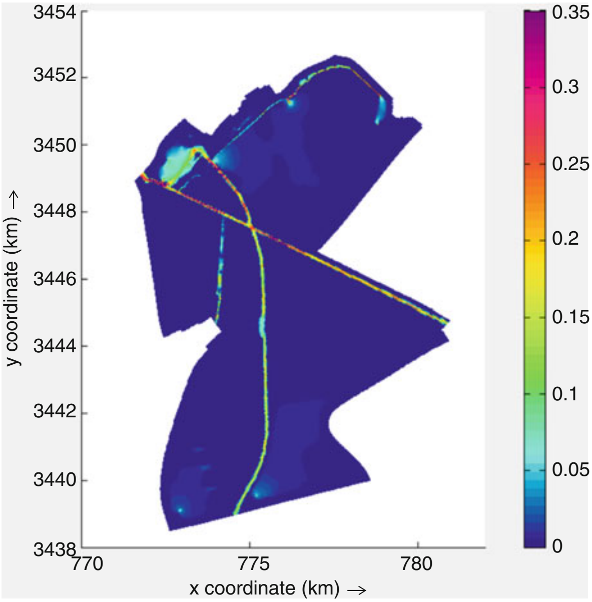


Fig. 15 The flow velocity map "Scenario-04"

4.1.5 Scenario-04

Scenario-04 simulates the effect of connecting the southwestern basin with the salt basin. The result of velocity distribution is presented in Fig. 15 which shows that the flow velocity increased at the main basin and at the canal and drains because closing all opening along the banks of the drains and canal, the flow velocity in both of the southern basin and the salt basin had a bit increased also. The water level at the lake basins is shown in Fig. 16, which shows that the water level at the southern basin is reduced by 0.5 m below the original water level after 10 days from starting simulation time with a discharge rate of 15 m^3/s.

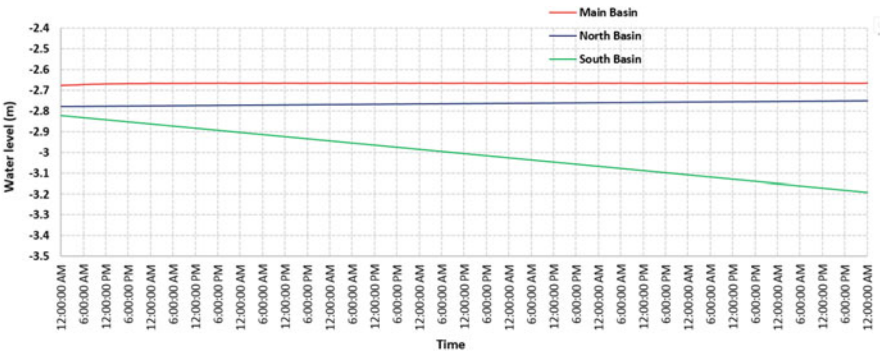


Fig. 16 The water level at the lake basins "Scenario-04"

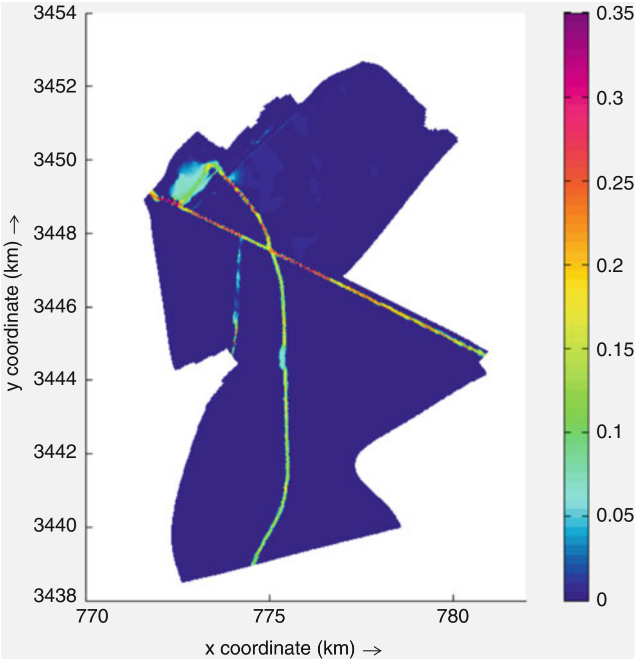


Fig. 17 The flow velocity map "Scenario-05"

4.1.6 Scenario-05

Scenario-05 simulates the effect of diverting the discharge of El-Qalaa drain indirectly to discharge into El-Omoum drain for irrigation purpose, and about 270,000 m^3 of the mixed water will dispose to the main basin of Lake Mariout to compensate for evaporation. The result of velocity distribution is presented in Fig. 17 which shows that the flow velocity decreased at the main basin especially

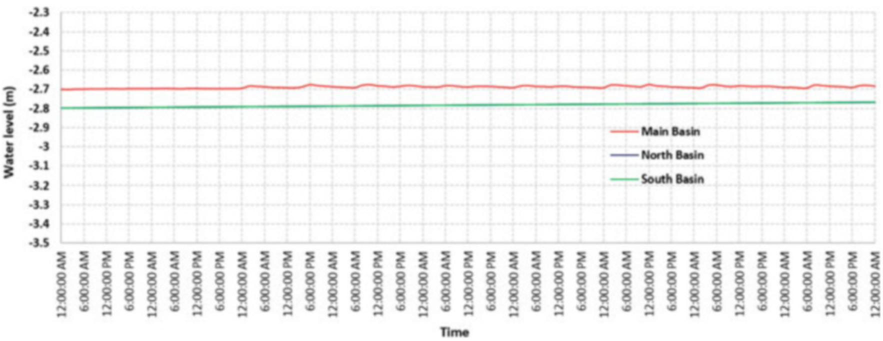


Fig. 18 The water level at the lake basins "Scenario-05"

at the Risha drain and at the canal and El-Omoum drain the velocity distribution almost is the same as the previous scenarios. The water level at the lake basins is shown in Fig. 18. The figure shows that the water level at the main basin was increased about 7 cm due to the amount of water which was directly discharged for compensation purpose and located outside the Risha drain.

4.2 Water Quality Modeling Results

The water quality results show the simulated water quality parameters inside the lake and the distribution of the effluents for the model scenarios.

4.2.1 Scenario-0 (Baseline)

Scenario-0 simulates Lake Mariout increase El Mex pumping capacity. Figures 19, 20, 21, 22, 23, 24, and 25 show the simulated water quality parameters in case of Scenario-0. For total coliform count, the value is 9×10^6 MPN near El-Qalaa drain outlet. The same pattern exists for fecal coliform. The maximum value is 3.5×10^5 MPN near El-Qalaa drain outlet; the fecal coliform count reduces at El Mex station to 1.6×10^5MPN and 3×10^6 MPN for total coliform. For eutrophication group parameters, Ammonia concentration is very high in Risha drain (18 mg/L) and is lower in the southern basin lake (2 mg/L). Nitrogen (25 mg/L) and phosphorus (1,000 mg/L) are high near the outlet of El-Omoum drain (0.5 mg/L) and in Risha drain (0.3 mg/L).

For oxygen group, BOD is very high in Risha drain and near WWTP outlet (120 mg/L) and much lower inside the southern basin of the lake (20 mg/L). COD is very high in Risha drain and near WWTP outlet (120 mg/L) and much lower inside the lake (80 mg/L). DO is very low in Risha drain and near WWTP outlet (0 mg/L) and higher inside the lake (5 mg/L).

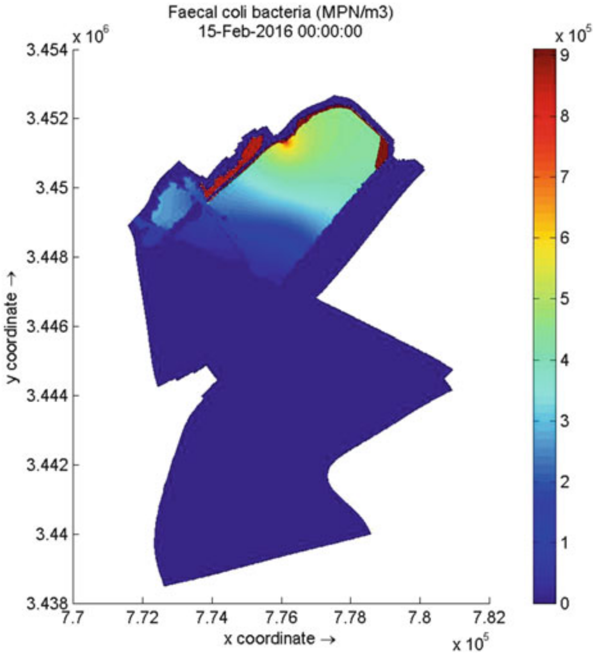


Fig. 19 The faecal coliform map "Scenario-0"

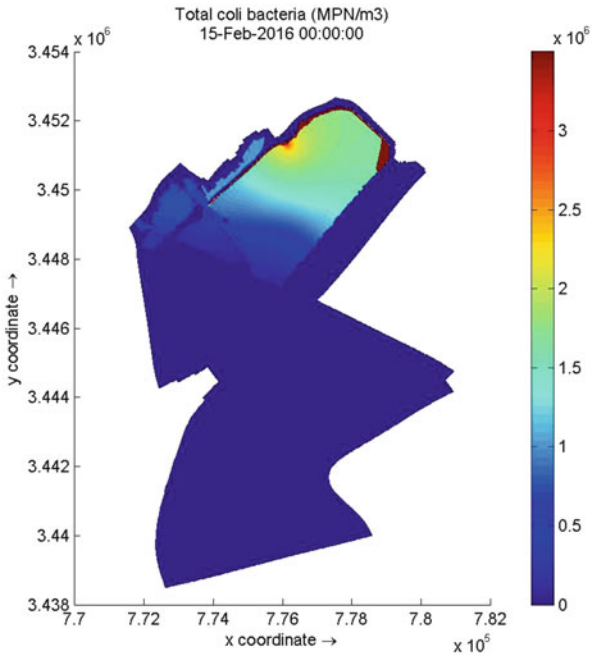


Fig. 20 The total coliform map "Scenario-0"

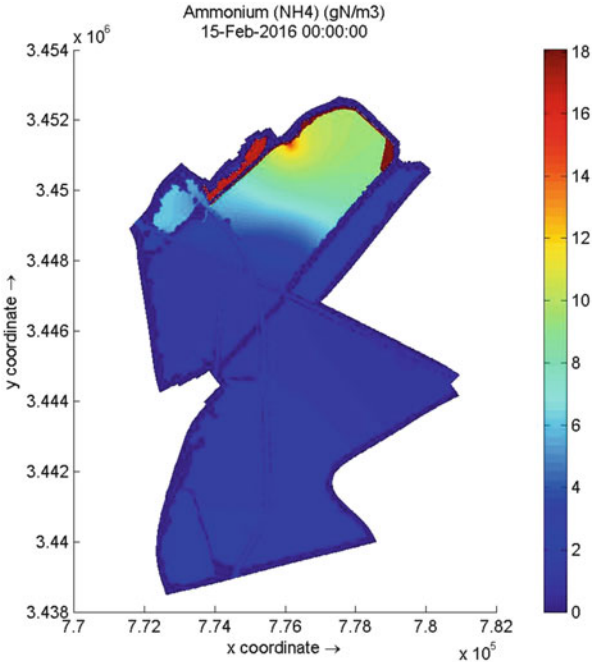


Fig. 21 Ammonia map "Scenario-0"

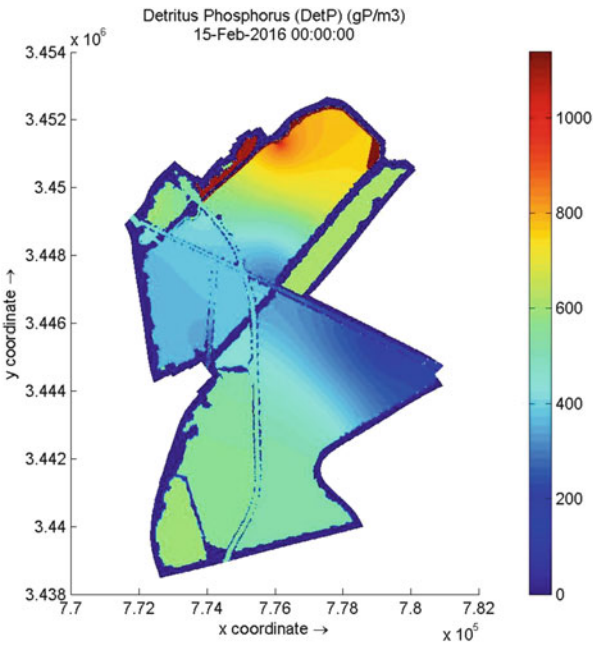


Fig. 22 Detritus phosphorus map "Scenario-0"

Fig. 23 BOD map "Scenario-0"

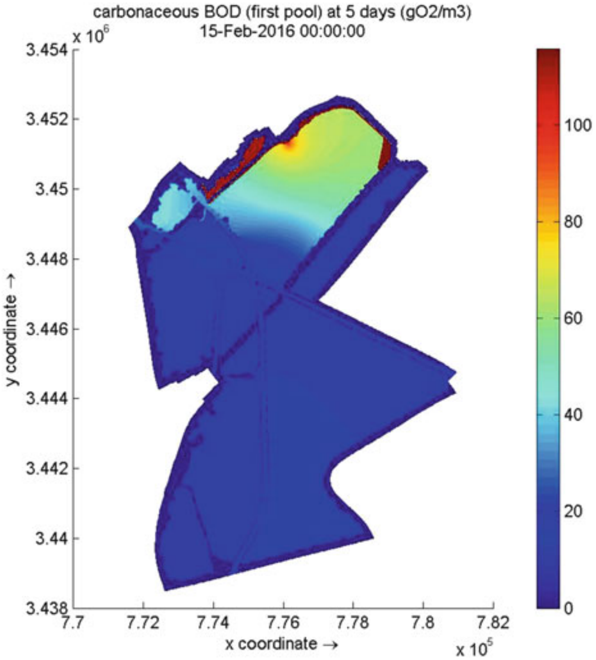
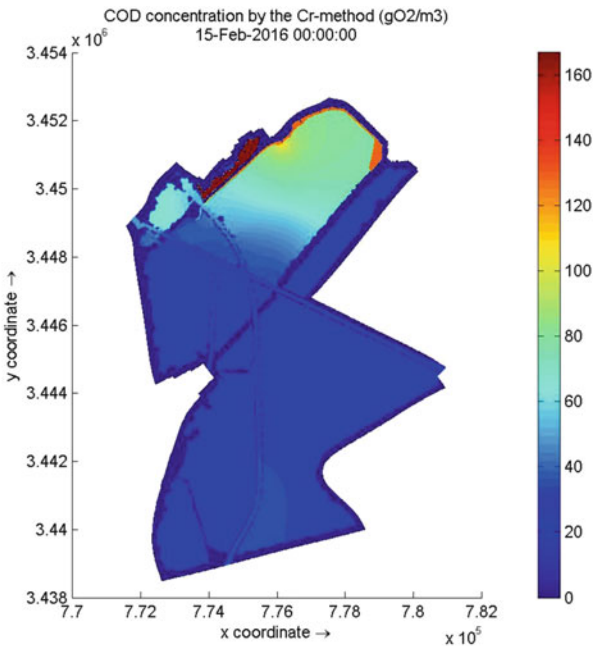


Fig. 24 COD map "Scenario-0"



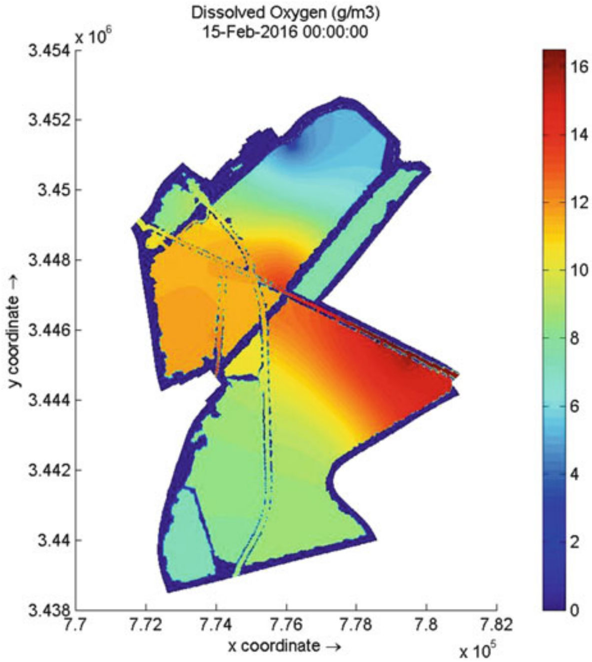


Fig. 25 DO map "Scenario-0"

4.3 Comparison of All Model Scenarios

The comparison between all scenarios has been conducted at El Mex station Figs. 22, 23, 24, 25, 26, 27, 28, 29, 30, 31, and 32 and middle of the lake as shown in Figs. 33, 34, 35, 36, 37, 38, 39, 40, and 41.

First at El Mex station, for total bacteria count, the best scenario is Scenario-02 followed by Scenario-04, whereas, for fecal coliform count, the best scenario is Scenario-02. For detritus nitrogen and ammonia, the best scenario is Scenario-02 followed by Scenario-04. For detritus phosphorus, the best scenario is Scenario-02. For COD and BOD, the best scenario is Scenario-02 followed by Scenario-04. For DO, the best scenario is Scenario-05 followed by Scenario-03.

Second at the middle of the lake, considering the count of the total bacteria, the best scenario is baseline scenario followed by Scenario-02, whereas for fecal coliform count, the best scenario is baseline scenario followed by Scenario-02. The highest coliform count is in Scenario-05 followed by Scenario-04.

For detritus nitrogen and ammonia, the best scenario is Scenario-02 followed by Scenario-04. For detritus phosphorus, the best scenario is Scenario-02. For nitrate, the best scenario is Scenario-05 followed by Scenario-02.

For COD and BOD, the best scenario is Scenario-02 followed by Scenario-04. For DO, the best scenario is the base scenario followed by Scenario-01. DO Concentration is very low in Scenario-03, moderate in Scenario-02 and Scenario-03.

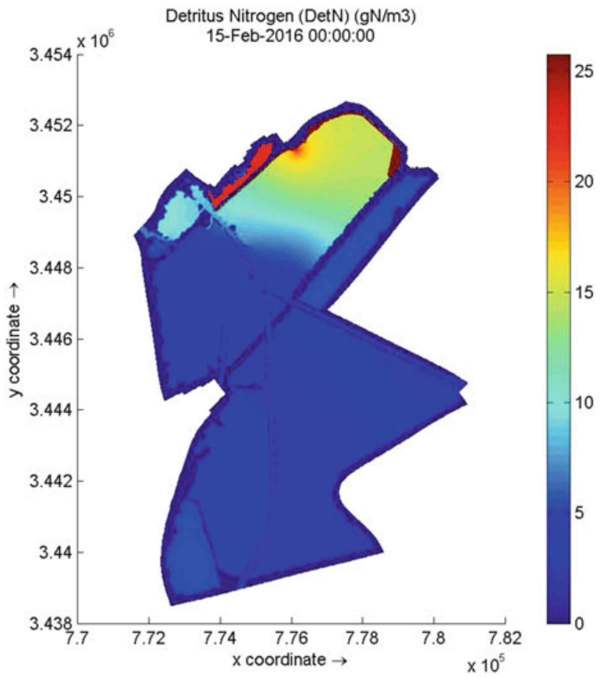


Fig. 26 DetN map "Scenario-0"

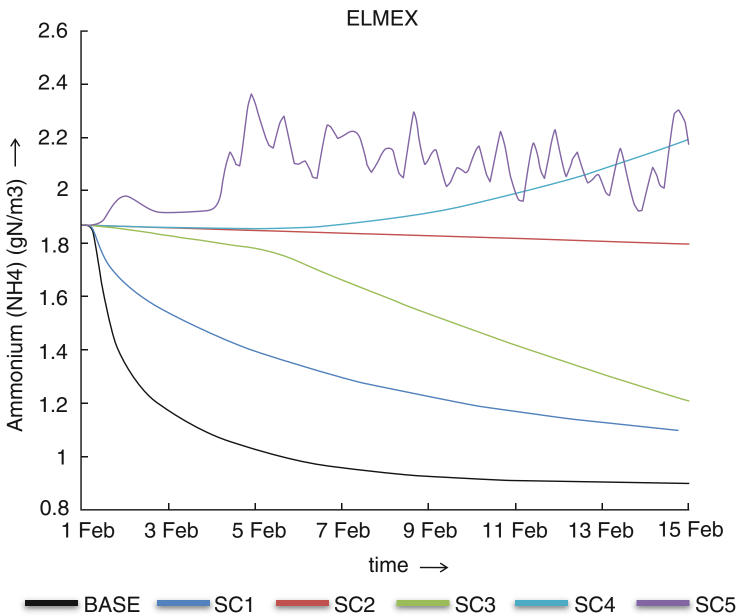


Fig. 27 Comparison between scenarios for ammonia at El Mex station

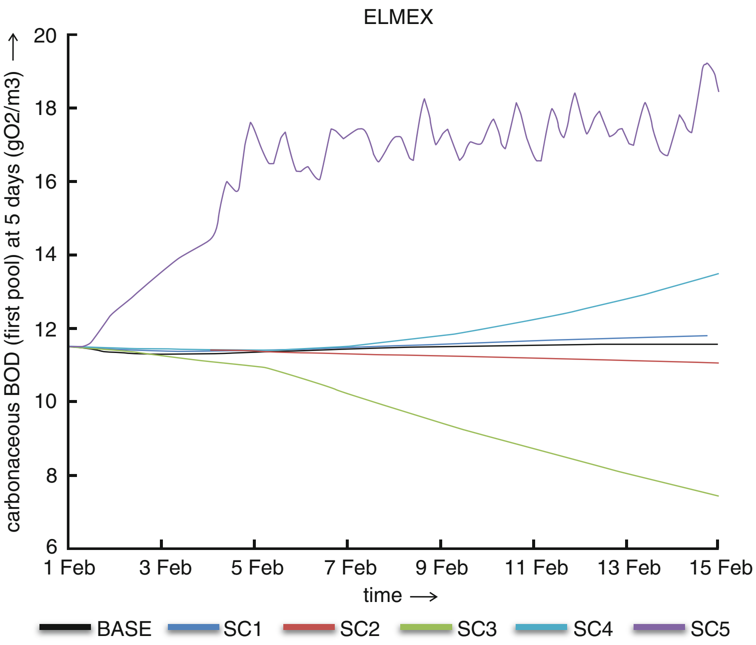


Fig. 28 Comparison between scenarios for BOD at El Mex station

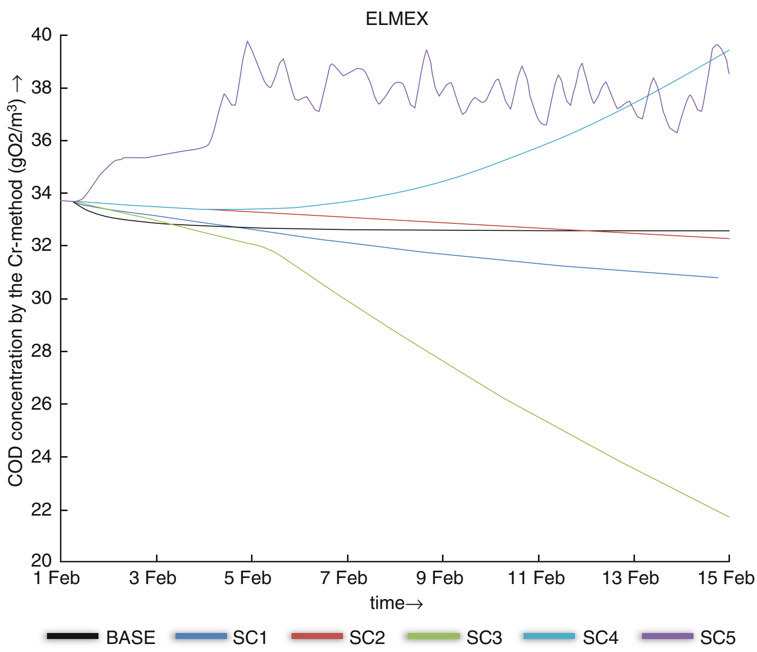


Fig. 29 Comparison between scenarios for COD at El Mex station

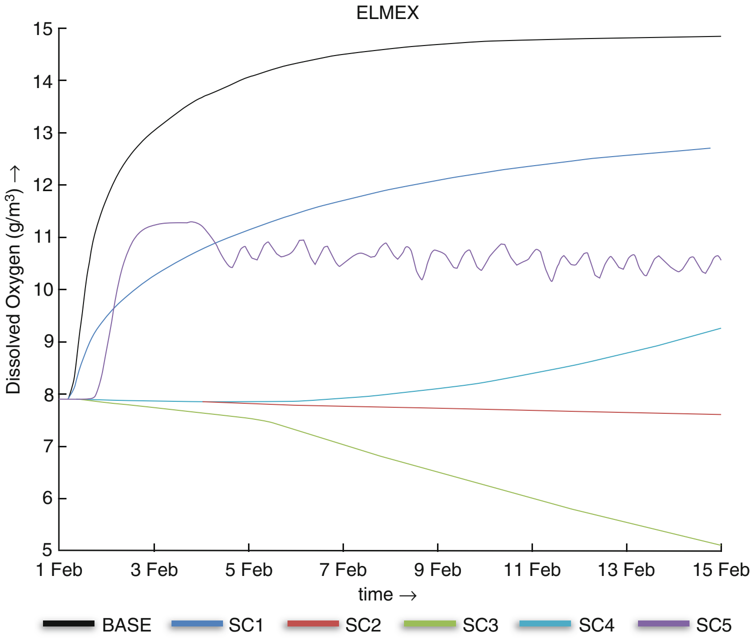


Fig. 30 Comparison between scenarios for dissolved oxygen at El Mex station

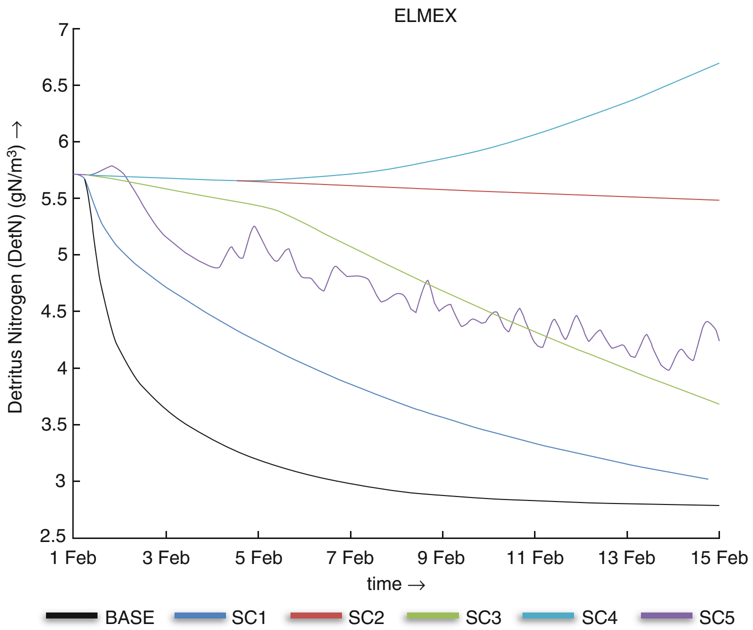


Fig. 31 Comparison between scenarios for detritus phosphorus at El Mex station

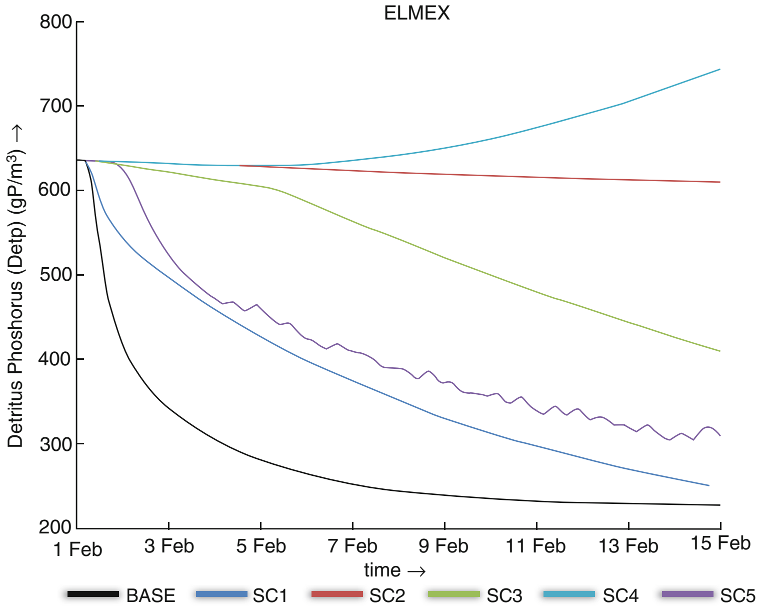


Fig. 32 Comparison between scenarios for water temperature at El Mex station

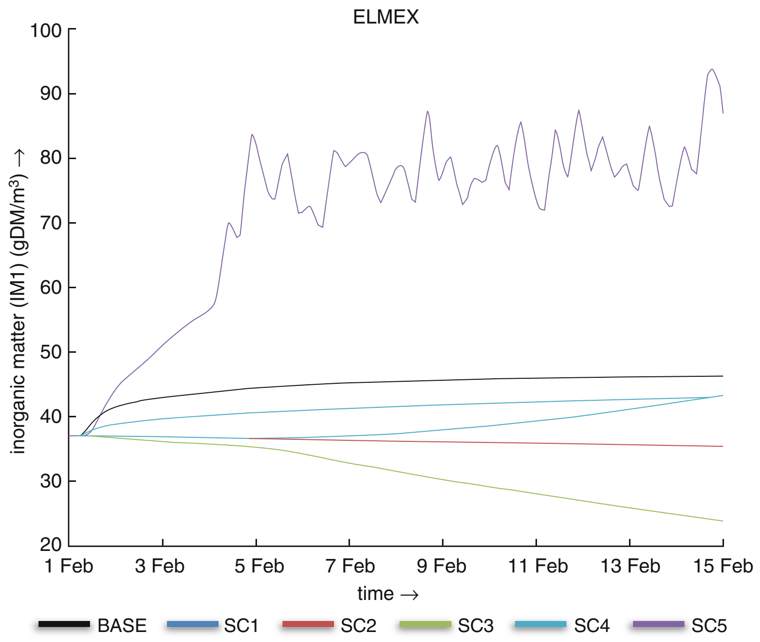


Fig. 33 Comparison between scenarios for cadmium at El Mex station

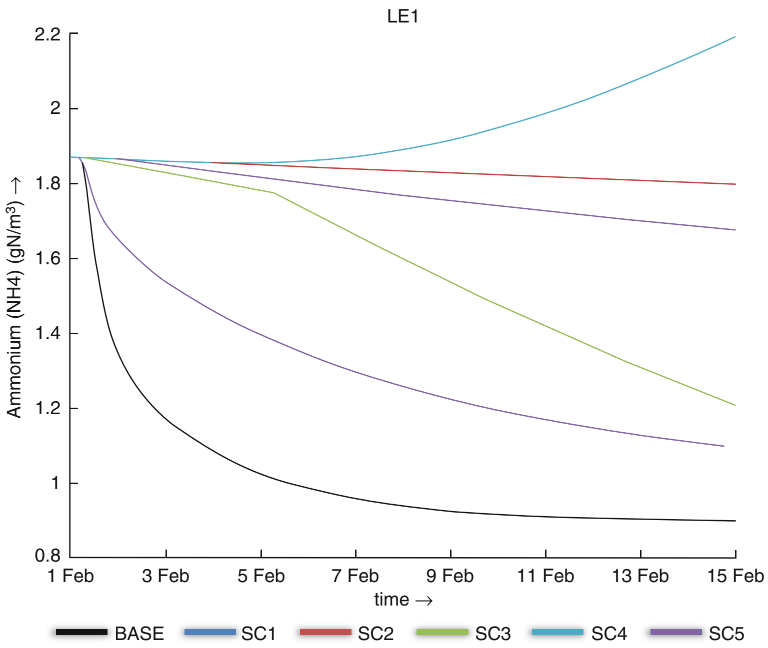


Fig. 34 Comparison between scenarios for ammonia at the middle of the lake

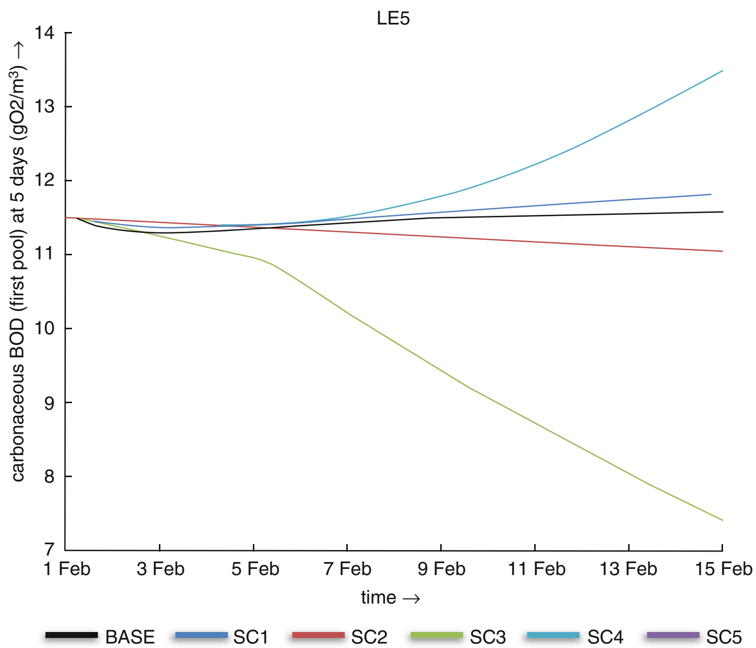


Fig. 35 Comparison between scenarios for BOD at the middle of the lake

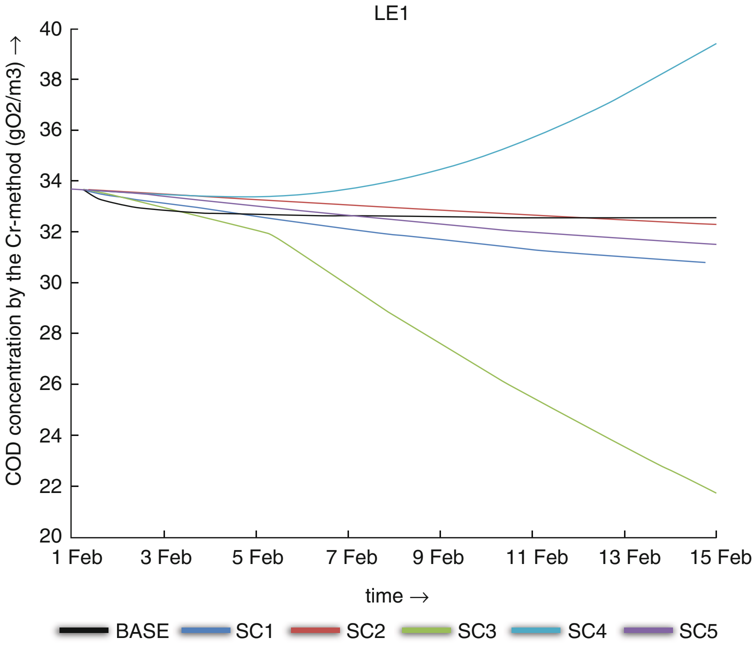


Fig. 36 Comparison between scenarios for COD at the middle of the lake

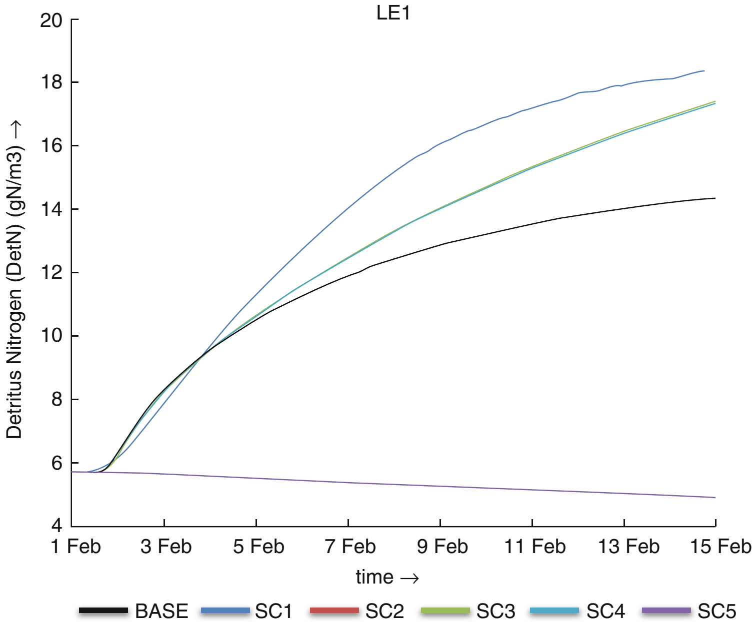


Fig. 37 Comparison between scenarios for detritus nitrogen at the middle of the lake

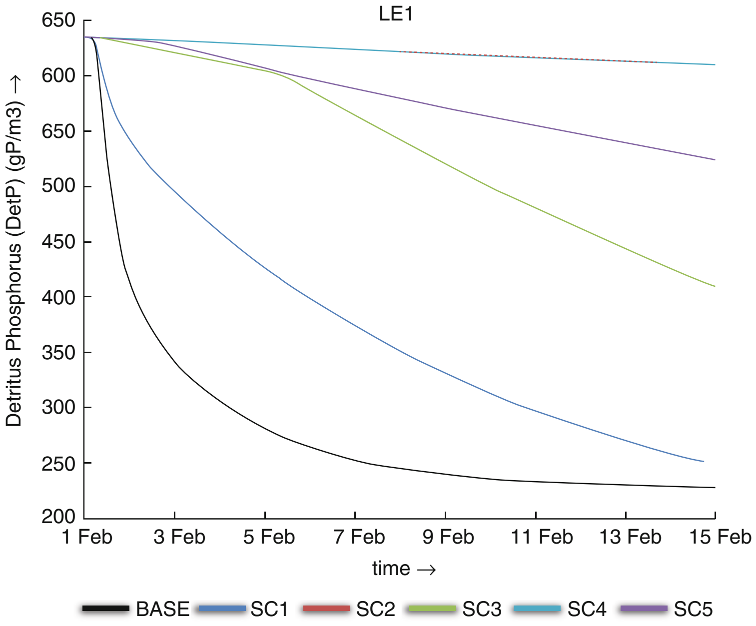


Fig. 38 Comparison between scenarios for detritus phosphorus at the middle of the lake

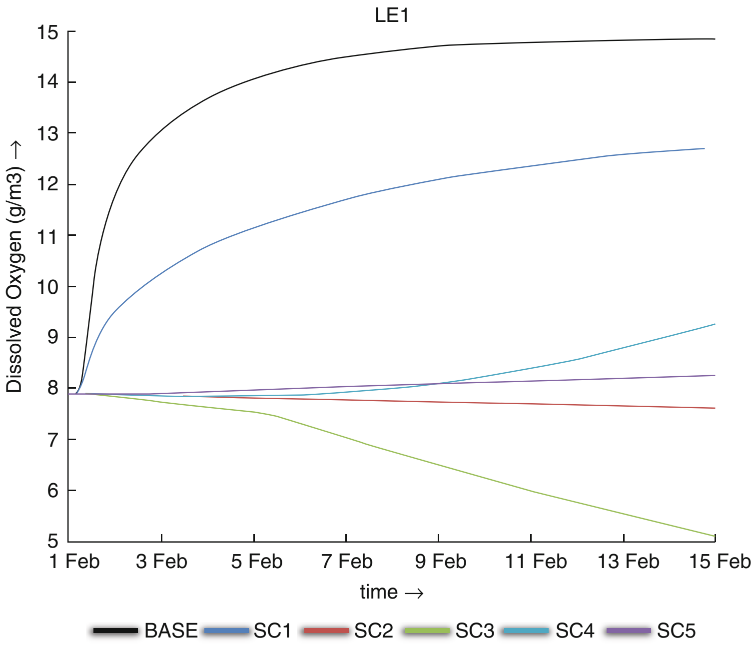


Fig. 39 Comparison between scenarios for DO at the middle of the lake

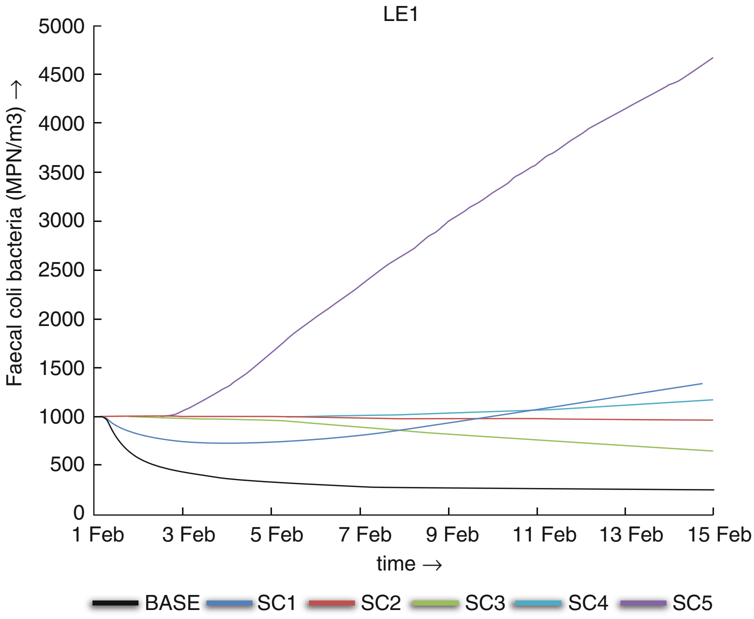


Fig. 40 Comparison between scenarios for fecal coliform at the middle of the lake

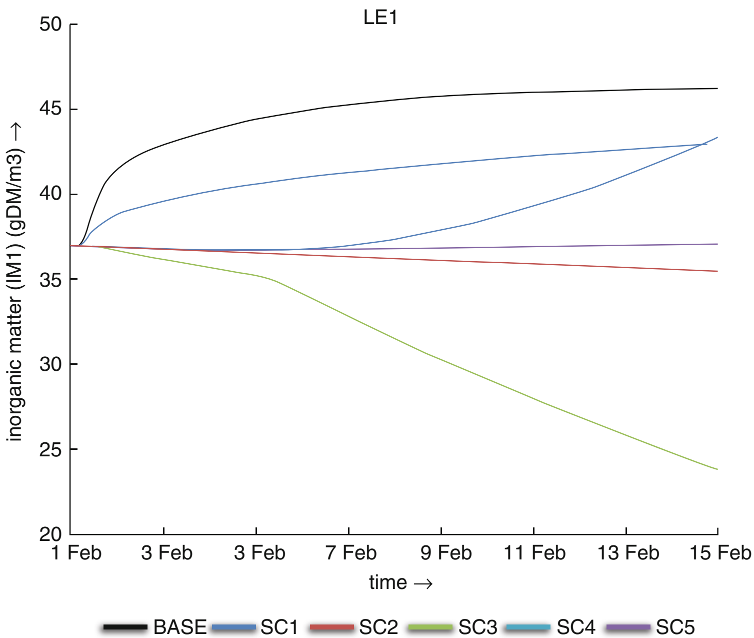


Fig. 41 Comparison between scenarios for the inorganic material middle of the lake

For inorganic matter, the highest value is in baseline scenario followed by Scenario-04 and Scenario-01. The lowest value of the inorganic matter is in Scenario-03 and Scenario-02 followed by Scenario-05.

The dredging option involves a number of steps. Those steps include:

- Planning and permitting
- Selection of a qualified contractor
- Verification of dredging depths/locations
- Actual removal of the sediments from the lake bottom
- Dewatering of the dredged material and
- Disposal of the dredged material

Cost estimates were broken down into the following categories: dredge cost, dewatering, and disposal. Unit costs associated with mechanical dredging are expected to range between \$7 and \$15/m^3. Dewatering is estimated to cost between \$20 and \$30/CM. If the dredged material does not meet the environmental requirements, disposal in a sanitary landfill is a likely option that costs \$15/ton for disposal within the landfill. Overall dredging option will improve the water quality, the lake environment, and hence the quality of the produced fish.

5 Conclusions

Since the shallow coastal lake at the downstream of the catchment is considered as a sink that receives all the wastewater discharged from the watershed, it was important to develop a more detailed modeling component for the lake system. The 2D hydrodynamic model was developed to facilitate a more detailed study of the lake hydrodynamics, taking into account the effects of the main driving forces on the flow which are wind and tides. The model was tested for different hydrodynamic scenarios to determine the most sensitive parameters that affect the flow conditions within the lake. The model showed that the main driving force that affects the flow velocities and currents in the lake is the wind force. The wind is responsible for mixing and resuspension in the lake due to its shallow depth, and this, in turn, is an important parameter to be considered during the water quality modeling of the lake system.

A reliable water quality model is based on a detailed and well-structured hydrodynamic model that is capable of describing the physical and hydrodynamic processes of the water system. Therefore the water quality modeling tools for the shallow lake system in this research work are coupled with the developed and calibrated hydrodynamic 2D model. The water quality modeling tools are the basic parameters model. The model results and calculations are in reasonable agreement with the measured concentrations. This model was able to predict the basic water quality indicators of the lake system. The predicted results indicated that the second scenario, 1 m dredging works in the northern, western, and southern basin will improve the circulation in the lake. Moreover, it will increase the storage capacity and will improve the water quality. Dredging work of 1 m in the northern, western, and southern basin will improve the circulation in the lake and increase the storage capacity and will improve the water quality. It is recommended to connect the southwestern basin with the salt basin to improve the circulation and storage capacity of the lake.

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References

1. ALAMIM (2009) Integrated action plan, EC-SMAP III (Alexandria Lake Mariout Integrated Management). American Public Health, Washington
2. Donia N (2016) Water quality modelling of Northern lakes case study (Egyptian Northern lakes). In: Rashed MN (ed) Lake sciences and climate change. ISBN 978-953-51-2557-0, Print ISBN 978-953-51-2556-3
3. Hamilton DP, Schladow SG (1997) Prediction of water quality in lakes and reservoirs. Part I – model description. Ecol Model 96(1–3):91–110
4. Haralampides K, Georgiou IY, McCorquodale AJ (2000) Water quality impacts on the Lake Pontchartrain Estuarine System. Proc Water Environ Fed 10:402–425
5. Jin KR, Hamrick JH, Tisdale T (2000) Application of three-dimensional hydrodynamic model for Lake Okeechobee. J Hydraul Eng 126(10):758–771
6. Chung EG, Bombardelli FA, Schladow SG (2009) Sediment resuspension in a shallow lake. Water Resour Res 45:W05422. https://doi.org/10.1029/2007WR006585
7. Jin KR, Ji ZG, James RT (2007) Three-dimensional water quality and SAV modeling of a large shallow lake. J Great Lakes Res 33(1):28–45
8. Schladow SG, Hamilton DP (1997) Prediction of water quality in lakes and reservoirs: part II – model calibration, sensitivity analysis and application. Ecol Model 96(1–3):111–123
9. Delft3D-FLOW (2015) Simulation of multi-dimensional hydrodynamic and transport phenomena, including sediments. Deltares, Delft
10. Delft3D-Water Quality (2015) Water quality and aquatic ecology modelling suite. Deltares, Delft