The Handbook of Environmental Chemistry 72

Series Editors: Damià Barceló · Andrey G. Kostianoy

Abdelazim M. Negm
Mohamed Ali Bek
Sommer Abdel-Fattah *Editors*

Egyptian Coastal Lakes and Wetlands: Part II

Climate Change and Biodiversity

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Aims and Scope

Since 1980, *The Handbook of Environmental Chemistry* has provided sound and solid knowledge about environmental topics from a chemical perspective. Presenting a wide spectrum of viewpoints and approaches, the series now covers topics such as local and global changes of natural environment and climate; anthropogenic impact on the environment; water, air and soil pollution; remediation and waste characterization; environmental contaminants; biogeochemistry; geo-ecology; chemical reactions and processes; chemical and biological transformations as well as physical transport of chemicals in the environment; or environmental modeling. A particular focus of the series lies on methodological advances in environmental analytical chemistry.

Series Preface

With remarkable vision, Prof. Otto Hutzinger initiated *The Handbook of Environmental Chemistry* in 1980 and became the founding Editor-in-Chief. At that time, environmental chemistry was an emerging field, aiming at a complete description of the Earth's environment, encompassing the physical, chemical, biological, and geological transformations of chemical substances occurring on a local as well as a global scale. Environmental chemistry was intended to provide an account of the impact of man's activities on the natural environment by describing observed changes.

While a considerable amount of knowledge has been accumulated over the last three decades, as reflected in the more than 70 volumes of *The Handbook of Environmental Chemistry*, there are still many scientific and policy challenges ahead due to the complexity and interdisciplinary nature of the field. The series will therefore continue to provide compilations of current knowledge. Contributions are written by leading experts with practical experience in their fields. *The Handbook of Environmental Chemistry* grows with the increases in our scientific understanding, and provides a valuable source not only for scientists but also for environmental managers and decision-makers. Today, the series covers a broad range of environmental topics from a chemical perspective, including methodological advances in environmental analytical chemistry.

In recent years, there has been a growing tendency to include subject matter of societal relevance in the broad view of environmental chemistry. Topics include life cycle analysis, environmental management, sustainable development, and socio-economic, legal and even political problems, among others. While these topics are of great importance for the development and acceptance of *The Handbook of Environmental Chemistry*, the publisher and Editors-in-Chief have decided to keep the handbook essentially a source of information on "hard sciences" with a particular emphasis on chemistry, but also covering biology, geology, hydrology and engineering as applied to environmental sciences.

The volumes of the series are written at an advanced level, addressing the needs of both researchers and graduate students, as well as of people outside the field of "pure" chemistry, including those in industry, business, government, research establishments, and public interest groups. It would be very satisfying to see these volumes used as a basis for graduate courses in environmental chemistry. With its high standards of scientific quality and clarity, *The Handbook of Environmental Chemistry* provides a solid basis from which scientists can share their knowledge on the different aspects of environmental problems, presenting a wide spectrum of viewpoints and approaches.

The Handbook of Environmental Chemistry is available both in print and online via www.springerlink.com/content/110354/. Articles are published online as soon as they have been approved for publication. Authors, Volume Editors and Editors-in-Chief are rewarded by the broad acceptance of *The Handbook of Environmental Chemistry* by the scientific community, from whom suggestions for new topics to the Editors-in-Chief are always very welcome.

Damià Barceló
Andrey G. Kostianoy
Editors-in-Chief

Preface

Egyptian Northern Coastal lakes (Mariout or Mariut, Edku or Edko or Idku, Burullus or Borollus, Manzala and Bardawil) could be a source of wealth for Egypt if the Egyptian and the concerning authorities intend, plan, and implement the needed measures to keep the lakes sustainable. Therefore, *The Egyptian Coastal Lakes and Wetlands* in two volumes is produced by the Egyptian researchers and scientists to help and support who are interested in these lakes. This second volume is divided into four parts consisting of 11 chapters written by 14 authors. It focuses on climate change, biodiversity, zooplankton, fish and fisheries, water quality modeling, and remote sensing applications.

Part I of this volume consists of three chapters dealing with the impacts of climate change and water quality modeling. In the chapter titled "Environmental and Climatic Implications of Lake Manzala, Egypt: Modeling and Assessment," the author presents the results of water quality modeling for Lake Manzala and their assessment and their connections to climate change. On the other hand, the chapter "Modeling of Water Quality Parameters in Manzala Lake Using Adaptive Neuro-Fuzzy Inference System and Stochastic Models" discusses the capabilities of Adaptive Neuro-Fuzzy Inference System (ANFIS) and stochastic models in prediction of water quality parameters based on field measurements in Manzala Lake. The use of ANFIS proved its effectiveness as a simple tool to predict water quality parameters and for onsite water quality parameters' evaluation. The chapter titled "Investigating the Impacts of Dredging on Improving the Water Quality and Circulation of Lake Mariout via Hydrodynamics" presents the results of hydrodynamics modeling of Lake Mariout based on testing different scenarios of deepening the lake bottom to improve circulation and the water quality.

Part II consists of four chapters dealing with the biodiversity, fish, and fisheries in Egyptian Coastal Lakes. The chapter "Environmental Impacts on Egyptian Delta Lakes Biodiversity: A Case Study on Lake Burullus" presents the status of biodiversity of the coastal Lakes and how it was affected by the degraded water quality of the lakes with a focus on Lake Burullus. In the chapter titled "Coastal Lakes as

Hot Spots for Plant Diversity in Egypt," the authors provide very useful information on landforms and morphometry, sediment and water characteristics, plant diversity and threatened species, conservation measures, and goods and services that the lakes offer as hot spot for plant diversity and nature conservation. The chapter is highly useful for decision makers to evaluate and valuate this ecosystem for biodiversity conservation. The third chapter of Part II titled "Responses of Zooplankton to Long-Term Environmental Changes in the Egyptian Coastal Lakes" presents zooplankton population dynamics including similarities and differences. It also discusses the zooplankton and environmental changes of coastal lakes and discusses the linking between zooplankton and fisheries. The last chapter of Part II is titled "Fisheries of Egyptian Delta Coastal Wetlands; Burullus Wetland Case Study." It presents fish species composition and biodiversity in delta wetlands (coastal lakes), fish production rates and quantities, fishing gears and techniques, and fisheries. Additionally, some management measures for decision/policy makers are recommended.

Part III contains three chapters on the remote sensing application to the Egyptian coastal lakes. The chapter titled "Earth Observations for Egyptian Coastal Lakes Monitoring and Management" describes geomorphological properties of the lakes and uses the RS/GIS to map lakes' boundaries and to detect the coastal changes. Also, the chapter presents how the water quality of the lakes and both physicochemical parameters and biological component (Chl-a) using RS/GIS are evaluated. The simulation of the climatic changes and prediction of the impacts are discussed. The chapter presents a future plan for decision/policy makers for rehabilitation and management of the coastal lakes. The chapter "Are the Egyptian Coastal Lakes Sustainable? A Comprehensive Review Based on Remote Sensing Approach" presents the up-to-date investigations and their findings connected to the applications of the remote sensing to detect the land use and land changes (among other applications) of the coastal lakes and discuss whether the water bodies of the lakes are sustainable or not. In the last chapter of this part "Changes in a Coastal Lake Dynamic System and Potential Restoration," the author discusses the aspects contributing to the changing structure of coastal lakes and the governing factors responsible for the declining dynamic system. Monitoring temporal and spatial changes of Burullus lake are presented based on the applications of the remote sensing technique and the use of the water quality index to assess the status of the lake.

Part IV summarizes the key points and the conclusions of the volume and presents a set of recommendations for future studies and to help the decision takers to take the necessary measures to develop, restore the lakes ecology, and keep them sustainable to support the Egyptian economy.

The editors would like to express their special thanks to all the authors who had contributed to this volume. Without their patience and effort in writing and revising the different versions to satisfy the high-quality standards of Springer, it would not have been possible to produce this volume and make it a reality. Great appreciation to all who contributed in one way or another to make this high-quality volume a real source of knowledge and with the latest findings in the field summarized to support

graduate students, researchers, scientists, and decision/policy makers in Egypt and everywhere who are interested in the coastal lakes. Acknowledgements must be extended to include all members of the Springer team who had worked hard for a long time to produce this high-quality unique volume.

The volume editor would be happy to receive any comments to improve future editions. Comments, feedback, suggestions for improvement, or new chapters for next editions are welcomed and should be sent directly to the volume editor.

Zagazig, Egypt — Abdelazim M. Negm
Tanta, Egypt — Mohamed Ali Bek
Hamilton, ON, Canada — Sommer Abdel-Fattah
14 April 2018

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Part III Remote Sensing Applications and Potential Restoration of Lakes

Part IV Conclusions

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

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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.

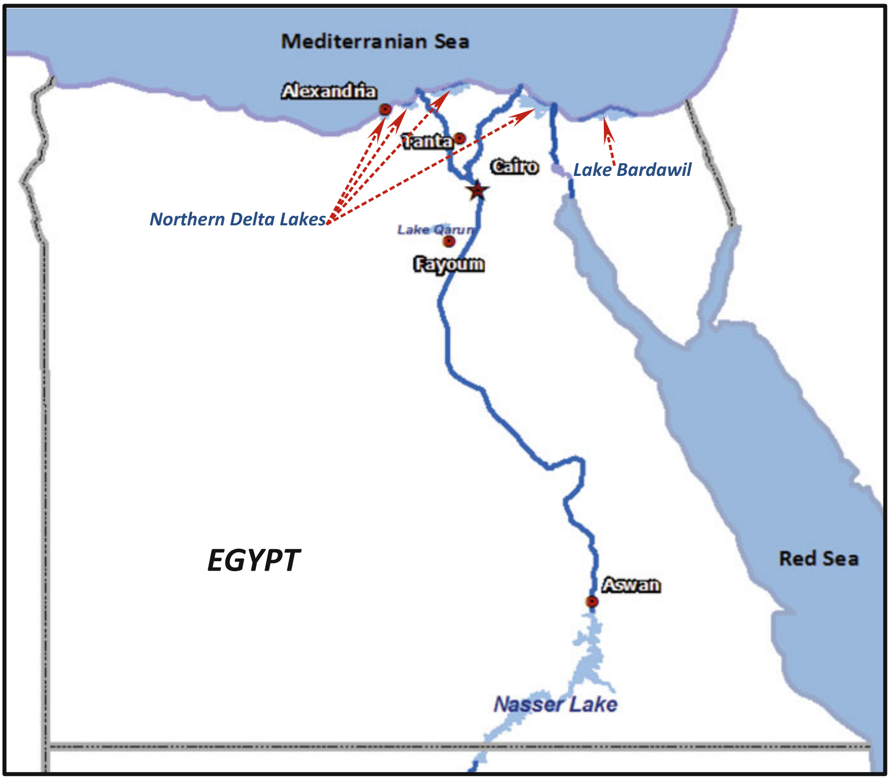

Fig. 1 Layout of Egyptian coastal lakes

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

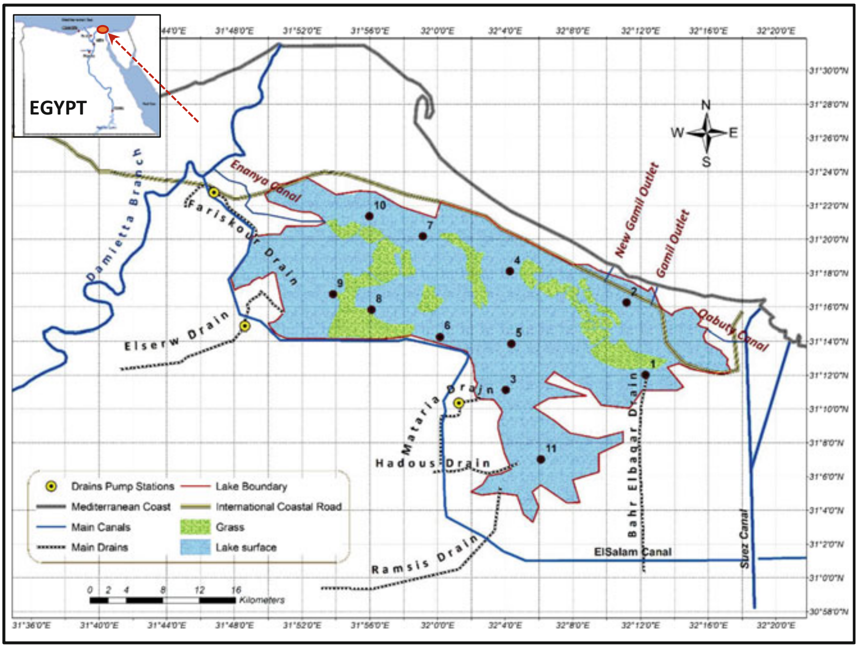

Fig. 2 Study area layout and field record stations

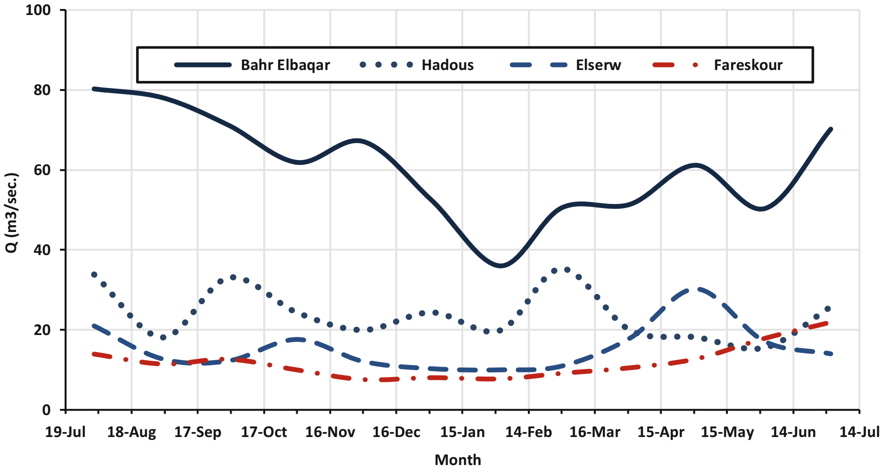

Fig. 3 Typical drains inflow in Lake Manzala

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.

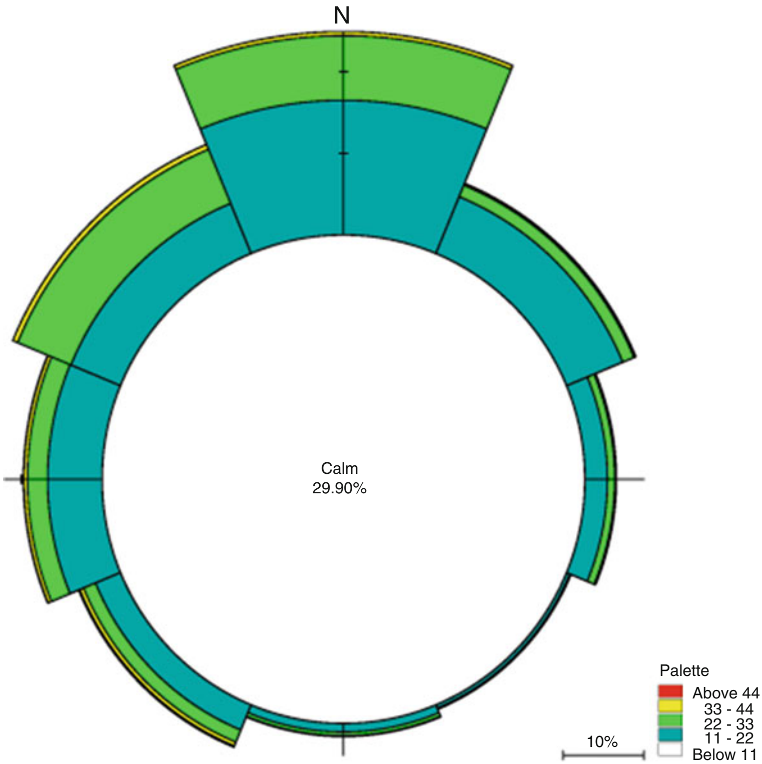

Fig. 4 Typical wind rose at Lake Manzala

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);

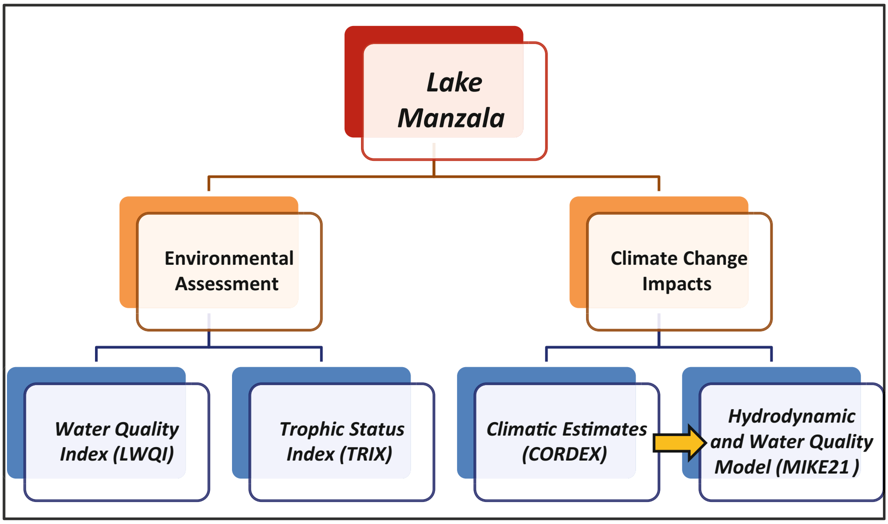

Fig. 5 Methodology approaches for the current research

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:

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

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

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:

$$\mathrm{TRIX} = (\log_{10}[\text{Chl-a} \times \mathrm{DO\%} \times \mathrm{minN} \times \mathrm{TPO_4}] + a)/b \tag{3}$$

Where:

Chl-a is chlorophyll-a concentration (μg/l).

DO% is oxygen as absolute % deviation from saturation.

min N is total dissolved inorganic nitrogen (DIN = N-NO_3 + N-NO_2 + N-NH_4) (μg/l).

TPO_4 is total inorganic phosphorus (P-PO_4) (μg/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

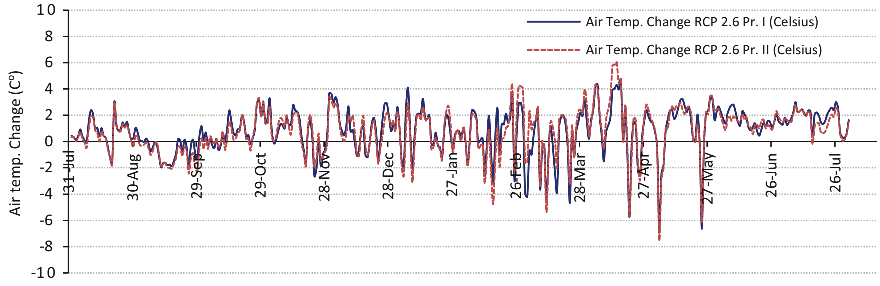

Fig. 6 Daily average changes for the study area in air temperature (Celsius) relative to 2010–2011 for RCP 2.6 scenario and for different periods

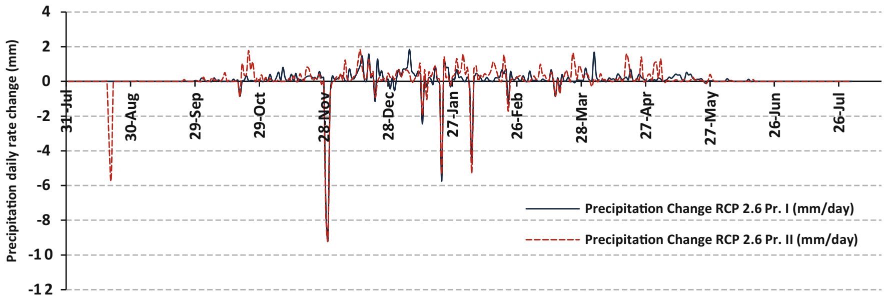

Fig. 7 Daily average changes for the study area in precipitation rate (mm) relative to 2010–2011 for RCP 2.6 scenario and for different periods

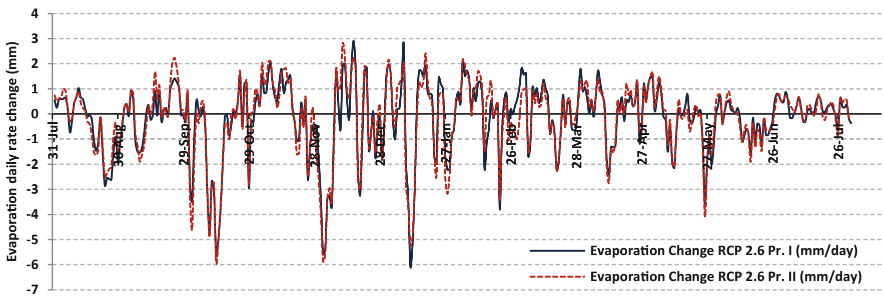

Fig. 8 Daily average changes for the study area in evaporation rate (mm) relative to 2010–2011 for RCP 2.6 scenario and for different periods

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.

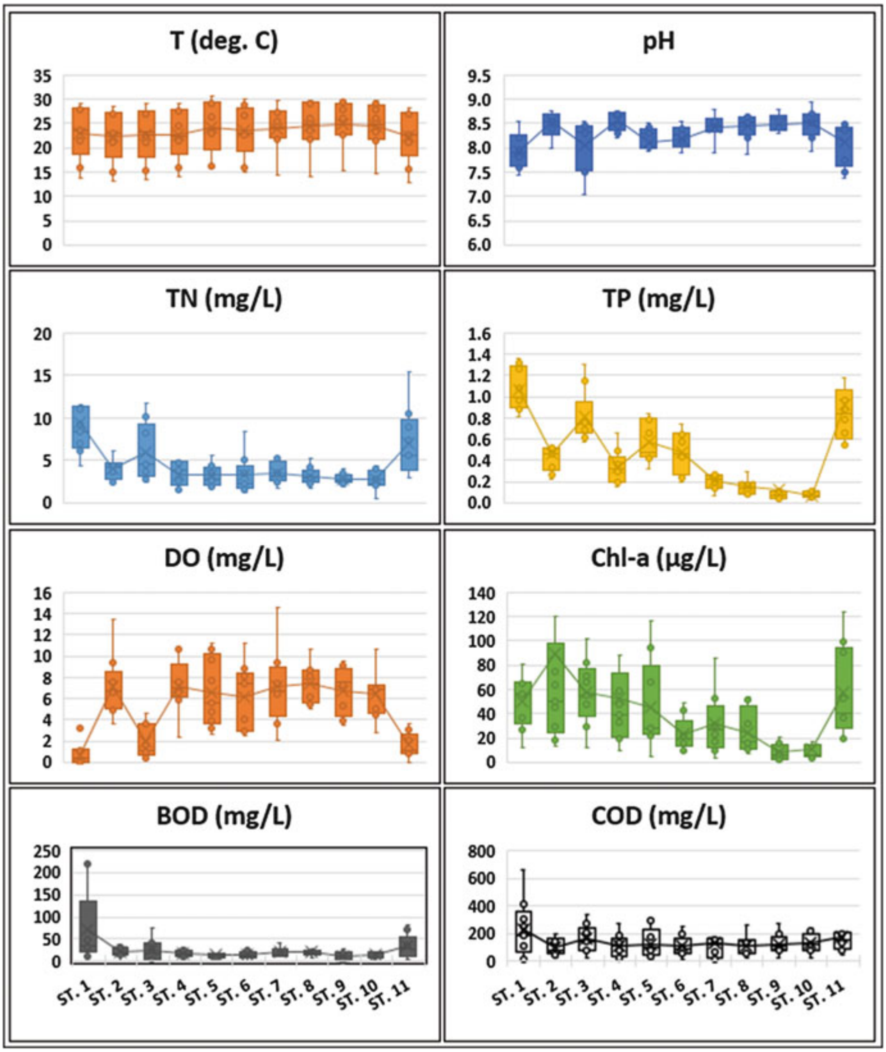

Fig. 9 Measured water quality records at different stations in Lake Manzala during the study period (Aug. 2010–Aug. 2012)

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."

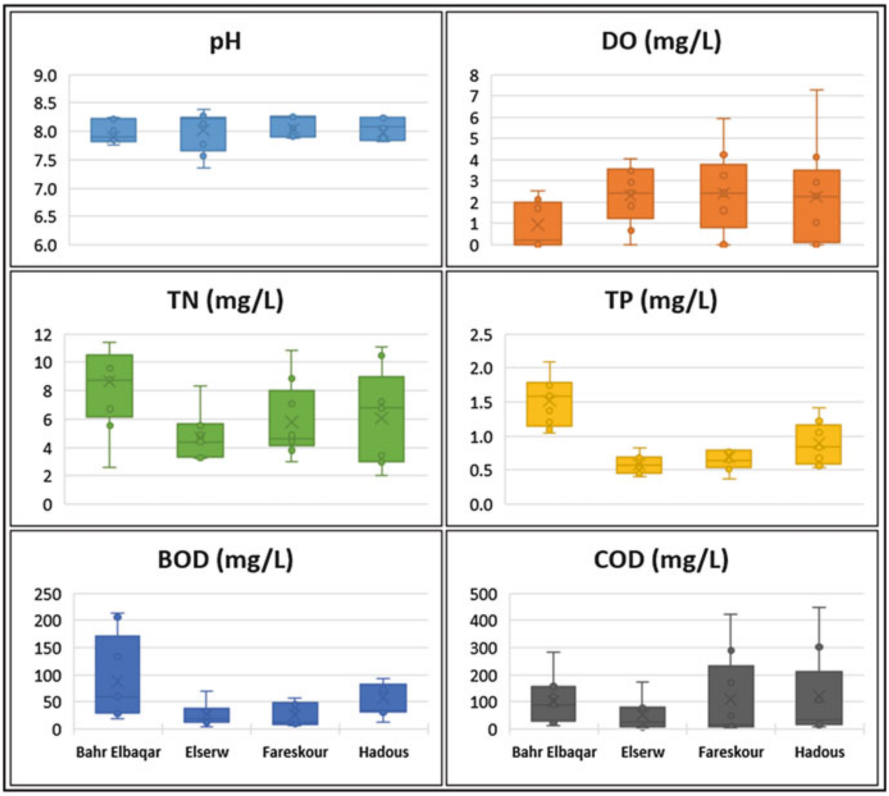

Fig. 10 Measured water quality records of the main drains at Lake Manzala during the study period (Aug. 2010–Aug. 2012)

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

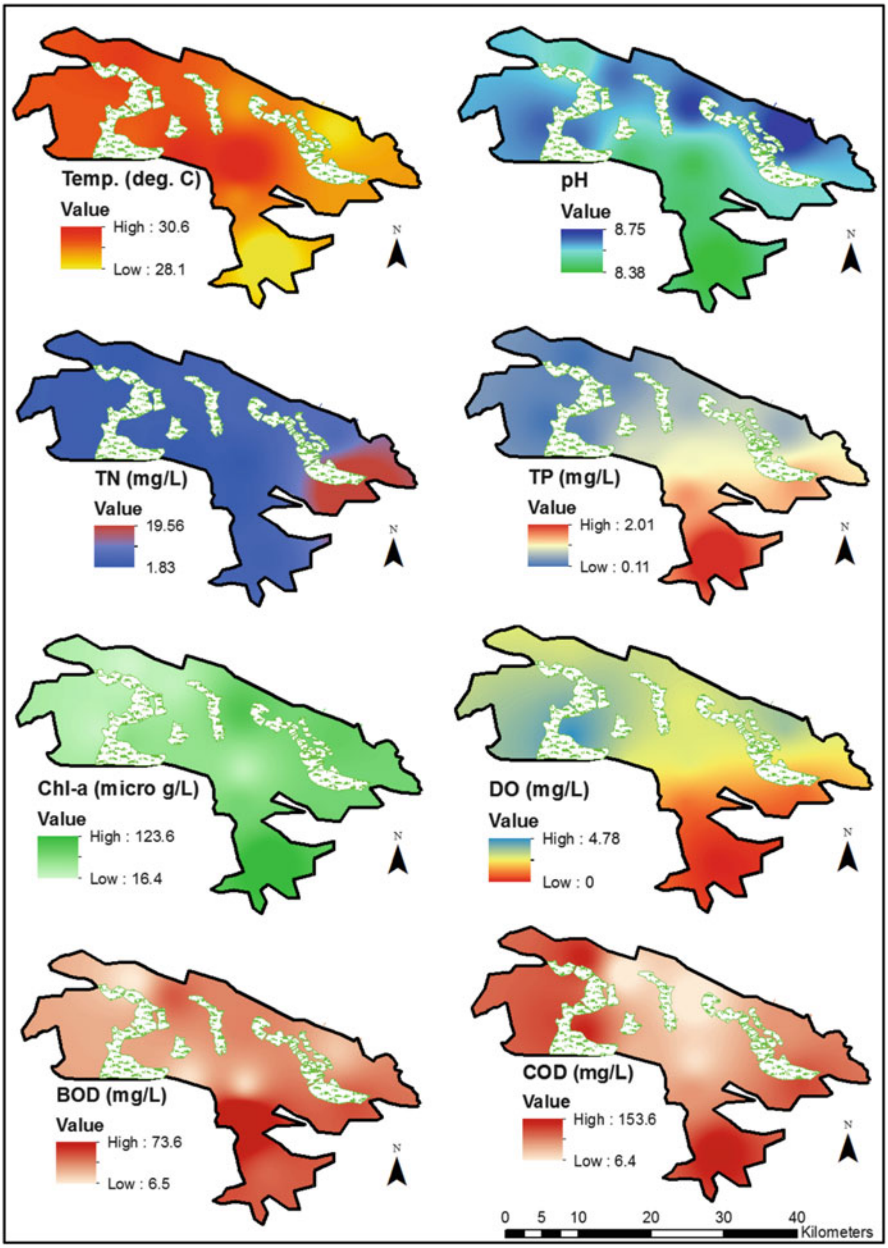

Fig. 11 Measured water quality records of Lake Manzala in Aug. 2011

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.

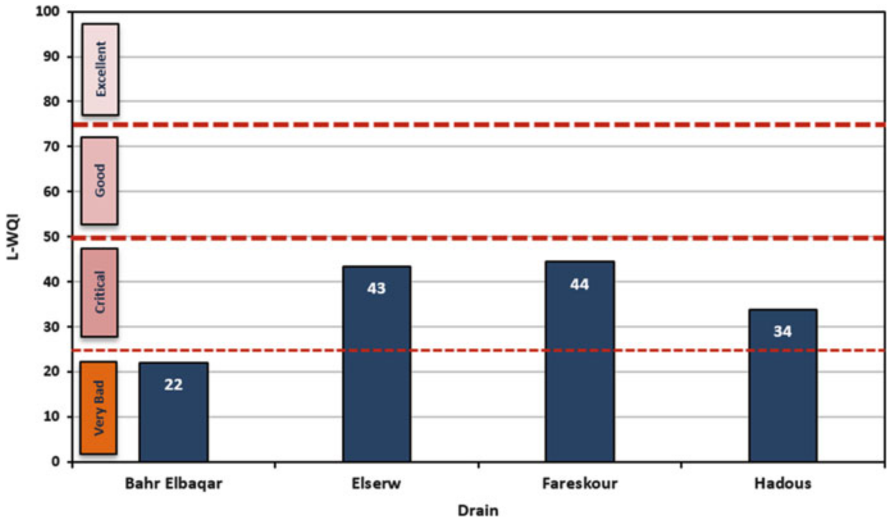

Fig. 12 Averages of L-WQI for the main drains of Lake Manzala during the study period (Aug. 2010–Aug. 2012)

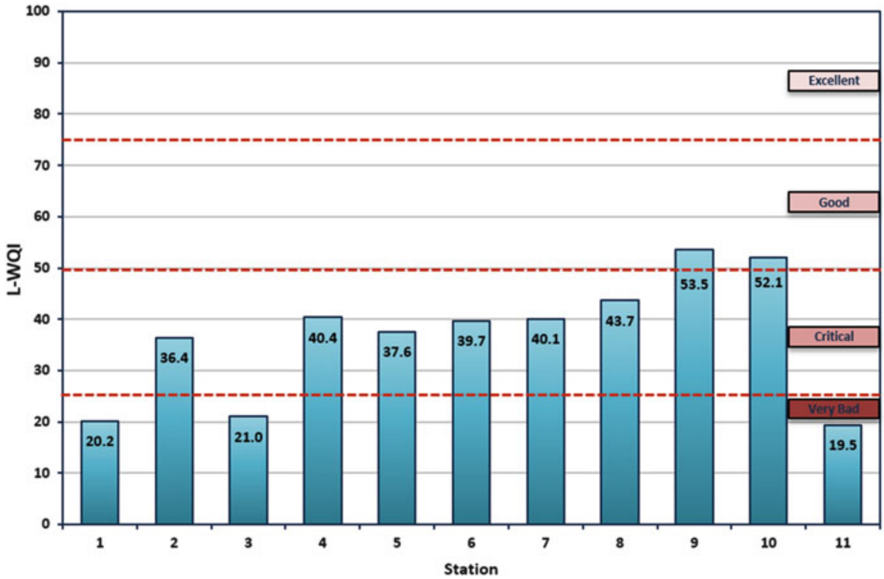

Fig. 13 Spatial averages of L-WQI at different stations in Lake Manzala during the study period (Aug. 2010–Aug. 2012)

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

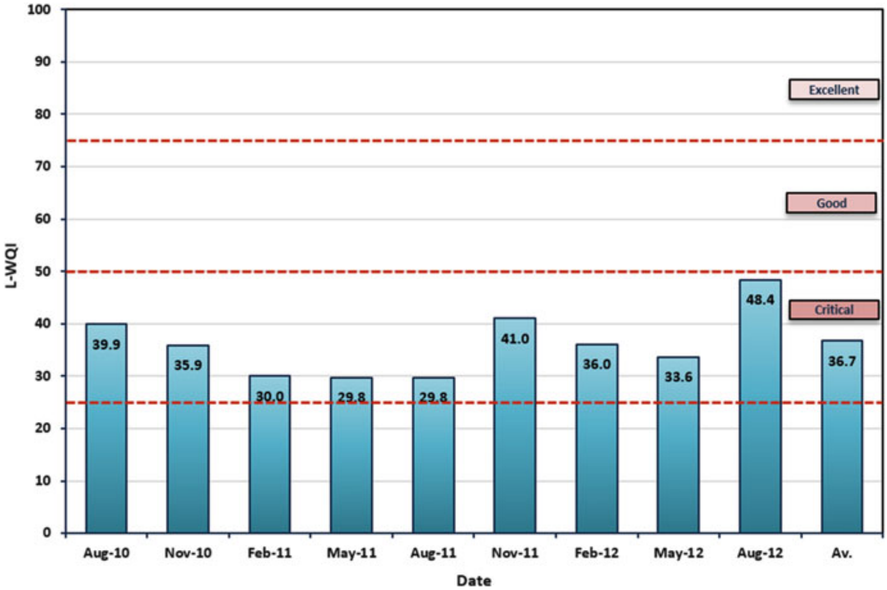

Fig. 14 Temporal averages of L-WQI for Lake Manzala during the study period (Aug. 2010–Aug. 2012)

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.

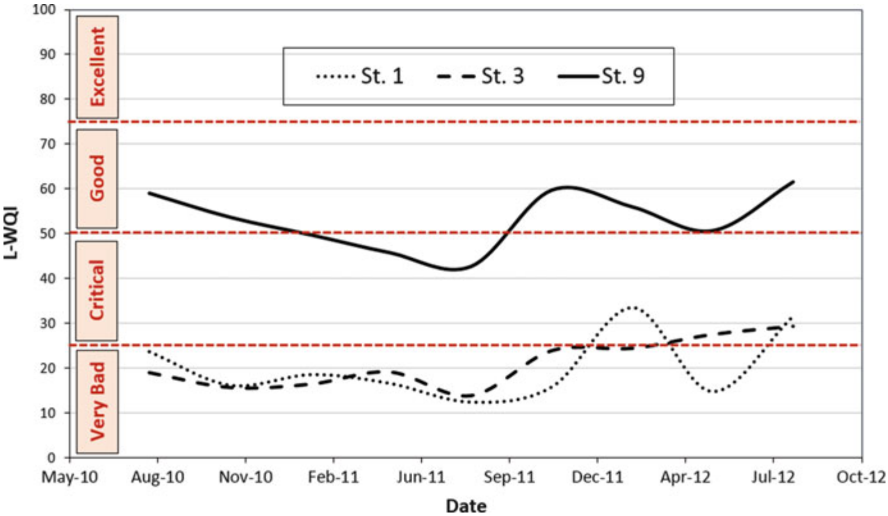

Fig. 15 Temporal distribution of L-WQI at stations No. 1, 3, and 9 in Lake Manzala during the study period (Aug. 2010–Aug. 2012)

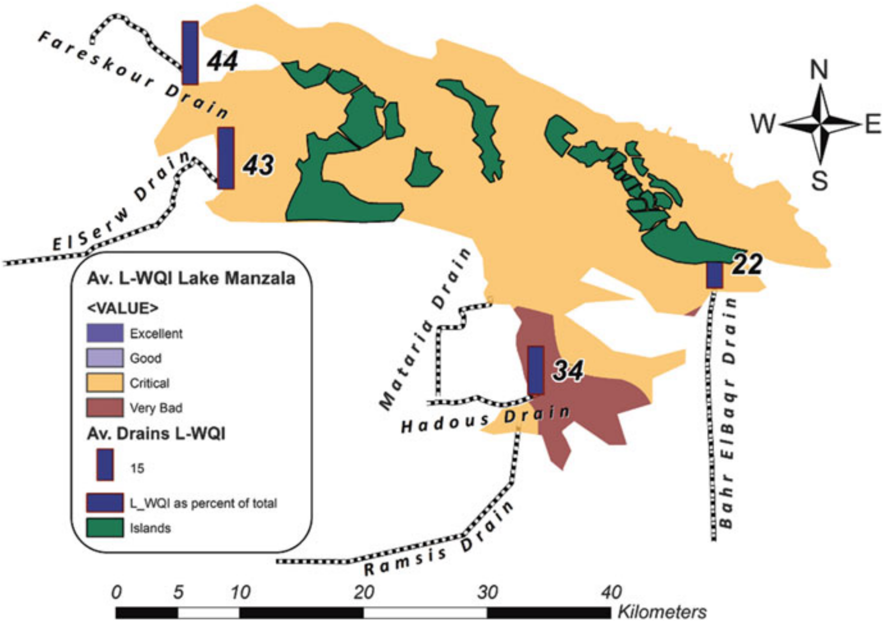

Fig. 16 Spatial distribution of average L-WQI for Lake Manzala during the study period (Aug. 2010–Aug. 2012)

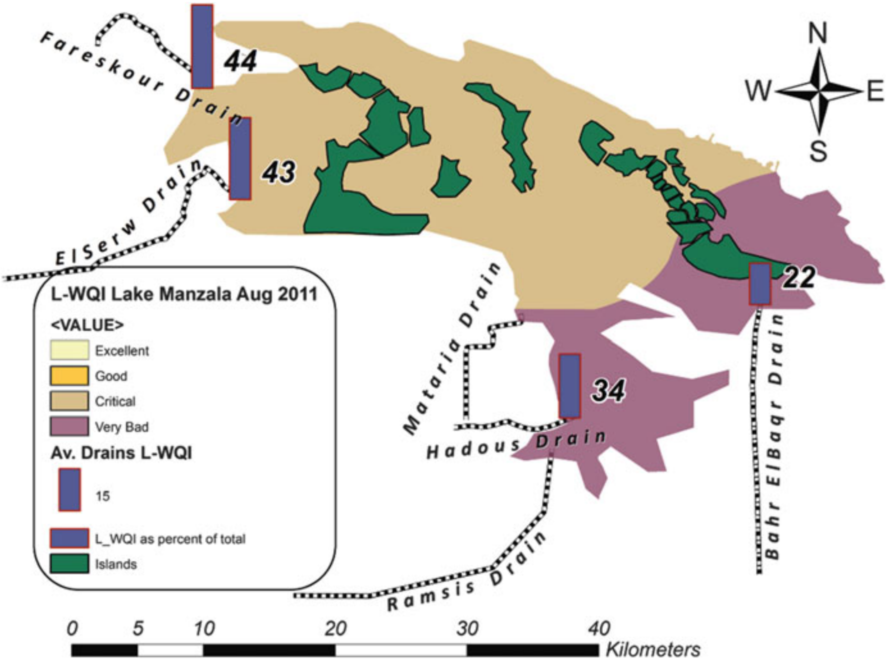

Fig. 17 Spatial distribution of L-WQI for Lake Manzala in August 2011

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].

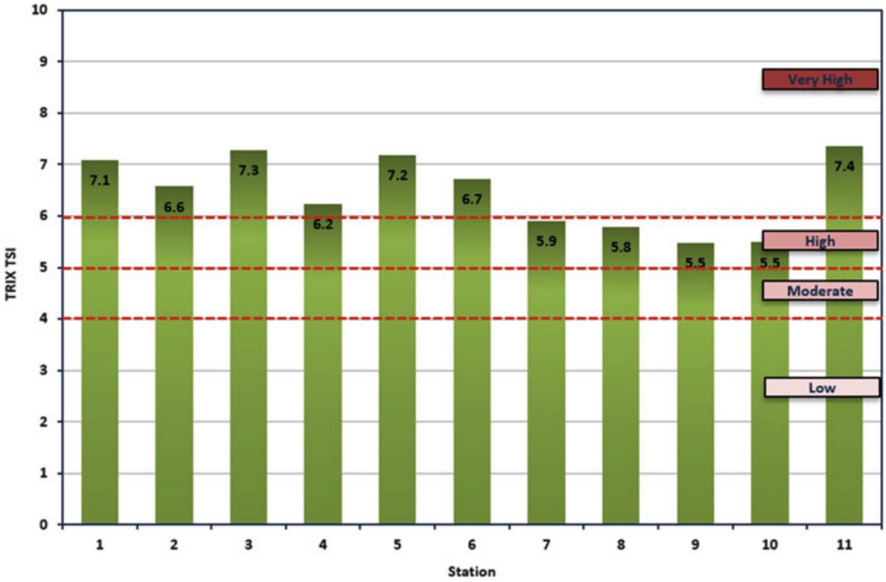

Fig. 18 Spatial averages of TRIX at different stations in Lake Manzala during the study period (Aug. 2010–Aug. 2012)

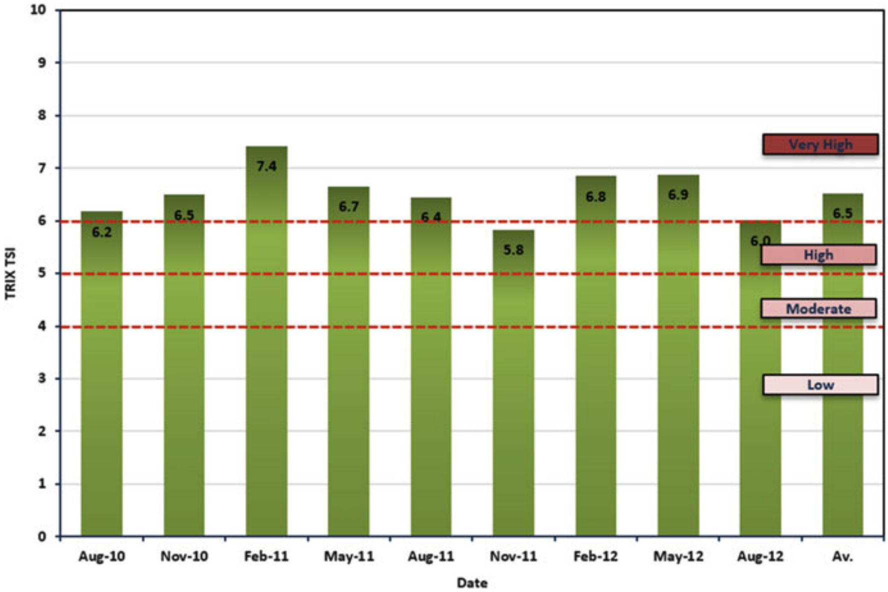

Fig. 19 Temporal averages of TRIX for Lake Manzala during the study period (Aug. 2010–Aug. 2012)

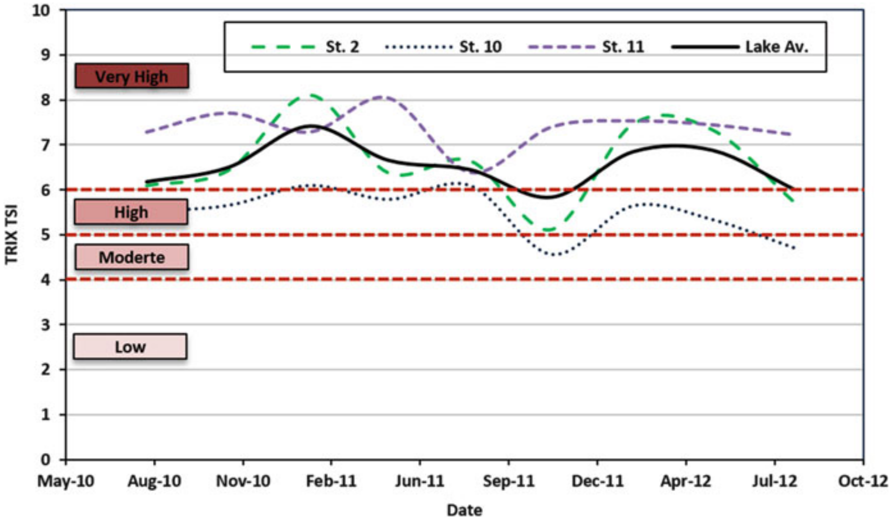

Fig. 20 Temporal distribution of TRIX at stations No. 1, 3, and 9 in Lake Manzala during the study period (Aug. 2010–Aug. 2012)

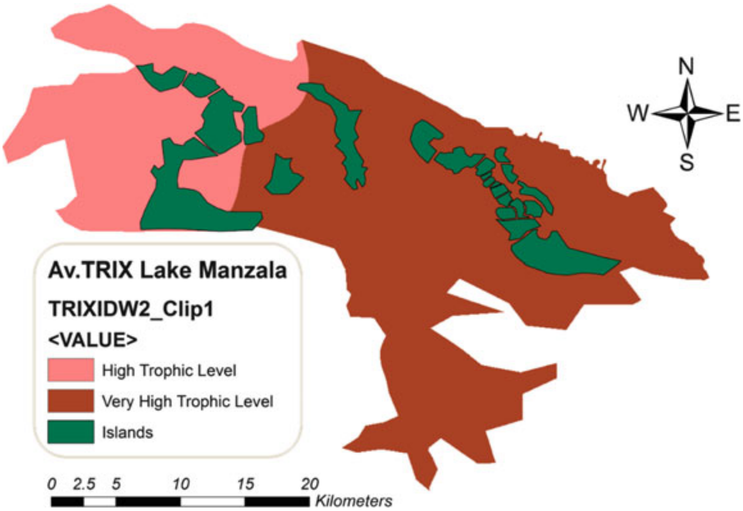

Fig. 21 Spatial distribution of average TRIX for Lake Manzala during the study period (Aug. 2010–Aug. 2012)

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

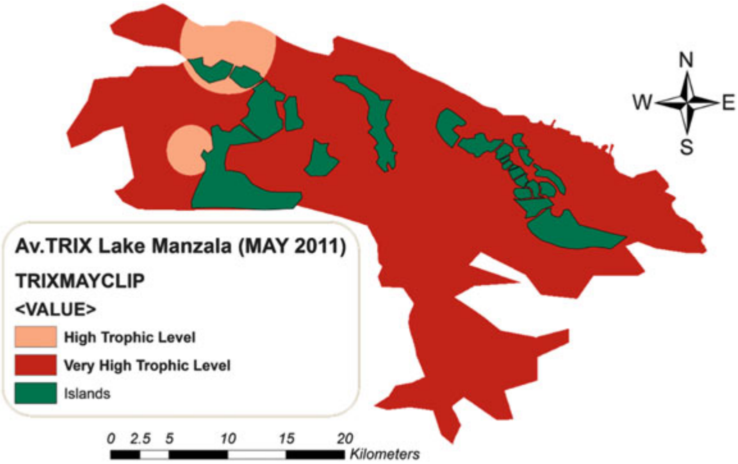

Fig. 22 Spatial distribution of TRIX for Lake Manzala in May 2011

(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 $\times$ 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

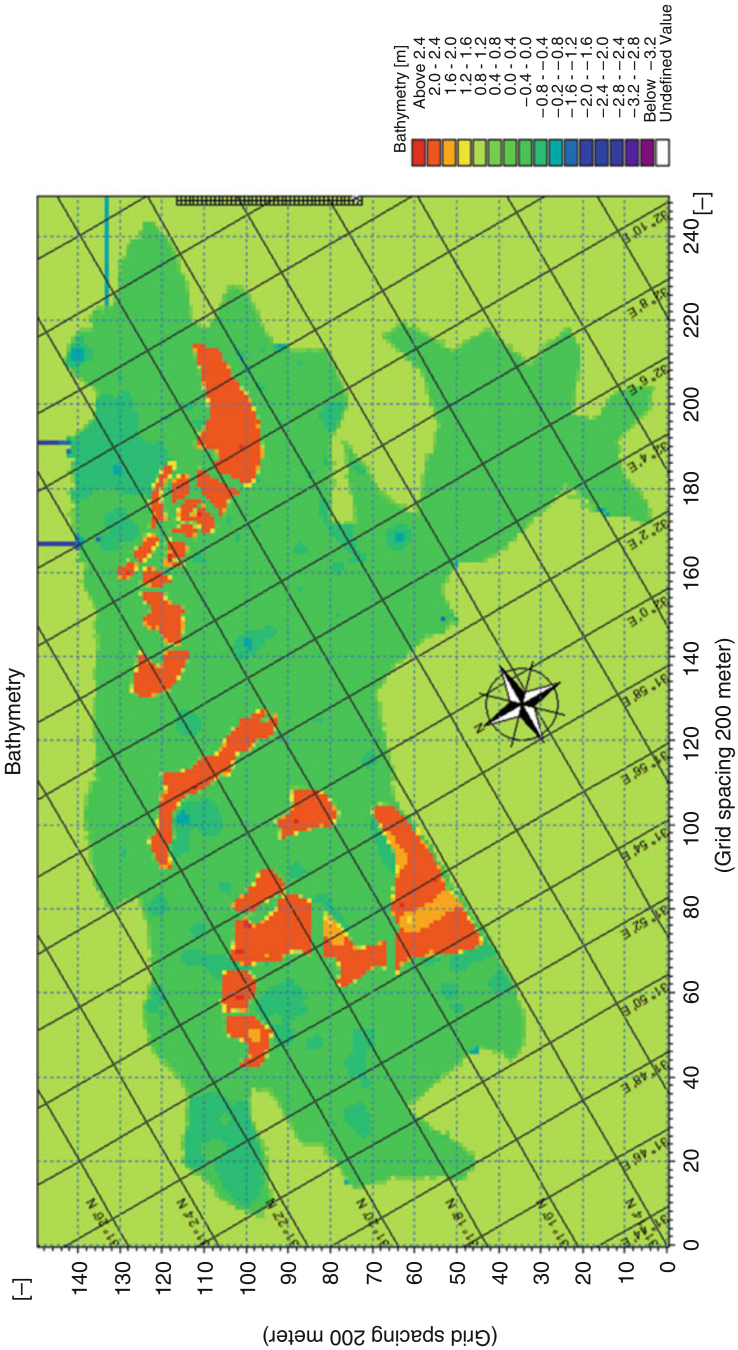

Fig. 23 Developed bathymetry for Lake Manzala model

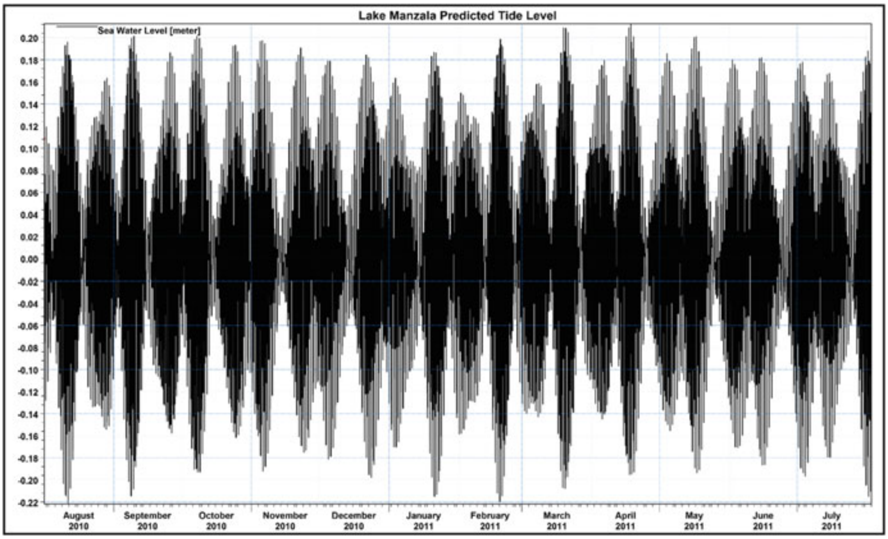

Fig. 24 Generated tide levels for Lake Manzala outlets for a typical year

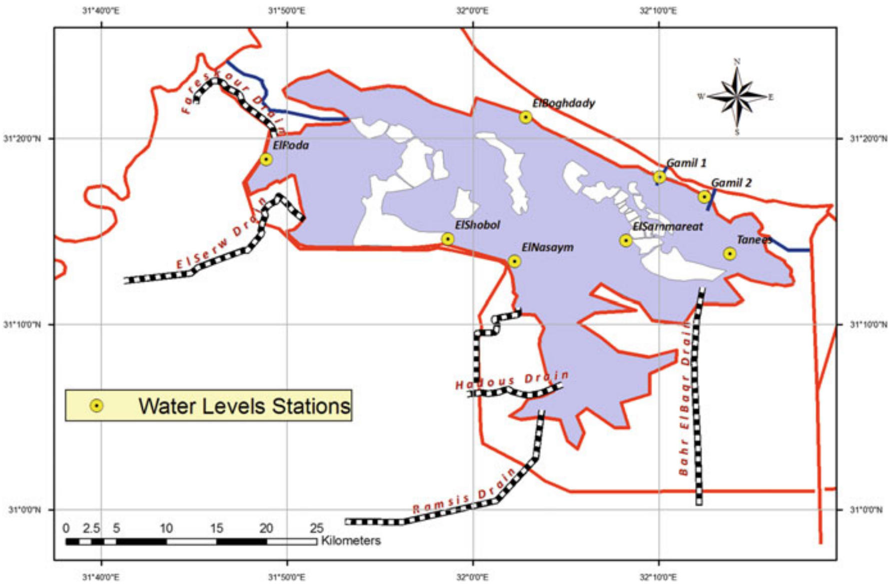

Fig. 25 Water levels recording stations for Lake Manzala

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 $m^{½} s^{-1}$
Wind friction coefficient	0.0018
Constant in Dalton's law	0.5
Wind coefficient in Dalton's law	0.9
Sun constant, a in Angstrφm's law	0.295
Sun constant, b in Angstrφm's law	0.371
Displacement (summer time)	1
Standard meridian for time zone	30
Integration method for heat exchange	1st-order Euler

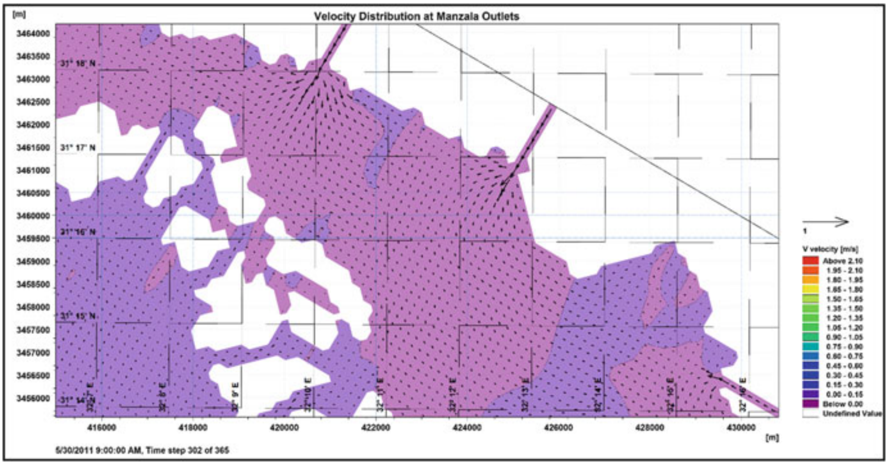

Fig. 26 Velocity distribution at Manzala outlets on May 30, 2011

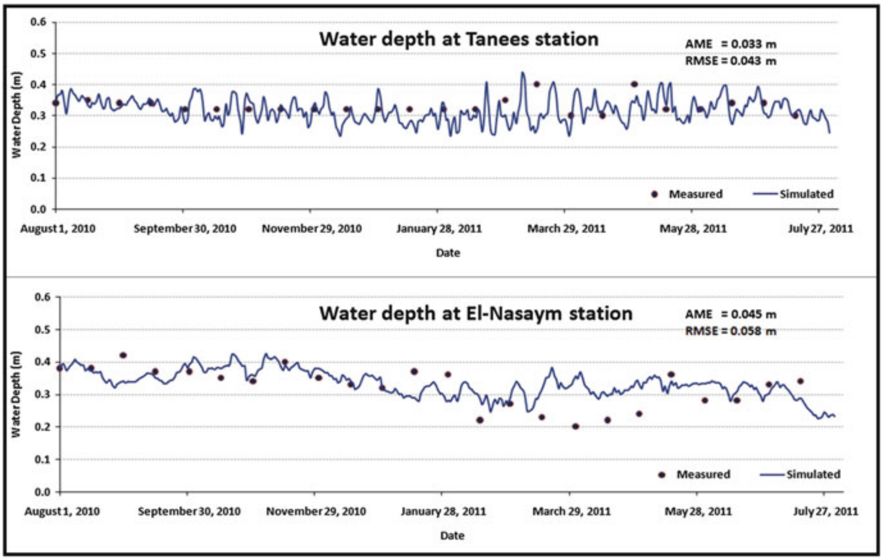

Fig. 27 Measured and simulated water depths at Tanees and El-Nasayem stations, Lake Manzala

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

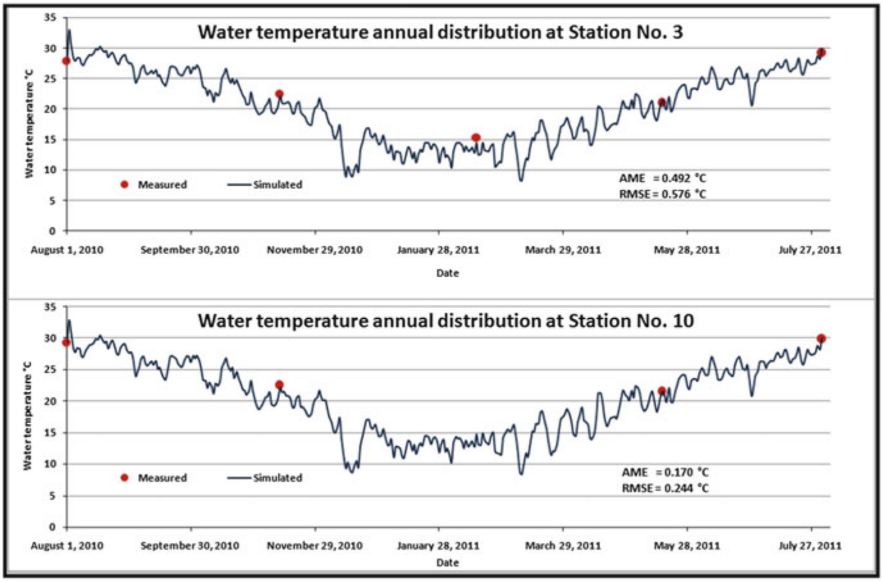

Fig. 28 Measured and simulated water temperature at stations No. 3 and 10, Lake Manzala

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

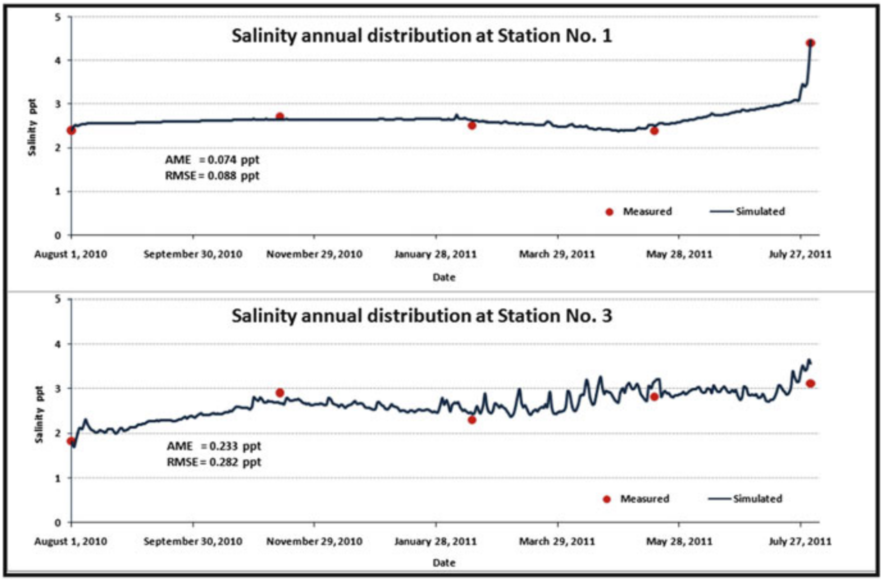

Fig. 29 Measured and simulated water salinity at stations No. 1 and 3, Lake Manzala

(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 (Δ%) between the scenario results and the base case results of the calibrated period 2010–2011 will be used: ΔWD for the water depth, ΔT for the water temperature, and Δ*S* 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 ΔWD 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 ΔWD will be about 48 and 90%, for RCP2.6_I and RCP2.6_II, respectively. In between of them,

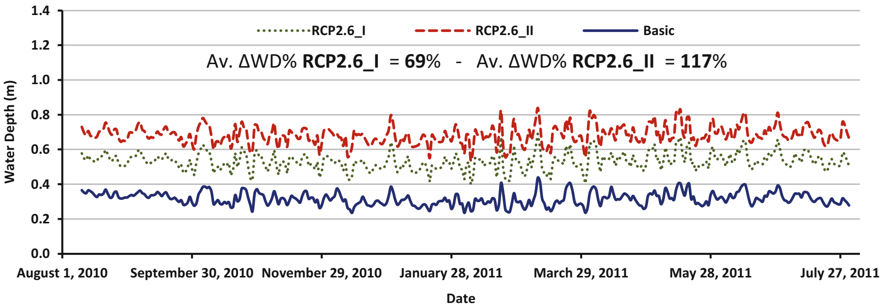

Fig. 30 Water depth distribution at Tanees station, Manzala Lake, for some selected future climatic scenarios and periods compared to the basic water levels (of model calibration)

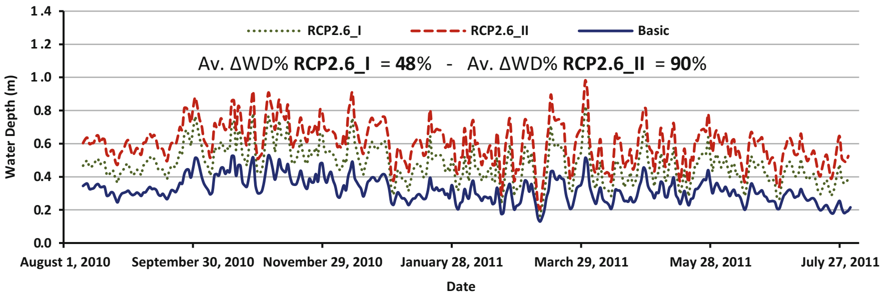

Fig. 31 Water depth distribution at El-Roda station, Manzala Lake, for some selected future climatic scenarios and periods compared to the basic water levels (of model calibration)

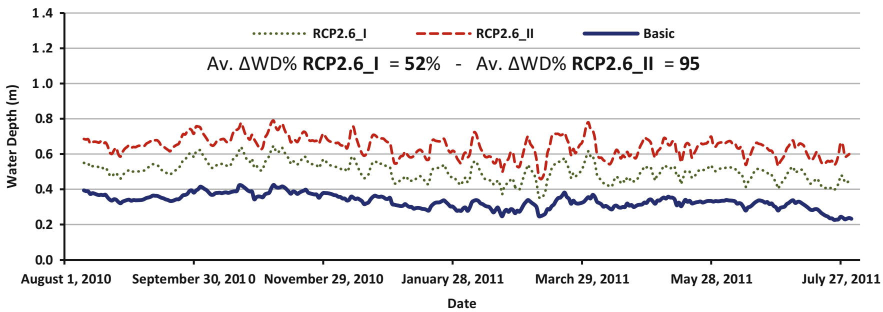

Fig. 32 Water depth distribution at El-Nasayem station, Manzala Lake, for some selected future climatic scenarios and periods compared to the basic water levels (of model calibration)

station of El-Nasayem shows moderate average changes (Fig. 32); the average ΔWD 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

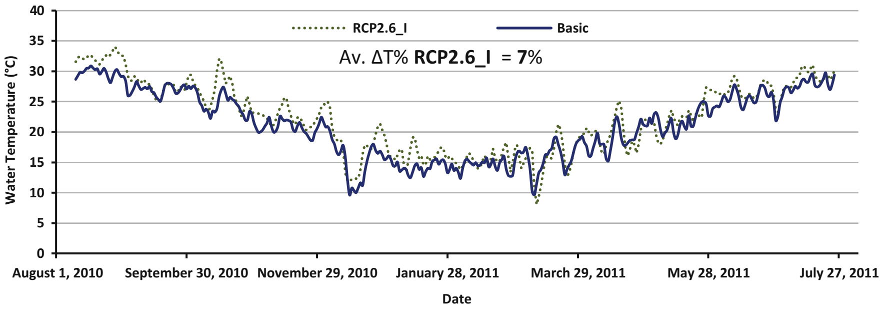

Fig. 33 Water temperature distribution at station No. 2, Manzala Lake, for RCP2.6_I climatic scenarios compared to the basic water levels (of model calibration)

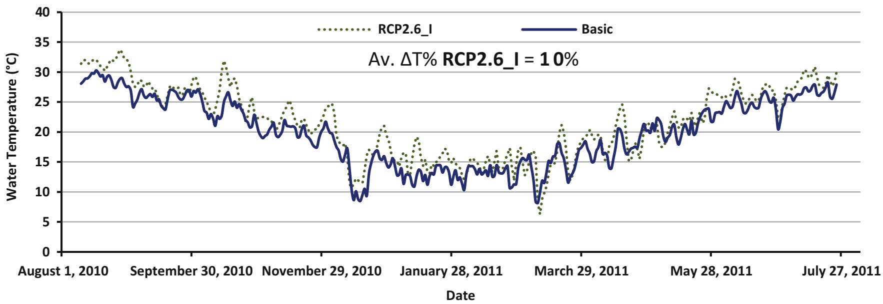

Fig. 34 Water temperature distribution at station No. 6, Manzala Lake, for RCP2.6_I climatic scenarios compared to the basic water levels (of model calibration)

(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.

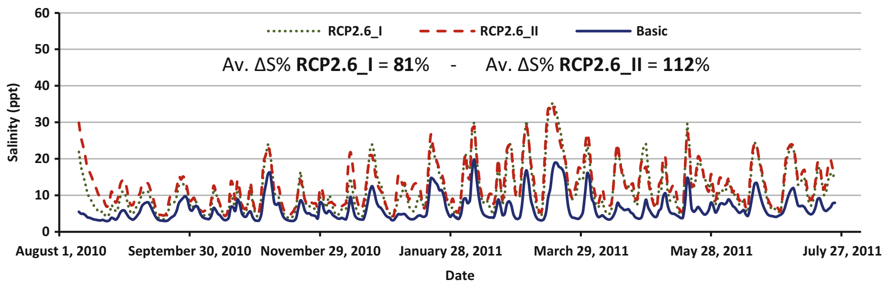

Fig. 35 Water salinity distribution at station No. 2, Manzala Lake, for some selected future climatic scenarios and periods compared to the basic water levels (of model calibration)

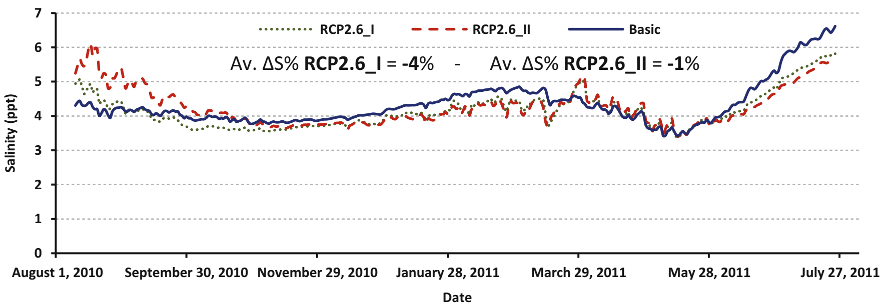

Fig. 36 Water salinity distribution at station No. 8, Manzala Lake, for some selected future climatic scenarios and periods compared to the basic water levels (of model calibration)

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.

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Modeling of Water Quality Parameters in Manzala Lake Using Adaptive Neuro-Fuzzy Inference System and Stochastic Models

Mosaad Khadr

Abstract Egyptian coastal lakes, four lakes, and two lagoons represent about 25% of the Mediterranean total wetlands, and the four lakes are located at the north of Nile Delta and are known as Northern Delta Lakes. Manzala Lake, the largest of the Egyptian lakes, is affected qualitatively and quantitatively by drainage water that flows into the lake. In water quality modeling, deterministic models are frequently used to describe the system behavior. However most ecological systems are so complex and unstable. In some cases, the deterministic models have high chance of failure due to absence of prior information. A deterministic model may also have inevitably errors originated from model structures or other causes. For such cases, new modeling paradigm such as data-driven modeling or data mining has recently been a considerable growth in the development and application of computational intelligence and computer tools with respect to water-related problems. This chapter illustrates the capabilities of adaptive neuro-fuzzy inference system (ANFIS) to predict water quality parameters in Manzala Lake based on water quality parameters of drains associated with the Lake. A combination of data sets was considered as input data for ANFIS models, including discharge, pH, total suspended solids, electrical conductivity, total dissolved solids, water temperature, dissolved oxygen, salinity, and turbidity. The models were calibrated and validated against the measured data. The performance of the models was measured using various prediction skills criteria. Results show that ANFIS models are capable of simulating the water quality parameters and provided reliable prediction of total phosphorus and total nitrogen and, thus, suggesting the suitability of the proposed model as a tool for on-site water quality evaluation.

Keywords Artificial intelligence, Egypt, Manzala Lake, Water quality parameters

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Contents

1 Introduction

Both quantity and quality of water resource worldwide are a subject of ongoing concern [1, 2]. One of the major challenging problems is management and assessment of long-term water quality of water resources [2, 3]. The process for determining water quality refers to the classification that includes the physical, chemical, and biological characteristics according to the water usage range [4, 5]. In this process, some measures are used to classify the condition of water relative to the requirements of one or more biotic species and/or to any human need or purpose. The term “water quality” is most commonly used by reference to a set of standards against which compliance can be assessed [6, 7]. The main two types of models that are used in water resources are physical model and empirical or data-driven (DD) model [8]. A physically based (process) model (also called knowledge-driven or simulation models) based on the description of the behavior is typically based on the first-order principles from physics, of a phenomenon, or system. Data-driven (DD) model involving mathematical equations assessed not from the physical process but from analysis of concurrent input and output time series [9]. A typical water quality mathematical simulation model consists of a collection of formulations characterizing physical mechanisms that determine position and momentum of pollutants in a water body. In water quality modeling, the mathematical modeling usually includes several parameters that cannot be measured or contain considerable expense [10–12]. A deterministic model may also have unavoidable errors originated from model structures or other causes. Therefore, water quality models are still considered as simplified approximations of reality, and they obviously contain certain types of errors that result in uncertainty in the results of the model [13, 14]. Therefore, the researchers recently tend to rely on conceptual or empirical models in practical applications in order to reduce this uncertainty. A new modeling paradigm such as the so-called data-driven models or data mining has recently been a common and considerable growth in the development and application of computational intelligence and computer tools with respect to water-related problems [10, 15–17].

These techniques are an approach that can be used to monitor water quality by estimation of the water quality parameters based on the field data sets and to map the relationship between the water quality parameter according to its temporal and spatial variation [18, 19]. Data-driven models associate in general to a wide range of models that simulate a system by the data experienced in the real life of that system. Data-driven modeling (DDM) is also based on analyzing of the data characterizing the system under study, in which a model can be defined on the basis of finding correlated connections between the system state variables (input, internal, and output variables) without obvious knowledge of its physical behavior [20–24]. DDM includes various categories generally categorized into statistical and artificial intelligent models which comprise neural networks, fuzzy systems, and evolutionary computing as well as other areas within artificial intelligence and machine learning [25].

The use of artificial neural network (ANN) and fuzzy logic has many successful applications in hydrology, including modeling of rainfall-runoff processes [26, 27], modeling stage-discharge relationships, replicating the behavior of hydrodynamic/ hydrological models of a river basin where ANNs are used to provide optimal control of a reservoir, simulating multipurpose reservoir operation, and deriving a rule base for reservoir operation from observed data [23, 26, 28]. The development and current progress in the integration of numerous artificial intelligence techniques (knowledge-based system, artificial neural network, fuzzy inference system, and genetic algorithm) in water quality modeling, sediment transportation, and dissolved oxygen concentration have been investigated by many researchers [29–31]. Monitoring of water quality of the drainage water input to the northern Egyptian lakes is a major issue for maintaining their ecology, since these lakes have been regarded highly as a fishery. In this chapter, adaptive neuro-fuzzy inference system (ANFIS) models were developed for prediction and simulation of water quality parameters in the outlet ends of the drain system associated with Manzala Lake, with emphasis on total phosphorus (TP) and total nitrogen (TN) [2]. TN and TP are considered as the most essential parameters to control and assess water quality and trophic status of water bodies. Measuring of these two parameters is costly and time-consuming because process of laboratory examinations must be done using water samples.

2 Manzala Lake

Manzala Lake, located at the northern edge of the Nile Delta, is considered as the largest of the Egyptian lakes along the Mediterranean coast (Fig. 1) [2]. It is considered as one of the most valuable fish sources in Egypt, shared with about 35% of the total country yield during the 1980s, and increased to about 56% in 2013 [32, 33]. The lake serves five provinces, namely, Damietta, Dakahliya, Sharkiya, Ismailia, and Port Said. The lake is bordered at the north side by a sandy margin, which separates the lake from the Mediterranean Sea except at three main outlets

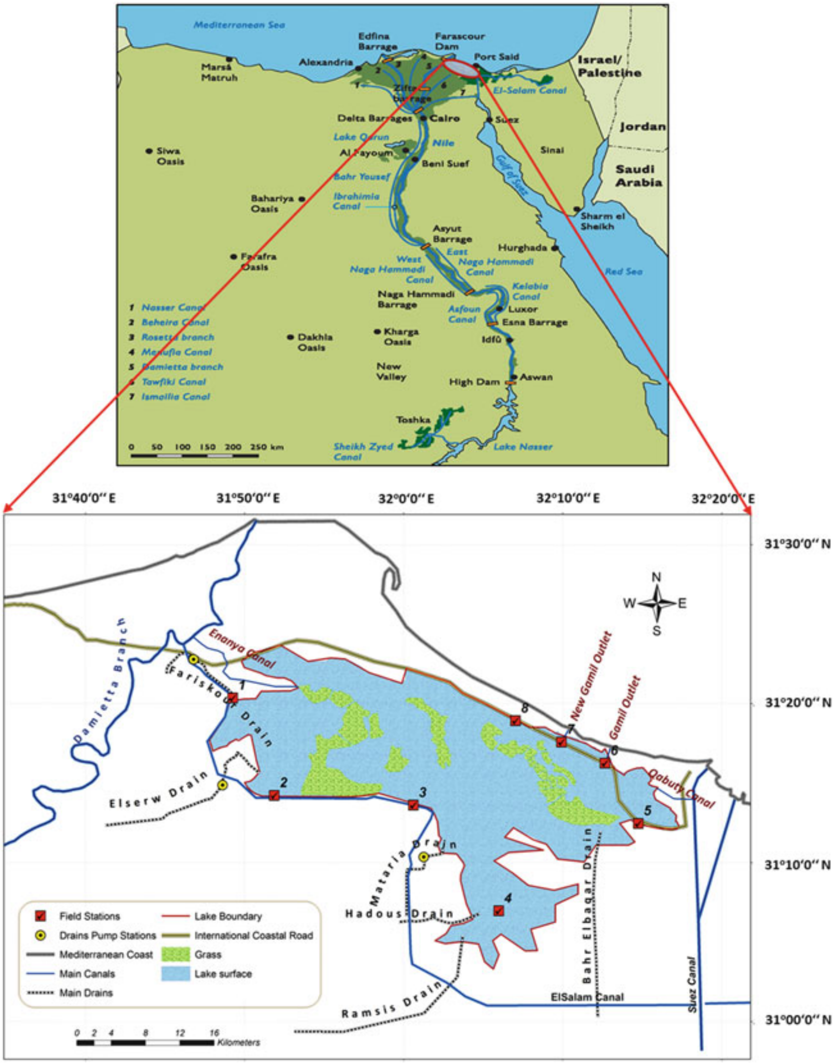

Fig. 1 Layout of Manzala Lake and main drain system associated with it

where exchange of water occurs. These three outlets are El-Boughdady, El-Gamil, and the new El-Gamil [34, 35]. Due to the wastewater discharge in the lake, these outlets are tightened; therefore, a continuous cleaning of the existing outlets is essential and construction of a new outlet is rising [36]. The eastern side of Manzala Lake is connected with the Suez Canal through El-Raswa Canal, a few kilometers to the south of Port Said City. To the west, the Damietta branch of the Nile River borders the lake and the southern side of the lake is bordered by cultivated land. The drained waters into the lake can be classified into agricultural, industrial, and domestic waste. Manzala Lake has been gradually transformed from a marine estuary environment to eutrophic freshwater system due to several human impacts [34]. The Lake is prone to high inputs of pollutants resulted from industrial, domestic, and agricultural sources. The southern region of the lake is characterized by slighter values of salinities and high concentration of nutrients and heavy metals because of receiving high volumes of low-salinity drainage water through various drains. The Lake is enhanced by drainage water conveyed by the drains, which are connected to the Lake at the south and southeastern borders. Six major drains contribute by a flow rate into the lake with about 4,170 million m^3 annually. The major two drains that flow into Manzala Lake are Bahr El-Baker drain system and Bahr Hadous drain system. Bahr El Baqar drain, which is classified as heavily polluted and anoxic over its entire length, transports untreated and poorly treated wastewater to the lake over a distance of 170 km. Manzala Lake is a shallow lake; the water depth is in the range 0.7–1.5 m and is composed of about 30 basins with different hydrological and water quality characteristics [2, 36]. Water quality data, that were used to develop the ANFIS models, are measured values at outfall measuring stations and have a record length of 10 years covering between 2001 and 2010. The records were obtained from Egyptian Environmental Affairs Agency (EEAA) and National Water Research Center (NWRC). The data set includes discharge (Q), pH, electrical conductivity (EC), dissolved oxygen (DO), total suspended solids (TSS), total dissolved solids (TDS), water temperature, salinity (S), turbidity (TU), total phosphorus (TP), and total nitrogen (TN). The consequent part is total phosphorus (TP) or total nitrogen (TN).

3 Data-Driven Modeling

Hydrological models can be classified as physical, mathematical (including grouped conceptual and distributed physically based models), and empirical models. The empirical models, in contrast to the first two class, include mathematical equations that are not derived from physical processes but from analysis of the available data time series. Data-driven modeling (DDM) is based on analyzing the data about a system under consideration, in particular finding connections between the system state variables (input, internal, and output variables) without obvious knowledge of the system physical behavior [25]. Data-driven modeling is therefore focused on computational intelligence (CI) and machine learning (ML) methods that can be used to build models for complementing or replacing physically based models. A machine learning algorithm (ML) is used to establish the relationship between a system's inputs and outputs using a set of training data, that is, representative of all the behavior found in the system (Fig. 2) [25]. Once the developed model is trained, it can be tested using an independent data set to find out how well it can generalize to unobserved data.

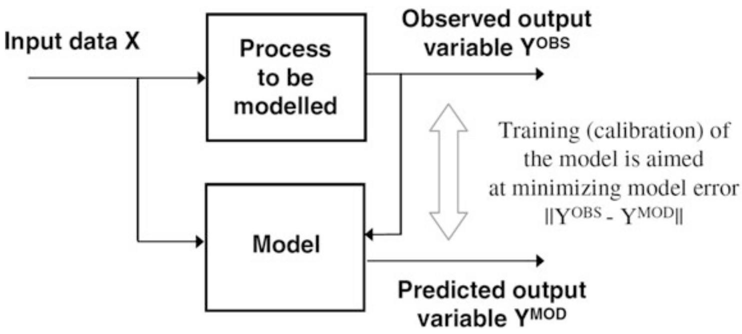

Fig. 2 General approach to modeling [25]

3.1 Monte Carlo Simulation

Simulation is a technique of performing sampling experiments on the model of the system [37]. Stochastic simulation is experimenting with the model over time and includes sampling stochastic varieties from probability distributions. Time series of discharge is an important information for planning, design, operation, and monitoring of many water resources systems. However, in many cases, time series of discharge records at the location of interest are limited [38]. In the case of nonavailability of a complete series of historical discharge record, generation of the data series is of utmost importance. Classical stochastic models such as the autoregressive moving average (ARMA) models, Thomas-Fiering model, and Monte Carlo simulation model are generally used for synthetic discharge generation [39–41]. Monte Carlo simulation is a technique which has enormous impacts in many several fields of computational science [42]. The Monte Carlo model is any method which solves a problem by generating convenient random numbers and observing that fraction of the numbers obeying some properties [43]. This method is effective for obtaining numerical solutions to some problems, which are too complicated to be solved analytically. Monte Carlo model uses random numbers generated from several statistical distributions using efficient generators that have been developed for the most commonly used distributions (such as uniform, Gaussian, and exponential) and general techniques (e.g., inversion) [44]. In several simulation applications, it would be necessary to generate random values that are similar to existing data, and this can be done by resampling from the original data. Alternative approach is to fit a parametric distribution from one of the families of the most common distributions and then generate random values from the selected distribution. However, choosing a suitable family can sometimes be difficult.

3.2 Neural Networks System

Neural networks system are a biologically excited computational model, which is based on the way in which the human brain works. Developing of neural network models is done by training the network to represent the relationships and processes that are representative within the data set. These relationships are nonlinear regression models; they perform an input-output mapping by using a set of interconnected simple processing nodes called neurons. Each neuron takes in inputs either externally or from other neurons in the network then passes it through an activation or transfer function such as a logistic or sigmoid curve. Selected data enter the designed network through the input units arranged in what is called an input layer. The data are then fed forward through a set of successive layers including the so-called hidden layer in the middle to emerge from the output layer on the right. The inputs can be any combination of all variables that are expected to be important to predict the output (Fig. 3). Therefore, in hydrological problems some knowledge about the behavior hydrological system is important.

3.3 Fuzzy Logic

Fuzzy logic approach was initiated by Lotfi A. Zadeh, professor for computer science at the University of California in Berkeley in 1965 [45, 46]. Fuzzy logic (FL) is a multivalued function that allows intermediate values to be defined between conventional evaluations like yes/no, true/false, high/low, etc. Variables of fuzzy logic may have a truth value which has a range between 0 and 1 and is not constrained to the both truth values of classic propositional logic notions like rather fast or tall can be formulated mathematically and processed by computers, in order to apply a more humanlike way of thinking in the programming of computers [45, 47, 48]. Fuzzy inference systems are fuzzy logic models that consist of a number of conditional "if-then" rules. For the designer who recognizes the system, these rules are easy to be written, and as many rules as necessary can be supplied to describe the system adequately. Unlike standard conditional logic, in fuzzy logic technique, the truth of any statement is a consequence of degree [46, 48, 49]. Fuzzy inference systems depend on membership functions in order to clarify to the computer how to calculate the correct value between 0 and 1. The degree to which any fuzzy statement is true is denoted by a value between 0 and 1 [50, 51].

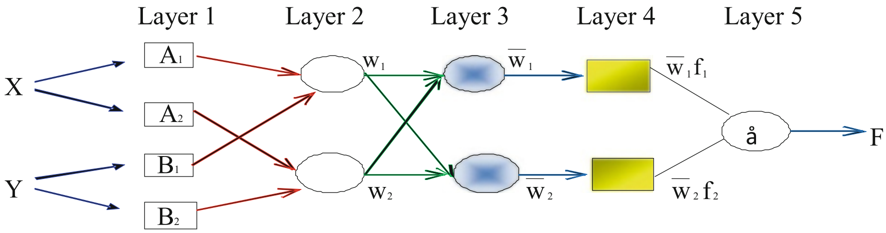

Fig. 3 An ANFIS architecture for a two-rule Sugeno system [22]

4 Adaptive Neuro-Fuzzy Inference System

In recent years, there has been a growing trend in the using of fuzzy logic in combination with neuro-computing in many of the research applications because of their ability to deal with uncertain systems [52]. An adaptive neuro-fuzzy inference system (ANFIS) is a fuzzy inference system formulated as a feed-forward neural network. Therefore, in ANFIS modeling the advantages of a fuzzy system are combined with learning algorithms [53]. ANFIS was introduced as an effective tool to represent both simple and highly complex functions more powerfully than the well-known conventional statistical methods. ANFIS is an adaptive network of nodes and directional links with related learning rules. It is called adaptive because some, or all, of its nodes have parameters which affect the output of the node [54]. The structure of the ANFIS model, presented in this chapter, consists of a Sugeno-type fuzzy system with generalized bell input membership and a linear output membership function. The Sugeno model makes use of "if-then" rules to produce an output for each rule. It is similar to the Mamdani method in many respects. The first two main parts of the fuzzy inference process, fuzzifying the inputs and applying the fuzzy operator, are the same. The main variance between Mamdani and Sugeno type is that in the Sugeno type rule outputs consist of the linear combination of the input variables plus a constant term; the final output is the weighted average of each rule's output. Figure 3 presents the typical architecture of ANFIS with a multilayer feed-forward network, which is linked with a fuzzy system for two inputs (x and y) as an example. Fuzzy inference systems are consisted of five functional blocks, and the ANFIS model contains the following [53, 55]:

1. A rule base containing a number of if-then rules
2. A database, which defines the membership function
3. A decision-making interface that operates the given rules
4. A fuzzification interface that converts the crisp inputs into "degree of match" with the linguistic values like high or low, etc.
5. A defuzzification interface that reconverts to a crisp output

The rule base in the Sugeno model has of the following form:

$$\text{If } x \text{ is } A_1 \text{ and } y \text{ is } B_1 \text{ then} f_1 = p_1 \times x + q_1 \times y + r_1 \quad (1)$$

$$\text{If } x \text{ is } A_2 \text{ and } y \text{ is } B_2 \text{ then} f_2 = p_2 \times x + q_2 \times y + r_2 \quad (2)$$

where x and y are predefined membership functions, A_i and B_i are membership values, p_i, q_i, and r_i are the consequent parameters that are updated in the forward pass in the learning algorithm, and f_i is the output within the fuzzy region specified by the fuzzy rule.

Let the membership functions of fuzzy sets A_i and B_j be μ_{A_i} and μ_{B_i}, respectively. The five layers that integrate ANFIS are as follows:

Let the output of the ith node in layer 1 denoted as $O_{1,i,}$ then,

Layer 1: Every node i in this layer is an adaptive node with node function:

$$O_{1,i} = \mu_{A_i}(x) \text{ for } i = 1, 2, \text{or } O_{1,i} = \mu_{B_{i-2}}(y) \text{ for } i = 3, 4 \quad (3)$$

where x (or y) is the input to the ith node and A_i (or B_{i-2}) is a linguistic labels.

Layer 2: This layer consists of the nodes labeled which multiply incoming signals and send the product out. Each node output represents the firing strength of a rule.

$$O_{2,i} = w_i = \mu_{A_i}\ (x)\ \mu_{B_i}\ (y) \text{ for } i = 1, 2 \quad (4)$$

Layer 3: In this layer, the nodes labeled N acts to scale the firing strengths to provide normalized firing strengths.

$$O_{3,i} = \bar{w}_i = \frac{w_i}{w_1 + w_2}, i = 1, 2 \quad (5)$$

Layer 4: The output of layer 4 is comprised of linear combination of inputs multiplied by normalized firing strengths. This layer's nodes are adaptive with node functions:

$$O_{4,i} = w_i f_i = w_i(p_i x + q_i y + r_i) \quad (6)$$

where, w_i is the output of layer 3, and $\{p_i, q_i, r_i\}$ are the parameter set. Parameters of this layer are referred to as consequent parameters.

Layer 5: This layer consists of a single node, computes the final output as the summation of all incoming signals.

$$O_{5,i} = \sum_{i=1} \bar{w}_i f_i = \frac{\sum_{i=1} w_i f_i}{\sum_{i=1} w_i} \quad (7)$$

5 Results and Discussion

Five main drains were considered as the freshwater sources of the lake, according to their discharges, namely, Bahr El-Baqar, Hadous, Mataria, Elserw, and Fareskour; Table 1 presents statistical characteristics of discharge measured at the outlet ends of the studied drains, and Fig. 4 shows the average monthly discharge measured at the same stations. Monthly discharges of the studied drains have been simulated using Monte Carlo simulation by applying several approaches, namely, Pearson distribution, gamma distribution, and Johnson system of distributions in order to fill in the missing data in the recorded discharge series. The gamma distribution was fitted to the observed monthly time series, then the parameters of the distribution were calculated, and then a synthetic discharge has been simulated. For adequate modeling, one must have a distribution, which would appropriately preserve the statistical properties of the data series. The result of the Pearson system showed that this approach is more capable than the other suggested approaches (gamma distribution and Johnson Systems) to preserve the statistical properties of the recorded data series because it covers a wide range of distribution shapes, including both symmetric and skewed distributions. To simulate the discharge using the Pearson distribution that closely matches the observed data, four sample moments have been computed (mean, standard deviation, skewness, kurtosis), and those moments have been treated as distribution parameters. Then one of the distributions within the Pearson system, which matches the combination, was selected in order to fill in the missing data in the data series.

Using the given input/output data set presented in Fig. 1, the adaptive neuro-fuzzy inference system (ANFIS) was used to construct a FIS whose membership function parameters are tuned using a backpropagation algorithm [35]. Therefore, the FIS can learn from the training data. In this chapter, the ANFIS models were developed in the Matlab environment. ANFIS was used to extract the relation of discharge (Q), pH, electrical conductivity (EC), dissolved oxygen (DO), total suspended solids (TSS), total dissolved solids (TDS), water temperature, salinity (S), turbidity (TU), total phosphorus (TP), and total nitrogen (TN). The consequent part is total phosphorus (TP) or total nitrogen (TN) (Fig. 5). All of these investigated parameters were recorded at the outlet of each drain of the five drains. The first step was to calculate the correlation coefficient matrix for the studied parameters in the five drains. This matrix has 275 elements (5 rows × 55 columns), where the number of rows represents the number of drains. Table 2 presents the correlation matrix for some parameters considered in this study. Results of correlation test

Table 1 Statistical characteristics of discharge at the outlet ends of the investigated drains in the study area (m^3/s) (2001–2010)

Drain	Mean	Std.	Min.	Max.	Skew.
Bahr El-Baqar	46.40	11.00	9.00	59.90	−2.72
Bahr Hadous	4.54	2.36	2.34	11.65	1.54
Farasqur	13.74	6.80	4.88	29.50	0.82
Matareya	15.14	7.22	6.74	37.79	1.32
El-Serw	13.89	4.27	8.50	34.87	1.86

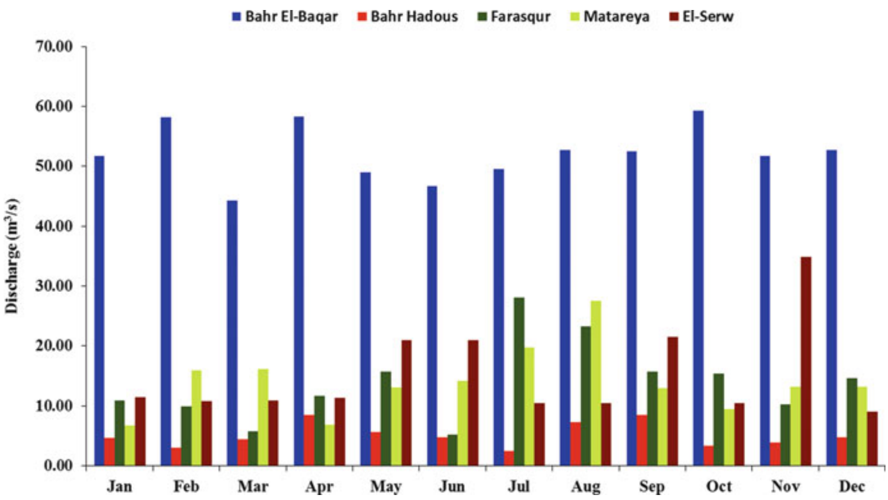

Fig. 4 Mean monthly discharge at the outlet ends of the investigated drains in the study area (m^3/s) (2001–2010)

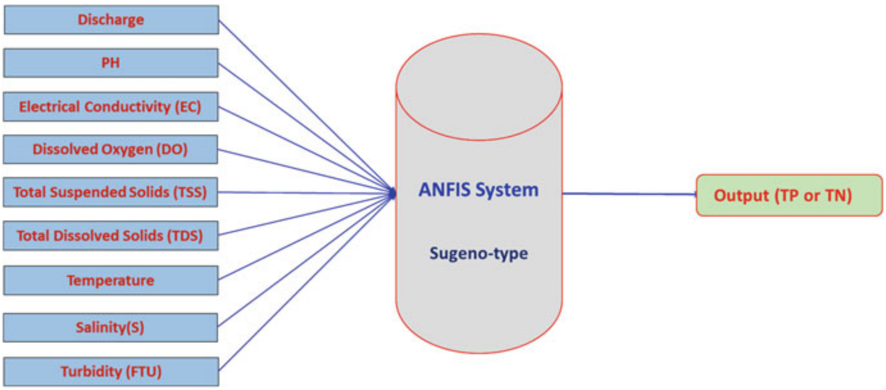

Fig. 5 An ANFIS architecture for TP and TN prediction

showed that most of the studied parameters in the five drains have statistically significant correlation as presented in Table 2.

The ANFIS was used to derive and to develop several models to predict the desired water quality parameters at the both outlet end of the drain and the investigated station presented in Fig. 1 as well. The modeling process presented in this chapter is shown in Fig. 6. To develop the required water quality simulation models, a time series of the 11 previously noted parameters in a 10-year (120-month) period was used. The structure of the ANFIS model presented in this study consists of a Sugeno-type fuzzy system with generalized bell input membership functions, which gave the best results, and a linear output membership function. In order to construct the ANFIS models, monthly data set was randomly

Table 2 Correlation coefficients for some water quality parameters between stations

Parameters	TP					TN				
Drain	Bahr El-Baqar	Bahr Hadous	Farasqur	Matareya	El-Serw	Bahr El-Baqar	Bahr Hadous	Farasqur	Matareya	El-Serw
Bahr El-Baqar	1.00	0.19	0.13	0.39	0.38	1.00	0.64	0.65	0.70	0.44
Bahr Hadous	0.19	1.00	0.58	0.43	0.03		1.00	0.62	0.88	0.48
Farasqur			1.00	0.47	−0.22			1.00	0.62	0.47
Matareya				1.00	0.41				1.00	0.53
El-Serw					1.00					1.00
Parameters	Temperature					Salinity				
Drain	Bahr El-Baqar	Bahr Hadous	Farasqur	Matareya	El-Serw	Bahr El-Baqar	Bahr Hadous	Farasqur	Matareya	El-Serw
Bahr El-Baqar	1.00	0.91	0.83	0.93	0.82	1.00	0.24	0.26	0.12	0.15
Bahr Hadous		1.00	0.87	0.98	0.84		1.00	0.17	0.13	0.17
Farasqur			1.00	0.86	0.75			1.00	0.16	0.15
Matareya				1.00	0.84				1.00	0.37
El-Serw					1.00					1.00

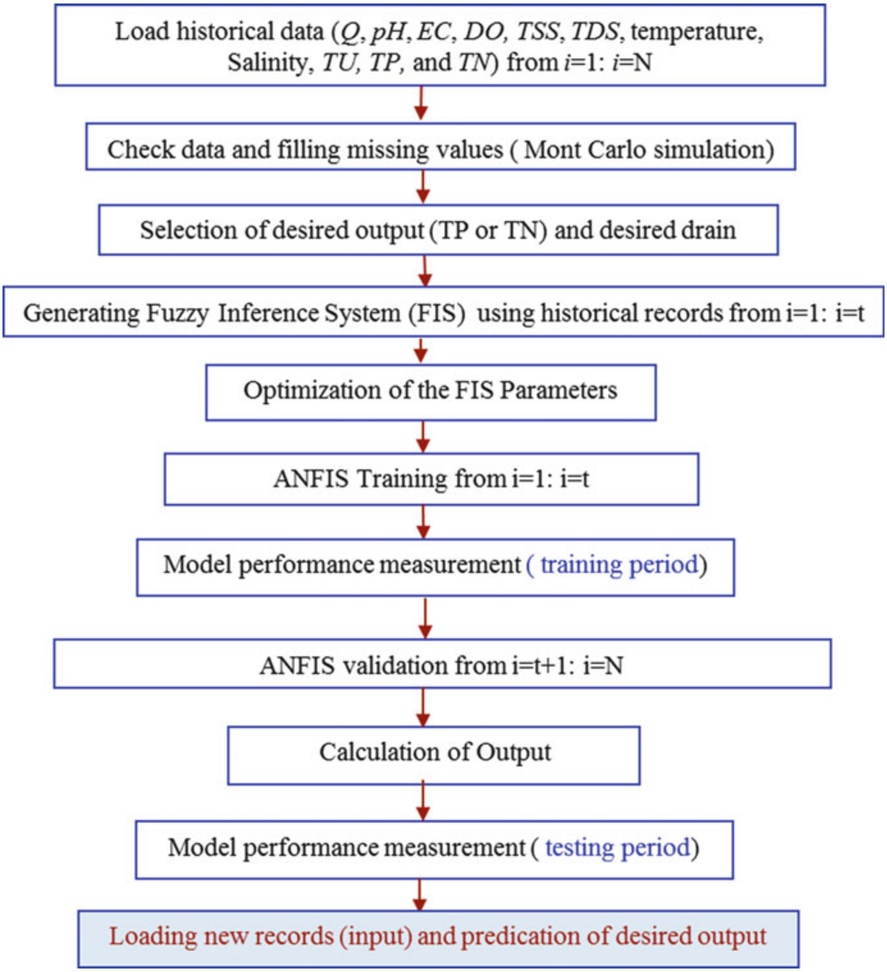

Fig. 6 Flowchart of the modeling process

partitioned into two main parts for the training and testing processes by considering 70 and 30%, respectively, which are common divisional percentages in data-driven models. Correspondingly, data set was divided into 7 and 3-year periods, respectively, for the training and testing data sets. A fuzzy inference system structure was then generated using the separate sets of input and output data as input arguments and subtractive clustering, and this step was done for both TP and TN as well. The main goal of this step was to find out the number of rules and antecedent membership functions and then use linear least squares estimation to determine consequent equations of each rule to cover the feature space. A hybrid learning algorithm was applied to identify the Sugeno-type fuzzy inference system parameters by applying a combination of the least squares method and the backpropagation gradient descent method in order to train the FIS membership function parameters to emulate a given training data set. The network was then trained to obtain the nearest output to the target. An optimization model was developed to determine the best ANFIS model parameters, which provide the best performance.

Several measures of goodness of fit were applied to evaluate the performance of all aforementioned ANFIS models in prediction of the target output. This measures that were used include mean absolute deviations (MAD), root mean square error (RMSE), the coefficient of determination (R^2), correlation coefficient (C_r), and Nash-Sutcliffe coefficient (E). The used performance criteria are calculated as follows:

$$\mathrm{MAD} = \frac{\sum_{i=1}^{n} \left| \mathrm{WQ}o_i - \mathrm{WQ}_{fi} \right|}{n} \tag{8}$$

where WQ_o is the observed value, WQ_f is the predicted value, and n is the number of data points.

In statistics, the absolute fraction of variance, R^2, is calculated as follows:

$$R^2 = 1 - \frac{\sum_{i=1}^{n} \left(\mathrm{WQ}o_i - \mathrm{WQ}_{fi} \right)^2}{\sum_{i=1}^{n} \left(\mathrm{WQ}o_i \right)^2} \tag{9}$$

With the variables already having been defined, the RMSE, which is the square root of the variance of the residuals, indicates the absolute fit of the model to the data – how close the observed data points are to the model's predicted values. RMSE is calculated as follows:

$$\mathrm{RMSE} = \sqrt{\frac{\sum_{i=1}^{n} \left(\mathrm{WQ}o_i - \mathrm{WQ}_{fi} \right)^2}{n}} \tag{10}$$

The correlation coefficient, which is a concept from statistics, measures of how well trends in the predicted values follow trends in actual observed values. The correlation coefficient is calculated as follows:

$$C_r = \frac{\sum_{i=1}^{n} \mathrm{WQ}o_i\ \mathrm{WQ}_{fi} - \frac{\left(\sum \mathrm{WQ}o_i\right)\left(\mathrm{WQ}_{fi}\right)}{n}}{\sqrt{\left[\left(\sum_{i=1}^{n} \mathrm{WQ}o_i^2 - \frac{\left(\sum_{i=1}^{n} \mathrm{WQ}o_i\right)^2}{n}\right)\left(\sum_{i=1}^{n} \mathrm{WQ}_{fi}^2 - \frac{\left(\sum_{i=1}^{n} \mathrm{WQ}_{fi}\right)^2}{n}\right)\right]}} \tag{11}$$

The efficiency E, which was proposed by Nash and Sutcliffe [56, 57], is defined as one minus the sum of the absolute squared differences between the simulated and observed values normalized by the variance of the observed values during the period under study. It is calculated as follows:

$$E = 1 - \left[\frac{\sum_{i=1}^{n} \left(\mathrm{WQ}o_i - \mathrm{WQ}_{fi}\right)^2}{\sum_{i=1}^{n} \left(\mathrm{WQ}o_i - \overline{\mathrm{WQ}}_o\right)^2}\right] \tag{12}$$

where $\overline{\mathrm{WQ}}_o$ is the average of the considered parameter.

More than 300 models were tested to select the best ten models (five models for each output) that fit data space with best performance. Once the best working models were selected through ANFIS training, both TP and TN predicted values would be computed and compared with actual measured values to examine the reliability of the developed ANFIS models. Examples of results obtained are illustrated in Figs. 7, 8, 9, 10, 11, 12, 13, and 14. These figures present the monthly values of the two outputs of total phosphorus (TP) and total nitrogen (TN), estimated by ANFIS, versus the corresponding measured values for the training and the test data set for the outlet ends of Bahr El-Baker drain and Bahr Hadous drains.

It can be clearly seen, in Figs. 7, 8, 9, 10, 11, 12, 13, and 14, that the two curves of observed and simulated data almost overlap each other, and the trend between the measured and estimated values is similar except few records, which are more deviated from actual recorder values. Performance measurements of both training and testing results for the total phosphorus (TP) and total nitrogen (TN) prediction models are summarized in Table 3. It is clearly seen from Table 3 that the ANFIS performs reasonably, and the overall prediction results are good from the MAD, RMSE, C_r, R^2, and E viewpoints. All values of RMSE presented in Table 3 are very small compared to mean values of both TP and TN for both training and testing periods, which are an indicator for the high efficiency of the developed ANFIS. Table 3 also shows that the RMSE, for all models, is almost closer to or equal to the MAD, *which* indicates that all the errors are of the same magnitude. Significant positive correlation coefficients were obtained between the two groups of data for both TP and TN in the case of the outlet ends of the five drains and in the case of the considered five stations in Manzala Lake (Table 3, Fig. 15). The large values of R^2

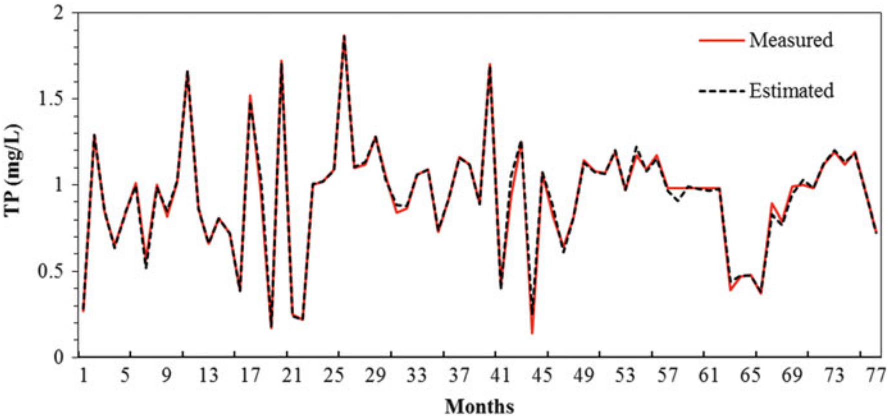

Fig. 7 Observed and predicted TP at the outlet end of Bahr El-Baker drain (training period)

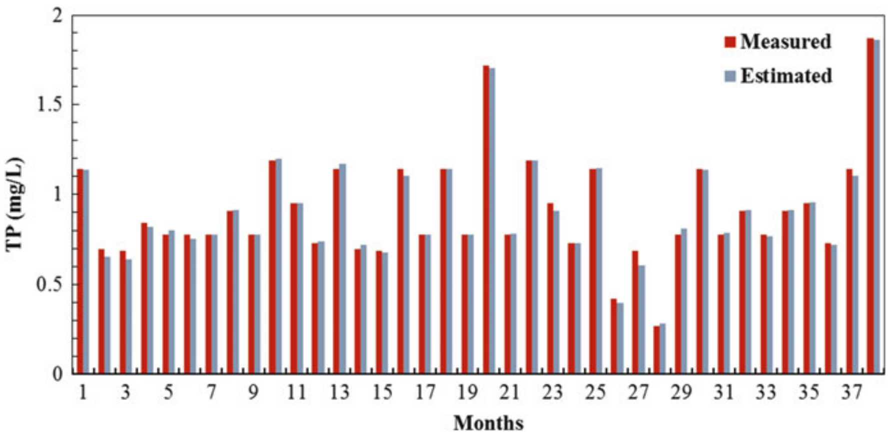

Fig. 8 Observed and predicted TP at the outlet end of Bahr El-Baker drain (testing period)

are indicative of a perfect relationship between the observed and predicted values. Based on Eq. 12, range of E is located between 1.0 (perfect fit) and $-\infty$. Values of E in the range $(-\infty, 0)$ arise when the prediction model has an unacceptable performance. Values of E shown in Table 3 are greater than 0.9, which indicate that developed models have perfect fit for the studied parameters in both training and testing data sets.

Table 3 Comparison of performance measures based on observed and predicted water quality parameters

		Training					Testing				
Drain	Parameter	MAD	R^2	RMSE	C_r	E	MAD	R^2	RMSE	C_r	E
Bahr El-Baqar	TP	0.02	0.98	0.03	0.98	0.99	0.02	0.94	0.02	0.90	0.94
	TN	0.46	0.99	0.76	0.95	0.98	0.68	0.92	1.11	0.86	0.93
Bahr Hadous	TP	0.02	0.94	0.02	0.90	0.99	0.04	0.97	0.12	0.80	0.95
	TN	0.68	0.92	1.11	0.86	0.97	0.21	0.91	0.48	0.83	0.93
Farasqur	TP	0.04	0.95	0.03	0.95	0.97	0.05	0.96	0.04	0.91	0.95
	TN	0.43	0.96	0.69	0.93	0.97	0.43	0.96	0.69	0.87	0.94
Matareya	TP	0.03	0.95	0.04	0.96	0.96	0.04	0.96	0.05	0.92	0.93
	TN	0.51	0.92	0.83	0.93	0.98	0.52	0.93	0.84	0.93	0.95
El-Serw	TP	0.04	0.97	0.05	0.96	0.96	0.06	0.99	0.07	0.95	0.94
	TN	0.37	0.93	0.89	0.95	0.95	0.39	0.95	0.91	0.88	0.94

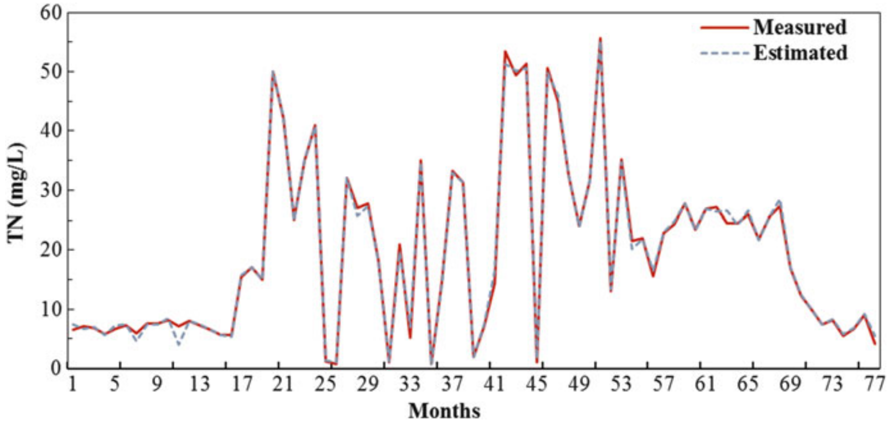

Fig. 9 Observed and predicted TN at the outlet end of Bahr El-Baker drain (training period)

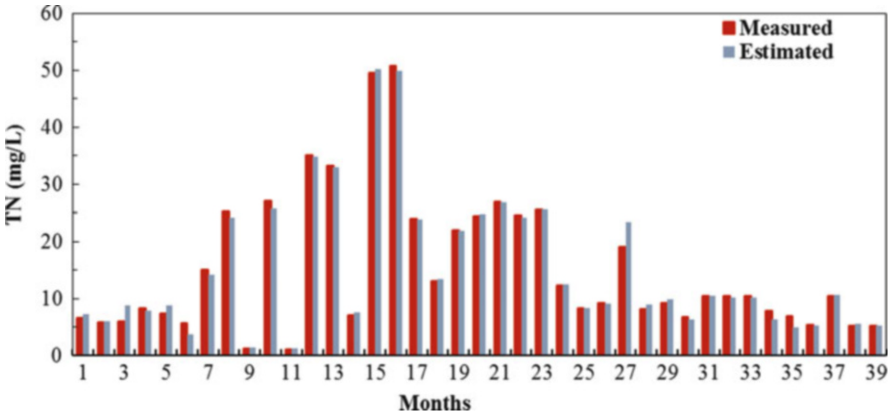

Fig. 10 Observed and predicted TN at the outlet end of Bahr El-Baker drain (testing period)

6 Conclusion

In this chapter, the capabilities of adaptive neuro-fuzzy inference system (ANFIS) and stochastic models in prediction of water quality parameters were investigated. ANFIS is a powerful fuzzy logic neural network model, which provides a method for fuzzy modeling to learn information about the data set that best allows the associated fuzzy inference system to trace the given input/output data. The approach presented in this chapter adopted ANFIS models to achieve easier and faster predictions for water quality parameter with emphasis on total phosphorus (TP) and total nitrogen (TN) at the outlet ends of drain system associated with Manzala Lake, the most important among all Egyptian lakes. Ten ANFIS models, two for each drain of the five investigated drains, were constructed for both TP and

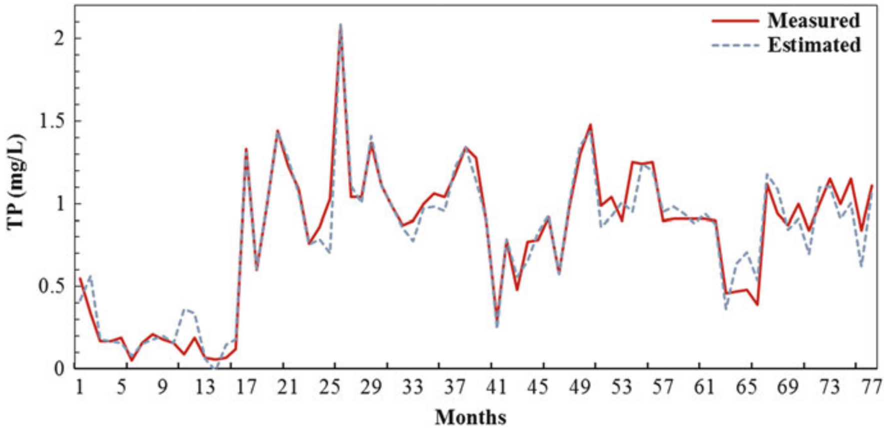

Fig. 11 Observed and predicted TP at the outlet end of Bahr Hadous drain (training period)

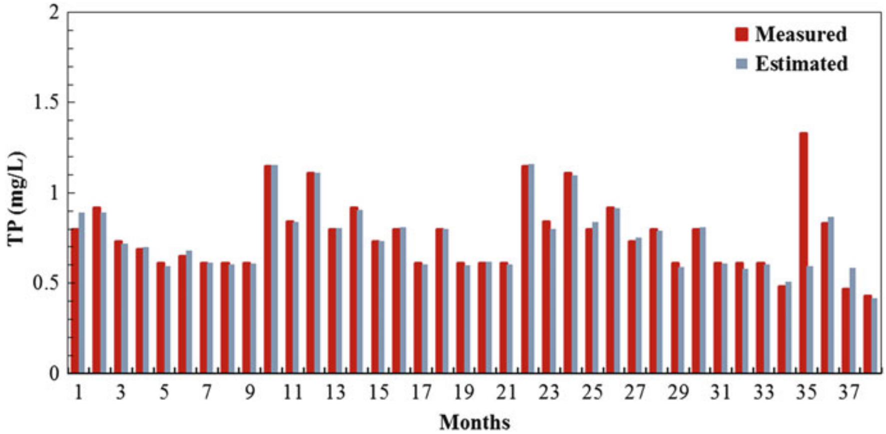

Fig. 12 Observed and predicted TP at the outlet end of Bahr Hadous drain (training period)

TN. The performance of the developed models was evaluated using several evaluation criteria based on a 10-year database of 11 water quality parameters. Comparison between simulated and observed data showed the effectiveness of the applied models and confirmed that the developed ANFIS models are accurate and consistent in different subsets, where most of the values of RMSE and MAD are small and close to each other, and most of correlation coefficients and R^2 are very close to unity. The main findings in this chapter recommend that the developed models can be used as a simple tool to predict water quality parameters and for on-site water quality parameters evaluation.

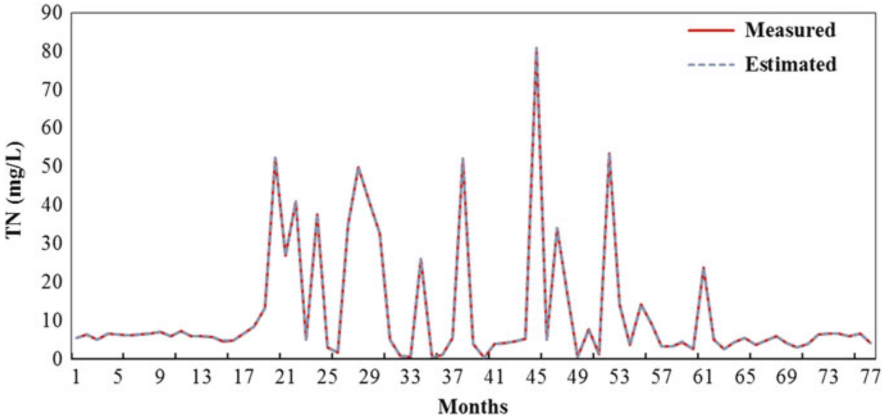

Fig. 13 Observed and predicted TN at the outlet end of Bahr Hadous drain (training period)

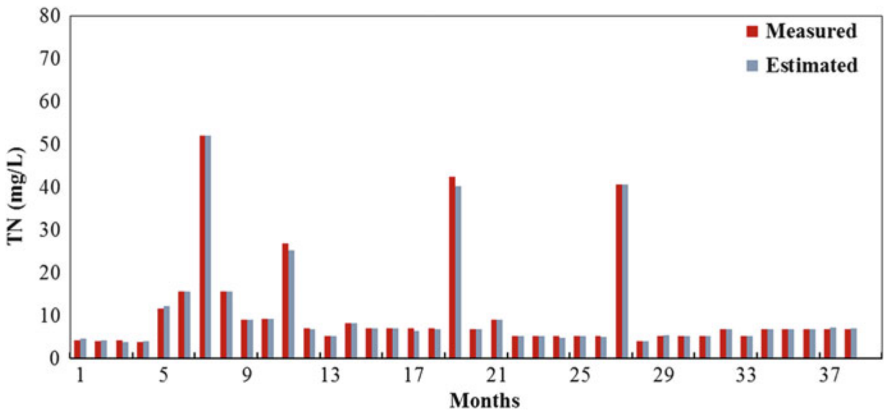

Fig. 14 Observed and predicted TN at the outlet end of Bahr Hadous drain (testing period)

7 Recommendations

The ANFIS models presented in this chapter can be used to develop an artificial measurement instrument through the integration of the model to the code of an in situ measurement device to predict the desired output based on other measured parameters. This may especially be useful to predict some parameters other than TP and TN, which are hard to measure, for the purposes of water quality monitoring and assessment. In addition, the ANFIS models can also be used to simulate the future status of the study area using various scenarios for the water quality parameters. One of the parameters that has a significant influence on the process of ANFIS modeling is the length of data and its quality. Therefore, it is highly recommended to exchange available records between all sectors that are involved with water issues. Sharing data are of higher value in providing better planning decisions and incentivizing collaborative efforts.

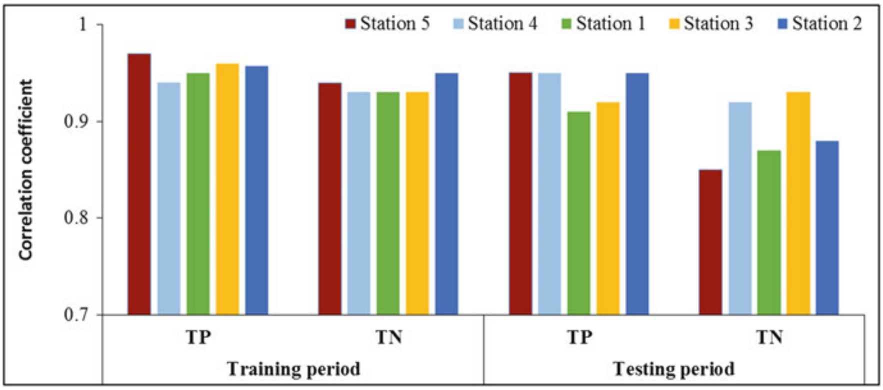

Fig. 15 Correlation coefficient between observed and predicted values for both TP and TN at the five stations investigated in Manzala Lake

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

Noha Donia

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

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

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Keywords Circulation, Egypt, Lake Mariout, Modeling, Storage capacity, Water quality

Contents

1 Introduction

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

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

Fig. 1 General layout of Mariout Lake basins

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

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

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

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

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

2 Model Development

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

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

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

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

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

2.1 Hydrodynamic Simulation

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

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

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

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

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

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

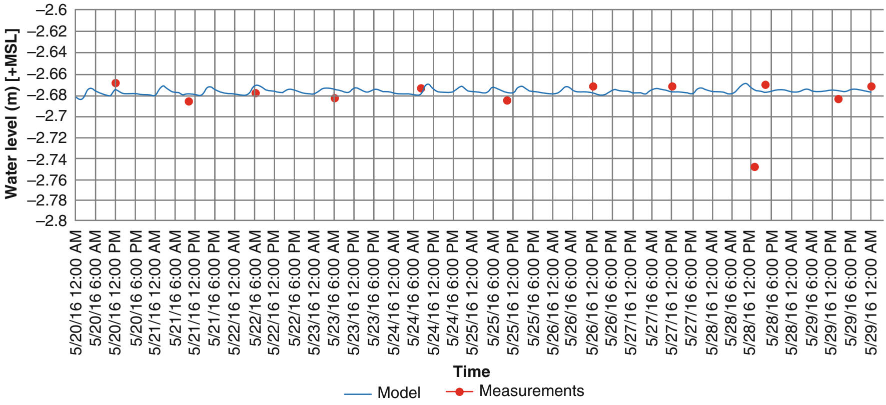


Fig. 2 Water level comparisons at main basin

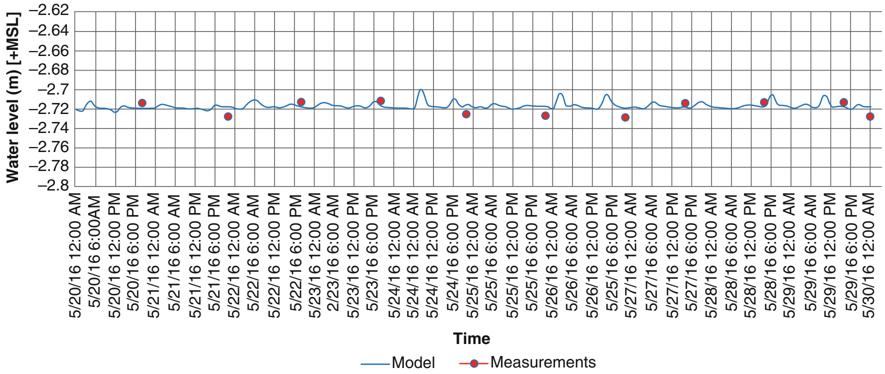


Fig. 3 Water level comparisons before El Mex

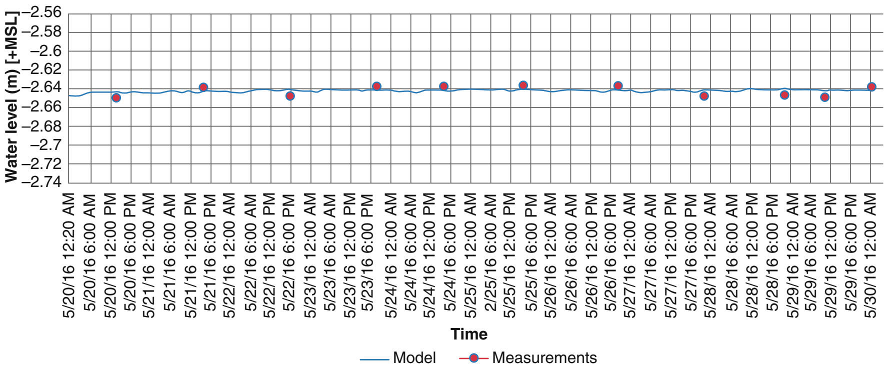


Fig. 4 Water level comparison at south basin

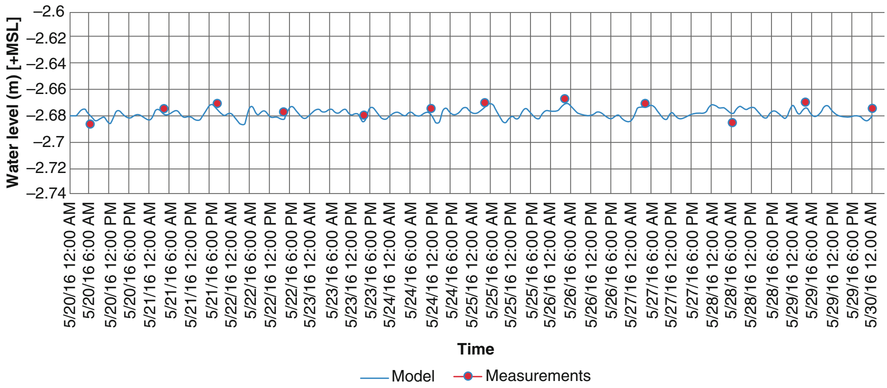


Fig. 5 Water level comparisons at the middle of western basin

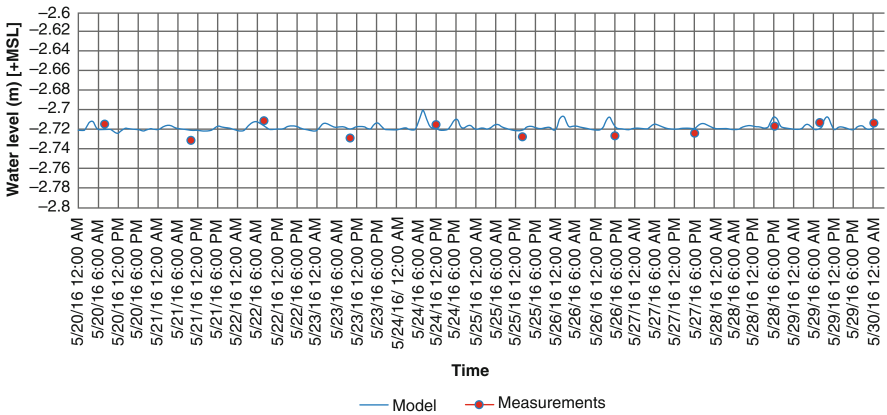


Fig. 6 Water level comparison at the north of western basin

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

2.2 *Water Quality Simulations*

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

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

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

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

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

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

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

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

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

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

Table 1 Relative error for the calibrated model parameters

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

3 Model Scenarios

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

The model scenarios are described as follows:

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

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

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

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

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

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

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

Table 2 Scenario-05 water flow and quality description

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

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

Table 3 Flow discharge input to the model

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

4 Model Results

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

4.1 Hydrodynamic Modeling Results

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

4.1.1 Scenario-0 (Baseline)

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

4.1.2 Scenario-01

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

4.1.3 Scenario-02

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

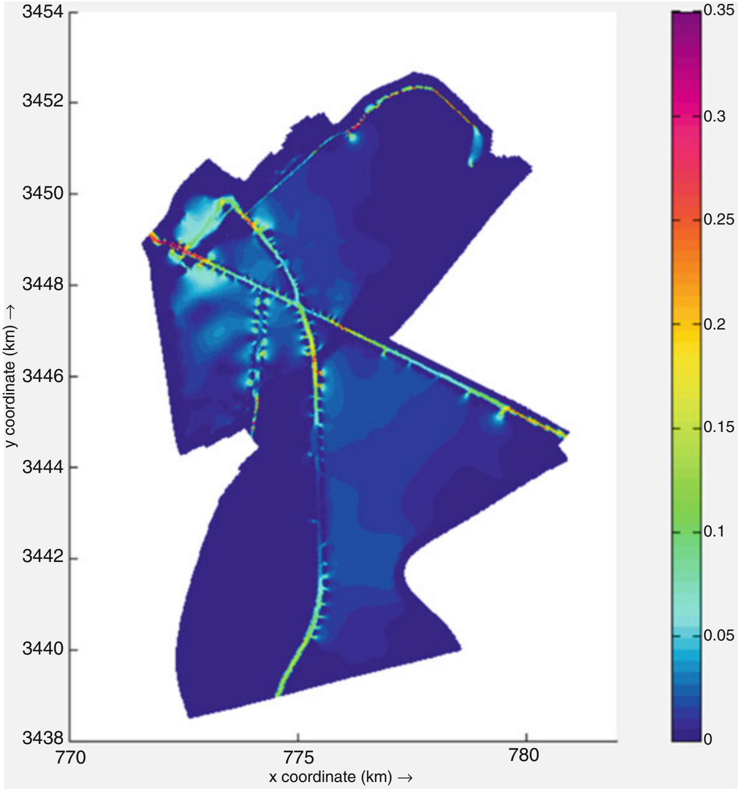


Fig. 7 The flow velocity map "Scenario-0"

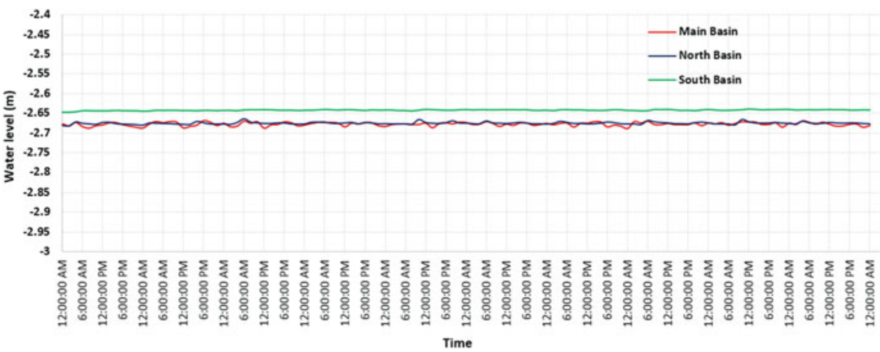


Fig. 8 The water level at the lake basins "Scenario-0"

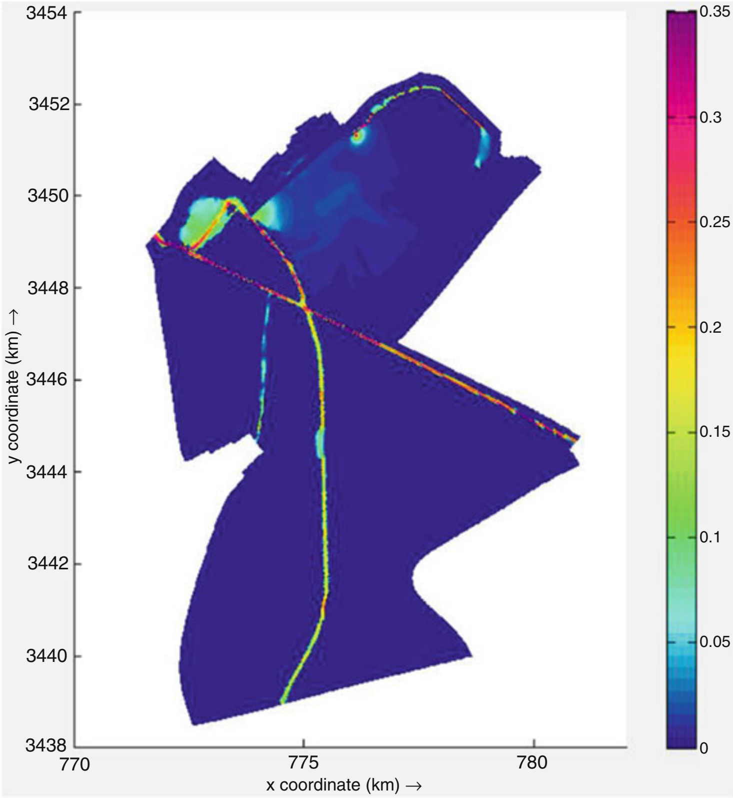


Fig. 9 The flow velocity map “Scenario-01”

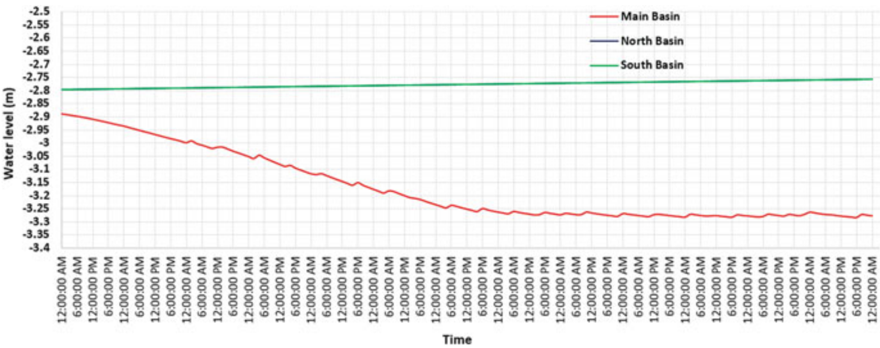


Fig. 10 The water level at the lake basins “Scenario-01”

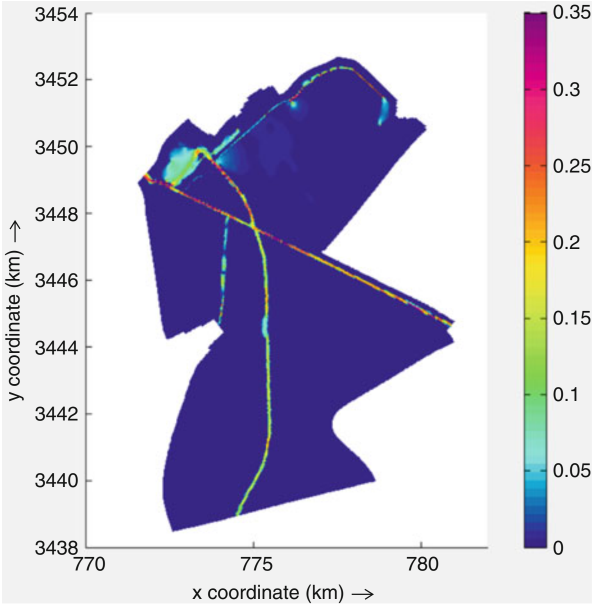


Fig. 11 The flow velocity map “Scenario-02”

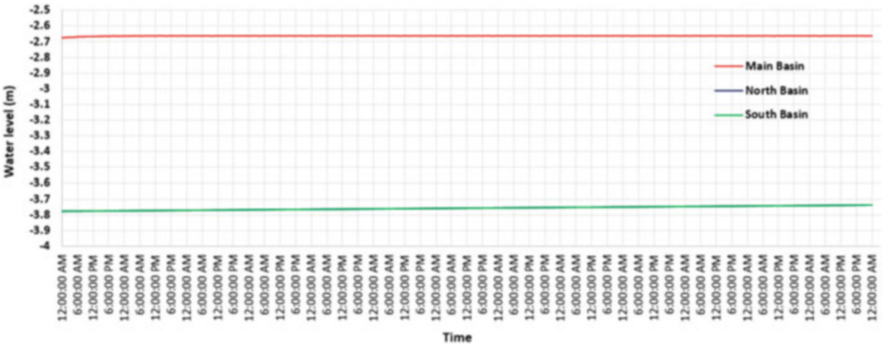


Fig. 12 The water level at the lake basins “Scenario-02”

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

4.1.4 Scenario-03

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

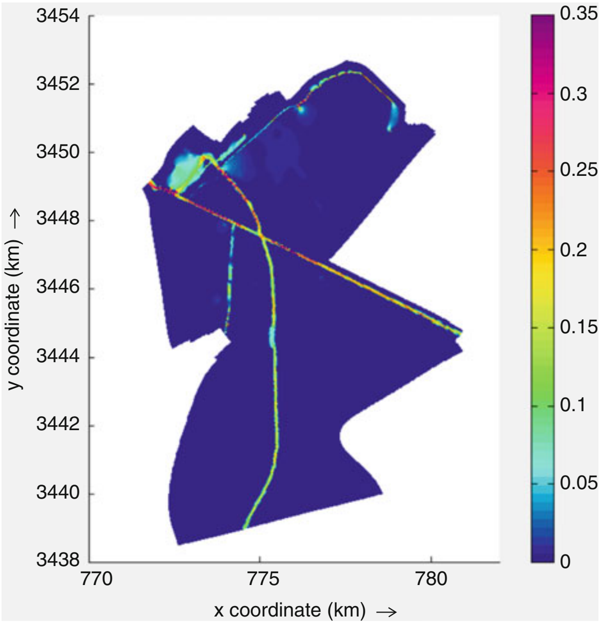


Fig. 13 The flow velocity map "Scenario-03"

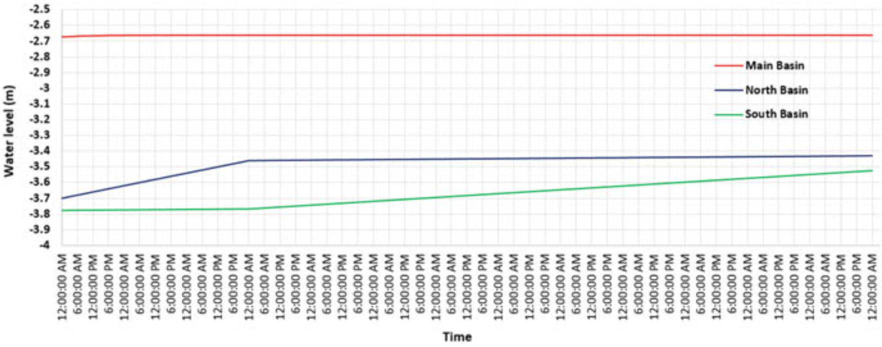


Fig. 14 The water level at the lake basins “Scenario-03”

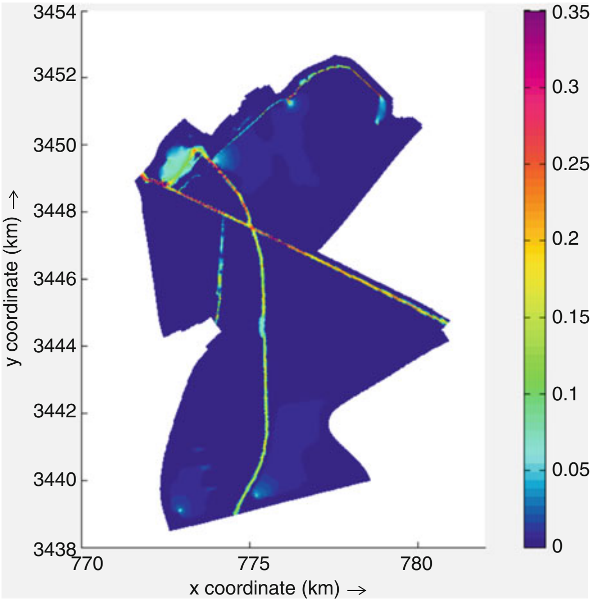


Fig. 15 The flow velocity map “Scenario-04”

4.1.5 Scenario-04

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

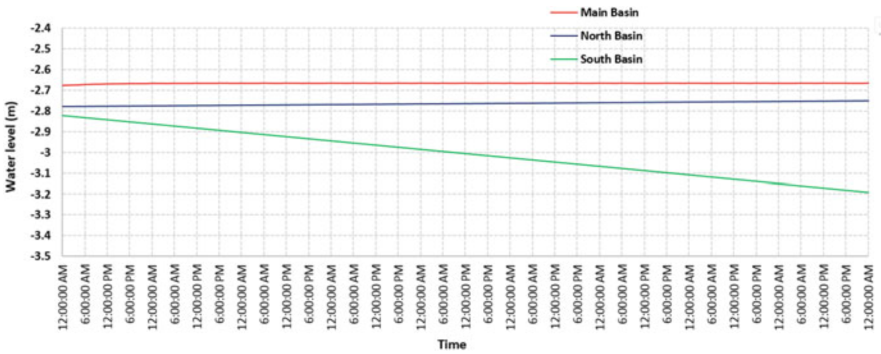


Fig. 16 The water level at the lake basins “Scenario-04”

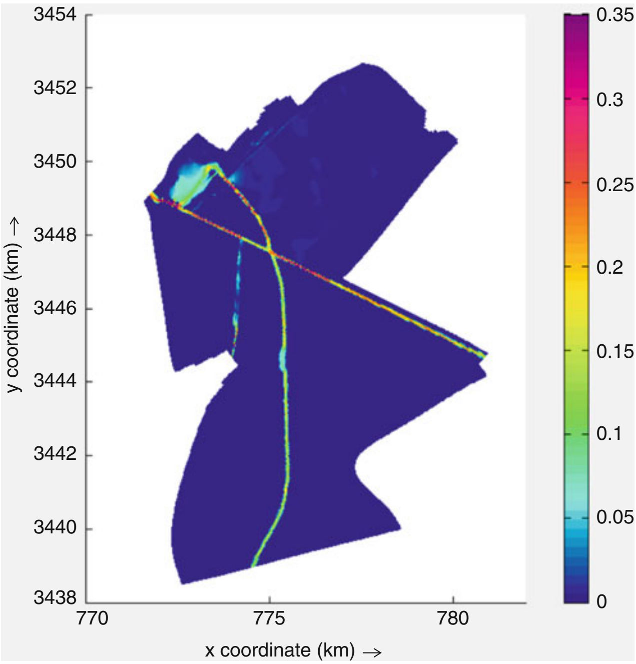


Fig. 17 The flow velocity map “Scenario-05”

4.1.6 Scenario-05

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

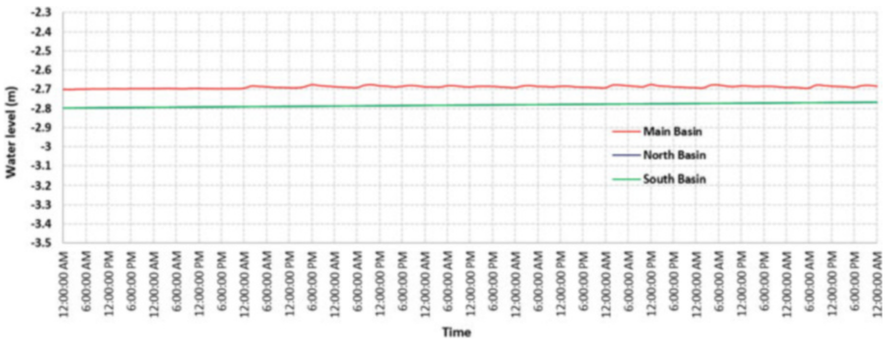


Fig. 18 The water level at the lake basins "Scenario-05"

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

4.2 *Water Quality Modeling Results*

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

4.2.1 Scenario-0 (Baseline)

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

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

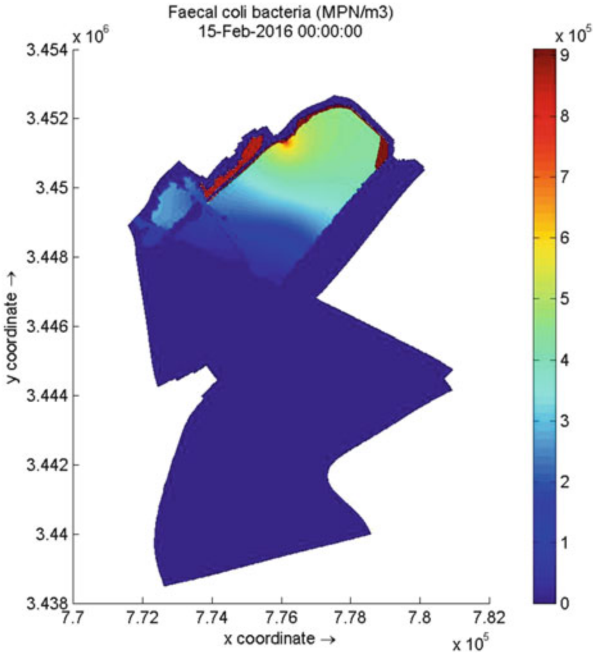


Fig. 19 The faecal coliform map "Scenario-0"

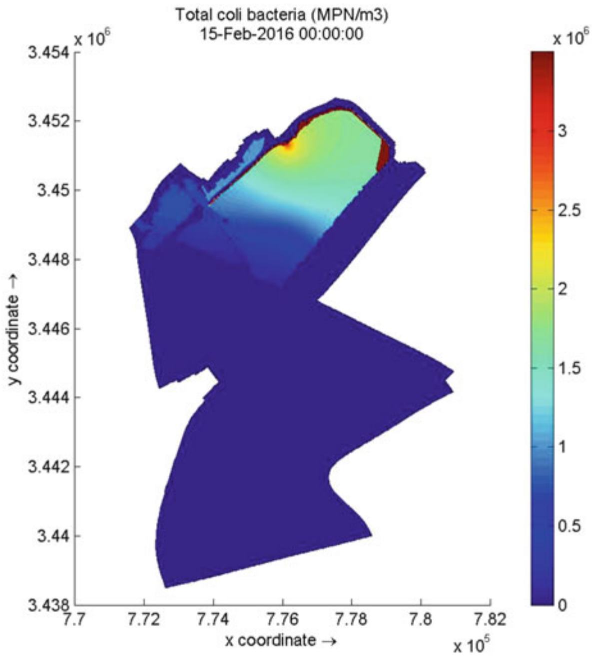


Fig. 20 The total coliform map "Scenario-0"

Fig. 21 Ammonia map "Scenario-0"

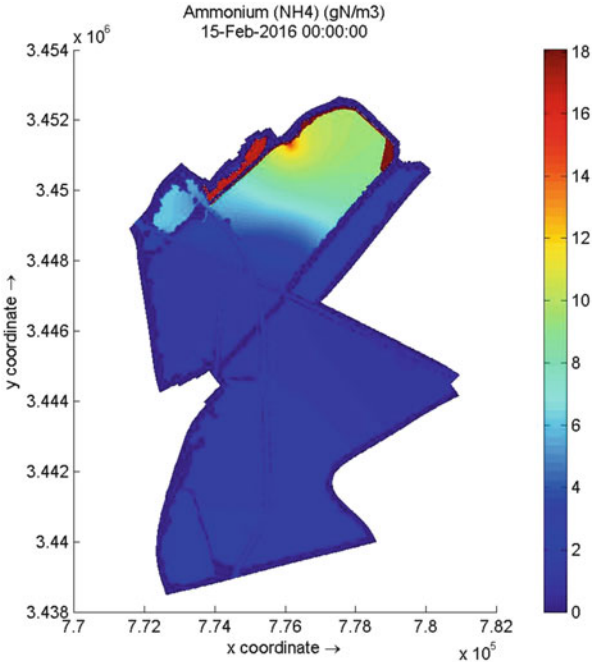
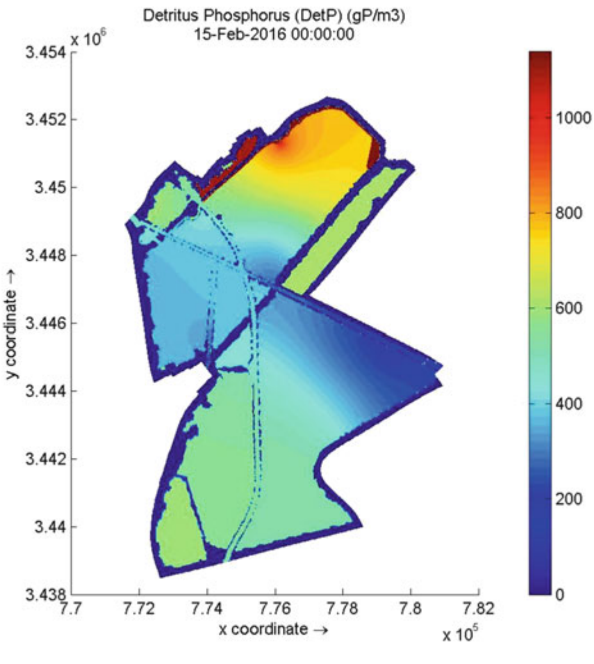


Fig. 22 Detritus phosphorus map "Scenario-0"



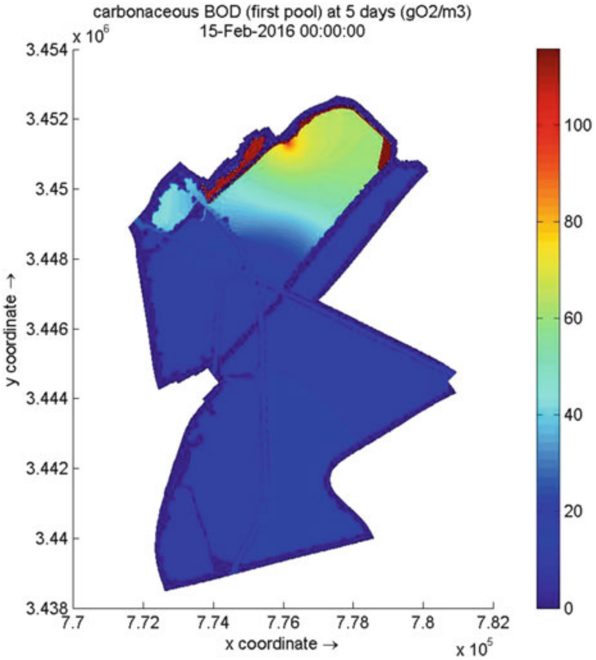


Fig. 23 BOD map "Scenario-0"

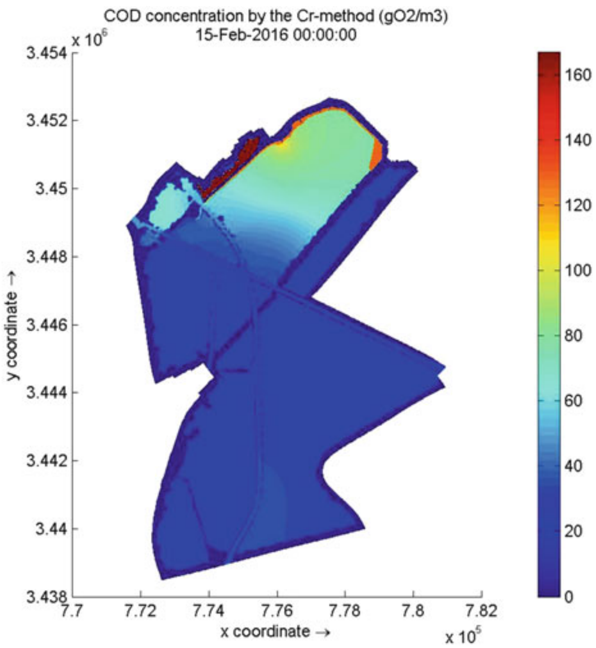


Fig. 24 COD map "Scenario-0"

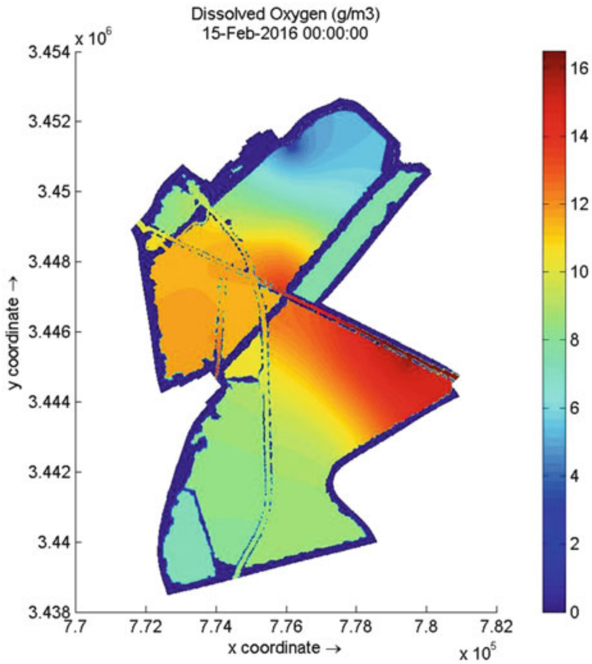


Fig. 25 DO map "Scenario-0"

4.3 Comparison of All Model Scenarios

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

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

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

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

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

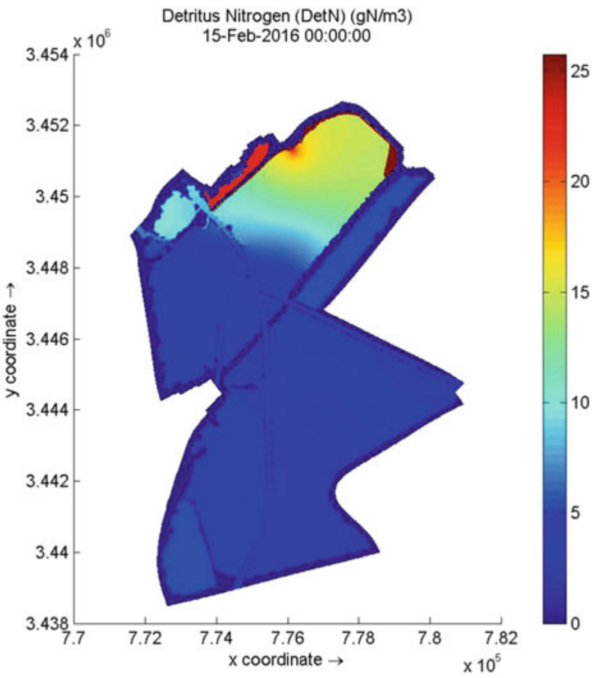


Fig. 26 DetN map "Scenario-0"

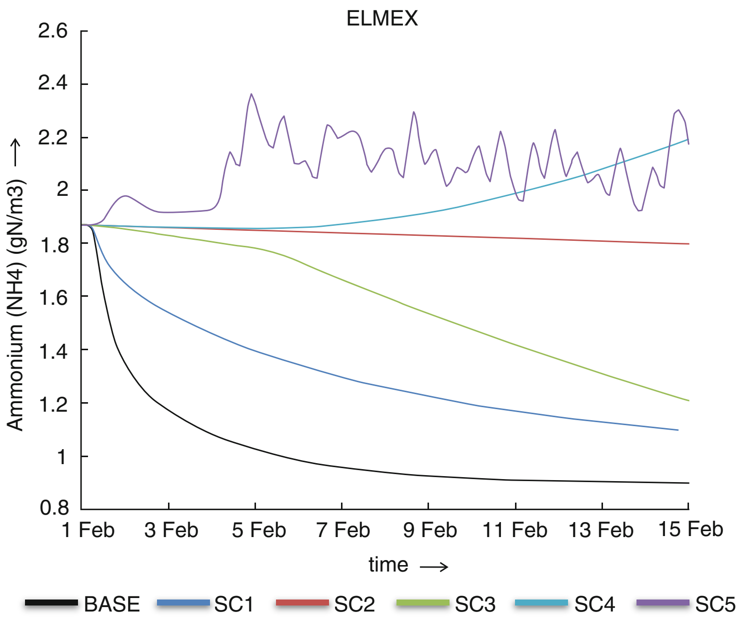


Fig. 27 Comparison between scenarios for ammonia at El Mex station

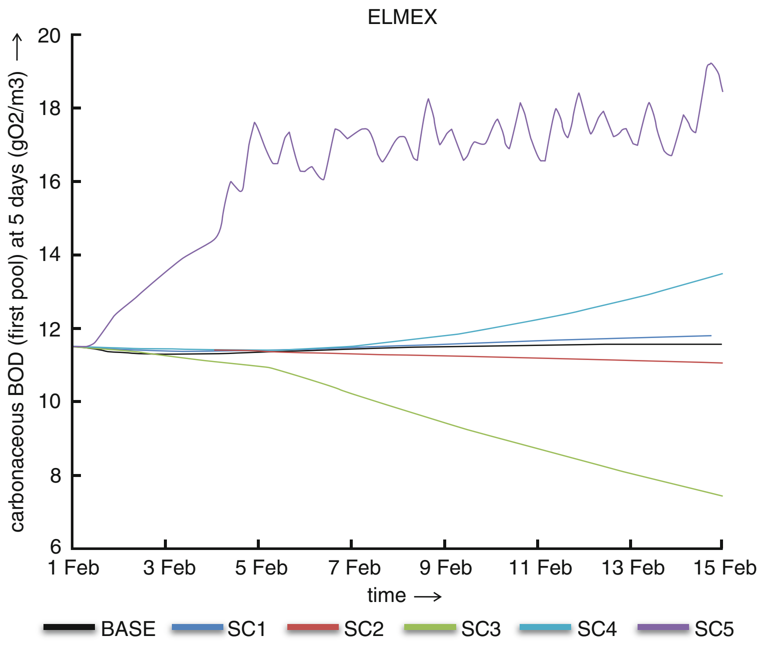


Fig. 28 Comparison between scenarios for BOD at El Mex station

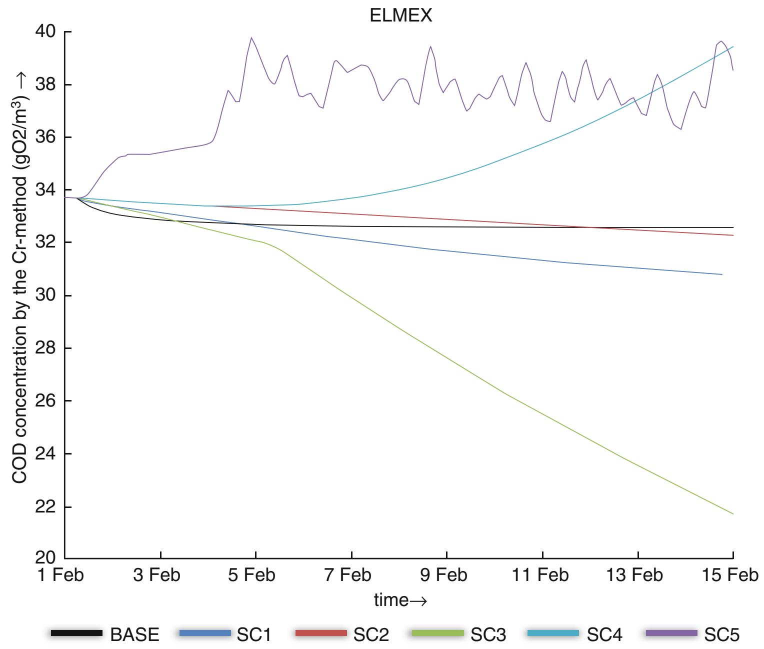


Fig. 29 Comparison between scenarios for COD at El Mex station

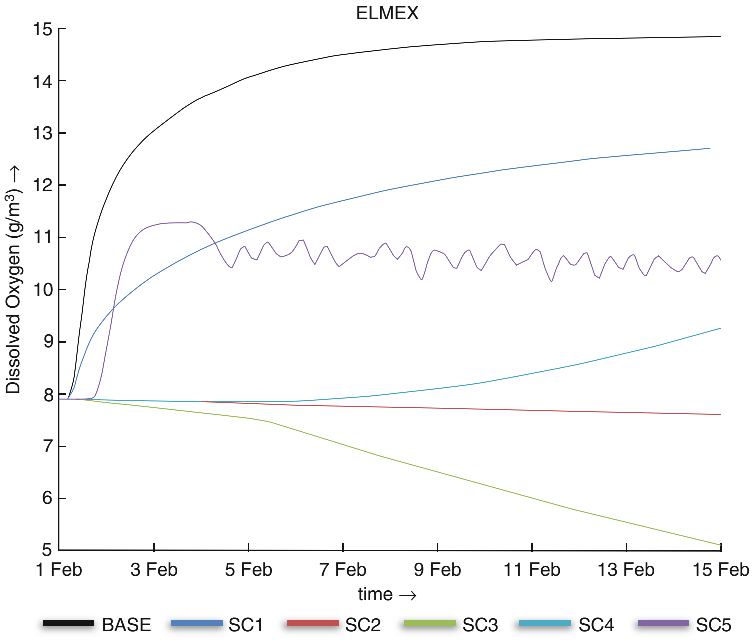


Fig. 30 Comparison between scenarios for dissolved oxygen at El Mex station

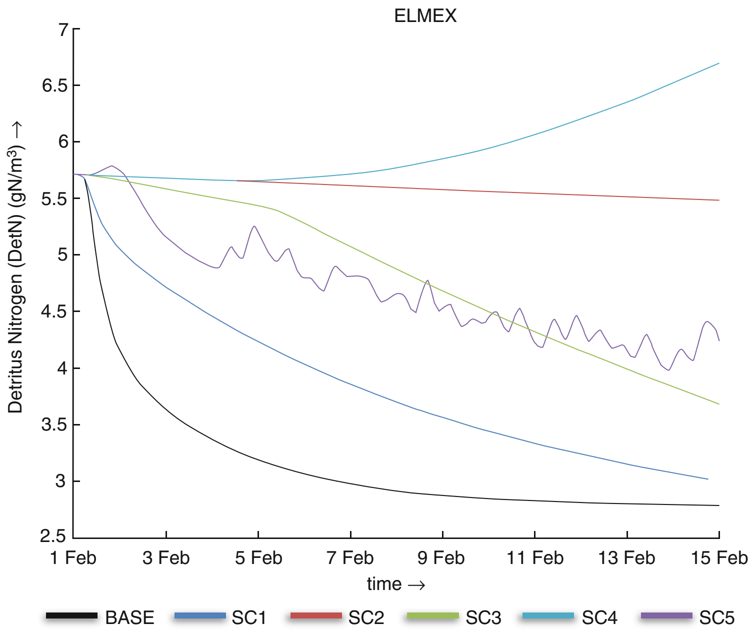


Fig. 31 Comparison between scenarios for detritus phosphorus at El Mex station

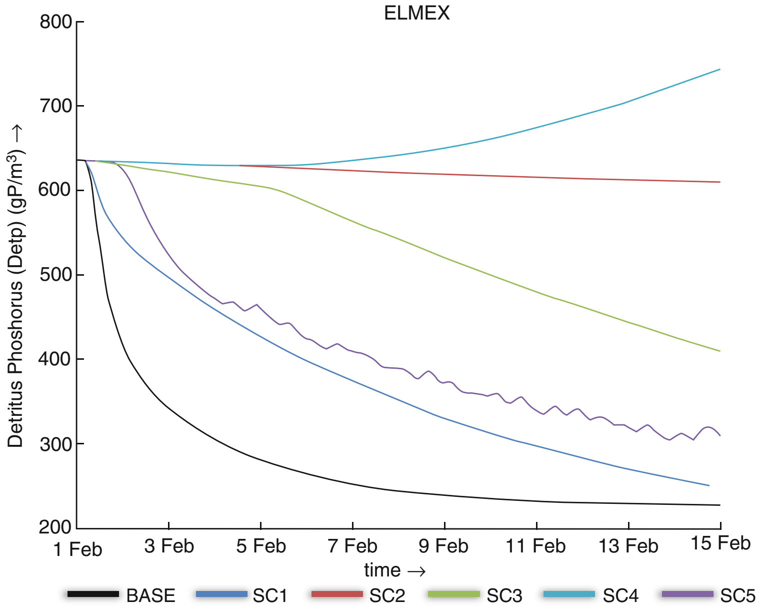


Fig. 32 Comparison between scenarios for water temperature at El Mex station

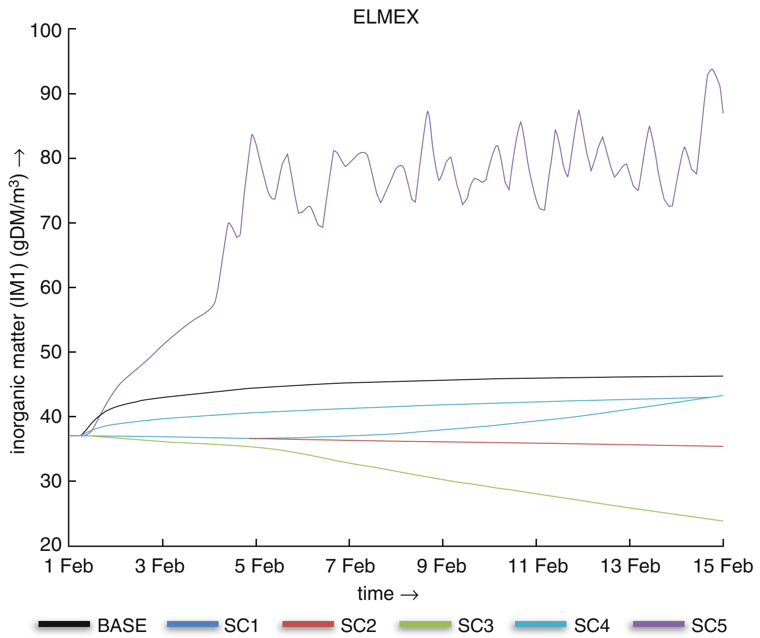


Fig. 33 Comparison between scenarios for cadmium at El Mex station

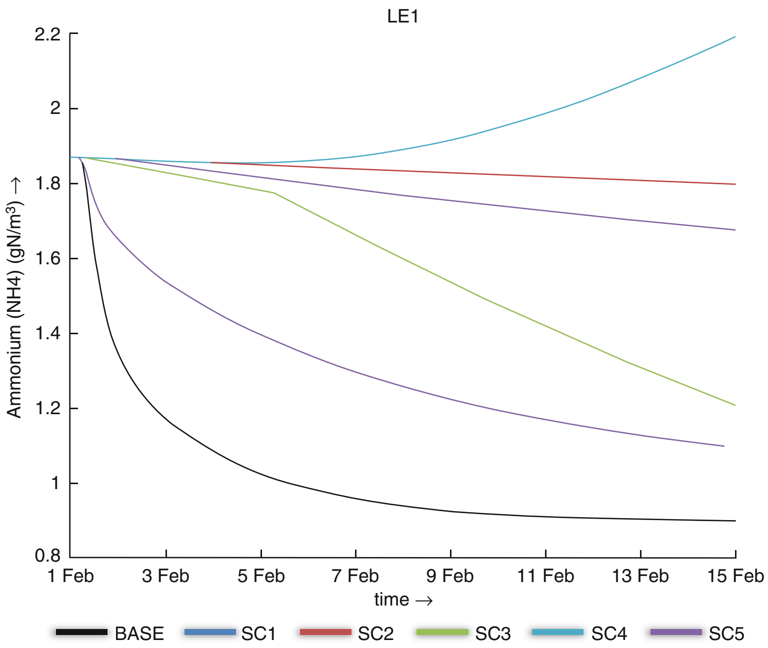


Fig. 34 Comparison between scenarios for ammonia at the middle of the lake

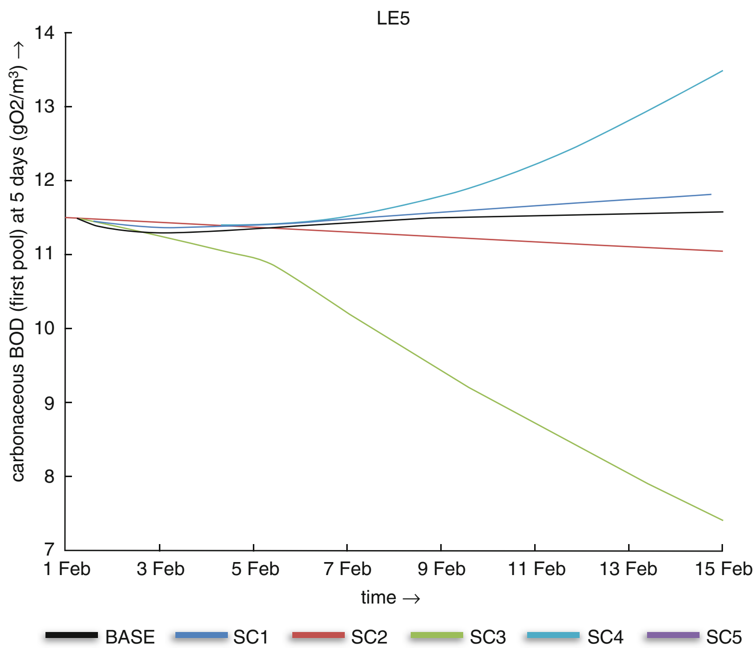


Fig. 35 Comparison between scenarios for BOD at the middle of the lake

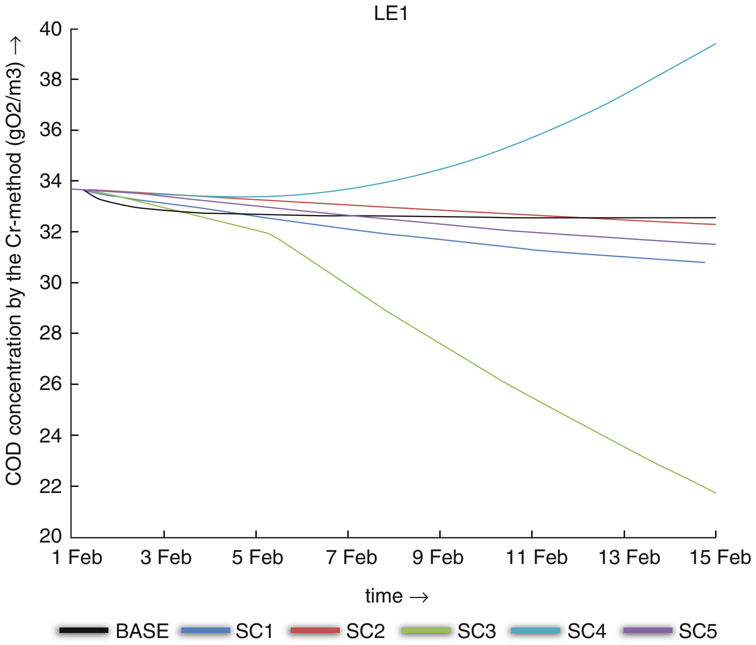


Fig. 36 Comparison between scenarios for COD at the middle of the lake

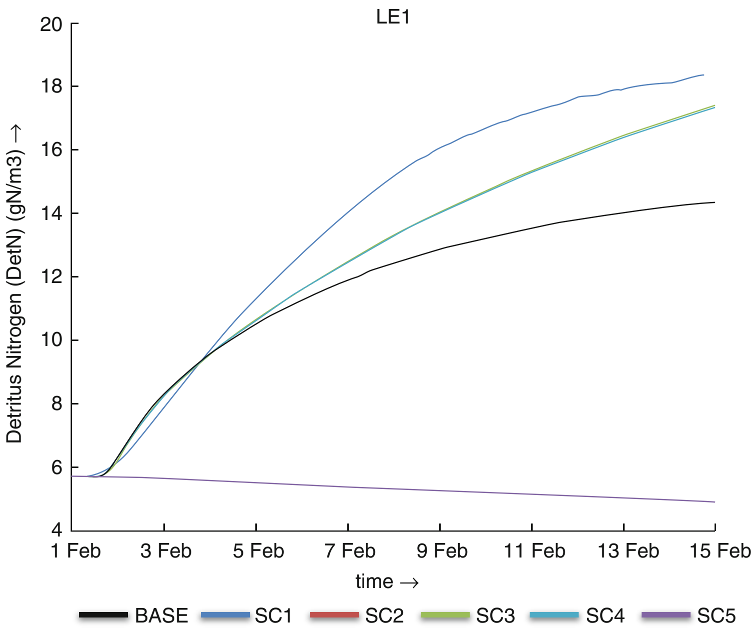


Fig. 37 Comparison between scenarios for detritus nitrogen at the middle of the lake

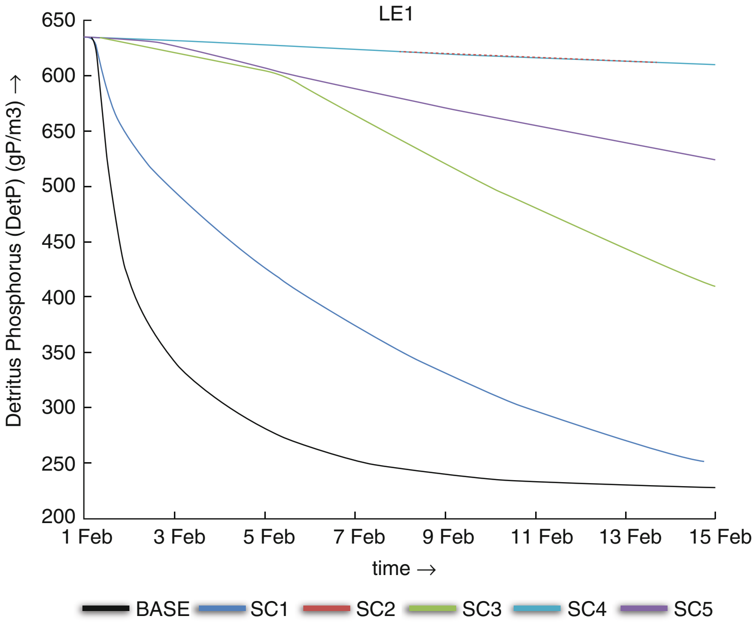


Fig. 38 Comparison between scenarios for detritus phosphorus at the middle of the lake

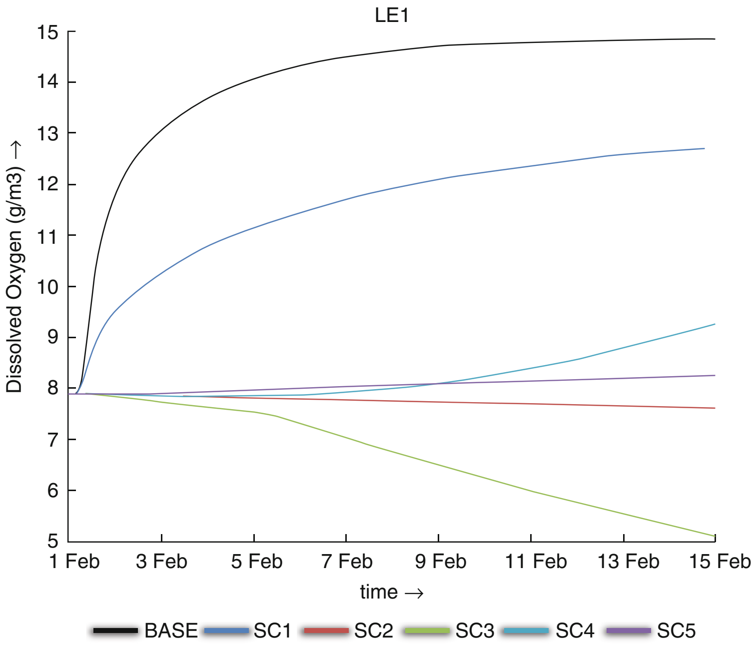


Fig. 39 Comparison between scenarios for DO at the middle of the lake

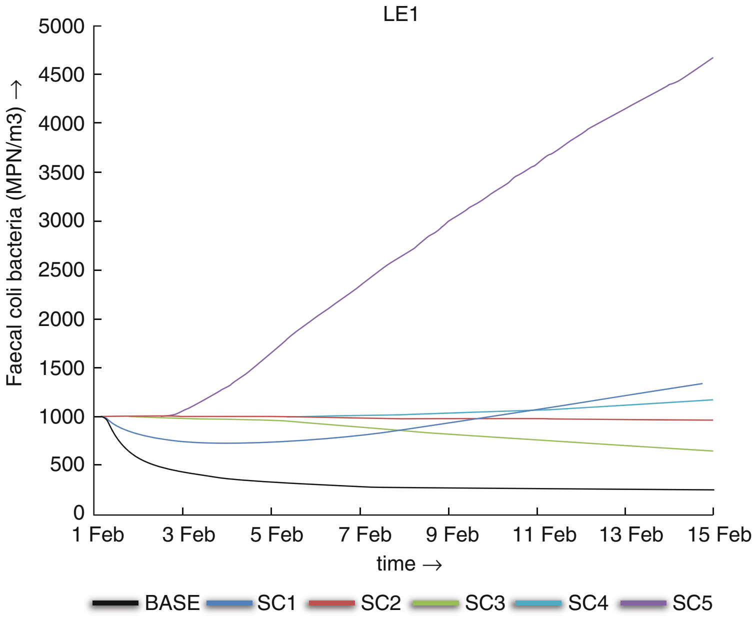


Fig. 40 Comparison between scenarios for fecal coliform at the middle of the lake

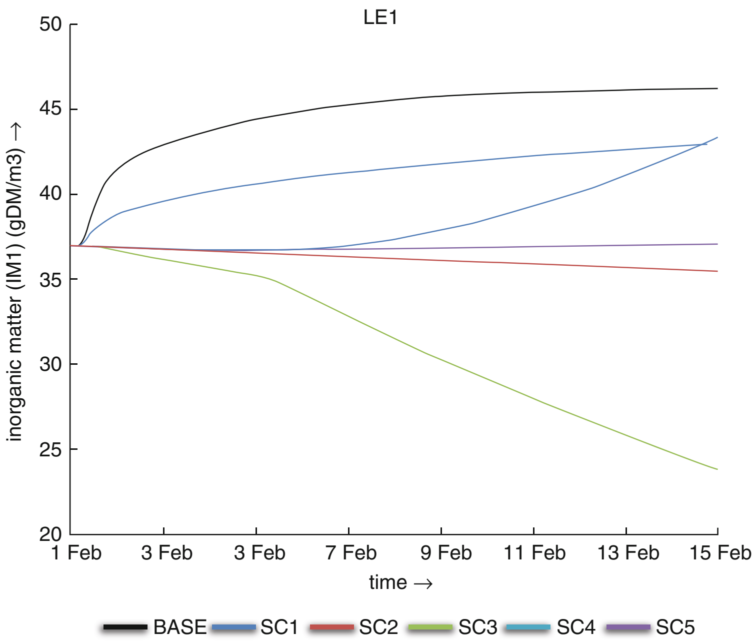


Fig. 41 Comparison between scenarios for the inorganic material middle of the lake

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

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

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

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

5 Conclusions

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

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

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Environmental Impacts on Egyptian Delta Lakes' Biodiversity: A Case Study on Lake Burullus

Alaa M. Younis

Abstract The Nile Delta lakes are proximate reservoirs of the Nile water flowing to the Mediterranean Sea. They play an important role in the nation's economy, not only because of producing more than 40% of the nation's fish catch but also for being resting areas for migrating birds. Moreover, they have an ecological importance due to a variety of biodiversity inhabiting the lakes and their hydrologic attributes. The expansion of agricultural reclamation after 1950 led to an increase in the amount of agricultural drainage to reach more than 4,000 million cubic meters which caused shifting in the biodiversity of the Lake Burullus. Therefore, the levels of salinity in the Lake Burullus decreased to reach 4.01‰ in 2015 which led to the fact that the freshwater biota became more predominant in the food web of the lake. In addition, the levels of nutrients derived from agricultural drains to the water body of Lake Burullus increased especially after 2001. Despite the gradual increase in fish production in the lake from 7,549 tons in 1963 to about 63,000 tons in 2015, the environmental factors also affected the variety of fish production causing the fish production in the lake to shift from marine species to freshwater fishes, and therefore, the diversity of marine fishes declined in the lake such as *Dicentrarchus labrax*, which has declined from 2,375 tons in 1991 to 346 tons in 2014, and some of these species have disappeared such as *Argyrosomus regius* and *crab*. As a result, the fisheries were shifted from mullet-based fish (marine) to tilapia-based fish (freshwater), while the production of mullets in the lake was declined from 44.7% in 1963 to 15.9% in 2015. On the other hand, the production of tilapia sharply increased from 42.8% in 1963 to 72% in 1992 and then decreased to around 62.1% in 2015. Environmental conditions of Lake Burullus results an increase and more abundance of freshwater aquatic macrophytes species while reduction of other species to one or two populations with few individuals on the shores of the Lake.

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Keywords Aquatic macrophytes, Biodiversity, Birds, Egypt, Environmental impacts, Fish, Lake Burullus, Nile Delta lakes

Contents

1 Introduction

The Egyptian Mediterranean coast exhibits five lakes or lagoons (northern coastal lakes) from the east in North Sinai Governorate to the west in Alexandria Governorate. These lakes are mainly ordered from east to west as follows: Bardawil, Manzala, Burullus, Edku, and Mariout. All of them, with the exception of Lake Mariout, are directly connected to the Mediterranean Sea. The northern delta lakes are economically the most important fishing ground. They provide rich and vital habitat diversity for estuarine and marine fish and their regeneration. Furthermore, they have always been major areas of fish production in Egypt. Hence, these lakes produce over 40% of the fish catch of Egypt. Moreover, they are worldwide important sites for birds, particularly those migrating from and to Africa and Europe [1, 2].

The Egyptian northern Nile Delta lakes suffer from some serious challenges such as incremental flow of freshwater, pollution, lakes degradation, high rate of population growth and erosion rates [3]. The northern delta lakes receive large amounts of freshwater via the working irrigation system, mainly drainage which are caused due to the expansion of agriculture and aquaculture, where these lakes connect several drains to convey their effluents inside the water body of the lakes to the spreading of aquatic vegetation which may reduce the water exchange through the lakes. Additionally, industrial development and urbanization during the last four decades led to increasing some serious problems within the lakes [3]. All these environmental impacts lead to the deleterious effects of damage and hazard to living organisms as well as the ecosystem.

Therefore, these lakes are under great threat of increasing freshwater via many agriculture drains and from eutrophication, pollution, and destruction of surrounding environments [4]. These environmental changes have reduced commercial fish species catch and greatly impacted the local fishery. Moreover, increasing the levels of pollution in the lakes impacted the ecosystem as well as human health [5–9].

The Egyptian delta lakes receive mainly a huge amount of agricultural waste water via drainage water from agricultural lands, as well as sewage and industrial wastes. Thus, these lakes suffer from an active process of pollution with anthropogenic materials [10, 11].

In each lake, however, the sequences and consequences are not necessarily the same. Nevertheless, the conclusion is similar, that is, "we may be killing our lakes and destroying our environment" [12].

2 Lake Burullus

Burullus Lake in Egyptian Nile Delta is one of the most vulnerable areas along the delta's coastline. It is the most centrally and the second largest of four shallow, brackish waters of the Egyptian northern lakes along the Mediterranean coast, together covering about 1,100 km^2. It extends between $31^{\circ}\ 22'–31^{\circ}\ 26'$ N and $30^{\circ}\ 33'–31^{\circ}\ 07'$ E, 60 km east of Rosetta branch and 70 km west of Damietta branch (Fig. 1). The length of the lake is about 65 km, but it is rather narrow, and its breadth varies between 5 and 16 km with the average being 11 km. The depth of the lake is subjected to comparatively large variations from day to day [13].

The eastern sector of the lake is the shallowest and saline, which contains a long canal connecting the lake to the Mediterranean Sea (El-Boughaz canal). While the western sector of the lake is the deepest part, which is also the freshest [12], the lake is extremely shallow, with a depth ranging between 0.42 and 2.07 m. The huge amounts of drainage water and the little amount of seawater entering the lake at its southern coast through several drains and El-Boughaz canal, respectively, bending on the wind direction, may have affected the water levels of the lake and rise in the lagoon level above sea level.

The present area of Lake Burullus is about 420 km^2 (100,000 feddan) of which 370 km^2 is open water [2]. Lake Burullus has an overall area of about 600 km^2 in 1900, while its area was estimated by 574 km^2 (136,620 feddan) in 1956 [14]. By 1974, land reclamation for agriculture in its southern part may have affected the size of the lake and caused it to decline to about 460 km^2 (110,000 feddan), and this decline continues today [13]. It seems that during the last 100 years, a reduction in the lake area by 30% took place [2]. This decrease is due to continuous land reclamation projects along the southern and eastern shores of the lake and fish farming processes [2]. The lake is separated from the Mediterranean Sea by a strip of land covered with sandbars and sand dunes of different width and height [12].

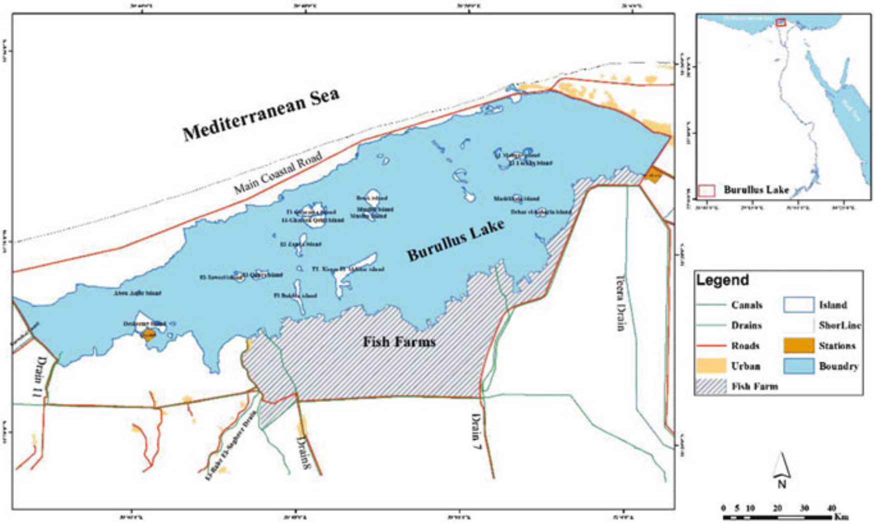

Fig. 1 Location of Lake Burullus, Nile Delta lakes, Egypt

3 Physicochemical and Limnological Features

Physicochemical and limnological features of the lake of Burullus have been impacted by drainage water that enters into the body through several drains (Fig. 1). The lake receives agricultural drainage water through nine drains and one freshwater canal (East Burullus Drain; Nasser Drain; Drain 7; El-Gharbia Drain; Drain 8, Tera Drain, Drain 9, El-Hoksa; Drain West Burullus Drain and Brimbal Canal) [2].

Generally, the amounts of agricultural wastewater entering the lake caused decreasing the levels of salinity and a trend toward a freshening as well as change from a saline toward a freshwater environment. Instead, a typical marine as well as freshwater biota continued to occur up to the late 1990s, but with changing proportions [13].

The average of the levels of water salinity in the Lake Burullus which is recorded by [12, 15–17] was presented in Fig. 2.

From the figure, it can be noticed that the average of salinity in the Lake Burullus decreased from 14‰ in 1966 to 4.01‰ in 2015. This is mainly due to increasing the total amount of drainage water which enters into the water body of the lake. Between 1935 and 1967, the total amount drained was about 2,300 2,700 million cubic meters, which increased in 1970 to about 3,200 million cubic meters, and in

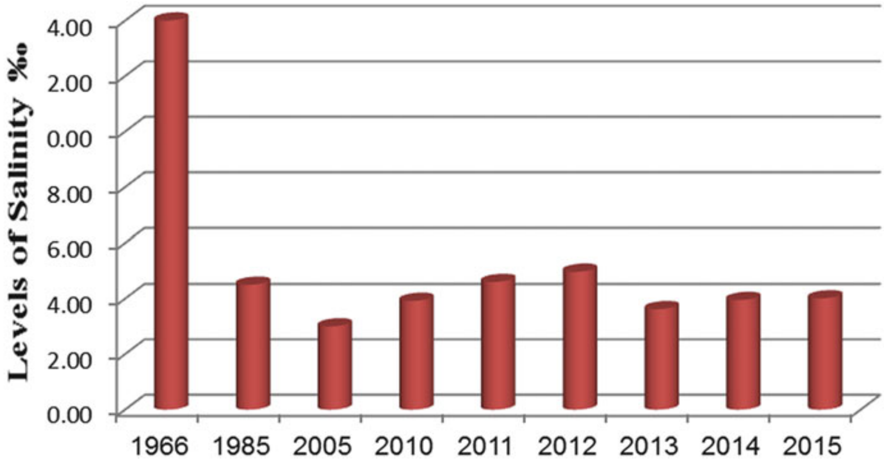

Fig. 2 Lake Burullus yearly average salinity levels, 1966–2015

2001 and later, a plateau value of about more than 4,000 million cubic meters was reached [13].

Beltagy [15] stated that the salinity distribution in the Lake Burullus is not constant and decreases going away from El-Boughaz canal, depending on the water drained by the drain system and canals, the water invading the lake from the sea, and the degree of mixing. He has shown that the lake can be divided into two distinct regions, the central and central-eastern part with salinity over 10‰ (19‰ maximum) and the western part with salinity between 1.5‰ and 10‰. However, by the early twenty-first century, during the period from 2001 to 2004, water salinity in the Lake Burullus was studied by Shaltout and Khalil [16]. They concluded that the average annual salinity decreased to about 3‰ due to increasing the total amount of freshwater discharged into the lake through the agricultural drains, while according to the Egyptian Environmental Affairs Agency report for Lake Burullus during the period from 2011 to 2015, the average annual salinity slightly increased to reach 4.01‰ in 2015.

During the last years in the Lake Burullus, this decline of the levels of water salinity was due to the increase in the amount of drainage water after 2001 through agricultural drains, which reached four billion cubic meters of water per year. This resulted in raising the water level for about 25–60 cm above sea level in the lake, resulting in preventing the seawater from entering the lake through El-Boughaz canal.

Nutrient salts are considered very important compounds essential for the living organisms in natural waters. Nutrients, chemical substances used for maintenance and growths of biota, are critical for the survival of organisms [18]. Plants require C, N, P, Si, Mg, K, and Ca and other essential elements to grow, reproduce, and overcome the disease. Of the essential nutrients, N and P are of particular concern in aquatic systems including estuaries, because their availability can limit the growth of aquatic plants. They are derived from different sources: human and animal wastes, decomposition of organic matter, and fertilizer runoff [19]. Rivers usually transport nutrients in both dissolved and particulate forms. Their estuarine reactivity can be brought about by physicochemical and geochemical (adsorption/desorption) and biological (e.g., photosynthetic production, biochemical degradation, excretion) processes. In the absence of these processes, the nutrients can behave conservatively, with their distribution being controlled by pure physical mixing of the river water and seawater. The phosphate ion concentration in the water of Lake Burullus is increased, as a result of expansion of agriculture, from 0.35 μg-at/l in 1985 to 232.01 μg-at/l in 2015 (Fig. 3).

Beltagy [12] stated that the phosphate levels in the southern regions of the lake have an average concentration of ca. 0.54 μg-at/l, while in the northern regions, the mean values may be as low as 0.20 μg-at/l. On the contrary, Abdel-Moati [20] indicated that higher averages observed in southern boundaries of the lake, few kilometers off the outlets, reflect the effect of large amounts of drainage water discharging. However, the levels of nutrients in the other zones are probably controlled by dynamical conditions between drain water supply and marine water invasion through the lake opening.

The annual average of nitrite-nitrogen content in the waters of the lake was 2.1 μg-at/l in 1985 [12] and gradually increased to reach 85.45 μg-at/l in 2015 [17] (Fig. 4). On the other hand, the annual average of silicate was 0.09 μg-at/l in 1985 (Fig. 5) and gradually increased to reach 3.02 μg-at/l in 2015 [17].

In comparison, the concentration of nitrate in the water body of Lake Burullus after 2001 with those studies conducted during the period from 1987 to 1997) Fig. 6), it was found that discharge of nutrients to the lake was rather modest until the mid-1990s, but had amplified tremendously by the end of the twentieth century [13].

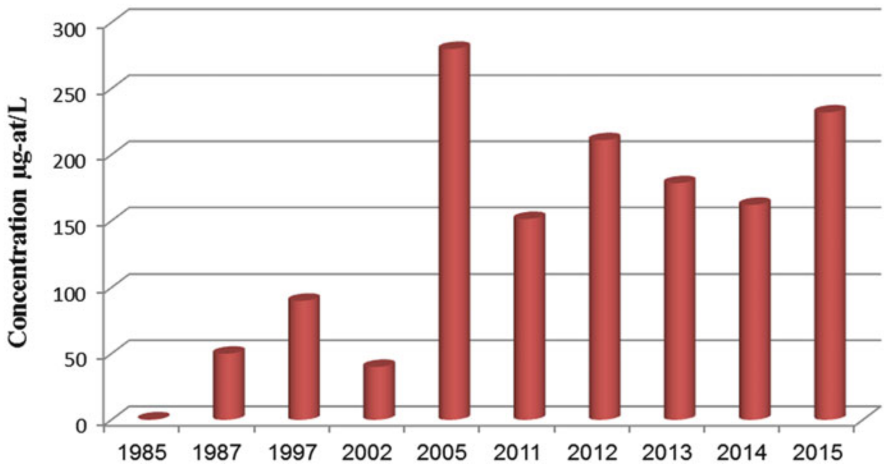

Fig. 3 Lake Burullus yearly average phosphate levels, 1985–2015

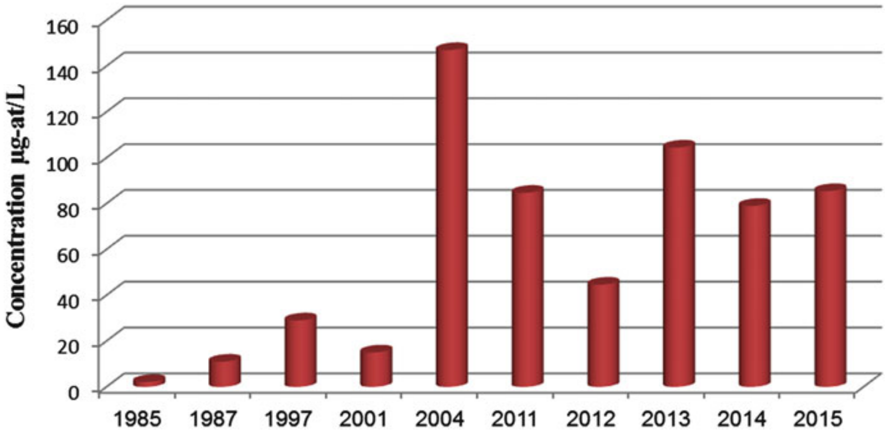

Fig. 4 Lake Burullus yearly average nitrite levels, 1985–2015

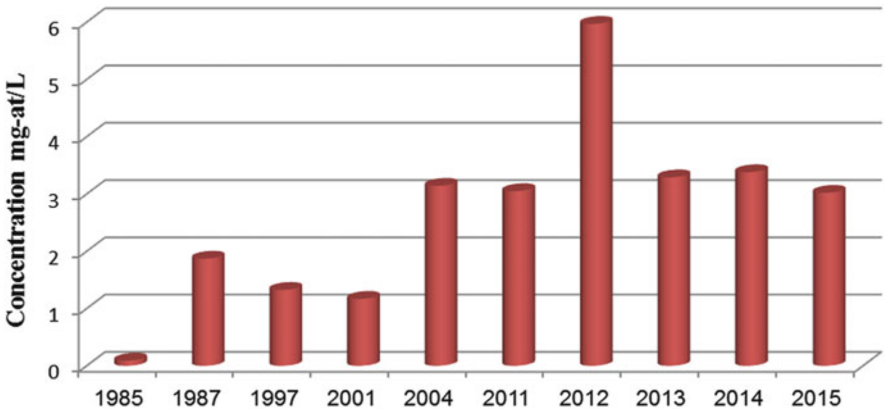

Fig. 5 Lake Burullus yearly average silicate levels, 1985–2015

A significant increase in the levels of nutrient after 2001 as drainage water has increased more than four billion cubic meters per year during that period. Dumont and El-Shabrawy [13] estimated the levels of nitrogen and phosphorus derived from agricultural drains to the water body of Lake Burullus during 2003 of 14,000 tons and 4,000 tons for nitrogen and phosphorus, respectively. The concentration of these elements in the drains is even higher than in the water body of the lake [13]. On the other hand, by comparing the levels of nitrate and silicate of the Lake Burullus during the period from 1970 to 1987, Abdel-Moati [20] found that significant changes had taken place in the nutrient chemistry of the lake since 1970. The concentrations of nitrate and silicate have decreased by one and three times since 1970, while on the contrary, the levels of phosphorus have increased about four times.

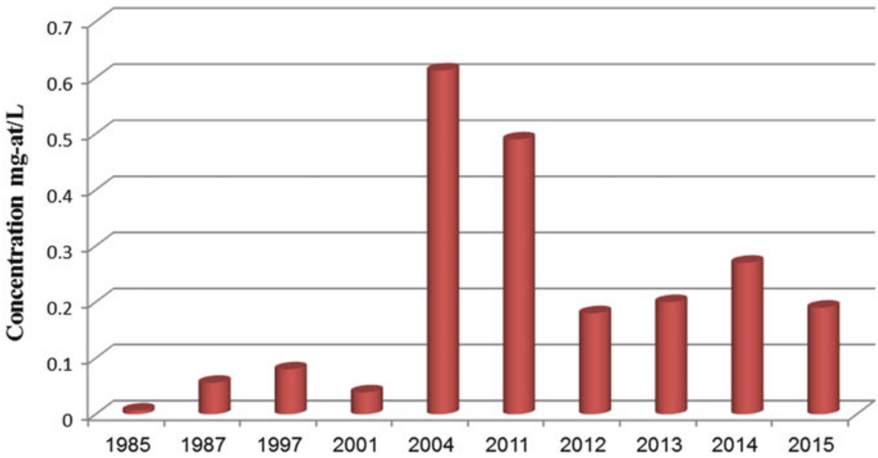

Fig. 6 Lake Burullus yearly average nitrate levels, 1985–2015

Not only the concentrations of nitrate and silicate have changed, but also their ratios have drastically declined. This variation is due to the increased rate of using the chemical fertilizers because of agricultural expansion.

4 Commercial Fishes in Lake Burullus

The annual fish production of the Lake Burullus has fluctuated between the 1930s and the mid-1960s around 4,000 to 8,000 tons per year and then slightly dropped in the early 1970s and finally was nearly stable until the mid-1980s [13]. According to the General Authority for Fish Resources Development (GAFRD) statistics, after 1985, the fish production in the lake gradually increased to about 63,000 tons in 2015 [21] (Fig. 7).

The previous studies showed that the presence of marine/ brackish waters in the water body of Lake Burullus resulted in a huge variety of fish species inhabiting the lake during the twentieth century. Approximately 32 species (Table 1) were recorded in the lake during this period [22, 23].

Several pure marine species of the fish stock in the lake, such as *Engraulis encrasicolus* (Linnaeus, 1758), *Belone belone* (Linnaeus, 1758), *Liza aurata* (Risso,1810), *Liza saliens* (Risso,1810), *Chelon labrosus* (Cuvier, 1829), *Dicentrarchus labrax* (Linnaeus, 1758), *D. punctatus* (Bloch, 1792), *Sparus aurata* (Linnaeus, 1758), *Johnius hololepidotus* (Lacepede, 1803), and *Solea solea* (Linnaeus,1758), comprise a significant proportion of fish production of the lake (Table 1).

These species are catadromous fishes; they enter the lake and spend most of their lives in the lake since the lake is their nursery and feeding grounds in order to

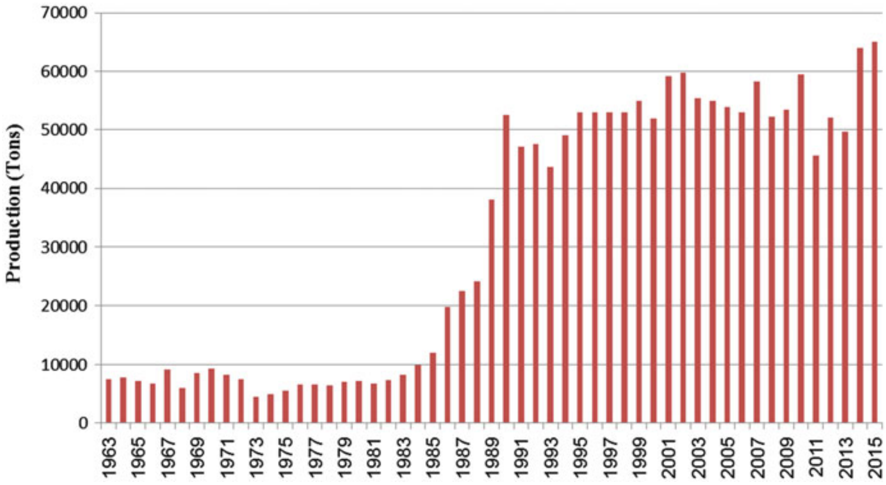

Fig. 7 Fish production from Lake Burullus during 1963–2015

continue their growth for adult stage. The marine fish species find the favorable conditions in the lake (e.g., nutrients and salinity) where the levels of nutrients in the lake higher than the sea and the salinity in the lake lower than the sea, therefore the marine fish species migrate to the sea through El-Boughaz channel for spawn [24].

Wider distribution of the brackish water species was observed such as *Aphanius fasciatus*, *Atherina mochon* and other representatives of family *Gobiidae*, *Anguilla anguilla*, *Mugil cephalus* and *Liza ramada* as well as some endemic freshwater species inhabit the lake, such as *Lates niloticus*, *Bagrus bajad*, *Hydrocynus forskalii*, *Barbus bynni*, *Clarias gariepinusas*, *Barbus prince* and *Labeo niloticus*, *Tilapia*, *Hemichromis*, *Haplochromis*, *Oreochromis*, and *Sarotherodon*.

But by 1950, as agriculture expanded, the amounts of drainage water increased, and therefore, the freshwater biota had decidedly begun to take a more prominent position in the lake's food web causing a shift in the fish production in the lake from marine species to freshwater fishes. Therefore, the fisheries have shifted from mullet-based fish (marine) to tilapia-based fish (freshwater) [13].

The change was more pronounced in the early of twenty-first century, during the field survey of Khalil and El-Dawy [25]. They pointed out that the diversity of commercial fishes in Lake Burullus declined from 32 species to 25 ones. The results of this study showed that all species which have disappeared from the lake are of marine origin. According to the General Authority for Fish Resources Development (GAFRD) statistics, some of the production of marine origin species were declined inside the lake and became settlement in El-Boughaz region, whereas others disappeared. This relates particularly to some species such as *Argyrosomus regius* which has disappeared from the Lake Burullus since 2001, while its production was 85 tons in 1994 (Fig. 8). Moreover, *crab* has also disappeared from the Lake Burullus since 2005, while its production was 189 tons in 1994 (Fig. 9), whereas the

Table 1 The commercial fishes in the Lake Burullus [16]

Family	Species	Habitat
Engraulidae	*Engraulis encrasicolus* (Linnaeus, 1758)	Seawater
Characidae	*Hydrocynus forskalii* (Cuvier, 1819)	Freshwater
Cyprinidae	*Labeo niloticus* (Forskal, 1775)	Freshwater
	Barbus bynni (Forskal, 1775)	Freshwater
	Barbus perince (Ruppell 1837)	Freshwater
Siluridae	*Clarias gariepinus* (Burchell, 1822)	Freshwater
	Bagrus bajad (Forskal, 1775)	Freshwater
Anguillidae	*Anguilla anguilla* (Linnaueus, 1758)	Fresh/saline water
Belonidae	*Belone belone* (Linnaeus, 1758)	Saline water
Cyprinodontidae	*Aphanius fasciatus* (Valenciennes, 1821)	Brackish water
Poeciliidae	*Gambusia affinis* (Baird & Girard, 1853)	Brackish water
Atherirudae	*Atherina mochon* (Cuvier, 1829)	Brackish water
Mugilidae	*Mugil cephalus* (Linnaeus, 1758)	Fresh/saline water
	Liza ramada (Risso, 1826)	Fresh/saline water
	Liza aurata (Risso, 1810)	Saline water
	Liza saliens (Risso, 1810)	Saline water
	Chelon labrosus (Cuvier, 1829)	Saline water
Serranidae	*Lates niloticus* (Linnaeus, 1762)	Freshwater
	Dicentrarchus labrax (Linnaeus, 1758)	Saline water
	D. punctatus (Bloch, 1792)	Saline water
Cichlidae	*Hemichromis bimaculatus* (Gill, 1862)	Freshwater
	Haplochromis bloyeti (Sauvage, 1883)	Freshwater
	Tilapia zillii (Gervais, l848)	Fresh/saline water
	Oreochromis niloticus niloticus (L., 1757)	Freshwater
	Oreochromis aureus (Steindachner, 1864)	Freshwater
	Sarotherodon galilaeus (Artedi, 1757)	Freshwater
Sparidae	*Sparus aurata* (Linnaeus, 1758)	Saline water
Sciaenidae	*Johnius hololepidotus* (Lacepede, 1803)	Saline water
Gobiidae	*Pomatoschistus minutus* (Pallas, 1767)	Brackish water
	Pomatoschistus (*lliinia*) *microps* (Krover, 1838)	Brackish water
	Lesueuria lesueuri (Risso, 1810)	Brackish water
Soleidae	*Solea solea* (Linnaeus, 1758)	Saline water
Pomatoschistus	*Johnius hololepidotus*	Saline water

production of some marine origin species in the lake such as *Dicentrarchus labra*x declined from 2,375 tons in 1991 to 387 tons in 2015 (Fig. 10). In addition, *Sparus aurata* declined from 582 tons in 2006 to 219 tons in 2015 (Fig. 11).

These GAFRD statistics were confirmed by the comparison of the production percentage of the mullets and tilapia in Lake Burullus in 1963 and 2015 [21] as presented in Fig. 12. From the figure, it is apparent that a gradual decline in the mullet catch was observed in 2015 from about 44.7% in 1963 to 15.9% in 2015 of the total catch. This was accompanied by an increase of tilapia production from

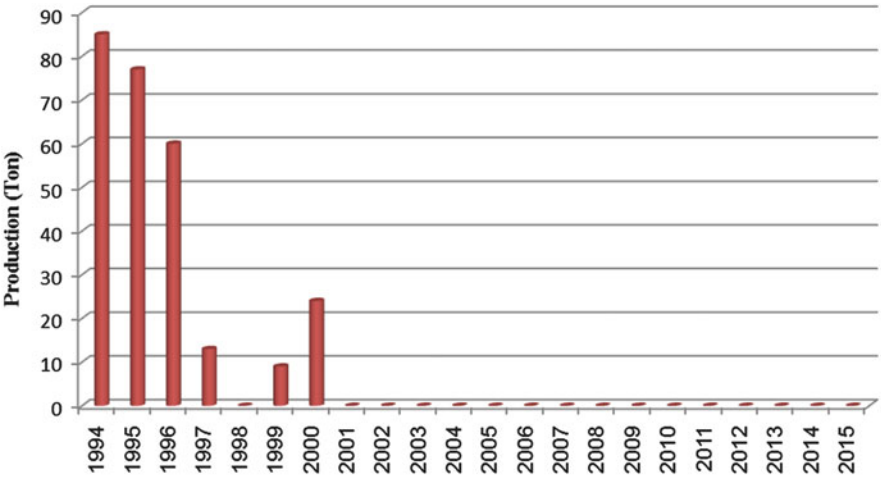

Fig. 8 *Argyrosomus regius* production in the Lake Burullus during 1994–2014

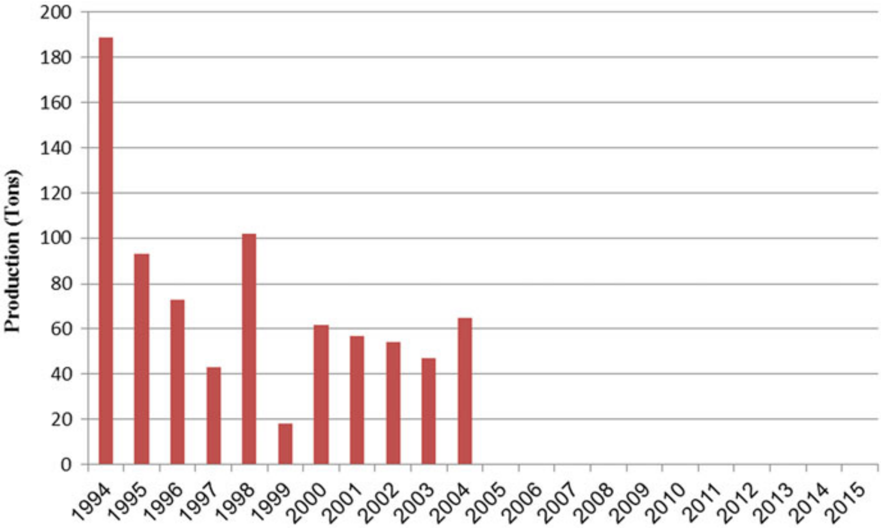

Fig. 9 Crab production in the Lake Burullus during 1994–2014

42.8% in 1963 to 72% in 1992, which was more pronounced during the 1980s and then decreased to about 62.1% in 2015. This is mainly due to the increase in the total amount of freshwater entering the water body of the lake.

Because of huge amounts of freshwater entering the lake, the freshwater biota inhabiting the lake and, therefore, some freshwater origin species such as tilapia were widely distributed in the lake (Fig. 12). The production of other freshwater

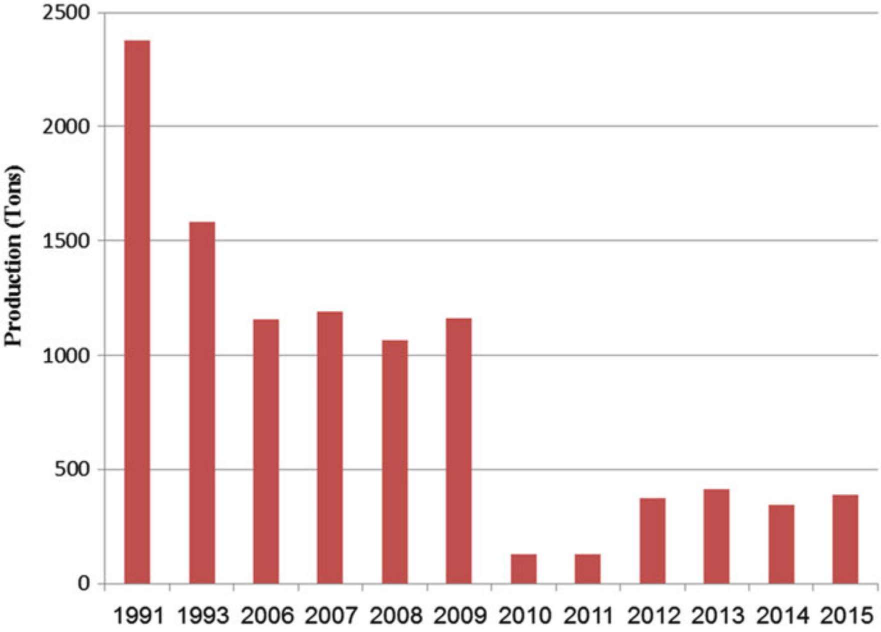

Fig. 10 European sea bass (*Dicentrarchus labrax*) production in the Lake Burullus during 1991–2014

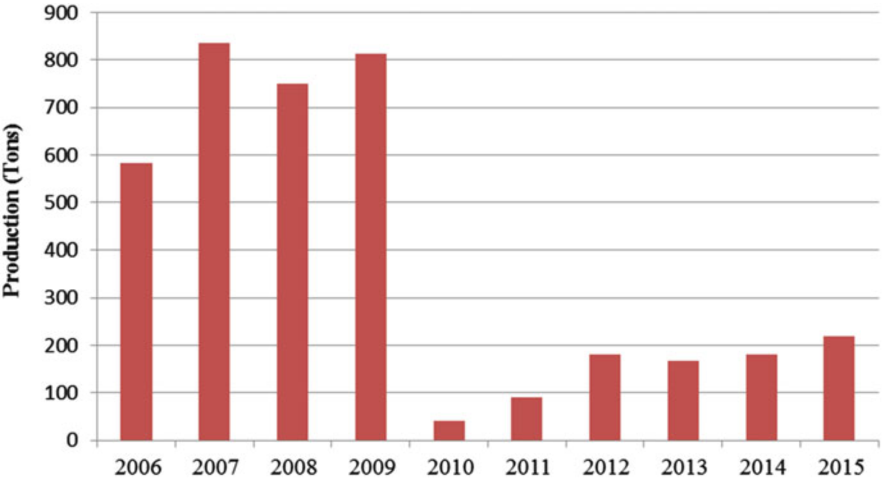

Fig. 11 *Sparus aurata* production in the Lake Burullus during 1994–2015

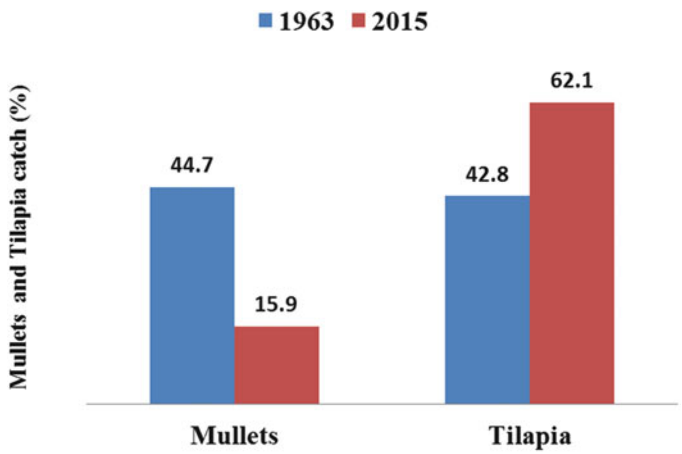

Fig. 12 Comparison of the production percentage of the mullet and tilapia in Lake Burullus in 1963 and 2015

origin species was sharply increased such as catfish production which increased from 188 tons in 1963 to 11,611 tons in 2009 (Fig. 13) [21].

5 Aquatic Macrophytes of Lake Burullus

The flora and vegetation of Lake Burullus have been investigated by [2, 16, 26–30]. During the early twenty-first century, the field survey of Shaltout and Al-Sodany [31] showed that the number of the recorded species in Lake Burullus was 197 species: 100 annuals and 97 perennials, including 12 hydrophytes, 44 families, and 139 genera. The number of the recorded aquatic macrophytes species in Lake Burullus, as estimated by Nafea [30], was 26 species: 4 submerged species, 8 floating species, and 14 emerged species (Table 2).

Of all environmental parameters, the salinity of water body of the lake appears to be the most important factor affecting the distribution and abundance of hydrophyte vegetation communities in the lake [2]. Younis and Nafea [2] classified the hydrophyte vegetation communities in the Lake Burullus into three categories. Some species are restricted to the more saline parts of the lake, e.g., *Ruppia maritima*, while others occur more abundantly in freshwater and slightly brackish water, e.g., *Myriophyllum spicatum*. Other species have wide ecological tolerance occurred in all parts of the lake, e.g., *Potamogeton pectinatus*, *Phragmites australis*, and *Typha domingensis*. High drainage water from agricultural and aquiculture projects in the south of the lake cause the reduction of many species to one or two populations with few individuals on the shores of Lake Burullus [32]. Therefore, during 2011–2012 in the field survey of Younis and Nafea [2], freshwater origin species *Myriophyllum spicatum* was recorded in front of Brimbal Canal that was not recorded in any of

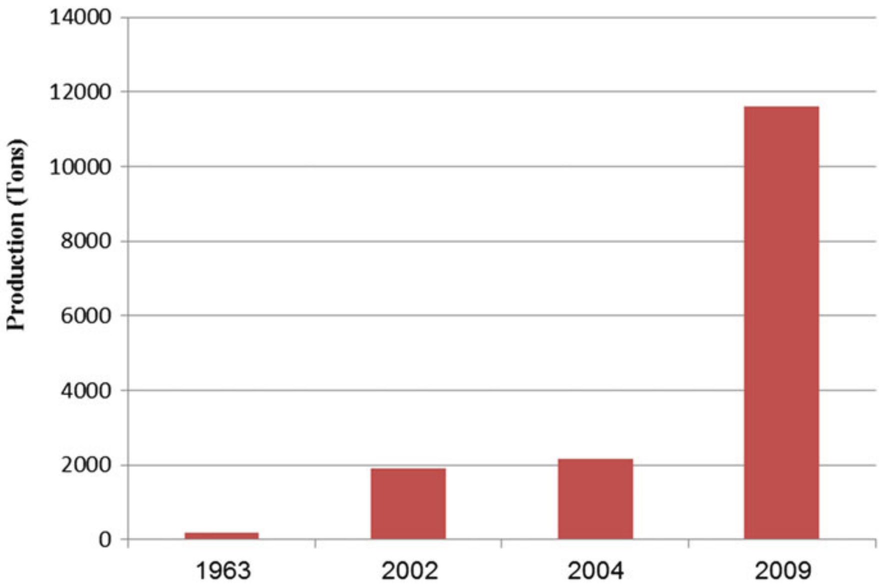

Fig. 13 Catfish catch of Lake Burullus from 1963 to 2009

the previous surveys. In addition, the results of this work showed that freshwater origin species *Ceratophyllum demersum*, *Najas armata*, and *Panicum repens* prefer more sheltered areas at the southern margins of the middle lake, around the outlets of southern drains where the water salinity was relatively low.

6 Birds

The lake of Burullus represents, most likely, a major route of migrating water birds coming from and to Africa and Europe [2]. Despite the huge numbers of migrated water birds passing Egypt from Europe toward wintering areas in Africa every year, the data on the function of Lake Burullus as a staging site for water bird migration is still quite limited [2].

Seven water bird surveys (1978/79, 1979/80, 1989/90, 1994, 2000, 2001, and 2011) were investigating the census of birds of Lake Burullus. According to the last census that was carried out during winter and spring of 2011 by Younis and Nafea [2], 137 bird species and subspecies were recorded. Thirty-three of these species are not recorded by Kassas [33] but one of them was recorded for the first time by Younis and Nafea [2] was not recorded in any of the previous surveys.

The dominating species of the last census that was recorded by Younis and Nafea [2] were *Ardeola ralloides*, *Ixobrychus minutus*, *Gallinula chloropus*, *Charadrius dubius*, *Tringa tetanus*, *Chlidonias hybrida*, *Sterna albifrons*, *Centropus senegalensis*, *Alcedo atthis*, *Hirundo rustica rustica*, *Riparia riparia*,

Table 2 Presence percentage (%) of the hydrophytes vegetation in lake Burullus (Nafea, 2005)

No.	Species	Percentage %
(a) Submerged species		
1	*Ceratophyllum demersum*	95
2	*Potamogeton pectinatus*	95
3	*Potamogeton crispus*	30
4	*Najas armata*	65
(b) Floating species		
1	*Eichhornia crassipes*	65
2	*Pistia stratiotes*	45
3	*Lemna gibba*	35
4	*Lemna minor*	15
5	*Nymphaea caerulea*	10
6	*Marsilea aegyptiaca*	15
7	*Azolla filiculoides*	15
8	*Spirodela polyrrhiza*	10
(c) Emerged species		
1	*Phragmites australis*	95
2	*Typha domingensis*	90
3	*Panicum repens*	80
4	*Ludwigia stolonifera*	85
5	*Persicaria salicifolia*	45
6	*Persicaria senegalensis*	75
7	*Echinochloa stagnina*	70
8	*Saccharum spontaneum*	65
9	*Scirpus maritimus*	30
10	*Scirpus littoralis*	15
11	*Juncus rigidus*	15
12	*Cynanchum acutum*	40
13	*Juncus subulatus*	5
14	*Cyperus articulatus*	–

Motacilla flava flavissima, *Motacilla alba alba*, *Acrocephalus schoenobaenus*, *Phylloscopus trochilus*, *Prinia prinia*, *Passer hispaniolensis*, *Passer domesticus*, *Porzana porzana*, *Acrocephalus scirpaceus*, and *Halcyon smyrnensis*.

The results of all surveys showed that there was a remarkable increase in species richness associated with a sharp decrease in the community density.

The first three censuses are those of Meininger and Atta [34], the fourth is that of Tinarelli [35], the fifth is that of Tharwat and Hamied [36], the sixth is that of Kassas [33], and the seventh is that of Younis and Nafea [2] (Table 3).

Table 3 List of the bird species recorded in Lake Burullus based on seven censuses extended from 1978 to 2012

Species	Recorded in					
	1978/79	1979/80	1989/90	1994	2000	2001	2011
Tachybaptus ruficollis	–	+	+	–	+	+	+
Podiceps cristatus			+			+	+
Podiceps nigricollis			+	+		+	+
Phalacrocorax carbo sinensis			+	+		+	+
Ardea cinerea	+	+	+		+	+	+
Ardeola ralloides			+	+	+	+	+ Dominant
Nycticorax nycticorax					+	+	+
Ixobrychus minutus		+	+		+	+	+ Dominant
Egretta alba alba	+		+	+		+	+
Egretta ibis ibis			+	+	+	+	+
Egretta garzetta		+	+	+	+	+	+
Phoenicopterus ruber roseus			+			+	+
Tadorna tadorna			+			+	+
Anas platyrhynchos	+	+	+	+		+	+
Anas crecca	+	+	+			+	+
Anas strepera	+	+				+	+
Anas penelope	+	+	+	+		+	+
Anas clypeata	+	+	+	+	+	+	+
Anas querquedula					+	+	+
Netta rufina	+	+	+	+		+	+
Athyene ferina	+	+	+	+		+	+
Athyene nyroca	+	+	+	+		+	+
Athyene fuligula	+	+	+	+		+	+
Elanus caeruleus				+	+	+	+
Circus cyaneus				+		+	+
Circus pygargus					+	+	+
Circus aeruginosus				+		+	+
Falco tinnunculus				+	+	+	+
Rallus aquaticus		+	+	+		+	+
Porzana porzana		+				+	+
Gallinula chloropus	+	+	+	+	+	+	+ Dominant
Porphyrio porphyrio		+	+	+	+	+	+
Fulica atra	+	+	+	+	+	+	+
Rostratula benghalensis						+	+
Himantopus himantopus			+			+	+
Recurvirostra avosetta		+	+	+	+	+	+
Glareola pranticola						+	+

(continued)

Table 3 (continued)

Species	Recorded in						
	1978/79	1979/80	1989/90	1994	2000	2001	2011
Charadrius hiaticula		+	+	+	+	+	+
Charadrius dubius				+		+	+ Dominant
Charadrius pecuarius				+		+	+
Charadrius alexandrinus		+	+	+	+	+	+
Charadrius leschenaultii		+	+	+	+	+	+
Pluvialis squatarola	+	+	+			+	+
Vanellus vanellus	+	+	+	+		+	+
Chettusia leucura				+		+	+
Haploporus spinosus	+	+	+	+	+	+	+
Calidris alba				+		+	+
Calidris temminckii			+			+	+
Calidris ferruginea				+		+	+
Calidris minuta	+	+	+	+	+	+	+
Calidris alpina	+	+	+	+	+	+	+
Philomachus pugnax	+			+	+	+	+
Gallinago gallinago	+	+	+	+		+	+
Limosa limosa			+	+		+	+
Numenius arquata			+			+	+
Tringa erythropus			+	+		+	+
Tringa totanus	+	+	+	+	+	+	+ Dominant
Tringa nebularia	+		+	+	+	+	+
Tringa ochropus	+	+	+	+		+	+
Tringa glareola		+	+	+		+	+
Tringa stagnatilis			+	+		+	+
Actitis hypoleucos		+	+	+		+	+
Arenaria interpres				+		+	+
Larus minutus	+	+	+	+		+	+
Larus genei	+	+	+	+	+	+	+
Larus canus	+	+				+	+
Larus fuscus	+	+	+	+	+	+	+
Larus ridibundus						+	+
Larus argentatus	+	+	+	+	+	+	+
Chlidonias niger	+					+	+
Chlidonias hybrida	+	+	+	+		+	+ Dominant
Chlidonias leucoptera					+	+	+
Sterna albifrons	+				+	+	+ Dominant
Sterna hirundo						+	+

(continued)

Table 3 (continued)

Species	Recorded in						
	1978/79	1979/80	1989/90	1994	2000	2001	2011
Streptopelia senegalensis				+	+	+	+
Centropus senegalensis				+	+	+	+ Dominant
Streptopelia decaocto					+	+	+
Cuculus canorus					+	+	+
Tyto alba				+		+	+
Athene noctua saharae				+		+	+
Athene noctua glaux					+	+	+
Alcedo atthis	+	+	+	+	+	+	+ Dominant
Ceryl rudis	+	+	+	+	+	+	+
Merops orientalis					+	+	+
Upupa epops				+	+	+	+
Hirundo rustica rustica				+	+	+	+ Dominant
Riparia riparia					+	+	+ Dominant
Calandrella rufescens				+		+	+
Galerida cristata				+	+	+	+
Anthus cervinus				+		+	+
Motacilla flava pygmaea				+		+	+
Motacilla flava flavissima					+	+	+ Dominant
Motacilla alba alba				+		+	+ Dominant
Motacilla cinerea					+	+	+
Lanius collurio					+	+	+
Sturnus vulgaris				+		+	+
Corvus corone				+	+	+	+
Acrocephalus stentoreus				+		+	+
Acrocephalus schoenobaenus						+	+ Dominant
Phylloscopus collybita				+		+	+
Phylloscopus trochilus						+	+ Dominant
Prinia prinia						+	+ Dominant
Prinia gracilis				+		+	+
Cisticola juncidis				+		+	+
Saxicola torquata				+		–	+
Saxicola rubetra						–	+
Passer domesticus				+		–	+ Dominant

(continued)

Table 3 (continued)

Species	Recorded in						
	1978/79	1979/80	1989/90	1994	2000	2001	2011
Passer hispaniolensis				+		–	+ Dominant
Emberiza calandra					+	–	+
Emberiza schoeniclus					+	–	+
Porzana porzana						–	+ Dominant
Gavia arctica arctica				+			
Lymnocryptes minimus					+		
Limosa lapponica lapponica					+		
Larus ichthyaetus	+	+	+	+			
Larus ridibundus	+	+	+	+	+		
Thalasseus sandvicensis sandvicens			+	+			
Centropus senegalensis aegyptius				+	+		
Prinia gracilis deltae				+			
Scotocerca inquieta inquieta					+		
Acrocephalus scirpaceus						–	+ Dominant
Acrocephalus arundinaceus						–	+
Ploceus manyar						–	+
Bubulcus ibis						–	+
Cutrinex cutrinex						–	+
Emberiza hortulana						–	+
Elanus caeruleus						–	+
Sylvia atricapilla						–	+
Sylvia borin						–	+
Sylvia communis						–	+
Sylvia curruca						–	+
Vanellus spinosus						–	+
Clamator glandarius						–	+
Erithacus rubecula						–	+
Phoenicurus phoenicurus						–	+
Oenanthe oenanthe						–	+
Muscicapa striata						–	+
Merops persicus						–	+
Halcyon smyrnensis						–	+ Dominant
Jynx torquata						–	+
Lanius senator						–	+
Luscinia svecica						–	+

(continued)

Table 3 (continued)

Species	Recorded in						
	1978/79	1979/80	1989/90	1994	2000	2001	2011
Hirundo rustica savignii						–	+
Accipiter nisus						–	+
Locustella luscinioides						–	+
Luscinia megarhynchos						–	+

7 Conclusions

The Egyptian Mediterranean coast exhibits five lakes or lagoons. These lakes are mainly ordered from east to west as follows: Bardawil, Manzala, Burullus, Edku, and Mariout, which are considered the most important sites in the Egyptian Mediterranean coastal water. Lake Burullus is one of the Nile Delta lakes located between the two main Egyptian Delta promontories Rosetta and Damietta. This lake is a *Ramsar* site and has been proclaimed as a protected area since 1998. The protectorate includes the water body of Lake Burullus as well as the numerous islets inside it.

Because of the presence of marine/brackish waters in the water body of Lake Burullus, a huge variety of biodiversity inhabits the lake. But unfortunately in the recent years, the amounts of agricultural wastewater and sewage entering the water body of the lake through several drains at the southern part impacted the physicochemical and limnological features of the lake. Decreasing the levels of salinity in Lake Burullus was due to the increase in the total amount of drainage water entering the water body of the lake which reached more than 4,000 million cubic meters which caused shifting in the biodiversity of the lake. Therefore, the freshwater biota has decidedly begun to take a more prominent position in the lake's food web. The Egyptian government represented in the Egyptian Ministry of Environmental Affairs and Egyptian Environmental Affairs Agency updated the National Biodiversity, Strategy and Action Plan (NBSAP). One of the important goals of this strategy is to minimize the rate of lake degradation by 50% and improve the water quality for farming by 50%. The major challenges for the Egyptian government in the Lake Burullus toward achieving the National Biodiversity Strategy are anthropogenic activities and land runoffs.

8 Recommendation

1. It is very important to design a management plan for restoring the ecological conditions.
2. Initiating a network for continuously monitoring water quantity and quality, treating water for reuse, and monitoring climate change.
3. The mechanical removal of reeds form 50 cm under water surface caused recycling of the lake water.

4. Maintaining the sea outlet (El-Boughaz) to flow seawater as well as marine fish origin into the lake.
5. The drainage water entering into the lake from fish farms surrounding the lake must be controlled.

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Coastal Lakes as Hot Spots for Plant Diversity in Egypt

Kamal Shaltout, Magdy El-Bana, and Tarek Galal

Abstract Five lakes (Mariut, Edku, Burullus, Manzala, and Bardawil) of global importance for migratory birds extend along the Egyptian Mediterranean coast. Burullus and parts of Lakes Manzala (i.e., Ashtum El-Gamil) and Bardawil (i.e., Zaranik) are managed protected areas. In addition, Burullus and Bardawil are Ramsar sites for the conservation of migratory birds. These lakes are evaluated for their plant diversity and ecosystem services. About 402 plant species, categorized into 45 plant communities, were identified in these lakes. Five of these species are endemics, while three are near endemics. Although the areas of these lakes (2,449 km^2) contribute <0.003 of the total area of Egypt (one million km^2), they are inhabited by 19% of the whole Egyptian flora; thus they are important hot spots for the Egyptian flora, particularly the aquatic plants. In addition, 70% of the total plant species offer, at least, one potential or actual good (e.g., grazing, medicinal drugs, human food, fuel, and timber), while 60% have at least one aspect of the environmental services (e.g., sand controllers, shaders, weed controllers, bank retainers, nitrogen fixers, and water purifiers). Most of these lakes receive excessive amounts of agricultural and industrial drainage water that is loaded with different pollutants, while Bardawil is still characterized by near-pristine conditions. The vegetation and sediment of these lakes are effective as carbon sinks; therefore, they play, in contribution with the other worldwide wetlands, a vital role in mitigation of global warming.

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Contents

1 Introduction

Wetlands are recognized as ecosystems of extreme importance to man and biodiversity. People derive many benefits from the goods and services provided by wetlands, while wetland systems are the "homes" of huge number of plants and animals and their habitats. Ramsar Convention defined the wetlands as areas of marsh, fen, peatland, or water, whether natural or artificial, permanent or temporary, with water that is static or flowing, and fresh, brackish, or salt, including areas of marine water, the depth of which at low tide does not exceed six meters [1]. In Africa, wetland awareness has been paralleled by the need to develop mechanisms for tropical wetland management both to maintain the human benefits from wetlands and to secure their biodiversity into the future. In a review of the worldwide status of wetland biodiversity, Gopal and Junk [2] provided abundant evidence to support their statement that "wetlands are highly valuable, yet the most threatened ecosystems," where little is known about "which factors regulate biodiversity and how." Wetlands are composed of a number of physical, biological, and chemical components such as soils, water, plant, and animal species. Interaction among and within these components allows the wetland to perform many vital functions such as water storage; storm protection and flood mitigation; shoreline stabilization and erosion control; groundwater recharge and discharge; water purification through retention of nutrients, sediments; and pollutants; and stabilization of local climatic conditions, particularly rainfall and temperature [3, 4].

Macrophytes are conspicuous aquatic plants that dominate wetland, shallow lakes, and streams. They grow in or near water and can be emergent, submerge, or floating. They play a vital role in healthy ecosystems by serving as primary producers of oxygen through photosynthesis, providing a substrate for algae and shelter for fish and many invertebrates, and helping nutrient recycling and are potential to be used to treat the wastewater [3]. The natural lakes of Egypt have a unique combination of physical and chemical features. The chemical and hydro-physical characteristics of soils affect the diversity and structure of the vegetation of these lakes [5]. The rapid reduction of the biotic resources threatens the integrity of the global biosphere and its life-support systems [6]. Although representing only a very small portion of all the terrestrial landscapes on earth, the Mediterranean Basin is of a special significance because of its unique evolutionary and cultural history which makes it one of the richest biological regions outside the tropics [7]. The Mediterranean Basin integrates a large variety of ecosystems whose climates vary from humid, semi-humid, arid, to hyperarid. These ecosystems are under extreme and increasing pressure from direct human intervention like intense land use and land use change, desertification, and global change [8].

The aim of this chapter is to give the reader a background on the Egyptian Mediterranean lakes (Mariut, Edku, Burullus, Manzala, and Bardawil) in terms of landforms and morphometry, sediment and water characteristics, plant diversity and threatened species, conservation measures and goods, and services which they offer. After reading this chapter, the reader should understand the value of these wetlands as a hot spot for plant diversity and nature conservation. Also, this study will help decision makers to evaluate and valuate this ecosystem for biodiversity conservation.

2 Sites Description

2.1 Land Forms

The Mediterranean coast of Egypt extends for about 970 km, from Sallum (31° 34′ N, 25° 09′ E) in the west to Rafah in the east (34° 20′ N, 31° 25′ E). Along this coast, five natural lakes are extended: Mariut (western coast), Edku, Burullus, Manzala (Deltaic coast), and Bardawil (Sinai coast) (Fig. 1). They are separated from the sea by strips of sandbars that are very narrow in several places and are connected with the sea through narrow straits, which are either remnants of the mouths of old Deltaic branches or merely gaps in weak sections of the bars known as tidal inlets [9]. After the construction of Aswan High Dam, considerable changes have been observed in the morphology, water characteristics, and biotic composition of the Egyptian northern lakes [10]. Nowadays, these lakes are threatened by

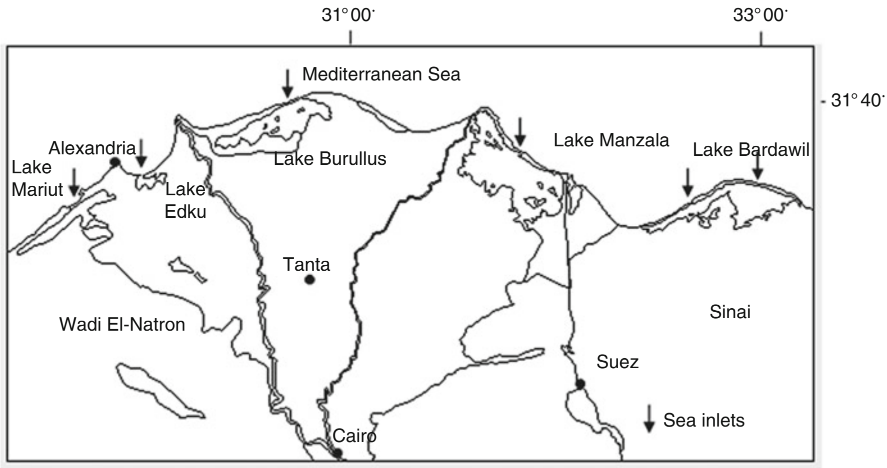

Fig. 1 Location map of the five Mediterranean lakes of Egypt [1]

several factors such as continuous land reclamation, construction of roads along the north coast, touristic development, pollution, and coastal erosion. All these current or planned human activities will not only cause the loss of important unique wetland habitats but will also create new artificial ecosystems.

2.2 *Lakes Morphometry*

Lake Manzala is the largest lake with an area of 1,200 km^2, while Mariut (63 km^2) is the smallest (Table 1). Lake Mariut is the deepest with an average depth of 1.2 m, while Lake Bardawil is the longest (75.0 km), and Manzala is the widest (49.0 km). Moreover, Bardawil is the most hypersaline, while the other lakes are brackish. Mariut is the only lake that has no natural connection with the Mediterranean Sea.

2.3 *Sediment and Water Characteristics*

In the Mediterranean region of North Africa, increasing water usage presents a major threat to natural wetlands [12]. Fresh water availability is a most pressing issue affecting natural and semi-natural North African wetland lakes [13]. The northern lakes of Egypt are bodies of fresh, brackish, and saline water. These habitats are highly structured, and they can provide a gradient from extremely inundated to relatively mesic. The chemical and hydro-physical characteristics of soils affect the diversity and structure of the vegetation of these lakes [5, 14].

Table 1 Morphometry of the five Egyptian northern lakes [11]

Lake	Coordinate		Dimension			Area (km^2)
	Latitude (N)	Longitude (E)	Depth (m)	Length (km)	Width (km)	
Mariut	31° 2′–31° 12′	29° 51′–29° 59′	*1.2*	*8.8*	7.7	*63*
Edku	31° 13′–31° 16′	30° 07′–30° 14′	*1.0*	21.0	*6.0*	126
Burullus	31° 25′–31° 35′	30° 30′–31° 10′	1.0	64.0	16.0	410
Manzala	31° 00′–31° 30′	31° 16′–32° 20′	1.1	64.5	*49.0*	*1,200*
Bardawil	31° 03′–31° 14′	32° 40′–33° 30′	*1.0*	*75.0*	22.0	650

The physicochemical analysis of the sediments of these lakes showed that the pH values are in the alkaline side with a range of 7.3 (Burullus and Bardawil) and 7.6 (the other lakes), while salinity had the minimum value (2.0 mS cm^{-1}) in Manzala but the maximum (6.6 mS cm^{-1}) in Bardawil (Table 2). Sand ranges between 60.8% (Edku) and 79.6% (Mariut), silt between 12.9% (Mariut) and 21.9% (Burullus), and clay between 7.4% (Manzala) and 17.8 (Edku). In addition, organic matter ranges between 3.6% (Edku) and 6.9% (Mariut). Regarding the water characteristics, pH values are also in the alkaline side with a narrow range of variation (7.7–7.8), while salinity had a wide range of 2.9 mS cm^{-1} (Edku) and 48.1 mS cm^{-1} (Bardawil). Moreover, water temperature ranges between 17.8 °C (Bardawil) and 23.6 °C (Burullus), while transparency has a range of 25.3 cm in Edku and 63.0 cm in Bardawil.

2.4 *Prevailing Climate*

The Mediterranean coast of Egypt belongs to the dry arid climatic zone of Koppen's (1931) classification system [16]. According to the map of the world distribution, the northern Mediterranean part of the Nile Delta belongs to the arid region [17]. The climatic conditions are warm summer (20–30 °C) and mild winter (10–20 °C). The aridity index (P/PET, where P is the annual precipitation, and PET is the potential evapotranspiration) ranges between 0.03 and 0.2 at the north Delta (arid region) and less than 0.03 at the south (hyperarid region).

Table 2 Sediment and water characters of the five Egyptian northern lakes [15]

Variable	Lake				
	Mariut	Edku	Burullus	Manzala	Bardawil
Sediment character					
pH	7.6	7.6	7.3	7.6	7.3
EC (mS cm^{-1})	3.2	2.1	3.5	2.0	6.6
Sand (%)	79.6	60.8	67.1	75.7	75.,0
Silt (%)	12.9	21.5	21.9	16.9	16.5
Clay (%)	7.6	17.8	11.0	7.4	8.5
OM (%)	6.9	3.6	5.2	5.6	4.3
Water character					
pH	7.8	7.8	7.8	7.7	7.7
EC (mS cm^{-1})	10.1	2.9	11.6	5.6	48.1
Temperature (°C)	21.0	22.4	23.6	18.3	17.8
Transparency (cm)	39.7	25.3	54.4	50.5	63.0

3 Prevailing Habitats

The Egyptian coastal lakes are characterized by 16 different habitats varied from one lake to another. The prevailing habitats varied between 8 in Mariut and Bardawil and 13 in Burullus. Shorelines, open water, and drains are the dominant habitats in all lakes, except Bardawil which has no connection with any drain. Sand formations (sheets, nebkhas, mobile dunes, calcareous, and siliceous-stabilized dunes) are well-represented habitats in Burullus and Bardawil.

4 Plant Diversity

4.1 Taxonomic Diversity

Four hundred and two species belonging to 248 genera and 68 families were recorded in the Egyptian coastal lakes (Table 3). Although the areas of these lakes (2,449 km^2) contribute <0.003 of the total area of Egypt (one million km^2), but they are inhabited by 19% of the whole Egyptian flora [18]. Thus, these lakes are important hot spots for the Egyptian flora, particularly the aquatic plants. Grasses have the highest contribution to the total flora (66 species and 40 genera), followed by composites (44 species and 35 genera), chenopods (38 species and 17 genera), legumes (32 species and 15 genera), and crucifers (27 species and 19 genera). According to Galal [10], 8 families (Gramineae, Compositae, Chenopodiaceae, Leguminosae, Cruciferae, Caryophyllaceae, Cyperaceae, and Polygonaceae) contributed nearly two-thirds of the total flora of these lakes. These families represent most of the floristic structure in the Mediterranean North

Table 3 Taxonomic diversity of the recorded species in the five Egyptian northern lakes [10]

Taxon	Lake					Total
	Mariut	Edku	Burullus	Manzala	Bardawil	
Species	198	120	224	144	136	402
Genera	148	100	149	107	109	248
Families	46	39	47	47	41	68
Confined species	56	6	50	10	67	189

African flora [19]. Burullus has 224 species, 149 genera, and 47 families; Mariut has 198 species, 148 genera, and 45 families; Manzala has 144 species, 107 genera, and 47 families; and Bardawil has 136 species, 109 genera, and 41 families, while Edku has 120 species, 100 genera, and 39 families (Table 3). The species to genus ratio for the flora of these lakes is 1.6, which is close to 1.9 recorded for the Nile Delta [20].Thus, the flora of these lakes goes below the average level of the Egyptian flora which has a ratio of 2.8. This means that the flora of the northern lakes is relatively richer than that of the Egyptian flora, as the region that has a certain number of species, each of which belongs to a different genus, is relatively more diverse than a region that has the same number of species but belongs to a few numbers of genera [21].

A total of 189 species was confined to only one of the five lakes (Table 3). Lakes Bardawil, Mariut, and Burullus had the highest number of confined species. Sixty-seven species were confined to Bardawil (e.g., *Ruppia cirrhosa*), while 56 species were confined to Mariut (e.g., *Arisarum vulgare*), and 50 species were confined to Burullus (e.g., *Amaranthus lividus*).

4.2 Habit and Life Form

Along the coastal lakes, 203 species (50.5% of the total species) are annuals (e.g., *Cakile maritima*, *Volutaria tubuliflora*, and *Erucaria hispanica*), while 199 species (49.5% of the total species) are perennials (e.g., *Phragmites australis*, *Tamarix nilotica*, and *Centropodia forsskaolii*). Mariut contributed the highest number of annuals (119 species), while Burullus contributed the highest number of perennials (110 species). On the other hand, the lowest numbers of annuals (55 species) and perennials (65 species) were recorded in Edku. Moreover, 48 species are aquatic weeds (e.g., *Echinochloa stagnina*, *Azolla filiculoides*, and *Nymphaea caerulea*), while 170 species are terrestrial weeds (e.g., *Malva parviflora*, *Cressa cretica*, and *Trigonella laciniata*), 169 species are natural (e.g., *Arthrocnemum macrostachyum*, *Suaeda vera*, and *Helianthemum stipulatum*), and 15 species are escaped plants from cultivations (e.g., *Anethum graveolens*, *Eruca sativa*, and *Hordeum vulgare*). The highest number of aquatic weeds (35 species) is recorded in Manzala, while the highest numbers of terrestrial weeds (116 species) and escaped plants (12 species) were recorded in Burullus and Mariut, respectively. The highest number of aquatic plants in Manzala may be due to the excessive nutrient budget transported to the lake through the main drains [22]. Bardawil had the highest number of natural plants (104 species) associated with the lowest of aquatic (4 species) and terrestrial weeds (27 species).

Life form spectrum provides information, which may help in assessing the response of vegetation to variations in environmental factors [23]. The life form spectra of the recorded species in the coastal lakes (Fig. 2) indicate the predominance of therophytes (49% of the total recorded species), followed by geophytes–helophytes (14.7%) and chamaephytes (14.5%). Burullus contributed the highest number of phanerophytes (12 species), hemicryptophytes (19 species), geophytes–helophytes (40 species), and parasites (4 species). The highest number of chamaephytes, hydrophytes, and therophytes (34, 16, and 111 species, respectively) were recorded in Bardawil, Manzala, and Mariut. The highest number of therophytes in Mariut may be attributed to the heavy rainfall on the Western Mediterranean coast [1].

4.3 Endemic and Near-Endemic Species

Five species are recorded in the coastal lakes as endemic taxa; these are *Zygophyllum aegyptium* (Burullus, Manzala, and Bardawil), *Sinapis allionii* (Mariut and Burullus), *Sonchus macrocarpus* (Burullus), and *Astragalus camelorum* and *Bellevalia salah-eidii* (Bardawil). In addition, three species are near-endemic taxa: *Biarum olivieri* and *Iris mariae* in Bardawil (Egypt and Palestine) and *Carduncellus mareoticus* in Mariut (Egypt and Libya).

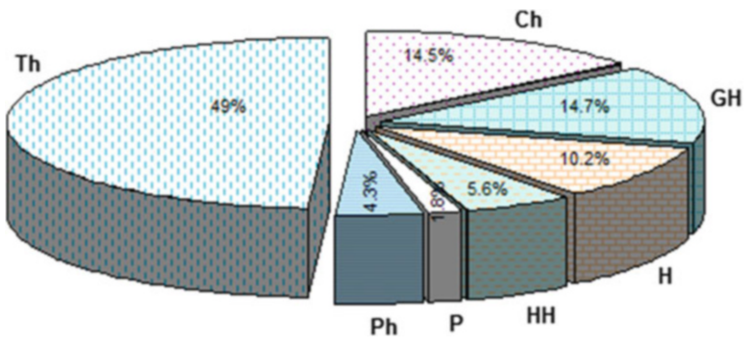

Fig. 2 Life form spectrum of the total species recorded in the five lakes of North Egypt. *Ph* phanerophytes, *Ch* chamaephytes, *GH* geophytes–helophytes, *H* hemicryptophytes, *HH* hydrophytes, *P* parasites, and *Th* therophytes [10]

4.4 Threatened Species

According to the IUCN Red List categories [24], 13 threatened species were recorded in the Egyptian coastal lakes, 7 of which are endangered (*Sinapis allionii* in Mariut and Burullus, *Nymphaea lotus* in Edku and Manzala, *Astragalus camelorum*, *Bellevalia salah-eidii*, *Biarum olivieri*, and *Salsola tetragona* in Bardawil, and *Nymphaea caerulea* in Lake Manzala). Six species were rare (*Juncus bufonius* in Burullus and Manzala, *Chlamydophora tridentata* in Mariut, *Iris mariae* in Bardawil, and *Clerodendrum acerbianum*, *Cynomorium coccineum*, and *Sonchus macrocarpus* in Burullus).

5 Plant Communities

The Egyptian coastal lakes are characterized by 45 plant communities (Table 4). *Halocnemum strobilaceum* is a halophytic community that dominates the five lakes, while *Sarcocornia fruticosa* community is represented in all lakes except Manzala. The aquatic plants communities (e.g., *Ceratophyllum demersum*, *Potamogeton pectinatus*, and *Typha domingensis*) are common in all lakes except Bardawil due to its higher salinity [25]. It is of great interest to compare the vegetation groups in the northern lakes of Egypt with those of North Africa (CASSARINA sites). Reed and sedge beds of *Phragmites*, *Typha*, and *Juncus* are particularly important for stabilizing shore regions and providing habitats for nesting birds. These reed beds, which are wide spread in the Egyptian northern lakes (Mariut, Edku, Burullus and Manzala), were now effectively absent at Merja Zerga and Merja Bokka (Morocco) and Ichkeul and Korba (Tunisia) by the late 1990s [26]. In addition, the communities dominated by the sea grasses (*Ruppia cirrhosa* and *Cymodocea nodosa*) are restricted to Bardawil. *Ruppia cirrhosa* is probably the most common submerged aquatic plant in the more brackish lakes of Morocco and Tunisia [26]. This plant flourishes in Sidi Bourhaba and has become abundant in Ichkeul where it has replaced *Potamogeton pectinatus* since the 1980s [13].

Most of the species recorded in Bardawil are present in dominant communities in the desert dunes and wadis at the south and southeast of the lake [27]. This indicates that the flora of Bardawil may be more related to the southern desert flora than to the flora of the Mediterranean, and this may be attributed to the fact that Bardawil sediments were supplied by desert inland wadis like Wadi El-Arish [28]. Moreover, 31 communities are recorded in only 1 lake; 7 communities are exclusively recorded in Mariut (e.g., *Atriplex halimus*, *Bromus rubens*, and *Volutaria tubiflora*); and 7 are in Edku (e.g., *Arundo donax*, *Bassia indica*, and *Rumex dentatus*). The communities dominated by *Salsola kali* and *Suaeda pruinosa* were restricted to Lake Burullus, while *Atriplex portulacoides*, *Azolla filiculoides*, *Ludwigia stolonifera*, *Ruppia maritima*, and *Scirpus maritimus* communities are exclusively recorded in Manzala. Moreover, ten communities are common in

Table 4 Community types of the five Egyptian northern lakes [1]

Plant community	Lake					Total
	Mariut	Edku	Burullus	Manzala	Bardawil.	
Halocnemum strobilaceum (Pall.) M. Bieb.	1	1	1	1	1	5
Ceratophyllum demersum L.	1	1	1	1		4
Phragmites australis (Cav.) Trin. ex Steud.	1	1	1	1		4
Potamogeton pectinatus L.	1	1	1	1		4
Typha domingensis (Pers.) Poir. ex Steud.	1	1	1	1		4
Sarcocornia fruticose (L.) A.J. Scott	1	1	1		1	4
Echinochloa stagnina (Retz.) P. Beauv.	1	1		1		3
Eichhornia crassipes (Mart.) Solms	1	1		1		3
Arthrocnemum macrostachyum (Moric.) K. Koch.	1		1			2
Juncus acutus L.		1	1			2
Najas marina v. *armata* (Lindb. f) Horn afRantzien	1			1		2
Limbarda crithmoides (L.) Dumort.		1	1			2
Suaeda vera Forssk. ex J.F. Gmel		1	1			2
Juncus rigidus Desf.	1					1
Atriplex halimus L.	1					1
Atriplex semibaccata R. Br.	1					1
Bromus rubens L.	1					1
Cynanchum acutum L.	1					1
Launaea nudicaulis (L.) Hook. F.	1					1
Tamarix nilotica (L.) Delile	1					1
Volutaria tubiflora Sennen	1					1
Arundo donax L.		1				1
Bassia indica (Wight) A.J.Scott.		1				1
Centaurea calcitrapa L.		1				1
Cynodon dactylon (L.) Pers.		1				1
Cyperus articulatus L.		1				1
Medicago polymorpha L.		1				1
Rumex dentatus L.		1				1
Salsola kali L.			1			1
Suaeda pruinosa Lange			1			1
Azolla filiculoides am.				1		1
Ludwigia stolonifera (Guill. &Perr.) P. H. Raven				1		1
Ruppia maritime L.				1		1

(continued)

Table 4 (continued)

Plant community	Lake					Total
	Mariut	Edku	Burullus	Manzala	Bardawil.	
Scirpus maritimus L.				1		1
Zygophyllum album L. F.					1	1
Artemisia monosperma Delile					1	1
Asparagus stipularis Forssk.					1	1
Calligonum polygonoides L.					1	1
Cymodocea nodosa (Ucria) Ascherson					1	1
Moltkiopsis ciliate (Forssk.) I.M. Johnst.					1	1
Nitraria retusa (Forssk.) Asch.					1	1
Panicum turgidum Forssk.					1	1
Ruppia cirrhosa (Petagna) Grande					1	1
Stipagrostis scoparia (Trin. &Rupr.) de Winter					1	1
Thymelaea hirsute (L.) Endl.					1	1
Total	18	18	12	12	13	45

Bardawil (e.g., *Artemisia monosperma*, *Asparagus stipularis*, *Calligonum polygonoides*, *Cymodocea nodosa*, and *Thymelaea hirsuta*).

6 Succession Trends

The decrease in moisture and changes in salinity and soil texture are the main operative factors in the successional process in the Egyptian Mediterranean lakes, depending on the regional and local conditions of topography and landforms (Fig. 3). The pioneer communities lead to the formation of submerged species (e.g., *Ceratophyllum demersum*). In the right part of the successional scheme, increasing salinity enhances the growth of the submerged species (*Najas marina*). Continuous decrease in moisture and building up of soil enhance the growth of terrestrial halophytic communities such as *Arthrocnemum macrostachyum* and then increase in aridity and formation of sand dunes lead to the formation of *Lotus halophilus* and *Stipagrostis scoparia* as a climax stage. This successional trend is more related to that of Bardawil [1]. On the other hand, the middle part of the scheme represents a succession closely related to that of the Deltaic lakes, which passes through the floating (e.g., *Eichhornia crassipes*) and emergent species (e.g., *Phragmites australis*) and ends by *Tamarix nilotica* as a climax stage. Moreover, coarser soil texture and decreased salinity may lead to the formation of *Atriplex*

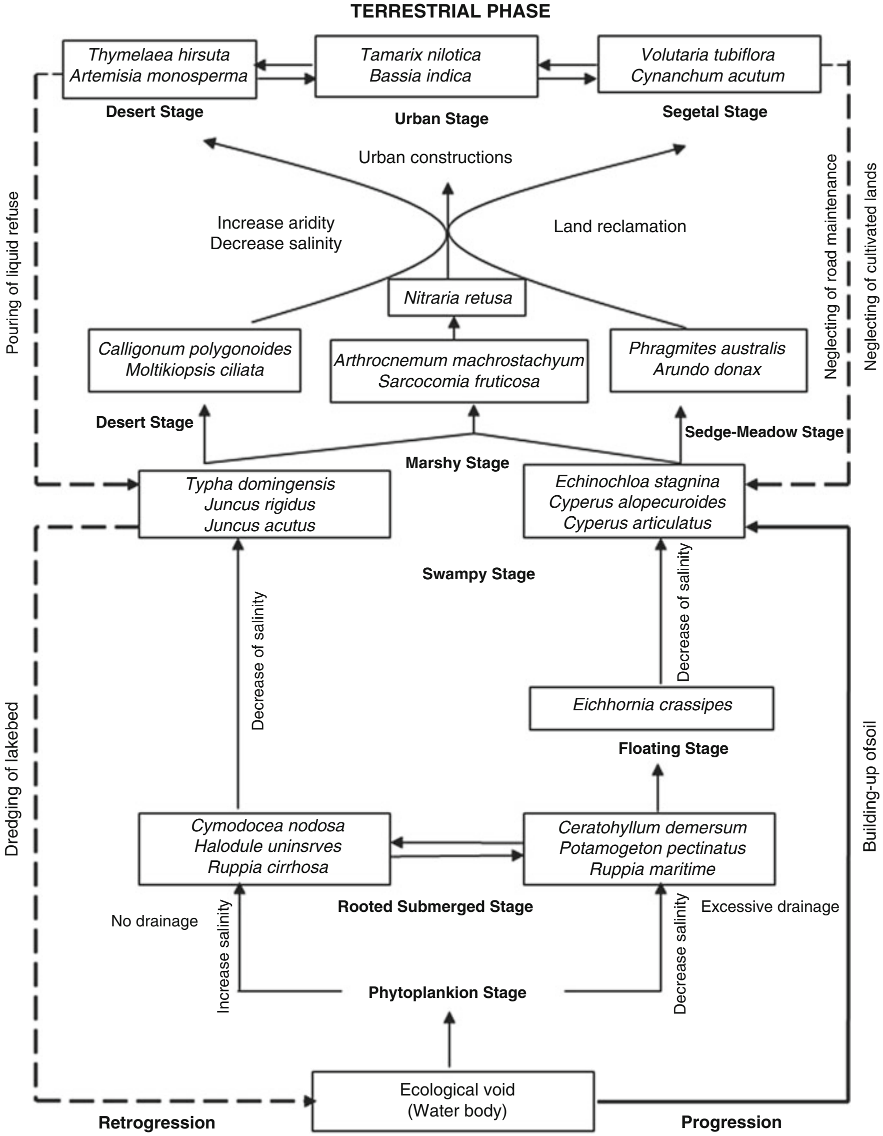

Fig. 3 Schematic representation of the presumed succession relationship between the plant communities in the Egyptian northern lakes [1]

glauca and *Juncus acutus* communities from a halophytic community such as *Sarcocornia fruticosa*. Furthermore, increasing aridity may result in a community such as *Thymelaea hirsuta* as a climax stage (xerosere succession of the Mediterranean coast).

7 Goods and Services

In the these lakes, 283 species (70% of the total) offer at least one potential or actual good [11] with the following arrangement: 73% grazing (*Adonis dentata* and *Avena barbata*), 62% medicinal (*Ammi visnaga* and *Artemisia monosperma*), 24% human food (*Anethum graveolens* and *Brassica rapa*), 17% fuel (*Thymelaea hirsute* and *Arthrocnemum macrostachyum*), and 2% timber species (*Tamarix nilotica*). In addition, 241 species (60% of the total) have at least one aspect of the environmental services [11, 29, 30]: 34% sand controllers such as wind breaks, sand binders and hummock formers (*Arthrocnemum macrostachyum* and *Retama raetam*), 6% shaders (*Salix tetrasperma* and *Tamarix nilotica*), 6% weed controllers (*Phyla nodiflora* and *Sphaeranthus suaveolens*), 5% bank retainers (*Arundo donax* and *Chenopodium ambrosioides*), 2% nitrogen fixers (*Argyrolobium uniflorum* and *Matthiola longipetala*), and 2% are water purifiers (*Eichhornia crassipes* and *Phragmites australis*).

8 Carbon Sequestrations Potential

The coastal wetlands are among the most effective carbon sinks on the earth. Worldwide, these systems are among the most endangered and rapidly disappearing natural environments mostly owing to anthropogenic activities and unsustainable exploitation. In Egypt, the five Mediterranean lakes are threatened by several factors such as continuous land reclamation projects, construction of roads along the north coast, touristic development, pollution, and coastal erosion [15, 31]. Based on the area of these lakes, their carbon sequestration potential (CSP) ranged from 0.95 Gg C year^{-1} in Bardawil to 7.79 Gg C year^{-1} in Manzala (Table 5). Thus, it is necessary to protect these lakes, which currently suffer from lack of effective protection, for conserving their vital role in carbon sequestration process as well as other ecosystem goods and services.

Table 5 Sedimentation rate (SR), mean ± standard error of the carbon sequestration rate (CSR) and carbon sequestration potential (CSP) of the five Egyptian northern lakes

Lake	SR (mm year^{-1})	CSR (g C m^{-2} year^{-1})	CSP (Gg C m^{-2} year^{-1})
Bardawil	0.54	1.5 ± 0.1a	0.95 ± 0.08a
Manzala	3.40	7.6 ± 0.7b	7.79 ± 0.67c
Burullus	4.70	10.9 ± 0.9b	4.47 ± 0.35b
Edku	3.50	7.9 ± 0.3b	0.99 ± 0.04a
Mariut	19.00	80.8 ± 4.1c	5.09 ± 0.26b

Sediment data refers to the upper 30 cm. Means in the same column with different letters are significantly different at $P < 0.05$ according to the Tukey test. Gg = 10^6 kg [15]

9 Identified Threats

Erroneous policies for the disposal of sewage and industrial and agricultural wastes of Alexandria and Beheira Governorates seem to have no regard from the environmental viewpoint and led to severe deterioration of Lake Mariut, so it has become the most polluted wetland in the country. A sizable portion of the lake is heavily exploited for salt extraction from the salt pan at El-Max [10]. The continuous reduction in the area of Lake Burullus and its adjacent reed swamps and marshlands through substantial land reclamation poses the most serious threat to this wetland ecosystem. Vast area used to be part of this ecosystem but are now cultivated mainly with sugar beet, rice, broad beans, barley, and clover. Excess fertilizers and pesticides from these fields are bound to pour into the water of the lake, thus adding to the danger of the shrinking area of the lake. The shores of Burullus wetland, which protrudes the furthest, are subjected to long-term erosion, which is seen obviously at the Burullus inlet [32]. The average erosion rate is about 1 m year^{-1} [11]. This leads to the risk that all adjacent regions and even the Burullus area would be subjected to heavy erosion. In addition, the continuous inflow of domestic, agricultural, and industrial wastes of Gharbia and Dakahlia Governorates is the major source of pollution to the lake and its surroundings, especially along its eastern and southern peripheries [11].

El Salam Canal is a national project aiming at carrying the Nile water to North Sinai in order to allow agricultural development of about 92,000 ha south of Lake Manzala and 168,000 ha in North Sinai [33]. The isolation of sub-basins has resulted in limited water circulation and increased pollution, more significantly in the basins with drain discharges as the geographic dispersal of pollutants became more confined [33]. The polluted area is situated in the southeastern part of the lake at the mouth of Hadous drain; it has the highest total dissolved salts delivered into the lake [10]. This area also receives large amounts of drain water from Bahr El-Baqar drain, which transports partially treated sewage from eastern Cairo for about 170 km to the lake. The sandbar separating Lake Manzala from the Mediterranean Sea has been subjected to severe changes by the physical and man-made processes in the area. Furthermore, coastal changes along the Nile Delta have been recognized since the late nineteenth century, but it was dramatically accelerated after the construction of Aswan High Dam [33].

Lake Bardawil is the only wetland in the Mediterranean coast of Egypt that is not connected to any irrigation or drainage canals [25]. Furthermore, the population density around the lake is the smallest among all the other northern lakes of the country [34]. Consequently, it might be claimed that Bardawil is the nearest of all Egyptian wetlands to environmental virginity [25]. At present, oil pollution from sea-going ships and the refuge from fishing boats in the lake are the most serious sources of threat to the balance of the entire ecosystem [34]. El Salam Canal is part of the agricultural development of North Sinai and will draw a mixture of water from various sources west of the Suez Canal including Bahr El-Baqar drainage with all its load of pollutants (mostly sewage from eastern Cairo), fauna, flora, and microorganisms [25].

10 Conservation Measures

There are no conservation measures taken for Mariut and Edku Lakes and their adjacent marshlands, which remain entirely unprotected. A small area of about 35 km^2 of Lake Manzala, including its connection with the Mediterranean Sea at Ashtum El-Gamil, has been declared as a protected area by the Prime Minister's Decree Number 459 in 1988 [35]. After that, a project had been launched by the Egyptian Government in 1997–1999, with a financial support from the Global Environment Facility (GEF) to clean up the polluted water of Bahr El-Baqar drain which pours its drainage water into Lake Manzala in order to reduce its pollution and their adjacent Mediterranean shoreline.

In 1988, Lake Burullus was included as a Ramsar site according to Ramsar Convention which deals with wetlands of international importance as waterfowl habitat. After that, the entire area of this lake and most of its surrounding sandbar and marshland has been declared as a protected area by the Prime Minister's Decree Number 1444 for 1998 [36]. Moreover, as Lake Bardawil falls on one of the major routes for bird migration in the world, thus its eastern sector, which includes the only natural outlet to the Mediterranean Sea at Zaranik, has been declared by the Prime Minister's Decree Number 1429 as a protected area in 1985 [34], and in 1988 it was also included as a Ramsar site. Two management plans were prepared for each of Burullus [36] and Bardawil [34] lakes, but unfortunately, application of these needs to be enforced and financially supported.

11 Conclusion and Recommendations

- About 402 plant species, categorized into 45 plant communities, were identified in the five Egyptian Mediterranean lakes. Five of these species are endemics, while three are near endemics (with Libya or Palestine).
- Although the areas of these lakes (2,449 km^2) contribute <0.003 of the total area of Egypt (one million km^2), but they are inhabited by 19% of the whole Egyptian flora, In view of this, these wetlands could be considered as important hot spots for the Egyptian flora, particularly the aquatic plants.
- Bardawil (67 species: e.g., *Ruppia cirrhosa*), Mariut (56 species: e.g., *Arisarum vulgare*), and Burullus (50 species: e.g., *Amaranthus lividus*) have the highest number of confined species.
- According to the IUCN Red List categories, 13 plant species were threatened in the 5 Egyptian coastal lakes, 7 of which were evaluated as endangered species, while 6 were evaluated as rare species.

- Seventy percent of the species (283 species) offer at least one potential or actual good (e.g., grazing, medicinal drugs, human food, fuel, and timber). In addition, 241 species (60% of the total) have at least one aspect of the environmental services (e.g., sand controllers, shaders, weed controllers, bank retainers, nitrogen fixers, and water purifiers).
- The vegetation and sediment of these lakes are effective as carbon sinks; therefore, they play, in contribution with the other world wetlands, a vital role in mitigation of global warming.
- Coordination between the stakeholders involved in the management of these lakes should be activated in order to apply the activities that enhance the biodiversity and productivity in these wetlands. The main stakeholders are association of fishermen societies, governorate administrations, general authority of development of fisheries resources, management team of Burullus, Ashtum El-Gamil and Zaranik protected areas, ministry of health, agency of north coast construction, coast guard, and police of water surfaces.
- Mariut and Edku lakes should be added (fully or partially) to the net of the Egyptian protected areas in order to reduce the severe human impact upon them.
- Evaluating their role in mitigating the thermal extremity, as the vegetated wetlands act as sinks for the absorption of CO_2 (one of the gases responsible for the global warming).

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Responses of Zooplankton to Long-Term Environmental Changes in the Egyptian Coastal Lakes

G. M. El-Shabrawy and M. A. Bek

Abstract The Egyptian Mediterranean coast has four brackish lakes (Northern delta lakes) and a hypersaline one. These lakes are, from east to west, Bardawil, Manzala, Burullus, Edku, and Mariout. All except Lake Mariout are directly connected to the sea. These lakes represent highly dynamic aquatic systems that have been undergoing continuous and pronounced changes through the late Holocene to the present time. Changing natural conditions are influencing the diversity of biological community and its function. Zooplankton is considered as a sensitive tool to any changes in water environment. Therefore, the impacts of any natural changes can be identified through changes in species composition, quantity, and size. Nowadays, despite their physical separation, the delta lagoons appear to have similar zooplankton populations. Rotifers comprise at least 80% and often higher than 90% of the total population in the lakes. In comparison with deltaic lakes, the non-deltaic one (Bardawil Lake) shows a different zooplankton assemblage which composed of marine species copepod seems the leading group followed by protista and pteropoda. The zooplankton assemblage shows no much change until the 1950s. By the 1970s, *Daphnia* had become a rarity and was actually not recorded from the lakes. The 1960s–1970s were marked by three new arrivals in the zooplankton, all of the Mediterranean origin: *Arctodiaptomus salinus*, *Acanthocyclops trajani*, and *Diaphanosoma mongolianum*. To accelerate the restoration of the delta lakes to better conditions for saving them as grounds for

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fisheries and places for recreations, the quality of the sewage and industrial wastes dumping directly into them or indirectly via agricultural drains must be treated.

Keywords Bardawil, Burullus, Edku, Manzala, Mariout, Northern coastal lakes, Zooplankton

Contents

1 Introduction

Coastal lakes are critical transition zones that link land, freshwater habitats, and the sea. These areas are usually recognized by their high productivity and the presence of habitats with conservation interest [1]. Recently, the health of coastal ecosystems has entered the agendas of environmental managers and politicians. Several measures have been undertaken in an attempt to reduce the pressure on these systems, allowing the return to natural conditions or at least to improve the present situation [2]. The Egyptian Mediterranean coast has five lakes (northern coastal lakes), four of them, i.e., Mariout, Edku, Burullus, and Manzala, are deltaic water bodies, while a fifth one is the non-deltaic Lake Bardawil (Fig. 1). Of all coastal water bodies, lagoons are thought to be among the most sensitive to environmental changes, particularly sensitive to human-induced alterations such as eutrophication and climate change [3]. Egyptian coastal lakes are characterized by unique water quality status. Consequently, the Egyptian lakes contain rich aquatic species and attract migrant birds every year. Currently, the lakes suffer from severe deteriorating conditions that badly affect the whole ecological system [4]. With growing concerns of climate change and possible impact on environmental stems, human intrusion and progressive development processes have had undeniable adverse fingerprints on maintaining a healthy environment in coastal lakes of Egypt [5]. The four lagoons situated in the Nile river delta are shallow basins (depth <3 m, with an average depth of ~ 1 m) of brackish waters. Lake Mariout is artificially enclosed and has long been without a major connection to the sea. Lakes Edku, Burullus, and Manzala display typical lagoon characteristics; are separated from the Mediterranean by low-lying, narrow coastal sand barriers; and are connected to the sea by protected channels. The deltaic lakes receive much of their freshwater input from irrigation drains located along the southern, eastern, and western margins. The fifth lagoon (the non-deltaic)

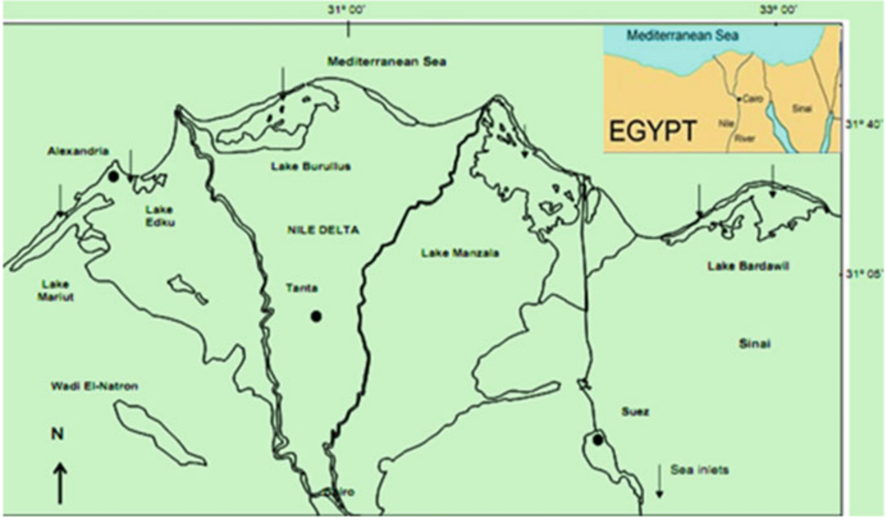

Fig. 1 Northern delta lakes

Lake Bardawil is situated away from the Nile delta region, in northern Sinai. Contrary to the others, it does not have any freshwater inflow and communicates only with the Mediterranean Sea. Delta lakes are the most polluted areas in Egypt. These lakes receive large amounts of waste including industrial, municipal, and agricultural wastewater without proper treatment. This causes spread of aquatic plants which covered vast areas from these lakes. Overfishing, illegal fishing practices, and illegal harvesting of fish fry. The blockage of Boughazes (the connections with the open sea). High levels of eutrophication resulting from the increased nutrient influx from agricultural drains carrying a significant amount of washed and leached fertilizers and pesticides.

2 Zooplankton

Zooplankton is usually defined as small free-swimming animals that can be caught in nets and live freely in the water column. They do not have the ability to move horizontally against water currents and must therefore "go with the flow." There are two different types of animals classified upon the time they spend in the plankton. "Holoplankton" are born and die as members of the plankton. Other animals, namely, "meroplankton," spend part of its early life in the plankton. After that their life involves either their settlement on the lake floor as an annelid, or a snail, or their metamorphosis into something which has the ability to move against currents such as a fish. Zooplankton ranges in size from about 0.1 to 1–3 mm in length. The main components of the zooplankton are protozoa, rotifers, and crustaceans. Although rotifers may be more abundant numerically, the crustaceans generally constitute most of the biomass. They include the cladocera and copepoda. Some zooplankton is herbivorous and feeds on phytoplankton or bacteria, whereas others are predacious and feed on other zooplankton. Zooplankton, in turn, is fed upon by small fish.

Zooplankton communities are highly diverse and thus perform a variety of ecosystem functions. Perhaps, zooplankton's most important role is working as the major grazers in aquatic food webs and providing the principal pathway for energy from primary producers to consumers at higher trophic levels, such as fish, marine mammals, and turtles. In addition, zooplankton support the bacterial and phytoplankton production process by regenerating nitrogen. Microbes colonize zooplankton fecal pellets and carcasses, making them rich sources of organic carbon for detrital feeders. These zooplankton products slowly yet consistently rain down on the dark bottom, sustaining diverse benthic communities of sponges, inoderms, anemones, crabs, and fish [6]. Zooplankton abundance and composition vary spatially in large lakes due to both abiotic (water temperature, currents, nutrients) and biotic (chlorophyll a, fish biomass) factors [7].

2.1 Zooplankton Population Dynamics: Similarities and Differences

An important link in the food chain of any aquatic ecosystem, especially as a food source for most of the consumable fishes, is the zooplankton. A few notes on zooplankton of the northern Egyptian lakes were given on the occurrence of some organisms in the reports including the results of the Cambridge Expedition to the Suez Canal in 1923. Faouzi [8] has listed some zooplankton organisms in his review of the hydrography and fauna of the Egyptian delta lakes. A total of 168 and 84 zooplankton species belonging to four main groups (Protista, Rotifera, Copepoda, and Cladocera) in addition to Appendicularians, Chaetognatha, Pteropods, and meroplankton species were recorded at the deltaic and non-deltaic lakes, respectively (see Table 1). Despite their physical separation, the delta lagoons appear to have similar zooplankton populations.

Rotifers, especially species of Brachionus (B. angularis, B. plicatilis, B. calyciflorus, B. urceolaris), Keratella, (K. cochlearis, K. quadrata, K. tropica), Lecane (L. bulla, L. closterocerca, L. luna, L ungulata), and Polyarthra (P. vulgaris, P. remata) are most abundant [9, 10]. This small, typically freshwater zooplankton (Rotifera) comprises at least 80%, and often higher than 90%, of the total population in the lagoons (Fig. 2). Other small animals that are present in smaller amounts include Cladocera (mainly Moina micrura), Copepoda, larvae of benthic invertebrates, and Ostracoda. In their study of zooplankton communities in Edku Lagoon, Aboul-Ezz and Soliman [9] found that, of the remaining zooplankton not identified as Brachionus (~25%), 16% were Copepoda, and most of these were nauplii of the genus Acanthocyclops.

General zooplankton abundances have increased dramatically in the lagoons. Gharib and Soliman [11] report a 44-fold increase in zooplankton counts (from 6.1×10^4 to 2.7×10^6 ind. m^{-3}) in Edku Lagoon from the mid-1970s to the mid-1990s. In Manzala, counts increased about 19-fold from 63×10^3 ind. m^{-3} in 1977 to $1,212 \times 10^3$ ind. m^{-3}

Table 1 A list of zooplankton species recorded in the Northern Egyptian lakes

Deltaic lakes (Manzala, Burullus, Edku, Mariout)		Non-deltaic lake (Bardawil)
Protista[a]	**Cyclopoida**	**Protista**
Acropisthium mutabile	*Acanthocyclops trajani*	*Eutintinnus lusus-undae*
Ammonia beccarii	*Afrocyclops gibsoni*	*Dictyocysta obtusa*
Arcella arenata	*Apocyclops panamensis*	*Codonella aspera*
Arcella discoides	*Cryptocyclops* cf *bicolor*	*Codonellopsis lusitanica*
Askenasia sp.	*Diacyclops b. odessanus*	*Eutintinnus medius*
Balantidium spp.	*Eucyclops serrulatus*	*Favella ehrenbergii*
Bursaria truncatella	*Halicyclops neglectus*	*Favella serrata*
Centropyxis aculeata	*Macrocyclops albidus*	*Codonella amphorella*
Centropyxis ecornis	*Mesocyclops ogunnus*	*Codonella agalea*
Colpidium sp.	*Paracyclops fimbriatus*	*Globigerina bulloides*
Cyclogramma sp.	*Thermocyclops crassus*	*Helicostomella subulata*
Cyclotrichium sp.	*Thermocyclops decipiens*	*Leprotintinnus bottnicus*
Cycloforina contorta	*Thermocyclops emini*	*Epiplocylis acuminata*
Dendromonas spp.	*Thermocyclops neglectus*	*Amphorellopsis acuta*
Didinium sp.	*Thermocyclops oblongatus*	*Metacylis mereschkowskii*
Difflugia spp.	*Oithona helgolandica*	*Codonella aspera*
Elphidium sp.	*Oithona nana*	*Dictyocysta muvileri*
Endosphaera spp.	*Oithona plumifera*	*Orbulina universa*
Euplotes patella	*Oithona robusta*	*Petalotricha major*
Eutintinnus sp.	**Harpacticoida**	*Tintinnopsis cylindrica*
Litonotus fasciola	*Canthocamptus staphylinus*	*Ptychocytis minor*
Oxytricha fallax	*Nitokra lacustris*	*Quinqinquilina* sp.
Paramecium caudatum	*Schizopera aegyptica*	*Rhobdonella elegans*
Paramecium spp.	*Canuella perplexa*	*Stenosemella nivalis*
Platycola sp.	*Cletocamptus confluens*	*Salpingella glackentoegeri*
Strombidium sp.	*Euterpina acutifrons*	*Tintinnopsis campanula*
Tintinnopsis sp.	*Harpacticus* sp.	*Tintinnopsis tocantinensis*
Trachelophyllum sp.	*Horsiella brevicornis*	*Tintinnopsis beroidea*
Vorticella sp.	*Macrosetella gracilis*	*Tintinnopsis lobiancoi*
Rotifera	*Mesochra rapiens*	*Tintinnopsis buetschlii*
Anuraeopsis fissa	*Onychocamptus mohammed*	*Tintinnidium neapolitanum*
Asplanchna girodi	*Tachidius discipes*	*Undella dohrni*
Asplanchna priodonta	**Cladocera**	**Copepoda**
Asplanchna sieboldii	*Evadne* sp.	*Acartia clausii*
Brachionus angularis	*Podon polyphemoides*	*Paracartia latisetosa*
Brachionus budapestinensis	*Ctenopoda*	*Clausocalanus furcatus*
Brachionus calyciflorus	*Diaphanosoma mongolianum*	*Paracalanus parvus*
Brachionus caudatus	*Alona rectangula*	*Lucicutia flavicornis*
Brachionus falcatus	*Alona verrucosa*	*Lucicuta ovales*
Brachionus plicatilis	*Alonella excisa*	*Temora longicornis*
Brachionus quadridentatus	*Alonella nana*	*Parvocalanus crassirostris*

(continued)

Table 1 (continued)

Deltaic lakes (Manzala, Burullus, Edku, Mariout)		Non-deltaic lake (Bardawil)
Brachionus rubens	*Bosmina longirostris*	*Paracalanus parvus*
Brachionus urceolaris	*Ceriodaphnia cornuta*	*Calanus finmarchicus*
Cephalodella gibba	*Ceriodaphnia reticulata*	*Eurytemora hiruridoides*
Cephalodella megalocephala	*Chydorus sphaericus*	*Centropages calaninus*
Colurella adriatica	*Daphnia barbata*	*Centropages potincus*
Colurella obtuse	*Daphnia longispina*	*Oithona nana*
Filinia longiseta	*Daphnia lumholtzi*	*Oithona plumifera*
Harringia rousseleti	*Daphnia magna*	*Oncaea conifera*
Hexarthra fennica	*Daphnia similis*	*Corycaeus clausi*
Kellicottia longispina	*Dunhevedia crassa*	*Isias clavipes*
Keratella cochlearis	*Euryalona orientalis*	*Sapphirina opalina*
Keratella quadrata	*Ilyocryptus spinifer*	*Euterpina acutiforns*
Keratella tropica	*Karualona* sp.	*Harpacticus littoralis*
Keratella valga	*Kurzia latissima*	*Microsetella norvegica*
Lecane arcula	*Macrothrix hirsuticornis*	*Amallothrix auropecten*
Lecane bulla	*Macrothrix laticornis*	*Canuella* sp.
Lecane closterocerca	*Moina brachiata*	*Harpacticus littoralis*
Lecane depressa	*Moina micrura*	*Metis jousseaumei*
Lecane elasma	*Oxyurella tenuicaudis*	**Cladocera**
Lecane luna	*Scapholeberis kingi*	*Bosmina coregoni*
Lecane lunaris	*Simocephalus vetulus*	*Evadne spinifera*
Lepadella ovalis	**Cirripedia**	*Evadne tergestina*
Lepadella patella	*Balanus improvisus* (nauplii)	*Podon polyphemoides*
Philodina roseola	**Mysidacea**	**Rotifera**
Polyarthra remata	*Diamysis bahirensis*	*Synchaeta calva*
Polyarthra vulgaris	*Mesopodopsis slabberi*	*Brachionus plicatilis*
Proalides sp.	**Decapoda**	*Brachionus angularis*
Pseudoploesoma formosa	*Palaemon elegans* (larvae)	*Keratella quadrata*
Rhinoglena frontalis	**Ostracoda**	*Keratella cochlearis*
Rotatoria sp.	*Cyprideis torosa*	*Trichocerca stylata*
Synchaeta oblonga	*Cypridopsis vidua*	*Lepadella cristata*
Synchaeta pectinata	*Potamocypris variegata*	**Coelenterates**
Testudinella patina	*Potamocypris villosa*	*Rhizostoma pulmo*
Trichocerca cylindrica	*Limnocythere inopinata*	*Obelia* sp.
Trichocerca elongata	*Loxoconcha elliptica*	*Cotylorhiza tuberculata*
Trichocerca gracilis	*Sarscypridopsis aculeata*	**Pteropods**
Trichocerca inermis	Polychaeta (larvae)	*Limacina inflata*
Trichocerca pusilla	**Chaetognatha**	**Appendicularians**
Tripleuchlanis plicata	*Sagitta* sp.	*Oikopleura longicauda*
Copepoda	*Sagitta inflata*	*Appendicularis sicuta*
Calanoida	**Appendicularia**	**Chaetognatha**
Arctodiaptomus salinus	*Oikopleura dioica*	*Sagitta enflata*

(continued)

Table 1 (continued)

Deltaic lakes (Manzala, Burullus, Edku, Mariout)		Non-deltaic lake (Bardawil)
Metadiaptomus mauretanicus	*Oikopleura longicauda*	*Sagitta setosa*
Neolovenula alluaudi	*Fritillaria borealis* **168**	**Meroplankton**
Thermodiaptomus galebi		Cirripedia larvae
Calanus brevicornis		Decapod larvae
Calocalanus pavo		Echinodermata larvae
Canuella perplexa		Mollusc larvae
Centropages sp.		Nematoda free living
Isias clavipes		Osteichthyes egg and embryos
Paracalanus parvus		Polychaete larvae
Paracartia latisetosa		84

[a]Bold font represents the kingdom name while normal font shows its examples

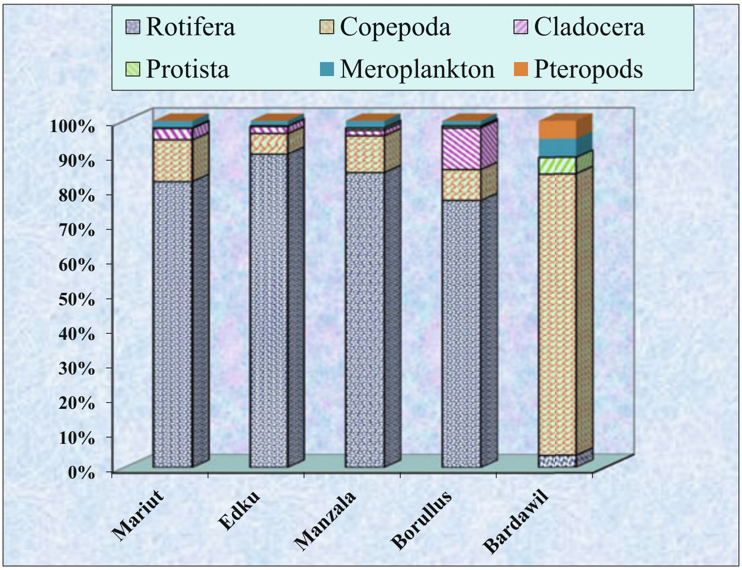

Fig. 2 Community composition of the different zooplankton groups at the northern Egyptian lakes

in 2003 [12]. Counts in Burullus have also increased about tenfold, with seasonal counts from 2001 to 2004 rarely falling below 4×10^5 ind. m^{-3} and peaking at $2.5–3.0 \times 10^6$ ind. m^{-3} [13]. In the mid-1990s, Mariout had a population of about 3.6×10^5 ind. m^{-3} despite tremendous amounts of sewage input and chronically low DO (annual average of 3.9 mL O_2 L^{-1}; [14]). Zooplankton populations are quite high in all of these lagoons, in particular when compared to the heavily impacted Venice Lagoon. Despite similar physical characteristics, mean seasonal zooplankton counts peak at about 1.9×10^4 ind. m^{-3} in the summer and typically do not exceed 1×10^3 ind. m^{-3} throughout the rest of the year [15].

While zooplankton population data are inherently very dynamic, there have been some clear shifts in the community composition over time. Soliman [16] has reported a rise in rotifers from 56% of the total counts in 1976–1977 to 92% in 1995–1996, as well as a decrease in copepods (from 32 to 7%) during this same time in Edku Lagoon. Dumont and El Shabrawy [13] have thoroughly documented similar shifts in the lagoons, and in particular Burullus lagoons, from the 1930s to the present. These authors describe how, in the 1930s, the zooplankton were marine for most of the year and then shifted to freshwater assemblages during the 4 months during and following the fall flood. Since then, the marine species have disappeared from most of the lagoons, except areas close to the sea. Further, all large-bodied freshwater species have disappeared, and small rotifers and cladocerans have increased by a factor of 10 or more [13]. This difference in zooplankton assemblies was concurrent with changes in Lake food chain, shifting from a marine fishery to a freshwater one dominated by omnivorous tilapia and to increased agricultural drainage. With the closure of the dam, the increase nutrient-rich agricultural drainage and associated eutrophication favored smaller species. Increased turbidity was likely detrimental to the vast filter feeders, including crustaceans, and favored micro-filtrators like rotifers. Compared with the deltaic lakes, the non-deltaic one (Bardawil Lake) shows a different zooplankton assemblage which is composed of marine species copepod and seems the leading group followed by protista and pteropoda. The following is a short note on zooplankton situation in each North Egyptian lakes.

2.1.1 Lake Manzala

During the study of El-Maghraby et al. [17], the typical zooplankton organisms of freshwater origin recorded in the lake (Rotifers, Cladocera) and those of marine origin (copepods). The winter zooplankton population was characterized by the rotifers *Keratella* and *Brachionus* and cirripede nauplii, spring population dominated by the cladoceran *Monia* and cirripede, summer population composed of the marine copepods (*Acartia latistosa*, *Oithona nana*, and *Labidocera brunescens*) while Autumn population dominated by the rotifer *Brachionus*. This periodicity seems to be mostly controlled by the seasonal variation in water salinity. Maclaren [18] demonstrated the abundance, distribution, species composition, and productivity of the major aquatic biota (phytoplankton, zooplankton, benthos, and macrophytes) in Lake Manzala. A total of 24 zooplankton groups, aggregated by genera, species, or development stage, were identified. Zooplankton exhibited a major peak in June (37,000 ind. m^{-3}) and two lesser maxima (October and December) of 23,000 Org. m^{-3}. Cladoceran comprised 75% by a number of the total zooplankton; *Diaphanosoma* and *Moina dubia* were most abundant during the period June to November, while *Bosmina* peaked in December to February and was absent during the summer months. The three Cladoceran species were mostly absent at station near seawater salinity for most of the year. The marine copopod *Acartia latisetosa* was present in very low numbers throughout the year, but it was most abundant at the saline station. Also, Cirripedia larvae were most important at the same station, but it peaked during July and August corresponding with the only significant saltwater intrusion in this area during 1979 to 1980. On the other hand, Cyclopidea dominated at the more freshwater stations. The community composition of the different zooplankton groups in 12 different localities of Lake Manzala was studied at approximately seasonal intervals between November 2000 and August 2001 [19]. A total of 51 zooplankton species was recorded, of these 32 species of rotifers comprised 82.3% of the total zooplankton density. The copepods represented about 17%, and all other groups formed less than 1%. The latter category included five species of Cladocera, three protozoan species in addition to meroplanktonic larvae of Mollusca, Cirripedia, Polychaeta, Insecta, and tychoplanktonic forms (free-living nematodes).

The average population density of zooplankton in the lake during this study [19] was about 935,800 ind. m^{-3}. It is clear that the density of zooplankton increased by more than 14-folds within 20 years since it was 63,250 ind. m^{-3} [20]. Zooplankton densities were maximal in winter and slightly decreased in spring and autumn, while summer was the least productive season. On the contrary, the most striking feature was the complete disappearance of rotifers in lake-sea connection station in summer, which affected by the periodic intrusion of seawater through El-Gamil outlet [19]. This may be explained by the fact that most rotifers cannot tolerate the highest chlorosity at such site that reached 24.8 g L^{-1}. *Brachionus* was the most dominant genus of rotifers in Lake Manzala [10, 21], as it is represented by six species, namely, *B. angularis* (represented 45 and 28% of the total rotifers), *B. calyciflorus*, *B. plicatilis*, *B. urceolaris*, *B. quadridentatus*, and *B. caudatus. Brachionus angularis* and *B. calyciflorus* were considered as indicators of eutrophic condition [22]. *B. plicatilis* flourished well during summer, Esparcia et al. [23] mentioned that *B. plicatilis* is adapted to high salinity and temperature. *B. urceolaris* flourished in spring and occurred in small numbers during autumn and winter. *B. quadridentatus* was poorly detected in some stations in winter, spring, and summer, while *B. caudatus* only represented at one station in spring. According to Angeli [24], "the simultaneous presence of several species of the genus *Brachionus* is a good indication of the eutrophic nature of an aquatic ecosystem." Three species of *Keratella* coexist in Lake Manzala [10, 19]. *K. quadrata* was the most frequently encountered species, which contributed about 10.5 and 28% of the total rotifers, followed by *K. tropica*, while *K. cochlearis* was rarely encountered. Guerguess [20] found *K. quadrata* in small numbers in all seasons, but common in winter in Lake Manzala. Radwan and Popiolek [25] found that in eutrophic lakes the clear dominants were *K. cochlearis* and *K. quadrata* and so considered as indicators of high trophic status. *Polyarthra vulgaris* occurred throughout the year (formed 2.6% of the total rotifers); spring was the most productive season for this species [19]. It completely disappeared from station near Bahr El-Baqar drain, indicating that *P. vulgaris* cannot withstand the sewage water. Crustacean copepods were dominated by *Acanthocyclops* sp. and Cyclopoida, while the euryhaline neritic copepods species *Acartia latisetosa*, *Oithona nana*, *Euterpina acutifrons*, *Paracalanus parvus*, and *Centropages kroyeri* invaded the northern regions of the Lake in autumn. Copepoda in Lake Manzala (14% by number and

20% by volume) are third in importance after Cladocera and Rotifera, but their contribution by volume is more important and is next to Cladocera owing to their larger sizes [20]. In the eutrophic eastern basin of Lake Manzala, *Acanthocyclops* sp. contributes 2.5–10 times as much as the total zooplankton than in any other lake basin, not only its standing crop is higher, but also the size of the individuals is increased. *Halicyclops magniceps* also thrives better in the eutrophic basin, while *Mesocyclops* sp. is more abundant in the less saline western than in the eutrophic eastern part of Lake Manzala [20]. Khalifa and Mageed [19] found that Copepoda represented the second important prdominance zooplankton group in Lake Manzala during the study period (2000–2001); nauplii comprised about 79% of their total count during different seasons. Similarly, El-Maghrabey et al. [17] mentioned that copepod nauplii formed an important item in the zooplankton in Lake Manzala. Among adult cyclopoids, *Acanthocyclops* attained its highest population density in winter. *Thermocyclops hyalinus* was rarely detected at some stations in winter, spring, and summer, while *Mesocyclops* was counted in relatively high numbers at two stations in spring. The absence of the marine copepod *Paracartia latisetosa*, which was previously considered as a main copepod in Lake Manzala during periods of high salinity [17, 18], is a result of freshening of the lake. During the study of Khalifa and Mageed [19], Cladocera was sparse in the zooplankton of Lake Manzala. Spring was the most productive season for Cladocera; the only common caldoceran was *Moina micrura* [19]. Guerguess [20] reported the peaks of Cladocera in Lake Manzala during summer. Nineteen species belonging to ten genera were recorded in Lake Manzala [20], of which three are marine, namely, *Evadne spinifera*, *E. tergestina*, and *E. nordmanni*, and *Diaphanosoma excisum* and *Moina micrura* were the most common species. Cladocerans represented less than 1% of the total zooplankton in 1959/1960 [17] versus 75% in 1979/1980 [18]. However, absolute abundance data is not available for comparison purpose and the apparent species shift could be mainly due to increase in abundance of cladoceran species in response to eutrification [18]. Caldocera were the most important component in the lake zooplankton contributing 57% by number and 41% by volume [20]. The distribution of Caldocera in Lake Manzala is governed mainly by two factors, the eutrophic condition and the chlorosity; generally they avoided polluted water and increased chlorosity [20].

Biomass, production, and biomass turnover rate (productivity, P/B) of zooplankton were calculated from monthly zooplankton samples in Lake Manzala to estimate the carrying capacity of zooplanktivore fish [26, 27]. The estimated mean biomass was 0.158 g Carbon m^{-3}. Spring followed by summer was the highest productive seasons due to the flourishing of rotifers during this period. The mean secondary production in Lake Manzala was 4.198 g Carbon m^{-3} $year^{-1}$. This production can increase zooplanktivore yield in Lake Manzala by 24.13% of the actual total catch of the fish yield per year. The dominance of freshwater eutrophic indicator species was mainly attributed to the freshening of the lake water and increase of the nutrient loading as a result of the direct discharge of untreated sewage and wastewater and discharge of irrigation water from drainage canals and land reclamation.

2.1.2 Lake Burullus

The study of zooplankton distribution of Lake Burullus is very useful in monitoring some important environmental properties such as pollution, eutrophication, warming trends, and long-term changes which in turn are signs of environmental hazards.

Aboul Ezz [28] studied the monthly variation and community structure of zooplankton of Lake Burullus during the late 1970s. She mentioned that Copepoda group was represented by 44 and 34 species, respectively. However, El-Sherif and Aboul Ezz [29] stated that both zooplankton and phytoplankton had a linear relationship in the western sector, which harbored the highest standing stock of both. Lake Burullus' etrophic condition was indicated by observing the low consumption rate of phytoplankton by zooplankton. Aboul Ezz [30] reported that there is remarkable increase in the zooplankton population during 1987–1988 (183,000 ind. m^{-3}), compared with that recorded during 1978–1979 (111,000 and 45,000 ind. m^{-3}, respectively). Copepoda has the largest amount when compared with other groups with a percentage of 36.6% and was represented by 26 species; Cladocera and Rotifera came next (21.8 and 15.5%, respectively) and was represented by 7 and 26 species, respectively. Ramdani et al. [31] investigated the open water zooplankton communities in North African wetland lakes where they included the zooplankton of Lake Burullus in their study. A total of 75 zooplankton species was recorded by Dumont and El Shabrawy [13]. They represent a mix of pelagic and littoral (phytophilic) species and reflect the fact that this shallow, water plant-rich lake hardly allows a distinction between a pelagic and a littoral space. Zooplankton abundance showed both seasonal and regional variation. Densities were higher in the west than in the center and east. Two peaks, 2,500,000–3,000,000 ind. m^{-3}, were recorded in the west in spring 2001–2002 and in winter 2003–2004, owing to blooms of *Brachionus angularis*, *Polyarthra vulgaris*, and *Keratella quadrata*. The lowest density (200,000 ind. m^{-3}) fell in autumn 2001–2002. Rotifers were the most abundant and spacious group in all seasons and sectors, comprising 70–75% of total zooplankton by numbers. Taxonomic errors in the older species lists are also suspected (e.g., *Lecane elasma* is an acid-water species, which is definitely out of place in Lake Burullus). The genus *Brachionus* was the most specious genus, represented by nine species since at least the 1970s, an indication of the naturally eutrophic nature of the lake. The spatial distribution and seasonal variation of the rotifers were similar to that of total zooplankton. There were outspoken specific differences in within-lake distribution. *Keratella quadrata* was the most abundant taxon, representing up to 34% of total Rotifera in 2001–2002 and 2003–2004. Its peak was clearly in the west, in winter and spring, with 1,950,000 ind. m^{-3} in 2003–2004. *Brachionus calyciflorus* was aestival and contributed 19–21% to total rotifers during 2001–2002 and 2003–2004. Contrarily to *K. quadrata*, its peak (690,000 ind. m^{-3}) occurred in summer but again in the west. *Brachionus angularis* was widely distributed, forming 17% of total rotifers in 2001–2002 and 15% in 2003–2004. The highest standing crop, 630,000 ind. m^{-3}, was recorded in the west in 2001–2002. *Polyarthra vulgaris* was abundant in 2001–2002, contributing 12% of total density and 6% in 2003–2004. It was abundant in the west, with 390,000 and 370,000 ind. m^{-3} during autumn and spring 2001–2002. All other species were predominantly littoral and occurred in small numbers. They added that Copepoda formed 22% of total zooplankton by density in 2001–2002, decreasing to 10% in 2003–2004. Copepoda was abundant in the center and west. Autumn and spring were the seasons with a highest standing crop of 440,000 and 550,000 ind. m^{-3}. The identity of the species of *Acanthocyclops* living in Lake Burullus has been a matter of uncertainty. The species listed in the 1970s were named exilis, americanus, and vernalis; however, exilis is a little known North American species, while vernalis has been misidentified countless times. The species currently present in Burullus is of Palaearctic, not African, extraction, and, according to the latest insights, should be named either *Acanthocyclops trajani*. *A. trajani* was found in high densities during spring, mostly in the center and west. Its stock was lowest in summer and winter. *Apocyclops panamensis* made up 5% of adult copepoda. It is an opportunistic brackish-water species that was typically seen in the center in summer. Cladocera represents seven and nine species with 4 and 12% of the total species, respectively, during 2001–2002 and 2003–2004. This species inventory, just like the rotifers, is expected to be incomplete. The number of expected species from a lake with the size of Burullus is about 50 [32]. There was an increase in abundance in summer, with a highest density of 580,000 ind. m^{-3} in the center. The west, in contrast, had the lowest abundance. The eutrytopic, euryhaline *Moina micrura* all but monopolized the cladoceran plankton in summer, with a peak of 540 ind. L^{-1} in the center in 2003–2004. *Diaphanosoma mongolianum*, one of two *Diaphanosoma*'s in the lake, is an aestival plankter, of Palaearctic origin, contributing 5% of total cladoceran density. Some marine species are detected again at the northern part of the lake near the lake sea opening following the 2002 management plan. These species include two of Protozoa (*Eutintinnus lusus-undae* and *Metacylis mediterranean*) and five of Copepoda (*Oithona nana*, *Paracalanus parvus*, *Euterpina acutifrons*, *Harpacticus* sp. and *Macrosetella gracillis*). [33] found *Keratella cochlearis* as the main rotifer in spring and winter. However, *Brachionus calyciflorus* and *Epiphanes macroura* dominated in summer, and *Collotheca pelagica* flourished in spring and autumn seasons in El-Rayah El-Menoufy.

Long-Term Changes in Zooplankton Communities in Lake Burullus

The first study on the zooplankton in Lake Burullus, following Steuer's, was S.M. Aboul Ezz's Ph.D. in the early 1980s [28], with a follow-up paper about a decade later [30]. The checklist for the years 1978, 1979, and 1987–1988 is useful as it may be interpreted with care. Dumont and El Shabrawy [13] mentioned that, in the late 1970s, a sizeable fraction of species extending from seawater to mesohaline conditions occurred, and this fraction was exceptionally large (about 14 species) in the calanoid and harpacticoid copepods. Only 3 of these survived in 2001–2005, while about 7 species, already present in the 1970s, had maintained themselves, and two new freshwater species had first appeared. All large freshwater calanoids reported by Steuer had disappeared, as well as the large cladocerans (*Daphnia* spp.). Such a change in the size spectrum of the zooplankton strongly suggests other changes in the food chain, in particular at the fish level, where zooplanktivores of freshwater origin had become more prominent. The same authors added that a further difference in the freshwater species that had survived was that their abundance had become about ten times higher than in the 1970s. This, in its turn, suggests fewer competitors (the more abundant species that had disappeared) and more abundant food (eutrophication). Currently, salt water intrusions with its saline animals only occur when Aswan dam closes. This happens infrequently and in winter only (the latest events were in early 2004 and 2005). During the rest of the year, Burullus mostly behaves like a freshwater lake, with a residual salinity gradient from the west to the east. Typical values for salinity in 2001–2004 are given by Dumont and El Shabrawy [34]. In the west, they amounted to 1–2.5 g L^{-1} and, in the east, 4–5 g L^{-1}, with the central sector showing intermediate values. In contrast, during the pre-damming period, mesohaline conditions (with salinities up to 20 g L^{-1}) prevailed for two-thirds of the year. Two typical freshwater groups, the cladocerans and the rotifers, abound in the lake and no doubt were also present in the first half of the century [35]. All species recorded are typical freshwater, but during the saline intrusion of 2005, the marine onychopod *Podon polyphemoides* briefly appeared around Bughaz. From a quantitative point of view, Aboul Ezz [30] gave figures on the numerical abundance of zooplankton in Burullus, averaged over the months of the year and over two sampling sites. The overall average for 1987–88 was ranging from 180,000 ind. m^{-3} in December to 580,000 ind. m^{-3} in February. She also found that in about 10 years of time (1978 and 1979) zooplankton abundance had more than doubled (45,000 and 110,000 ind. m^{-3}, respectively). In 2001–2005, we rarely recorded abundances of less than 500,000 ind. m^{-3} and found peaks of up to 3,000,000 ind. m^{-3}, i.e., another increase by about one order of magnitude had occurred (Fig. 3). However, this increase was mainly due to smaller components of the zooplankton (rotifers), with increasing in rotifer species number too, concurrently with diminished in Copepoda species numbers (Fig. 4).

Dumont and El Shabrawy [13] mentioned that not too much appears to have changed in zooplankton assemblage until the 1950s, except that *Neolovenula* was never seen again. By the 1970s, *Daphnia* had become a rarity and was actually not recorded from the lakes, although ephippia continued to be deposited in the sediments [36]. The 1960s–1970s were marked by three new arrivals in the zooplankton, all of mediterranean origin: *Arctodiaptomus salinus*, *Acanthocyclops trajani*, and *Diaphanosoma mongolianum* (first cited under *D. brachyurum*). The reasons for this sudden influx of "northern" species are unknown. They are small to medium-sized, and all but the calanoids are good and coexisting with most fish predators. *Acanthocyclops* is one of the few copepods that may maintain and even increase its abundance. As a result of high dam construction in the Nile valley, mild changes happened in the zooplankton of Lake Burullus and three other delta lakes. The construction of the Aswan dam strongly reduced the marine influence in the lakes, and an elimination of some large grazers by freshwater fish took place. The significant changes occurred in the late 1980s and 1990s, however. They were caused by an intensified agriculture that eutrophied the lake and eliminated several large to medium-sized crustaceans. These were replaced in a small measure by northern immigrants but mainly by small filtrators, in particular, rotifers. Concurrently with zooplankton the phytoplankton community of Lake Burullus is considered moderately wealthy, but most of the species are fresh or brackish as it is found along the species richness scale

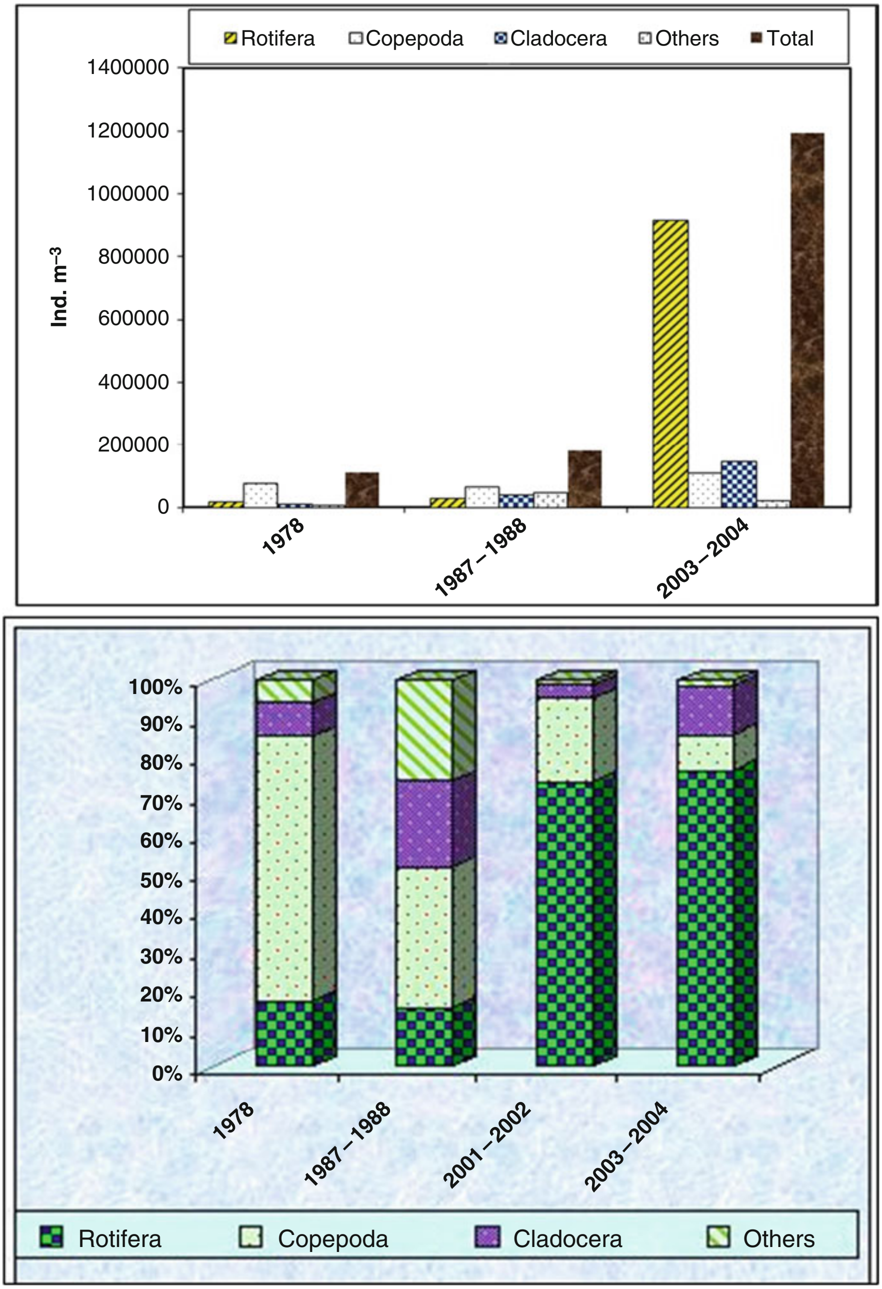

Fig. 3 Long-term changes in standing crop and community assemblage of zooplankton

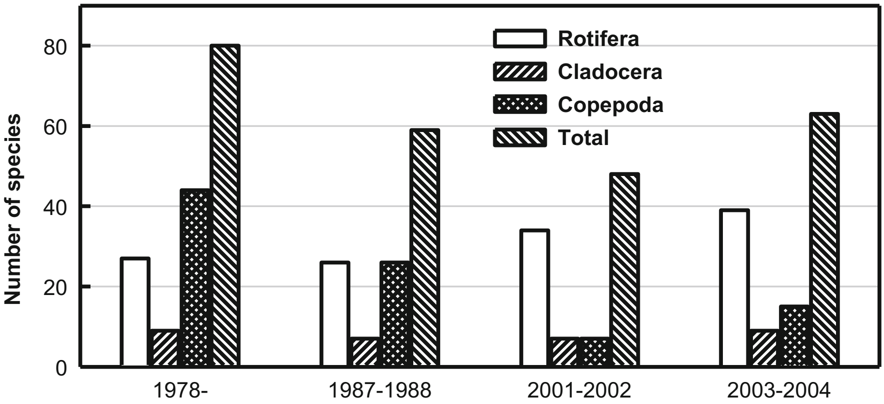

Fig. 4 Species diversity of zooplankton groups in Lake Burullus during different periods

and few are saline water forms. Diatoms were the most productive algal group, of which genus *Cyclotella* was the most dominant among the other genera. Chlorophyta was the second diverse and dominant group. Genus *Scenedesmus* was the first dominant among the other genera of this group. Cyanophytes were rarely recorded where *Microcystis aeruginosa*, *Lyngbya limnetica*, *Anabaena* sp., and *Oscillatoria limnetica* are the most common species [37].

The dominant and common zooplankton species recorded in non-deltaic lake (Bardawil) during 1985 *Tintinnopsis labiancoi* (Protista) and *Acartia clausii* (Copepoda) were replaced by *small*-sized species *Tintinnopsis tocantinensis* (Protista) and *Oithona nana* (Copepoda) in 2003. Moreover, 21 zooplankton species have been recorded for the first time in the lagoon [38].

2.1.3 Lake Edku

El-Hawary [39] studied the zooplankton of Lake Edku and reported that it is poor in a number of genuinely planktonic species and the cladoceran *Daphnia* spp. and *Moina dubia* are the characteristic species of zooplankton in the lake. Moreover, similar results were obtained by Samaan [40] for the Lake and added that the increased density of the submerged hydrophytes was met by a decrease in a number of the zooplankton. He also pointed that rotifers were a less frequent group in the lake. On the contrary, Aboul-Ezz and Soliman [9] studied the zooplankton community in Lake Edku and declared that there are five zooplankton groups found in Lake Edku, namely, Protozoa, Rotifera, Copepoda, Cladocera, and Ostracoda. Rotifera represented the most dominant group. These results clearly display the changes occurred in zooplankton community structure, where it shifted from the dominance of Cladocera to the dominance of Rotifera. This is due to the change of the physicochemical parameters in the lake. It is established that Rotifera is dominating the organically polluted environments, however, Cladocera dominating non-polluted waters. Additionally, since the lake is connected to the

Mediterranean Sea, zooplankton community was found to be influenced by the entrance of marine water. Therefore, Ramdani et al. [31] studied the zooplankton communities in North African wetlands, including Lake Edku, and found that the sites influenced by marine waters generally exhibited slightly lower numbers of species. This work was supported by Abdel-Aziz and Dorgham [41] who studied the zooplankton diversity in Boughaz area of the lake.

Soliman [16] recorded a total of 80 species in the whole area including in the main groups, namely, 26 Rotifera, 23 Protozoa, 16 Copepoda, 4 Cladocera, and 4 Ostracoda besides, free-living nematodes, meroplanktonic. The frequency of appearance of different species revealed that 5 species were specific to the sea, 2 to Boughaz, 4 to the lake, and 5 to drains sectors. Otherwise, 15 species (9 rotifers, 3 protozoan, 1 ostracod, polychaete larvae, and nematode) were common to the whole area, and others were present only in 2 or 3 sectors. The most considerable majority of the recorded species (68 species) showed seasonal occurrence. However 6 rotifers, 4 protozoans, and 2 copepods were perennial. Among these perennial species, *Globigerina inflata* (16.5%) and *Favella serrata* (21%) were restricted to the sea sector where *Brachionus calyciflorus*, *B. Plicatilis*, and *B. angularis* were common in the other sectors. Also, *Centropyxis aculeata* was likewise in drains (13.2%). Magnitudes of zooplankton abundance in this study 2,664,000 ind. m^{-3} are much higher than that of previous works 61,000 ind. m^{-3} as mentioned by Gharib [42]. Also, the species composition showed a different pattern of dominance. According to Gharib [42], the protozoan *Acanthocystis* sp. and *Glaucoma scintillans* were dominant in the sea sector, while *Brachionus plicatilis* and *Mesodinium acarus* were dominant in Boughaz sector. In Lake sector, *Monostyla bulla* and *M. closterocerca* dominated the population, while *Vorticella* sp. and *Astramoeba radiosa* were dominant in drains sector [43]. These species were minor constituents or absent in 1996 Soliman [16]. Ahmed [44] listed 72 species of zooplankton at Edku Lake. The zooplankton community was dominated by Rotifera, Copepoda, and Cladocera, with percentages 90.35%, 5.96%, and 2.51%, respectively. Protozoa and meroplankton groups were represented only 0.01% and 1.18% in proportion to the total number of zooplankton. The group Rotifera was represented by 36 species in the present survey. It was dominated by six species, namely, *Brachionus calyciflorus* (108,000 ind. m^{-3}), *B. angularis* (88,000 ind. m^{-3}), *B. plicatilis* (27,000 ind. m^{-3}), *Brachionus urceolaris* (7,000 ind. m^{-3}), *Polyarthra vulgaris* (24,000 ind. m^{-3}), and *Keratella quadrata* (16,000 ind. m^{-3}). Copepoda (Arthropoda, Crustacea) was represented by 14 species. It was dominated by nauplius larvae (13,000 ind. m^{-3}), 66.2% of the total copepods, and immature cyclopoid copepodid (3,000 ind. m^{-3}), 16%, whereas the adult, *Acanthocyclops tragani*, contributed 2,000 ind. m^{-3}, 9% of the total copepods. Cladocera was represented by only eight species. Two species were the most dominant in the group, namely, *Moina micrura* (3,000 ind. m^{-3}), comprising 34.68% of the total Cladocera, and *Bosmina longirostris* (3,000 ind. m^{-3}), 33.05%. These are small-sized Cladocera; however, the large-sized species such as *Diaphanosoma excisum*, *A. rectangula*, and *Ceriodaphnia reticulata* are less dominant, and consequently, they have lower values.

2.1.4 Lake Mariout

Preliminary reports on the zooplankton in Lake Mariout were made by Faouzi [8] and Steuer [35, 45], who compiled a partial list of the zooplankton organisms of the lake. Later, El-Hawary [39] conducted a preliminary study on the zooplankton of Lake Mariout during 1957, 1958, and 1959. He recorded ten species of zooplankton organisms in Lake Mariout. Most of the zooplankters identified in that study were benthic forms, captured in the water column due to the shallowness of the lake. Organisms observed were *Cyprideis littoralis* (an ostracod), free-living nematodes, *Pirenella conica* and *Planorbis* spp. (gastropods), and insects. Rotifers were represented by the genus *Brachionus* and copepods by the genus *Acanthocyclops*. In addition, *Mesopodopsis slabberi* and *Leander squilla* var. *elegans* (including its mysis larvae) were also recorded. El-Hawary [39] concluded that the lake was poor in the number of truly planktonic species. The characteristic type of zooplankton in Lake Mariout was *Brachionus* spp. (rotifers). Later the ecological conditions that affected the distribution and periodicity of the zooplankton organisms in Lake Mariout were studied. About eighteen species were identified: one cladoceran (*Moina dubia* [*micrura*]), one ostracod (*Cyprideis* sp), two amphipods (*Gammarus locusta* and *G. oceanicus*), one mysid shrimp (*Mesopodopsis slabberi*), one decapod (*Leander squilla*), and seven copepod species. The copepods were all brackish-water species: *Arctodiaptomus salinus*, *Harpacticus* spp., *Halicyclops* spp., *Diacyclops bicuspidatus*, *Mesocyclops* sp., and *Thermocyclops neglectus*, Rotifers were represented by five species of the genus *Brachionus*: *B. plicatilis*, *B. urceolaris*, *B. angularis*, *B. quadratus*, and *B. quadridentatus*. The meroplankton also included larvae of polychaetes, gastropods, insects, free-living nematodes, and the cirripede larvae of *Balanus* (a barnacle). It was observed that while Lake Mariout basin generally constituted a brackish-water environment with chlorosity values ranging from 1.5 to 5.6 g Cli, some zooplankton that are typically freshwater were observed in the lake. These included the cladoceran *Moina micrura* (*dubia*) and freshwater species of the rotifer genus *Brachionus*. Each of these two forms was widely distributed in the lake. Limnological studies of the zooplankton in the main basin of Lake Mariout showed that most of the dominant and prevalent zooplankton species were eurythermic forms, organisms tolerant of wide ranges of temperature exposures. The maximum abundance of zooplankton occurred in the spring and late autumn and the lowest in summer. Rotifers were the most dominant zooplankton, contributing numerically about 80% to the total population of zooplankton. They comprised thirteen species, belonging to seven genera: *Brachionus*, *Filinia*, *Polyarthra*, *Asplanchna*, *Harringia*, *Lepadella*, and *Lecane*. The genus *Brachionus* dominated the other genera, forming 89% of the total rotifer population, by count. This genus was represented in the lake by six species: *B. angularis*, *B. calyciflorus*, *B. caudcuus*, *B. urceolaris*, *B. plicatilis*, and *B. quadridentatus*. The highest densities were observed in the middle portion of the Main Basin. The copepod population was composed of ten species; all except *Acartia latisetosa* were freshwater forms: *Acanthocyclops* sp., *Mesocyclops* sp., *Thermocyclops crassus*, *Diacyclops* *bicuspidatus* var. *lubbocki*, *Halicyclops magniceps*, and *Ergasilus sieboldi*. Cladocerans were represented only by *Moina micrura*. The other organisms observed, i.e., free-living nematodes, chironomid larvae, and polychaete larvae, all appeared rarely. Abdel Aziz and Aboul Ezz [14] listed a total of 112 species of zooplankton varying in the 4 basins between a minimum of 5 species during November and a maximum of 59 species during September. The marine forms had a limited role in the community structure, as they were represented by 13 species in the whole area and mainly restricted to the Fishery Basin. Zooplankton community comprised 4 main components (Rotifera, Copepoda, Cladocera, and Protozoa) which had the highest species richness formed together 78.2% of total zooplankton. The minor component contributed 21.8% to the total zooplankton including Nematoda, Coelenterata, Annelida, Ostracoda, and Amphipoda. Besides, meroplanktonic larvae of polychaetes, cirripedes, decapods, molluscs and insects were appeared.

2.1.5 Lake Bardawil

Kimor [46] investigated the plankton population on the hypersaline lake, Lake Bardawil. Fouda et al. [47] reported 87 different zooplankton species. They indicated the existence of some particular species over a relatively wide range of habitats, while others were limited to certain locations. In addition, they highlighted the poor variety of zooplankton species compared to phytoplankton. However, Ibrahim et al. [48] included zooplankton in their studies from the management point of view. El-Shabrawy [38] studied the zooplankton community structure during 2002/2003, and he selected 12 stations to represent different habitats of the Lake. A total of 58 zooplankton species were recorded; copepods were the most abundant species, contributing about 69.9% of total zooplankton density. Zooplankton reached the highest density at the western area during summer (198,500 ind. m^{-3}). Protists (23 species) made up 10.3% of total zooplankton. Winter was characterized by the highest standing crop. *Favella serrata* was found to be the most common and dominant protozoan species in Bardawil Lagoon, comprising 27.1% of total protozoan density. Regarding seasonal variation, spring is the season of highest production of this species (avr. 8,792 ind. m^{-3}). *Tintinnopsis tocaninnus* occupied the second predominant position among protozoa: 13.1% of total protozoan population density. *T. tocaninnus* had the highest density in winter with an average density of 4,083 ind. m^{-3}, while the minimum density occurred in autumn (avr. 333 ind. m^{-3}). Nauplii larvae numerically dominated the copepod fauna and usually contributed more than 63% to total copepod density. They peaked in spring and summer, with a mean value of 81,667 and 93,958 ind. m^{-3}, respectively. The lowest population density of these larvae occurred in winter (avr. 18,000 ind. m^{-3}). The numerically dominant copepod species was obviously *Oithona nana*, which contributed 59.1% of total adult copepod density (range 26.2–77.6%). *O. nana* exhibited clear peak in abundance only during summer (avr. 14,000 ind. m^{-3}). It persisted with a population density fluctuated within 2,000 ind. m^{-3} during the rest of the year. *E. acutifrons* is a perennial species that makes up 12.4% (range 4.9–31.9%) of total adult copepod density. In contrast to the previous mentioned copepod species, *E. acutifrons* is peaked in spring and was highly abated in autumn. Mageed [26, 27] listed a total of 58 zooplankton species, and taxa belonging to 17 groups were recorded. Three groups were dominant (Copepoda, Protozoa, and Mollusca) and three were rare (Polychaeta, Rotifera, and Planocera), whereas the others were very rare which occasionally occurred in the plankton hauls. Copepoda comprised the most abundant and ubiquitous zooplankton organisms in Bardawil Lagoon, forming about 57% to the total zooplankton density (70% to the total holoplankton). August and October were the months of highest production of these crustaceans (avg. 263,000 and 213,000 ind. m^{-3}, respectively). *Oithona nana* was the most dominant followed by *Lucicutia flavicornis*, while other copepods including *Centropages calaninus*, *Clausocalanus furcatus*, *Parvocalanus crassirostris*, *Paracalanus parvus*, *Acartia clausii*, *Euterpina acutifrons*, *Oncaea conifera*, *Microsetella norvegica*, *Canuella* sp., and *Harpacticus littoralis* appeared as rare types.

3 Zooplankton and Environmental Changes of Coastal Lakes (Case Study Lake Burullus)

Coastal lakes have been considered as sentinels of environmental changes, such as anthropogenic effects and global warming due to their vulnerability [49]. With growing concerns of climate change and possible impact on environmental stems, "human intrusion and progressive development processes have had undeniable adverse finger-prints on maintaining healthy environment in coastal lakes of Egypt" [5]. For many lakes, one of the most threatening anthropogenic effects is eutrophication [50]. Eutrophication has dramatically affected phytoplankton biomass and community [51] in lakes. "To an extreme condition, harmful algal bloom may occur causing severe social-economic costs" [52]. Eutrophication effects often propagate up to higher trophic levels resulting in changes to the zooplankton community [53]. Zooplankton is considered as a successful monitoring tool to detect environmental changes in coastal lagoons. This is because zooplankton due populations react immediately to variations in trophic status and salinity increases [54]. Moreover, eutrophication and warming often have synergistic effects on whole lake ecosystems [55, 56]. Burullus, Edku, Manzala, and Mariout are large (50–500 km^2), shallow (~1 m deep) lagoons along Egypt's northern coast that lie at the intersection of the fertile Nile Delta and the extremely oligotrophic eastern Mediterranean Sea. They have been changing, both naturally and by human activities, since ancient times [57]. However, it seems that the most rapid changes related to increasing inputs of nutrient-rich agricultural drainage and sewage and area loss to urbanization and aqua-culture have been occurring since the middle of the twentieth century, well within the timeframe in which reliable measurements of the chemistry and ecology of the systems have been made and allowing us to assess how some of these changes may be impacting the productivity of the lagoons [13, 58–60]. All the water quality studies demonstrate an increase in drainage water loaded with nutrients therein, as well as lake area loss to urbanization, aquaculture, and agriculture, and have caused a series of dramatic changes, such as increased eutrophication, in the delta lagoons. Oczkowski and Nixon [3] mentioned that dissolved inorganic nitrogen (ammonium, NH^{4+}; nitrite, NO^{2-}; and nitrate, NO^{3-}; or DIN) and phosphorus (PO^{4-}, DIP) concentrations in all four lakes have been rising since the late 1950s, especially in Mariout Lagoon. Prior to about 1970, combined NO^{3-} + NO^{2-} were generally less than 10 μM in the lakes. However, a recent data from the 1990s to 2003 reported DIN concentrations more than double earlier observations and greater than 10 μM. In Mariout Lagoon, concentrations increased more than 50 times to very high values (>500 μM DIN). Concentrations exceeding 100 μM are extremely rare for coastal systems. Rotifers can be regarded as a good indicator of water quality in lakes. Since rotifers, opportunistic organisms with short life cycles respond quickly to environmental changes and they may prove useful for biological monitoring [61]. The use of rotifers as indicators relies on the assumption that differences in their abundance and species composition between the sites are regulated mainly by "bottom-up" forces, not by "top-down" predatory interactions. The rotifer trophic state index (TSIROT) based on rotifer abundance and species composition was developed recently by Ejsmont-Karabin [61], who suggests that it should be included in the ecological quality standards of water bodies.

In the deltaic lakes, genus *Brachionus* with its nine representing species is the most predominant and common rotiferan plankter. Its simultaneous presence is a good indication of the eutrophic status of the lake Angeli [24]. Sládecek [62] established a *Brachionus*:*Trichocerca* quotient (QB/T): *QB/T* = *No*. of species of *Brachionus/*No. of species of *Trichocerca.* According to this quotient in Lake Burullus, QB/T = 9/4 = 2.5, the lake is a eutrophic ecosystem. Pejler and Berzins [63] listed many species that indicate organic pollution; many of these species have been recorded in Lake Burullus such as *Brachionus claciflorus*, *B. urceolaris*, *Polyarthra vulgaris*, *Filinia longiseta*, and *Synchaeta oblonga*.

Nassar and Gharib [64] mentioned that there was no sign of eutrophication cyanophytes blooming as observed, suggesting a significant improvement in the water quality of Lake Burullus.

But by far the most critical factor in the lake's resistance to eutrophication follows from the water balance of the lake. Kassas et al. [65], in their monthly figures for water gains and losses, show that on average 97% of the lake inflow is drainage water, with less than 2% derived from local precipitation. In contrast, of water losses, 80% are due to outflow through Al-Bughaz and only 16% to evaporation and other factors. This highlights the fact that Burullus is a well-flushed lake and that most imported nutrients are rapidly washed out to the Mediterranean Sea, with a sizeable fraction of whatever remains in the lake being exported as fish flesh.

The hydrographic condition of Lake Burullus has been changed during the past few decades. This is confirmed by the disappearance of marine zooplankton species which were previously recorded by Aboul-Ezz [28, 30]. These species are *Oithona nana*, *Oithona helgolandica*, *Oithona robusta*, *Macrosetella gracilis*, *Canuella perplexa*, *Euterpina acutifrons*, *Isias clavipes*, *Paracalanus parvus*, *Calanus brevicornis*, *Centropages* sp., *Sagitta* sp., *Oikopleura dioica*, and *Fritillararia* *borealis.* So. the increase of the freshwater fish type associated with the disappearance of marine fishes is another sign for the decrease in the lake water salinity.

4 Linking Zooplankton and Fisheries

As shown in Table 2, a total of 64 fish species had been recorded in the Northern Egyptian lakes; the recorded species in the non-deltaic lake was obviously higher (43 sp.) than the deltaic ones (35 sp.). Both produced 8.73% of Egypt's national fish catch in 2015 [66]. The two most significant lagoons (Burullus and Manzala) provide about 90% of the total lagoonal landings (Fig. 5). While Edku, Mariout, and Bardawil are an order of magnitude smaller in size and today contribute little to the overall commercial fish catch, this has not always been the case. Mariout, in particular, contributed about 30% of the total lagoonal catch in 1980, but today provides just 4%. The total lagoonal landings have been increasing in the Burullus, Edku, and Manzala lagoons (Fig. 6). This was concurrent with increasing in zooplankton standing crop (Fig. 7). Mariout had a rise in its landings from 1960 to 1980 and then a dramatic decline from 1980 to the present. Fishing in Manzala appears to be the most profitable, with fishermen catching 4 t per person in the late 1980s, while Burullus and Edku yielded about half as much (1.8 t per person) during this same time. Tilapia dominate the deltaic lagoonal fisheries with four species present (*Oreochromis aureus*, *O. niloticus*, *Sarotherodon galilaeus*, and *Tilapia zillii*). Nile tilapia (*O. niloticus*) is the most dominant type, representing between 75 and 94% of the total catch in these lagoons [67]. Mullet and catfish also contribute in a small way to the deltaic lagoonal landings. In Burullus Lagoon, 2% and 4% of the catch are mullet and catfish, respectively [67]. Landings consist of four types of mullet (*Liza*

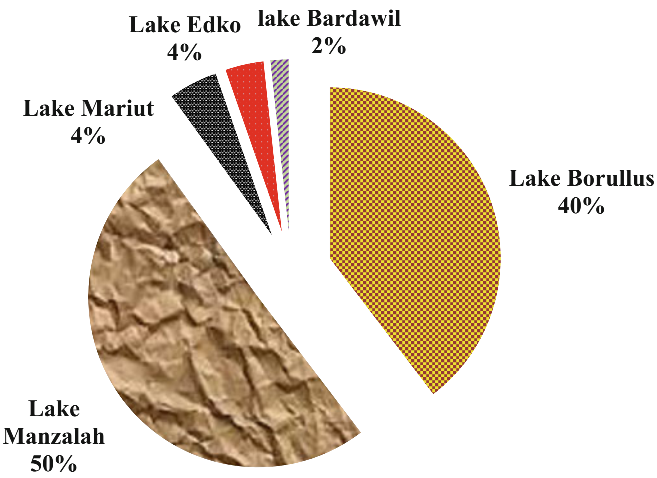

Fig. 5 Presenting sharing of each lake in total North lakes' fish landings

Table 2 A list of the fish species recorded in the Northern Egyptian lakes

Species	Lake Burullus	Lake Manzala	Lake Mariout	Lake Edku	Lake Bardawil
Alestes dentex Linnaeus			*		
Anguilla anguilla	*	*		*	*
Aphanius fasciatus	*				
Argyrosomus regius					*
Atherina boyeri	*		*		*
Boops boops	*	*	*	*	*
Barbus bynni	*			*	
Barbus perince	*	*	*	*	
Belone belone	*		*	*	
Callinectes sapidus					*
Caranx rhonchus					*
Chelon labrosus	*		*	*	*
Clarias gariepinus	*	*		*	
Crenidens crenidens					*
Cyprinus carpio		*			
Dentex dentex					*
Dicentrarchus punctatus	*	*		*	*
Dicentrarchus labrax	*	*		*	*
Diplodus annularis					*
Engraulis encrasicolus	*				
Epinephelus aeneus					*
Erugosquilla massavensis					*
Gambusia affinis	*		*	*	
Haplochromis bloyeti	*	*	*	*	
Hemiramphus far	*	*			*
Hemiramphus sp.		*			
Hippocampus fuscus					*
Hydrocynus forskahlii	*		*	*	
Labeo niloitcus	*	*			
Lates niloticus	*	*	*	*	
Lesueuria lesueuri	*				
Lithognathus mormyrus					*
Liza aurata	*			*	*
Liza ramada	*	*		*	*
Liza saliens	*	*		*	*
Liza carinata					*
Johnius hololepidotus	*		*	*	
Metapenaeus monoceros					*
Metapenaeus stebbingi					*
Mugil cephalus	*	*	*	*	*
Mullus barbatus					*
Mullus surmuletus					*

(continued)

Table 2 (continued)

Species	Lake Burullus	Lake Manzala	Lake Mariout	Lake Edku	Lake Bardawil
Oreochromis niloticus niloticus	*	*	*	*	
Oreochromis aureus	*	*	*	*	
Pelates quadrilineatus					*
Penaeus japonicus					*
Penaeus kerathurus					*
Penaeus semisulcatus					*
Pomadasys stridens					*
Pomatoschistus minutus	*			*	
Pomatoschistus (lliinia) microps	*				
Portunus pelagicus					*
Sarotherodon galilaea	*	*		*	
Scorpaena porcus					*
Siganus luridus					*
Siganus rivulatus					*
Solea aegyptiaca					*
Solea solea	*	*		*	*
Sparus aurata	*	*		*	*
Syngnathus spp.					*
Terapon puta					*
Tilapia zillii	*	*		*	*
Trachypenaeus curvirostris					*
Tylosurus acus					*
Umbrina cirrosa					*

*Observed or recorded

auratus, *Liza ramada*, *Liza saliens*, and *Mugil cephalus*) and two primary species of catfish (*Bagrus bayad* and *Clarias lazera*).

The catch of the non-deltaic lake (Bardawil) was entirely different. It composes mostly of the high-value saltwater fish such as *Mugil cephalus*, *Liza ramada*, *L. saliens*, *Chelon labrosus*, and *L. aurata* (Mugilidae). They contributed about 35.8% of the total catch; *Sparus aurata* (Sparidae) which constituted about 8.6%; *Solea solea* and *S. aegyptiaca* (Soleidae) (5.5%); *Dicentrarchus labrax* and *D. punctatus* (Moronidae) (1.5%); *Argyrosomus regius* (Sciaenidae) (0.4%); *Epinephelus* spp. (Serranidae); *Terapon puta* (Terapontidae); *Siganus* spp. (Siganidae); and *Tilapia zillii* (Cichlidae). Also, crustaceans were represented in the catch by shrimp mainly *Metapenaeus stebbingi* (19.2%) and crabs mainly *Portunus*

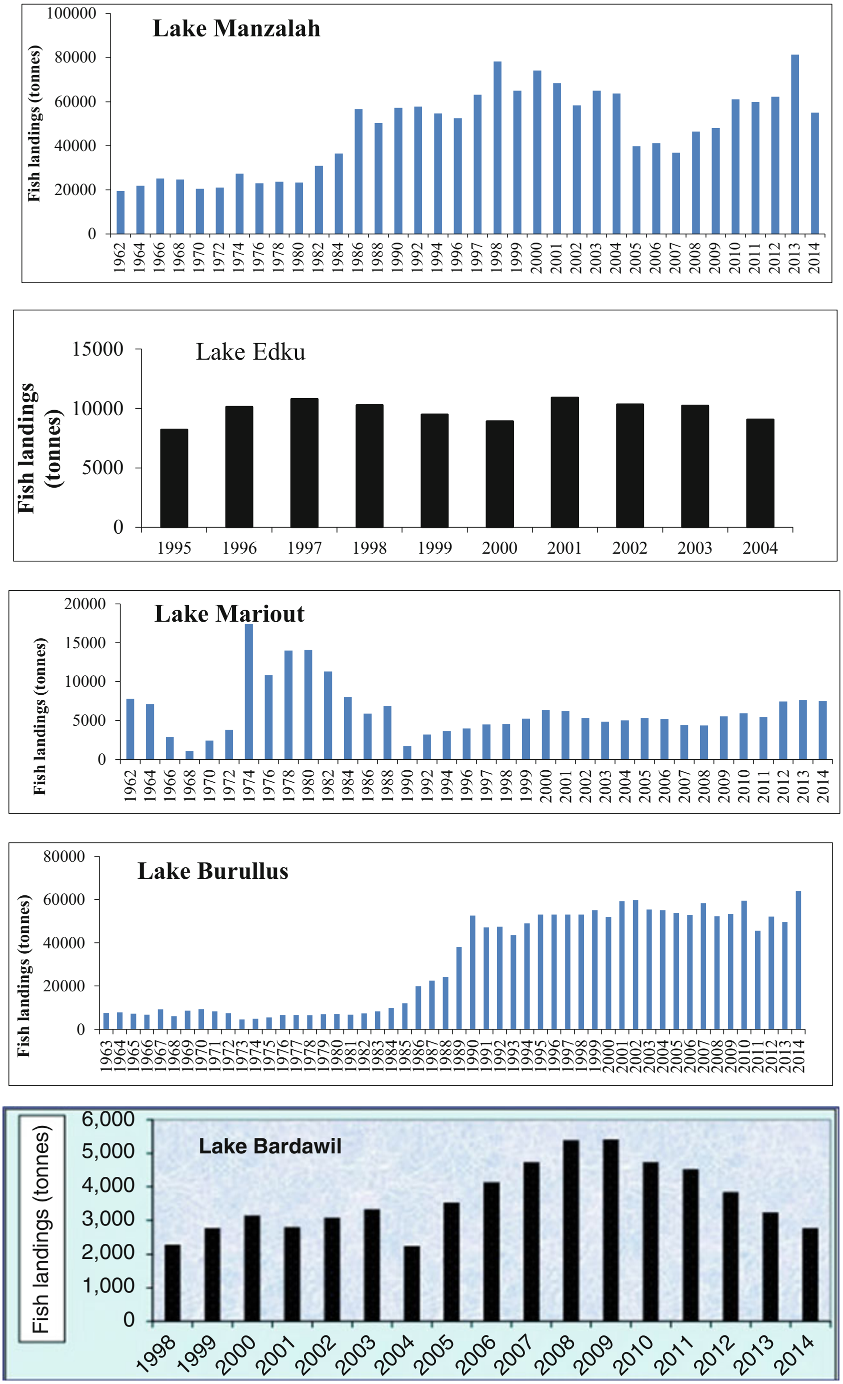

Fig. 6 Long-term changes in fish landing of the Northern Lakes, from top to bottom Manzala, Edku, Mariout, Burullus, and Bardawil

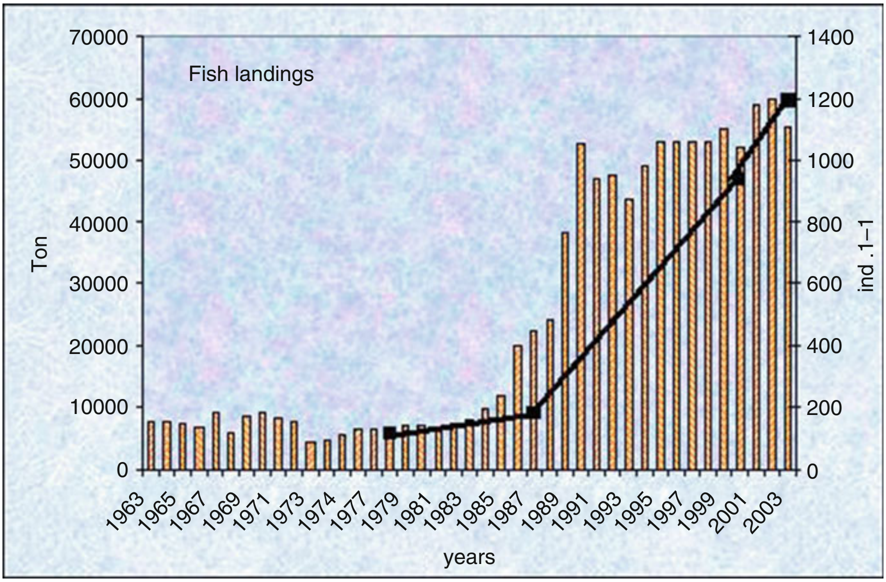

Fig. 7 Fish yield and zooplankton standing crop in Lake Burullus during different time intervals

pelagicus (24.7%). In addition, the "others" group contains the unsorted species or those of lesser importance [68].

4.1 Zooplankton and Gut Contents of Fishes

Dumont and El Shabrawy [13] studied the gut contents of Nile tilapia and mullets to investigate the importance of zooplankton for different fish species in the deltaic and non-deltaic lakes.

4.1.1 Tilapias

In Lake Burullus, zooplankton was infrequently found, contributing 13–18% of the total Tilapias' food except in winter, when it was highly detected, forming 45% of total food items (Fig. 8). *Keratella quadrata* monopolized the other species.

4.1.2 Mullets

Mullets rely on phytoplankton in winter as their food, forming about 64.1% of total food items, and were found in the gut of all the studied fish species. Zooplankton

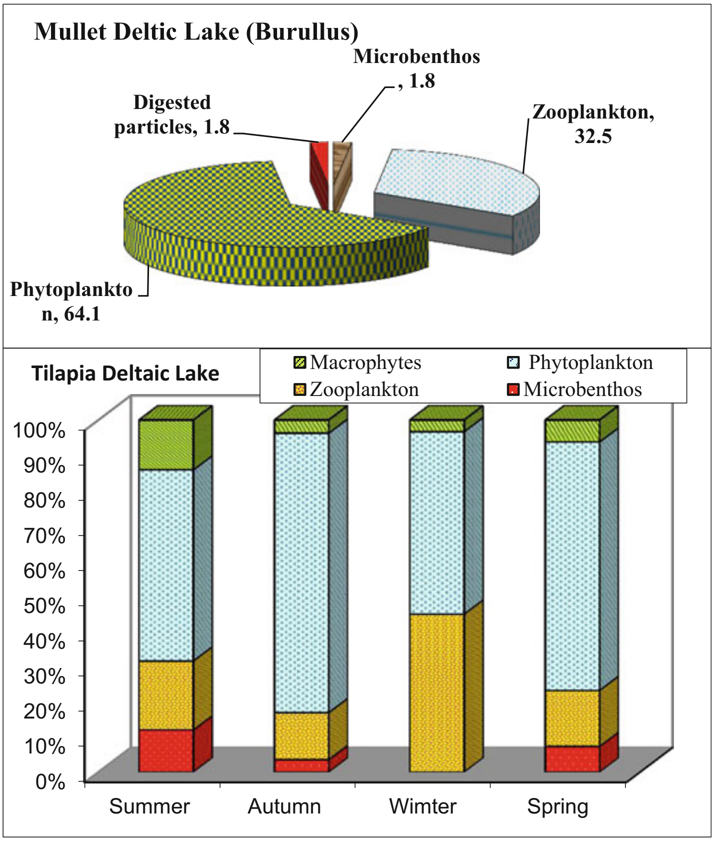

Fig. 8 Percentage composition of zooplankton in the gut contents of mullet and Tilapia in deltaic northern lakes

represents 32.5% of the food during winter. *Keratella quadrata* can be considered as important food item, forming 21.3% of total gut contents. *Brachionus angularis* and *Acanthocyclops taryaini* were infrequently detected.

Zooplankton is contributing about 28.3 and 11% of the food items content of mullet and prawn in non-deltaic lake (Bardawil) (Fig. 9).

5 Conclusion

The five northern delta lakes provided 35% of Egypt's fish catch during the 1970s. They now account for only 8.7% of the catch in 2015. The dwindling catch is attributed to pollution and improper resource management, among other factors. The

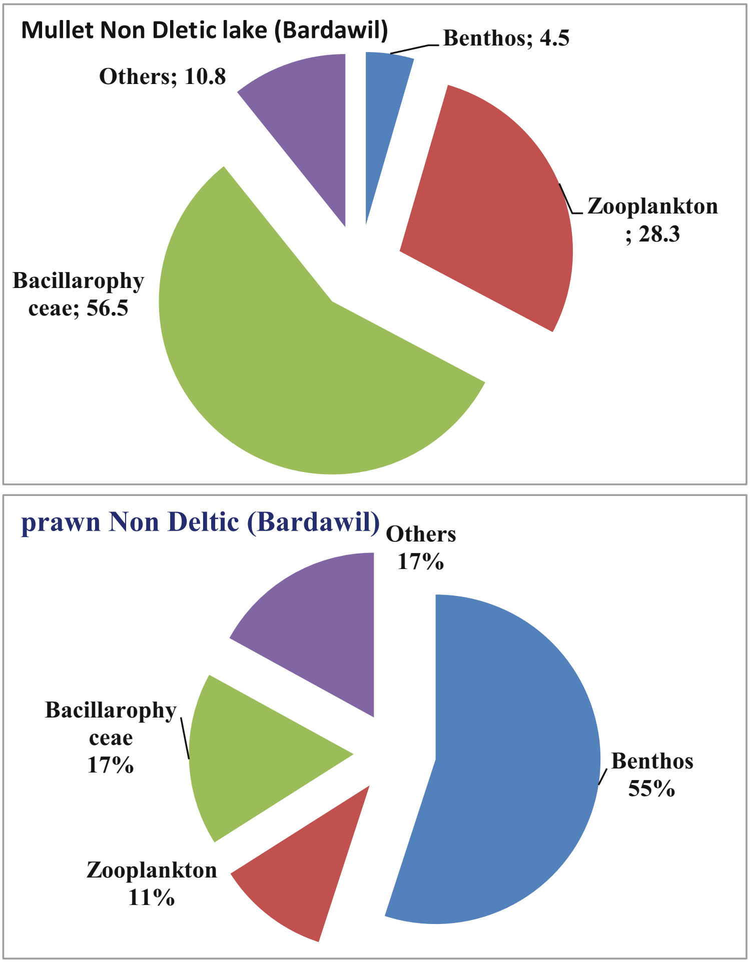

Fig. 9 Percentage composition of zooplankton in the gut contents of mullet and prawn in non-deltaic northern lakes

deltaic lake in its new, "freshwater" state is increasingly subject to nutrient-loaded agricultural drains. It is naturally eutrophic but has so far resisted excessive eutrophication by a combination of a large throughput of water and heavy fisheries exploitation. The increased standing crop of the zooplankton in the presence of heavy fish predation suggests an erosion of the lake's resilience and thus a future degradation, with blue-green algal blooms. Effluents from fish farms provide a large number of nutrients, the status of the lake may tip from eutrophic to hypertrophic, with all undesirable consequences.

6 Recommendations

1. To accelerate the restoration of the delta lakes to better conditions for saving them as grounds for fisheries and places for recreations, the quality of the sewage and industrial wastes dumping directly into them or indirectly via agricultural drains must be treated. The spread of aquatic plants that cover large areas of these lagoons must be removed. Degradation, habitat loss, filling up, and drought, which lead to a decrease in the size of all deltaic lagoons by over 70% of their original areas, should be stopped.
2. Because agriculture is a considerable source of nutrients causing eutrophication, substantial changes may be required in the use of fertilizers in agriculture for reduction of nitrogen and phosphorus inputs into the delta lakes. With the expected increases in urbanization, industrialization, and socioeconomic activities following the increase in population, the existing pollution control policies and measures should be enforced, especially before new industries are established around the North lakes to prevent the introduction of processes which may have detrimental effects on the lake environments. A continuous monitoring of the biotic features of the lake water as well as studying the biology, dynamics, and reproductive cycle of the commercial fishes is an essential step in establishing guidelines for fishery regulation measures and constructing a management policy for the rational exploitation of the lake fish resources.
3. The public awareness of the North lake issues is very limited; it is necessary to upgrade it for the valuable role of the lake ecosystems in our daily lives. This can be done by providing the public with special training programs on environmental and pollution problems with illustrative examples for protection and management.

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Fisheries of Egyptian Delta Coastal Wetlands; Burullus Wetland Case Study

Magdy T. Khalil

Abstract The occurrence of brackish and saline waters in Delta Egyptian wetlands during the seventies and early eighties of the last century have resulted in a large variety of fish species inhabiting these ecosystems; approximately 32 species were recorded during these periods. Decreasing salinity and domination of drainage water during the last four decades has led to a change in species composition and biodiversity of fish and other organisms. A field survey conducted during 2014 showed that the diversity of fish in the Burullus wetland has declined from 32 to 25 species. All the species which have disappeared are of marine affinity. On the other hand, the total production of this wetland has increased gradually from 7,349 tonnes in 1963 to 63,980 tonnes in 2014.

As far as the main groups of fishes are concerned, a gradual decrease in the mullet catch was recorded from about 44.7% in 1963 to 15.5% in 2014 of the total catch. This was accompanied by an increase of tilapia production from 42.8% in 1963 to 72% in 1992, and then decreased to about 62.0% in 2014. The shift was more pronounced during the eighties of the last century. On the other hand, some fresh water fish; like *Clarias gariepinus* and *Bagrus bajad* increased their production during the last seven years.

Keywords Burullus, Egyptian wetlands, Fish biodiversity, Fisheries, Mediterranean coast

Contents

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1 Introduction

The occurrence of brackish and saline waters in Egypt's Delta wetlands during the seventies and early eighties of the last century has resulted in a large variety of fish species inhabiting these ecosystems; approximately 32 species were recorded during these periods. Decrease of salinity and domination of drainage water during the last four decades in these wetlands has led to a change in species composition and biodiversity of fishes and other organisms.

The Burullus wetland is the most productive ecosystem on Egypt's coast. A field survey during 2014 showed that the diversity of fishes in this important wetland has declined from 32 to 25 species. All the species which have disappeared are of marine affinity. On the other hand, the total production of this wetland has increased gradually from 7,349 tonnes in 1963 to 63,980 tonnes in 2014.

Species composition of fishes was with high diversity due to the variation of salinities in different regions of the ecosystem. Thus, some pure marine species, such as *Engraulis encrasicholus. Sparus aurata, Johnius hololepidotus,* and *Solea solea* entered the wetland for some time from the Mediterranean along with some halophilous species of mullets (*Chelon labrosus, Liza aurata and L. saliens*). Brackish water species included *Aphanius fasciatus*, *Atherina mochon*, *Mugil cephalus* and *Liza ramada*. Many fresh water fishes inhabit the wetland, such as *Hydrocynus forskalii, Labeo niloticus, Barbus bynni, Barbus perince, Clarias gariepinus*, *Bagrus bajad, Lates niloticus* as well as the cichlids which belong to five genera namely: *Hemichromis, Haplochromis, Tilapia, Oreochromis* and *Sarotherodon* [1].

Tilapia zillii is widely distributed in the wetland on account of its high tolerance to saline water; while *Oreochromis niloticus* was the second common species of cichlids. *Sarotherodon galilaeus* as well as another cichlid, *Hemichromis bimaculatus,* avoid salty water. Their occurrence was restricted to areas of low chlorosity. *Mugil cephalus* and *Liza ramada* are spread out all over the wetland. The introduced species *Gambusia affinis* shows a similar wide distribution [1].

The largest numbers of fish species were caught at the wetland side of El-Boughaz opening. Twenty-one species were sampled at that locationa [2]. The species composition consisted of a mixture of marine as well as fresh water and euryhaline fishes. Moreover, the region at the mouth of the Nasser drain was recorded to be rich in fish biodiversity; 17 species were found at that site. Marine fishes were absent from that location and were replaced by fishes of fresh water origin, such as *Hydrocynus* *forskalii, Labeo niloticus, Barbus bynni* and *Lates niloticus*. The number of fish species collected in the remaining sites shows low frequency.

1.1 Present Status of Fish Species

During the 2000–2002 period, the field survey of Khalil and El-Dawy [3] showed that the diversity of fishes in the Burullus wetland decreased from 32 species to 25. All species which have disappeared from the wetland are of marine origin; some of these include: *Engraulis encrasicholus*, *Belone belone*, *Pomatoschistus minutus*, *Pomatoschistus* (*Iljinia*) *microp*, *Lesueuria lesueuri*, *Liza aurata* and *Chelon labrosus* [2] (Table 1).

2 Fish Production

The total fish production of Burullus wetland for the years 1963 to 2014 is shown in Fig. 1. Following different years of the survey, it is seen that the total production of the wetland increased gradually from 7,349 tonnes in 1963 to a maximum of 63,980 tonnes in 2014. In the course of these 50 years, a sharp decline in the total yield was recorded, especially in the mid-seventies of the last century, where the production declined to 4,556 and 4,875 tonnes in 1973 and 1974, respectively. Higher yields were regained in 1976 (6,573 tonnes).

The mullet fish catch declined gradually from about 44.7% in 1963 to 15.5% of the total catch in 2014 [1]. This was accompanied by an increase of tilapia production from 42.8% in 1963 to 72% in 1992 and then decreased to about 67.8% in 2003 and 62% in 2014 (Fig. 2). The shift was more pronounced during the eighties of the last century.

Contrary to that, the production of some fresh water fish species have gradually increased, especially during the last 7 years. This was very obvious particularly for two species namely: *Clarias gariepinus* and *Bagrus bajad*, where their production increased from 188 and 220 tonnes in 1963 to 2,272 and 935 tonnes in 2014, respectively [4]. Meanwhile, the production of marine fishes, such as *Johnius hololepidotus* and *Dicenlrarchus labrax* greatly decreased (Fig. 3).

The production of the fresh water introduced fish; the grass carp has increased progressively during the period from 1993 to 2014 (Fig. 4). This carp is herbivorous, resistant to diseases, well adapted to live in extreme environmental conditions; can tolerate increasing of salinity, decreasing in oxygen and organic pollutants. Therefore, its production has increased from 291 tonnes in 1993 to 2,375 tonnes in 2014 [1] (Fig. 4).

Table 1 Fish species in the Delta Coastal wetlands [1]

Family	Species	Habitat
Engraulidae	*Engraulis encrasicholus* (Linnaeus, 1758)	Sea water
Characidae	*Hydrocynus forskalii* (Cuvier, 1819)	Fresh water
Cyprinidae	*Labeo niIoitcus* (Forskal, 1775)	Fresh water
	Barbus bynni (Forskal, 1775)	Fresh water
	Barbus perince Ruppell 1837	Fresh water
Siluridae	*Clarias gariepinus* (Burchell, 1822)	Fresh water
	Bagrus bajad (Forskal, 1775)	Fresh water
Anguillidae	*Anguilla anguilla* (Linnaueus, 1758)	Fresh/saline water
Belonidae	*Belone belone* (Linnaeus, 1758)	Saline water
Cyprinodontidae	*Aphanius fasciatus* (Valenciennes, 1821)	Brackish water
Poecilidae	*Gambusia affinis* (Baird & Girard, 1853)	Brackish water
Atherirudae	*Atherina mochon* Cuvier, 1829	Brackish water
Mugilidae	*Mugil cephalus* Linnaeus, 1758	Fresh/saline water
	Liza ramada (Risso, 1826)	Fresh/saline water
	Liza aurata (Risso,1810)	Saline water
	Liza saliens (Risso,1810)	Saline water
	Chelon labrosus (Cuvier, 1829)	Saline water
Serranidae	*Lates niloticus* (Linnaeus, 1762)	Fresh water
	Dicentrarchus labrax (Linnaeus, 1758)	Saline water
	D. punctatus (Bloch, 1792)	Saline water
Cichlidae	*Hemichromis bimaculatus* Gill, 1862	Fresh water
	Haplochromis bloyeti (Sauvage, 1883)	Fresh water
	Tilapia zillii (Gervais, l848)	Fresh/saline water
	Oreochmmis niloticus niloticus (L.,1757)	Fresh water
	Oreochromis aureus (Steindachner, 1864)	Fresh water
	Sarotherodon galilaeus (Artedi, 1757)	Fresh water
Sparidae	*Sparus aurata* Linnaeus, 1758	Saline water
Sciaenidae	*Lohnius hoIolepidotus* (Lacepede, 1803)	Saline water
Gobiidae	*Pomatoschistus minutus* (Pallas, 1767)	Brackish water
	Pomatoschistus (lliinia) microps (Krover)	Brackish water
	Lesueuria lesueuri (Risso, 1810)	Brackish water
Soleidae	*Solea solea* (Linnaeus, 1758)	Saline water

All these changes confirm a pronounced predominance of fresh water fish stock of the Burullus wetland, reflecting the changes that took place in the ecosystem in the water supply, mostly from drains, and reduced chlorosity of water, especially in the eastern part, in association with the new huge drains constructed at that area.

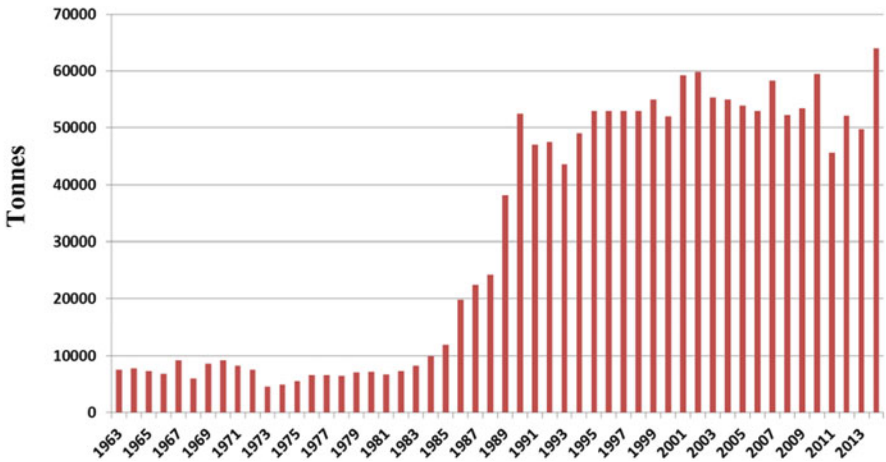

Fig. 1 Fish production of Burullus wetland during the period from 1963 to 2014 [1]

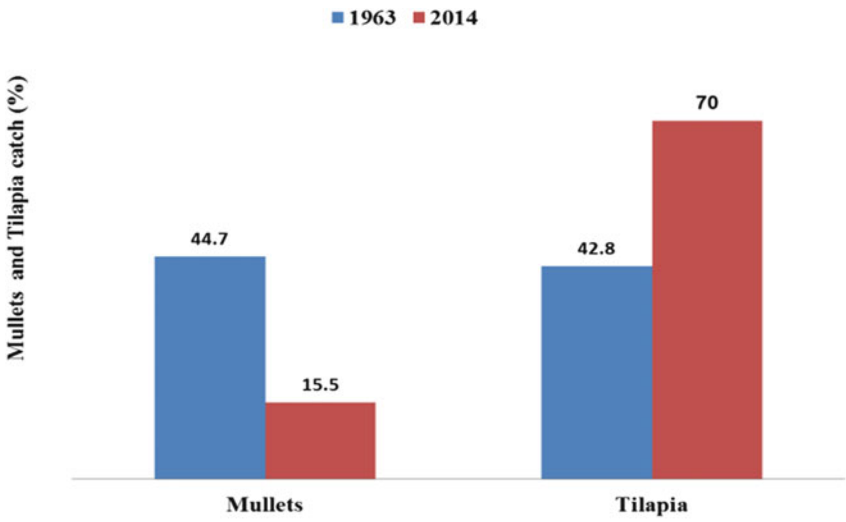

Fig. 2 Fish production of mullets and tilapia in Burullus wetland during 1963 and 2014

3 Fishing Equipment and Techniques

Shaltout and Khalil [2] described the fishing gear used in the Burullus wetland and classified them according to their technique of capturing fish. The equipment given here are only the most popular types, which are of common use in Burullus and other Northern Delta wetlands.

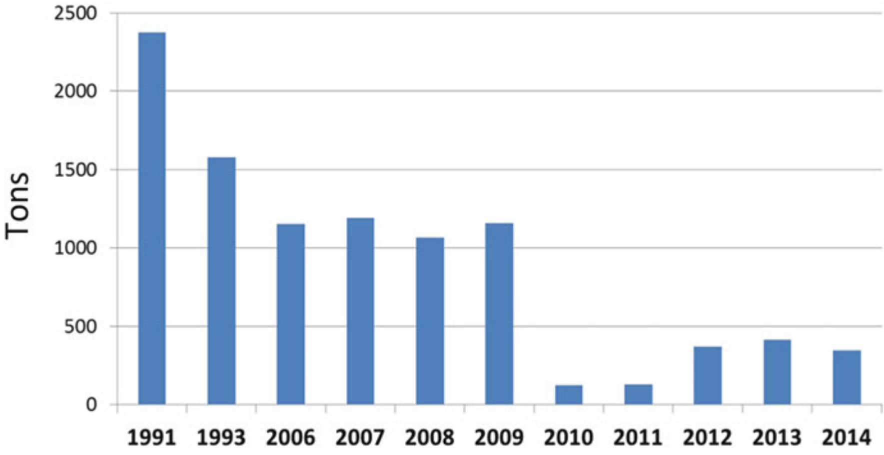

Fig. 3 Declining of *Dicentrarchus labrax* production in the Burullus wetland during the period from 1991 to 2014

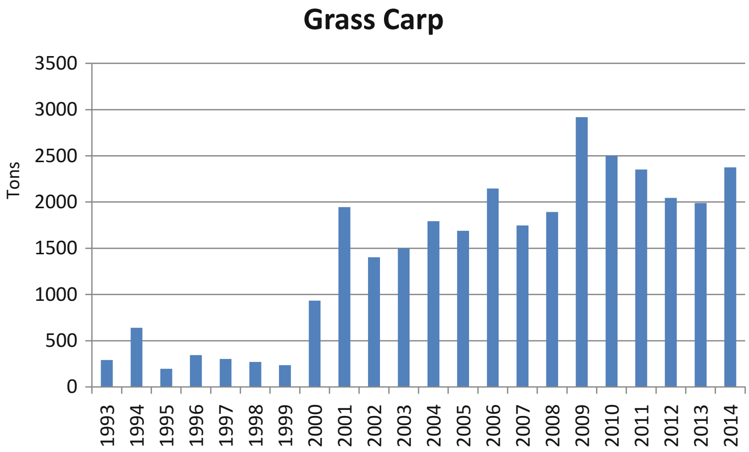

Fig. 4 Increasing of Grass Carp production in Burullus wetland during the period from 1993 to 2014

Entangling Gear

1. Gill net
2. Trammel net (Nasha and Takem)
3. Stationary trammel net (Saksook)

Encircling Gear

1. El-Gafsha
2. El-Ganeb

Trawl Gear (Dragged Gears)

1. Lawat
2. Lokkafa
3. Kerba

Seine Nets

1. Eshalta

3.1 Entangling Gears

3.1.1 Gill Net

The net mesh size is such as to allow the passage of the head only, but not the body of the fish. So, the fish is usually caught behind the gill covers, and the under-sized fish usually escape [2].

The gill net is used to catch *Lates niloticus*, sometimes fishes of family mugilidae or tilapia. The fishing operation is carried out usually at night. The gill nets are usually manufactured of cotton twine No. 80/6 or nylon twine Td 210/3. Gill nets without floats and leads are mostly used to build weirs, fastened to bamboo sticks, mainly during migrations of mullets. They are also used for other special methods of fishing. The length and the height of a part of gill nets varies between 10–20 m and 30 and 160 cm respectively while the number of mesh per 50 cm varies from 14 to 26.

3.1.2 Trammel Net

The Trammel net is the most common net in all the northern wetlands and is used to catch many fish species including tilapia, mullets, and others. A trammel net consists of three layered walls of webbing, which are hanged from a single cork and lead line. The mesh size depends on the species and size of fish to be caught [2]. When fish are passing between the outer walls, then by pushing of the inner wall into a pocket between the large meshes of the wall on the opposite side of the net, the fish are captured. The central wall stretched length usually equals 1.5 to 2.0 times the stretched length of the outer wall. This gear is used with difficulty in some areas and seasons due to an increase of crabs or aquatic plants which entangle the net and render it difficult to remove.

This net is usually operated by two boats. It is used as an entangling floating net when set from a boat in the littoral part of the wetland among the vegetation. The fishermen use flags on bamboo poles to mark the net, so as to be visible from quite a distance. The net is set overnight; the fish caught in the net are removed several times while the net is left setting. In deeper water, a common type of this net is used that called locally by fishermen as “Takem” (Fig. 5). Usually, it is about 1.25 m in height

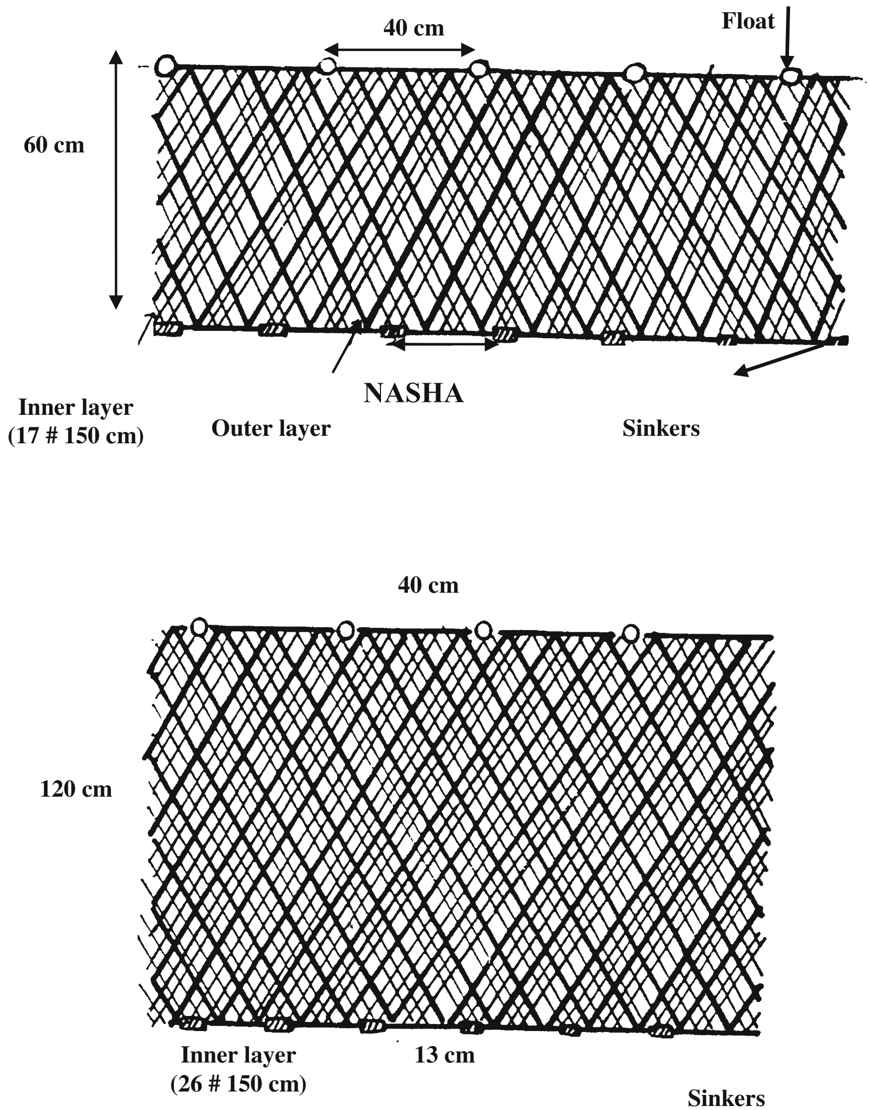

Fig. 5 The two common types of trammel nets used in Burullus wetland

and is set from a boat. Nasha is another type specifically used to catch *Tilapia* spp. In this net, the length of the basic part is some 20 m and the height is 60 cm.

According to the water turbidity and season of the year, nets of various colours are used, to suit the water turbidity and fishing time of the day (Fig. 6).

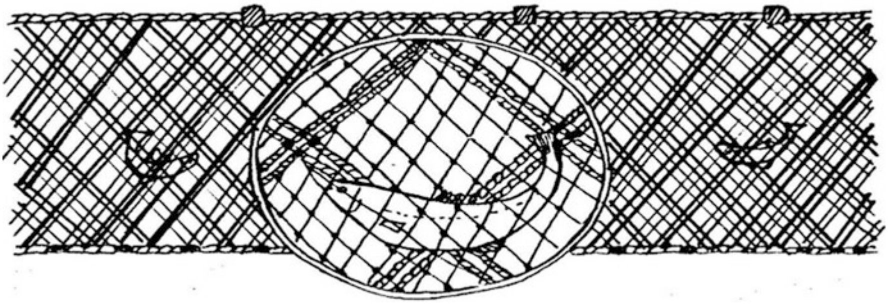

Fig. 6 A section of trammel net showing the pocket formed by trapped fish

3.1.3 Stationary Trammel Nets (Saksook)

Saksook (Fig. 7) is a modified type of trammel nets used in the Burullus wetland. It consists of three layers, formed of nylon similar to the ordinary trammel net. The upper rope of the net dry bamboo sticks are fixed at regular distances. This keeps the net suspended in the upper 40 cm of the wetland water. It is well known that this type of framed net is called beamed trammel net; that is more efficient than the ordinary gill or trammel nets. The height of the net hardly reaches 50 cm where lead pieces are attached to the lower rope, and several pieces of the net are joined together constituting a set of 400 m long. This net is used mainly in the Burullus wetland to At lake-sea connection; we can find several nets of this type set in the area. The catch can be collected several times, while the net is left setting [2].

3.2 Encircling Gears

3.2.1 El-Gafsha (Shebak El-Habl)

El-Gafsha is the largest of all nets used in northern wetlands. There are no floats and weights, and its dimensions are about 500–1,000 m long, 4 m height. The net is usually formed of cotton twines No. 20/4. At the middle portion of the net, it has 30 mesh bars per 50 cm, which decreases to 26 towards the ends. It needs about 30 persons to operate [2].

This net is usually used in shallow waters; and the upper edge of the net is kept 60 cm above the water. The fishermen hold the net with short stalks of bamboo. The lower edge is kept touching the bottom by their feet.

In this way, the encircled fish (especially mullets which are excellent jumpers) are prevented from escaping either by jumping the upper head rope or by running under the lower edge of the net. Usually, one fishing operation takes about one hour. This net is mainly used for catching mullets, therefore it is operated in summer and fishing is carried out during the daytime [2].

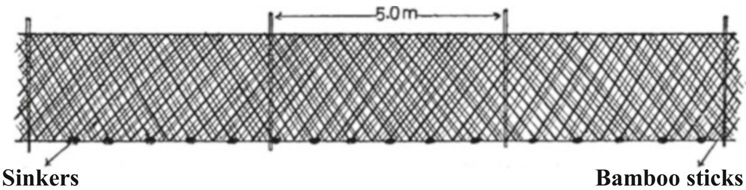

Fig. 7 Fixed trammel net (Saksook)

3.2.2 El-Ganeb

El-Ganeb is made up of 2 parts; each of about 15 m long and 1.5 m wide attached together. The net is manufactured of cotton twine No 20/4. There are no floats or sinkers in the upper and lower ropes. It is operated with 2 or 3 small boats with about eight fishermen. It is used in shallow areas covered with aquatic plants. The fisherman goes around beating the water with bamboo stalk, and then observe the movement of fish in the area, indicating the size of fish shoals. Once a considerable density of fish is detected, a fishing spot is fixed [2]. It is used usually for fishing *Clarias* fish.

3.3 Trawl Gears (Dragged Gears)

3.3.1 Lawat

Lawat (Fig. 8) is a big trawl net used in the Burullus wetland. It consists of 180–200 m netting, 8 m height at the middle decreasing to 4 m at the ends of the net. It has 35 mesh bars per 50 cm at the middle portion, decreasing to 30 at the wings. The net is formed of cotton twine No 20/4 or No 50/9, and lead is hung to the foot rope, while cork pieces are hung to the upper rope [2].

Two boats tow the net; each carries half the net. Both of the two halves are joined when the fishing operation starts. To prevent the fish from escaping, it is important to keep the bottom line close to the ground. Wind speed and abundance of fish are the main factors controlling the time of trawling. When the wind is satisfactorily strong, only trawling is possible. The net is more or less dragged for about one km distance. The net is lifted on the two boats after trawling, and the catch is collected. The two boats sail to the next fishing spot once the fishing operation is completed. Fishing with this net starts by sunrise and ends at sunset; usually carried out during the daytime. All fish species are caught by this net [2].

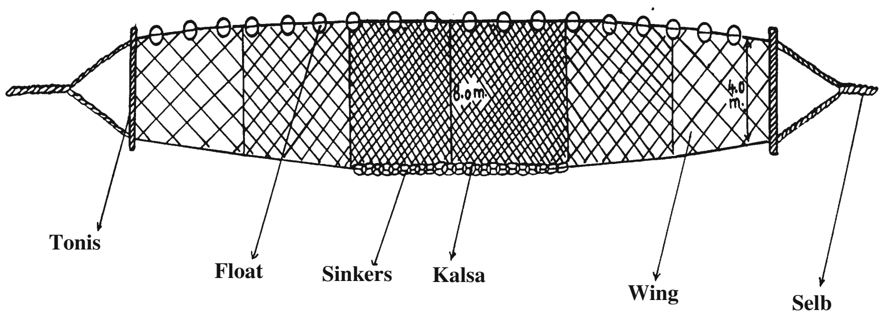

Fig. 8 Sketch of Lawat or Wannan net

3.3.2 Lokkafa

The lokkafa is a sac-like funnel-shaped net (Fig. 9), about 8 m long, fastened to a wooden frame shaped like a triangle. It is formed from cotton twine No 20/9 and sometimes of nylon twine Td 210/8. Between the ends of the two wooden pieces, a wire of about 120 cm long is fastened forming the base of the triangle. At the edges of the sack, the netting has 30 mesh bars per 50 cm. Towards the ends of the funnel, the number of meshes diminishes gradually, reaching 80 meshes.

This net is tied to the side of the boat and is dragged. Consequently any fish that may be enclosed fall back into the net. The net is usually lifted after half hour trawling, and more catch is collected on dark stormy nights. Lokkafa is not specific to certain fish species [2].

3.3.3 E1-Kerba

El-kerba net is more or less similar to lokkafa (Fig. 10), but smaller in size, with a wooden frame; triangular in shape. A 90 cm long- sharp iron plate, constitutes the edge of the base of the frame. The triangle is strengthened by cross bars. A funnel-shaped webbing about 6 m long is attached to the frame. The funnel webbing is usually formed of nylon twine Td 210/6 or 210/9.

With a strong rope, el-kerba is tied to the side of the fishing boat and is carried out in areas where aquatic vegetation is wide-spread. The net is held by the fishermen themselves during trawling, where they push the wooden frame downward, cutting the aquatic plants by the sharp edges of the frame. Consequently, all fish living within the plants fall back into the funnel of the net. The net is then lifted on the boat where the catch is collected. More catch is collected at dark stormy nights. El-kerba is not specific to any certain fish species [2].

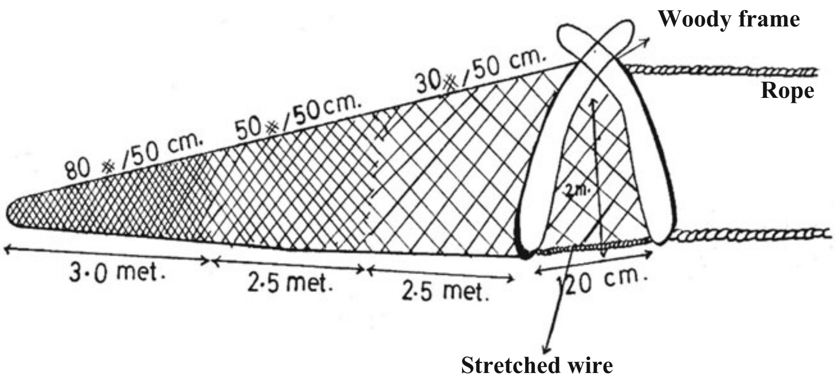

Fig. 9 Small trawl net (Lokkafa)

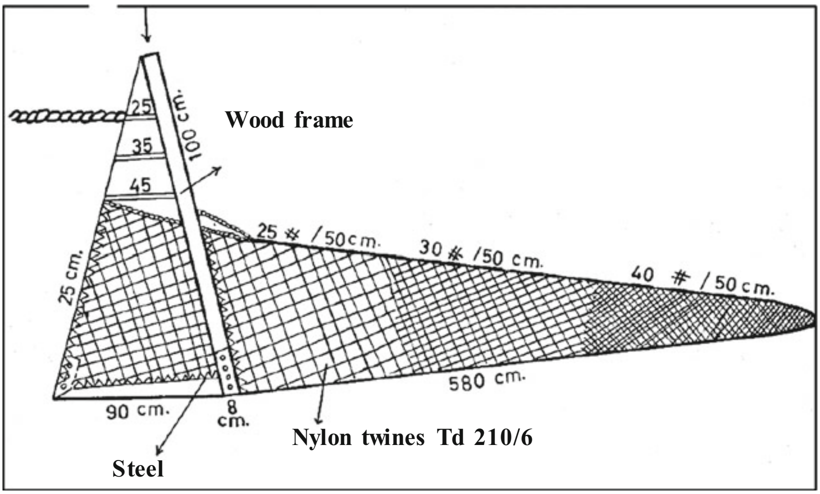

Fig. 10 El-Kerba net

3.4 Seine Nets (El-Shalta)

E1-shalta is the common type of seine nets used in the northern wetlands. The webbing is formed of cotton twine No 20/4, usually treated with seed oil as a net preservative. The length of the net is usually 10 m. The lower rope carries pieces of lead, while the upper one is furnished with cork pieces as floats. There are poles tied to the ends of the net. The webbing has 40 meshes per 50 cm. This net is commonly used for hauling towards beaches. About 2 or 3 fishermen usually haul with this net.

4 Fisheries

4.1 Cichlidae

Cichlids are represented in the Burullus wetland by four main species which are *Tilapia zillii, Sarotherodon galilaeus*, *Oreochromis niloticus* and *O. aureus* (Fig. 11), and in addition to two species of cichlids (*Hemichromis bimaculatus* and *Haplochromis bloyeti*) that are of little economic importance due to their small size.

4.1.1 Abundance of Different Cichlid Species in the Burullus Wetland

The catch per unit effort (CPUE) of trammel nets left over-night shows that *T. zillii* is the most abundant cichlid, followed by *O. aureus, S. galilaeus,* then *O. niloticus.* This method is usually set near the vegetated areas, which are a preferable feeding zone for *T. zillii* [5], while the CPUE of trammel nets using a sound stimulus showed that *S. galilaeus* dominates the catch followed by *O. aureus* and *O. niloticus*.

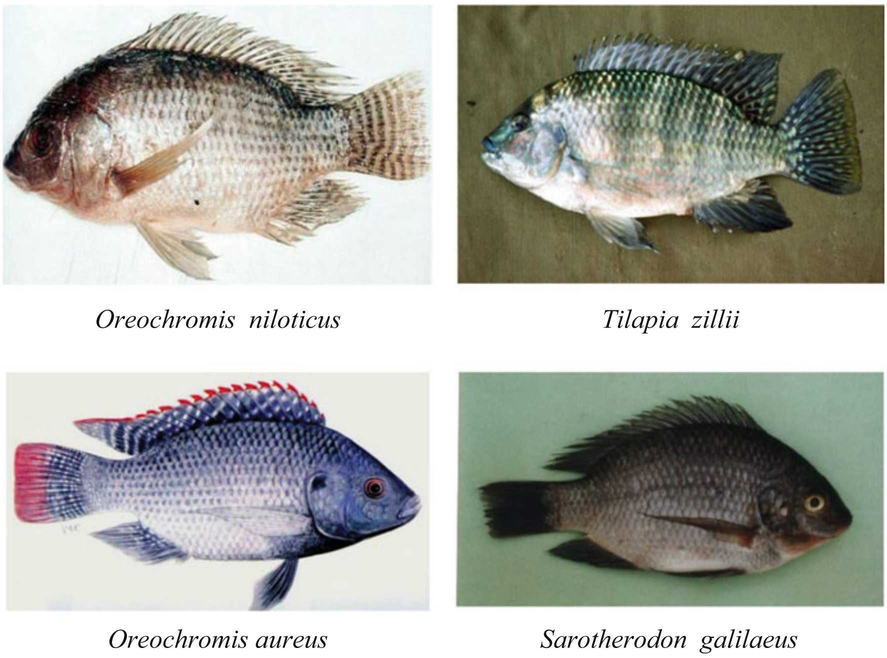

Fig. 11 Tilapia species in Burullus wetland

4.1.2 Seasonal Variations of Cichlid Species in the Catch

Spring and summer are the proper time for fishing cichlids with trammel nets left over-night, due to the more active behavior of these species in warm seasons. Most fishermen are using other fishing gear and techniques for catching mullet species during autumn and winter months. During spring, the most abundant species in the catch is *T. zillii* followed by *O. aureus* and *S. galilaeus* then *O. niloticus*. During summer, *Haplochromis bimaculatus* is the most abundant species followed by *T. zillii*, then *O. niloticus*, *O. aureus*, and *S. galilaeus*. *O. niloticus* is the most abundant species in autumn, followed by *S. galilaeus* and *O. aureus*, while *T. zillii* is rare. During winter, *T. zillii* is the most abundant, followed by *O aureus*, then *S. galilaeus*, while *O. niloticus* is rare [2].

Regarding wire traps, the catch is generally very poor in winter, and this could be due to the low water temperature that prevails in the wetland, especially in areas of dense aquatic plants, where traps are usually set. In winter, the four tilapia species are more or less of equal abundance in the catch. In spring, *S. galilaeus* and *O. aureus* are represented by the same percentage in the catch, followed by *T. zillii* then *O. niloticus*. During summer and autumn, *S. galilaeus* is the most dominant species in the production, followed by *O. niloticus* and *S. aureus*, while *T. zillii* is less abundant [1].

4.1.3 Mortality and Survival Rates

T. zillii has the lowest mortality rates (i.e., 0.646, 0.899 and 1.545 for natural, fishing and total mortality rates, respectively). Following this species, *S. galilaeus* and *O. niloticus* having about equal mortality rates (about 0.7, 1.3 and 2.1 for natural, fishing and total mortality rates, respectively). While, *O. aureus* has the highest mortality rates (i.e. 0.868, 2.119 and 2.987 for natural, fishing and total mortality rates, respectively). It is very important to mention that, the highest survival rate of *O. niloticus* occurs after the second year, while for the other three species it is after the first year [2]. So, we can say that *T. zillii* would have the highest survival rate, i.e. about 21%, followed by *S. galilaeus* and *O. nilolicus* (each about 13%), while *O. aureus* has the lowest survival rate (about 5% of the population annually).

The lower survival rates and consequently the high mortality rates of the four cichlid species in Burullus indicate that cichlid fishes in the wetland suffer from an annual decline in the stock.

The exploitation rates were estimated for the four cichlid species in the wetland by Hashem et al. [6]; *O. aureus* was the most exploited cichlid species ($E = 0.71$) followed by *O. niloticus* and *S. galilaeus* ($E = 0.63$) and at last *T zillii* ($E = 0.58$). The increase of the exploitation rate of cichlid species in the Burullus wetland increases the yield per recruit, but the biomass of these species shows an annual decrease in the wetland. Therefore, it is highly recommended to reduce the effort exerted on the cichlid populations in northern wetlands, since higher effort would eventually severely deteriorate their biomass.

The recruitment patterns of cichlid species in Burullus show that during almost all year-round the new recruits enter the exploited population. There are two recruits for *S. galilaeus*; a pronounced one during December and January (41%), and a lesser in October (28%). The recruits of *T. zillii* have two peaks, the first during November and December (44%), while the second in May (37%). On the other hand, *O. niloticus* has a peculiar pattern in its recruitment, extends from August to January with two peaks; a high one in September (59%) and a low peak in December (26%). The recruitment pattern of *O. aureus* involves a prolonged period from September to June with two peaks; the higher one in March (72%) and the low in September (16%) [1, 6].

Moussa [7] found that *O. niloticus* is the most common species in the catch, constituting more than 40.49% of the total catch, followed by *O. aureus* 34.74%, while *S. galilaeus* was the least frequent species, contributing 24.77%. In the middle and western regions, *O. niloticus* is the common species with 39.78% and 53.62%, respectively. In the eastern region, *O. aureus* is the most common (38.48%) followed by *S. galilaeus* (31.45%), then *O. niloticus* (30.08%). *O. aureus* represents 35.69 and 28.88%, whereas *S. galilaeus* is the least with 24.53 and 17.49% in the two regions, respectively.

4.2 Muglidae

Five species of mullets are present in the Burullus wetland as follows: *Mugil cephalus* Linnaeus 1758, *Liza ramada* (Risso, 1826), *Liza aurata* (Risso. 1810), *Liza saliens* (Risso, 1810) and *Chelon labrosus* (Cuvier, 1829) (Fig. 12).

4.2.1 Seasonal Fluctuation of the Mullet Catch

Liza ramada is the dominant species of mullet caught throughout the year in most of the northern wetlands. When the fish are fully ripe, they swarm and migrate from the wetland to the sea. Its catch in the wetland is very high in November and December. The production in autumn equals three times its catch in other seasons [2].

Mugil cephalus production ranks next to that of *L. ramada.* Its maximum yield is attained during summer, representing the maturation period. Large-sized mature fish appear during July to September, where they swarm in the wetland migrating to the sea to spawn.

Liza saliens production comes next to that of *M. cephalus*; its fishery extends from late spring to the beginning of autumn. In September, *L. saliens* leaves the area of the wetland-sea connection, where it is localized and migrates to the sea, so its maximum fishing was recorded during this period [2].

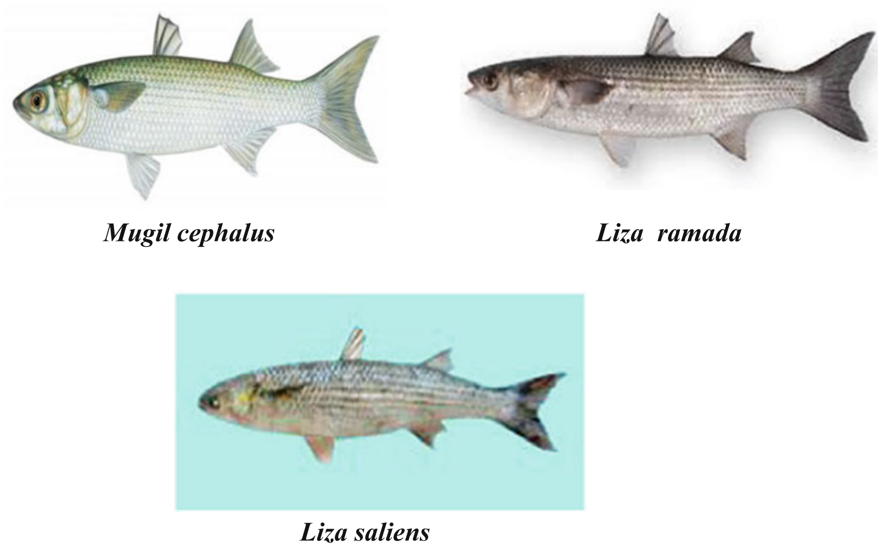

Fig. 12 Muglidae species in Burullus wetland

Chelon labrosus and Liza aurata have disappeared completely from the mullet catch. They were only recorded in the wetland-sea connection area. Their absence from the wetland water is explained by their inability to adjust to low salinity [1].

4.2.2 Factors Affecting the Distribution of Mullet Fry

The hydrographic factors which characterize the wetland year-round, have a great impact on the population dynamics of any species. The success of any year class depends mainly on the favorable conditions during the different stages of life. The success of early developmental stages in the case of mullet is determined at the breeding sites in the sea. The rate survival of the fry and young that enter the wetland depends on many environmental factors such as water movement, water temperature, chlorosity and the amount of food.

Water Movement

It has been found that the number of fry depends upon the water current direction. This was observed during collection of the fry at the wetland-sea connection area. A large number of fry were caught when the water was streaming into the sea. This confirms that the fry seems to prefer swimming against the current. Also, the fresh water flowing into the sea attracts the fry to the interior of the wetland [8, 9].

The water in the wetland is almost calm near the shore and in the vegetative pans, but it may be strongly agitated in the open areas even when the wind is of modern velocity. Due to the shallowness of the wetland, the eastern wind drives the water from Baltim region to the North West leaving the whole area dry. Consequently, all the existing mullet fry are forced to seek other areas. The eastern area of the wetland is not affected by such winds, as all the water mass rushes to it and raises the water level in the wetland, and the mullet fry can be seen swimming among the aquatic plants, especially the reeds (*Phragmites australis*) found near the shore. The vegetative regions decrease the impact of wind and create a suitable favorable shelter for the fry. On the other hand, western winds never dry the western part of the wetland because it is rather deep; however, large amounts of water are driven to the eastern sector of the wetland [2].

Water Temperatures

In the Burullus wetland, the temperature of water varies between 26.0 and 29.0°C in summer and from 12.5 to 15.5°C in winter. There is no thermal stratification, due to the shallowness of the wetlands. The comparatively higher temperature attracts the fry to invade the wetland. They prefer warm water, which stimulates the development of algae and other microorganisms needed as the basic food source for the fry and young mullet [10].

Chlorosity

The chlorosity of the wetlands is greatly affected by the amount of seawater, drainage and fresh water [11]. The chlorosity of the different areas of the wetland controls the distribution of the fry and even the adults. The fry of euryhaline fishes like *L. ramada* and *M. cephalus* can invade the whole wetland and are found in all areas, while the fry of *L. saliens* prefer areas with high chlorosity and does not leave the wetland-sea connection area. Because of their stenohaline nature, *L. aurata* and *Chelon labrosus* were always found much closer to the sea. El-Boughaz area acts as a transition area between the seawater and brackish water of the wetland. Huge amounts of fry were found in this area and they seem to stay for a while to acclimatize themselves before invading the different sectors of the wetland [2].

Amount of Food

The mullet as a whole is a grazer, feeding on living organisms or organic material accumulated on the wetland bottom. It was reported by many researchers e.g. [1, 2] that the observed fry of *L. ramada* and *M. cephalus*, move to the bottom and gulp a part of the sand or mud and then reject it after retaining the organic content in their special filtering mechanism that exists in the oesophagus. The amounts of organic materials in

Delta wetlands are abundant, and the variety of plant and animal microorganisms living on their bottom provide a rich source of suitable food for the mullet [1].

5 Conclusion

A decrease in salinity and drainage water in northern wetlands during the last four decades has led to a change in species composition and biodiversity of fishes and other organisms. A field survey showed that the diversity of fishes in the Burullus wetland has declined from 32 to 25 species. All the species which have disappeared are of marine affinity.

There are many threats to fisheries of Egypt's coastal wetlands, which include:

- Neglecting of clearing and dredging the wetland-inlet to the Mediterranean is the first complaint of fishermen. Decreasing of salinity levels has damaged the fish habitat and nursery of some marine high-valued fish.
- Hosha, an illegal method of fish catching is widely practiced in all Delta Coastal wetlands that harvests all sizes of fish that certainly affects the fish production of these ecosystems.
- Illegal capture of small fishes and fry directly from the only existing inlet by illegal operating gangs to provide fish farms established on the southern shores of the wetlands.
- Using illegal fishing gear with small mesh leads to catching non-commercial fish, which are dried up and used in the feed industry.
- Hydrological and water balance studies revealed that the drainage water had dominated the wetland ecosystems, and the water inflows into these wetlands are always greater than outflows. That means water in the wetlands is continuously moving toward the sea, and salinity has been reduced in these wetlands, which undoubtedly is reflected upon the disappearance of marine fish species from these important ecosystems.
- Pollution and waste disposal:
  - *Agricultural drainage* water increased the quantities of fertilizers and pesticides that were released into coastal wetlands, contributing significantly to the eutrophication and pollution of these ecosystems.
  - *Municipal wastewater*. Untreated wastewater out skirting these wetlands has led to the rapid eutrophication of southern regions of these ecosystems and further promoted the extensive growth of *Phragmites australis* beds. Moreover, the drainage of toxic and industrial wastes into the wetlands led to the disappearance of some sensitive fish species.
- Some of the basic factors that hinder the proper fisheries management of these wetlands and threaten their integrity in the long run include weak awareness of local residents and fishermen of environmental issues as well as the existing management plans and their importance, combined with limited

understanding of the role of protected areas and their value (at both local and national levels).

6 Recommendations for Fisheries Management

- Economically, the main activity in coastal wetlands is fish production, where the population majority declared that their income source comes from fishing. Therefore, fisheries activities must have priority in developing the population standards because this is the first step for sustainability.
- It is essential that the preparation of the fisheries management plan includes the interests of Governmental Authority (GADFR/Ministry of Agriculture) as well as other national agencies. A supplementary participation of local people in management efforts is needed, because when the local inhabitants feel part of development and progression, then the conservation organizations can be sure that the protection and management of the wetlands can be implemented successfully.
- At the initial stage of the management and monitoring process, baseline data needs to be established, to serve as a starting point, with which subsequent monitoring results are compared.
- Obtaining regular data on fisheries from local fisheries authorities should be given high priorityHigh priority). It is particularly important to collect accurate information on the economic value of the fisheries and fish production in these wetlands. This information will be very useful in determining and evaluating fisheries management options.
- The water inflow of the agricultural drainage canals into these wetlands should be examined regularly to control polluted water inflow into the wetlands.
- Monitoring the wetlands water level and salinity through an adequate management program to control the quantity of drainage water inflow into the wetlands.
- Illegal fishery practices should be banned, such as the capture of fry and small fishes from the sea inlet areas, “Hosha” fishing procedure, and using illegal fishing gears with small meshes.
- Fishery management of cichlid species must be based on the criterion of gaining extra fish weight because the mean size of cichlid species in the catch of these wetlands does not affect their breeding activities, i.e. the first maturity is usually attained at small sizes. By this procedure, the total catch of cichlid species from the wetland could be increased two or three times than that available today.
- Fishery management and increasing of mullet fish production are based on raising the salinity of wetlands water and regulating of a closed fishing season from December 20th to January 20th; the peak period of migration of juvenile mullets from the Mediterranean into the wetlands.

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Earth Observations for Egyptian Coastal Lakes Monitoring and Management

Islam Abou El-Magd and Elham Ali

Abstract Earth observation tools started as early as 1970s with some limited technologies at both spectral and spatial resolution. Since then, this technology has advanced at both dimensions. Data availability and data sharing policies are also improved enabling data availability for developing countries. Such availability fostered various environmental researches among which, the coastal monitoring and management. The coastal lakes' system in Egypt has been developed with the formation of the delta and undergone severe changes in the last decades. Remote sensing has been used as a good monitoring and mapping tool for physical, biochemical, and geomorphological features of the northern coastal lakes. For example, the accelerated area cutoff occurred due to the continuous human activities and infrastructures that could be delineated through satellite imageries. Remote sensing helped to determine the lost area of each lake with the highest rate at Lake Idku (73% in 40 years), followed by Lake Manzala (42% in 60 years), and Lake Burullus (38% in 60 years). Lake Bardawil – to some extent – is isolated from the excessive land use and land cover activities, and therefore it is partially saved from severe changes and area losses. On the other hand, the existence of several national infrastructures such as railways and highways has changed the shape of the coastal lakes. For example, Lake Mariout has changed from only one body of water mass into four dissected basins, and Lake Manzala is divided into two sectors by the new national coastal road.

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Remotely sensed data also enabled to estimate biophysical parameters including surface temperature, salinity, turbidity, and chlorophyll-a. For instance, it showed that Lake Bardawil has reduced levels of Chl-a (<13 mg/L) all over the year due to its isolation from drainage water and wastes (i.e., human and/or agriculture). The other coastal lakes, however have higher Chl-a levels that vary seasonally and even monthly due to the various wastes and drainage inflows. It also showed the spatial variations and Chl-a distribution along the lake on a single time with minimum values at northern part of the lakes, where the connection to the sea and higher levels downward confirms the effect of wastes and pollutants entering the lakes. With regard to spatial modeling and prediction, the IPCC model for sea level rise simulation indicated that the Egyptian coastal lakes are highly vulnerable to inundation through sea level rising with more than one predicting scenario and this would affect dramatically the whole ecosystem, particularly the aquatic environment. From a positive perspective, existence of these coastal lakes along the Mediterranean coast would play as the first-row defense for the delta zone. In this regard, applications of remotely sensed data could be used for the rehabilitation and management planning for lakes and help to exploit their natural resources and save their contribution to the national economy.

Keywords Coastal lakes, Egypt, Models, Nile Delta, Remote sensing

Contents

1 Introduction

More than 40% of the Egyptian people live along the country coastlines, mostly within the delta of the River Nile between Alexandria and Port Said [1]. The northern coast of Egypt is nearly 1,000 km long, of which about 275 km are for the Nile Delta. This coastal line is wealthy with various natural resources and activities that accommodate the higher percentage of population. These activities include agriculture, fishing, trade ports, industry, etc. [2].

The northern coastal zone is geologically formulated with coastal lakes and lagoons that were the downstream of the Nile River tributaries. The northern coastal zone of Egypt has five coastal lakes that highly contribute to the national fish stock. These lakes are, namely – from the east to the west – Bardweil, Manzala, Burullus, Idku, and Mariout. The Egyptian coastal lakes are represented as bays that were isolated by the longshore developments of beach ridges, sand barriers, and spits. Figure 1 shows the coastal zone lakes' system in relation to the ancient Nile tributaries showing the final destination into one of these lakes. They are surrounded with extensive wetlands which form a highly productive buffer zone between the Mediterranean Sea and the uplands [4]. The coastal wetlands are important to maintain the existence and quality of coastal environments. They play important roles in fishing, carbon fixation, nutrient assimilation, geochemical cycling, water storage, and sediment stabilization. These wetlands would also be important as suitable habitats for fish, some invertebrates, wild-life, and some plants.

On increasing urbanization and developmental activities, considerable human-induced changes happened to the coastal zone and its geomorphology including land reclamation and wetlands dry up [5–7]. In addition, the surrounded lands have been converted into fish farms in order to enhance the economic output of the country. Population increase, together with rural and urban activities, not only affects the availability and quality of natural resources in a direct way but also induces secondary impacts and needs to be regionally evaluated [8]. In consequence, the vulnerability of the northern lagoons is rapidly impacted by eutrophication process resulted from wastewater drainage and human activities, particularly during the last few decades [9, 10].

Due to the great value of the coastal lakes to local economy and their contribution to support the livelihoods and in order to overcome the continuous

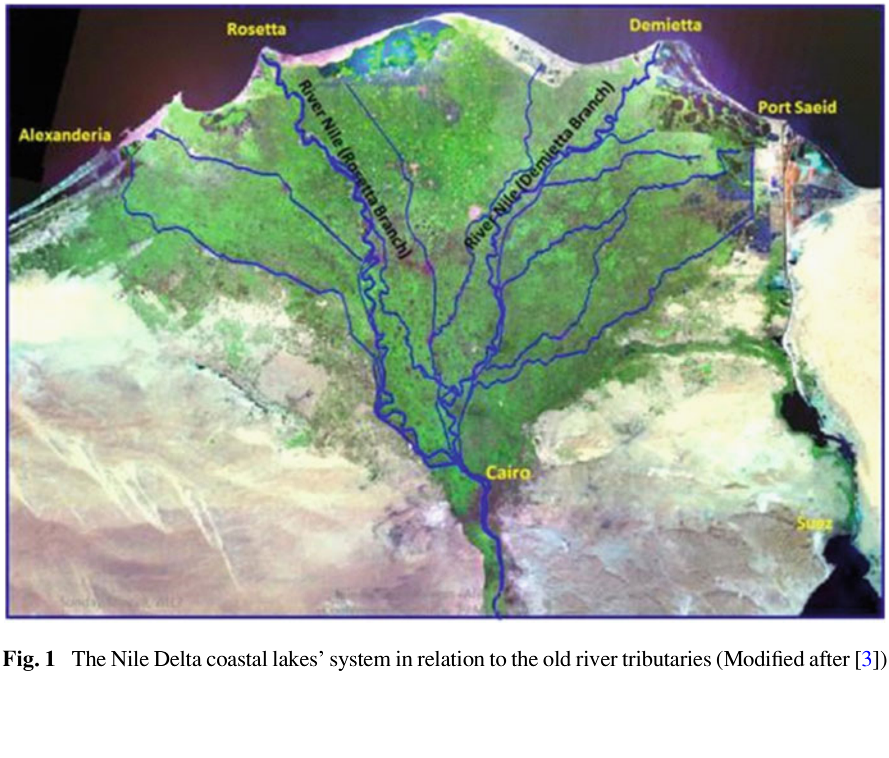

Fig. 1 The Nile Delta coastal lakes' system in relation to the old river tributaries (Modified after [3])

environmental stresses, there is a growing demand for a regular and accurate monitoring system. Remote sensing technologies could be a good source of information and provide the required real – or near-real – time information for monitoring the lakes and retrieve their biophysical parameters. Satellite remote sensing can be an effective alternative for studying coastal ecosystems [11] as for mapping aquatic micro- and macrophytes distribution over the lakes' large areas compared with traditional ship's site-specific samplings [12].

As a matter of fact, in situ measurements are often inappropriate for studying complex temporal and spatial dynamic systems such as lakes. In recent decades, remote sensing became a fundamental tool to explore the spatial and temporal behavior of aquatic ecosystems with wide coverage. Remotely sensed data was used worldwide in various directions to support research and decision-making process for coastal lakes since 1970s. The recently developed sensors and advanced technologies of remote sensing and geospatial information analysis enabled to provide regular thoughts on lakes' systems in terms of monitoring, management, and in some cases proposing rehabilitation scenarios, for example, the study of the implications in Taihu Lake, which is a large freshwater lake in the Yangtze Delta plain in Wuxi, China, for its ecological restoration [13].

In reality, there are various studies that have used optical remote sensing to map different categories such as chlorophyll distribution [14], algal blooms [15, 16], and aquatic macrophytes [17, 18] in coastal lagoon environments even in eutrophic [13] or highly turbid [14] systems.

This chapter aims to provide insights on the effective roles and applications of Earth observation and remote sensing for monitoring and management of the Egyptian coastal lakes.

2 Remote Sensing Applications in the Northern Coastal Lakes

2.1 Describing Lakes' Geomorphological Properties

2.1.1 Mapping Lakes Boundaries and Coastal Changes

One of the key advantages of the remotely sensed data is the temporal dimension of the revisit time that enables regular monitoring of the land ecosystems. This advantage helps in monitoring the actual changes occurring in the coastal lakes' boundaries and the dried-up areas of the water mass. Therefore, there is a growing need for a regular monitoring protocol that deals optimally with both temporal and spatial dimensions. The following section presents examples of the various changes/alterations in some lakes as resulted in response to the dynamic interaction between the lakes' system and the surrounding local community.

2.1.2 Case Studies

Lake Bardawil

Lake Bardawil (Bardawil lagoon) is one of the largest coastal lagoons in the northern coast of Sinai Peninsula, Egypt. It is the only of the northern lakes that maintains the sea connection with the Mediterranean via three outlets. The salinity level of lake water is similar to the sea or higher at some parts. The lagoon extends for about 76.37 km length and a maximal width of 16.65 km, with area of approximately 519 km^2 [19]. The average water depth is about 1.2 m; however, it varies from 0.5 m to a rather rare of 3 m depth at some sites. There is a sedimentary bar of 2 km at maximum that separated the lake from the Mediterranean Sea. However, it is connected to the Mediterranean Sea through two artificial outlets in the western side (Boghazes I & II) and one natural outlet to the eastern side (Zarnik) [20–22]. Lake Bardawil is fortunate being isolated within the desert area of Northern Sinai with nearly nil human community or/and activities. This helps to maintain the lake boundary – to some extent – unchanged and safe the water mass body.

Lake Manzala

Lake Manzala is considered the largest lake along the Egyptian north coast; it lies in the eastern corner of the Nile Delta and is governed by five different governorates (Port Saied, Sharkia, Dkhahlia, Damietta, and Ismaelia). During the last few decades, the lake went through extraordinary changes in its morphology and water mass body. The area was dramatically changed across the time from 1,411.2 km^2 in 1952 (as estimated from the topographic maps) to 501 km^2 in 2013 (as estimated by the satellite imagery – Fig. 2) [23, 24]. Remotely sensed data helped to give extensive description, classification, and changes of the various

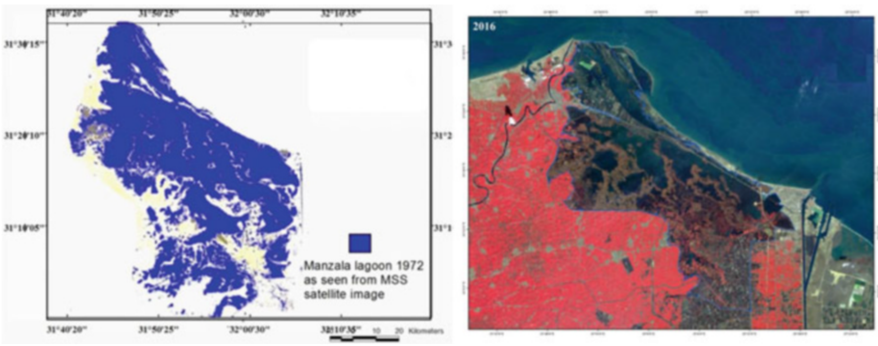

Fig. 2 Lake Manzala as seen from satellites – *left* lake water mass as seen from MSS in 1972 and *right* as seen from Landsat 8 2016

categories within the lake and surroundings (i.e., water mass, floating vegetation, islands, sand bars, and agriculture areas) between 1984 and 2015 with a dramatic decrease in water mass and increase in natural vegetation [25].

Lake Burullus

Lake Burullus lies in the middle of the coastal zone of the Nile Delta, and it is designated as a protected area managed by EEAA and registered as a Ramsar site (No. 408) since 1990. Lake Burullus is very shallow (≅1.5 m) and has a connection to the Mediterranean Sea at Boughaz El-Burullus in the northeastern part of the lake. The lake is surrounded by agricultural land and various human activities. The area of the lake was 553.4 km^2 – estimated from topographic maps in 1952. Remotely sensed data enabled to monitor and delineate the further changes that occurred, and it showed that the lake size has been reduced by 17% by 2003 and became about 461.4 km^2 [26, 27]. Further dramatic reduction continued to occur, and the lake size reached 284.7 km^2 in 2012 as estimated through satellite images. This extensive reduction in the lake size is attributed to many causes of which the rapid increase in fish farms around the lake which is considered as a major one (Fig. 3). Areas of fish farms have been increased from 30 km^2 in 1987 to about 272 km^2 in 2010 with around eightfold increase within 23 years [24].

Lake Idku

Lake Idku is a shallow lagoon lies south to Abu Qir Bay in the western corner of the Nile Delta. The lake has a narrow connection to the Mediterranean Sea to exchange and circulate water. In 1972 the area of Lake Idku was estimated using MSS satellite image at 139.9 km^2. The rate of changes in the lake area was monitored by satellite imageries that determine the reduction of the lake size reaching

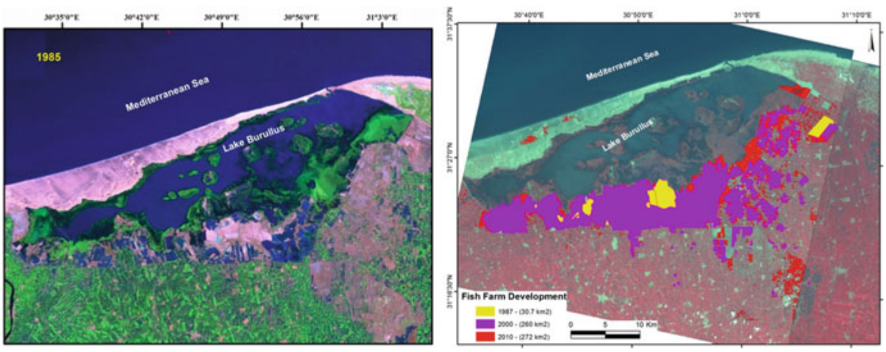

Fig. 3 Lake Burullus – *left* as seen from Landsat satellite in 1985 and *right* the growth of fish farms around the lake as monitored from satellite imageries

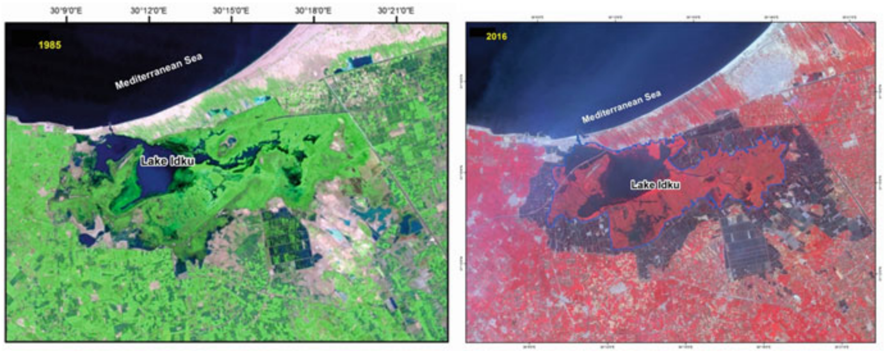

Fig. 4 Lake Idku as seen from Landsat satellite images – *left* in 1985 and *right* in 2016

113.8 km^2 in 2003, then 26 km^2 in 2012. Remote sensing information determined that such changes are mainly attributed to the excessive increase in human activities that end up with a dramatic reduction of nearly 73% of the lake water mass within 40 years [24] as seen in Fig. 4.

Lake Mariout

Lake Mariout is a longitudinal lake occupies the southern border of Alexandria city. It is separated from the Mediterranean Sea by a narrow isthmus on which Alexandria city was built. Originally the lake was one water mass body, which is further artificially divided into four basins due to man-made constructions (e.g., roads and embankments) and other activities. The total area of the lake is estimated as 190.8 km^2 and is primarily occupied by four categories: (a) water mass, (b) islands and barren land, (c) natural vegetation, and (d) fish farms. Remotely sensed data enabled to map these categories and estimate their specific area and changes occurred over time as seen in Fig. 5 and Table 1.

2.2 Evaluating Lakes Water Quality

2.2.1 Physicochemical Parameters

Physical and chemical properties of water could be – at a certain level – estimated from remotely sensed data. For example, surface water temperature is estimated from the thermal-infrared images, which could be used as an indicative for the lake water pollution and its environmental status. Normally, the visible light is penetrating the water column; this enables to map the water level of clarity/turbidity along the lakes using satellite data. Shallow dynamic water with suspended sediments and/or organic matter reduces the clarity of water, which is reflected in the

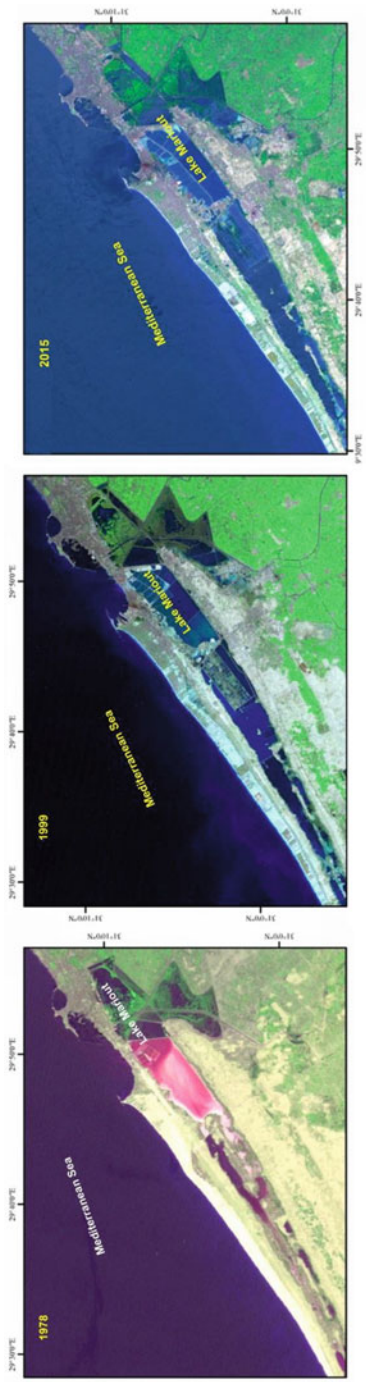

Fig. 5 Historical record of satellite images 1978, 1999, and 2015 that reflect the changes of lake Mariout on the time dimension

Table 1 Changes of the area of Lake Mariout as observed from satellite images since 1978

	1978	1986	2000	2003	2015
Water mass	31.5	52.5	74.6	68.7	68.7
Land	54.8	54.1	43.2	40.9	69.2
Fish farms	0	14.8	20.5	24.3	23.2
Natural vegetation	104.5	69.4	52.5	56.9	29.7
Total	190.8	190.8	190.8	190.8	190.8

short waves of blue and green radiation creating slicing of the turbidity as function of the interaction between the contents of the water column and the electromagnetic radiation. Figure 6 shows an example of the turbidity and clarity of Lake Bardawil as estimated from satellite images. The degree of blue color reflects the turbidity and clarity of the water. Salinity change is another water feature that can be estimated through satellite imagery. Figure 7 shows an example of the monthly distribution of salinity along Lake Bardawil during 2009 and shows maximum salinity levels during summer [28]. This is mainly attributed to the fact that Bardawil Lake is subjected to excessive water evaporation, particularly in summer leading to a progressive increase in water salinity. Both outlets connecting the lake with the Mediterranean are essential to flush water into the lake and allow for salinity exchange. It is determined that water temperature varies from 27 to 33°C in summer with high salinity reaching a maximum of 61.6% in August. The environmental condition of both temperature and salinity is suitable to sustain food web growth and consequently fish growth in the lake.

2.2.2 Biological Component (Chl-a)

Chlorophyll a is a universal indicator of phytoplankton that reflects the lake water quality and indicates for system fish stock. Optical remote sensing and models enabled to evaluate chlorophyll distribution in water based on the interaction with electromagnetic radiation. Various indices and regression models were used worldwide; however, for the Egyptian coastal lakes, it was estimated based on the available data source, such as Landsat series satellite data, SPOT data, and, recently, Sentinel data. Most of the statistical models used to correlate the irradiance at specific location and the measured in situ of Chl-a concentration. Outputs are then checked for the best-fit spectral bands that are driving the model. This ratio was based on the correlation between the reflection and absorption of Chl-a in the visible spectrum bands and near-infrared spectrum. In this research the ratios of TM4/TM3 then TM3/TM2 were the best fit to estimate Chl-a concentration from Landsat 8 data for three of the northern coastal lakes (Fig. 8). Both ratios were highly positive correlated at r^2 0.89 and r^2 0.63 for TM4/TM3 and TM3/TM2, respectively. These ratios correspond with the maximum reflectance in the infrared spectrum (TM band 4) and the green visible spectrum (band TM2) and absorption in the red spectrum (TM3).

Applying this ratio in Lake Bardawil determined the reduced level of pigment and estimated the very low Chl-a concentrations during the whole year (<1 mg/L).

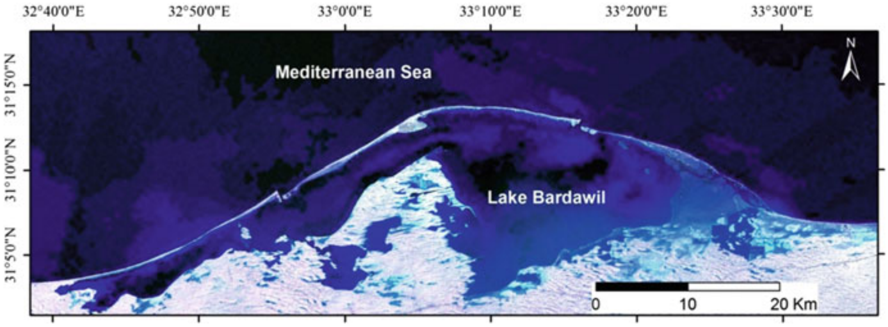

Fig. 6 Example of the turbidity and clarity in Lake Bardawil from satellite images

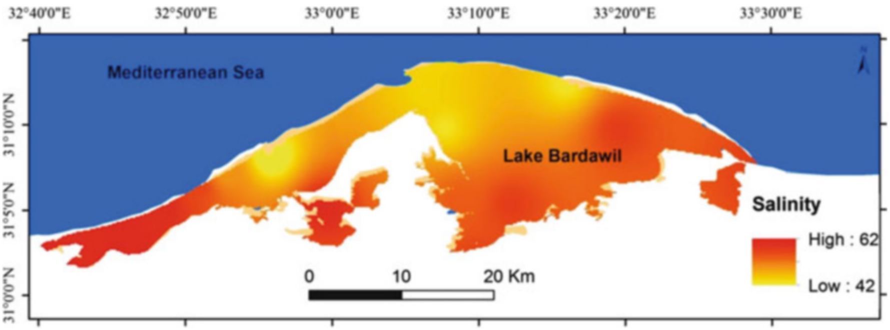

Fig. 7 Lake Bardawil water salinity as estimated from satellite images

It also estimated a maximum level Chl-a (13 mg/L) during spring. Applying the satellite-derived ratios in other lakes enables to estimate different levels of Chl-a, for example, in Lake Burullus, (16–47 mg/L) and Lake Idku (11–43 mg/L). Remotely sensed data could also determine the exponential high peaks of Chl-a (up to 120 and 125 mg/L) during summer season in 2105. This is the general trend of low Chl-a concentrations in the northern area and high concentrations in the southern parts for all lakes. This trend is controlled by the effect of the marine saline water flushed regularly into the lake through the sea-lake connection in the north and the effect of organic matters, wastes, and human activities in the south, which led to phytoplankton flourishing. The consolidation of these models could be operated on routinely bases to provide decision makers and planners with regular real-time or near-real-time information about the status and functionality of lakes. The simulated maps in Fig. 8 shows the pattern of Chl-a spatial distribution along three lakes (Idku, Burullus, and Bardawil) estimated from using satellite data sources and band ratios and the projected Chl-a from the same model.

These mathematical models are well operated and provide valuable information; however, they are controlled by various parameters, including (1) the varying range of spectral bands from sensor to others, (2) the sensor's spatial resolution, (3) the

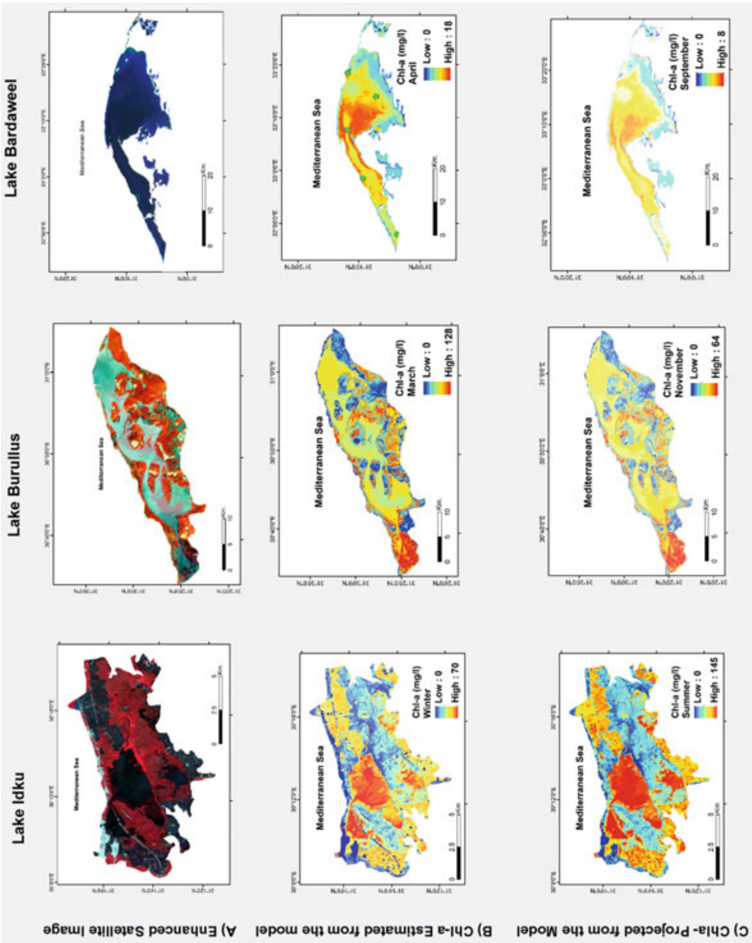

Fig. 8 Example of the retrieved Chl-a from the coastal lakes – *top* is the original satellite image, *middle* is the monthly estimated Chl-a from satellite images based on the statistical model, and *bottom* is the forecasted Chl-a using the same model

sampling time in relation to the satellite over path, and (4) lakes dynamicity. To get an operational system of obtaining such dynamic information from satellite data, it should be tested and validated regularly to improve the model operation and outputs as well as to minimize the level of uncertainty.

2.3 Retrieving the System "Good Conditions"

The operational management of water quality for aquatic ecosystems requires methodologies that can offer precise information on cycles and trends of water quality in an objective and reproducible manner. Advanced Earth observation sensors could be among the good sources for such information and could be timely operated and cost-effectively, especially the images captured in the wide range of electromagnetic radiation. Outputs of remotely sensed data could be then integrated with in situ measurements and fed into numerical models to enhance the lake system database, enhance our understanding of such complicated system, and enable to retrieve the system parameters, including water quality attributes (e.g., physical, chemical, and biological).

The well-integrated and multisourced data could guide for an effective rehabilitation or restoration plan or directive framework suggestion for the lake health status through identification and formulation of the system "good conditions" particularly, for nutrient inputs in relation to the system capacity. Simulating the standard conditions and proposing an optimal strategy for the lake restoration with applicable mitigation measures and good alternatives would be a good approach to improve the lakes ecosystems. The "optimal" strategy should adopt an effective (decreasing nutrient loading) and cost-effective (at the lowest possible cost) manners [29].

Remote sensing is in use on worldwide as an effective tool to provide regular information for rehabilitation of coastal lakes to stop the overgrowth process, either in the natural aquatic vegetation; the openness of canopy; the amounts, forms, and orientation of leaves; effluents of drainage; or areas' cutoff [17, 30–32]. However, remotely sensed data is effectively used to monitor the coastal lakes of Egypt; it is not yet at the same magnitude used for rehabilitation process [33].

3 Simulating the Climatic Changes and Predicting Impacts

The Egyptian coastal zone, particularly the Nile Delta, is one of the highly vulnerable areas in the world for climate changes and sea level rise. This is mainly attributed to the nature of the delta with low topography and the low-lying areas that are already below sea level. This means that the dense population of large cities and small villages distributed along the northern coast are also vulnerable to the threat of sea level rise. The Intergovernmental Panel on Climate Change (IPCC) in the Fourth Assessment Report suggested three scenarios of impacts and indicated that a global sea level rise of 18–59 cm is expected by the end of this century [34]. In addition, the Nile Delta land is experiencing land subsidence, which is an adding factor that worsens the risk of sea level rise, increases the flooded area, and exacerbates the impacts. Earth observation is an enabler for various applications and services that are currently playing a key role in the area of societal benefit and security particularly for coastal zone management.

Previous studies (e.g., [35]) indicated that the northern delta region is subsiding at a rate varying from 2 mm/year (at Alexandria) to about 2.5 mm/year (at Port Said). LiDAR system (airborne or orbital) enabled mapping of the topography at even millimeters accuracy in most of the development countries. Other technology of remote sensing using interferometric SAR radar enables for estimating the land subsidence up to millimeters on pixel size. The range of estimated land subsidence from interferometric SAR in the Nile Delta is about 2.8 mm in the eastern side of the delta to 0.9 in the eastern corner [36, 37].

Ali and Abou El-Magd [6] simulated a spatial scenario for sea level rise along the northern coast of the Nile Delta of Egypt by integrating both drivers (i.e., land subsidence and the IPCC worst case scenario for sea level rise). The simulation led to a suggestion of about 89 cm rise in sea level by the end of this century and indicated an area of about 2,671 km^2 susceptible to flooding. Figure 9 is simulating the same drivers to be extended to northern Sinai area of Lake Bardawil; it shows nearly 1/3 of the coastal zone is under risk of flooding. The existence of the northern coastal lakes plays as the first defense row to the country accommodating big quantities of the flooded water. However, this would certainly leave negative impacts and significantly will alter/damage the lakes' ecosystems (e.g., affect lakes' biodiversity and threat sensitive species).

Suggesting an operational system that combines and integrates Earth observation information and spatial analysis could improve the mitigation plans for climate changes. Such system could enhance the placement plans for coastal infrastructure (e.g., housing, industrial facilities, energy, and sanitation systems, transportation

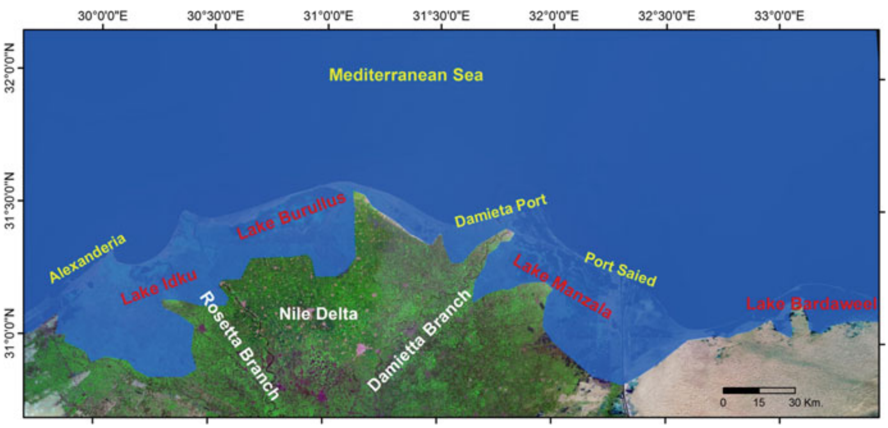

Fig. 9 Projected sea level rise according to the IPCC model (Modified after [6])

and communication networks, and tourist and cultural sites) in a way to be safe from sea level vulnerability and also help to propose mitigation measures to the environment of the coastal zone including the lakes.

4 Future Plan: Rehabilitation and Management

To improve the ecosystem of the coastal lakes, a rehabilitation plan should be prepared based on defining the standard conditions targeted for the lakes with applicable strategies help approaching such conditions as well as some good alternatives for restoration [10]. Adoption of a national water framework directive similar to the European Water Framework Directive (WFD) could be a good step forward to protect and prevent further deterioration and enhance the status of the coastal lakes in Egypt [10]. Therefore, a prior determination for the “high-status conditions” is needed. Numerical simulation models together with a regular and continuous coverage dataset for the coastal lakes using remote sensing technologies are crucial for that step and enable to assess the ecological component of the surface water status of lakes’ water bodies. As defined by the European WFD, the good surface water status (see Fig. 10) will be achieved when the quality elements of a water body show only slight deviation from its “high-status conditions” (i.e., the ecosystem is only under “very minor” human-made alterations or distortions).

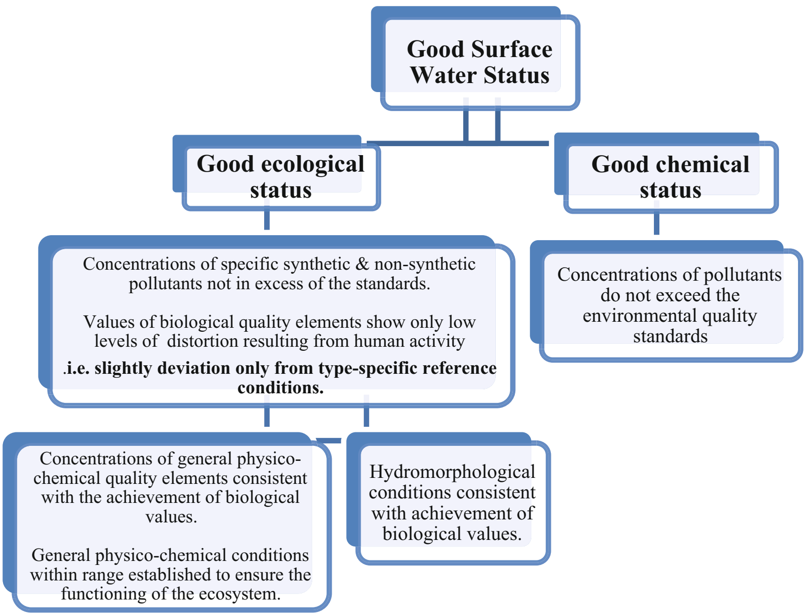

Fig. 10 Proposed conditions required to achieve good surface water as defined by the European Water Framework Directive

These conditions must cover three groups of variables, the "physicochemical (i.e. physical and chemical), hydro-morphological, and biological' characteristics of the lake ecotype with a sufficient level of confidence based on the statistical rigor of sampling [38].

Remote sensing models also enabled to observe the water quality and environmental status on a large scale of the coastal lakes. Satellite imageries of several types of sensors (e.g., Landsat, SPOT, Sentinel, Hyperion, etc.) are used nowadays as an accurate and real-time or near-real-time source of information. These images could be an input into a model that retrieves several physical and chemical attributes of water characterization that could efficiently aid in determining the previous and current situation of lakes' ecotype and simulate for the enhanced situation through the defined "high-status conditions." The optical statistical models enabled to map the natural vegetation and chemical properties of the lakes. Spatial analysis provided tool to overlay the drainage network that drains directly into the lakes creating probabilities of eutrophication and oxygen depletion that lead to fish death and/or deteriorate the fish quality. The dense populated urban areas around the lakes together with the development of complex irrigation and drainage systems in the catchment areas of each lake affect the system quality and functionality through dumping untreated sewages and agricultural effluents.

With regard to the description of lakes' biological components, this level of accuracy achieved in monitoring Chl-a by remote sensing (e.g., TM) confirmed the applicability to use the modeled data to define phytoplankton blooming in the coastal lakes without in situ measurements at an accuracy of $>80\%$ [39] which is comparable to other similar applications (e.g., [40]). Adopting such model of band rationing is merely supporting the decision makers in managing such economically valuable resources [41, 42]. Generating such algorithms can be tested and calibrated and robustly quantify phytoplankton pigment concentration, which will greatly benefit for the valuable natural resource management (such as inland, coastal, and estuarine ecosystems).

Further challenges growingly emerge to test the applicability of other data sources rather than Landsat (e.g., Sentinel 2) for Chl-a quantification as well as for other accessory pigments (e.g., phycoerythrin, phycocyanin, chlorophyll-b, and chlorophyll-c). The latter would maximize the outcomes of biological characterization through finer classification of phytoplankton community structure without being highly dependent on the tedious microscope work.

5 Conclusion

Remote sensing technology and accompanying application and services proved to be efficient tools to monitor the coastal ecosystems and coastal lakes. Remote sensing has been used for Egyptian coastal lakes since the first launch of the MSS Landsat satellite in 1970s. Various sensors with different spatial, spectral, and temporal resolution enabled to keep an eye on the coastal lakes and monitor their changes. Significant changes with high rate of losses from the lake's water mass area were recorded in the last decades, as well as recording the variables which accelerated the deterioration of their aquatic environment. For example, monitoring the lakes' bodies and their geomorphological changes, Lake Manzala recorded the highest rate of area loss at 14.9 km^2/year, followed by Lake Burullus at 6.7 km^2/year, then Lake Idku with the lowest rate at 2.8 km^2/year. Geomorphological and land use changes are mainly controlled by the local community, activities, and developmental plans. The construction of national projects, such as ElSalam Canal and the northern national coastal road, played key role in accelerating such changes. For example, El Salam Canal and the northern coastal road were the major drivers for the recent cutoff area from Lake Manzala and the land transformation into agriculture land. In Lake Burullus, cutoff areas were converted into fish farms. Land transformation and unplanned activities for socioeconomic benefit are other drivers for coastal changes. For instances, growing fish farming activities was the major land use change around the coastal lakes in the last decades that continue with incremental rate. Social and economic situation played key roles in such leverage of fishing in response to increasing meat prices. The results indicate an example of the extension of fish farms around the deltaic coastal lakes.

Earth observations not only offer an effective technique to monitor the rapid environmental changes of inland lakes, but also it could retrieve the physicochemical and biological variables. Optical satellite images such as Landsat are used to map the concentration of Chl-a in correlation between the irradiance and the actual Chl-a concentration. This demonstrates clearly the value of the multispectral instrument in providing a fine resolution of the water reflectance due to various photosynthetic pigments. Further parameters such as salinity, temperature, turbidity, TN, and TP could be estimated by correlation between the reflectance and the actual concentration measured on-site. Advanced remote sensing sensors will create a very productive future for lakes monitoring and retrieving of environmental parameters for operational use and management. In the last few decades, a large number of researches were carried out on the coastal lakes of Egypt with main focus on monitoring and mapping; however, further researches are needed to use remotely sensed data for management and rehabilitation.

6 Recommendations

Sustainable development goals (SDGs) are global agenda to improve the economic, social status for people with great attention to save and preserve the environment. Egypt put national vision for 2030 SDGs agenda based on mega and strategic projects. Unless there is reliable and precise information, the implementation of these projects will be under threat. Satellite data could routinely on a daily basis provide information of the status of the Earth, which when modeled could estimate valuable information that could not be easily obtained on-site. The improved research models are important to allow obtaining direct information from the satellite images. It could be concluded that the application of recent technology of Earth observation in sustainable development goals to improve the social, economic, and environment in Egypt could be summarized as follows:

1. Medium-resolution satellite images to monitor the natural resources of Egypt that meet the development plans and achieve the SDGs goals.
2. High-resolution satellite images to locate and map the proposed new development of 1 million housing cities.
3. Remotely sensed data to evaluate the existing development plans and evaluate the natural resources in the areas proposed for new development plans.
4. Use newly developed technologies in remote sensing such as LiDAR and radar to resolve planning issues, such as using radar to explore the archeological sites buried under the soil particularly in the areas under development.
5. Harmonize the spatial data into one system to provide support to the decision makers.

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Are the Egyptian Coastal Lakes Sustainable? A Comprehensive Review Based on Remote Sensing Approach

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Abstract Lakes play pivotal roles in the biological and environmental systems and prove several ecosystem facilities. Unfortunately, in Egypt, there are many factors which directly or indirectly threaten the ecological system of the Egyptian coastal lakes (lakes Mariout, Edku, Burullus, Manzala, and Bardawil). For example, reduction of water bodies, deterioration of water quality, eutrophication, and climate changes are among the present common challenges. These challenges may potentially act against the sustainability of the coastal lakes. The use of the remote sensing (RS) data offers a better perception of analyzing water bodies (water quality and lake ecology) by providing synoptic and spatiotemporal ideas to help in assessing their present conditions. Moreover, it will promote the lakes sustainability by implementing the needed measures. This chapter provides an updated review of the present literature that applied the remote sensing (RS) technique for monitoring and assessing the sustainability conditions of the Egyptian coastal lakes. It covers different areas such as extracting lake surface areas and their changes, examining lake bathymetry (levels), and monitoring lake water quality. Meanwhile, a review of the worldwide-related studies is presented. The present chapter concluded that most of the Egyptian coastal lakes are suffering from lack of sustainability. In addition, urgent actions from the concerning authorities should be taken shortly to maintain the sustainability of these lakes.

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Contents

1 Introduction

RS is the art and science of obtaining information about an object without physical contact [1]. The availability of time series of RS data is considered as the primary source that provides wealth information concerned with environmental monitoring, especially in lakes. The essential environmental functions of lakes are represented in providing habitat for a comprehensive range of species and forming crucial components in carbon, nutrient, and hydrological cycles [2]. Climate change effects, inorganic and organic contaminants, morphological alterations, morphological alterations, and eutrophication are considered the main factors that threaten the ecological function of lakes all over the entire globe [3, 4]. Improving the ecological state of inland water areas are supported by implementing frequent and consistent long-term monitoring approaches for these water bodies [5–8]. Recently, there are various spatial and radiometric resolutions offered by earth observation satellite sensors, such as ESA's Sentinel-2, NASA's Landsat 8, etc. The integration of RS into water research and monitoring is aimed to benefit from these variations in different research applications (i.e., [9–16]).

The potential offered by remote sensing is strongly demanded, where the capacity of in situ lakes monitoring is limited. Lakes have innate differences in function and geomorphology, and some have undergone significant spatiotemporal changes. RS provides a rich body of spatial and temporal data for monitoring these changes. Whether concerning lake area, volume, temperature, water quality status, etc., RS has shown to be an appropriate tool for lake monitoring. To indicate the role of RS for lake monitoring and research, this review study, therefore, provides an overview of RS applications for lake monitoring which is considered as a foundation for future innovation in lakes researches. In this context, an extensive review of the salient features of available literature on lakes using RS is presented. In the last section, the use of RS to monitor the environmental features of coastal lakes of northern Egypt will be discussed and reviewed to decide their sustainability based on RS.

2 Application of Remote Sensing on Lake

RS in general help in deriving information of a specific ground object, such as obtaining information on lake properties via analyzing the measured radiation by a remote sensor [17]. The radiation passes the water surface and propagates through the water body, or it is reflected at the water surface. For lake with deep water, information on the water surface and water properties can be obtained using RS data; as in this case, water surface and water body are considered the primary sources of radiation from a lake. In a lake with shallow water, information on bottom substrate and bathymetry can be derived; as in this case radiation has been reflected at the bottom [18]. The reflected radiations from lake water bodies are affected by scattering and atmospheric absorption through its way toward the satellite sensors. More than 90% of the signals obtained by an RS sensor originate from the atmosphere and the water surface together [19]. The remaining signals of less than 10% include the obtained signals from water surface only. For this, it is essential to remove the effect of the atmosphere accurately to get accurate information about the water bod [18]. According to the difference in the spectral characteristics between water and land features, it can be easy to place the water pixels alone in separated classes. The spectral signatures of the separated classes (for each pixel location) can be used when differentiating between turbid, clear, and shallow water classes. Moreover, based on these spectral signatures, vegetation cover, bottom bathymetry, and other effects of land can be estimated for the water pixels within the area of the lake [20].

Applications of RS in lake research and monitoring are divided into two main categories; the first category is related to lakes' water amount, and the other one is related to lakes' water properties. The first category contains studies that are interested in measuring lake area using RS data throughout visible and near-infrared (NIR) bands for lake boundaries delineation, thermal imagery for differentiating lake area from surrounding land, and active microwave sensors for detecting water surface changes in the presence of cloud cover. Moreover, this category includes studies concerned with examining lake bathymetry throughout: active altimetric (microwave) sensing, gravimetric sensing, and indicators of bathymetry. The second category reflects the use of RS for detecting the physical characteristics via the thermal observations for lake surface temperature. The results include the physical aspects related indicators (an indicator of temperature, ice phenology, and transparency). Also, it is possible to detect the biological properties throughout visible and NIR bands for monitoring macrophyte extents, microwave sensors for classification of lakes' vegetation cover, and visible wavelength images for trophic condition determination via measuring euphotic depth and chlorophyll-a. Few of the studies reviewed here concerned only with one of the above RS applications; most papers make use of a combination of two or more of these applications. For example, one that uses altimetric observations to estimate lake bathymetry changes might also use visible and NIR bands to detect the changes in the lake area.

2.1 Surface Water Area of Lakes

2.1.1 Lake Boundaries Delineation by Visible and NIR Bands

Visible and near-infrared (NIR) images are considered as one of the most straightforward and earliest applications of RS in lake monitoring to analyze the lake's extent changes. Most literature are concerned with detecting changes in lake boundaries by visible and NIR bands implemented on Africa lakes (i.e., [21–25]). Harrris [21] used the NIR band of AVHRR to estimate changes in the shoreline of Lake Abiyata, Ethiopia. Birkell [22] proposed an approach to map lake extension changes, in general, using the AVHRR's NIR Channel 2. He used a classification technique relying on a simple histogram technique of the digital number (DN) values to estimate changes in the lake extents. Bohme et al. [23] applied maximum likelihood classification (MLC) technique depending on visible and NIR bands from MSS, TM, ETM+, and ASTER satellite data to observe the annual changes in the area of Lake Urema, Mozambique, in the period 1979–2000. Ouma and Tateishi [24] developed a new water index (WI) and normalized difference water index (NDWI) by using visible and NIR bands from Landsat TM and ETM+ images to map shorelines changes in five lakes in Kenya in the period from 1986 to 2001. Also, Turada [25] used visible and NIR bands from the European Space Agency (ESA) satellite Envisat data, to detect changes in land cover classes (soil, vegetation, and water) in the Lake Chad basin.

2.1.2 Differentiating Lake Area from Surrounding Land by Thermal Imagery

Delineation of lake boundaries depends on the spectral differences between the lake water and its surrounding land area in the visible and NIR bands as indicated in the previous section. It is also possible to use thermal bands of the satellite images to achieve the same work. The main benefit of using thermal imagery is to work at night since the received electromagnetic radiation by the satellite sensor is emitted from the target and not reflected from the sun. Leblanc et al. [26] used Meteosat data (10.5–12.5 μm) to sense water under vegetative cover thermally during the period from 1986 to 2001. They reported that it was difficult to apply the thermal technique during the rainy season due to producing a signature that is similar to open water by the high-water content of non-lake areas.

2.1.3 Extraction of Lake Water Bodies Using RS Techniques

There are numerous water extraction methods have been applied in studies that concerned with lake water body extraction via using the RS satellite sensors. These methods are mainly depending on the electromagnetic (EM) spectrum covered by the sensors that include the shortwave infrared (SWIR), the thermal infrared (TIR), the long-wavelength infrared (LWIR), and the visible and near-infrared (NIR) bands. These methods involve an automatic extraction method to extract water area from high-resolution satellite image [27]: decision tree and programming method for extracting water areas within regions that affected by the flood [28]; the conceptual clustering approach [29]; the semiautomated change detection technique [30], the original entropy-based method [31]; the multivariate regression technique [32]; thematic classification, supervised and unsupervised classification techniques [33–35]; the unsupervised classification technique alone [36]; and single-band thresholding [37]. Furthermore, recently some popular spatial water indices were applied to discriminate between the water and land in multispectral satellite images [38–43]. Sundal et al. [44] applied a set of fuzzy logic membership functions which is considered as an automatic method to map lakes boundaries. To track lakes' changes, a semiautomatic approach was developed [45]. Liang et al. [46] proposed an automatic method for mapping lake and tracking its changes. Johansson and Brown et al. [47] applied the adaptive lake classification (ALC) method to identify the types of the changes in lakes and their surroundings.

2.1.4 Water Surface Area Changes Using RS

Temiz and Duduran [48] used multispectral Landsat images from the years of 1985, 2000, and 2015 to detect the coastline change of Acıgöl Lake, Turkey, with the help of geographic information systems (GIS). The results showed that there was a significant decrease in Acıgöl Lake in between 1985 and 2000. At the end of their study, they detected significant coastline movements for a period of 30 years. Feyisa et al. [40] mapped the change in the water surface area of the Vembanad Lake, India, by using four Landsat satellite images acquired between 1973 and 2015. They applied the normalized difference water index (NDWI) and modified normalized difference water index (MNDWI) to estimate the water area changes inside the lake. The results showed that the total decrease in the estuarine area was about 6.93% during the study period. Jeihouni et al. [49] in their study depended on time series images from Landsat satellites, GIS, 3D modeling, and water level field measurements to assess and monitor Urmia Lake, Iran, status over a period from 1984 to 2014. The results indicated that during the study period, about 86% of the lake became a salt desert, and the volume of the lake water decreased by about 99.17% in the period from 1998 to 2013. Sultan et al. [50] detected the changes in the area of Lake Malaha, Egypt, which is considered one of the most important fisheries resources along the northern coast of Egypt by utilizing a set of Landsat ETM+

and OLI/TIRS images acquired in 2005, 2010, 2015, 2016, and 2017. The results of their study showed the area of the lake decreased by about 11.7 km^2 within 12 years from 2005 to 2015. Acharya et al. [51] applied three spatial water indices to detect the change of lakes in Pokhara city, Nepal, utilizing Landsat data of 25 years' gap from 1988 to 2013. Normalized difference water index (NDWI), modified NDWI (MNDWI), and normalized difference vegetation index (NDVI) were used to extract the water surface areas from Landsat data and to detect the changes in the extracted water surfaces. The results showed that there was an increase in the areas of Rupa and Dipang Lakes, whereas the water area of Lake Phewa decreased. The results also indicated that Began Lake suffered from few changes. They highlighted that the obtained results considered helpful tools to reclaim and restore the area of lakes under investigations, consequently to maintain and preserve the wetland ecosystem in Pokhara city. Xie et al. [52] proposed an unsupervised water extraction method based on the Operational Land Imager (OLI) imagery (Landsat 8). Darwish et al. [53] estimated the geomorphologic changes along the coastline of Nile Delta, Egypt, in between 1945 and 2015. They used Landsat satellite images obtained between 1973 and 2015 and old topographic maps generated in 1945 by the Egyptian Geological Survey. The results showed that there was a significant change along the coastline (erosion) during this period, particularly at Rosetta and Damietta promontories. El-Hattab [54] used the post-classification approach of RS satellite images, during the period from 2004 to 2013, for assessing and detecting land cover changes within Abu Qir Bay zone, Egypt. The results showed that the rates of change increased dramatically during the study. Also, the results indicated that rapid urbanization was observed along the coastline of Abu Qir Bay accompanied with a rapid decrease in the water area of this bay.

2.2 *Bathymetry of Lakes*

2.2.1 Bathymetry Detection by Active Altimetric Sensing

Developing online databases that process the obtained raw data from various sensors fostered the use of altimetric data obtained by the active altimetric sensing. The main ones are divided into three altimetry websites [55]. The first one is the US Department of Agriculture (USDA) website [56] that uses data obtained from TOPEX/Poseidon, Envisat, Jason-1, Jason-2, and GFO. The second one is the ESA's River and Lake website (ESA) [57] that uses data from Envisat, Jason-1, and Jason-2. The third is the Laboratoire d'Etude en Géophysique et Océanographie Spatiale (LEGOS) website [58] that uses data from the European Remote Sensing 1 and 2 (ERS-1 and ERS-2), satellites Envisat, Jason-1, Jason-2, Geosat Follow-On (GFO), and TOPEX/Poseidon. Munyaneza et al. [59] monitored the water level of Lake Kivu, Congo, by using ERS-2 and Envisat from ESA website. Velpuri [60] validated the hydrological models for Lake Turkana, Kenya, by using Envisat, Jason-1, and TOPEX/Poseidon from the USDA website.

2.2.2 Lake Bathymetry Indicators

RS is a valuable method to derive water levels (water depths or bathymetry) by applying empirical detection methods of bathymetry. Empirical estimation of bathymetry utilizing multispectral satellite data with high spatial resolution is considered an appropriate method in areas with homogenous water characteristics (e.g., [61, 62]). Mohamed et al. [63] used data from Landsat 8 and Spot 6 satellite images to evaluate the performance of three proposed empirical models for bathymetry derivation in three different areas: Lake Nubia entrance zone, Sudan; Shiraho, Ishigaki Island, Japan; and Alexandria port, Egypt. The results of the applied models to obtain bathymetric maps from the reflectance of red, green, green/red, and blue/red band ratios showed that applying the bagging algorithm was the most accurate method for bathymetry estimation. Mohamed et al. [64] used SPOT-6 imagery to detect bathymetric information at the entrance of Lake Nasser/Nubia. They applied the least square boosting (LSB) and the bagging algorithms for bathymetry detection. The results showed that the bagging approach was the accurate approach for detecting depths of up to 6.5 m within the shallow water.

2.3 Water Quality by RS

In recent years, RS techniques are widely used in monitoring water quality due to the low cost of satellite data and its capability of covering remote and large areas with a spectral, spatial, and temporal resolution [65, 66]. Nas et al. [65] and Alparslan et al. [67] indicated that for analyzing the water quality from RS data, empirical relationships could be established between the in situ measurements of water quality and Landsat reflectance values. Vignolo et al. [68] correlated Landsat 7 ETM+ with the water quality index of surface water. Most of the studies concerned with monitoring the water quality of lakes via RS data used various spectral bands (single band, band ratio, and band combinations) as independent variables when building models for predicting water quality parameters. Recently, RS is integrated with GIS in water quality studies [69].

3 Egyptian Coastal Lakes

Survey of the literature on the applications of RS to the Egyptian northern coastal lakes indicates that there is a wide range of lakes' aspects that were investigated such as bathymetry, water properties and quality, environmental conditions, and water surface area of the lakes. This means that an extensive survey of the available published articles should lead to a conclusion about the conditions of sustainability of the Egyptian coastal lakes. Consequently, through this section, we will present and discuss the findings of related studies which utilized the satellite RS data from various sensors, such as the Systeme Pour l'Observation de la Terre (SPOT), Enhanced Thematic Mapper Plus (ETM+), Multispectral Scanner (MSS), Thematic Mapper (TM), etc. In this context, analyses of area, bathymetry, and water quality of the lakes under investigation throughout RS data are discussed within the available literature.

3.1 Lake Mariout

Considering Lake Mariout, there are few studies concerned with monitoring of this lake using RS data (i.e., [70, 71]). El-Hattab [70] used three Landsat images of 1991, 2004, and 2013 and one scene of the SPOT-HRV image acquired in 1995 to detect changes that occurred in Lake Mariout. He classified the images using maximum likelihood classification (MLC) algorithm for change detection. The results showed that in the last few years, severe land cover changes occurred in different land cover classes of the lake basin due to political and socioeconomic problems. Also, Ahmed and Barale [71] used a series of Landsat MSS, Landsat TM, SPOT HRV, and EgyptSat-1 acquired in 1972, 1985, 1999, and 2007, respectively, to monitor changes in the water surface shape and extension of Lake Mariout. Changes in the lake basin surface, over the last four decades, were quantified utilizing GIS as presented in Fig. 1 [71].

This plot indicates that there is a decrease in the water surface area of the lake. They concluded that the reduction in the water surface area of Lake Mariout was occurred due to the growth of urban areas. This indicates that the water body of the lake is not sustainable and actions should be taken to maintain the lake water body.

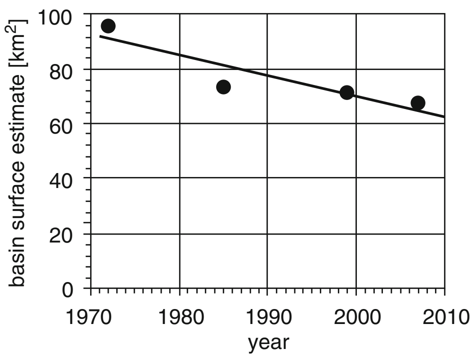

Fig. 1 Estimated Lake Mariout total basin surface area and their changes from MSS (1972), TM (1985), Spot (1999), and EgyptSat-1 (2007) data after [71]

3.2 Lake Edku

There are few studies regarding the monitoring of Lake Edku using RS data (i.e., [71, 72]).

Ahmed and Barale [71] estimated the changes occurred within Lake Edku during the period from 2003 to 2009 using SPOT HRG images. The quantitative results are represented in Fig. 2 [71], which represents the land cover classes within the lake basin. This figure indicates that the water surface area decreased from about 62.12 km^2 in 2003 to 61.06 km^2 in 2009, while the lake area that covered by floating and submerged vegetation increased from 38.82 km^2 in 2003 to 40.04 km^2 in 2009. Also, the sites of aquaculture increased from 59.17 km^2 in 2003 to 65.98 km^2 in 2009. Also, the figure shows that a part of the lake area was replaced by fish farms within the same period.

Hossen and Negm [72] monitored changes in Edku Lake to assess the water body sustainability. To achieve the change detection process, they applied the maximum likelihood supervised classification to subsets of the Landsat TM, ETM+, and OLI/TIRS images acquired in 1984, 1990, 1998, 2003, and 2015. The results indicated that water bodies of the lake decreased by 25.33% in the period from 1984 to 2015, while there was an increase in the floating vegetation area by 108.65% in the same period. They concluded that the increase of the floating vegetation and reclamation of a large area for cultivation purposes are the main reasons for the decrease in water body of Edku Lake.

3.3 Lake Burullus

There are many studies concerned with monitoring of this lake using RS data (i.e., [71, 73–78]).

Ahmed and Barale [71] presented the changes occurred in Lake Burullus from 1984 to 1997 and 2000 utilizing a series of Landsat TM images. They detected the

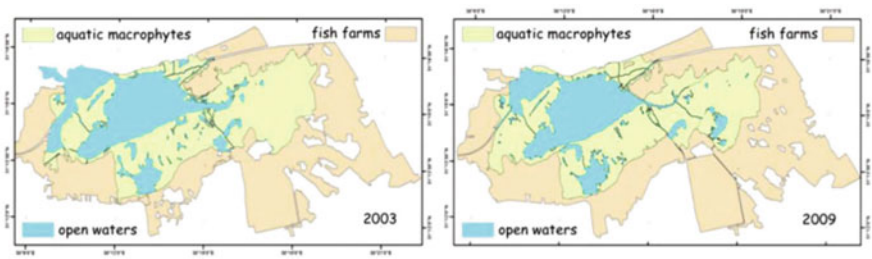

Fig. 2 Mapping of Lake Edku and surrounding area, based on 2003 (left panel) and 2009 (right panel) SPOT data after [71]

changes in the lake via the classified satellite images shown in Fig. 3 [71]. Their results indicated that most of the substantial changes in the lake occurred due to barrier erosion, rising sea level, and inlet siltation.

EL-Zeiny and El-Kafrawy [73] detected the most vulnerable areas for water pollution within Lake Burullus using Landsat OLI image acquired in 2015. Results indicated that there are multiple sources for pollution. They concluded that using of RS in water quality studies help in lakes assessment and management with a cheaper and easier manner than traditional methods.

El-Kafrawy et al. [74] used RS data, represented in Landsat ETM+ image acquired in 2014, and a geographic information system (GIS) for monitoring water quality of Lake Burullus. They generated maps for surface water quality conditions of the lake based on the correlation between reflectance values of the ETM+ image and the measured water quality parameters. The results showed that in the eastern and southern parts of the lake suffer from deterioration in the water quality more than the other parts, due to the discharged wastewater and polluted drainage water into these parts. In general, they confirmed that the integration of RS with GIS is considered an appropriate approach for water quality mapping.

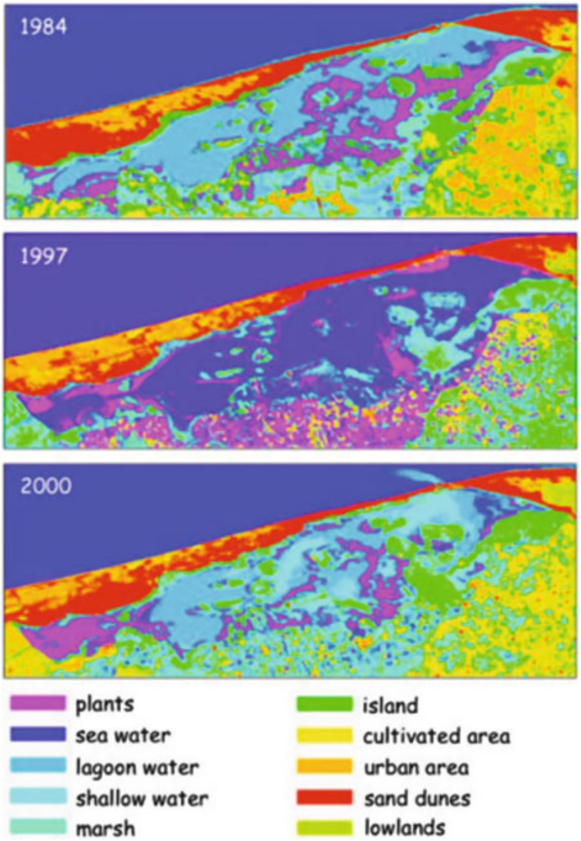

Fig. 3 The classified Landsat TM images of Lake Burullus and surrounding area for the period from 1984 to 2000 [71]

Dewidar and Khedr [75] utilized a combination of field data measurements and Thematic Mapper (TM) data in 2004 to map the depth, salinity, sand, and sediment in the Lake Burullus.

Hossen and Negm [76] monitored the changes in Lake Burullus by applying the maximum likelihood supervised classification technique to subsets of Landsat TM, ETM+, and OLI/TIRS images captured in 1984, 1990, 1998, 2003, and 2015. Their results showed that there was a decrease in water bodies of the lake by 44.97% during the period from 1984 to 2015, while there was an increase in the floating vegetation area by the same amount during the same period. They reported that results of their study should help the decision-makers to take the necessary measures to sustain the water area of the lake against further reduction.

Mohsen et al. [77] used 12 Landsat {(1,3-MSS), (4,5-TM), and (7-ETM+)} images in addition to water indices approach to monitor the spatiotemporal changes within Lake Burullus in the period from 1972 to 2015. They applied the water ratio index (WRI) and the normalized difference water index (NDWI) to extract water area from the satellite images. The authors concluded that there was a significant decrease in water surface area of the lake by about 49% during the period under consideration. This finding is with a good agreement with [76].

Negm et al. [78] used four approaches from the most popular bathymetry detection approaches to be applied in Lake El-Burullus using SPOT-4 satellite image. The corrected satellite image bands from atmospheric and sun glint systematic errors, which effect on the accuracy of bathymetry detection, were used within the four approaches.

3.4 Lake Manzala

There are many studies concerned with monitoring of Lake Manzala using RS data (i.e., [71, 79–83]). Ahmed and Barale [71] used a group of Landsat MSS, TM, and ETM + images, captured in 1973, 1978, 1983, 1987, 1990, 2000, and 2003, to examine the changes of Lake Manzala. Their results indicated that there was a decrease in the total area of this lake by more than 50% in the period from the year 1973 to 2003 as shown in Fig. 4 [71].

They also analyzed the 1987 and 2000 TM images of the lake to assess the lost in lake area due to land reclamation for agricultural purposes. They pointed that this loss in the lake surface area was about 100.73 km^2 between the year 1987 and 2000. Also, they indicated that the rate of land reclamation was about 7.75 km^2 per year within this study period. Also, El-Asmer and Hereher [79] utilized a set of four satellite images from the Systeme Pour l'Observation de la Terre (SPOT), Thematic Mapper (TM), and Multispectral Scanner (MSS) sensors for estimating the spatiotemporal changes that occurred in Lake Manzala between 1973 and 2007. Results showed that the Lake Manzala water surface area was reduced by about 34.5% within this period. Additionally, Ahmed et al. [80] used six Landsat images for Lake Manzala, including three Landsat MSS images of years 1973, 1978, and 1983, two

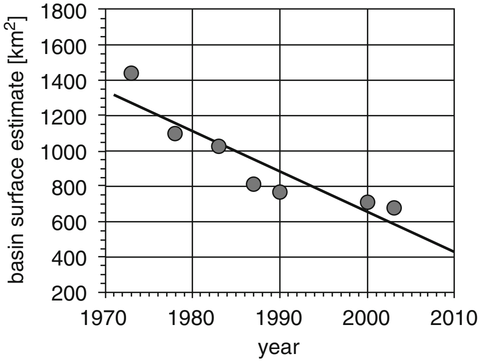

Fig. 4 Cumulative percent decrease of total Lake Manzala area in the period 1973–2003 after [71]

Landsat TM images of years 1987 and 1990, and a Landsat ETM+ image of the year 2003 to monitor changes within this lake from the year 1973 to the year 2003. These changes are indicated in Fig. 5 [80], which shows the classified images of Lake Manzala into three land cover classes of vegetation, land, and water. According to these classified images, there was a decrease by 50% in the total lake area from the year 1973 to the year 2003. The significant change occurred in the areas of open water and emergent vegetation. However, the proportion of vegetation, concerning the total lake area, has the same over the period 1973–2003. Also, the percentages of both land and water have remained relatively stable in the same period.

Ahmed et al. [81] estimated the ecological changes in the Lake Manzala, particularly in aquatic vegetation type and cover, as well as in open water areas during the past two decades over the period 1973–2003 by using a combination of Landsat MSS, TM, and ETM+ data. They analyze these changes to evaluate the human activities effects on the lake. To detect the changes within the lake, they applied some of image processing techniques such as unsupervised classification and enhancement. Their results indicate that there were numerous biological and physical changes occurred within Lake Manzala due to the different human activities, which threaten its quality and its ecological parameters. The main objective of this research was to use remote sensing techniques to measure the spatial distribution of aquatic and marginal vegetation and open water areas in Lake Manzala. Also, they indicated that there was a decrease in the total area of the lake by about 50% from 1973 until 2003. Also, Donia [82] analyzed GeoEye satellite (Google Earth) images to estimate the long-term changes in the physical characteristics of the lagoon during the period from the year 2002 to 2012. The results indicated that there was an annual decrease in the overall size of the lake by the rate of 200,000 square meters. The most changes within the lake are represented in decreasing the water area due to landfill. The lake water area changes were detected by delineating the changes in the lake boundaries using on-screen digitizing.

Negm and Hossen [83] estimated the changes in Lake Manzala during the period from 1984 to 2015 by applying the maximum likelihood supervised classification to a group of the Landsat TM, ETM+, and OLI/TIRS images. The results show that there was a decrease in water bodies of Lake Manzala by 57.06%, while there was an

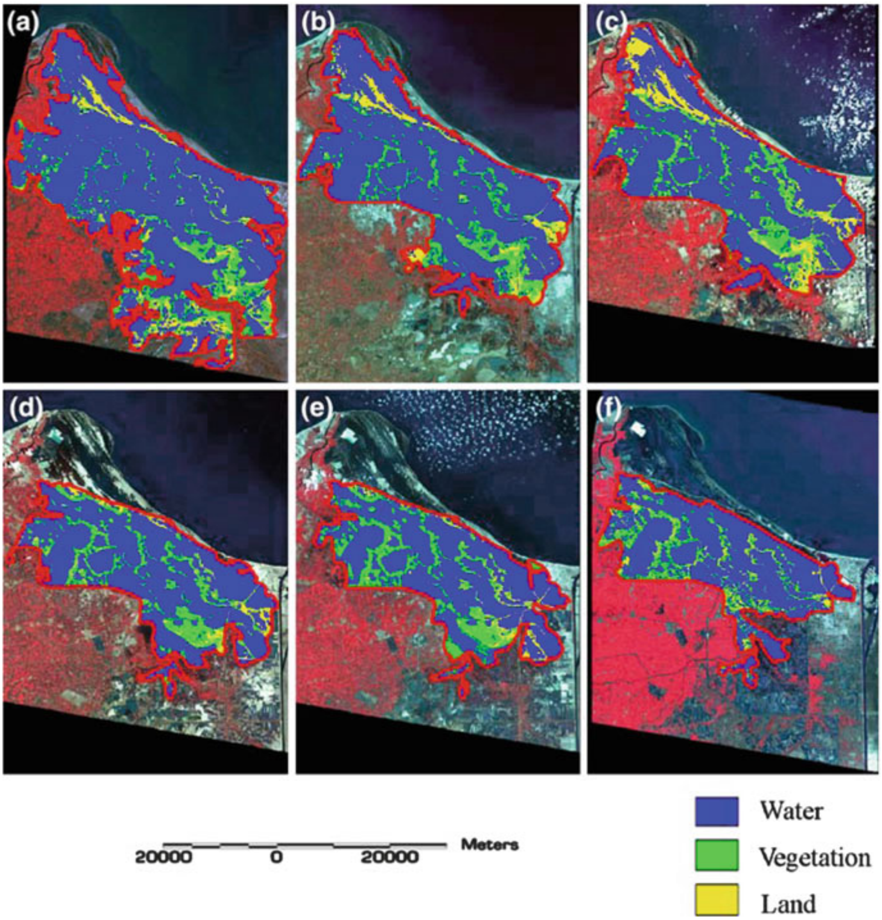

Fig. 5 The classified RS images of Lake Manzala: (**a**) image of 1973; (**b**) image of 1978; (**c**) image of 1983; (**d**) image of 1987; (**e**) image of 1990; (**f**) image of 2003 [80]

increase in the floating vegetation and island by the same amount during the period under investigation. They concluded that the free water body of the lake would disappear by the year 2040 if the increase in the floating vegetation is continued. Also, in this case, actions are needed to maintain the lake water body.

3.5 Lake Bardawil

The most previous studies are concerned with traditional methods in studying water properties of this lake (i.e., [84–88]). Nevertheless, there are few studies that deal with monitoring of Bardawil lake using RS data (i.e., [71, 89, 90]).

Ahmed and Brale [71] monitored the characteristics of both water surface and land around Lake Bardawil utilizing a series of Landsat TM images, collected in 1993, 1996, and 2000.

They used the 1996 image for geo-referencing the other satellite images, while they used the 1993 and 2000 images to detect changes in lake size. The derived change map between 1993 and 2000 is shown in Fig. 6 [71].

The results indicated that the size of the lake was decreased with an annual rate of 0.71 km^2 within the period from 1993 to 2000. Additionally, Khalil et al. [89] used a combination of in situ water measurements and Landsat 8 Operational Land Imager (OLI) data to derive the water quality indicators of Lake Bardawil to sustain its management. They proved the usefulness of Landsat 8 data in quantifying water quality dynamics. They concluded that the applied methods in their study for retrieval of water quality indicators from Landsat 8 could frequently be applied for sustainable water quality monitoring of Bardawil lake. On the other hand, Embabi and Moawad [90] proposed a semiautomated method for mapping the geomorphological forms within Lake Bardawil and its surrounding areas utilizing RS and GIS techniques. To achieve their aim, Landsat ETM+ data and fieldwork were integrated with the aid of GPS device to map the morphological forms, estimate bathymetry, and reveal the sediment movements into this lake.

4 Conclusions

To investigate the sustainability of the coastal lakes, the current chapter presents a comprehensive review of the published literature on monitoring of lakes with a special attention of the coastal lakes in Egypt. The covered areas include water surface area extraction, bathymetry detection, and water quality of the lake. The technique used for monitoring was basically the remote sensing because the RS data become an essential source of many ways for monitoring vast water bodies including the lakes.

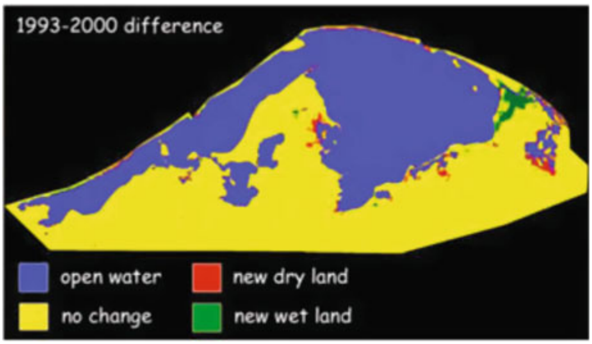

Fig. 6 Map of changes of Lake Bardawil derived from Landsat TM (1993, 2000) data after [71]

To sum up, monitoring the Egyptian coastal lakes using RS showed that most of the Egyptian coastal lakes are suffering from a remarkable reduction in water surface area, increasing quantities of agricultural drainage, massive amount of anthropogenic damages, eutrophication and pollution, land reclamation, urban encroachment, waste dumping, loss of biodiversity, and aquaculture challenges, and even recreational uses are reduced. Most of these environmental challenges are directly or indirectly connected to the exponentially expand of the local population and the loose applications of the law and the related environmental regulations. Consequently, they continue to threaten the sustainability conditions and the usefulness of these lakes as a source of the national income.

5 Recommendations

- To improve the water quality of the Egyptian coastal lakes, regular monitoring of these water bodies using both field visits and RS technique is an entire crucial issue.
- The Egyptian authorities should enforce the applications of the law and the concerned regulation associated with the protection and development of the coastal lakes in Egypt. Fortunately, Egypt stated to implement several measures to improve the lake's environment and to increase its overall usefulness to the society and its fish productively as well.

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Changes in a Coastal Lake Dynamic System and Potential Restoration

Hala Abayazid

Abstract Northern coastal zone of Egypt hosts lakes with distinguished characteristics. Earlier, certain coastal lakes were acknowledged as nature reserve, with their rich aquatic environment as well as playing a hosting role to migratory birds. However, maintained conditions with ever-expanding development activities are a challenge. This chapter addresses aspects in the changing structure of coastal lakes; governing factors responsible for the declining dynamic system. Hence, challenges with sustainability and capacity to recover are discussed. As remote sensing techniques proved cost-effective tool, with reasonable accuracy, for monitoring temporal and spatial changes, an application is presented to a case study of the deltaic coastal lake, Lake Burullus. Among the wide information that can be derived from satellite imageries, water quality index is selected as a key indicator to gain insight into evolving environmental state of the coastal lake. Finally, the chapter discusses proposed strategies to regain efficient functionality and sustainable beneficial uses of coastal lakes, while considering applicability.

Keywords Coastal lake, Dynamic system, Egypt, Hydrodynamics, Remote sensing, Restoration, Water quality index

Contents

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1 Introduction

Egypt is rich with natural resources that play a main role in the development processes, among which are the coastal lakes. Located north of Egypt, five lakes, namely, Bardawil, Manzala, Burullus, Idku, and Mariut, acquire special geographic and environmental importance. These lakes occupy a transitional position between the Mediterranean Sea and the Nile river network. For decades, coastal lakes have been the sponge alleviating pollution impact of wastewater discharges before reaching the sea. Besides, coastal lakes are responsible for greater part of fishery production and, in turn, cover an important socioeconomic sector in the country. Moreover, while acknowledged as a nature reserve with rich aquatic life and role as a stopping point for migratory birds, coastal lakes are also expected to act as buffer and important defense line to potential climate change-related sea level rise. Yet, all beneficial uses are compromised with severe deterioration in lake conditions that start to be alarming.

As development wheel advance, along with growing population and increasing needs, anthropogenic activities caused a drastic change in once considered a healthy ecosystem. Coastal zone, especially within the Nile delta, has witnessed increased agricultural, industrial, and fish farming practices as well as urbanization expansion that even invaded into lakes' open water area. Systematic discharge of agricultural drainage loaded with fertilizer, pesticide and herbicide residues, fish farms and industrial wastewaters, as well as partially treated domestic wastewater is a daily practice. Additionally, expanding urbanization in coastal lakes' served area has a slower rate of infrastructural development, which results in discharged wastewater with compromised treatment.

Excessive intrusion into lakes caused a drastic alteration in environmental condition and hydrodynamic mechanism. Destructive effects include deterioration of water quality state, high intensity of unwarranted vegetation, sedimentations and disturbance to water circulation, compromised functional outlets, and, consequently, disturbed water exchange with the Mediterranean Sea and altered salinity level within lakes. Challenges with changing environmental, physical, biological, and chemical conditions in coastal lakes have alerted concerned parties and triggered several research studies [1–8]. Also, El-Adawy et al. [9], Saad El-Din et al. [10], Rostom et al. [11]. Studies addressed concerns with the deteriorating conditions of coastal lakes in Egypt and gave special interest to those within the Nile delta region, for the environmental as well as socioeconomic importance in the development process.

As remote sensing techniques proved promising potential in monitoring temporal and spatial changes, with reasonable accuracy, an application is presented to a case study of deltaic coastal Lake Burullus. Among the wide information that can be derived from satellite imageries, water quality index is selected as a key indicator to gain insight into evolving environmental state of a coastal lake.

This chapter was designed to provide background information on Egyptian coastal lakes and main issues of concern on changing system within that eventually reflected on water quality status. Aspects of the altered structure and inner mechanism of lakes are highlighted, along with the governing factors responsible for declining dynamic system. On this basis, challenges with sustainability as well as capacity to recover are reviewed. However, proposing remedial strategies to regain efficient functionality of coastal lakes should address the dilemma between effective recovery measure and practicality in an actual application with inevitable continual developments.

2 Developments Versus Sustainability

During the last decades, the concept of sustainability with development activities was mainly following the definition “sustainable development is a development that meets the needs of the present without compromising the ability of future generations to meet their own needs.” However, with continual anthropogenic pressure and undeniable threats to the ecosystem, the United Nations Development Programme (UNDP) issued a renewed commitment to sustainable development goals, effective in January 2016, which acknowledge concerns in water sector such as life below water and clean water.

2.1 Aspects of Changing Features of Coastal Lakes

The discussion will be ruling out Bardawil Lake. Being fed only by seawater and characterized with minimum developments and anthropogenic interference in served watershed [1, 12], this lake is considered unique among the Egyptian coastal lakes. Oppositely, lakes within the Nile delta region experienced drastic changes. Significant shrink in the surface water area, extended earth-filled parts, and an increase in the vegetative cover ratio are the visibly figured changes in deltaic coastal lakes. To have an illustrated validation, changes in Normalized Difference Indexing for Vegetation and Water (NDVI and NDWI) from the year 1984 to the year 2014 were quantified using Landsat imageries green, red, and near-infrared bands. Figures 1 and 2 demonstrate results of systematic lake invasion and loss of

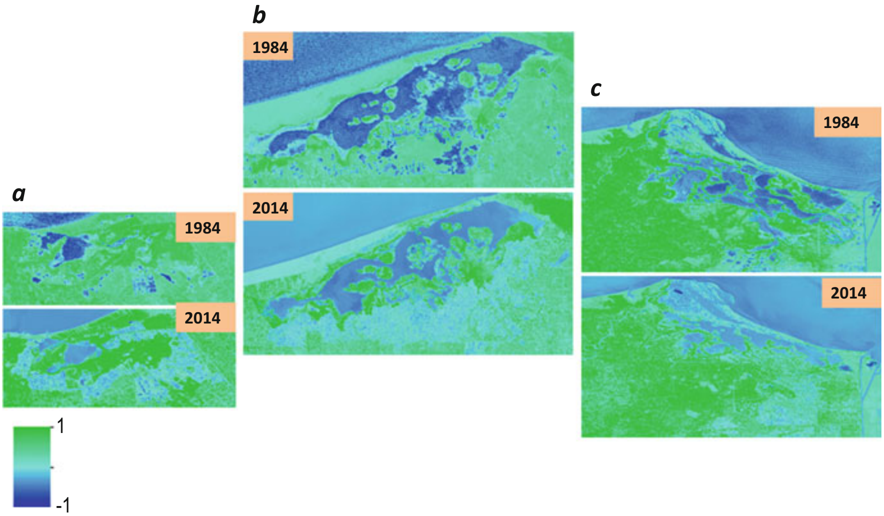

Fig. 1 Change in Normalized Difference Vegetation Index (NDVI) from 1984 to 2014 in three deltaic coastal lakes. (**a**) Idku Lake. (**b**) Burullus Lake. (**c**) Manzala Lake

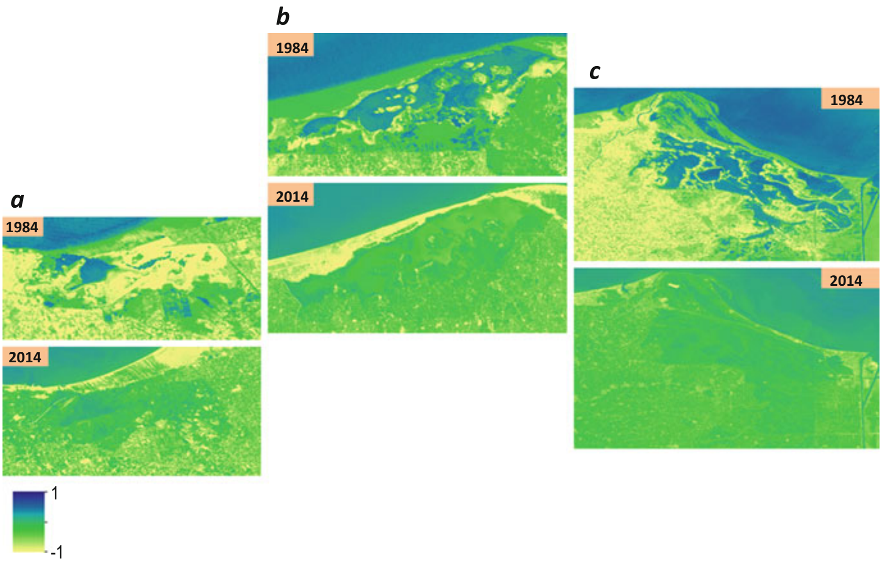

Fig. 2 Change in Normalized Difference Water Index (NDWI) from 1984 to 2014 in three deltaic coastal lakes. (**a**) Idku Lake. (**b**) Burullus Lake. (**c**) Manzala Lake

natural structure for selective deltaic lakes, namely, Idku, Burullus, and Manzala, represented in the form of NDVI and NDWI, respectively.

It is hard to pinpoint one specific main cause, land reclamation, modern agricultural practices, expanding urbanization, insufficient infrastructure, industrialization, etc. Yet collective contribution results in the observed deteriorating condition, with different degree. In some sort of sequential cause-effect interpretation, following three components would help summarize the changing pattern.

2.1.1 Sea Water Exchange and Salinity Level

Originally, deltaic coastal lakes are directly connected to the Mediterranean Sea through inlets. In a balanced environment, the direction of currents alternates mainly due to the tidal force, experiencing direct effects of either ebb or flow. Yet wastewater discharges into lakes conquer the exchange rate with seawater through inlets. That, in turn, decreases salinity concentration within the lakes, causing change in biophysical structure, and consequently disappearance of once-common aquatic species and fish production, as reported from local settlers. Further, low water salinity level provokes vegetation intensity, which dictates water health state, not to mention trapped flow and sediment transport, weakened circulation, etc.

2.1.2 Nutrient Loadings into Lakes

Lakes assimilate excessive nutrient loads from various sources, municipal sewage discharges, extended fish farms, industrial wastewaters, and agricultural drainage influx with a drastic increase in nitrogen fertilizers consumption since 1980, according to the Egyptian third national communication. Besides the obvious water quality problem associated, nutrient enrichment encourages both floating and rooted aquatic plants. Increased nutrient-derived vegetation causes trap for natural water movement and smooth circulation. Slowing water velocity causes sedimentation and expanded islands within the lakes.

2.1.3 Internal Circulation and Localities of Sand Accumulation

Obstruction of flow dynamics and created segmentation resulted in weak circulation, a locality in the quality state with possible stagnation, expanded island existence, and loss in the water area. Therefore, formed zones within the coastal lakes are expected to have a direct effect on mixing process, water quality, and sediment transportation mechanism.

A vicious circle, change in salinity, and nutrient content cause extending vegetative cover that causes water slowing and sediment accumulation, causing an alteration in flow dynamics and inefficient circulation, and loss of naturally occurring self-purification, hence further salinity and nutrient disturbance.

2.2 Understanding Impact on Functional Dynamic System

This section intends to reflect the previously mentioned changing features into hydrodynamic behavior within a coastal lake system. As an intermediate region between the coastal regime and freshwater network, northern lake region has a complex hydrodynamic system. Principally, changes in a lake as a control unit are governed by conservation laws of fluid mechanics, conservation of mass (continuity), conservation of momentum, and conservation of energy [13–15].

In hydrological system of a lake, mass balance for water budget is governed by inputs, including inflow from point sources, such as wastewater treatment plants (WWTPs) and industrial facilities, tributaries of the agricultural drainage network, precipitation onto the lake surface, subsurface and groundwater inflow, as well as seawater input, and, on the other hand, governed by outputs, namely, outflow into sea and evaporation from the lake surface. Continuity equation, representing mass conservation, quantifies the change rate of stored water (S) within a lake system as the net difference between inflows and outflows:

$$\frac{\partial S}{\partial t} = Q_e + Q_d + Q_{\mathrm{gw}} + Q_{\mathrm{in}} + PA_s - EA_s - Q_{\mathrm{out}} \tag{1}$$

Where Q_e is effluent flow of point source from activities, Q_d is flow from drainage network discharging into the lake, Q_{gw} is flow from groundwater contribution, Q_{in} is inflow from sea, P is precipitation, A_s is surface area of the lake, E is losses by evaporation, Q_{out} is loss of water outflow from estuary.

Circulation in lakes is customarily driven by heat fluxes, wind stress, density currents, and tidal effect. Yet, net energy is to be conserved constant within the lake system, even though conversion in energy form is expected. Meanwhile, the total rate of change in a fluid property (W_p) with time (t), moving in x, y, and z directions with velocity components u, v, and w, respectively, can be followed as:

$$\frac{\mathrm{d}W_p}{\mathrm{d}t} = \frac{\partial W_p}{\partial t} + u\frac{\partial W_p}{\partial x} + v\frac{\partial W_p}{\partial y} + w\frac{\partial W_p}{\partial z} \tag{2}$$

Based on Newton's second law, momentum conservation is reflected by a change in momentum within the lake system, which is governed by forces such as pressure and acceleration of gravity and related to flow velocity and bathymetry. Mathematical formulation of this principle is found in several representations [14].

In application, assuming steady-state, well-mixed system is mostly considered, despite that changes throughout lake system are undeniable. Thomann and Mueller [16] argued that assumption of a well-mixed system for lakes as simplification can be justified to acquire an overall evaluation of system behavior, but should be acknowledged as an approximation to the actual state. However, assuming steady-state or well-mixed system within deltaic coastal lakes is hard to consider.

Characterizing hydrodynamics within coastal lakes is different from the well-established flowing pattern in the river system or systematic coastal regime. Understanding the complex structure within lakes, changes in flow velocity and direction, physical processes, biochemical interactions, inflows and tidal patterns, etc. requires the use of modeling. Models offer an effective way to address complicated processes simultaneously, as well as predicting response changes. Promising ready-to-use packages are now available to calibrate with a wide range of lake hydrodynamics and water quality conditions, e.g., Delft3D Software [17, 18].

In model application, numerous data are needed for a comprehensive system representation before simulating hydrodynamic processes within a lake. Necessary data for hydrodynamic modeling include measurements of tributary inflows and lake outflow rates, water quality and physical properties, bathymetry, as well as meteorological and hydrological data. However, data are customary faced by limitations [19]. Field data, if available, are mostly collected at low frequency and partial spatial coverage, not to mention lacking long-term observations. This fact highlights the role that remote sensing techniques offer to overcome the possible shortage in needed information.

2.3 Risks and Ability to Recover

Besides playing an essential role in the development process, lakes in the coastal region are expected to act as a natural adaptive measure to buffer potential climate change-related sea level rise. Yet, significant changes have been detected in structure and recovery functionality during recent decades and in an alarming rate. A prime concern is the water quality status of lakes. Deteriorating condition leads to compromised ecosystem that, in turn, endangers ecological health as well as socioeconomic benefits.

Usually, water bodies in nature have self-purification ability. But in the case of the deltaic coastal lakes, external effects exceed their assimilative capacity. Nutrient-driven vegetation and sedimentation build up hindered smooth circulation. With expanding islands and aquatic flora intensity, sediment accumulation pattern is redistributed. Sediment behavior (e.g., settling, resuspension, etc.) is governed by factors such as particle size, density current, and wind. Yet an overwhelming impact comes from flow velocity within lakes, inflows from irrigation-drainage network, and outlets connected to sea tidal action.

As drainage discharges with higher velocity enter lower energy impoundment of the lake, sediment tends to settle. Meanwhile, areas in close proximity to sea inlets experience direct effects of ebb/flow action. In either case, areas located further away are less affected by the changes at the confluence point neighbor zone, which create segments with different flow pattern, along with dispersion and mixing mechanism and, hence, water quality characteristics within the same lake. As a result, the declining trends are getting more complicated as time pass and discard the concept of self-recovery with the natural environmental cycle. Immediate management action is needed. However, dealing with established assets and local community requires certain sensibility and applicable approaches. Despite the need for fast response, the abrupt measure should be avoided.

3 Employing Remote Sensing Techniques in Tracking Transformation Pattern

3.1 Role of Satellite-Based Products in Change Monitoring

Decision making and planning for management action require multidisciplinary studies as well as extensive surveys. Data collection for analysis of changing features can be expensive, time-consuming, and even unfeasible, in certain locations, to carry out. Meanwhile, remote sensing techniques proved successful in several applications in land use and water science fields. This section investigates aspects in remote sensing potential for water quality monitoring within coastal lakes.

Launched Landsat 1 in the 1970s can be considered a starting point for a new level of remote observation of earth. Landsat 1, which was back then called “Earth Resources Technology Satellite,” have had a multispectral scanner (MSS) detecting four separate spectral bands between 500 and 1,100 nm at 82 m resolution [20]. Ever since, the industry of advancing satellite specifications, and hence capabilities, offers improved temporal, spatial, and spectral resolutions.

Remotely sensed water quality status is mainly retrieved for parameters with optical reflective nature, e.g., turbidity, phytoplankton, suspended organic matters, etc. Yet indirect analyses are used to cover more water quality indicators, e.g., nutrient-related Nitrogen and Phosphorus contents. It should be noted that correlation with satellite imagery spectral characteristics not necessarily give exact concentrations [21], but offer enlightenment of trends and spatiotemporal distributions.

In Egypt, researchers have been addressing remote sensing-based water quality assessment, especially with the growing concerns of adverse effects of anthropogenic disturbance to environmental condition [1, 4, 6, 8, 10]. A most recent study by Rostom et al. [11] showed successful remote sensing-based heavy metal retrieval in Maruit Lake waters. For the purpose of demonstration, the following section intends to present an application of employing remote sensing to observe changes in water quality within an important coastal lake, namely, Burullus, which lately triggered many concerns.

3.2 Case Study: Water Quality Indexing for Lake Burullus

In an attempt to have a simple characterization of spatial variability within Lake Burullus, an index comprised of key indicators of water quality is developed.

3.2.1 Water Quality Index

Water quality is the principal indication of functionality and healthiness of an ecosystem. Water quality refers to the chemical, physical, and biological characteristics of the system water, and it has to be quantified with reference to the requirements of the desired beneficial uses. Water Quality Index (WQI) concept was initially developed by the National Sanitation Foundation during 1970 [22]. The effect of selective believed influensive, water quality parameters are combined in a single meaningful expression that reflects the water body quality state with respect to its uses. An expert panel was consulted for selecting quality parameters to consider in developed index. Recommended parameters for indexing were dissolved oxygen, fecal coliforms, pH, BOD, nitrate, phosphate, temperature, turbidity, total solids, toxic elements, and pesticides, with quality curves. As unequal effects were expected, significance weight (w_i) was allocated to each parameter quality (q_i), to be aggregated in an overall water quality index (WQI), (more details are found in [23])

$$\mathrm{WQI} = \sum_{i=1}^{n} w_i \ q_i \tag{3}$$

The concluded index is then scaled, categorized, and comparably judged based on intended beneficial use. While sharing a similar concept, several indices were then developed and applied for different condition and water uses. Commonly used is the WQI of the Canadian Council of Ministers of the Environment (CCME-WQI). The index is the result of combined measures of variance, namely, scope, frequency, and amplitude, which then categorize water quality from excellent to poor in six classes [24].

Application of indexing offers a means for defining a meaningful representative measure of the overall water quality state, in the form of a single number that simplify monitoring changes as well as following the effectiveness of management strategy. An advantage of WQI is that it facilitates communicating water quality conditions among all concerned parties, policy makers, nontechnical personnel, general public, etc. and not restricted water science profession [25].

3.2.2 Study Area

Lake Burullus is the second largest natural lake in Egypt located in north of the Nile delta east of Rosetta branch, along the Mediterranean coast, between longitudes 30°, 30′–31°, 10′E and latitudes 31°, 35′–31°, 21′N. The lake can be classified as shallow, mostly unstratified, with spatial difference in depth from 0.4 to 2.0 m. The deepest zone is sited in the western sector, which also has the lowest water salinity levels while, oppositely, the eastern sector is characterized as shallower and more saline [26]. Distinguished dual front is manifested in Lake Burullus, while connecting to the sea to the north through only one opening (Boghaz), branches of the irrigation-drainage network spread out along the lake boundary to the south, namely, Brimbal Canal, Drain 11, Drain 9, Drain 8, Drain 7, Nasser drain, Al-Gharbia drain, and El-Burullus drain (Fig. 3).

3.2.3 Selected Variables and Spectral Processing

This application follows the principal indexing concept, selecting representative parameters, and allocating weight to each parameter involved in WQI calculation according to its relative importance in the overall estimation. Accordingly, categorizing with reference to targeted beneficial purposes of the productive fishery and aquatic ecosystems, as well as healthy body contact recreational. In performing an assessment of water quality index for coastal Burullus Lake, variables related to key indicators that can be derived from satellite imageries were selected to be temperature, turbidity, and chlorophyll.

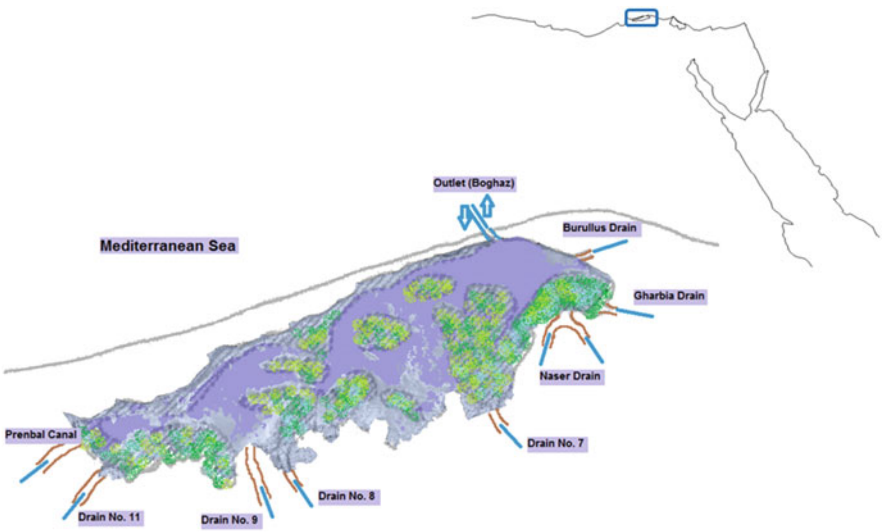

Fig. 3 Schematic of Burullus coastal lake

While dissolved oxygen (DO) is a vital indicator of water quality health and self-purification ability, yet it cannot be directly retrieved from satellite imageries. However, the temperature can be considered a reflective physical parameter of DO content. The increase in water temperature is customarily regarded as thermal pollution that negatively affects water quality status, aquatic ecosystem, and physical and biochemical processes. Raised temperature increases the metabolic rate of aquatic organisms and subsequently increases DO consumption. Moreover, like all gases, oxygen has decreased solubility in warmer water, which in turn reduces the oxygen concentration in water as temperature rise. Meanwhile, turbidity is considered an indication of optical properties of water that dictates the light penetration pattern and, hence, essential biochemical processes and natural process such as the ability of flora to photosynthesis to occur [27]. Chlorophyll-a content is selected to reflect nutrient existence and excessive growth of aquatic plants that would turn from beneficial to nuisance. The calculation of the WQI in this case study was done using weighted arithmetic water quality index (Eq. 3), giving the temperature 40% of the weight and turbidity and chlorophyll equal weight of 30% for each.

It is well-established that short wavelength of the spectrum has the stronger capability of water column penetration than longer wavelength [28]. Therefore, spectral bands of satellite image used for chlorophyll and turbidity derivation are those in the visible and near-infrared region of Landsat 8 imagery acquired in spring of the year 2015. Landsat 8 offers multispectral imageries sensed by both Operational Land Imager (OLI) and Thermal Infrared Sensor (TIRS). Calculations of chlorophyll concentrations were based on early work by Akbar et al. [29] that has shown a strong relationship with band ratio of blue to red bands. Meanwhile, turbidity was derived following recent study findings [30] that concluded acceptable accuracy for developed algorism relating turbidity to the natural logarithm of red band and band ratio of blue and red. Surface temperature extraction from remote sensing product is deducted using thermal bands of the Landsat images. Transformation of thermal radiance image at surface temperature was deducted using imagery metadata information.

3.2.4 Result Analysis: WQI

For retrieving water quality-related properties within the lake, islands were masked out, and only water area was considered. Results show that higher turbidity is found in the eastern zone of the lake (Fig. 4), whereas chlorophyll-a exists at the highest level in the west of the lake, which coincide with raised temperature grades, as demonstrated in Figs. 5 and 6, respectively. Aggregated Water Quality Index within the lake is illustrated in Fig. 7. Notably, results show good agreement of concluded WQI trend with actual observations to a great extent. According to findings, it can be concluded that remote sensing of selective parameters would give a sensible idea of tendency and spatial difference within a lake with such multi-aspect interactions. Therefore, the potential of remote sensing techniques for monitoring and management is worth considering in further applications. It should be emphasized,

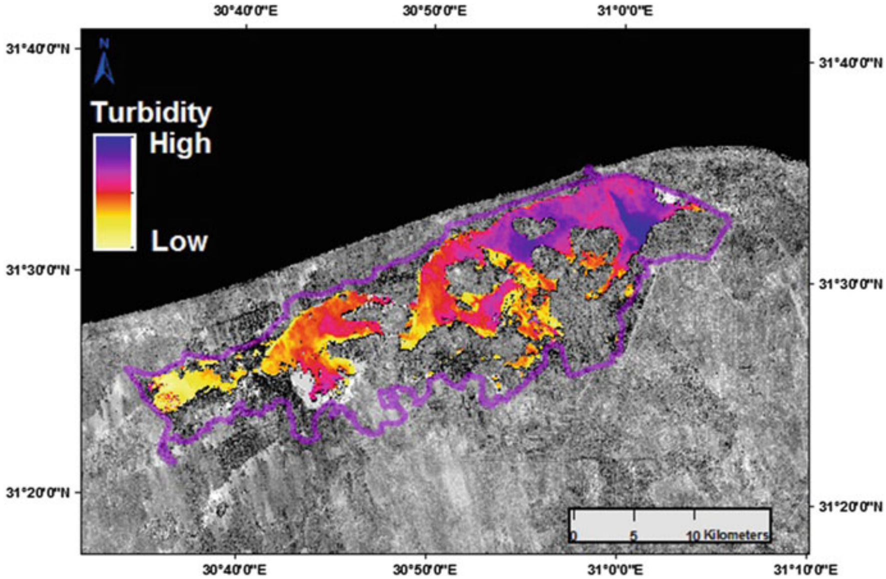

Fig. 4 Remotely sensed turbidity trend within Lake Burullus in spring 2015

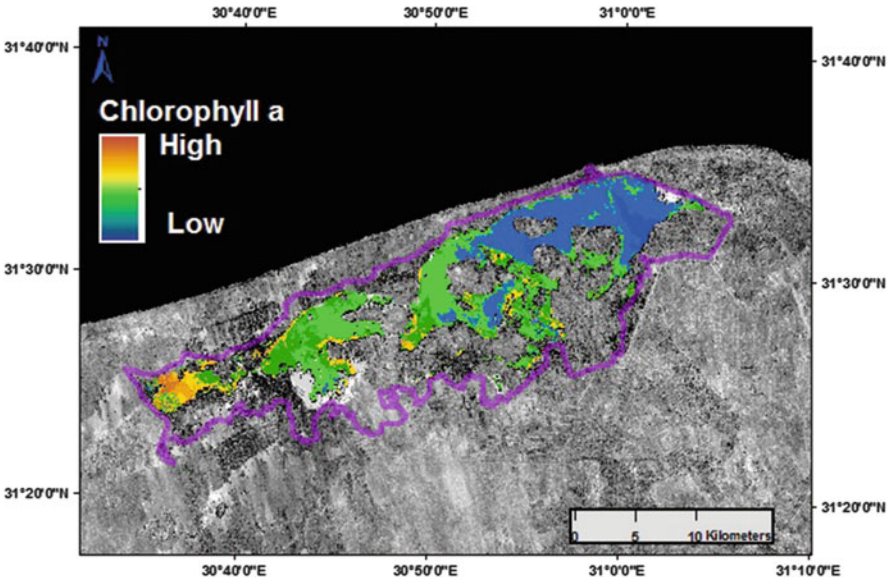

Fig. 5 Remotely sensed chlorophyll-a trend within Lake Burullus in spring 2015

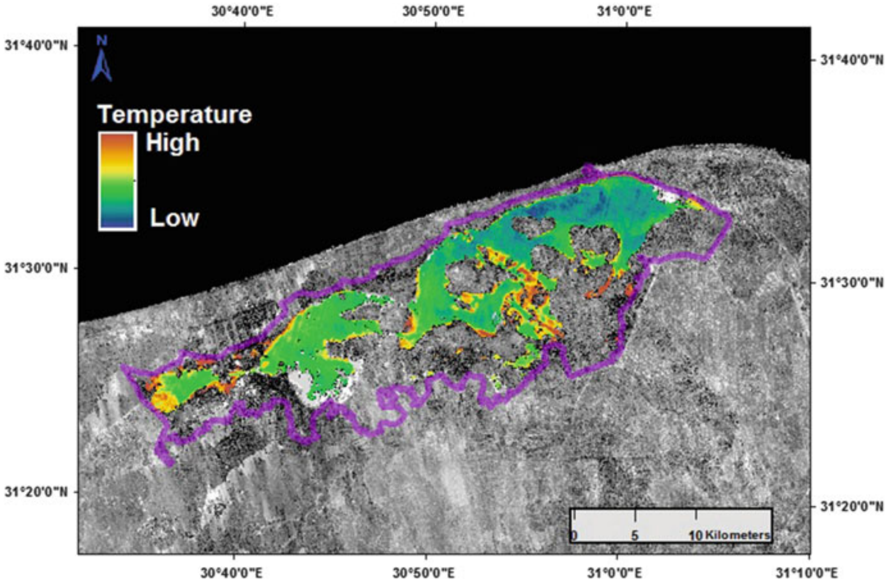

Fig. 6 Remotely sensed thermal trend within Lake Burullus in spring 2015

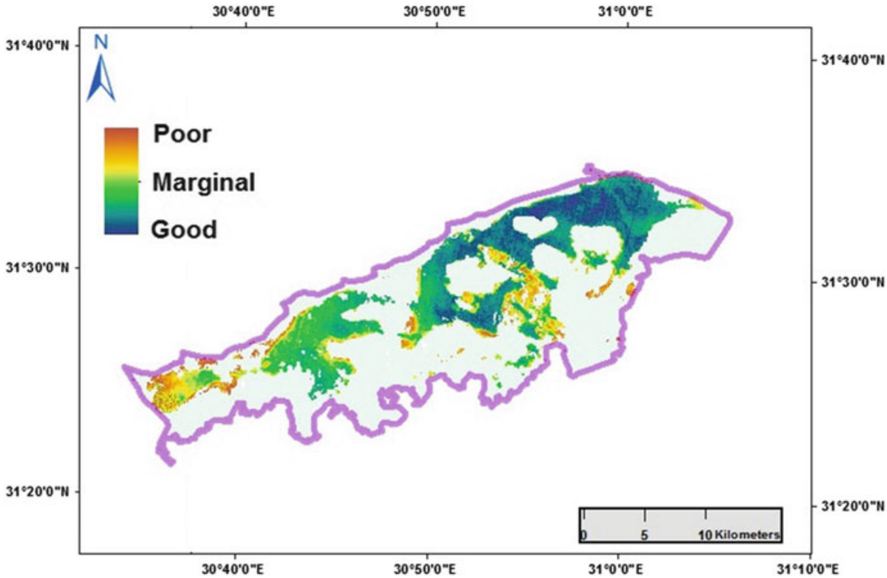

Fig. 7 Water quality index in Lake Burullus, spring 2015

however, that the main purpose of using WQI in this case study is to get initial representative quality trend within the lake under consideration, using simple methodology. Advanced application including more water quality parameters, accompanied with ground truth measurements, is recommended to obtain more detailed information.

4 Strategy for Coastal Lake Restoration

4.1 Proposed Management Strategies

Keeping steady balanced ecosystem while aggressively moving ahead in development processes is a dilemma that concerns many parties, environment advocates, energy expert, natural resources managers, and decision makers. Threats involving resource depletion and socioeconomic instability have encouraged a number of studies to investigate causes and possible remedial actions. It was widely established that major part of the coastal lake problems is caused by increasing municipal, agricultural, and industrial discharges. Drained wastewaters into the lakes considerably changed nutrient and salinity levels within that, in turn, negatively affected aquatic species structure and population density. Consequent disturbance in hydrodynamics and sediment transport pattern hindered smooth circulation and, hence, reflected harmfully on water quality condition within the lakes.

The perfect corrective strategy would be targeting comprehensive restoration to the former healthy environmental system of coastal lakes. This would entail lessening nutrient-loaded freshwater inputs while increasing exchange rate with seawater, preserving acceptable water quality condition that meets the stipulated environmental laws, as well as ensuring functional water flow and circulation mechanism that prevent sedimentation and allow active self-purification. Therefore, suggested measures to be considered are:

- Add outlet (Boghaz) for more seawater exchange.
- Lessen incoming discharges from irrigation-drainage network through redirection of drainage flow with alarming quality condition.
- Strictly enforce, and update stipulated regulations with discharging facilities.
- Manipulate flow velocity within lakes.
- Perform more frequent dredging and reed removal, as well as deepen lake bed levels, e.g., ray streams.
- Stop drying and earth-filling invading into lake water surface.
- And, to be addressed with integrated viewpoint, coastal lakes restoration should be mainstreamed within the Integrated Coastal Zone Management (ICZM).

However, sensibility in finding an effective strategy that helps regain productive, environmentally safe coastal lake dictates acceptance to inevitable sacrifices. Also, and despite the need for immediate response, it should be recognized that swift application is not expected.

4.2 Reasoning Challenges, Effectiveness, and Adaptability

The right to develop and benefit from resources to get a better life cannot be denied, yet adverse effect comes right back hitting strongly. Obviously, established assets and ongoing activities cannot be stopped abruptly. Concepts such as instant decrease of wastewater effluent rate discharged into coastal lakes, or even aspire to have perfect pre-discharge treatment in a developing country that already struggles in many areas, are unachievable. Therefore, management strategy should be designed with gradual application plan, while avoiding complex measures.

It is important to acknowledge the advantage of coordination among concerned parties. Collaborative efforts with effective communication mechanism would avoid conflict or repeated works. An additional benefit would be gained by raising awareness of local communities and ensure smooth information exchange. Last but not least, with the inherited issue of insufficient data coverage, benefit from the ever-advancing earth observation and remote sensing techniques would help filling data gaps and to have more spatial and temporal observation records.

5 Conclusions and Recommendations

Being an essential source for fish production, recreational and flood control potential gave the coastal lakes of Egypt a treasured status. Coastal lake in the Nile delta region is a meeting point for different types of water properties, affected by coastal characteristics and development processes in served watershed. For decades, coastal lakes have alleviated polluting impact reaching the Mediterranean Sea. Yet multiple sources of wastewater released, e.g., agricultural, industrial, and municipal, beside discharges from expanding fish farms, all contribute to dramatic alteration in salinity and nutrient levels within coastal lakes. Changes in aquatic biota structure, dense plants, as well as drying and earth-filling practices shift dynamic patterns of flow velocity, circulation behavior, and sedimentation tendency.

Maintaining functional ecosystem condition in coastal lakes of Egypt with ever-expanding development activities is a challenge. Footprints of the progressive development processes are undeniably beating natural ability for self-purification and fast recovery of those water bodies. Therefore, comprehensive management strategy is due.

Reaching educated decision for managerial measures, with multidisciplinary nature, should be backed with detailed information of well-monitored lake system. Yet reference data are not always available as extensively as required. Advances in earth observation field are expected to provide a boost to data collection and monitoring processes. Among the benefits of introducing remote sensing techniques in coastal lake management is the vast pool of data offered, with more frequent interval and expanded spatial coverage. Beside possible establishment of a historical database, analyzed satellite imageries would also facilitate regular monitoring for key management indicators. Potentiality of remote sensing in the field of water resources management and quality monitoring was addressed, through a case study application. Processed earth observation satellite imageries proved liable in reflecting the spatial change of key water quality features in the Burullus coastal lake.

While pursuing an integrated management plan, it is important to establish effective networking, information exchange, and coordination among concerned parties. Also, a useful act to consider is to raise awareness; communicate lake conditions and risks ahead to the public in order to gain their support, and cooperation.

Finally, it is recommended to incorporate modeling techniques in further studies to reach a gradual restoration of deltaic coastal. Modeling scenarios facilitate investigating several concerns simultaneously, checking alternate managerial measures, and then following potential success and, hence, optimum selection to be adopted.

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Summary, Conclusions, and Recommendations for Egyptian Coastal Lakes and Wetlands: Climate Change and Biodiversity

Sommer Abdel-Fattah, Abdelazim M. Negm, and Mohamed Ali Bek

Abstract The Egyptian coastal lakes and wetlands play an essential role in the culture, livelihood, environment, and social foundation in Egypt. The root of this system is the Nile River and the associated Nile Delta lakes that are reservoirs of the Nile water flowing to the Mediterranean Sea. The Egyptian coastal lakes represent about 25% of the Mediterranean total wetlands. These lakes (ordered from east to west) include Bardawil, Manzala, Burullus, Edku, and Mariout. All, except Lake Mariout, are directly connected to the Mediterranean Sea. Lake Manzala, the largest of the Egyptian coastal lakes, is considered as one of the most valuable fish sources in Egypt. These coastal lakes and wetlands play an important role in the nation's economy, not only because they produce a great amount of the nation's fish catch but also serve as resting areas for migrating birds. The expansion of agricultural reclamation after 1950 led to an increase in

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the amount of agricultural drainage to reach more than 4,000 million cubic meters which caused many changes in the region. This volume “Egyptian Coastal Lakes and Wetlands: Part II – Climate Change and Biodiversity” aims to understand some of these changes through examining the impacts of climate change and environmental changes such as water quality as well as impacts to biodiversity such as zooplankton, fish, and plants. This chapter will break down these findings into the following categories (1) Climate Change and Water Quality; (2) Biodiversity of Zooplankton, Fish, and Birds; and (3) Remote Sensing Applications and Potential Restoration of Lakes.

Keywords Bardawil, Biodiversity, Burullus, Climate change, Coastal lakes, Edku, Manzala, Mariout, Modeling, Remote sensing, Water quality

Contents

1 Summary

The Egyptian coastal lakes and wetlands play an important role in society, economics, and the environment and are vital to the sustainability of Egypt. The coastal lakes largely extend from the Nile River as the root of this system. The associated Nile Delta lakes that are reservoirs of the Nile water flow largely to the Mediterranean Sea. The Egyptian coastal lakes include four lakes and two lagoons. These lakes (ordered from east to west) include Bardawil, Manzala, Burullus, Edku, and Mariout. All, except Lake Mariout, are directly connected to the Mediterranean Sea. These coastal lakes also host important wetland areas that make up roughly 25% of the Mediterranean’s total wetland area. The Egyptian coastal lakes also play a vital role in the nation’s economy, not only because they produce a significant amount of the nation’s fish catch but also are home to many native animals and transient birds. The expansion of agricultural activities after 1950 led to an increase in the amount of agricultural drainage which caused many changes in the region and negative impacts in this region. This volume “Egyptian Coastal Lakes and Wetlands: Part II – Climate Change and Biodiversity” aims to understand some of these changes through examining the impacts of climate change and environmental changes such as water quality as well as impacts to biodiversity including zooplankton, fish, and plants. This chapter will break down these findings into the following categories: (1) Climate Change and Water Quality;

(2) Biodiversity of Zooplankton, Fish, and Birds; and (3) Remote Sensing Applications and Potential Restoration of Lakes.

1.1 Climate Change and Water Quality Modeling

As part of an assessment of the coastal lakes in Egypt, the water quality status of Lake Manzala has been studied, as there is concern that the lake has been inundated with 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. The study by Elshemy et al. 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. The research involved conducting a comprehensive water quality assessment of the lake, based on water quality index (WQI) and trophic status index (TSI). The MIKE 21 modeling approach was used to understand the hydrodynamic and water quality dynamics and the future projected lake characteristics and how this might change current estimates of water quality parameters. The model showed good agreement with the observed water depth, water temperature, and salinity records; 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. Two periods (2046–2065) and (2081–2100) were studied for one representative concentration pathway (RCP2.6), using the average of two downscaled (spatially and temporally) GCM outputs. The results show significant spatial changes of water temperature of the lake. Moreover, 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.

The results revealed that Lake Manzala is in a critical state having very bad water quality status and the high and very high trophic conditions, especially in the southern and eastern zones. The future models show that if wastes continue to enter the system, the Lake will be in a very severe degraded condition.

To further understand this situation, modeling of water quality parameters in Manzala Lake using adaptive neuro-fuzzy inference system and stochastic models was conducted by Mosaad Khadr. His research found used deterministic models to try to understand the system behavior. The adaptive neuro-fuzzy inference system (ANFIS) was used to predict water quality parameters in Lake Manzala based on the measured water quality parameters of drains associated with the Lake. ANFIS models can achieve easier and faster predictions for water quality parameter with emphasis on total phosphorus (TP) and total nitrogen (TN) at the outlet ends of the drain system. The model used input data including discharge, pH, total suspended solids, electrical conductivity, total dissolved solids, water temperature, dissolved oxygen, salinity, and turbidity. The models' results show that the ANFIS model is capable of simulating the water quality parameters and provided a reliable prediction of total phosphorus and total nitrogen, thus suggesting the suitability of the proposed model as a tool for on-site water quality evaluation.

1.2 Biodiversity, Zooplankton, and Fish

Egypt's coastal lakes represent highly dynamic aquatic systems that have been undergoing continuous and pronounced changes away from the natural condition, which is influencing the diversity of the biological community and its function.

The occurrence of brackish and saline waters in Egypt's Delta wetlands during the 1970s–1980s has resulted in a broad diversity of fish species inhabiting these areas (approximately 32 species). However, a field survey conducted in 2014 showed that the diversity of fish in the Burullus wetland has declined from 32 to 25 species. All the species which have disappeared are those having a marine affinity. Conversely, the total production of this wetland has increased from 7,349 tons in 1963 to 63,980 tons in 2014. Freshwater biota also became the predominant food source. These changes in the community of fish inhabiting the lake and the increased productivity are likely due to the high volume of drainage water entering the system during the last four decades. The drainage water contains nutrients such as phosphorus, nitrogen, and other fertilizers which would promote productivity but also contains lower salinity levels than are preferable to marine species. As far as the main groups of important fishes are concerned, decreases were found in the *Dicentrarchus labrax*, *Argyrosomus regius*, crab, and mullet. Some freshwater fish, like *Clarias gariepinus* and *Bagrus bajad*, have increased in number during the last 7 years. Overall, there has been an increase in fish production from 7,549 tons in 1963 to about 63,000 tons in 2015, but this came with a loss of the variety of species as presented in [1]. As a result, the fisheries were shifted from mullet-based fish (marine) to tilapia-based fish (freshwater); this caused a later decline in the tilapia population. Changes to the diversity in other species have also been observed, such as in plants and birds.

The Egyptian coastal lakes are essential sites for migratory birds along the Mediterranean coast. Burullus and parts of Lakes Manzala (i.e., Ashtum El-Gamil) and Bardawil (i.e., Zaranik) are managed protected areas. Also, Burullus and Bardawil are Ramsar sites have a focus on the conservation of migratory birds. Birds tend to gravitate toward areas that have a high plant diversity. As such, these lakes were also evaluated for their plant diversity and ecosystem services. The study found 402 plant species, categorized into 45 plant communities; 5 of these species were endemics, while 3 were endemics. Although the areas only contribute <0.003 of the total area of Egypt, they are inhabited by 19% of all the Egyptian flora, particularly aquatic plants. Also, 70% of the total plant species are of commercial importance, such as for grazing, medicinal drugs, human food, fuel, and timber, while 60% contribute to environmental services such as soil or bank stabilization, shade, weed control, nitrogen uptake, and water purification. According to the IUCN Red List categories, 13 plant species were threatened in the 5 Egyptian coastal lakes, 7 of which were evaluated as endangered species, while 6 were evaluated as rare species. Due to the excessive amounts of agricultural and industrial drainage water, the vegetation and sediment of these lakes are effective as carbon sinks; therefore they play an essential role as hot spots for the Egyptian flora.

Zooplankton has often been used as an indicator of change as the changes in the water environment can be identified through changes in species composition, quantity, and size. Interestingly, despite their physical separation, the Delta lagoons appear to have similar zooplankton populations. Rotifers comprise at least 80% and often higher than 90% of the total population in the lakes [2, 3]. Bardawil Lake shows slightly a different zooplankton assemblage which composed mainly of marine species copepod followed by Protista and Pteropoda, likely because this lake is the most pristine of the coastal lakes and receives less drainage water. The zooplankton assemblage shows little change until the 1950s. By the 1970s, Daphnia had become a rarity and was not recorded from the lakes. The 1960s–1970s were marked by three new arrivals in the zooplankton, all of them have Mediterranean origin. Zooplankton is important because it also contributes to the fish community. For example, zooplankton contributes about 28.3 and 11% of the food items content of mullet and prawn in a nondeltaic lake such as Bardawil. It is clear in any case that these drainage inputs have affected a change in the community of the wetlands of the coastal lakes including fish, plants, birds, and zooplankton. To further investigate these changes, it is useful to use new technologies and modeling applications to gain a better understanding.

1.3 Remote Sensing Applications and Potential Restoration of Lakes

Earth observation tools started as early as the 1970s. Since then, this technology has advanced in both spectral and spatial resolution. Data availability has also increased substantially including data sharing and collaboration among environmental researches in science, monitoring, and management. Remote sensing has been used as an effective tool for mapping physical, biochemical, and geomorphological features of the northern coastal lakes. Applications of RS are divided into two main categories: the first category is related to water quantity, and the other one is related to water quality properties. Remote sensing helped to determine the lost area of each lake due largely to the continuous human activities and infrastructures. The results of the remote sensing showed that Lake Edku (or Idku) lost the greatest amount (73% in 40 years), followed by Lake Manzala (42% in 60 years), and Lake Burullus (38% in 60 years); Lake Bardawil suffers less land use activities. Infrastructures such as railways and highways have dramatically changed the shape of the coastal lakes; for example, Lake Mariout has changed from only one body to four dissected basins, and Lake Manzala is now divided into sections.

Aside from imagery of the lakes, remotely sensed data could also be used to estimate biophysical parameters including surface temperature, salinity, turbidity, and chlorophyll a. Remote sensing data showed that Lake Bardawil had reduced levels of Chl-a (<13 mg/l), largely due to its isolation from drainage water and wastes, while the other coastal lakes have higher Chl-a levels. Remote sensing data also shows a spatial variation of Chl-a concentration on the lake at a single time. Concentration was lower in the northern parts of the lakes (where it connects to the sea) and higher levels downward. This result confirms the suspicion that Chl-a is influence by the wastes and pollutants entering the system.

The investigation of the water quality parameters in the coastal lakes revealed that that higher turbidity is found in the eastern zone of the lakes, whereas chlorophyll a exists at the highest level in the west of the lake, which coincides with raised temperature grades. Results show good agreement of the water quality index (WQI) trend with actual observations. The author recommends including more water quality parameters, accompanied with ground-truth measurements, to rerun this type of analysis to obtain more detailed information.

Further studies relating to the use of RS on the Egyptian northern coastal lakes indicate that there is a wide range of lakes' aspects that were investigated such as bathymetry, water properties and quality, environmental conditions, and water surface area of the lakes. The findings of related studies which utilized the satellite RS data from various sensors, such as the Systeme Pour l'Observation de la Terre (SPOT), Enhanced Thematic Mapper plus (ETM+), Multispectral Scanner System (MSS), and Thematic Mapper (TM), are reviewed. The covered topics include water surface area extraction, bathymetry detection, and water quality of the lake. The monitoring of the Egyptian coastal lakes using RS showed that most of the Egyptian coastal lakes are suffering from a remarkable reduction in water surface area, increasing quantities of agricultural drainage, massive amount of anthropogenic damages, eutrophication and pollution, land reclamation, urban encroachment, waste dumping, loss of biodiversity, aquaculture challenges, and even reduced recreational use. The comprehensive survey indicated that the water bodies of the lakes are not sustainable.

2 Challenges Facing the Egyptian Coastal Lakes

Egyptian Environmental Affairs Agency (EEAA) and the National Institute of Oceanography and Fisheries (NIOF) have agreed to implement a periodic monitoring program for the northern lakes as of July 2009. The periodic monitoring program implemented by NIOF for Egyptian lakes aims to:

1. Monitoring water quality and sediments in lakes.
2. Assessment of the current environmental and geological conditions of each lake.
3. The establishment of a comprehensive database of lakes based on the quality control and quality assurance work that will be relied on in the management of all these lakes.

The outcomes of these regular monitoring are a set of reports (in Arabic) which are available at http://www.eeaa.gov.eg/portals/0/eeaaReports/water/reportFeb17/. These reports summarize the challenges facing the Egyptian northern coastal lakes. A summary of these challenges are presented here as follows:

Lake Mariout and Lake Edku

Alexandria is the second most important industrial center in Egypt, where 37% of the industry is concentrated where the industries produce more than 1 million cubic meters of liquid waste with about 260 tons of suspended solids per day and deliver these wastes untreated into sea, into Mariout Lake south of Alexandria, and in the freshwater canal and in the drains and into the sewage and sewerage system. Also, the city produces more than 1 million cubic meters of mixed sewage waste daily, industrial waste, hospital waste, and gas stations' waste. Almost half of this amount was delivered untreated in the water bodies, while the other half is delivered to Mariout Lake after receiving a preliminary treatment. Additionally, there are 200,000 feddans (1 feddan = 4,200 m^2) of agricultural land in Alexandria governorate, resulting in agricultural drainage with residues of insecticides and chemical fertilizers that ultimately reach the water bodies. Added to the above, oil refining plants, cement, steel, and petrochemicals industries pollute the lake with chemical waste. Also, spread of weeds and other aquatic plants affects the flow of water and impacts the quality of ecosystem of the lake (http://www.eeaa.gov.eg/portals/0/eeaaReports/water/reportFeb17/مريوط.pdf).

Added to the above, for Edku Lake, there is an increase in the amount of sanitary and agricultural wastewater loaded with insecticides (the lake receives about 2,062 million cubic meters of sewage water from the different sewers). A major challenge is that the lake water that flows in one direction toward the sea deprives the lake waters from being remediated by the sea waters which can enter the lake if its level is lower than the sea level (http://www.eeaa.gov.eg/portals/0/eeaaReports/water/reportFeb17/ادكو.pdf).

Burullus Lake

The lake area was reduced from 165,000 feddans to less than 70,000. Also, about 25,000 feddans are covered by aquatic plants. Additional challenge is the high percentage of silt in the lake making islands, which increases the bed level of the lake by about 35 cm and, therefore, reducing the inflow of seawater to the lake. Also, about 30 billion cubic meters of sewage and agricultural drainage, and the disposal of fish farms southern of the lake are delivered to the lake leading to a high level of pollution which is much higher than the permitted one by EEAA (http://www.eeaa.gov.eg/portals/0/eeaaReports/water/reportFeb17البرلس.pdf).

Manzala Lake

The lake suffers from a great reduction in its area from 750,000 to 100,000 feddans. The lake receives a continuous pollution from huge quantities of sewage, agricultural, and industrial water. It received annually a significant amount of wastewater without any treatment from two main sources. The first is Bahr Albakar which delivers around 650 million cubic meters of sewage water in the lake, followed by

Hadous drain which delivers 1.7 million cubic meters into the lake. Added to the above, the spread of aquatic plants over large area of the lake affects the movement of water inside the lake and leading to degradation of lake water quality and fish quality (http://www.eeaa.gov.eg/portals/0/eeaaReports/water/reportFeb17/المنزلة.pdf).

Bardawil Lake
Bardawil Lake is suffering from three main challenges. The first is the clogging of Boughas and lack of environmental awareness among the fishermen community. Also, the expected change in both water quality and qualitative composition of the fish in the lake is due to the agricultural expansion where 400,000 feddans will be reclaimed near to Bardawil Lake and an expected large amount of waste will be received by the lake (http://www.eeaa.gov.eg/portals/0/eeaaReports/water/reportFeb17البردويل.pdf).

3 Conclusions

Coastal lakes in the Nile Delta region are an essential resource for Egypt in all social, economic, and environmental aspects. As such, it is important to gain a better understanding of these systems and the human activities affected on coastal characteristics, contamination, and changing the ecosystem of these watersheds. For decades, coastal lakes have alleviated pollution from reaching the Mediterranean Sea. Yet multiple sources of wastewater released are release from agricultural, industrial, and municipal sources greatly affecting these lakes. Recently, expanding fish farms have also exacerbated the problems and have contributed to a dramatic alteration in salinity and nutrient levels within the coastal lakes. Changes in aquatic biota structure, plant diversity, and a general change in the ecosystem services have had a large impact.

Large amounts of agricultural wastewater and sewage entering these water bodies through several drains have impacted the physicochemical and limnologic features of the lakes. Increased levels of nutrients, combined with decreased levels of salinity, have caused a shift in the biodiversity of the lake. Therefore, freshwater species have begun to take a more prominent position in the lake's food web. Furthermore, this has caused a shift in the types of fish available and impacted the diversity of zooplankton, plants, and birds.

Coordination between the stakeholders involved in the management of these lakes should consider activities that enhance the biodiversity and productivity in these wetlands. There is also low awareness of local residents and fishermen about environmental issues as well as management plans and their importance, combined with a limited understanding of the role of protected areas and their value, which hinders the proper fisheries management of these wetlands and threaten their integrity in the long run. Continued research of these lakes will also be vital.

In the last few decades, a large number of research studies were carried out on the coastal lakes of Egypt with the main focus on monitoring and mapping; however, further research is needed to use remotely sensed data for management and rehabilitation. Furthermore, when pursuing an integrated management plan, it is important to establish effective networking, information exchange, and coordination among concerned parties. Managerial actions, with multidisciplinary nature, should be backed with detailed information from science and well-monitored lake systems.

Remote sensing technology is an effective tool to study and monitor the coastal lakes. Remote sensing has been used by Egyptian's coastal lakes since the first launch of the MSS Landsat satellite in the 1970s. Among the benefits of introducing remote sensing techniques in coastal lake, management is the vast pool of data offered, with more frequent interval and expanded spatial coverage. Processed earth observation satellite imageries proved liable in reflecting the spatial change of key water quality features in coastal lakes. For example, significant changes with respect to the high rate of losses from the lake's water mass area were recorded in the last few decades. The construction of national projects, such as El Salam Canal and the Northern National Coastal Road, played key role in accelerating such changes. For example, El Salam Canal and the Northern Coastal Road were the major drivers for the recent cutoff area from Lake Manzala and the land transformation into agriculture land. In Lake Burullus, cutoff areas were converted into fish farms.

Earth observations not only offer an effective technique to monitor the rapid environmental changes of inland lakes but also it could retrieve the physicochemical and biological variables.

Advanced remote sensing sensors will be important for future lake monitoring and retrieving the environmental parameters for operational use and management. Finally, it is recommended to incorporate modeling techniques to reach a gradual restoration of the coastal lakes.

4 Recommendations

It is imperative to develop a management plan for restoring the ecosystem of the Egyptian coastal lakes that have been compromised. Some recommendations for management actions include:

- Initiating a network for continuously monitoring water quantity and quality, treating water for reuse, and monitoring climate change.
- Removal of invasive species such as reeds and dredging.
- Active maintenance of the sea outlet for ease of water movement as well as marine fish origin enter into the lake.
- The drainage water from municipal, industrial, and other wastewaters such as from fish farms must be controlled or treated.
- A periodic hydrological monitoring program, including water levels, drains and outlets discharges, and lake bathymetry.
- A physical, chemical, and biological monitoring program must be included (biotic and abiotic).

- A regional climatic model should be developed for Egypt.
- LiDAR and radar and other remote sensing data should continue to be gathered across Egypt; harmonize the spatial data into one system.
- Agriculture is a considerable source of nutrients; changes may be required in the use of fertilizers in agriculture to reduce nitrogen and phosphorus inputs.
- Pollution control policies and measures should be enforced, especially before new industries are established; strictly enforce regulations for discharging facilities.
- Establishing guidelines for fishery regulation measures and construction a management policy for the rational exploitation of the lake fish resources.
- Build public awareness through providing special training programs on environmental and pollution problems with illustrative examples.
- Illegal fishery practices should be banned, such as the capture of fry and small fishes from the sea inlet areas.
- Fishery management efforts aimed at increasing the populations of declining fish such as mullet and tilapia.
- All stakeholders should participate in achieving the goals connected to the coastal lakes in the sustainability agenda 2030.

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Erratum to: Earth Observations for Egyptian Coastal Lakes Monitoring and Management

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Inadvertently, the name of the first mentioned author of the cited reference number 16, Blondeau-Patissier D, was incorrectly mentioned in this chapter. This has now been corrected.

The updated online version of this chapter can be found at DOI 10.1007/698_2017_79

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