

Environmental and Climatic Implications of Lake Manzala, Egypt: Modeling and Assessment



Mohamed Elshemy

Abstract Lake Manzala, the greatest Egyptian coastal lakes, is considered as one of the most valuable fish sources in Egypt. Recently, the water quality status of the lake has been sharply deteriorated due to the excessive discharge of industrial, agricultural, and municipal wastewater. Moreover, the lake is considered vulnerable to the impacts of future climatic changes, which will affect its hydrodynamic and water quality characteristics. This study has two main objectives: assessing the lake water quality status and quantifying the future climatic change impacts on the hydrodynamic and water quality characteristics of the lake. A comprehensive water quality assessment of the lake, based on water quality index (WQI) and trophic status index (TSI) approaches, has been presented to spatially assign the lake water quality conditions. A calibrated hydrodynamic water quality model (MIKE21 modeling system) and future projected estimates of the climatic changes have been used to investigate the impacts of climate change on the lake characteristics. The results revealed the critical and very bad water quality status and the high and very high trophic conditions, particularly in the southern and eastern zones due to the drainage of the polluted drains. The developed model results closely mimic the measured profiles of the simulated parameters. Severe spatial changes of the lake water temperature, water depth, and salinity due to future climatic changes are noticed. Based on the study results, an urgent water quality management strategy should be implemented for the lake, and an adaptation plan for the Egyptian coastal lakes should be investigated.

Keywords AR5, Climate change, IPCC, Lake Manzala, LWQI, MIKE21, TRIX, TSI, WQI

M. Elshemy (✉)

Irrigation and Hydraulics Department, Faculty of Engineering, Tanta University, Tanta, Egypt
e-mail: m.elshely@f-eng.tanta.edu.eg; m.elshely@yahoo.com

Contents

1	Introduction	4
2	Lake Manzala Characteristics	6
3	Lake Manzala State of the Art	7
3.1	Environmental Assessments	8
3.2	Hydrodynamic and Water Quality Modeling	10
3.3	Climate Change Impacts	11
4	Research Deficits and Study Objectives	13
5	Methodology	13
5.1	Lagoon Water Quality Index (LWQI)	14
5.2	Trophic Index (TRIX)	15
5.3	MIKE21 Modeling System	16
5.4	Climate Change Estimates	17
6	Data Collection and Analysis	17
7	Water Quality Assessment of Lake Manzala	20
8	Trophic Status Assessment of Lake Manzala	27
9	Impacts of Future Climatic Changes on the Lake Characteristics	30
9.1	Developing of Manzala Model	30
9.2	Climate Change Impacts	35
10	Conclusions	40
11	Recommendations for Future Work	41
	References	41

1 Introduction

Five coastal lakes are exhibited by the Mediterranean along the Egyptian northern coast; they constitute about 25% of the total Mediterranean wetlands; four of them lie on the Nile Delta coast; see Fig. 1. These Northern Delta lakes are, namely, from west to east, Lake Mariut, Lake Edku, Lake Burullus, and Lake Manzala. Economically, they are important sources of fish production; in the past, these lakes contributed by more than 50% of Egypt total fish production [1], but now their contribution is decreased to be about 11% (2004–2013) [2]. Northern Delta lakes are severely environmentally degraded due to several reasons; human activities are considered as the greatest reasons.

The largest Egyptian coastal lake is Lake Manzala which is considered as one of the most valuable fish sources in Egypt; it contributed by about 35% of the total country yield during the 1980s [3]. In the present, it is considered as the most productive lake in Egypt and contributed by about 44% of the total annual production of the Northern Delta lakes (2004–2013) and increased to be about 56% in 2013 [2]. The lake hydrological and water quality status have been degraded due to the progressive increasing of industrial and agricultural wastewater discharge. It faces many challenges that lead to serious changes in its water quality and fish production as well as the catch composition [1]. Due to its critical environmental situation and its economic importance, Lake Manzala is selected to be the case study of this work.

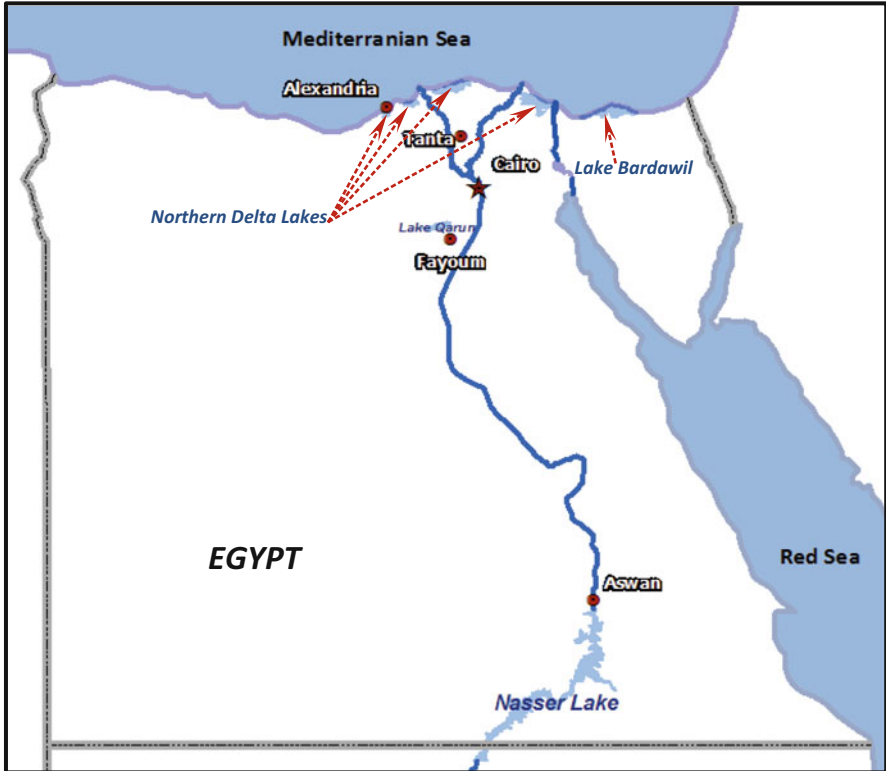


Fig. 1 Layout of Egyptian coastal lakes

The present work is a part of a project titled “Assessment of vulnerability and adaptation to sea level rise for the Egyptian coastal lakes” and funded by the Alexandria Research Centre for Adaptation (ARCA), Alexandria University, Egypt. The main project objective is assessing the impacts of future climatic changes on the hydrodynamic and water quality characteristics of a case study of Egyptian coastal lakes (Lake Manzala).

Some parts of the first draft of this chapter were published in IWTC18 [4] and IWTJ [5] for climate change impacts (four different scenarios), in *Environmental Earth Sciences* [6] for model developing (including statistical tests for the model calibration results), and in IJSRES [7] for water quality assessment using WQI approach (two different WQIs were used), while the trophic status assessment using TRIX TI part wasn’t published earlier.

2 Lake Manzala Characteristics

Lake Manzala was chosen as the case study for this work as an example of the Egyptian coastal lakes. The lake is considered as the largest, according to its surface area; it stretches for about 47 km long and 30 km wide. It is a shallow lake; its average water depth is about 1.0 m. It lies on the eastern coast of Egypt, between the western branch of the River Nile (Damietta Branch) and the Suez Canal. The lake is surrounded by five governorates: Damietta, El-Dakahlia, El-Sharkiya, El-Ismailia, and Port Said.

The layout of Lake Manzala is shown in Fig. 2. The lake receives freshwater through the Enanya Canal, to the west, and through some agricultural drains, to the south and west. The Enanya Canal discharges small amounts of the Damietta Branch freshwater to the lake, while the agricultural drains discharge their agricultural, industrial, and domestic wastes to the lake. The most important drains are Fareskour, Elserw, Hadous, and Bahr Elbaqar; typical flow discharges of these drains can be seen in Fig. 3. The drain polluted inflows, in addition to other human activities such as land cultivation and human settlements, transformed the lake water quality status from a marine estuary environment to a eutrophic freshwater system composed of about 30 basins which are varying in their hydrological and water quality characteristics [8]. An improvement in the lake water quality status can be noticed due to the lake connections to the Mediterranean Sea to the north, the

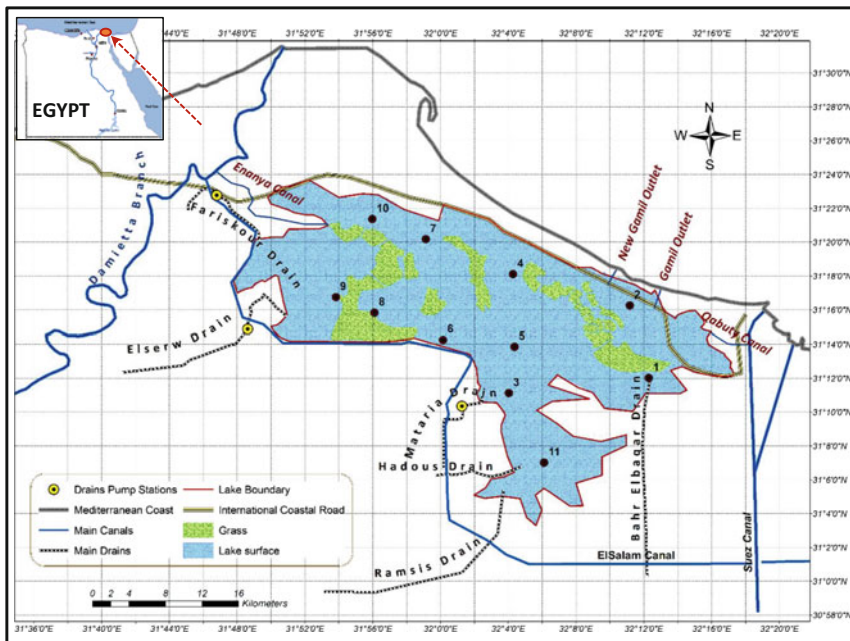


Fig. 2 Study area layout and field record stations

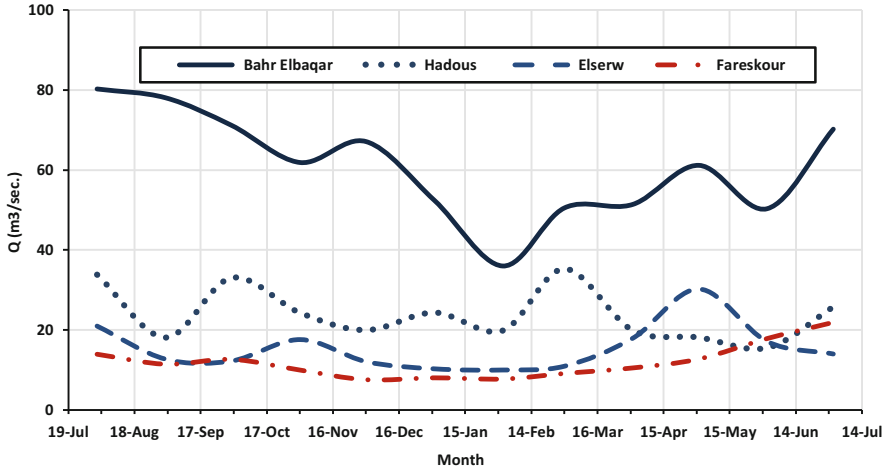


Fig. 3 Typical drains inflow in Lake Manzala

lake outlets such as El-Gamil and the New El-Gamil outlets, in addition to the connection of the lake to the Suez Canal to the east through a small and narrow canal (El-Qabuty Canal).

The lake vegetated islands cover about 23% of the lake total area [9]. The hydrological status of the lake was investigated by Thompson et al. [10]; the authors reported that the tidal oscillations in water levels are not extending throughout the lake due to the vegetated islands within the lake. This is the reason for the dominant influence of drainage inflows. While close to the outlets, they added that the water levels are more strongly influenced by the tides. They concluded that due to the very low precipitation and high evaporation rates over the Nile Delta, any reduction in drainage inflow will strongly affect the lake hydrology and its salinity status.

The lake study area has variable climatic conditions, and the air temperature ranges from 16 °C in January to 29 °C in August. The rainfall is limited, from December to February, usually below 50 mm. The wind speed ranges from 10 to 40 km/h ([11, 12] database), and its main direction is the north and the western north as can be seen in the typical wind rose of the lake in Fig. 4.

3 Lake Manzala State of the Art

Previous studies which investigated the environmental status of Lake Manzala, water quality modeling and management of the lake, and its vulnerability to the impacts of future climatic changes are discussed in the following sections.

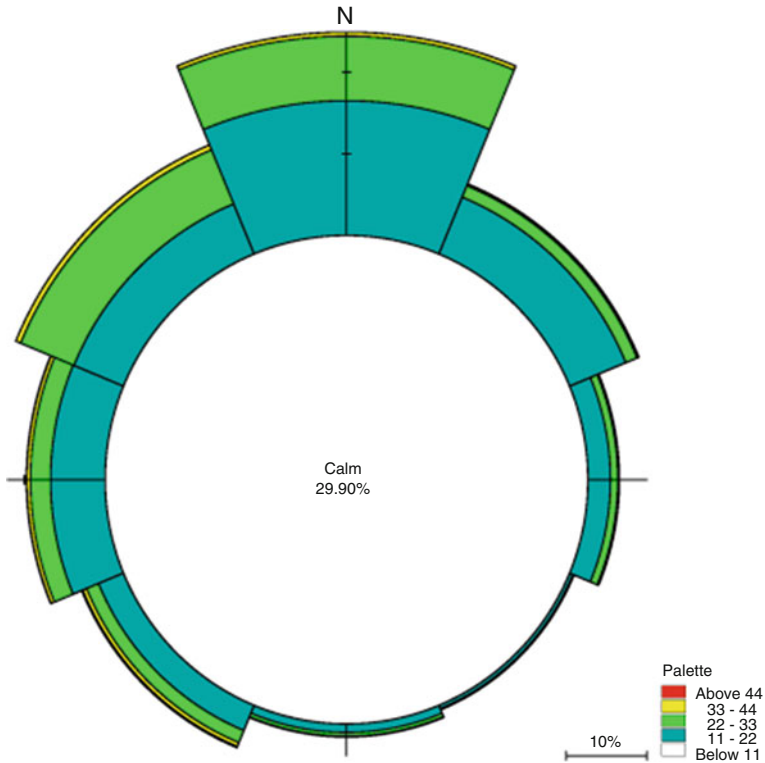


Fig. 4 Typical wind rose at Lake Manzala

3.1 Environmental Assessments

The environmental problems of Lake Manzala were discussed in some publications. In 2001, the lake was selected to be as one of nine primary sites of North Africa wetland lakes to be biodiversity studied within the CASSARINA Project [13]. While in 2003, a pilot-scale engineered wetland model of Lake Manzala Engineered Wetland (LMEW) was constructed at the outlet of Bahr Elbaqar Drain to demonstrate a low-cost treatment alternative for polluted drainage water [14]. It is a diversity of treatment options which allow primary, secondary, and tertiary treatments. Water samples were collected, for 2 years (on a biweekly monitoring basis), from the inlet and outlet of the treatment system to assess the performance of Lake Manzala pilot-scale engineered wetland. Within the same project, later, the impact of flow rate change and water temperature on the removal efficiency of different parameters was investigated [15]. The lake trophic status was investigated in 2004 [16] and in 2006 [17]. A spatial distribution map of the lake trophic status was presented. That map clearly shows that the southern sector of the lake has environmental problems. The Overseas Environmental Cooperation Center

(OECC), Japan, presented a study on the comprehensive support strategies for environment and development in the early twenty-first century for Egypt [18]. The author reported that the lake's fish have had a reputation for being chemically and microbially contaminated. In 2013, Hamed et al. confirmed that the lake fish is highly polluted and dangerous for human health based on their investigations. The authors concluded that great efforts and cooperation between different authorities are needed to protect the lake from pollution. They suggested that it can be achieved by treatment of the agricultural, industrial, and sewage discharge [19]. In 2015, the heavy metal risks of the eastern zone of Lake Manzala were assessed [20]. Remote sensing data and GIS were used to detect the relationship between the water and sediment load of contamination and the land use change. The results showed that the heavy metal concentration is found in riskier levels than the world permissible limits. It returns to the abandoned heavy metal concentration effluents from the industrial, agricultural, and domestic wastes in addition to the commercial activities in and around this zone. This study revealed that the sediments are more critically contaminated, with respect to heavy metals, than the water concentration. The author recommended that removing of contaminated sediments in this zone to increase the water depth to 3 m and upgrading of the treatment systems of drainage discharge and sewage effluent into the studied zone should be done to conserve the lake water quality. Zahran et al. [21] assessed the heavy metal spatial distribution in Lake Manzala using some heavy metal indices and GIS. The results indicated that the northeastern and the southern parts of the lake are the most polluted zones by the heavy metals in the lake. The authors recommended developing of a regular monitoring program for the lake and treating of the agricultural, industrial, and sewage sources. The trophic status of Lake Manzala was assessed using Carlson TSI [22]. Field data, satellite data, and GIS were used to classify and map the trophic state. The authors reported that the TSI varied from mildly eutrophic in the northern parts of the lake to eutrophic and hyper-eutrophic in the southern parts. The results also revealed that the southern parts of the lake were enriched with nutrients, and the N/P ratio indicated that P was the limiting factor in the nearby El-Boughaz area. However, N was the limiting factor in the southern parts close to drains. In 2017, the water quality and trophic status of Lake Manzala were assessed using WQI (quality rating) and Carlson TSI [23]. The results showed that the lake is categorized into bad and poor water quality, while the trophic state is ranked to eutrophic and hyper-eutrophic conditions. The authors highly recommended that drainage water should be treated, unwanted plants be removed, and decision makers be provided with data. The spatial distribution of heavy metals in water and sediments of Lake Manzala was evaluated using different heavy metal indices [24]. The results showed that the lake is highly polluted with the studied heavy metals. The pollution indices confirmed that the lake sediment was contaminated with these elements. The authors recommended that the treatment of agricultural, industrial, and sewage discharge, in addition to regular evaluation of pollutants in the lake, is essential.

The ecological changes of the lake due to the human activities, including the discharge of sewage and industrial waste and the establishment of El-Salam Canal

and road networks, were studied using satellite images [25]. The authors reported a decrease by about 50% from 1973 to 2003 in the overall size of the lake. Relationships between some water quality parameters and radiance data from Landsat-5 Thematic Mapper (TM), using regression models, were developed in 2001 [26], while in 2011, an integration between real-time water quality (RTWQ) monitoring, for some water quality parameters, and satellite systems, by developing statistical relationships, was achieved [27]. Satellite imageries (1984–2014) and remote sensing techniques were employed by Abayazid [28] to monitor the temporal and spatial changes in four Egyptian coastal lakes: Edku, Burullus, Manzala, and Bardawil. The author reported that Lake Manzala is suffering progressive shrink of its water body with advancing development projects into the lake waters (land reclamation and fish farming activities), as well as increased vegetation intensity, particularly in the southern and western zones. The results revealed a considerable acceleration in the change rate in the late 1990s and in the first years of this millennium, with an increase in the developments within the lake to cover about 65% of the area in 2014. The change detection of Lake Manzala was monitored by Hossen and Negm [29, 30], using three satellite images (1984, 1998, and 2015) and GIS. The results showed that the surface water area has been decreased by about 57% during the study period. The authors reported that an increase in the vegetation area in the lake has been increased by the same ratio due to the discharge of agriculture wastes and municipal wastes in the lake without adequate treatment. A decrease by about 85% of its water surface area is expected in the next 15 years (based on the annual rate of change) if the same conditions continue.

In 2017, El-Gammal [31] reviewed the critical situation of the Egyptian coastal lagoons. The author declared that the Egyptian Ministry of State for Environmental Affairs has set a priority to protect the northern lakes from pollution and to maintain their sustainable development; many efforts have been done for environmental conservation and socioeconomic development to the coastal lagoon. El-Manzala Lake, as an example, is environmentally unprotected, but a part of it (at the Ashtum El-Gamil site) is considered as a “protected area” (declared by Prime Ministerial Decree 459/1988). Moreover, EEAA initiated a monitoring program to check the coastal lake water quality. The results of this program are presented in different EEAA publications. The author recommended that the setting of the priorities for rehabilitation and development to ensure the sustainability of these lakes is highly required.

3.2 Hydrodynamic and Water Quality Modeling

A hydrodynamic and/or water quality models for Lake Manzala were developed in very limited publications due to the difficulty in collecting the model-required data. Lake Manzala was selected as one of three studied cases, in the southern Mediterranean region, for the MELMARINA Project [32]. That project aimed to establish an integrated hydrological and ecological monitoring at the selected lagoons to

improve the understanding of its ecological functions and to investigate the impacts of environmental and management changes through hydro-ecological models. Within the frame of this project, MIKE21 FM was used to develop a hydro-ecological model for Lake Manzala [33]. The model was developed to identify the required magnitude of nutrients for the lake to reach acceptable water quality conditions. Some reduction scenarios of drain nutrients (relative to the nutrients amount in 2003–2004) were investigated. In 2010, FVCOM ocean model was used to develop a hydrodynamic model for the lake to assess a range of sustainable water management strategies [34]. For a 40% reduction in the polluted drain water inflows to the lake, one of the studied scenarios, the authors concluded that an improvement in the water circulation of the northwestern sector of the lake and salinity increasing in the southern part of the lake will happen.

3.3 Climate Change Impacts

Generally, the investigation of climate change impacts on the hydrodynamic and/or water quality characteristics of Egyptian water resources is seldom. The climate change impacts, particularly sea level rise and temperature, on international coastal lakes are addressed in limited publications [35–39]. Regarding Egyptian coastal zone, there are some studies that are addressed to assess the impact of sea level rise on the Egyptian coastal zone and its protection works [40–44]. The Organisation for Economic Co-operation and Development (OECD) presented a study which analyzed the climate change significant risks on Egypt [45]. The authors stated that the northern Egyptian lakes are highly vulnerable to the impacts of climate change. Since the lakes are relatively shallow, climate change can lead to an increase in water temperature, which could result in changes in the lake ecosystems as well as changes in yield. Changes in salinity of Lake Manzala, as an example, may lead to impacts on lake ecology and fisheries. Further, given that the lake is unlikely to migrate inland, sea level rise will lead to a decline in shallow wetland areas and less abundant reed beds. They reported that so far, in-depth studies on potential impacts of climate change on lake ecosystems are not available. The study suggested some adaptation options for coastal resources such as breakwaters and integrated coastal zone management (ICZM). In their significant paper, which is published by the World Bank in 2007 [46], Dasgupta et al. ranked Egypt as one of the most vulnerable countries (in addition to Vietnam and the Bahamas) to the severe impacts of sea level rise (SLR). The results revealed that with a 1 m SLR, approximately 10% of Egypt's population would be impacted (most of this impact takes place in the Nile Delta) and approximately 12.5% of Egypt's agricultural extent would be impacted, which experiences the largest percentage impact all over the world. The authors showed that there is little evidence that the international community has seriously considered the implications of SLR for population location and infrastructure planning in developing countries. The author recommended an immediate planning for adaptation. The second Egyptian communications report

[47] reported that based on IPCC Fourth Assessment Report [48–50], which indicates that a global sea level rise of 18–59 cm is expected by the end of this century, and land subsidence rates, two models have been initiated by the Coastal Research Institute (CoRI) in 2009: the first is the business as usual one, while the second is the actual situation in progress. The results represent the actual situation that the Nile Delta could face, considering that the boundaries of the lakes are above zero level. Hydrodynamic simulation and observations of recent surge levels in the Mediterranean Sea offshore the delta were presented in 2015 [51]. The results indicated a higher surge (about 1 m) during a severe storm on December 11, 2010, compared to typical surge values (0.4–0.5 m) observed previously. The author reported that the Nile Delta coast is expected to be impacted with about 1 m sea level rise by 2100, which may affect low-lying urban areas and infrastructures in the Delta coastal zone, in addition to submerging the wetlands and breaching of the coastal lagoon barriers in Lake Manzala and Lake Burullus. Adaptation strategies that deal with coastal risks are highly recommended by the authors. A feasibility study of using a diaphragm wall (DW) for protecting the northern coasts of Egypt from sea level rise was published in 2016 [52]. The authors reported that the expected rise in sea levels would be between 20 and 88 cm by 2100. The study included an assessment of the environmental and the socioeconomic impacts of the expected sea level rise. The effectiveness of using DW in preventing the seepage of saltwater was examined using a finite element model. The authors concluded that the cost of constructing DW along the coast is about 1.0% of the expected losses due to the expected sea level rise by 2100. In 2016, satellite images (from 1990 to 2014) and GIS techniques were used to spatially analyzing the rate of change in the Nile Delta land use [53]. The results showed that the inland lakes (Manzala and Burullus) have been significantly decreased by half of their original surface area during the study period. It returns to the excessive enlargements of the fish farms and the drying up and reclaimed for agricultural developments (particularly around Lake Manzala). In this study, also the impacts of expected SLR on the Nile Delta were assessed, based on the IPCC scenarios (i.e., the 59 cm sea level rise by the end of this century) and the proposed land subsidence (2.5 mm/year). The authors reported that one fifth of the Nile Delta will be seriously vulnerable to inundation. They concluded that it might be crucial to set up new policies for new adaptation approaches. Koraim and Negm in 2016 [54] reviewed the available SLR adaptation works all over the world. They concluded that the use of barriers is a successful strategy for protecting the harbors and lagoon entrances in different countries. The authors recommended that enhanced research activities for coastal vulnerability assessments and adaptation works are essential. In 2017, Elshinnawy et al. [55] assessed the vulnerability of the Nile Delta coast to SLR using GIS and developed digital elevation model (DEM) for the Nile Delta. Estimated trends for SLR at Alexandria, Al-Burullus, and Port Said are 1.6, 2.3, and 5.3 mm/year, respectively. These values associate the effect of both SLR and land subsidence. The results indicated that less than 1.0% of the Nile Delta area will suffer from coastal flooding resulted from SLR expected by the end of the current century for two moderate scenarios and about 3% for the worst scenario. The authors recommended further

detailed studies to quantify impacts of SLR on coastal physical systems, infrastructure, saltwater intrusion, water resources, wave climate and water current patterns, erosion/accretion patterns, and socioeconomic sectors.

4 Research Deficits and Study Objectives

Clearly, based on the previous sections, it can be noticed that there are some research deficits regarding Lake Manzala environmental assessments and the impacts of future climatic changes, such as:

1. A specific WQI for lagoons has never been used to investigate the lake water quality status. All addressed publications investigate the water quality parameters and the lake trophic status.
2. Only one general trophic status index (TSI), Carlson TSI, is used for the trophic status assessment. A specific TSI for brackish water and lagoons should be used.
3. The climate change impacts on hydrodynamic and/or water quality characteristics of the lake have never been investigated.

So, the main objectives of this study are assessing the lake water quality and trophic status using WQI and TSI approaches and investigating the climate change impacts on the hydrodynamic and water quality characteristics of the lake. The specific objectives are as follows:

1. Using a specific WQI to assess the water quality status of the lake
2. Using a GIS tool to spatially assign the water quality conditions of the lake
3. Using a specific TSI to assess the trophic status of the lake
4. Developing a hydrodynamic and water quality model for the lake
5. Investigating the climate change impacts on the hydrodynamic and water quality characteristics of the lake

5 Methodology

As declared before, this work has two main objectives: assessing the overall water quality and trophic state conditions of Lake Manzala and investigating the climate change impacts on the hydrodynamic and water quality characteristics of the lake. Figure 5 summarizes the used approaches of the methodology.

The water quality status of the lake is assessed using a specific water quality index for lagoons (LWQI) (see Sect. 5.1), while the trophic state is evaluated using a specific trophic state index for brackish water (TRIX) (please refer to Sect. 5.2). To investigate the impact of future climate change scenarios on the hydrodynamic characteristics of Manzala Lake, projected changes in climate conditions and a developed hydrodynamic model for Manzala Lake are required. A hydrodynamic and ecological model of Lake Manzala should be developed (based on MIKE 21);

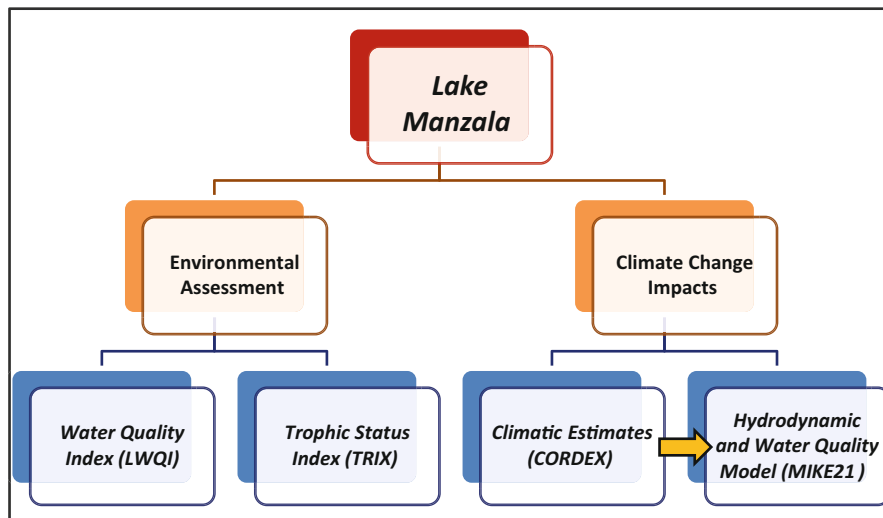


Fig. 5 Methodology approaches for the current research

see Sect. 5.3. The downscaled regional projected climate conditions are available from CORDEX project [56]; see Sect. 5.4.

5.1 Lagoon Water Quality Index (LWQI)

To control and design water quality management strategies for water bodies, a water quality assessment tool, such as a water quality index (WQI), should be used. WQI is defined as a mathematical approach which aggregates data on two or more water quality parameters (pH, BOD, etc.) to produce a single number. Based on this number, WQI can classify the water quality status of water bodies according to a ranking scale (0–100). There are different WQIs which can be chosen according to the uses of the water body (i.e., irrigation, drinking, etc.) or its hydrological characteristics (rivers, lakes, etc.). Due to the transitional characteristics of lagoons, it is difficult to choose a suitable WQI.

In 2011, Taner et al. [57] developed a specific WQI for lagoon systems (L-WQI). Ten water quality variables are required to use this index: DO, TN/TP ratio, nitrate, orthophosphate, Chl-a, COD, pH, turbidity, and EC. This index is based on establishing a new normalization function for each variable and using of a modified version of the weighted aggregation method [57]. L-WQI can classify the lagoon water quality status – on a scale from 0 to 100 – into four classes: Excellent (100–75), Good (75–50), Critical (50–25), and Very Poor (25–0). L-WQI can be calculated using the following equations:

$$L\text{-WQI} = \sum_{i=1}^n C_i P_i \quad (1)$$

$$L\text{-WQI} = 0.25C_{DO} + 0.25C_{TS} + 0.23C_{COD} + 0.10C_{pH} + 0.09C_{EC} + 0.09C_{TRB} \quad (2)$$

Where:

C_i is the normalized value for each variable. It can be determined using “variables normalization curves” in Taner et al. [57].

P_i is the weight factor for each parameter (e.g., $P_{DO} = 0.25$, $P_{COD} = 0.23$, $P_{pH} = 0.10$, etc.).

TS is the trophic status condition which is determined according to TN/TP ratio [57].

The water quality status of the Küçükçekmece Lagoon was assessed by the index developers [57]. The results were compared to the Oregon WQI and the Arithmetic Coastal WQI to evaluate the developed index (L-WQI). L-WQI was satisfactorily performed and could highlight the pollution impacts of the connected tributaries on the lagoon. For this study, turbidity parameter wasn't recorded, so it is not included in the index calculations.

5.2 Trophic Index (TRIX)

The trophic state does not directly imply the water quality but assigns the productivity of the water body due to the occurring biological and chemical activities and is dependent on nutrient concentrations and other characteristics. Lakes and reservoirs, according to their biological productivity and nutrient conditions, are commonly grouped into three different trophic states: oligotrophic, mesotrophic, and eutrophic. The trophic state falls under two terms “oligotrophic” (Greek for “little food”) and “eutrophic” (Greek for “well fed”) and was originally used to describe the soil fertility in northern Germany; subsequently these terms were applied to lakes [58].

Numerous attempts have been made to define the trophic states in terms of both nutrient and productivity water quality parameters. Carlson [59] developed a numerical trophic state scale from 0 to 100 for lakes. The index number can be calculated from any of several parameters including Secchi depth (SD) transparency, chlorophyll (Chl-a), and total phosphorus (TP). The Carlson TSI has been widely used to evaluate many lakes and reservoirs [60–67].

For coastal marine waters and brackish waters (lagoons), Vollenweider et al. [68] and Giovanardi and Vollenweider [69] proposed a new trophic index (TRIX), which is based on Chl-a, oxygen saturation, mineral nitrogen (dissolved inorganic nitrogen DIN), and total inorganic phosphorus. The index is scaled from 0 to 10, covering a range of four trophic statuses: low trophic level (0–4), moderate

trophic level (4–5), high trophic level (5–6), and very high trophic level (6–10). TRIX can be calculated from the following equation:

$$\text{TRIX} = (\log_{10}[\text{Chl-a} \times \text{DO}\% \times \text{minN} \times \text{TPO}_4] + a)/b \quad (3)$$

Where:

Chl-a is chlorophyll-a concentration ($\mu\text{g/l}$).

DO% is oxygen as absolute % deviation from saturation.

min N is total dissolved inorganic nitrogen ($\text{DIN} = \text{N-NO}_3 + \text{N-NO}_2 + \text{N-NH}_4$) ($\mu\text{g/l}$).

TPO₄ is total inorganic phosphorus (P-PO₄) ($\mu\text{g/l}$).

a and b are scale coefficients to fix the lower limit value of the index and the scale range from 0 to 10, $a = 1.5$ and $b = 1.2$.

This index has been frequently used to evaluate the trophic status of coastal marine waters, estuaries, and lagoons [70–76]. TRIX was used as an evaluation tool of the eutrophication status for a landscape lake HMLA located in Tianjin City, North China, with a mixture of point source pollution and nonpoint source pollution [71]. In 2013, TRIX was used to assess the eutrophication and water quality of Arvand River, Iran [76]. The results demonstrate the river is in the first trophic state (0–4) which represents high quality and low trophic level. Christia et al. [72] used TRIX, in addition to five ecological indices, to assess the ecological status of six coastal lagoons located along the western coast of Greece under real conditions. The trophic status ranged from oligotrophic to hypertrophic according to the index applied.

5.3 MIKE21 Modeling System

Limited software are available for modeling shallow coastal environment, such as MIKE21 [77], DELFT3D [78], or MOHID [79] modeling systems. Due to the extensive and wide application of MIKE 21 all over the world [80–83] and due to its technical support, MIKE21 modeling system has been chosen for this study.

MIKE 21 Flow Model is a general numerical modeling system for two-dimensional free-surface flows. It is applicable to the simulation of hydraulic and environmental phenomena in lakes, estuaries, bays, and coastal areas, wherever stratification can be neglected. It simulates unsteady two-dimensional flows in one-layer (vertically homogeneous) fluids and has been applied in a large number of studies [33, 84–92]. This code contains three modules, hydrodynamic (for hydraulic simulation such as water levels), advection-dispersion (for thermal and conservative simulation such as water temperature and salinity), and ECO Lab (for water quality simulation such as dissolved oxygen). MIKE 21 HD makes use of a so-called Alternating Direction Implicit (ADI) technique to integrate the equations for mass and momentum conservation in the space–time domain [77].

Some examples of using MIKE21 modeling system to simulate lakes and wetlands can be noticed in the literature. MIKE 21 was employed to evaluate the water quality of Anzali Wetland, which lies on the southern coast of the Caspian Sea in Northern Iran [93]. In the Flinders catchment in North Queensland, Australia, MIKE 21 tool was used to assess the impacts of climate change on the hydrological connectivity between floodplain wetlands and main rivers [94]. MIKE 21 and STELLA software were used to establish a zoning-based environmental–ecological-coupled model for Baiyangdian Lake, the largest freshwater lake in northern China, to study the spatial variations of ecological conditions in response to changes in lake water quantity and quality [95]. In 2015, MIKE21 was used to examine some water quality management scenarios for Lake Burullus, which lies in the Nile Delta, Egypt [96].

5.4 Climate Change Estimates

Projected changes in the climate conditions and sea level rise (SLR) estimates are essential to investigate the impact of future climatic change scenarios on the hydrodynamic and water quality characteristics of Lake Manzala. Based on the Fifth Assessment Report of IPCC [50], climatic change estimates of one Representative Concentration Pathway (RCP2.6) for two future periods I [2046–2065] and II [2081–2100], as examples, were used to modify the developed hydrodynamic and water quality model of Lake Manzala. Global mean SLR of RCP2.6 was estimated as 0.24 and 0.4 m for periods I and II, respectively, relative to the average sea level for 1986–2005. The other climatic conditions, namely, near surface air temperature, evaporation, precipitation, relative humidity, and surface wind speed, were obtained from CORDEX project (CORDEX project) for the same RCP (2.6) and future periods (I and II). The results of two global circulation models (GCM), ICHEC and EC-EARTH, were spatially and temporally downscaled by the Swedish Meteorological and Hydrological Institute (SMHI) using RCA4 regional climate model. These projections were downscaled in space to 0.44° latitude–longitude resolution (about 50 km) for the Middle East–North Africa (MENA) domain and in time to daily average. Figures 6, 7, and 8 present the projected changes for some climatic conditions, as examples, for RCP2.6 relative to the base records of 2010–2011.

6 Data Collection and Analysis

To assess the water quality status of the lake and develop a hydrodynamic and water quality model to investigate the climatic change impacts on its characteristics, hydrological, physical, chemical, biological, and meteorological data series for the study area covering, at least, 1 year should be available. Data limitation for

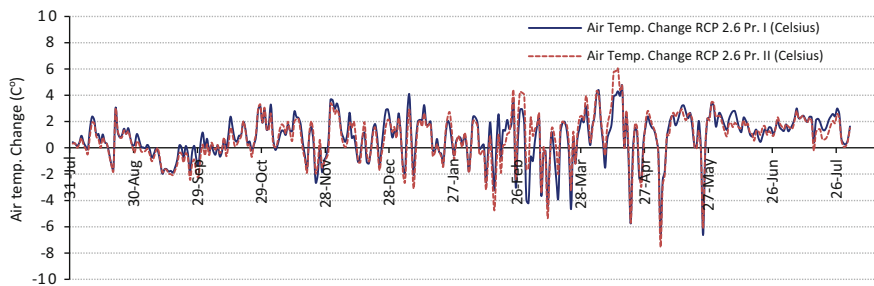


Fig. 6 Daily average changes for the study area in air temperature (Celsius) relative to 2010–2011 for RCP 2.6 scenario and for different periods

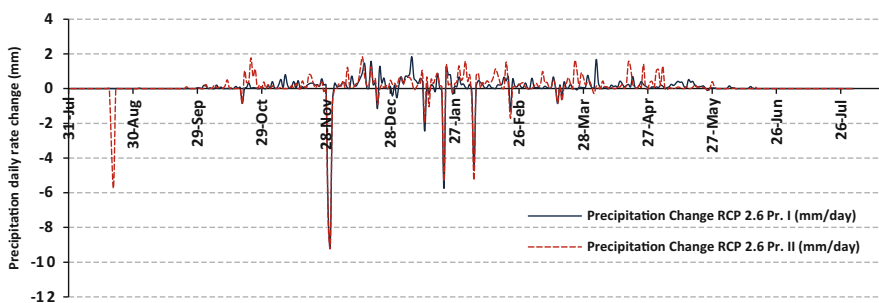


Fig. 7 Daily average changes for the study area in precipitation rate (mm) relative to 2010–2011 for RCP 2.6 scenario and for different periods

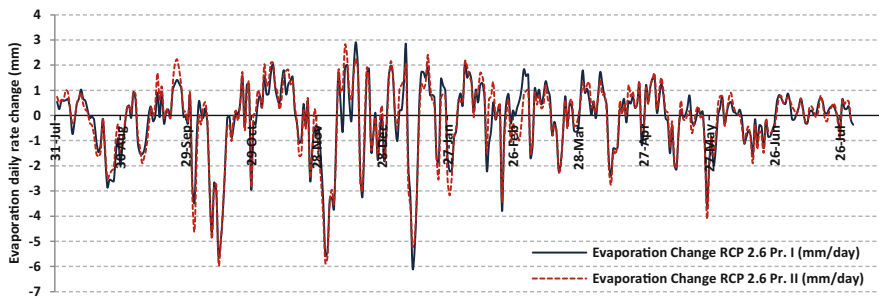


Fig. 8 Daily average changes for the study area in evaporation rate (mm) relative to 2010–2011 for RCP 2.6 scenario and for different periods

this study area, in particular the hydrological data, is considered as the main constraint of this work.

Some hydrological records and drain discharges were collected by the National Water Research Center (NWRC), Egypt. Other required characteristics, such as water levels, were collected from the international publications of the previous projects on the lake [10, 97]. Meteorological conditions of Lake Manzala during

simulation periods were obtained from the Internet (weather underground [12] and Infospace [11] websites) at the nearest meteorological station to the lake, Port Said Airport station.

Physical, chemical, and biological records were collected by the Egyptian Environmental Affairs Agency (EEAA). The records were collected from eleven stations in the lake and four stations at the outlets of the four main drains; see Fig. 2. These records were seasonally, in August, November, February, and May, measured for 2 years (starting from August 2010 to August 2012). These parameters include water temperature (Temp.), electric conductivity (EC), total suspended solids (TSS), pH, dissolved oxygen (DO), biological oxygen demand (BOD), chemical oxygen demand (COD), total nitrogen (TN), total phosphorus (TP), nitrate, orthophosphate, and chlorophyll-a (Chl-a).

Statistical representations for these records are presented in Table 1, for the lake, and Table 2, for the drains. Box plot charts for some parameters are presented in Figs. 9 and 10, for the lake and the main drains, respectively. Figure 11 shows a spatial representation for some water quality records in the lake in August 2011, as an example.

Figure 9 reveals the critical water quality conditions of the lake, particularly at the eastern zone (ST. 1) and at the southern zone (ST. 3 and ST. 11). ST. 1, which is located in the front of Bahr Elbaqar Drain, had the minimum average DO concentration, average pH record, and maximum average concentrations of TN, TP, BOD and COD, during the study period. The southern sector which stretches from ST. 3 to ST. 11 has a particular concern. This zone is far away than the Nile water source (Enanya Canal) and the outlets, which made this zone the most stilled zone in the lake. In addition, this zone receives drainage water through one main drain (Hadous Drain) and two other minor drains (Mataria and Ramsis Drains); see Fig. 2. For that, ST. 11 had a very low DO average concentration and high average concentrations of TN, TP, Chl-a, and BOD, during the study period. On the other hand, better water quality conditions can be found at the northern and western zones of the lake. ST. 2 is located in front of the two main outlets, while ST. 10 is located

Table 1 Summary of descriptive statistic of water quality data over 2 years (Aug 2010–Aug 2012) in Lake Manzala

Parameter	Unit	Min	Max	Mean	SD
Temp	°C	12.70	30.60	23.43	5.01
EC	µS/cm	1.50	30.29	7.35	6.05
TSS	mg/l	16.10	171.5	56.92	31.34
pH		7.00	9.40	8.30	0.43
DO	mg/l	0.00	14.56	5.36	3.41
BOD	mg/l	0.58	218.7	23.87	32.62
COD	mg/l	6.40	660.3	138.3	107.9
TN	mg/l	0.57	19.56	4.43	3.09
TP	mg/l	0.02	2.01	0.49	0.39
Nitrate	mg/l	0.01	1.29	0.19	0.24
Phosphate	mg/l	0.01	0.90	0.22	0.22
Chl-a	µg/l	1.55	394.0	41.90	48.68

Table 2 Summary of descriptive statistic of water quality data over 2 years (Aug 2010–Aug 2012) in the drains of Lake Manzala

Parameter	Unit	Min	Max	Mean	SD
Temp	°C	12.70	29.87	23.05	5.26
EC	μS/cm	0.85	5.69	2.18	1.40
TSS	mg/l	23.25	137.0	62.31	27.94
pH		7.05	8.39	7.99	0.35
DO	mg/l	0.00	7.28	2.00	1.79
BOD	mg/l	4.09	213.8	49.64	52.49
COD	mg/l	4.35	448.0	96.36	117.7
TN	mg/l	2.05	17.41	6.30	3.31
TP	mg/l	0.37	2.10	0.92	0.45
Nitrate	mg/l	0.07	2.08	0.53	0.45
Phosphate	mg/l	0.16	1.08	0.44	0.23
Chl-a	μg/l	1.74	99.90	24.10	26.47

in front of the Nile water source (Enanya Canal). ST. 10 had the maximum average record of pH and the minimum average concentrations of TP, TN, Chl-a, and BOD, during the study period.

The bad water quality situation of the main drains can be seen in Fig. 10. As can be clearly noticed, Bahr Elbaqar Drain had the worst water quality records during the study period. This drain has a severe impact on the lake water quality status due to its greater discharge than the other considered drains (see Fig. 3). Better water quality conditions and less drainage discharges are provided by Elserw and Fareskour drains which discharge their drainage at the western zone of the lake.

7 Water Quality Assessment of Lake Manzala

Figure 12 presents the averages of L-WQI for the considered drains during the studied period (Aug. 2011–Aug. 2012). The water quality status of Bahr Elbaqar Drain is classified as a “Very Bad”; its average L-WQI is about 22. While the water quality conditions of the other drains are classified as a “Critical,” their L-WQI ranges from 34 to 44. These results should be expected due to the very bad concentrations of the drain water quality parameters, particularly Bahr Elbaqar Drain, as can be seen in Fig. 10. Bahr Elbaqar Drain receives excessive and heavy domestic and industrial effluents; the average BOD concentration (during the study period) was about 87.5 mg/l which was considered as the maximum concentration for the studied drains, while the average COD concentration was about 102 mg/l, which was considered as a very high concentration. The average DO concentration for Bahr Elbaqar Drain was about 0.94 mg/l which is a very low concentration and represents a killing environment for fish; in the summer, DO concentration decreased to zero (oxygen depletion). The average TN and TP were 6 and 0.9 mg/l, respectively, which were considered as the highest nutrient concentrations during the study period.

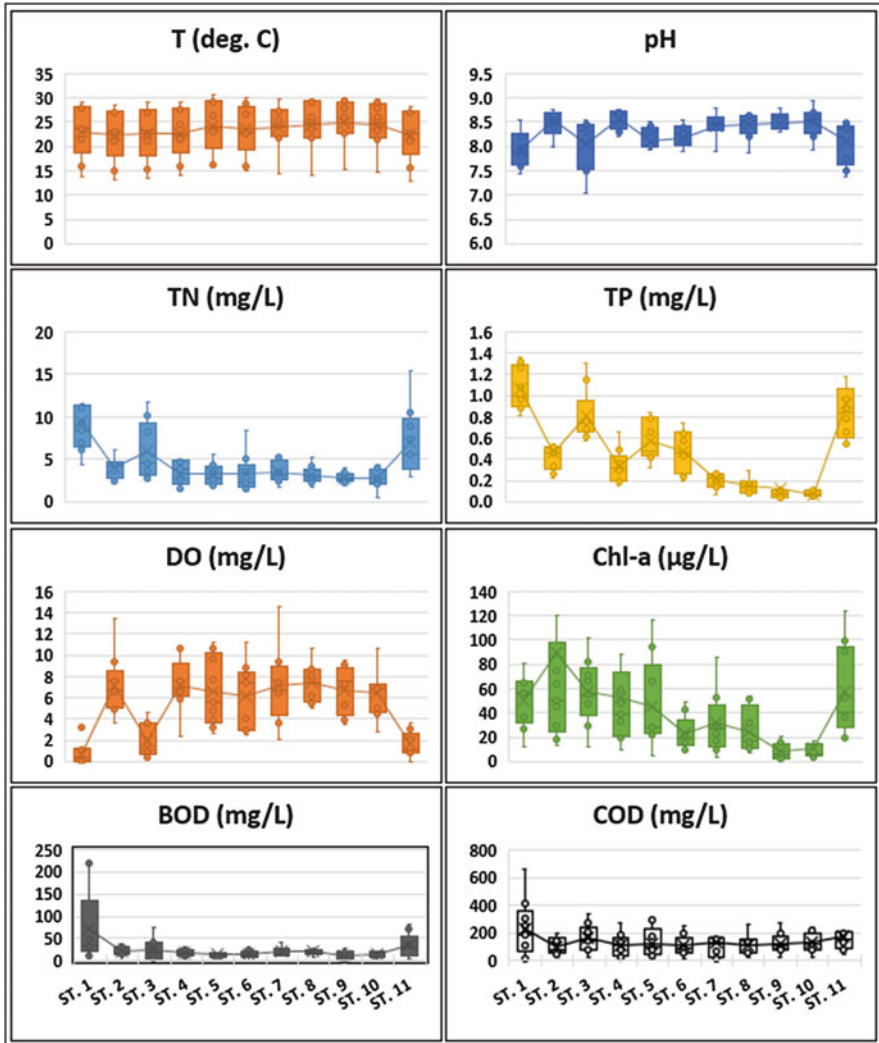


Fig. 9 Measured water quality records at different stations in Lake Manzala during the study period (Aug. 2010–Aug. 2012)

In Fig. 13, the spatial averages (for all seasons) of L-WQI for Lake Manzala are presented. The water quality status of three stations is classified as a “Very Bad,” according to L-WQI; L-WQI of station No. 1 (in the lake eastern sector) and stations No. 3 and 11 (in the lake southern sector) ranges from 19.5 to 21. The water quality status of two stations is classified as a “Good”; L-WQI of stations No. 9 and 10 (in the lake western sector) ranges from 52.1 to 53.5. However, the water quality status of other stations is classified as a “Critical.”

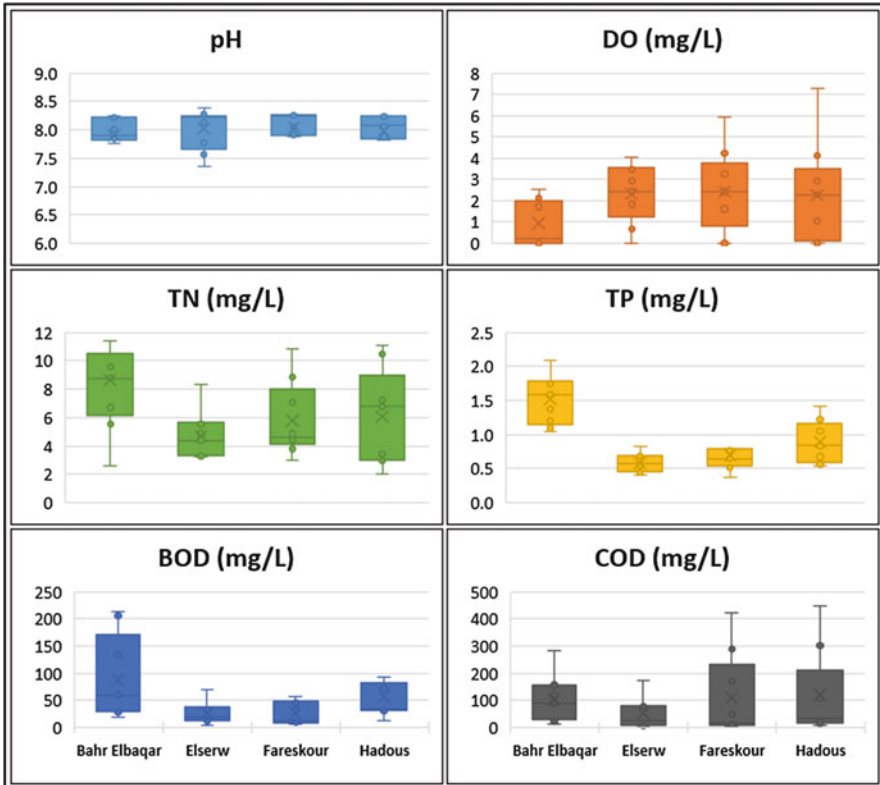


Fig. 10 Measured water quality records of the main drains at Lake Manzala during the study period (Aug. 2010–Aug. 2012)

These results return to the locations of these stations. Station No. 1 lies in the front of Bahr Elbaqar Drain outlet, and for that, the worst average water quality records in the lake were recorded at this station: the minimum averages of pH (7.9) and DO concentration (0.82 mg/l) and the maximum average concentrations of BOD (72.5 mg/l), COD (230 mg/l), TN (9.4 mg/l), and TP (1.07 mg/l). Stations No. 3 and 11 lie in the shallowest part of the lake, in the front of some drains including Hadous Drain, far away from the lake outlet and the source of the freshwater canal (Enanya Canal). Both stations, No. 3 and 11, have the maximum average concentration of Chl-a (57 µg/l), low average concentrations of DO (1.9 and 1.7 mg/l), and high average concentrations of COD (162 and 172 mg/l), BOD (24 and 33 mg/l), TN (5.9 and 7 mg/l), and TP (0.81 and 0.93 mg/l), which refer to a very polluted zone.

Stations No. 9 and 10 have the best water quality conditions of the lake due to their locations in front of the freshwater source (Enanya Canal) and some less polluted agricultural drains (Fareskour and Elserw). Both stations (No.9 and No. 10) have high average concentrations of DO (6.8 and 6.4 mg/l) and low average

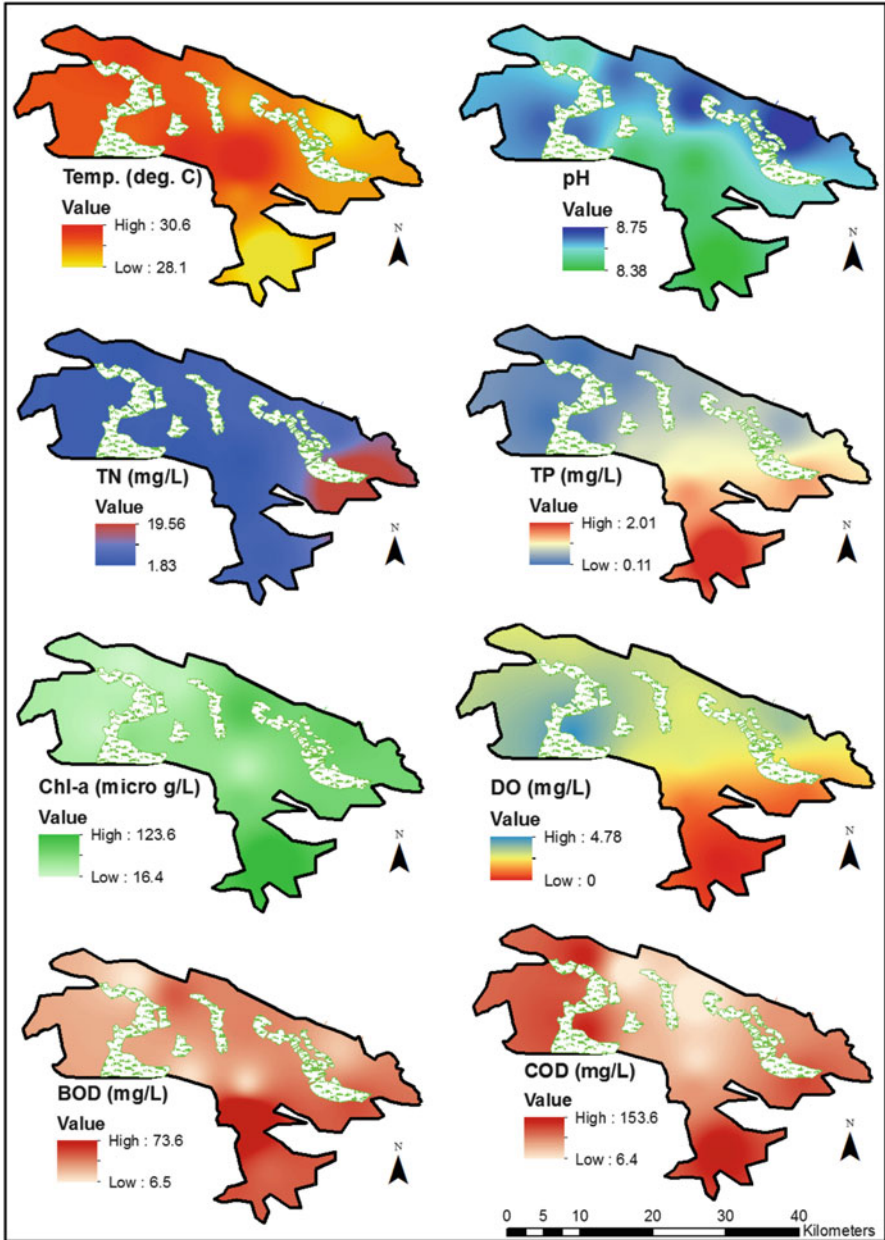


Fig. 11 Measured water quality records of Lake Manzala in Aug. 2011

concentrations of BOD (12.8 [the minimum] and 14.3 mg/l), COD (125 and 132 mg/l), TN (2.8 mg/l [the minimum]), and TP (0.12 and 0.07 mg/l [the minimum]) which reveal a good water quality condition.

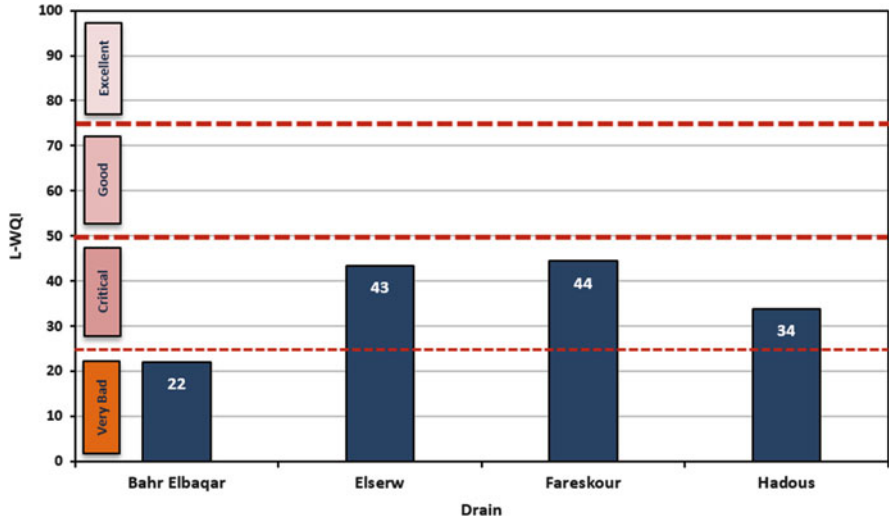


Fig. 12 Averages of L-WQI for the main drains of Lake Manzala during the study period (Aug. 2010–Aug. 2012)

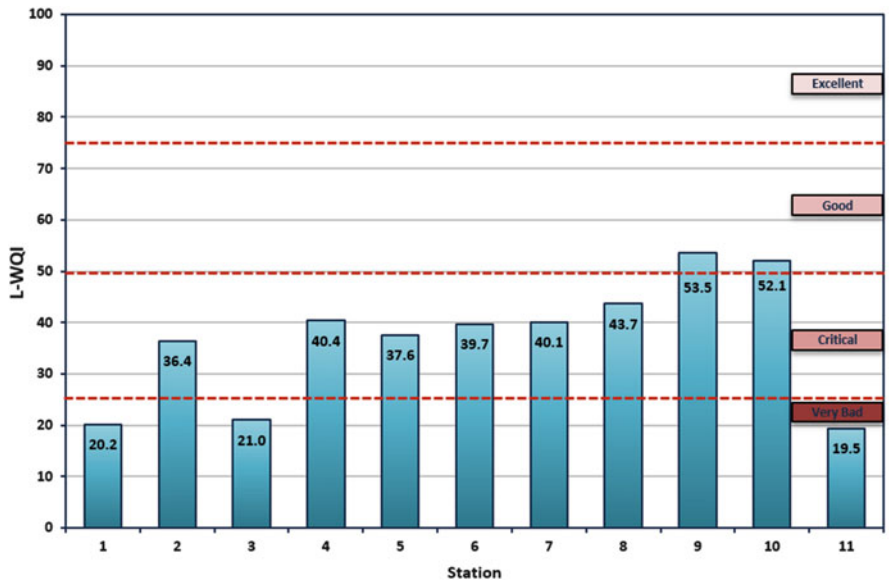


Fig. 13 Spatial averages of L-WQI at different stations in Lake Manzala during the study period (Aug. 2010–Aug. 2012)

The seasonal averages (for all stations) of L-WQI for Lake Manzala during the studied period are presented in Fig. 14. The water quality status of the lake is classified as a “Critical” for all seasons; L-WQI ranges from 28.9 (May and August

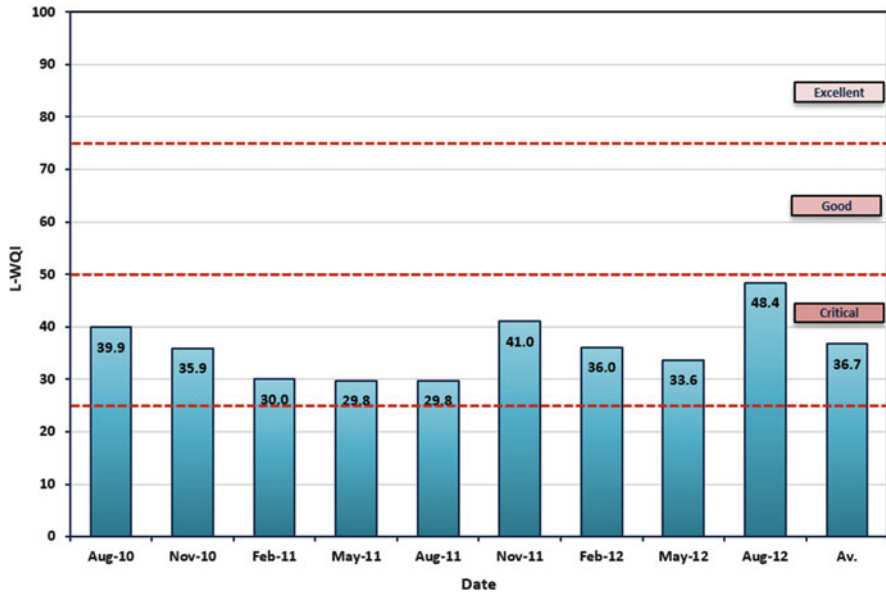


Fig. 14 Temporal averages of L-WQI for Lake Manzala during the study period (Aug. 2010–Aug. 2012)

2011) to 48.4 (August 2012). These results can be clearly confirmed in Fig. 15, which shows the temporal L-WQI of some selected stations covering the different sectors of the lake, station No. 1 (the eastern sector), station No. 3 (the southern sector), and station No. 9 (the western sector), where the minimum L-WQI occurred in August 2011 for the three selected stations, while the maximum L-WQI occurred in August 2012 for stations No. 3 and 9 and in February 2012 for station No. 1. This returns to the concentrations of the considered water quality parameters in these seasons.

Comparing Figs. 13 and 14 reveals that the spatial distribution of the averages L-WQI of Lake Manzala (Fig. 13) is more accurate and representative than the seasonal averages (Fig. 14) due to the different characteristics of the lake sectors. For that, the spatial distribution of the average L-WQI in the lake for the studied period is presented in Fig. 16, and the L-WQI for August 2011 is presented in Fig. 17, which represents the worst water quality status of the lake during the study period. The lake is divided into two zones, the western and middle zone, which has a “Critical” water quality status, and the eastern and southern zone, which has a “Very Bad” water quality status due to the locations of the polluted drains. The results of this study confirm the results of the water quality status evaluation studies [20–24], which concluded that the southern sector of the lake has environmental problems.

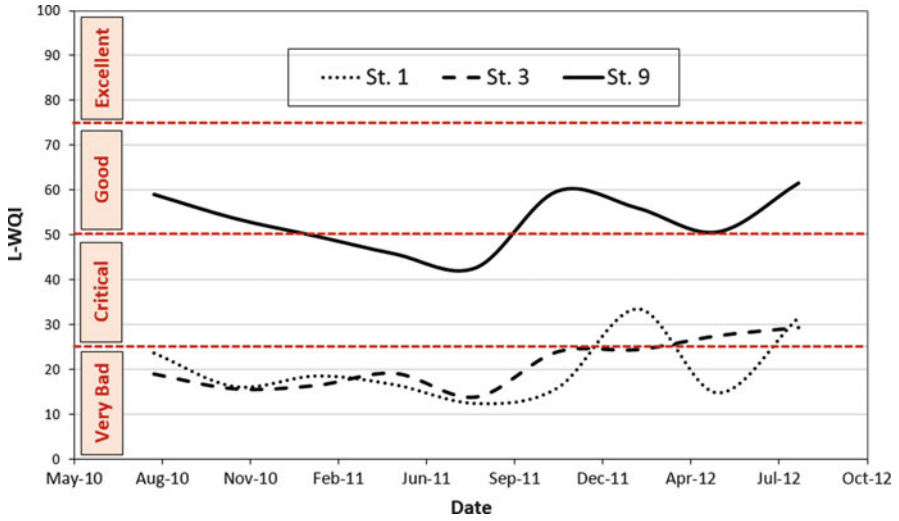


Fig. 15 Temporal distribution of L-WQI at stations No. 1, 3, and 9 in Lake Manzala during the study period (Aug. 2010–Aug. 2012)

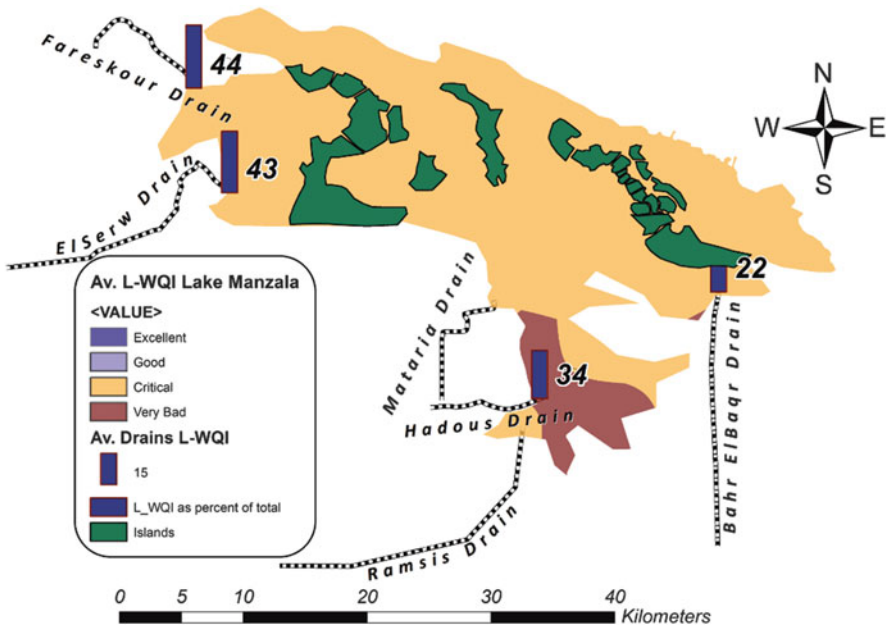


Fig. 16 Spatial distribution of average L-WQI for Lake Manzala during the study period (Aug. 2010–Aug. 2012)

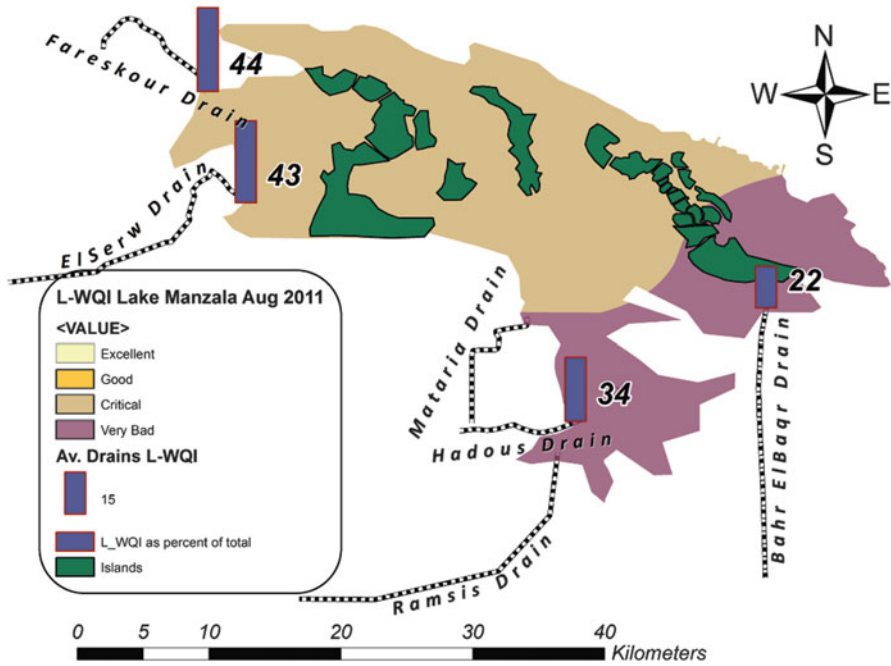


Fig. 17 Spatial distribution of L-WQI for Lake Manzala in August 2011

8 Trophic Status Assessment of Lake Manzala

Similar to the used WQI approach, TSI approach was used to spatially and temporally assess the trophic status of Lake Manzala. TRIX was used to assess the lake trophic status during the studied period (Aug. 2011–Aug. 2012). Figure 18 presents the spatial averages of TRIX for the lake, while Fig. 19 shows the seasonal averages of TRIX. Figure 20 shows the temporal TRIX at some stations in the lake as examples. The spatial distribution of the average TRIX in the lake for the studied period can be seen in Fig. 21, while TRIX for May 2011, as an example, is presented in Fig. 22, which represents one of the highest trophic status of the lake during the study period.

As clearly can be noticed, stations No. 11, 3, 5, and 1, which represent the southeastern part of the lake, have the highest trophic conditions. It returns to the hydrological and water quality conditions of this zone which is considered as the shallowest part in the lake and is located away from the outlets and the sources of freshwater canal facing some drain outlets. As mentioned before, station No. 11 has the maximum average concentration of Chl-a (57 µg/l), a low average concentration of DO (1.7 mg/l), and high average concentrations of COD (172 mg/l), BOD (33 mg/l), TN (7 mg/l), and TP (0.93 mg/l), which refer to a very polluted zone. These results are confirming the previous studies which stated that the southern sector of the lake has environmental problems [16, 17, 22, 23].

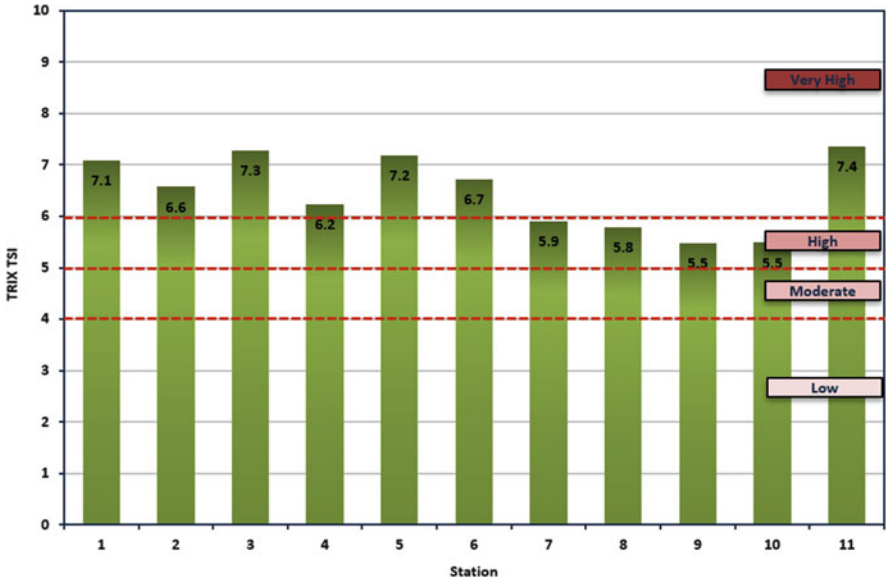


Fig. 18 Spatial averages of TRIX at different stations in Lake Manzala during the study period (Aug. 2010–Aug. 2012)

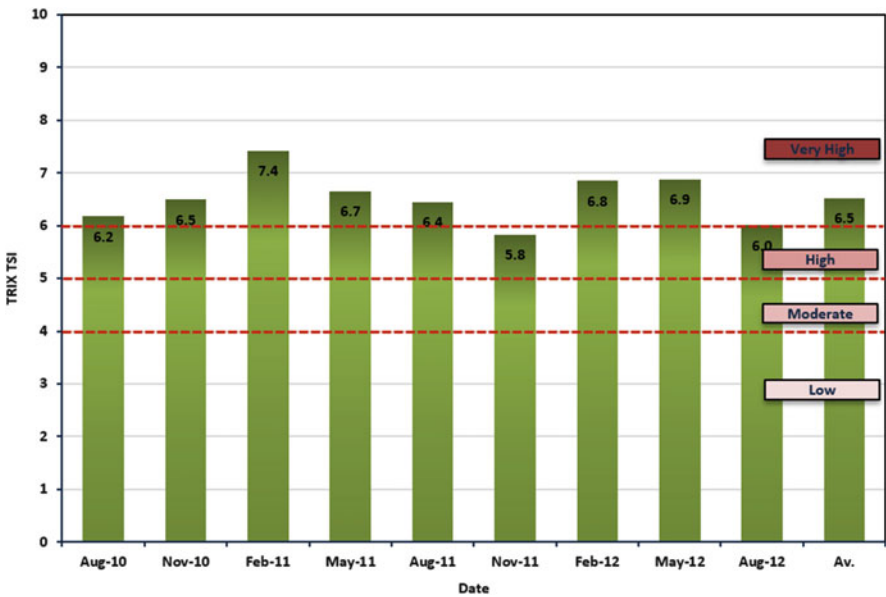


Fig. 19 Temporal averages of TRIX for Lake Manzala during the study period (Aug. 2010–Aug. 2012)

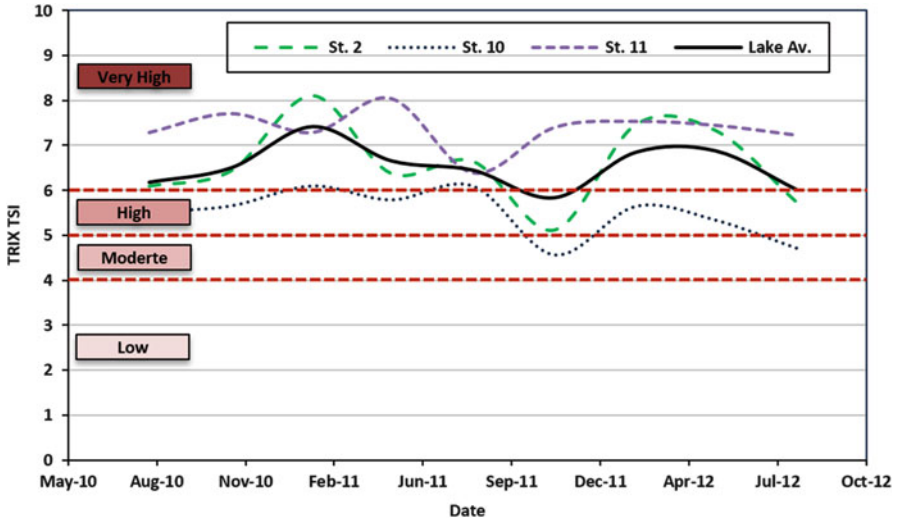


Fig. 20 Temporal distribution of TRIX at stations No. 1, 3, and 9 in Lake Manzala during the study period (Aug. 2010–Aug. 2012)

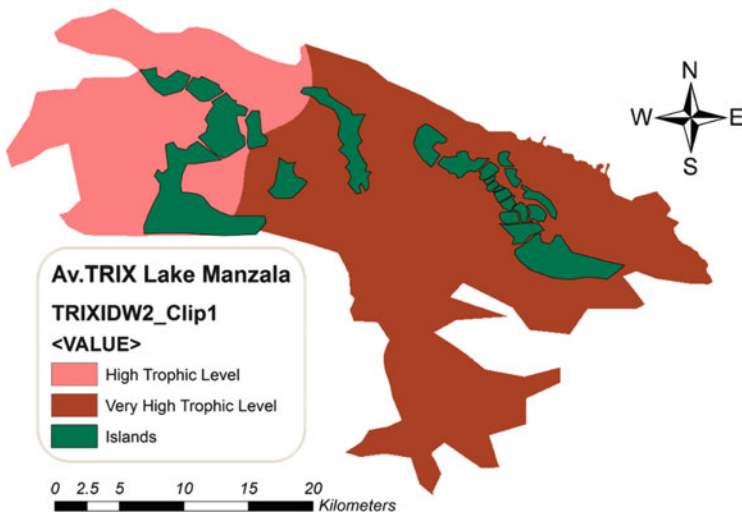


Fig. 21 Spatial distribution of average TRIX for Lake Manzala during the study period (Aug. 2010–Aug. 2012)

Unlike the situation of the eastern zone of the lake, the western sector of the lake has a better trophic status, which is also considered high, according to TRIX. Stations No. 10, 9, 8, and 7 represent this zone. This returns to their location which receives freshwater through the Enanya Canal and the agriculture drains of Fareskour and Elserw. Station No. 10, as an example, has a high average concentration of DO

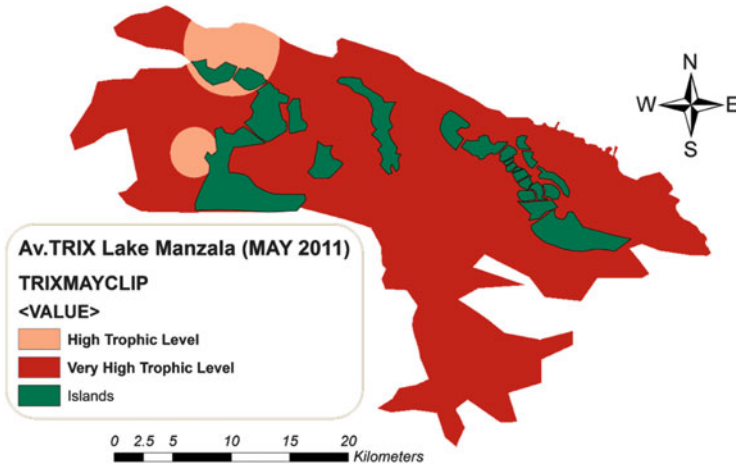


Fig. 22 Spatial distribution of TRIX for Lake Manzala in May 2011

(6.4 mg/l) and low average concentrations of BOD (14.3 mg/l), COD (132 mg/l), TN (2.8 mg/l [the minimum]), and TP (0.07 mg/l [the minimum]) which reveal a good water quality condition, compared to other studied stations.

9 Impacts of Future Climatic Changes on the Lake Characteristics

9.1 Developing of Manzala Model

Lake Manzala hydrodynamic and water quality model was developed, based on MIKE21 modeling system. The model input files included a lake bathymetry (topography), boundary conditions (flow discharges, water levels, and water quality records for the considered drains and outlets), initial conditions (the water levels and water quality records of the lake at the beginning of the simulation), and meteorological information.

For lake bathymetry, Fig. 23 shows the developed model bathymetry which consists of 37,500 cells; each is 200×200 m resolution, and some islands in the lake can be seen in the figure (colored in red). Model bathymetry was developed using MIKE Zero (the graphical user interface for all MIKE models), and UTM-36 map projection was used for the study area. As can be seen in Fig. 23, three outlets were considered, El-Gamil 1 and El-Gamil 2 to north and El-Qabuti Canal to east, and the predicted (by MIKE21) outlet tide levels can be seen in Fig. 24. While for freshwater resources, five drains were considered, according to their discharges (Bahr Elbaqar, Hadous, Mataria, Elserw, and Fareskour). For the lake water levels, five stations were considered (Fig. 25), while eleven stations were considered for the

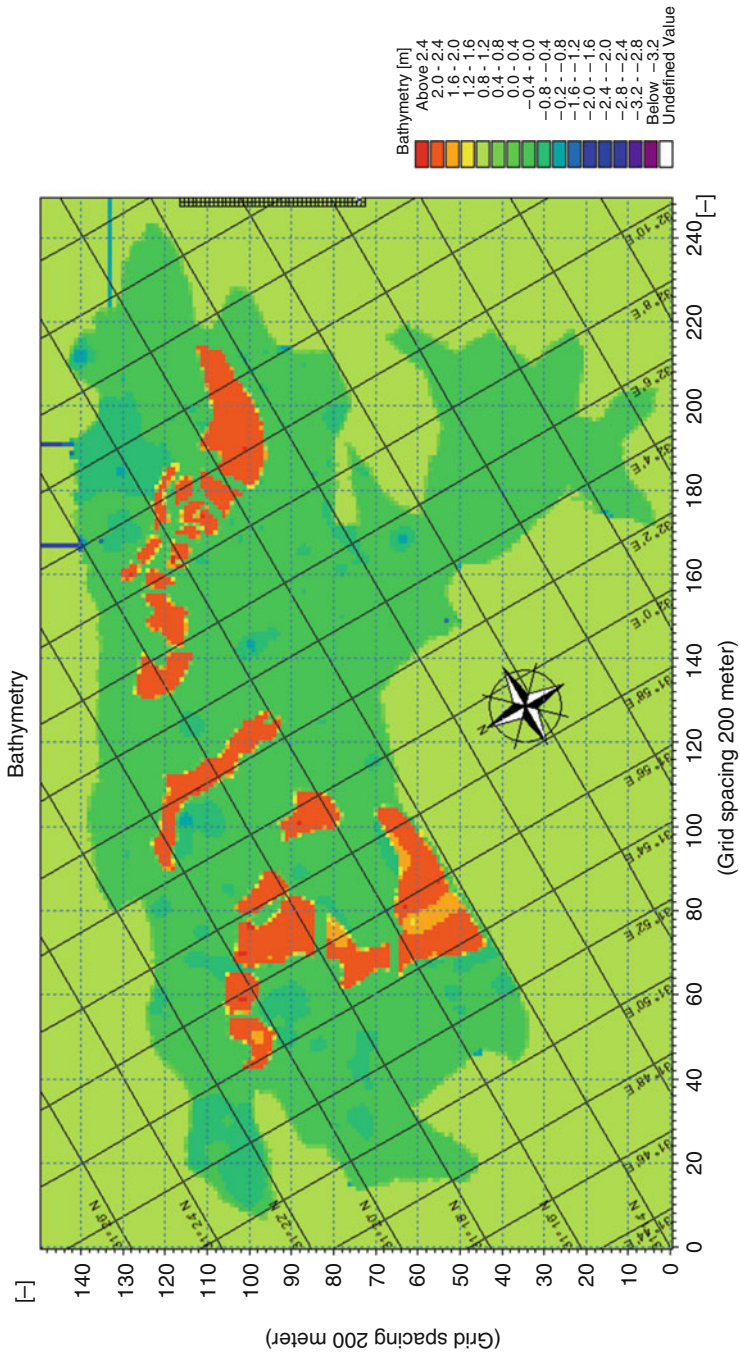


Fig. 23 Developed bathymetry for Lake Manzala model

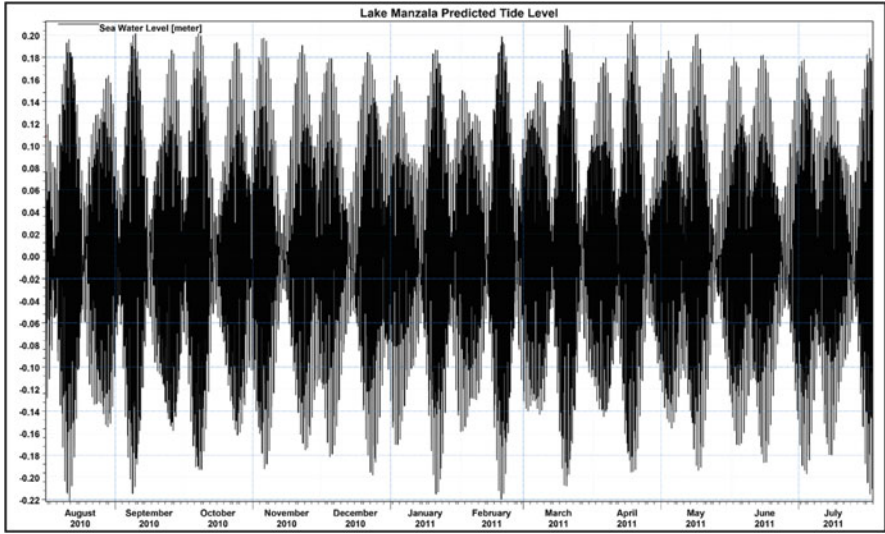


Fig. 24 Generated tide levels for Lake Manzala outlets for a typical year

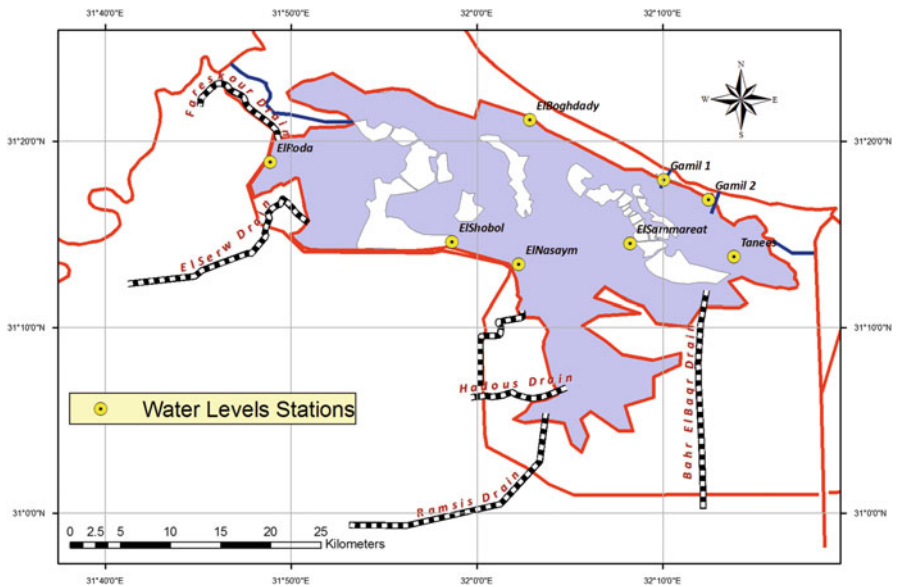


Fig. 25 Water levels recording stations for Lake Manzala

lake water quality records (Fig. 2). Two hydrodynamic parameters (water depth and water temperature) and a water quality parameter (salinity) were chosen to present the model results. Due to the severe lack of required data for the model, some hydrological records and drain discharges were collected by the National Water Research Center (NWRC), Egypt. Other essential required characteristics, such as

water levels, were collected from the international publications of the previous projects on the lake. A GIS database system was developed to arrange, manage, and present the spatial distribution of collected data. According to the available data, the lake was modeled for a typical simulation year (August 2010–July 2011).

The proposed model was calibrated using coefficients determined for the simulation period, for about 1 year (August 2010–July 2011). Table 3 presents the non-default calibrated coefficients which were chosen during calibration process. For the other model coefficients not measured in this study, default values provided by the code software were used as recommended by MIKE 21 modeling manual [77]. The main three outlets were considered as “Boundary Conditions” due to the sea–lake exchange, while the drains were considered as “Sources,” as there is always an inflow to the lake. Initial surface water levels were inserted using a GIS spatial distributed interpolated file that includes different water levels at different stations on the beginning of simulation period. Moreover, drying and flooding depths were carefully tested to avoid the “Blow-Up Error.” Such error can easily occur due to the change in water depths, in particular for shallow environments.

Two statistical parameters were used to compare simulated and in-lake observations, the absolute mean error (AME) and the root mean square error (RMSE). AME indicates how far, on the average, simulated values are from measured values, while RMSE indicates the spread of how far the simulated values deviate from the measured data.

Figure 26 shows the water velocity distribution around the outlet zone (northern east corner of the lake) on May 30, 2011, as an example during the calibration period. The velocity distribution around the islands and the sea–lake flow exchange can be noticed.

For water depth, Fig. 27 presents the calibrated water depth profiles at two stations (Tanees and El-Nasayem) in the lake, as examples, compared to the

Table 3 List of non-default calibration coefficients of MIKE 21 used in this study

Coefficient	Value
Time step interval	300 s
Warm-up period	800 s
Drying depth	0.05 m
Flooding depth	0.3 m
Eddy viscosity (flux based)	0.2 m ² /s
Chezy bottom friction factor	50 m ^{1/2} s ⁻¹
Wind friction coefficient	0.0018
Constant in Dalton’s law	0.5
Wind coefficient in Dalton’s law	0.9
Sun constant, a in Angström’s law	0.295
Sun constant, b in Angström’s law	0.371
Displacement (summer time)	1
Standard meridian for time zone	30
Integration method for heat exchange	1st-order Euler

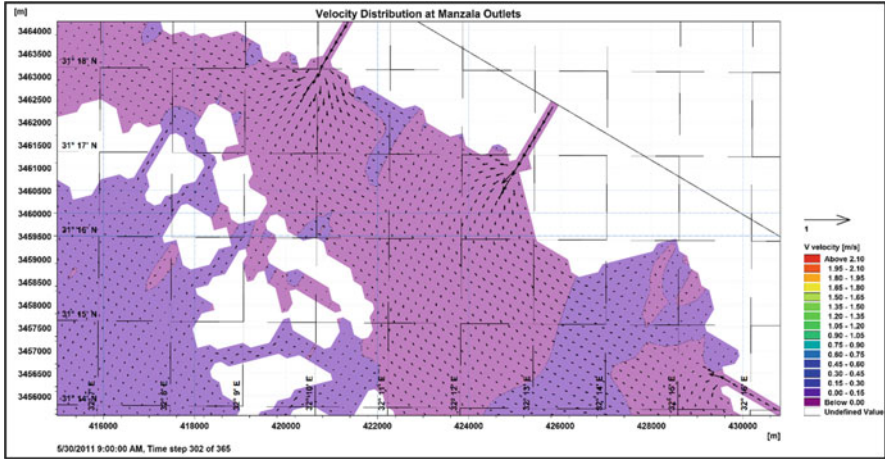


Fig. 26 Velocity distribution at Manzala outlets on May 30, 2011

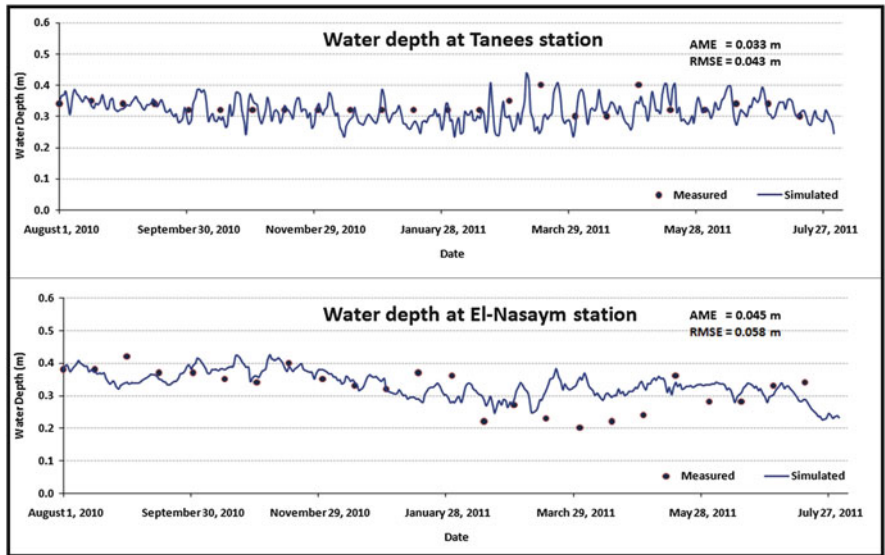


Fig. 27 Measured and simulated water depths at Tanees and El-Nasayem stations, Lake Manzala

measured records. The AME values were 0.033 and 0.045 m, while the RMSE values were 0.043 and 0.048 m, respectively. Based on the AME and RMSE values, the developed model performs satisfactorily, and the overall simulated results are good.

Figure 28 shows the calibrated water temperature profiles at two stations (stations No. 3 and 10) in the lake, as examples, compared to the measured records. The average AME and RMSE values for all the considered eleven stations were 0.56

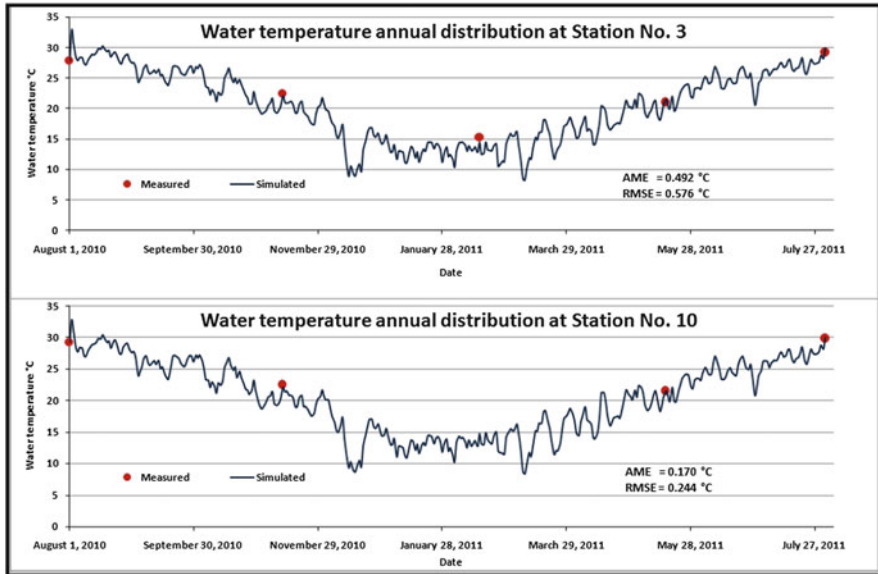


Fig. 28 Measured and simulated water temperature at stations No. 3 and 10, Lake Manzala

and 0.72 °C, respectively. Despite the severe lack of observed hydrodynamic and water quality parameters (only five or four records per year), it can be noticed that the measured records closely match the simulated records.

For salinity, Fig. 29 presents the measured and simulated profiles at two different stations in the lake, as examples, during the simulation period. AME and RMSE for station No. 1 (eastern sector) were 0.07 and 0.09 ppt, respectively, while for station No. 3 (middle sector) AME and RMSE were 0.23 and 0.28 ppt, respectively. The average AME and RMSE for all recording stations were 1 and 1.4 ppt, respectively.

The missing of observed salinity records, particularly for outlets, may lead to that variety in AME and RMSE values. In general, the presented examples may be considered as accepted (AME and RMSE values are very small) as the model is limited by several assumptions and approximations used to simulate hydrodynamics, transport, and water quality processes, besides the uncertainty of the recorded field data and the missing parameters which have been completed from different sources.

9.2 Climate Change Impacts

The results of the Lake Manzala calibrated model for the period of 2010–2011 were used as a base case for quantifying the impacts of future climatic changes on the hydrodynamic and water quality characteristics of the lake. The investigated climatic scenarios (RCP2.6_I and RCP2.6_II) cover the same calibrated period

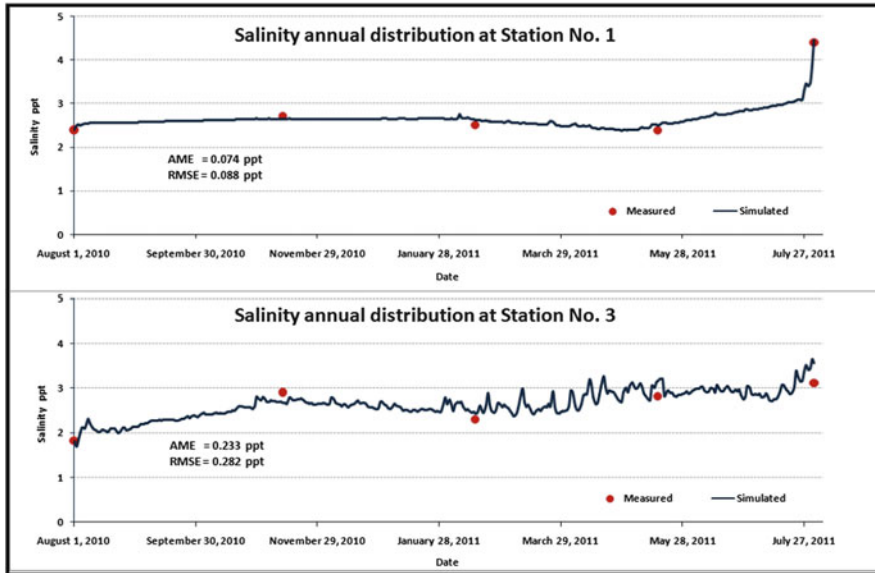


Fig. 29 Measured and simulated water salinity at stations No. 1 and 3, Lake Manzala

(on a daily scale). Two hydrodynamic parameters (water depth and water temperature) and a water quality parameter (salinity) were selected, due to their important impacts on the hydrodynamic and water quality characteristics of the lake, to present the impacts of future climatic changes. To quantify the changes of the studied parameters, an average relative percentage difference ($\Delta\%$) between the scenario results and the base case results of the calibrated period 2010–2011 will be used: $\Delta W D$ for the water depth, ΔT for the water temperature, and ΔS for the salinity.

The future water depth profiles of three stations in Lake Manzala (as examples), compared to the calibrated base case, are shown in Figs. 30, 31, and 32. The selected three stations cover the different zones of the lake (see Fig. 25); station of Tanees lies in the northern east sector (Fig. 30), and station of El-Roda lies in the western sector (Fig. 31), while station of El-Nasayem lies in the southern middle sector (Fig. 32). The relative water depth change is directly proportional to the change in the SLR, in addition to the location of the considered station which controls its impacts due to the change in climatic conditions. For that, station of Tanees which is located close to the lake outlets will have the maximum effect due to the change in SLR (Fig. 30); the average $\Delta W D$ will be about 69 and 117%, for RCP2.6_I and RCP2.6_II, respectively. The big values of the changes return also to the small average basic water depth in 2010–2011 which was only about 0.32 m. On the other hand, El-Roda station which is away from the outlets will have the minimum effect due to the climatic changes (Fig. 31); the average $\Delta W D$ will be about 48 and 90%, for RCP2.6_I and RCP2.6_II, respectively. In between of them,

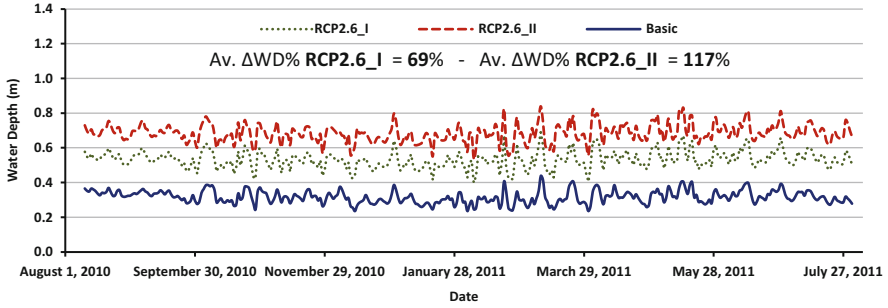


Fig. 30 Water depth distribution at Tanees station, Manzala Lake, for some selected future climatic scenarios and periods compared to the basic water levels (of model calibration)

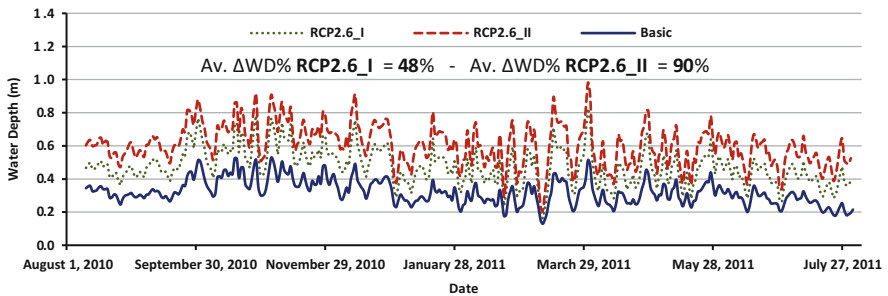


Fig. 31 Water depth distribution at El-Roda station, Manzala Lake, for some selected future climatic scenarios and periods compared to the basic water levels (of model calibration)

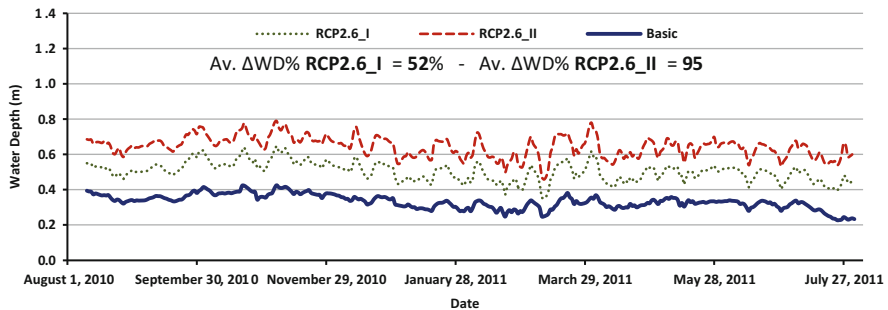


Fig. 32 Water depth distribution at El-Nasayem station, Manzala Lake, for some selected future climatic scenarios and periods compared to the basic water levels (of model calibration)

station of El-Nasayem shows moderate average changes (Fig. 32); the average Δ WD will be about 52 and 95%, for RCP2.6_I and RCP2.6_II, respectively.

Regarding the water temperature, Figs. 33 and 34 present the future water temperature profiles (for RCP2.6_I scenario) of two stations in the lake

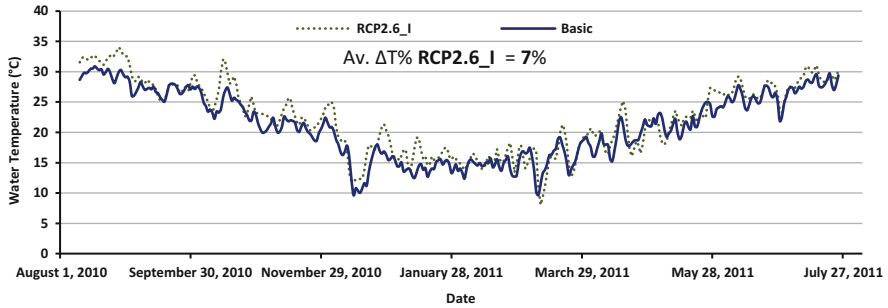


Fig. 33 Water temperature distribution at station No. 2, Manzala Lake, for RCP2.6_I climatic scenarios compared to the basic water levels (of model calibration)

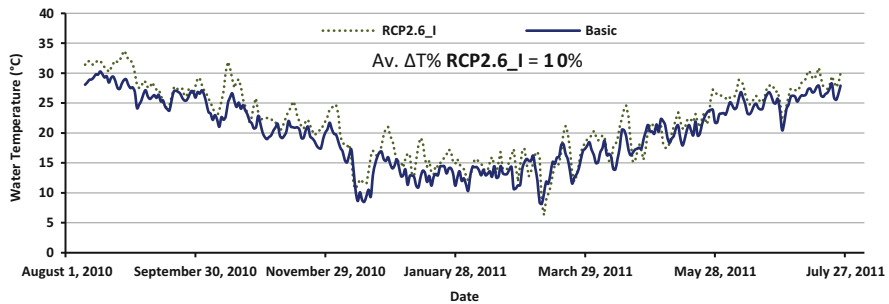


Fig. 34 Water temperature distribution at station No. 6, Manzala Lake, for RCP2.6_I climatic scenarios compared to the basic water levels (of model calibration)

(ST. 2 and ST. 6), as examples, compared to the basic calibrated profile of 2010–2011. Referring to Fig. 2, ST. 2 lies in the northern east corner of the lake in front of the two considered outlets, while ST. 6 lies in the southern middle sector of the lake away from the outlets and the agriculture drains. The future change in the water temperature of the lake is directly proportional to the change in the air temperature and inversely proportional to the change in the SLR. For that, the minimum future average changes in the lake will occur at ST. 2 which will be affected by the change in SLR reducing its effect by the change in air temperature (Fig. 33); the average ΔT will be about 7 and 8%, for RCP2.6_I and RCP2.6_II, respectively. While at ST. 6 where there is no effect to the change in SLR, the maximum change in water temperature can be noticed (Fig. 34); the average ΔT will be about 10 and 12%, for RCP2.6_I and RCP2.6_II, respectively. The future change in the water temperature of the lake is considered as a dangerous impact of climatic changes; this change will affect all the chemical and biological process in the lake which in turn will affect its water quality status and its eutrophic conditions.

Figures 35 and 36 show the future salinity profiles (for RCP2.6_I and RCP2.6_II scenarios) of two stations in the lake (ST. 2 and ST. 8), as examples, compared to the basic calibrated profile of 2010–2011. As mentioned before, two factors control the future change of salinity at any station in the lake: firstly, the change in the future SLR, as the change in salinity is directly proportional to the change in the SLR, and, secondly, the location of the considered station. Referring to Fig. 2, ST. 2 lies in the northern east corner of the lake in front of the two considered outlets, while ST. 8 lies in the southern west sector of the lake away from the outlets. For that, the maximum average ΔS in the lake will occur at ST. 2 (Fig. 35); the average ΔS will be about 81 and 112%, for RCP2.6_I and RCP2.6_II, respectively, due to the significant effect of SLR change at this station. While the minimum change in salinity in the lake will occur at ST. 8 (Fig. 36), the average ΔS will be about -4% and -1%, for RCP2.6_I and RCP2.6_II, respectively, due to the increase in the future water depth and the limited effect of SLR at this station.

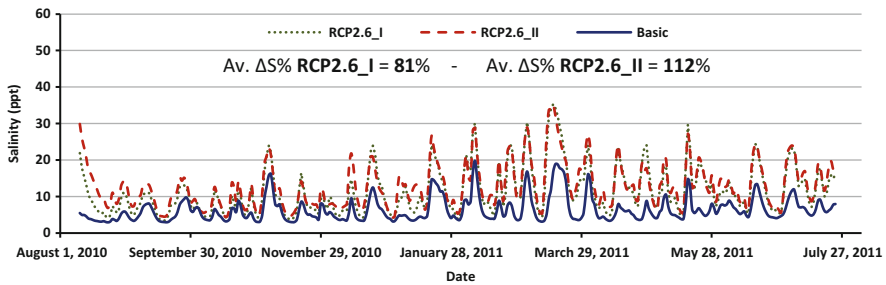


Fig. 35 Water salinity distribution at station No. 2, Manzala Lake, for some selected future climatic scenarios and periods compared to the basic water levels (of model calibration)

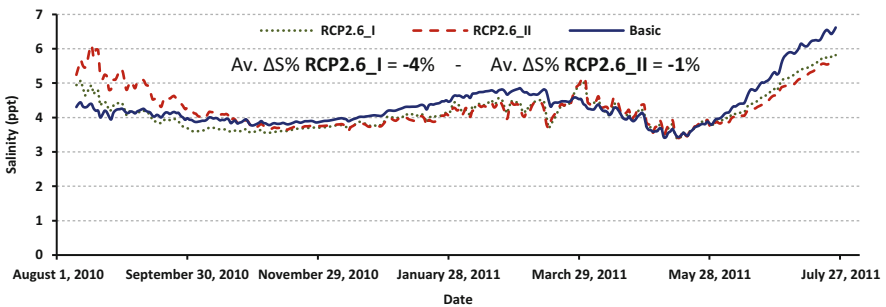


Fig. 36 Water salinity distribution at station No. 8, Manzala Lake, for some selected future climatic scenarios and periods compared to the basic water levels (of model calibration)

10 Conclusions

Lake Manzala, as an example of the Egyptian Northern Delta lakes, was chosen as the case study of this research work. The main objectives of this work were assessing the water quality and trophic status conditions of the lake and investigating the lake vulnerability to future climatic changes. L-WQI and TRIX were used to assess the water quality and trophic status conditions of the lake. The results revealed the critical and very bad water quality status and the high and very high trophic conditions, particularly in the southern and eastern zones due to the drainage of polluted drains. Based on the results of this study, an urgent water quality management for the main drains, particularly Bahr Elbaqar Drain, should be implemented. And the lake should be divided into two sectors, the western and middle sector which can be allocated for fishing, while the eastern and southern sector should be controlled.

Despite the difficulty of modeling this lake, due to the scarce of its hydrological data and the missing water quality data, the two-dimensional hydrodynamic and ecological MIKE 21 modeling system was developed and calibrated with data for 1 year, from August 2010 to July 2011. The proposed model shows good agreement with the observed water depth, water temperature, and salinity records, and the model results closely mimic the measured profiles of the simulated parameters.

The developed model was used to investigate the impacts of expected future climatic changes on the hydrodynamic and water quality characteristics of the lake. Due to the limitations of this modeling approach including the uncertainty in GCMs output, the downscaling approaches, and the hydrodynamic and ecological model, the presented results for this study can be considered as an indication for future climate change impacts and shouldn't be considered as accurate predictions. Two periods (Period I: [2046–2065] and Period II: [2081–2100]) for one Representative Concentration Pathway (RCP2.6), including the average of two downscaled (spatially and temporally) GCMs outputs, were used to derive the model. The global climate change effects are presented relative to the calibrated model results of the year 2010–2011 base case. The presented results show significant spatially changes of water temperature of the lake. Such change will affect physical, chemical, and biological processes in water bodies and, therefore, the concentration of many characteristics. Moreover, severe spatially changes in water depths and salinity concentrations will occur, due to the sea level rise. The increase in water levels and water salinity of the lake will severely affect the surrounding agricultural land by inundation and the quality of these agricultural lands. Suitable crop distribution for the expected land quality should be investigated.

11 Recommendations for Future Work

- A periodic hydrological monitoring program, which records water levels, drains and outlets discharges, and lake bathymetry, should be managed by MWRI (Ministry of Water Resources and Irrigation), to be simultaneously done with the physical, chemical, and biological monitoring program of the EEAA (Egyptian Environmental Affairs Agency).
- An Egyptian regional climatic model should be developed to provide more accurate future climatic estimates for Egypt.
- An adaptation plan including protection works for the Egyptian coastal lakes and surrounding lands should be issued by MWRI and investigated using different climatic and hydrodynamic models.

Acknowledgments This paper originated as part of a project titled “Assessment of vulnerability and adaptation to sea level rise for the Egyptian coastal lakes” and funded by the Alexandria Research Centre for Adaptation (ARCA), Alexandria University, Egypt. The field data for this modeling study were provided by the National Water Research Center (NWRC), Egypt; the Department of Irrigation and Hydraulics Engineering, Faculty of Engineering, Tanta University, Egypt; and the Egyptian Environmental Affairs Agency (EEAA), Egypt, and their help was greatly appreciated. The author extremely thanks the reviewers for their hard work to improve the quality of this work.

References

1. Mehanna SF, Shaker IM, Farouk AE-d (2014) Impacts of excessive fishing effort and heavy metals pollution on the Tilapia production from Lake Manzala. In: 4th conference of central laboratory for aquaculture research, pp 57–74
2. GAFRD (2014) Fish statistics yearbook 2013. General Authority for Fish Resources Development (GAFRD), Cairo, Egypt
3. Khalil MT (1990) The physical and chemical environment of Lake Manzala, Egypt. *Hydrobiologia* 196(3):193–199. <https://doi.org/10.1007/bf00006132>
4. Elshemy M, Khadr M (2015) Hydrodynamic impacts of Egyptian Coastal Lakes due to climate change-example Manzala Lake. In: Eighteenth international water technology conference, IWTC18 Sharm El-Sheikh, Egypt
5. Elshemy M, Khadr M (2015) Hydrodynamic impacts of Egyptian Coastal Lakes due to climate change-example Manzala Lake. *Int Water Technol J* 5(3):235–247
6. Elshemy M, Khadr M, Atta Y, Ahmed A (2016) Hydrodynamic and water quality modeling of Lake Manzala (Egypt) under data scarcity. *Environ Earth Sci* 75(19):1329
7. Elshemy M (2016) Water quality assessment of Lake Manzala, Egypt: a comparative study. *Int J Sci Res Environ Sci* 4(6):196–207. <http://dx.doi.org/10.12983/ijres-2016-p0196-0207>
8. Rashad HM, Abdel-Azeem AM (2010) Lake Manzala, Egypt: a bibliography. *Assiut Univ J Bot* 39(1):253–289
9. El-Bayomy J (1994) Lake Manzala area “Geomorphological Study”. Faculty of Arts, Cairo University, Egypt, Cairo
10. Thompson JR, Flower RJ, Ramdani M (2009) Hydrological characteristics of three North African coastal lagoons: insights from the MELMARINA project. *Hydrobiologia* 622 (1):45–84. <https://doi.org/10.1007/s10750-008-9680-x>

11. Infospace. The Russian Weather Server. <http://meteo.infospace.ru/climate/html/>. Accessed 26 Aug 2017
12. Weather Underground. The Weather Underground Website for Climatic Data. <http://www.wunderground.com/>. Accessed 26 Aug 2017
13. Flower RJ (2001) Change, stress, sustainability and aquatic ecosystem resilience in North African wetland lakes during the 20th century: an introduction to integrated biodiversity studies within the CASSARINA project. *Aquat Ecol* 35(3–4):261–280. <https://doi.org/10.1023/a:1011978420737>
14. Rashed AA, El-refaie GG, El-hawary AM (2007) Assessing the effectiveness of surface wetland treatment system on drainage water quality. In: The National Water Quality and Availability Management Project (NAWQAM), Sharm El-Sheikh, Egypt, pp 1–12
15. El-refaie G (2010) Temperature impact on operation and performance of Lake Manzala Engineered Wetland, Egypt. *Ain Shams Eng J* 1(1):1–9. <https://doi.org/10.1016/j.asej.2010.09.001>
16. Donia N, Hussein M (2004) Eutrophication assessment of Lake Manzala using GIS techniques. In: Eighth international water technology conference, IWTC8 2004, Alexandria, Egypt, pp 393–408
17. Ahmed M, Donia N, Fahmy M (2006) Eutrophication assessment of Lake Manzala, Egypt using geographical information systems (GIS) techniques. *J Hydroinf*:101–109. <https://doi.org/10.2166/hydro.2006.014>
18. OECC (2005) Study report on comprehensive support strategies for environment and development in the early 21st century (Arab Republic of Egypt). Ministry of Environment, Japan
19. Hamed YA, Abdelmoneim TS, ElKiki M, Hassan M, Berndtsson R (2013) Assessment of heavy metals pollution and microbial contamination in water, sediments and fish of Lake Manzala, Egypt. *Life Sci J* 10(1):86–99
20. Arnous MO, Hassan MA (2015) Heavy metals risk assessment in water and bottom sediments of the eastern part of Lake Manzala, Egypt, based on remote sensing and GIS. *Arab J Geosci* 8(10):7899–7918
21. Zahran MAE-K, El-Amier YA, Elnaggar AA, Mohamed HAE-A, El-Alfy MAE-H (2015) Assessment and distribution of heavy metals pollutants in Manzala Lake, Egypt. *J Geosci Environ Protect* 3(06):107
22. El-Amier YA, Elnaggar AA, El-Alfy MA (2016) Investigation of eutrophication state of Manzala and Burullus lakes in Egypt by using remote sensing and GIS. *J Environ Sci Pollut Res* 2(4):121–125
23. El-Hamid HTA, Hegazy TA, Ibrahim MS, Khalid M (2017) Assessment of water quality of the Northern Delta Lakes, Egypt. *J Environ Sci* 46(1):21–34
24. Goher M, Abdo M, Bayoumy W, El-Ashkar TM (2017) Some heavy metal contents in surface water and sediment as a pollution index of El-Manzala Lake, Egypt. *J Basic Environ Sci* 2:210–225
25. Ahmed MH, Leithy BME, Thompson JR (2009) Application of remote sensing to site characterisation and environmental change analysis of North African coastal lagoons. *Hydrobiologia* 622(1):147–171. <https://doi.org/10.1007/s10750-008-9682-8>
26. Dewidar K, Khedr A (2001) Water quality assessment with simultaneous Landsat-5 TM at Manzala Lagoon, Egypt. *Hydrobiologia* 457:49–58. <https://doi.org/10.1023/a:1012281416096>
27. Ibrahim MD (2011) Integration of real time and satellite water quality monitoring systems: case study Lake Manzala, Egypt. Memorial University of Newfoundland, Canada
28. Abayazid H (2015) Assessment of temporal and spatial alteration in Coastal Lakes-Egypt. Paper presented at the eighteenth international water technology conference (IWTC18), Sharm ElSheikh, Egypt, 12–14 Mar 2015
29. Hossen H, Negm AM (2016) Change detection of Manzala Lake using remote sensing and geographic information system. *Egypt Int J Eng Sci Technol* 19(2):353–358

30. Negm AM, Hossen H (2017) Sustainability of water bodies of northern Egyptian Lakes: case studies, Burullus and Manzala Lakes. In: Negm AM (ed) *The Nile Delta*. Springer International Publishing, Cham, pp 455–467. doi: https://doi.org/10.1007/698_2016_65
31. El-Gamal AA (2017) Egyptian Nile Delta coastal lagoons: alteration and subsequent restoration. In: *Coastal Wetlands: alteration and remediation*. Springer, pp 411–434
32. Flower RJ, Thompson JR (2009) Integrated hydro-ecological studies in the MELMARINA project: monitoring and modelling coastal lagoons – making management tools for aquatic resources in north. *Hydrobiologia* 622(1):3–14. <https://doi.org/10.1007/s10750-008-9674-8>
33. Rasmussen EK, Petersen OS (2009) Hydrodynamic-ecological model analyses of the water quality of Lake Manzala (Nile Delta, Northern Egypt). *Hydrobiologia* 622(1):195–220. <https://doi.org/10.1007/s10750-008-9683-7>
34. Bek MA, Lowndes IS, Hargreaves DM (2010) The application of a validated hydrodynamic model to improve the water management of an Egyptian shallow water coastal lake. In: Swayne DA, Wyaavartf (ed) *iEMSSs*, Ottawa, Canada, iEMSSs, pp 1–9
35. Anton-Pardo M, Armengol X (2012) Effects of salinity and water temporality on zooplankton community in coastal Mediterranean ponds. *Estuar Coast Shelf Sci* 114:93–99
36. Hinkel J, Klein RJ (2009) Integrating knowledge to assess coastal vulnerability to sea-level rise: the development of the DIVA tool. *Glob Environ Chang* 19(3):384–395
37. Schallenberg M, Hall CJ, Burns CW (2003) Consequences of climate-induced salinity increases on zooplankton abundance and diversity in coastal lakes. *Mar Ecol Prog Ser* 251:181–189
38. Simas T, Nunes J, Ferreira J (2001) Effects of global climate change on coastal salt marshes. *Ecol Model* 139(1):1–15
39. Ticehurst J (2008) Evolution of an approach to integrated adaptive management: the Coastal Lake Assessment and Management (CLAM) tool. *Ocean Coast Manag* 51(8):645–658
40. El-Raey M (1997) Vulnerability assessment of the coastal zone of the Nile delta of Egypt, to the impacts of sea level rise. *Ocean Coast Manag* 37(1):29–40
41. Frihy OE (2001) The necessity of environmental impact assessment (EIA) in implementing coastal projects: lessons learned from the Egyptian Mediterranean coast. *Ocean Coast Manag* 44(7):489–516
42. Frihy OE, Dewidar KM, El Raey MM (1996) Evaluation of coastal problems at Alexandria, Egypt. *Ocean Coast Manag* 30(2–3):281–295
43. Malm A (2013) Sea wall politics: uneven and combined protection of the Nile Delta coastline in the face of sea level rise. *Crit Socio* 39(6):803–832
44. SWITCH-Project (2007) *Climate change: Alexandria – Egypt*. <http://switchurbanwater.lboro.ac.uk/outputs/>. Accessed 26 Aug 2017
45. Agrawala S, Moehner A, Raey ME, Conway D, Aalst MV, Hagenstad M, Smith J (2004) *Development and climate change in Egypt: focus on coastal resources and the Nile*. OECD, Organisation for Economic Co-operation and Development. OECD, Organisation for Economic Co-operation and Development
46. Dasgupta S, Laplante B, Meisner CM, Wheeler D, Jianping Yan D (2007) *The impact of sea level rise on developing countries: a comparative analysis*. World Bank Policy Research Working Paper 4136, Washington, DC, USA
47. EEAA (2010) *Egypt second national communication under the United Nations Framework Convention on Climate Change*. Egyptian Environmental Affairs Agency (EEAA)
48. Parry ML (2007) *Climate change 2007-impacts, adaptation and vulnerability: working group II contribution to the fourth assessment report of the IPCC, vol 4*. Cambridge University Press
49. Solomon S (2007) *Climate change 2007-the physical science basis: working group I contribution to the fourth assessment report of the IPCC, vol 4*. Cambridge University Press
50. Stocker TF, Qin D, Plattner G-K, Tignor M, Allen SK, Boschung J, Nauels A, Xia Y, Bex V, Midgley PM (2013) *Climate change 2013: the physical science basis. Contribution of working group I to the fifth assessment report of the intergovernmental panel on climate change*, Cambridge Univ. Press, Cambridge, UK, 1535 pp

51. Eldeberky Y, Hünicke B (2015) Vulnerability of the Nile delta to recent and future climate change. In: E-proceedings of the 36th IAHR World Congress
52. Abd-Elhamid H, El-Kilany M, Javadi A (2016) A cost-effective method to protect the coastal regions from sea level rise. A case study: northern coasts of Egypt. *J Water Clim Change* 7 (1):114–127
53. Ali EM, El-Magd IA (2016) Impact of human interventions and coastal processes along the Nile Delta coast, Egypt during the past twenty-five years. *Egypt J Aquat Res* 42(1):1–10
54. Koraim AS, Negm A (2017) Protection methods against sea-level rise caused by climatic change: case study of the Nile Delta coastal zones. *Nile Delta* 397–423
55. Elshinnawy I, Foad IE, Salama I, Issa UH (2017) Impacts of sea level rise on coastal flooding of Nile Delta, Egypt. *Int J Sci Res Sci Eng Technol* 3(2):71–77
56. CORDEX_Project. <http://wcrp-cordex.ipsl.jussieu.fr/>. Accessed 26 Aug 2017
57. Taner MÜ, Üstün B, Erdinçler A (2011) A simple tool for the assessment of water quality in polluted lagoon systems: A case study for Küçükçekmece Lagoon, Turkey. *Ecological Indicators* 11(2):749–756. doi: <https://doi.org/10.1016/j.ecolind.2010.08.003>
58. Ryding S-O, Rast W (1989) The control of eutrophication of lakes and reservoirs. Man and the biosphere series; v. 1. UNESCO and Parthenon Pub. Group, Paris
59. Carlson RE (1977) A trophic state index for lakes. *Limnol Oceanogr* 22(2):361–369
60. Arfi R (2003) The effects of climate and hydrology on the trophic status of Selingue Reservoir, Mali, West Africa. *Lake Reserv Res Manag* 8:247–257
61. Barnwal P, Mishra S, Singhal SK (2015) Risk assessment and analysis of water quality in Ramgarh Lake, India. *J Integr Sci Technol* 3:22–27
62. Chang CL, Liu HC (2015) Applying the back-propagation neural network model and fuzzy classification to evaluate the trophic status of a reservoir system. *Environ Monit Assess* 187:567. <https://doi.org/10.1007/s10661-015-4513-7>
63. Gupta I, Kumar A, Singh C, Kumar R (2015) Detection and mapping of water quality variation in the Godavari River using water quality index, clustering and GIS techniques. *J Geogr Inf Syst* 7:71–84
64. Hassan AA (2000) Evaluation of the eutrophication status in the southern part of Lake Manzala, Egypt. *Sci Bull Fac Eng Ain Shams Univ* 35(1):155–173
65. Koussouris T, Diapoulis A, Bertahas I, Photis G (1991) Evaluating trophic status and restoration procedures of a polluted lake, Lake Kastoria, Greece. *GeoJ* 23:153–161
66. Mullins ML, Whisenant AS (2004) Somerville reservoir water quality study. vol WQTS-2004-02. Texas Parks and Wildlife Department, Austin, TX
67. Thiemann S, Kaufmann H (2000) Determination of chlorophyll content and trophic state of lakes using field spectrometer and IRS-1C satellite data in the Mecklenburg Lake District, Germany. *Remote Sens Environ* 73:227–235
68. Vollenweider RA, Giovanardi F, Montanari G, Rinaldi A (1998) Characterization of the trophic conditions of marine coastal waters with special reference to the NW Adriatic Sea: proposal for a trophic scale, turbidity and generalized water quality index. *Environmetrics* 9:329–357. [https://doi.org/10.1002/\(SICI\)1099-095X\(199805/06\)9:3<329::AID-ENV308>3.0.CO;2-9](https://doi.org/10.1002/(SICI)1099-095X(199805/06)9:3<329::AID-ENV308>3.0.CO;2-9)
69. Giovanardi F, Vollenweider RA (2004) Trophic conditions of marine coastal waters: experience in applying the trophic index TRIX to two areas of the Adriatic and Tyrrhenian seas. *J Limnol* 63(2):199–218
70. Balkis N, Toklu-Aliçli B, Balci M (2012) Evaluation of ecological quality status with the trophic index (TRIX) values in the coastal waters of the gulfs of Erdek and Bandırma in the Marmara Sea. *CdnIntechopenCom*
71. Chen Y, Niu Z, Zhang H (2013) Eutrophication assessment and management methodology of multiple pollution sources of a landscape lake in North China. *Environ Sci Pollut Res* 20:3877–3889. <https://doi.org/10.1007/s11356-012-1331-0>

72. Christia C, Giordani G, Papastergiadou E (2014) Assessment of ecological quality of coastal lagoons with a combination of phyto-benthic and water quality indices. *Mar Pollut Bull* 86:411–423. <https://doi.org/10.1016/j.marpolbul.2014.06.038>
73. Pavlidou A, Simbora N, Rousselaki E, Tsapakis M, Pagou K, Drakopoulou P, Assimakopoulou G, Kontoyiannis H, Panayotidis P (2015) Methods of eutrophication assessment in the context of the water framework directive: examples from the Eastern Mediterranean coastal areas. *Cont Shelf Res* 108:156–168. <https://doi.org/10.1016/j.csr.2015.05.013>
74. Primpas I, Karydis M (2011) Scaling the trophic index (TRIX) in oligotrophic marine environments. *Environ Monit Assess* 178:257–269. <https://doi.org/10.1007/s10661-010-1687-x>
75. Vargas-González HH, Arreola-Lizárraga JA, Mendoza-Salgado RA, Méndez-Rodríguez LC, Lechuga-Deveze CH, Padilla-Arredondo G, Cordoba-Matson M (2014) Effects of sewage discharge on trophic state and water quality in a coastal ecosystem of the Gulf of California. *Sci World J* 2014:7
76. Zoriasatein N, Jalili S, Poor F (2013) Evaluation of ecological quality status with the trophic index (TRIX) values in coastal area of Arvand, northeastern of Persian gulf, Iran. *World Journal of Fish and Marine. Sciences* 5:257–262. <https://doi.org/10.5829/idosi.wjfm.2013.05.03.7297>
77. DHI (2012) MIKE 21 flow model: user guide. DHI. <http://www.mikebydhi.com/products/mike-21>. Accessed 26 Aug 2017
78. DELFT3D by Deltares. <https://www.deltares.nl/en/software/delft3d-4-suite/>. Accessed 26 Aug 2017
79. MOHID. <http://www.mohid.com/index.html>. Accessed 26 Aug 2017
80. Siah SJ (1997) Applications of hydrodynamic models in Chinese Taipei. Paper presented at the proceedings of the first workshop on ocean models for the APEC regions (WOM-1), Taipei, Taiwan, 9–12 Dec
81. EPA (1994) Establishment of major engineering databanks and marine assimilative capacity evaluation models along Taiwan shorelines
82. Cox BA (2003) A review of currently available in-stream water-quality models and their applicability for simulating dissolved oxygen in lowland rivers. *Sci Total Environ* 314:335–377
83. Wang Q, Li S, Jia P, Qi C, Ding F (2013) A review of surface water quality models. *Sci World J* 2013:1–7. <https://doi.org/10.1155/2013/231768>. Hindawi Publishing Corporation
84. Daly R, Wallace T (2015) River Murray channel environmental water requirements. In: Goyder Institute Water Research Conference 2015, Australia
85. Jusoh WHW, Tangang F, Juneng L, Hamid MRA (2014) Numerical modeling of hydrodynamic in southwestern Johor, Malaysia. Paper presented at the 2014 UKM FST Postgraduate Colloquium, Selangor, Malaysia
86. Kaiglová J, Langhammer J, Jiř P, Janský B, Chalupová D (2014) Numerical modelling of fine-grained sediments remobilization in heavily polluted streams. Case study: Elbe and Bílina River, Czech Republic. Paper presented at the EGU General Assembly 2014, Vienna, Austria
87. Lopes JF, Dias JM, Cardoso aC, Silva CIV (2005) The water quality of the Ria de Aveiro lagoon, Portugal: from the observations to the implementation of a numerical model. *Mar Environ Res* 60(5):594–628. <https://doi.org/10.1016/j.marenvres.2005.05.001>
88. Min JH (2007) Two-dimensional (depth-averaged) modeling of flow and phosphorus dynamics in constructed wetlands. University of Florida
89. Paliwal R, Patra RR (2011) Applicability of MIKE 21 to assess temporal and spatial variation in water quality of an estuary under the impact of effluent from an industrial estate. *Water Sci Technol* 63(9):1932–1943
90. Panda US, Mohanty PK (2008) Monitoring and Modelling of Chilika environment using remote sensing data. Paper presented at the Taal 2007: the 12th World Lake Conference, Jaipur, Rajasthan, India

91. Petersen G, Fohrer N (2010) Two-dimensional numerical assessment of the hydrodynamics of the Nile swamps in southern Sudan. *Hydrol Sci J* 55(1):17–26. <https://doi.org/10.1080/02626660903525252>
92. Rasmussen EK, Petersen OS (2009) Model analyses of the future water quality of the eutrophicated Ghar El Melh lagoon (Northern Tunisia). *Hydrobiologia* 622(1):173–193. <https://doi.org/10.1007/s10750-008-9681-9>
93. Hosseinzadeh Y, Saghaian B, Bakhtiary A (2013) Impact assessment of periodical variation discharges on water quality of Anzali wetland. *Switzerland Res Park J* 102(4):228–234
94. Karim F, Dutta D, Marvanek S, Ticehurst C, Petheram C (2013) Hydrodynamic modelling of potential impacts of climate change on hydrological connectivity of floodplain wetland. Paper presented at the 20th international congress on Modelling and simulation, Adelaide, Australia
95. Zhao YW, Xu MJ, Xu F, Wu SR, XA Y (2014) Development of a zoning-based environmental–ecological coupled model for lakes: a case study of Baiyangdian Lake in northern China. *Hydrol Earth Syst Sci* 18(6):2113–2126. <https://doi.org/10.5194/hess-18-2113-2014>
96. Assar W, Elshemy M, Zeidan B (2015) Water quality modeling for Lake Burullus, Egypt, part I: model calibration *Mansoura Eng J* 40(2)
97. Ayache F, Thompson JR, Flower RJ, Boujarra a RF, Makina H (2009) Environmental characteristics, landscape history and pressures on three coastal lagoons in the southern Mediterranean region: Merja Zerga (Morocco), Ghar El Melh (Tunisia) and Lake Manzala (Egypt). *Hydrobiologia* 622(1):15–43. <https://doi.org/10.1007/s10750-008-9676-6>