Investigating the Efficiency of the Water Circulation System to Assess Water Quality inside Artificial Lagoons "Case Study Hacienda Bay"

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Abstract

This research is aimed to study the effect of the retention time and its impact on the water quality inside an artificial lagoon through checking the functionality of both feeding and drainage system inside the lagoon. Increasing the retaining time of the water inside the lagoon may cause some water quality problems such as having the opportunity for algae growth, which in turn changes the color and smell of the water inside the lagoon, this will alienate the use of the lagoon as a swimming pool for tourists. For this purpose, 2D and 3D hydrodynamic and water quality numerical model using Delft3D software package was used to study the water circulation and water quality parameters inside the lagoon with its designed feeding and drainage system.

Four model scenarios were tested to study the flow pattern under different operation modes of the lagoon feeding system. The flow velocity distribution in the horizontal direction for all model scenarios was obtained. The simulation results showed that the total volume of the water inside the lagoon will be fully exchanged with the seawater within 24 hours in three different operation modes of the lagoon (three model scenarios). The model results of one scenario showed that, the total volume of the water inside the lagoon will be fully exchanged within 27 hours. The model computations showed that the exchange of water in the lagoon with the seawater is within the international water quality standards which stats that the maximum retaining time of water inside the lagoon should not exceed 36 hours. This will help in preserving the water quality and minimizing the algae formation and the blocking of the nozzles by the algae and tiny plants. Hopefully, this research will preserve the environment and contribute to the benefit of the man health as well.

Key words: Lagoon, hydrodynamic, water quality, numerical model, retention time, water circulation.

1. INTRODUCTION

Hacienda Bay is located at 124 km west of Alexandria on the Mediterranean Sea. It is oriented in West north – East south direction. The beach in the bay is mainly sand with a rocky head to the west of the bay which introduces natural protection to the beach. A prestigious development through a master planning of Hacienda Bay has been implemented in that area. The master plan includes several artificial lakes within the development scheme. The main lake consists of five basins directed towards south and connected to each other from the north direction through one big basin. The water feeding system of the lake consists of pump station pumping the sea water into a pipeline network distributed along the bed of the lake. The water flows out from the pipelines to the lake through a number of nozzles distributed along the pipes. The residence time is the average amount of time water residing within a given lagoon, it plays an important role in environmental impacts by determining the exposure time of residence biota to water-borne materials, and in influencing the accumulation of sediments or adsorbed substances (Prager, 1991). The flushing of the water from the lake is done by the overflow of the water in the lake over flow structure surrounding the entire lake, where it is collected and discharged back to the sea. In shallow, narrow lagoons flushing periods may be relatively rapid, less than one day (Robert and Suhayda 1983).

The aim of this research is to investigate the efficiency of the water circulation system and as a result the water quality in the lake using hydrodynamic numerical model. The hydrodynamic and water quality numerical model was used to simulate the water circulation and its effect on water quality parameters inside the lake, this to minimize the negative impacts on the water quality.

2. DESCRIPTION OF THE LAKE

The artificial lake in the study area is composed mainly of five fingers-like structure connected together as shown in the general layout presented in Figure 1. The lake has approximately surface area of about 31071m^2 with 1.5m depth at the deepest point getting shallower gradually at the sides; the total water volume inside the lagoon is 33810 m^3.

The feeding system consists of pump station pumping the sea water into the lake through main five feeding pipelines. Each feeding pipeline has a number of nozzles distributed along the bed of the lake, the total number of nozzles are 197 distributed on the main feeding pipeline where 48 nozzles, 36 nozzles, 40 nozzles, 30 nozzles, and 43 nozzles are included in pipeline 1, 2, 3, 4, and 5 respectively.

According to the received design for the main feeding pipelines and nozzles, HRI Report No. 166/2009, the discharge for each nozzle on pipeline-1 and pipeline-5 is 5.16 m^3/hr. However, the discharge for each nozzle on pipeline-2, pipeline-3 and pipeline-4 is 8.86 m^3/hr. the discharged water flows over a structure surrounding the entire lake, and discharged back into the sea. The bed level of the lake is +0.30 m MSL and the water level will be +1.80m MSL. The lake bed material is sand with thickness of 30 cm.

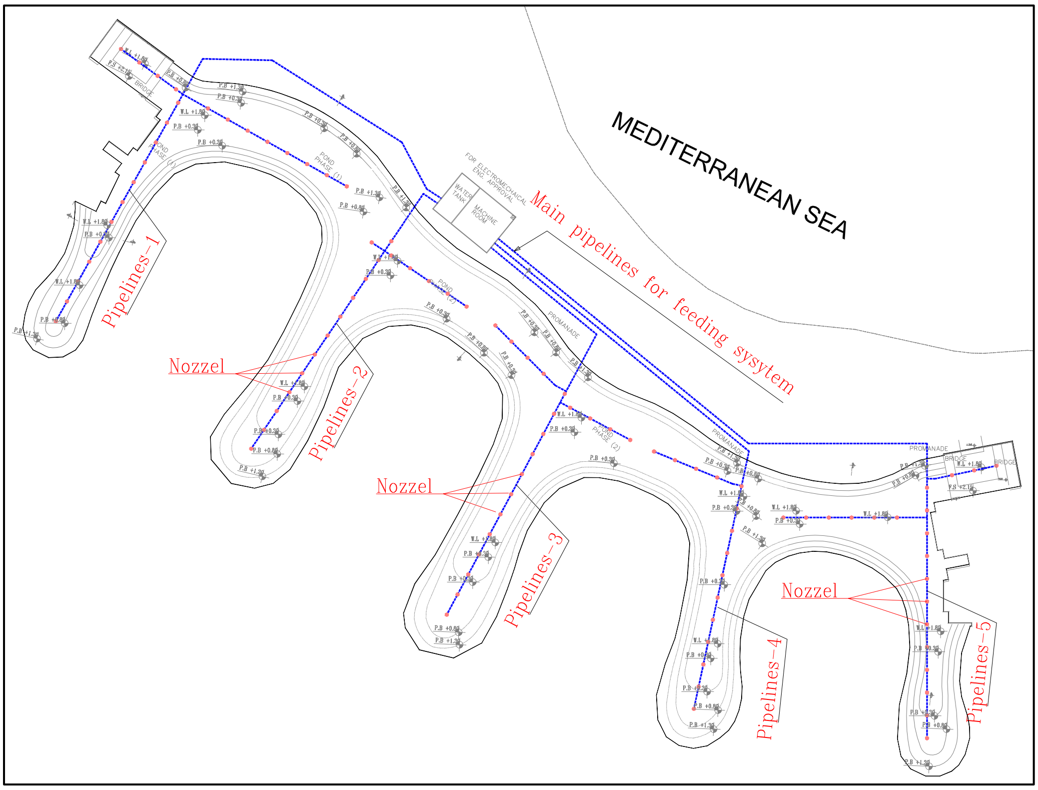


Figure 1: General Layout for the lake and it's feeding system

3. HYDRODYNAMIC NUMERICAL STUDY

Delft3D Software package of Delft Hydraulics, the Netherlands was used to study the circulation of the water inside the lake and to investigate the effect of the water retention time on the water quality inside the lake. Delft3D is a multi-dimension simulation program designed to deal with several different physical, chemical and biological processes in estuary and coastal areas. This program is applicable for areas of hydrodynamic, sediment transport, morphological, water quality, particle tracers and ecology, delft3d user manual; 2011.The numerical model was used to describe the characteristics of the flow in the lake area. Based on the map of the project area and the expected flow patterns in this area the numerical model was setup for a length of about 450 m parallel to shore line and 150 m for each finger of the lake. To be able to setup a numerical model that represents reality well the data about bathymetry, Lake Boundary were collected.

Boundary conditions: d'Angremond, 2001a introduced the storage area approach to determine the local boundary conditions for a closing structure, which in this particular study is lagoon system. The discharge points have been used to simulate the discharges of each nozzle at the bottom of the lake. The water is discharged from the lake to the surrounding channel through free over flow. The open boundary (water level boundary condition) was used at the external edges of the channel to keep the water level at the lake constant. The available data gives sufficient information on the material at the bottom of the lake to define roughness coefficients for the numerical model. The roughness coefficient in the model is based on Chezy formula and is taken as 65.

The computational grid: The computational grid for the hydrodynamic model is curvilinear and covers the area of the lake Figure 2 shows an overview of the computational grid in the model. Due to the complex geometry of the simulated lake and to get a good represent, the grid resolution varies from 0.3m to 2m. The coarser grid is close to the ends of fingers. Overall grid cells in the model are 920 nodes.

Depth schematization: The bathymetric data was used to setup the water depth, HRI Report No. 166/2009. The bed level was set to be +0.30 m MSL at the lake area. The side slope of the lake was started from +0.3m MSL at the bottom to +1.80m MSL at the top of the lake.

The model construction: The simulated coordinates of the lake are exactly obtained from the master plan from the client. The coordinate system is based on the WGS84 universal system. The nozzles were simulated as point discharge with same location and orientation at the bottom of the lake. The discharge for each point on pipeline-1 and pipeline-5 was 5.16 m^3/hr with total number of points 91. The discharge for each point on pipeline-2, pipeline-3 and pipeline-4 was 8.86 m^3/hr with total number of points 106. Figure 3 shows the distribution of the discharge points in the model. A channel was constructed in the model at the external edges of the lake which simulates the over flow structure surrounding the entire lake.

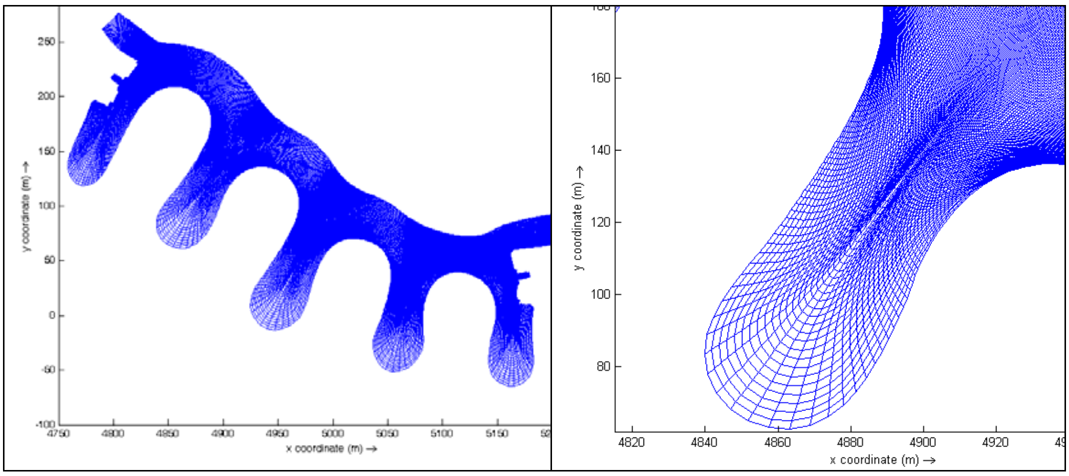


Figure 2: Active computational grids in the model area

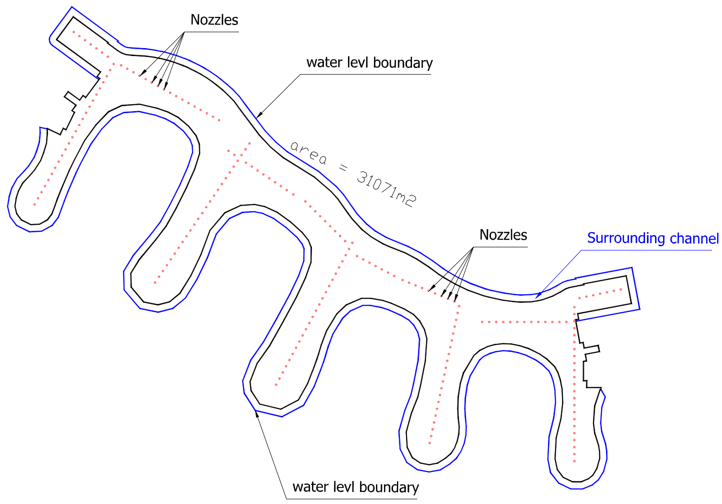


Figure 3: Lake boundary condition in the design

3.1. Model Scenarios

Four different scenarios have been simulated to test the lake under different operation modes. 3D simulations were done for each scenario to study the flow pattern in the study area.

3.1.1. Scenario 1

The water feeding system was assumed to be working with its full capacity, which means that the nozzle discharge at the ends of pipelines will be the same as the nozzles discharge at the beginning of the pipelines. For each source point (nozzle) on pipeline-1 and pipeline-5 the discharge was designed to be 5.16 m^3/hr and the total number was 91 source points. The discharge for each source point (nozzle) on pipeline-2, pipeline-3 and pipeline-4 was 8.86 m^3/hr and the total number was 106 source points.

3.1.2. Scenario 2

This scenario represents the case in which, the nozzles discharge at the beginning of the pipelines will be increased by 10%. On the other hand, the nozzles discharge at the ends of pipelines will be decreased by 10% in order to keep the total nozzles discharges constant. The aim of the redistribution of the discharges in nozzles is to consider the overall losses which may occur along the pipelines.

3.1.3. Scenario 3

Scenario 3 represents the lake during scheduled maintenance or accidental conditions, 10% of the total nozzles don't work at the ends of the pipelines and the rest nozzles have no changes in the discharge.

3.1.4. Scenario 4

This scenario is an analogy to scenario 3 with increasing 10% of the total working nozzles discharges and redistributed to the rest nozzles. The details of different scenarios were shown in table 1.

Table 1: The details data of different scenarios

scenario	Discharge (m^3/hr) for one nozzle		No of Nozzles		Total discharge (m^3/hr)	
	Pipelines 1 and 5	**Pipelines 2, 3,and 4**	**Pipelines 1 and 5**	**Pipelines 2, 3,and 4**	**Pipelines 1 and 5**	**Pipelines 2, 3,and 4**
1	5.16	8.86	91	106	470	940
2	From 5.418 at the beginning to 4.902 at the end	From 9.303 at the beginning to 8.417 at the end	91	106	470	940
3	5.16	8.86	82	95	423	845
4	5. 676	9.746	82	95	470	940

4. THE MODEL RESULTS AND ANALYSIS

4.1. Water Exchange

The water overflow from the lake to the surrounding channel was calculated in the model for each scenario to know the time needed for exchanging the water in the lake. To do this, the flow rate overflows from the lake to the surrounding channel were obtained. Four locations where the water overflows from the lake were specified.

The water overflows only from these locations with crest level of +1.80 to the surrounding channel, these locations are CS-1 with 470 m long, CS-2, CS-3 with 60 m long each one, and CS-4 with 1290 m long. Due to the existence of some structures at the end of first and last finger the overflow system was replaced by suction points at these areas to minimize the possibility of creating dead zone area. The specified locations for the overflow discharge and the suction points are shown in figure 4. Table (2) presents the detailed calculations for the discharge overflow from the lake to the surrounding channel.

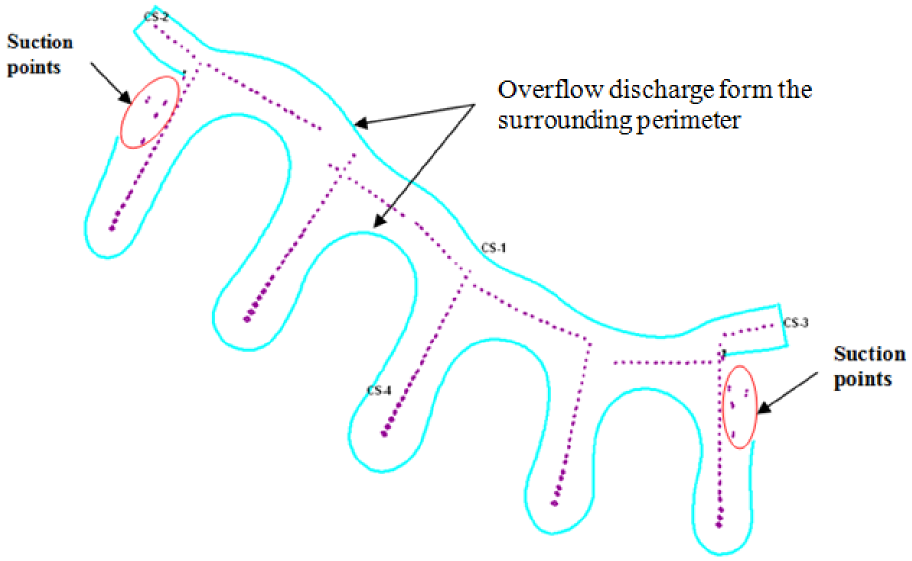


Figure 4: The locations of the overflow discharge

Table 2: The discharged flow rate from the lake (output results)

Flow rate (m^3/sec)				
Boundary	**Scenario 1**	**Scenario 2**	**Scenario 3**	**Scenario 4**
1	0.16	0.17	0.15	0.17
2	0.00046	0.00046	0.00046	0.00046
3	0.00046	0.00046	0.00046	0.00046
4	0.19	0.18	0.16	0.18
Sub-total	0.35092	0.35092	0.31092	0.35092
Suction Points	0.04	0.04	0.04	0.04
Total (m^3/sec)	0.39092	0.39092	0.35092	0.39092
Total (m^3/day)	**33775.5**	**33775.5**	**30319.5**	**33775.5**

Designed flow rate (inflow) from the water feeding system *(input data)*:

- ✓ Pipelines 1 and 5 = 8.86 (m^3/hr) × 106 × 24 = **22539** m^3/day
- ✓ Pipelines 2, 3, and 4 = 5.16 (m^3/hr) × 91 × 24 = **11269** m^3/day
- ✓ Total flow rate = **22539 + 11269 = 33808** m^3/day
- ✓ Total volume of water inside the lagoon = **33810** m^3

The model results show that for each of scenarios 1, 2, and 4 the outflow distributed along the exit boundaries with total rate of 33775.5 m^3/day, which is approximately equal to the total water volume (33810 m^3) of the lagoon. This means that the amount of water discharged in the lake through the water feeding system will be flushed and fully exchanged with the seawater within 24 hours. Only scenario 3 shows difference between the outflow (30319.5 m^3/day), which means that the time needed to exchange the total amount of water in the lake with the seawater will be about 27 hours. According to the international water quality standards, the maximum age of water inside the lake shouldn't exceed 36 hours to avoid the negative impact on the water quality in the lake. For all scenarios implemented in this study the time needed to exchange the water in the lake will not affect the water quality inside the lake.

4.2. Velocity comparison

At each scenario, the velocity distribution results were computed and compared. The results show that, the horizontal velocity has a good distribution in the whole area which means that there are no dead zones. Figure 5 shows sample of flow pattern inside the lake for the worst case (scenario-3). The computed velocity in the lake is from 0.1 cm/s to 0.5 cm/s. The velocity in the lake guarantees no dead zone areas and is enough to move the water body inside the lake to be exchanged within 24 hours. Moreover the predicted velocity in the lake will not create significant currents which may affect the swimmers. The model results show that the effect of the changes in scenario 3 doesn't have significant differences on the velocity results obtained from scenarios 1, 2 and 4.

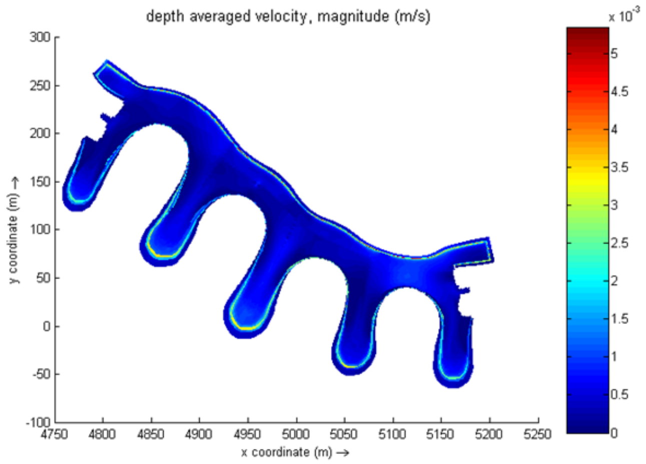
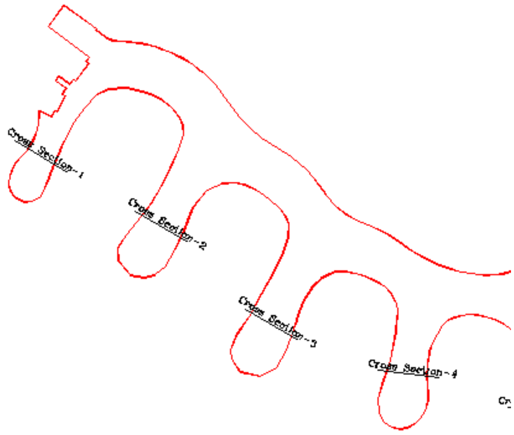


Figure 5: The depth average flow velocity inside the lake, scenario-3

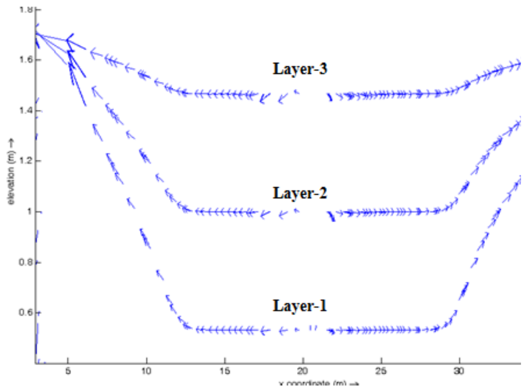
Also, the results of 3D numerical simulations show that, the velocity is well distributed along the water column in the lake for all scenarios. This proves that there is a water movement all over the water column and that there are no dead zone areas inside the lake. Figure 6a shows the location of the cross sections in which the flow pattern profiles were obtained and the 5 drawings in the figure show the flow pattern results at three layers along the water column at the cross sections, these three layers are uniformly distributed along the water depth (layer-1 near to the bed, layer-2 at the middle of the water depth, and layer-3 at the surface).

The model calculations were done at the middle of each layer, and as the layer thickness gradually decreases along the side slope, therefore the level of arrows goes toward the top when moving towards the upper end of the side slopes. These drawings show the vertical distribution of the flow along the water column. The arrows represent the flow direction at each layer, and the change in the size of the arrows means change in flow magnitude, where the small arrow's size means small flow value as shown near the bottom, and the relatively large arrow's size means relatively high flow values as shown near to surface and at the end of both side slopes.

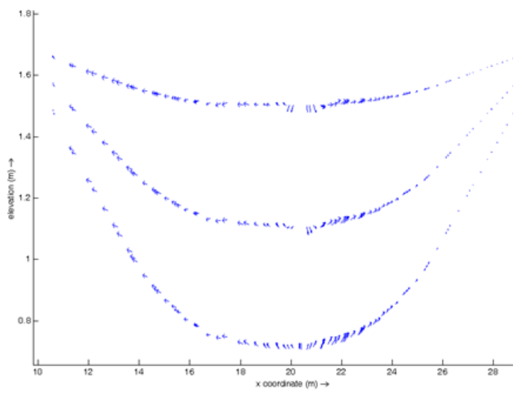
Figure 6b shows a sample of the velocity distribution in one of these cross-sections, presenting a contour map of the magnitude of the flow velocity. In all drawings of both figures, the x-coordinate in the horizontal axis represents the distance along the cross section started from the left side. The elevation in the vertical axis represents the elevation of the middle of each of the 3 layers above the level of the horizontal bed in the central part of each finger; that is why we see the level of the arrows at the centre of the cross section lower than the level of the arrows along the side slope (decreasing depth towards the upper side of the slope).



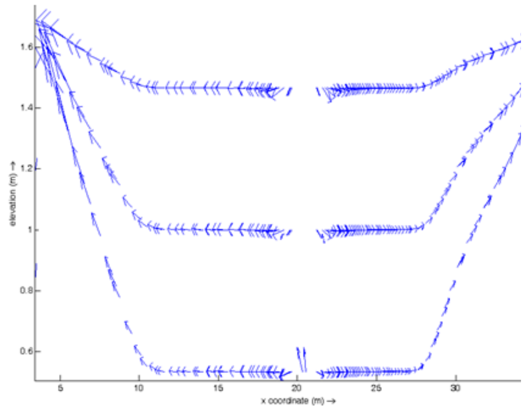
Cross sections locations



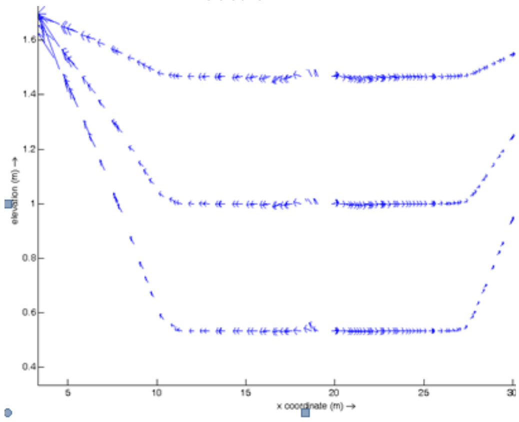
flow pattern results (3D simulation) at Cross section-1



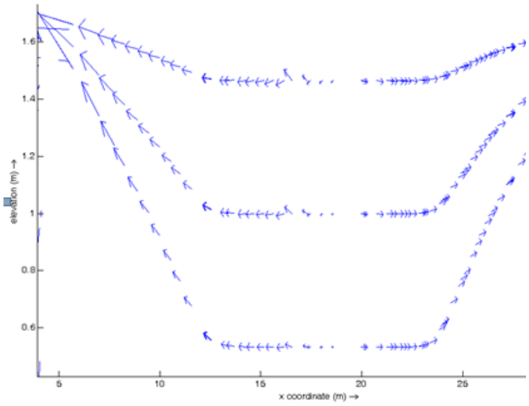
Flow pattern results (3D simulation) at Cross section-2



Flow pattern results (3D simulation) at Cross section-3



Flow pattern results (3D simulation) at Cross section-4



Flow pattern results (3D simulation) at Cross section-5

Figure 6a: Flow pattern results from 3D model simulation, scenario-3

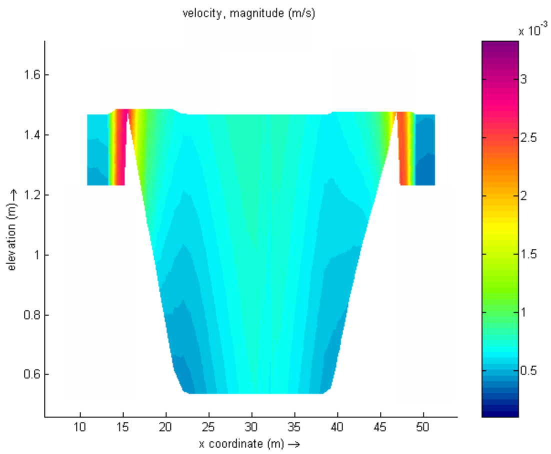


Figure 6b: Sample of flow magnitude in cross section profile at one finger

5. WATER QUALITY ASSESSMENT

5.1.1. Methodology

Seawater samples were taken during the survey campaign. The seawater samples were used to obtain the water quality parameters in the vicinity of the project. The methodology used in the water analyses were as follows:

- Samples used for the chemical analyses were kept frozen till reached to the laboratory then, the methods discussed in the American Public Health Association (APHA, 1992) were used for the determination of the abiotic parameters except where noted.
- pH and electrical conductivity values were measured using Hydrolab Multiset 340i WTW after calibration. BOD was determined by using 5 days method. COD was carried out using potassium dichromate method.
- Ammonia was determined by phenate method. Nitrate determined by reduction method as described by Mullin and Riley (1956). Silicate was determined by using oxalic acid and alkaline molybdate method as described in (APHA, 1992).
- Chlorophyll-a was extracted using acetone and measured by double beam spectrophotometer Kontron MMKON930 using the trichromatic equation according to APHA (1992), with the precautions of Nusch (1980) and Marker at al., (1980).

5.1.2. Results of the Water Analyses

The water quality parameters were obtained from the water samples taken at five stations, located far from the pumping station at about 1.25 km in the offshore direction at water depth 8 m, and parallel to the shoreline with 500 m the distance between the first and last station. The inlet is extended to a distance of 150 m from the pump station to off-shore. The distance of the inlet from the shoreline to offshore is about 100 m. The outlets were designed to be onshore and above the highest seawater level, Table 3 presents the summery of the measured seawater quality parameters at the five stations.

Table 3. Abiotic water quality parameters obtained from the investigated samples

Parameters Stations	pH	EC mS/cm	Salinity ‰	BOD g/m^3	COD g/m^3	NH_3 µg/l	NO_2 µg/l	NO_3 µg/l	PO_4 µg/l	SiO_2 g/m^3	Chl_a µg/l
1	8.19	57.70	38.70	2.20	6.20	46.75	0.87	28.33	17.60	2.83	10.71
2	8.12	58.10	38.90	2.30	8.20	40.38	1.45	29.35	15.50	2.48	17.53
3	8.13	58.00	38.80	2.40	6.40	52.28	1.16	26.04	13.10	3.03	8.70
4	8.12	58.10	38.90	2.50	6.20	38.25	0.87	30.33	12.20	3.41	14.78
5	8.13	58.00	38.80	2.60	4.60	36.13	0.87	36.33	16.50	4.32	18.46

The following results can be concluded:

- pH values presented in the Table 3 showed that pH in the seawater in the study area is within the normal specification The pH values showed slight fluctuation and ranged between 8.12 and 8.19 which is within the Egyptian standards (6.5 to 8.5). The pH values presented in the table indicates that the water is alkaline.
- The table shows that the salinity is about 39 ppt and electrical conductivity is about 58. These values are in the range characterizing the seawater in this part of the Mediterranean.
- The results of the measured Biochemical Oxygen Demand (BOD) and Chemical Oxygen Demand (COD) were generally within the healthy limits. These values are less than those recorded in other coastal sites along Alexandria and Abu Qir Bay (Shams El-Din and Dorgham, 2007). The obtained results are coinciding with the results obtained by Ali (2006) in Marina Resort during 2006. The ratio between BOD/ COD is less than one which indicate that the water in the study area has a less biodegradable nature.
- The measured levels of ammonia, nitrite, nitrate, were found within the water quality standards. According to the water quality standards, the ammonia, nitrite and nitrate should be less than 0.4 g/m^3, 0.005 g/m^3 and 1 g/m^3, respectively. The levels of orthophosphate and silicate were found within the normal specification characterized the northern coastal area.
- On the basis of trophic status concept which based on the fact that changes in nutrient levels (measured mainly by phosphates) causes changes in algal biomass (measured by chlorophyll a) which in turn causes changes in lake clarity (measured by Secchi disk transparency). A trophic state index is a convenient way to quantify this relationship. The most popular index was developed by Carlson (1977).
- According to Carlson trophic state index values (TSI) calculating from chlorophyll- a and phosphates values. Also presented in Table (10) that lists the trophic state values and the corresponding measurements of the two parameters. Ranges of trophic state index values are often grouped into trophic state classifications. The range between 40 and 50 is usually associated with mesotrophy (moderate productivity). Index values greater than 50 are associated with eutrophy (high productivity). Values less than 40 are associated with oligotrophy (low productivity).
- The calculated TSI for the study area about 50 for chlorophyll-a concentration ranged between 8 - 18 µg/l and phosphorus concentration ranged between 12.2 – 17.6 µg/l (recent data).In the light of the measured data and according to Carlson classification, the trophic state of study area becomes mesotrophic. This means that the possibility of algae bloom formation is very low.

Table 4: trophic state gradient in temperate lake*

TSI	Chl (µg/L)	Phosphates (µg/L)	Attributes
30-40	0.95 - 2.6	6 - 12	**Oligotrophy**
40-50	2.6 - 17.3	12 -34	**Mesotrophy**
50-80	20 - 56	48 - 96	**Eutrophy**
> 80	> 155	192 - 384	**Hypereutrophy**

* *according to variation of chlorophyll-a, Secchi depth and total phosphorus (Carlson, 1977).*

5.2. Water Quality Model

The water quality model is coupled with the 2D hydrodynamic model developed for the lake system. The Delft3D-WAQ module is used for the water quality modeling component coupled with the hydrodynamic module. The parameters selected for the water quality model were based on the main water use of the lake for swimming purpose. The main objectives of the water quality model are; i) to ensure that the circulation in the lakes allows water renewal according to a reasonable residence time which is based on the operational design of the lakes, and the results of the hydrodynamic modeling and ii) the water quality inside the lakes within the accepted ranges for the swimming purpose. Therefore, the selected basic parameters for the water quality model were the salinity, biological oxygen demand (BOD), chemical oxygen demand (COD), and dissolved oxygen (DO). The data set used was based on the following parameters shown in table (5), the data in the table describe the basic water quality parameters for the incoming water based on the analysis of water sample during the field measurements (incoming water).

Table 5: The selected parameters for the water quality model

WQ parameter	Concentration
Average Temperature	24 °C
BOD	2.4 g/m^3
COD	6.4 g/m^3
DO	8.13 g/m^3
Salinity	38.8 g/kg

5.2.1. Model Results and Analysis

The model was run under the normal condition without taking into account any external source of pollution to show only the effect of the retention time on the basic water quality parameters, the model results show accepted range of variation in the different parameters under investigation, the salinity average concentrations after 48 hours is of 39 g/kg, the average DO is 7.7 g/m^3, average COD is 6 g/m^3 and average BOD is 2.25 g/m^3. The concentrations averages of basic parameters are accepted taking into consideration that the flushed water will be returned back to the sea. The following figures (7,8,9, and 10) show the results from the water quality model first run, the figures show that the computed values of the water quality parameters has very small difference on the whole simulated area.

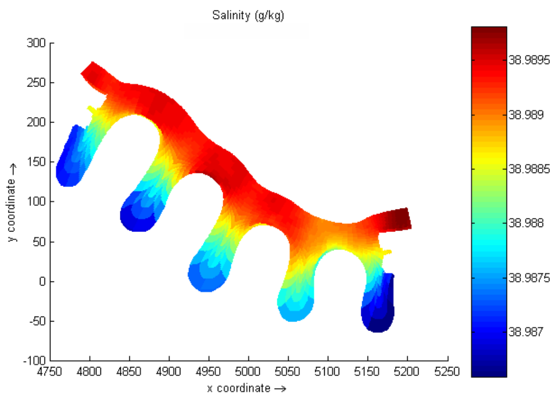


Figure 7: Salinity concentration after 48 hrs simulation

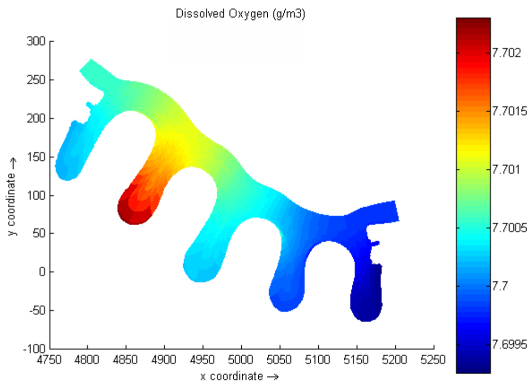


Figure 8: DO concentration after 48 hrs simulation

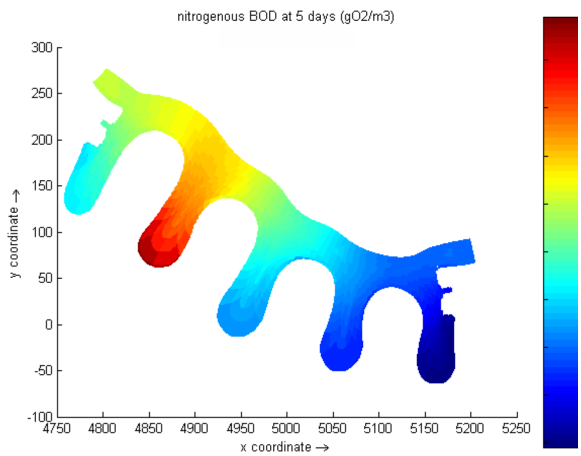


Figure 9: BOD concentration after 48 hrs simulation

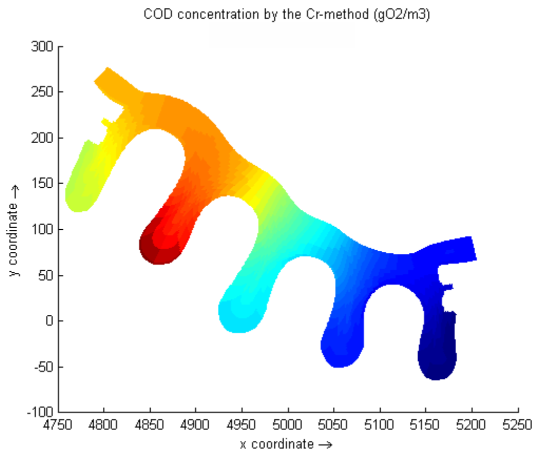


Figure 10: COD concentration after 48 hrs simulation

6. CONCLUSIONS

Four scenarios have been simulated to test the lake under different operation modes. The horizontal velocity distribution for all scenarios was obtained from the model results. The effect of changes in different scenarios doesn't show significant changes in the velocity results. The results of the horizontal velocities show that the velocity is well distributed all over the lake for all scenarios. This means that there are no dead zone areas in the lake. The simulation results showed that the velocity in the lake is sufficient to prevent the dead zone areas with no effect on the swimmers inside the lake.

The total volume of the water inside the lake will be fully exchanged with the seawater within 24 hours for each of scenarios 1, 2, and 4. In the other hand, the time needed to exchange the total amount of water in the lake will be about 27 hours for scenario 3. The computations showed that the exchange time of the water in the lake with the seawater is within the international water quality standard which states that the maximum age of water in the lake should not exceed 36 hours. This will help in preserving the water quality and minimizing the algae formation and the blocking of the nozzles by the algae and tiny plants.

The water quality model results show accepted range of variation in the different parameters under investigation. The air bubble system which will be installed in the lake will help in improving the water mixing in the lake and improving the aeration processes which will maintain the dissolved oxygen concentration levels in the lake.

The flushing of the water from the lake in 24 to 27 hours in addition to the presence of the air bubble system will help in controlling the water temperature in the lake. The water temperature in the lake will not significantly increase above the ambient seawater temperature.

7. REFERENCES

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