The Handbook of Environmental Chemistry 71

Series Editors: Damià Barceló · Andrey G. Kostianoy

Abdelazim M. Negm
Mohamed Ali Bek
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Egyptian Coastal Lakes and Wetlands: Part I

Characteristics and Hydrodynamics

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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; geoecology; 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, Burullus or Borollus, and Manzala and Bardawil) could be a source of wealth for Egypt if the Egyptian and the concerning authorities intend, plan, and implement the necessary measures to keep the lakes sustainable. Therefore, this book *The Egyptian Coastal Lakes* in two volumes is produced by the Egyptian researchers and scientists to help and support those who are interested in these lakes. This volume consists of 6 parts divided into 13 chapters written by 10 authors and focuses on the characteristics and hydrodynamics of these lakes.

The introduction of this volume I is presented in Part I which contains the chapter "An Overview of the Egyptian Northern Coastal Lakes". This chapter presents basic information on the five northern coastal lakes, their origin, description, and the current development activities that were derived from problems from which the lakes are suffering.

Part II of this volume consists of two chapters presenting the opportunities, challenges, and adaptive management of the lakes. The chapter titled "Land Use in Egypt's Coastal Lakes: Opportunities and Challenges" shows that the lakes are promising zones in Egypt and could be of great importance to the Egyptian economy. It presents in some detail the challenges facing these lakes including shrinking, pollution, and climate change and how to face these challenges. In the chapter titled "Adaptive Management Zones of Egyptian Coastal Lakes", the authors present the classification and evaluation of lakes. Also, the challenges facing the sustainable development of these lakes were identified. They presented how the adaptive management approach would facilitate the investigation and classification of the Egypt's lakes and depressions.

Part III of this volume consists of three chapters dealing with the physical and chemical properties of the five lakes with a focus on Burullus wetland and Manzala. The first chapter "Sediment Contaminants in Northern Egyptian Coastal Lakes" presents the contaminations of coastal lakes due to contaminated water feeding the lakes. On the other hand, the variation of the physical and chemical parameters of the five lakes is presented and discussed in the chapter "Physical and Chemical

Properties of Egypt's Coastal Wetlands; Burullus Wetland as a Case Study". In the chapter "Lake Manzala Characteristics and Main Challenges", the authors present an extensive background of the Lake Manzala including physical, chemical, and biological characteristics to date and, in addition, the main challenges facing the lake.

Part IV contains two chapters dealing with phytoplankton and macrobenthos in coastal lakes. The chapter titled "Phytoplankton Ecology Along the Egyptian Northern Lakes: Status, Pressures and Impacts" provides how phytoplankton characteristics differ from one lake to another considering the water quality and the seasonal and spatial differences in the quantitative and qualitative composition of the phytoplankton communities at eachlake. The relevance of phytoplankton data and information to the assessment process of lakes status is addressed. The chapter titled "Macrobenthos Diversity of Egypt's Coastal Wetlands" presents how the macrobenthos are affected by the lakes environment and by seasonal variation. Two macrobenthos indicators are discussed, namely, eutrophication-indicator species and salinity-indicator species. Also, they present the biodiversity of the macrobenthos in the lakes with an emphasis on Lake Bardawil macrobenthos.

Part V consists of four chapters dealing with the hydrodynamics modelling of the coastal lakes of Egypt. The chapter "Lakes and Their Hydrodynamics" presents the seven main different formation processes of lakes in its first part, as tectonic activity, volcanic activity, glacial activity, fluvial action, aeolic action, and anthropogenic and marine action. In the second part of the chapter, the authors focus on the hydrodynamics within lakes, and they provide information on main hydrodynamic processes in lakes such as inflows and outflows, wind shear, vertical circulation, thermal stratification, and gyres and seiches. In the chapter titled "Basics of Lake Modelling with Applications", the authors present a review of the hydrodynamics modelling studies of coastal lakes, with an emphasis on Egyptian coastal lakes with applications in water quality management and sediment transport scenarios. A summary of the available hydrodynamic models categorized and an evaluation for their suitability for hydrodynamic modelling the Egyptian coastal lakes are provided. The chapter titled "Numerical Simulation of Lake Mariout, Egypt" and the chapter titled "A Three-Dimensional Circulation Model of Lake Bardawil, Egypt" present the latest findings of the modelling studies for Lake Mariout and Lake Bardawil, respectively. The results of these studies are published in this volume for the first time.

Part VI summarizes the key points and the conclusions of the volume and presents a set of recommendations for future studies and to help the decision- and policymakers 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 those 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 postgraduate students, researchers, scientist, and decision/policymakers in Egypt and everywhere who are interested in the coastal lakes. Particular and special appreciation and thanks are due 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. Acknowledgements must be extended to include all members of the Springer team who had worked hard for a long time to produce this 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 welcome and should be sent directly to the volume editors.

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

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An Overview of the Egyptian Northern Coastal Lakes

Sameh B. El Kafrawy, M. A. Bek, and Abdelazim M. Negm

Abstract Egyptian coastal lakes are valuable sources of wealth and sensitive environments. Egypt has two forms of coastal lakes, deltaic lakes such as Mariout, Edku, Burullus, and Manzala and non-deltaic lakes such as Lake Bardawil. Ramsar Convention recognized Burullus and Bardawil lakes as important wetlands, which are located in the Egyptian Mediterranean coastal area. These lakes with some attention could financially support the Egyptian government as being an economical source of huge fishing industry. Also, it could be a valuable source of jobs and food. Currently, it provides 40% of the harvested fish, and it is expected to be increased after completing the ambition new Egyptian development project. In 2017, the first phase of the largest fish farm in the Middle East is materializing on the international coastal road in the Berket Ghalioun area in the Metoubas locality, in Kafr al-Sheikh governorate (State). This project is to be built on an area spanning 2,750 feddan, costing LE 1.7 billion. Also, these valuable resources got the attention of the Egyptian government. The Egyptian Ministry of Environmental Affairs (MEnA) updated the National Biodiversity Strategy and Action Plan (NBSAP) for the years 2015–2030. The main goal of the new strategy is reducing the rate of wetlands loss by 50%. The Egyptian coastal lakes suffer major problems, such as degradation; habitat loss; pollution as they receive great amounts of industrial, municipal, and agricultural

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wastewater without treatment; and the spread of aquatic plants. Moreover, the illegal fishing practices and illegal harvesting of fish, the blockage of Boughazes, and the low awareness of fishermen are other types of challenges to be solved. Although two lakes, Burullus and Bardawil lakes, have got the attention of the government, Edku and Mariout lakes still in urgent need for an action plan toward sustainable development. An initial step toward better lake management is presented in the following chapters as it will address the lakes' current situation and discuss how to sustain it.

Keywords Northern Egyptian Coastal lakes, Bardawil, Manzala, Burullus, Edku, Mariout

Contents

1 Introduction

The northern coastal zone of Egypt (see Fig. 1), including lakes environment, is of great socioeconomic and environmental significance. In Egypt, the lakes areas along the Mediterranean coast comprise five lakes. Four lakes are deltaic water bodies (Mariout, Edku, Burullus, and Manzala) and the other is non-deltaic, Lake Bardawil. The deltaic lakes are brackish, shallow (<2 m), with an average depth of ~1.0 m. Among these water bodies, Mariout Lake is artificially enclosed and has been without a major connection to the sea. The other three display typical lake characteristics separated from the Mediterranean by low-lying, long narrow coastal sand barriers and connected to the sea by protected inlets. These inlets are vital for a dozen of species of fish that depend on the lakes for at least a part of their life cycles, and they are the only inlet/outlet available for thousands of commercial fishing boats that use the lake. Delta lakes receive much of their freshwater input from irrigation drains that entering the lakes from the southern, eastern, and western margins. The non-deltaic lake is situated away from the delta region at north Sinai, Lake Bardawil. The ecosystem of these lakes has been controlled by the interaction of natural and man-induced factors.

The southern and eastern margin of the delta lakes is bordered by extensive marshes of aquatic macrophytic plants. Surficial sediments of the delta lake are composed of plant- and shell-rich muds and sandy silts, whereas Lake Bardawil is covered by sand-size sediments mixed with evaporates [1]. The coarsest sediments are found near the inlet where current velocities are maximum, and the finest sediments are in the

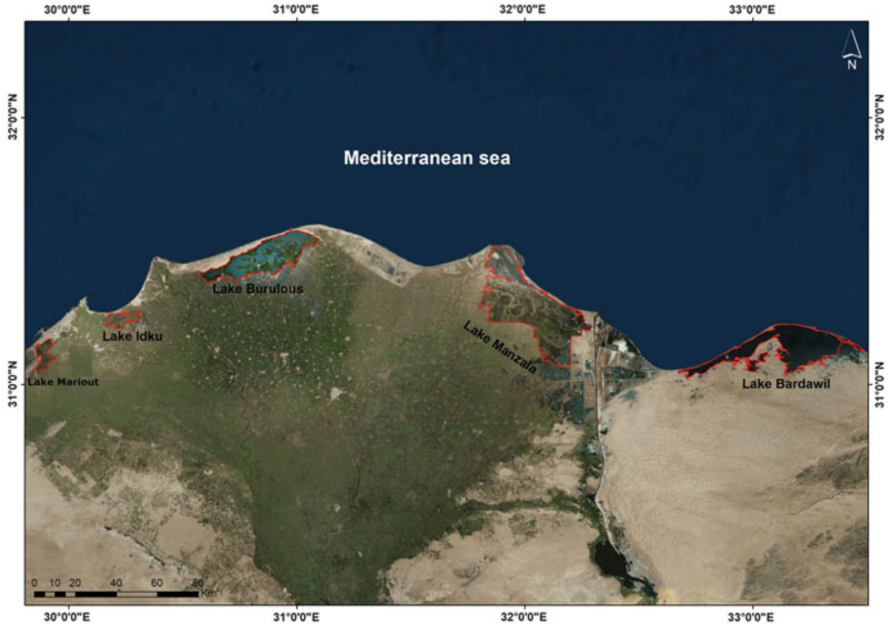

Fig. 1 Locations of the Egyptian northern coastal lakes

innermost reaches where current velocities approach zero and where drains are localized. Biological processes contribute significantly to the production of carbonate sediment through the formation of mollusk shells, ostracod, and foraminiferal tests [2].

The primary objective of this chapter is to introduce the northern coastal lakes of Egypt. Also, an attempt is made to highlight the environment of these lakes to be used as a lesson learned for any other lake management processes. Most of the existing environmental problems of the Egyptian northern lakes are derived from anthropogenic and natural influences. In contrast, the other is hypersaline water bodies (Bardawil). On the other hand, ongoing natural factors have induced substantial changes in the lake environment. These changes include barrier erosion, inlet siltation, land subsidence and rising sea level, subsidence, and prevailing sedimentary processes. Monitoring of these problems of these lakes is discussed herein in view of identifying problems, causes, impacts, and proposed actions for protecting and managing the northern Egyptian lakes.

2 Origin and Description of the Northern Egyptian Lakes

The Nile and other Mediterranean deltas contain a widespread and consistent late Pleistocene to Holocene stratigraphic succession. In respect to the Nile Delta [3], it is divided into three main sequences. This section consists of late Pleistocene to Holocene stratigraphic succession of a basal sequence I of late Pleistocene fluvial deposits, an overlying sequence II of late Pleistocene to early Holocene shallow marine transgressive sandy deposits, and an upper sequence III of Holocene deltaic of variable lithologies. Of the importance of this study is sequence III which acquires the lake facies. This sequence was mostly formed by a change in sea level rather than by regional climate factors. The rate of sea-level rise decelerated markedly from about 7,000 to 5,000 BC to ~1 mm/year. This is due to the fact that the sea level slowly was elevated and gradient decreased to 1:5,800. During this period, the rate of sediment accumulation matched or exceeded sea-level rise, shoreline position became relatively stable, and formation of the modern Nile Delta began (sequence III), locally included lake facies. With a slow rise of sea level, a series of smaller individualized lakes and marshes were developed in the northern delta, landward of coastal barrier beaches, or dune ridges [4]. The other is hypersaline Lake Bardawil, which probably has been developed in a process similar to the delta lakes combined with neotectonic land subsidence. The following is a brief description of these lakes [5].

2.1 Lake Mariout

Lake Mariout (see Fig. 2) has strategic importance at the regional and local level. It plays an important role in the water balance in the Delta western region. "Without Lake Mariout and without direct drainage to the sea, the level of water would continue to rise, which would eventually flood wide areas of land. Also, due to the scarcity of land for new development in Alexandria, Lake Mariout, and the surrounding area are now viewed as prime land for urban expansion as well as a significant economic resource for the city" (http://www.araburban.com/files/file/CDS/Alexandria%20CDS.pdf). Accordingly, Lake Mariout represents a vital economic resource to the governorate of Alexandria (see Fig. 2) [6, 7].

Fishing is one of the major activities in Lake Mariout and was characterized in the past by large fish harvest rates with reputed quality. According to available estimated statistics, there are over 2,000 fishing boats owned and employed by about 5,000 fishermen representing an estimated community of about 25,000 individual. This community relies solely on fishing as the only profession they know and practices it for many years. Their adaptability and willingness to explore and engage in new earning venues are very remote. The current total estimated fish catch is about 4,000 tons annually and is declining steadily due to the deterioration of water quality and the drying of vast areas for land acquisition [8].

Around the lake, there is a wide area of reclaimed land which includes various residential, industrial, commercial, recreational, and other settlement activities such as the Mubarak Sports City with a projected total area of 500 acres of which 130 have been already utilized, International Garden, and mega market Carrefour. A variety of industrial activities also exist around Lake Mariout comprising a host of activities and including oil refining. The discharges of the combined activities, human and industrial, are the main culprits for Lake Mariout's current and future vitality [9]. The assessment of the current concerns and challenges facing the sustainable development of Lake Mariout emphasized the following areas:

- Deterioration of water quality
- Continuous shrinkage of lake's area resulting from drying

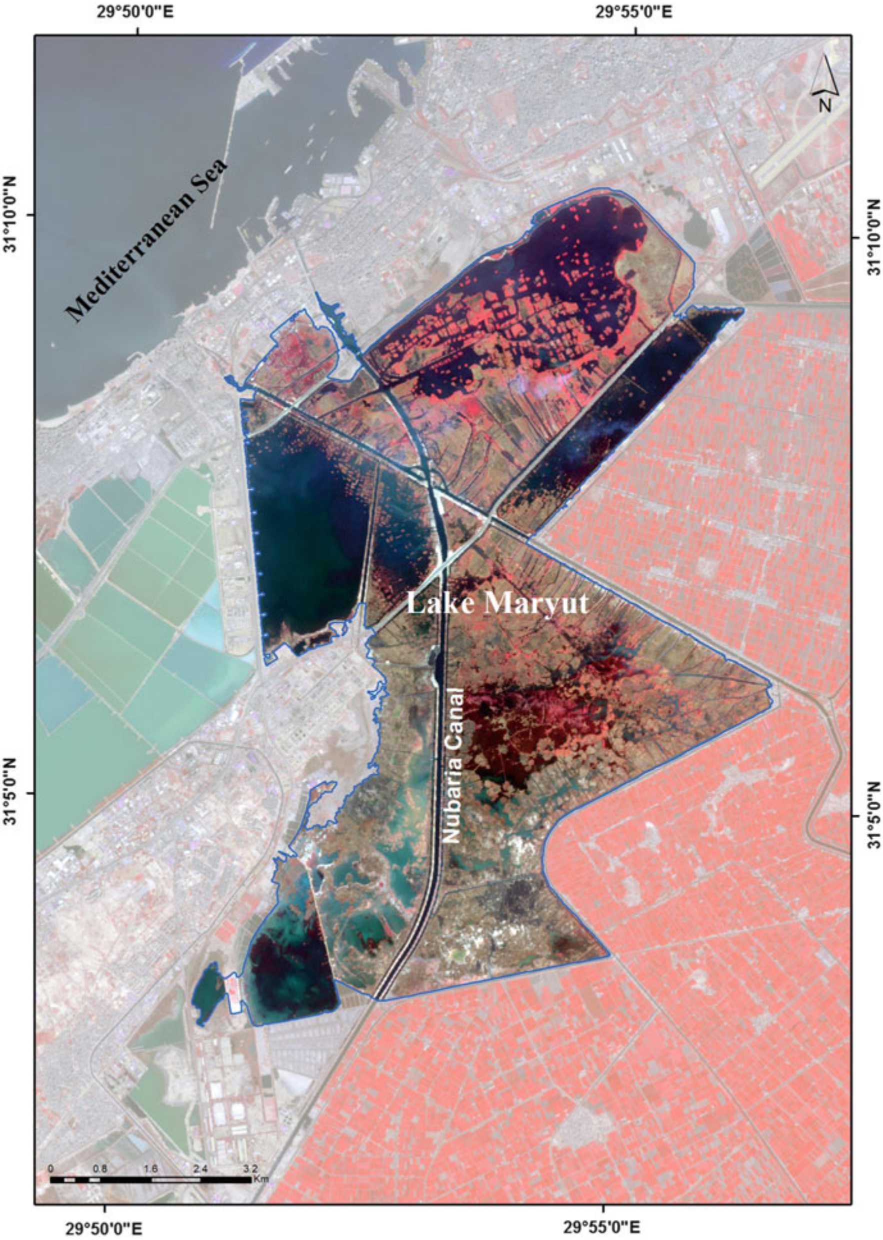

Fig. 2 Lake Mariout outline after [7]

Declining fish production and biodiversity leading to deterioration of livelihood of fishermen society

- Spread of water reeds and vegetation and emission of foul odors
- Negative impacts on public health and the high cost of medical care

- The spread of uncontrolled (squatter) settlements
- Occurrence of illegal, informal, and socially threatening groups and racketeers

Despite the many challenges facing the sustainable development of Lake Mariout, however, the issues of Lake Mariout were never absent of the minds of officials, active civil society, the general public, and international development organizations. They all share the common interest in the proper development of this vital natural resource and its surroundings important to Alexandria's future development and as part of the larger Mediterranean basin environmental sustainability.

2.2 Lake Edku

Lake Edku (see Fig. 3) is a coastal lake in the eastern Mediterranean and is located about 40 km east of Alexandria city and 18 km west of Rosetta branch of the River Nile. It is located west of the River Nile Delta between longitudes 30°8′30″ and 30°23′ E and latitudes 31°10′ and 31°018′ N. The lake is connected to the adjacent Abu Qir Bay through Boughaz El-Maadia. The actual surface area of the lake has been decreased since 1964 due to the reclamation of a large area from the eastern side for cultivation purposes. Water depths in the lake vary from 10 to 140 cm, the maximum depths being in the central and eastern parts (see Fig. 3). The lake receives large quantities of drainage water released from the agricultural lands of the Beheirah

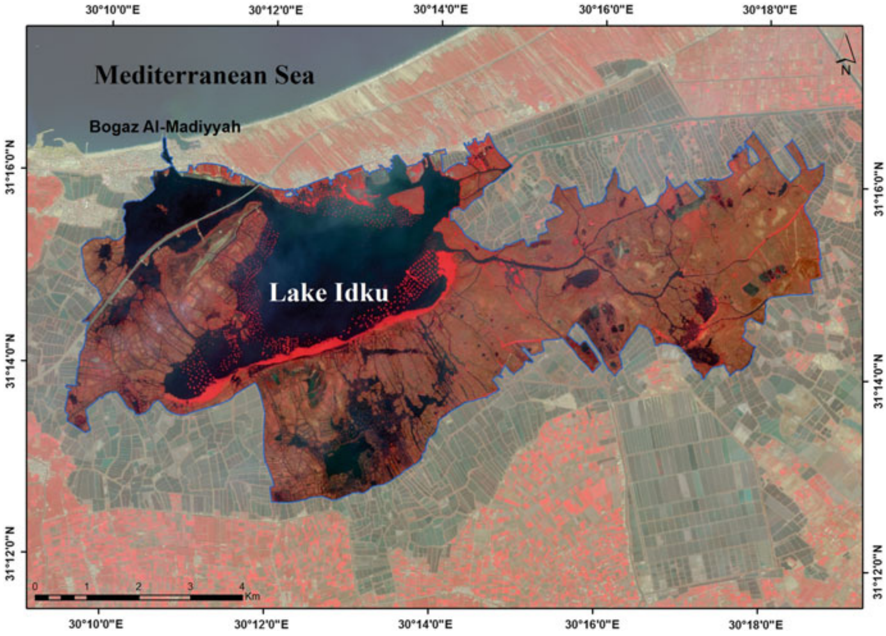

Fig. 3 Lake Edku outlines

province, through the Barsik, Edku, and El-Bosely drains, where the last two drains meet together before entering the lake and discharge their water through the extension of Edku drain. During the period of high discharge, there is an outflow of fresh water from the lake, and during the other period, seawater influx occurs. The marine water influence is limited to the areas near the Boghaz El-Maadia.

There are two main drains discharge their wastes into the lake, namely, El-Khairy and Barsik drains. The first drain is joined to three sources of drainage water coming from El-Bosely, Edku, and Damanhur subdrains, which transport domestic, agriculture, and industrial wastewaters as well as the drainage water of more than 300 fish farms. The second drain transports mainly agricultural drainage water to the lake. This drainage water moves through the lake from both west and south to the north toward the sea.

2.3 Lake Burullus

Lake Burullus (see Fig. 4) is the second largest coastal lakes in the northern lakes of Egypt and covers an area of about 410 km^2. Its long axis lies parallel to the coastline and separated from the Mediterranean by a sand barrier. The only connection of the lake with the Mediterranean Sea is the Burullus inlet. The lake margin is irregular and bordered by marshes. It is about 54 km long and has a maximum width of 12 km. Water depth ranges from 0.1 to 2.4 m and chlorinity from 0.32 to 2.4 g/L

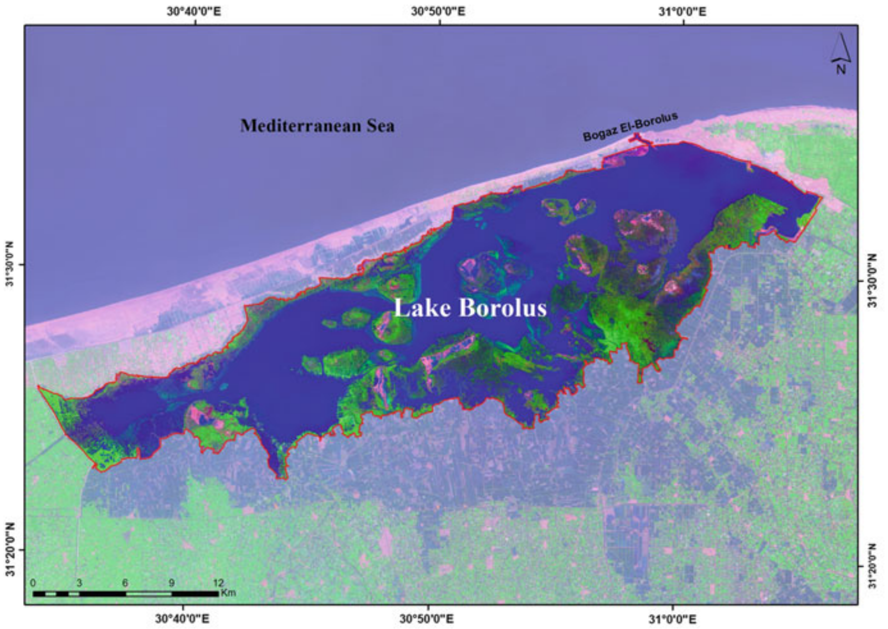

Fig. 4 Lake Burullus outlines

[10, 11]. The lake receives fresh water from numerous drains along the southern and eastern margins (see Fig. 4). Lake Burullus receive only agricultural runoff water not contaminated by industrial wastes. The southern margin is bordered by marshes. Lake water is brackish and its salinity is up to 3.51 [12]. The lake is divided into several subbasins by natural and artificial barriers. The annual freshwater influx into the lake through drains is about 2,100 × 10^6 m^3 [13]. The input runoff contains mainly agricultural waste and completely free from industrial wastes.

The drainage water enters the lake at the southern coast through several drains, causing dilution of water and rise in the Lake level above sea level. The Lake current toward the sea at certain seasons of the year is weak leading to accumulation of deposits at the lake-sea connection area. To sustain fish life in the Lake, these deposits have to be removed periodically.

Lake Burullus receives 2.46 × 10^9 m^3/day of brackish water through drains. It also receives about 100 × 10^6 cm/year of precipitation. Compared with the present total size of the lake, the residence time of water should be 2.5 months. This contrasts with the measured amount of water leaving the Lake annually, i.e., 446 × 10^6 m^3/year through Boughaz El-Burg. This leaves about 2,000 × 10^6 m^3 in excess that has to find another pathway to leave the Lake. Part of this amount is lost through evaporation estimated to be about 0.71 × 10^9 m^3/year [14] and possibly the rest through the bottom and consumption by aquatic plants.

Numerous islands characterize Lake Burullus. Most of these islands are elongated from south to north. Others are oriented either parallel or normal to the present coast. These islands consist mostly of mud. However, others are formed of sand (e.g., El-Kom El-Akhdar). These islands are important paleogeographic indicators of relict deltaic features such as beach ridges, dunes, and riverbanks [10].

The bottom sediments in Lake Burullus have a specific textural composition. Shells and shell fragments constitute a significant part of the sediments. Mostly shells, shell fragments, quartz, feldspar, Ostracoda, and Foraminifera dominated sand. The fine fraction of the sediments is composed of silt and clay together with fine carbonate particles. Calcium carbonate content of the sediments is less than 30%. In the central and western region of the Lake, the carbonate contents reach higher values (up to 75%) due to the dominance of Mollusca. The sediments in the eastern part of the Lake have the lowest carbonate content. The organic matter content of the sediments of Lake Burullus varies between 1 and 2% with an average of 1.8%. The organic matter content becomes higher near the southern, eastern, and western parts of the Lake.

Several water plants like reeds (*Phragmites*, *Typha*, etc.) spread all over the Lake affecting the movement of water. These plants play an important role to keep the internal coasts of the Lake from immolation. The decrease of the area of *Elodea* in Lake Burullus indicates the increase of the salinity in the Lake.

2.4 Lake Manzala

Lake Manzala (see Fig. 5) is the largest of the northern coastal lakes. It is an important and valuable natural resource area for the fish catch, wildlife, the

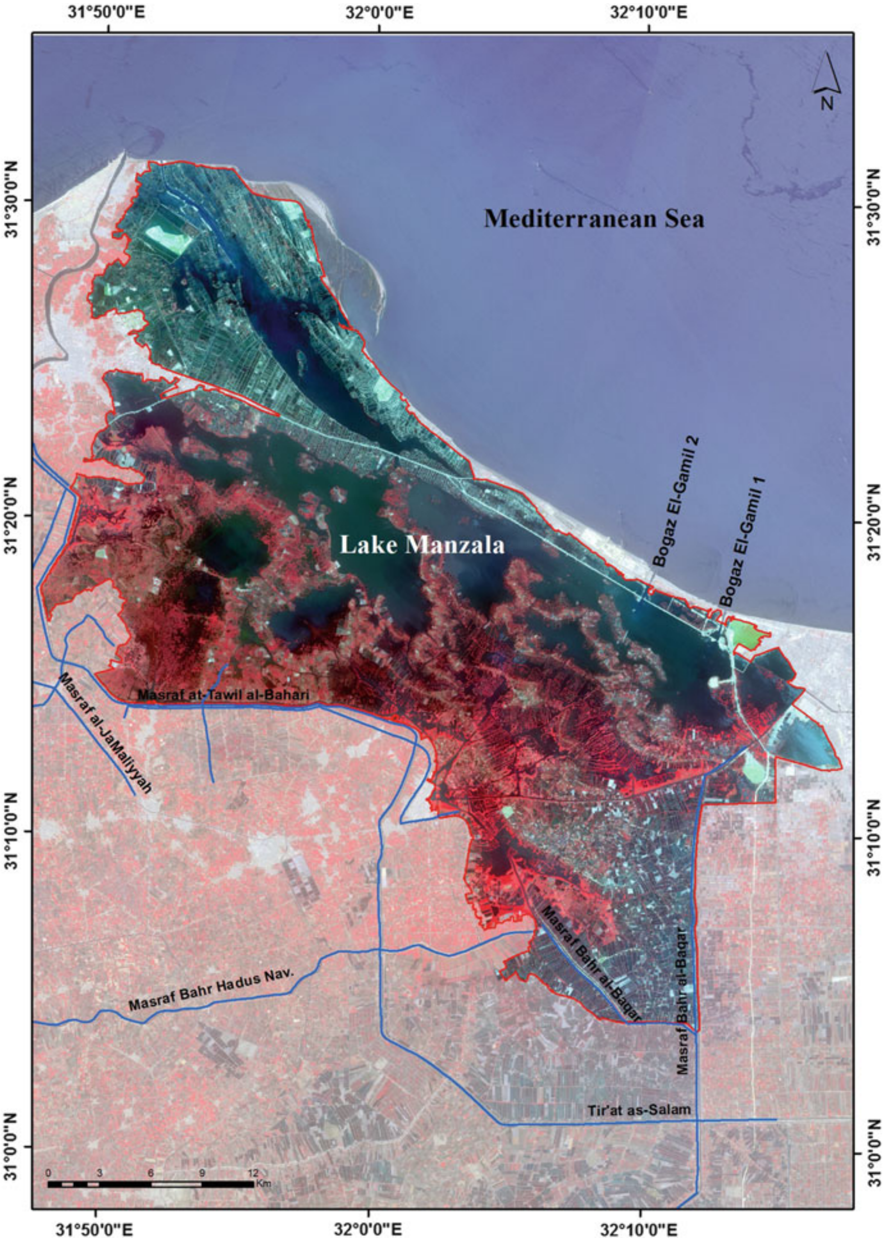

Fig. 5 Lake Manzala sea connection and fresh water in flow

hydrologic and biologic regime, and table salt production. It produces about 50% of the fish catch of the northern lakes and freshwater fisheries [15].

Lake Manzala is not only the biggest one among the Egyptian lakes (area = 300,000 feddan) but also serves five provinces of Nile Delta, namely, Port

Said, Ismailia, Sharkiya, Dakahlia, and Damietta. It has been recognized as the most productive fishery ground of the country's lakes since it contributed nearly 50% of the total country yield during the early 1970s and about 35% during the 1980s [16] (see Fig. 5).

The lake is the largest brackish water body (~1,000 km^2) and is located in the northeastern shoreline of the Nile Delta. The lake is about 50 km long and has a maximum width of 30 km. The lake is shallow (<2 m, with an average depth of ~1.0 m), and chlorosity varies from 0.77 to 11.67 g/L [12]. The western and southern sectors are supplied by drainage water from seven main sources. As in Edku and Burullus lakes, emergent and submerging marshes border the southern margin. The sand barrier which separates the lake from the sea suffers from erosion. As a result of this erosion, the coastal road between Damietta and Port Said had been replaced by a new road farther inland connecting the lake islands. Manzala lake is supplying about 50% of the total Egyptian fish catch. El Gamil inlet is the only inlet for the release of marine water inflow into the lake. Two jetties were constructed to protect this inlet from siltation and longshore migration [17] (see Fig. 5).

It is divided into subbasins by natural and artificial barriers. These subbasins are the sites of aquaculture development. The Ginka subbasin in the southeast sector of the lake is identified as "black spot." This subbasin is heavily polluted by heavy metals and high nutrient discharging from Bahr El-Baqar drain (Global Environmental Facility 1992). This subbasin receives a discharge of municipal sewage, industrial effluent, and agricultural runoff. High concentrations of metal pollutants are recorded in the upper 20 cm of the Ginka subbasin, probably from industrial sources. High values for Hg (822 ppb), Pb (110 ppm), Zn (635 ppm), and Cu (325 ppm) were recorded in bottom sediments of Ginka subbasin [18, 19].

2.5 Lake Bardawil

Lake Bardawil (see Fig. 6) is situated along the northern coast of Sinai, from a point about 45 km east of Port Said and extending to a point 20 km west of El-Arish. Its geographical boundaries extend from 32°40″ to 33°30″ E longitude and from 31°03″ to 31°14″ N latitude. Lake Bardawil is mainly a flat low-lying plain. It is bordered from the north by Sinai Mediterranean coast, from the south by a sand dune belt which extends inland to the region of the fold and anticlinal hills, from the west by the Tineh Sabkha flat constituting an eastern margin of the Nile Delta plain, and from the east by Arish-Rafah sector. Its elliptical shape represents a major morphological feature in north Sinai coast (Fig. 6). This lake has an area of about 164,000 feddan (c. 685 km^2) and extends for a distance of about 80 km, with a maximum width of about 20 km and a maximum depth of about 3 m. It is separated from the Mediterranean by a long convex sand bar. The main water body of the lake lies toward the east occupying a section along the coast of about 30 km long ending with Zaranik pond in the east (has an area of about 58,000 feddan, of which Zaranik pond occupies about 10,000 feddan). The latter is now exploited for salt production

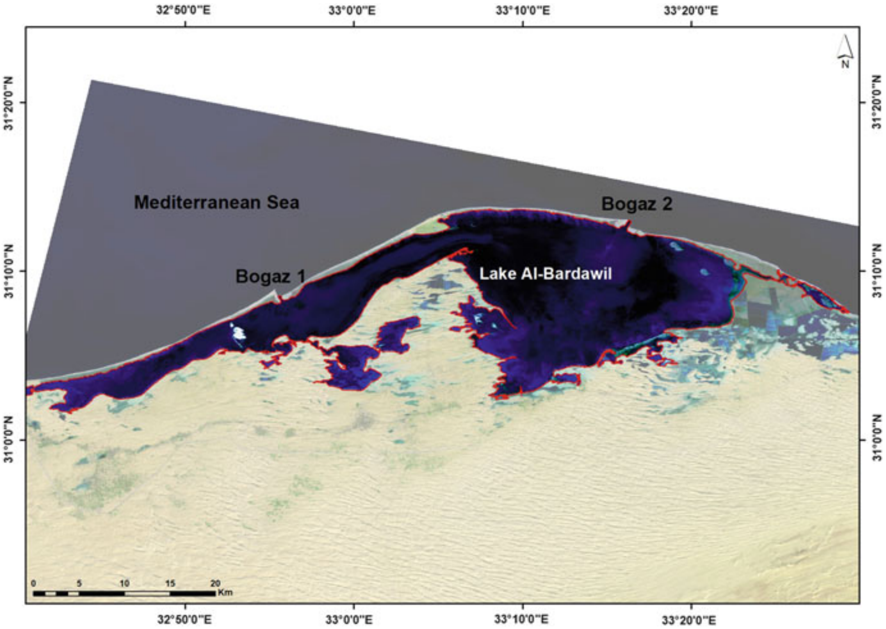

Fig. 6 Land use/cover map of Lake Bardawil

(locally, it is called Malahat Sebikah). The western part of the lake extends as a long narrow arm of about 50 km length (it has an area of about 106,000 feddan).

Historically, Bardawil (also called Sabkhat El-Bardawil or the Sirbonian Lake) is named after King Baldwin I, who took part in the Crusades and according to tradition was killed at El-Arish [20]. During the Roman period, the lake was called Port Sirbon. Many historians and archeologists speculate that the Exodus of the tribes of Israel from Egypt passed through this area and the biblical “Red Sea” or “Sea of Reeds” is the Lake Bardawil. Some recent excavations on the wide part of the sandy bar (Kals or Mount Cassius) have been reported and found evidence of settlements from the period of the Early Iron Age and a town, evidently Cassius, from the Hellenistic-Roman period [21].

Seawater enters the lake at present through three inlets: two artificial tidal inlets (270 and 300 m wide and 4–7 m deep), which are maintained open by periodic dredging, and a natural eastern inlet of Zaranik which is now occasionally closed by silting (Fig. 6). Fish production of Lake Bardawil depends on the water exchange between the lake and sea, which regulates lake salinity. Joined to Lake Bardawil are a number of bays (e.g., El-Telul and Misfiq) and a few restricted shallow water ponds (e.g., El-Rowaq and El-Marqab to the south) in which water depth is only a few centimeters. In the southern areas of the lake, extensive salt pans-sabkha complex occurs mostly interrupted by a series of sand dunes (ridges) running mostly parallel to the coast and extending southward. Thus sabkha of Bardawil may be coastal flat sabkha fringing the lake particularly at the extreme eastern margins or dunal sabkha south the lake [22].

The bar separating the lake from the sea is arc shaped and 300–1,000 m wide. Its highest point is El-Kals (Mount Cassius), a 60 m high dune located about midway. The western part of the bar is an extension of a dune-covered higher ground which starts at Qantara on the Suez Canal. This ridge is part of the Pelusium Line, a compressional zone dividing the thin Mediterranean crust on the east from the oceanic-type crust on the west. However, there is little evidence that the lake was the estuary of the Pelusiac branch of the Nile. Pelusiac branch debouched at a site situated to the west of the abovementioned ridge [23], but undoubtedly the Nile supplied the quantities of sand that formed of the bar separating the depression from the sea.

The existence of Lake Bardawil depends upon its connective with the Mediterranean Sea. Sea water often covers the low sand bar which separates the lake from sea. Lake El-Zaranik is joined to the sea by a narrow inlet; thus its water is constantly being replenished. In 1955, two inlets (i.e., two Boughazes) were dug to connect the lake with the Mediterranean, one at the western end and the other at the eastern end of the lake. Each canal is 1 km long and 150 m wide. Lake Bardawil is the most saline of the northern Egyptian lakes, for it is connected only with the sea. Salinity increases with distance from the inlet canals.

Lake Bardawil is characterized by approximately 51 islets, some of which are elongated, oriented subparallel or normal to the present coast and of few kilometers in diameter. They comprise a total area of about 3,170 feddan which approximates 1.9% of the lake area. These small islands include El-Mahasnah in the northeastern part of the Lake Bardawil, El-Watawite in the north-central part, El-Gouz El-Ashhab in the south, and El-Romaia in the western arm of the lake. These islands are mostly made of muddy sand, covered by vegetation. A mud surface layer with dense vegetation occurs in El-Mahasnah Island. El-Romaia Island is about 2 m above sea level and covered with a sand sheet and scattered vegetation (Fig. 6).

The productivity (kg/feddan) of Lake Bardawil ranged between 9.7 kg/feddan in 1994, 24.38 kg/feddan in 1999, and 21.4 kg/feddan in 2006. It is clear that the productivity per feddan fluctuated over the years, based on the change in gross production of fish and the water area of the lake. Fishing gained significance for the Lake Bardawil. Although it is considered to be one of the best quality fishing areas in Egypt, its production was accounting to about 3,534 tons and 0.7% of the national fish production in 2005 [8].

3 Conclusions

The results of this chapter indicated that these lakes had been increasingly subjected to intensive and diverse development activities including fishing, aquaculture industry, dumping wastes, land reclamation, lake drying, urbanization, salt pan, and recreational uses. Some of these activities have derived from several environmental problems as well; the population is expanding exponentially. These problems are pollution, eutrophication, reclamation, fragmentation, over-fishing, and illegal harvesting of fry fish and are considered as major environmental issues threatening the fragile ecosystem of these lakes. For example, steps which could facilitate improvement in the Lake Manzala ecosystem through reductions in nutrient loads include (1) treatment at source of the domestic and industrial wastewater which is at present responsible for the high BOD and nutrient loads within the Bahr El-Baqar drain, (2) treatment of wastewater from lakeside communities so that the use of the lake as a secondary and tertiary wastewater treatment unit declines and eventually ceases, (3) diversion of nutrient-rich wastewater from the Port Said wastewater treatment plant away from the lake and instead out to the sea using a deep-water delivery system, and (4) improved control and regulation of fish farms within the lake. These steps will require that Lake Manzala is managed sustainably as a large shallow lake ecosystem which supplies important goods and services. Restoration of Lake Manzala will undoubtedly bring about major ecosystem improvements that will benefit both people and biodiversity. Nevertheless, such changes will require political will, considerable financial resources, and careful environmental planning. The present-day coastal lakes that host the Mediterranean coast of Egypt are mainly different in shape, dimension, depositional environment, water quality, runoff of tributary streams, and inlet stabilization. The delta lakes (Mariout, Edku, Burullus, and Manzala) are brackishly influenced by freshwater runoff from drains and irregular canals. In contrast, the other lake is hypersaline and not connected with any freshwater flow (Bardawil). Like other Mediterranean lakes, they were generally originated as a result of changes in sea level combined with neotectonic land subsidence. These lakes are socially and economically important for the coastal population. The quality of these lakes is influenced to a large degree by various types of human activities and human habitats. Human activities differ throughout these lakes including fishing, wastewater through drains, lake reclamation, recreation, salt pans, hunting of water birds, and engineering works at inlets.

Some of these lakes are presently experiencing environmental problems which resulted from natural and human activities. Because these lakes are very valuable in terms of natural resources and related economic activities, these problems have caused serious implication on the lake ecosystem, resources, fauna, flora, and human beings as well. Moreover, the lack of effective and consolidated earlier management of these lakes has accelerated such implications. This chapter and the following chapters present an attempt to integrate the existing scientific knowledge to obtain an ecological understanding of the Egyptian coastal lakes. They may lead to practical solutions for the environmental problems of the Egyptian coastal lakes.

4 Recommendations

- An integrated management program be implemented for the development of the lakes and adjacent area.
- Periodic monitoring and assessment are necessary.

- A decentralized remote sensing and geographic information system (GIS) capability must be developed to collect and upgrade available data and to help decision-makers on local and national scales.
- A sensitivity analysis must be carried out for all coastal lakes in Egypt to assess vulnerabilities to various problems including pollution, lake reclamation, erosion of lake barrier, illegal harvesting of fry fish, etc.
- A contingency plan for protection and emergency measures must be developed.

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Land Use in Egypt's Coastal Lakes: Opportunities and Challenges

Fathy Elbehiry, M. A. Mahmoud, and Abdelazim M. Negm

Abstract Coastal lakes in Egypt are very important for the wetlands they support in North Africa. They contain five of the most productive wetland ecosystems in the world. The Nile Delta lakes, which are located along the Mediterranean coast, are very important economically because of fish production, which makes up nearly 50% of Egypt's production. These lakes are vital to the livelihoods in these areas. However, these lakes are suffering from degradation and environmental stress. The total area of many of these lakes is decreased because of drying and reclamation for agriculture. Furthermore, increased pollution and ecological risks are affecting these vital and valuable lakes. One of the biggest issues is the discharging of agricultural drainage, industrial waste, and domestic waste water into these wetlands. In addition, these lakes are vulnerable to the negative impacts of climate change such as rising sea level and saltwater intrusion. The coastal lakes in Egypt are very important and vital to ecosystems and need continuous monitoring and good management practices.

Coastal lakes can have a significant impact on the surrounding agricultural areas through waterlogging, secondary salinization, and groundwater pollution. In this chapter, the authors will provide an overview of the coastal lakes in Egypt, the main challenges, and how to manage these challenges for the sustainability of these lakes.

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Contents

1 Introduction

Egypt has 11 lakes, all of which have significant economic importance for fish and salt production. Globally, five of them are considered among the most productive ecosystems. These lakes are shallow brackish or marine bodies. They are isolated from the Mediterranean Sea by a boundary island, reef, or sandbank and are associated at any rate discontinuously by one or more restricted tidal inlets. The coastal lakes of the Nile River in Egypt represent about 25% of the total lakes of the Mediterranean Sea. Moreover, they are the largest lakes in Northern Africa [1]. The northern lakes of the Nile Delta are in common shallow, wind-mixed basins, with salinity level from fresh to brackish, and are important wetland supplies for the maintenance of biodiversity in Egypt. These lakes are also considered as optimal fishery grounds, providing approximately 50% of the annual Egyptian fish production. At the same time, these lakes act as collector basins for agricultural drainage and municipal and industrial wastewater. Consequently, these Egyptian lakes are subject to severe ecological degradation with respect to societal development [2].

There is a common feature among lakes Edku, Burullus, and Manzala in that they are freely connected in the northern regions with the southeastern Mediterranean waters which gives a chance for exchanging water and renewing the lakes' ecosystems. On the contrary, water is pumped from Mariout lake to the Mediterranean Sea due to their site in a depression on the Mediterranean shore plain and separated from the sea by an oolitic limestone ridge. Although its formation is from a previous rudimentary Nile branch, there is no connection with the Nile river [3]. Manzala, Burullus, and Edku lakes are producing more than 60% of the fish production in Egypt. Furthermore, they are characterized by high habitat diversity and hence have high biodiversity. For this reason, these lakes are considered notable refuge for aquatic plants and animals, as well as important habitats for birds, particularly those migrating to and from Europe [4].

Despite the economic importance of the coastal lakes for fish production in Egypt, they are subject to many challenges such as shrinking of the areas due to land reclamation projects, pollution due to the expansion of agricultural, industrial, and fishing activities, and the projected impacts of climate change. So these coastal lakes need integrated management plans for improved sustainability of these lakes.

2 The General Description of the Coastal Lakes

The coastal lakes are called Mariout, Edku, Burullus, Manzala, and Bardawil from west to east, respectively, as shown in Fig. 1. These lakes are natural sources of fish production, natural aquaculture plants, and commercial fishing. Also these lakes are considered good places for other activities as agriculture in dried and reclaimed areas, urbanization, and industrial activities.

2.1 Manzala Lake

Manzala lake is the largest lake on Egypt on the Mediterranean Sea. It is located on the northeastern edge of the Nile Delta, between latitudes 31°30′–31°00′ N and longitudes 31°45′–32°15′ E. Its area is about 127,500 ha, with a maximum length of

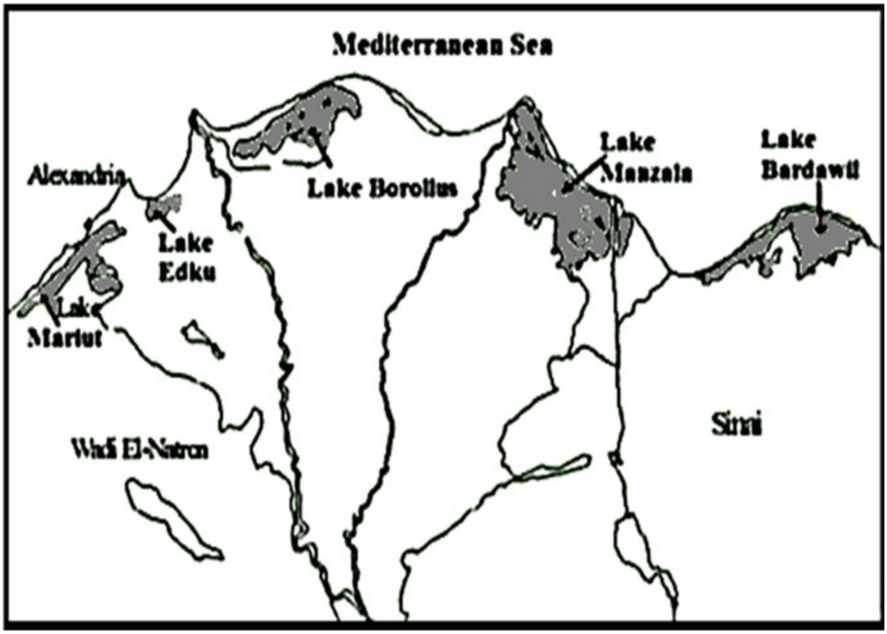

Fig. 1 North coastal lakes in Egypt [5]

nearly 64.5 km, and a maximum width of about 49 km [4]. This lake is almost rectangular with a long axis extended from the northwest to the southeast. It is connected to the Mediterranean Sea through the main opening at Al-Gameel region, close to Port Said, and it is connected to the Suez Canal throughout a small canal at Al-Gabouty close to Port Said. Nile freshwater enriches the lake through three canals originating from the Damietta branch; they are called Al-Enania, Al-Rotma, and Al-Sufara canals [6]. Water in this lake is generally brackish with salinity ranging from a low of 2 gl^{-1} in the western and southern regions to 16–23 gl^{-1} in the southeast and near the outlets at the north.

Manzala lake is very shallow with a maximum depth of about 2.5 m; its area is shrinking recently due to land reclamation projects which converted some parts of the lake to agricultural areas [4]. The lake is enriched by drainage water from five main drains (i.e., Al-Serw, Al-Gamaliah, Bahr Hadus, Ramsis, and Bahr-Bagar) connected to the lake at the south and southeastern borders. There are more than 1,000 islets dividing the lake into approximately 30 basins with a total area of 1,318 ha. Most of these islets are inhabited by fishermen and farmers [6].

2.2 Burullus Lake

Burullus lake is located in a central position along the Mediterranean Nile Delta coast of Egypt. The lake has an elongated elliptical shape. It is located in the northern part of the Nile Delta between the two Nile branches Rosetta in the west and Damietta in the east. It connects with the Mediterranean Sea at its northeastern edge through the Burullus inlet. This inlet is approximately 250 m wide and 5 m deep [7–9]. The lake extends between longitudes $30°30'$ and $31°10'$ E and latitudes $31°21'$ and $31°35'$ N. It is the second largest lake of the coastal lakes in Nile Delta with about 53 km long and 13 km wide. It occupies an area of 42,000 ha; 37,000 ha is open water, and approximately 5,000 ha comprises a group of islands distributed within the water body. Water depths range from 0.5 to 2.5 m. The eastern part of the lake is the shallowest, with an average depth of 0.8 m [8, 9]. This lake is separated from the sea by a narrow coastal strip covered by sand sheets and sand dunes ranging from 0.4 to 5.5 km in width. They are generally higher than the mean sea level by 1.5 m, with beach face slopes ranging from 1:50 to 1:130. Low relief backshore and foredunes characterize the western barrier. The eastern barrier is narrow and supported by backward coastal barchans dunes. These dunes infringe landward onto a cultivated coastal plains [9].

Commercial fishing is the main human activity on Burullus lake. This lake receives annually up to 4 billion m^3 of the agricultural drainage water in the Nile Delta, approximately 97% of the water inflow, while rainfall represents 2%, groundwater 0.8%, and domestic discharge 0.2%. This lake is alkaline, brackish, shallow, and polluted [7]. In the southern coast of the lake, there are networks of the channels where the sewage from the local villages can directly reach the lake [10]. The lake receives agricultural drainage water basically from eight drains (i.e., Burullus, Baltim, El Gharbia, Nasser, and drains 7, 8, 9, and 11) and only one canal (i.e., Brimbal). Due to the high inflow of freshwater to the lake through the drains, the salinity of water in the lake becomes very low ranging from 1.235 to 2.535 gl^{-1}. However, industrial, agricultural, and domestic waste discharges have increased the levels of heavy metals in the lake [8].

Because of the arid climate which is characterized as warm summer 20–30°C and mild winters 10–20°C, it is an important area for wintering and breeding birds and as habitat for fish. It has been recognized as a significant site by the Ramsar Convention. The agricultural land borders the lake in the south, and a sandbar separates it from the Mediterranean Sea to the north [7, 11].

2.3 Edku Lake

This lake is smaller than Burullus lake and covers an area of about 12,400 ha. It is situated between latitude 31°12′–31°17′ N and longitude 30°07′– 30°23′ E, it is connected with the Mediterranean Sea at its northeastern edge through the Boughaz El-Madaya inlet. This lake is very shallow, with a maximum depth of about 2 m. Its water is brackish with salinity ranging from 2.5 to 15 gl^{-1} near the northern inlet. It is bounded by valuable agriculture to the south, continuing land reclamation activities to the east, and housing and factories to the west side where much reclamation has occurred since the nineteenth century [4].

2.4 Mariout Lake

Mariout lake is located alongside the Mediterranean Sea coast of Egypt south of Alexandria. It is a saline lake of about 25,000 ha in northern Egypt. This lake is localized between latitude 31°01′ 48″ to 31°10′ 30″ N and longitude 29°57′ 00″ E. It represents the southern boundary of Alexandria city. Its depth is about 1–3 m. This lake represents a small portion of a large ancient basin (Mariout lake) that is divided artificially into four basins: the main (2,400 ha), southwest (2,000 ha), northwest (1,200 ha), and aquaculture or fisheries (400 ha) [12, 13].

Mariout lake is fed by several canals from the Rosetta branch of the Nile. Many branches of these canals allow water flow from and to these basins. The main canals are Al-Kalaa drain, Omum drain, and Nubaria canal. These resources are the main water inflow source to the lake, in addition to those from wastewater treatment plant and the discharge from the west Nubaria drain and from a petrochemical area. El-Max pumping station is the only source of outflow from the lake [13].

2.5 Bardawil Lake

Bardawil lake is located on the southeastern Mediterranean coast at 31°09′ N, 33°08′ E. It is an oasis for migrating birds as well as the Zaranik protected area. This lake is an important economic source from fishing and salt production and a high diversity of habitat. The lake is almost clear, and it is the least polluted in the whole Mediterranean region. It represents a transitional zone between land and sea, and it is separated from the Mediterranean Sea along most of its length by a long and narrow sandbar. It is connected to the sea via three narrow artificial inlets, in western and eastern ones are manmade, while the third one has been naturally closed. The lake extends along the coast, and for this reason, it has a micro-tidal regime. The Mediterranean Sea tides govern water exchange in the lake and have a mean tidal excursion of 0.25 m during neap tides and about 0.35 m during spring tides. Bardawil has shallow water with irregular topography in the bottom with average water depth around 1.21 m. Sand and silt are the main composition of the lake bottom. Bardawil lake is characterized by low air and water temperatures in winter and high in summer (13.7–27.0°C and 13.9–24.6°C, respectively). There are many investments close to the lake, such as tourism developments. There is an intensive agriculture reclamation project in the North Sinai close to this lake. The inflow of freshwater from the new reclamation lands will change the lake from a saline to a brackish lake, leading to the deterioration of water quality. Furthermore, Bardawil lake development, including urbanization and lake engineering such as artificial inlets, promotes some adverse changes in its system [14].

According to [15], a summary of the basic characteristics of the Egypt's northern lakes is shown in Table 1.

Table 1 The basic characteristics of the northern coastal lakes in Egypt [15]

Lakes	Location		Total area (ha)	Depth (m)	Fish production (M ton)	Mean temperature (°C)
	Longitude	Latitude				
Manzala	31°45′–32°15′ E	31°30′–31°00′ N	42,017	0.3– 2.5	60	16.74
Burullus	30°30′–31°10′ E	31°21′–31°35′ N	29,412	0.3–2.5	49	21.00
Bardawil	33°08′ E	31°09′ N	273	0.3–3.0	2.3	15.40
Edku	30°07′–30°23′ E	31°12′–31°17′ N	1,681	0.3–4.2	9.5	22.20
Mariout	29°57′ E	31°01′–31°10′ N	7,143	0.3–2.7	4.7	21.70

3 Coastal Lake Opportunities

Wetlands are of ecological importance due to their hydrologic attributes and their role as ecotones between terrestrial and aquatic ecosystems [16]. Wetlands represent a significant sink for carbon (C) and should be considered a key ecosystem when managing and weighing the earth's C pool. The total soil organic C pool, for 1 m depth, is estimated by $1{,}550 \times 10^{15}$ g, and wetlands are responsible for storing approximately one-third of this pool although they cover only 6–8% of the land and freshwater surface. Hence, wetlands represent one of the largest biological C pools and play a critical role in the global C cycle [7].

Lakes in the Nile Delta are a vital source for thousands of people in Egypt. The Egyptian northern coastal lakes are among the most productive natural systems in Egypt, and they are internationally renowned for their abundant bird life. Coastal lakes play an essential role in the Egyptian economy, where they provided about 39% of harvested fish in Egypt during the 1980–2006 period [17]. The coastal zone of the Nile Delta is a promising area because it contains essential wetland ecosystems, moreover industrials activities an energy resources [18].

4 Coastal Lake Challenges

Wetlands function as downstream receivers of water and waste from both natural and human sources and have often been transformed to dry lands for agriculture and human settlements purposes, among others. Also, river control schemes have often caused the loss of wetlands. The attributes of wetlands include high productivity sources, sinks and transformers of numerous chemical, biological and genetic materials, and valuable habitats for fisheries, wildlife, and birds [16]. Recently, due to rapid economic development, increasing population in the Delta region and associated industrialization high environmental pressures were exerted. Industrial waste and municipal effluents have been largely discharged into coastal lakes and wetlands in the Delta, causing environmental degradation with significant public health concerns [9].

The Delta lakes represent highly dynamic aquatic systems that have been suffering continuous and marked changes from the late Holocene to the present time, particularly after the Aswan High Dam construction in 1965. Before this date, there was a continuous annual recharge of freshwater due to Nile floodwater entering through many canals and drains. This continuous recharge controlled seawater intrusion into these lakes. The flood season had led to markedly increased suspended matter while decreasing ion concentration. After the construction of the Aswan Dam, these lakes received large amounts of freshwater from irrigation schemes, as well as seasonal backflow of sea water. Furthermore, urbanization and industrial development during the last decades led to increased pollution from various sources, such as industry, agriculture, and sewage. These inputs create unique areas within the lakes [4]. Therefore, conservation associations worldwide have noted and described the alarming changes in these important habitats. This led to the convention on wetlands known as Ramsar Convention in 1971. Burullus wetland along the deltaic Mediterranean coast of Egypt is one of the Ramsar sites and was declared as a natural protectorate in 1998 [16].

Currently, the coastal zone of Egypt and its lakes are suffering from many serious problems, such as high rate of population growth, land subsidence, unplanned urbanization, excessive erosion rates, seawater intrusion, soil salinization, extensive land use, pollution, degradation, and lack of appropriate institutional management systems. Such ecological changes have reduced fish yield and greatly impacted the local fishery, increased insects, and pests and have impacted human health [4, 19].

According to [20], the Delta lakes especially are suffering from several severe problems. Foremost among these are the following:

- A continuing decrease in the open water area, not only due to land reclamation but also to the increase in aquatic vegetation which is a result of the common practice of building Hoshas, basins to isolate water bodies to catch fish, and a local custom of isolating water bodies to catch fish.
- A high level of lake water pollution, due to the industrial, agricultural, and domestic discharges into the lakes through the drains.
- A deterioration of the fisheries in the lakes, due to overfishing, and the use of illegal fishing methods. It is estimated that the lost catch from the Manzala lake open fisheries under the existing fishing methods is about 67,000 ton/year (estimated as worth 255.8 million LE at market prices).
- Extreme impacts of sea level rise on these lakes: a study concerning the effects of sea level rise on the Delta lakes focused on only Manzala and Edku lakes, which represent two extreme examples of poor lake management in Egypt. Similar results are expected from sea level rise on the other delta lakes. However, it should be noted that the impact of sea level rise on different parts of the lakes may be influenced by various interrelated factors. Among these factors are land reclamation, reduction of drainage water inflows, change in fishing practices, infrastructure works and the erosion of the coasts, and various other human activities.

4.1 Shrinking and Decreasing the Total Area of the Coastal Lakes

Coastal lakes in Egypt are subject to decreasing total areas because of drying and reclamation for agriculture. For example, Burullus lake is the second largest lake in Egypt and is a UNESCO-protected Area. It is supplying a considerable percentage of the annual Egypt's fish yield. However, the lake area decreased by 30% in the last 10 years due to continuous and illegal fish-farming processes and land reclamation especially on the south and east shores [9, 21]. Therefore, the environment of

Burullus lake has been subjected to significant change during the last three decades as many drains were constructed to transport agricultural wastes to the lake. Also, a large area has dried up to agricultural land [9]. The cultivated lands, urban, and wetlands have increased rapidly in the Burullus region. The urban has doubled during the 1984–1997 period; the cultivated lands have increased due to reclamation and drying projects in the south and the eastern part of Burullus lake. Also, sand dunes have decreased due to reclamation processes [22]. The area of water bodies of Burullus lake declined by 44.97% during the period from 1984 to 2015 and is projected to decrease by 58.95% by 2030. These results are alarming for policymakers who must take the suitable necessary measures to reduce the environmental risk and conserve the lake in order to sustain the water area against future decline [23].

Manzala lake also had a remarkable decreased of surface area by 34.5% from 1973 to 2007. This change was attributed mainly to the control of the Nile flooding and the change of land use by anthropogenic activities [18]. The lake surface area decreased by about 50% between 1973 and 2003 [24]. Results showed that the lagoon lost 42.8% of its open water area due to the severe anthropogenic activities, such as the reclaiming of its southern margins for agricultural purposes and the filling caused by the discharge of agricultural waste [25].

During the twentieth century, human activities through hydrologic modifications and reclamation for agricultural purposes affected all coastal lakes in North Africa. "The loss of lake area by reclamation is substantial for the Nile Delta lakes (Edku, Burullus, and Manzala) in the latter half of the 20th century" [26].

4.2 Pollution

Due to the huge amount of agricultural drainage, municipal sewage, and industrial wastewater which enrich with many pollutant especially heavy metals and discharging to the coastal lakes, there is continued deterioration of water quality and degradation of ecosystems in these lakes. Heavy metals and related environmental conservation of the Nile coast need more attention. Many projects implemented have targeted heavy metal distribution and transportation in relation to aquacultural health [10]. For example, cadmium (Cd) and lead (Pb) expelled into the lagoons have increased by 8–70 times during the past 25 years [3]. Also pancreatic cancer risk in the Manzala region seems to be closely associated with cadmium concentration [10]. They also attributed the enrichment of Manzala lake by Pb, Zn-Hg, and Cu to cheaper power generation after the High Aswan Dam construction in 1964. This has considerably degraded aquaculture products quantity and quality in the Manzala region, where it has long been the most important aquacultural base providing more than 50% of aquaculture products for Egyptians.

Lake sediments are the final pathway of both natural and anthropogenic components produced or derived from the environment. With regard to the continuous invasion of different types of pollutants to the Nile Delta lakes during the past

10 years, there is an urgent need for recent surveys to follow up the subsequent alterations in the geochemical composition of the lakes' sediments, especially metal concentrations, in response to these changes [3].

Burullus lake is one of the most vulnerable coastal lakes due to the high density of aquatic plants, overfishing, expansion in fish farming and agricultural drainage, and increasing human activities [9]. Heavy metals of anthropogenic origin are toxic pollutants, which can transfer to humans through the food chain and can be further transformed into more toxic compounds under certain circumstances [9, 10]. In addition, heavy metals are serious pollutants in the natural environment due to their persistence and bioaccumulation problems. Cadmium, mercury, lead, copper, and zinc are concerned as serious pollutants of aquatic ecosystems because of their environmental persistence, toxicity, and ability to be incorporated into food chains [8].

Edku lake is the least affected among other delta lakes with man-made impact, while Mariout lake receives annually about $1.08 \times 109\ \mathrm{m}^3$ and $0.78 \times 109\ \mathrm{m}^3$ of raw sewage and untreated industrial discharges, respectively. Such amounts make the lake water nearly anoxic where hydrogen sulfide levels in Mariout Lake are almost $>25\ \mathrm{mLl}^{-1}$, especially during summer time. Burullus lake receives only agricultural drainage water ($3.2 \times 109\ \mathrm{m}^3\ \mathrm{year}^{-1}$) at its southern and southwestern regions. Although the huge amount of untreated sewage and the agricultural and industrial water discharging to Manzala lake, i.e., $6.7 \times 109\ \mathrm{m}^3\ \mathrm{year}^{-1}$, the lake is regarded as the most productive Nile Delta lake [3].

Burullus lake serves as reservoirs for drainage waters, from agricultural areas through seven drains in addition to the freshwater from Brimbal canal situated in the western part of the lake [21]. Therefore, this lake is suffering severe ecological degradation in relation to societal development. The water sources for the lake are mainly from the agricultural drainage canals, municipal sewage, and industrial wastewater through which sewerage either treated and/or untreated directly reaches the lake approximately 4 billion m^3 of drainage water per year [2, 9]. Thus, the environment of the lake is vulnerable to environmental changes particularly to enhanced anthropogenic pressure [1]. According to [15], chemical characteristics of water in north coastal lake is shown in Table 2.

4.3 Impact of Climate Change

There is no doubt that climatic changes due to global warming present potentially dramatic and far-reaching threats to the environment, especially wetland lakes, human welfare, and socioeconomic systems on a global scale. Egypt is located in the semiarid – Mediterranean – region and will be strongly affected by global warming and climatic changes. This area is considered dynamic transitional zone linking the North African climate system to Western Europe. This region could play a key role in understanding the present and future of continental climatic trends [4].

Table 2 Some chemical characteristics of water in the northern coastal lakes [15]

			DOC	NH4	P	Fe	Zn	Pb	Cu	Cr	Mn	Ni	Cd	Hg
Lakes	pH	TDS (g/L)	(mg/L)		(μg/L)									
Manzala	7.62	3.77	7.7	1.52	925	30.54	13.13	6.34	18.84	11.56	7.62	5.71	0.48	0.008
Burullus	8.54	4.71	8.61	0.34	62.8	188.9	136.1	45.92	39.78	31.63	22.76	8.49	1.8	0.1
Bardawil	7.88	46.2	6.59	1.32	32.5	20.20	15.88	3.72	0.65	3.74	7.57	4.14	0.54	0.01
Edku	8.57	1.52	8.61	1.07	48.5	99.75	68.90	28.87	16.32	14.03	7.79	6.49	0.81	0.09
Mariout	8.68	3.6	7.16	2.08	54.5	145.5	120.8	31.57	19.33	13.68	8.56	6.90	0.99	0.09

Climate change is expected to cause increases in sea temperature which may cause a shift in fish distribution northward and to deeper waters. Additionally, increased water salinity in the coastal lakes in Egypt is expected to affect fish species in these lakes and may gradually reduce the existence of freshwater fish. In addition, this also leads to an increase in the portion of saline water fish which is more sensitive to environmental changes and has higher price as well. This will negatively affect most of the coastal population who rely to a high extent on cheap freshwater fish. Therefore, more studies are required to understand the vulnerability of the fishing sector and possible adaptation options to climate change [19]. The northern part of the Nile Delta is subject to severe coastal erosion and threatened by the expected sea level rise due to the greenhouse effect and expected global warming. Among the expected impacts of sea level rise on the Egyptian coastal lakes are the following: saline sea water will penetrate far into the northern Delta, weed swamps will disappear, properly functioning infrastructure facilities directly exposed to the sea will be disrupted, and the natural fry supply will be affected. Among the proposed adaptation measures are protection by increasing the depth of the lake and lake closure by building dikes to store water in the lakes [20].

The coastal zones of Egypt are vulnerable to the impacts of climate change, not only because of the direct impact of sea level rise but also because of the potential impacts on their water resources, agricultural resources, and tourism and human settlements. In particular, the low-lying Nile Delta region, which constitutes the main agricultural land of Egypt and hosts over one-third of the national population and nearly half of all crops, industrial activities, and commercial centers, is highly vulnerable to various impacts of climate change [19].

According to [20], the following impacts are among the major expected impacts of sea level rise:

- Saline seawater intrusion into the northern delta may turn the current lakes into shallow saline lagoons and bays.
- Weed swamps will disappear, and large areas of salt marshes might be created.
- The proper functioning of infrastructure facilities directly exposed to the sea will be disrupted.
- The water balance in the lakes will be affected causing a possible extension of the lake boundaries southward.
- A slight to moderate sea level rise may be quite beneficial. Fish production may go up due to an increase in the lake area. However, there is an expected serious negative effect on birds.
- The expected submerged wetland will form grounds for an increase in rooted aquatic plants, will increase the wintering grounds for migrating birds, and can also be used for aquaculture activities.
- Increasing the salinity of the lake will also result in the dying off and decomposition of aquatic plants which play an important role in decreasing the heavy metal concentration of the water coming in from the drains.
- Deterioration of coastal water quality that attracts marine fry to the direction of the lakes will affect natural fry supply for the aquaculture activity in Egypt.

5 Impacts of Coastal Lakes on the Surrounding Agricultural Areas

Agricultural areas surrounding the lakes are highly affected by the condition of the lake. The continuous flooding led to increasing water table in surrounding areas. The shallow water table, heavy clay texture, and dry condition led to secondary salinization through capillary rise causing salt accumulation in the soil surface. Shallow groundwater plays an important role in soil salinization [27]. In shallow water table areas, water and salt will transport upward from shallow groundwater and may result in the salinized soil in a short amount of time. It is highly dependent on water table level and its salinity [28]. Salt accumulation from groundwater is the major cause of salinization [29]. Wetlands are often facing the risk of secondary salinization which may be due to the lower elevation in the landscape that causes an increase in saline groundwater inflows by rising water tables [30].

Also, shallow water table causes waterlogging and damage to crop roots, thus reducing crop productivity. Crop production will be negatively affected due to the shallow saline water table which causes salts accumulation in the soil surface through the capillary rise and/or directly as a result of waterlogging [31]. About one-third of the world's irrigated lands have decreased productivity as a consequence of poorly managed irrigation that has caused salinization and waterlogging [32]. In the irrigated lands such as the Delta and Nile Valley, groundwater levels have risen to produce waterlogging. This process has caused excessive salinity build up in crop root zones and created yield reductions or caused land abandonment in severe cases [33]. Shallow groundwater table may have negative effects on crops; if water table is too shallow, crop yield could decrease due to waterlogging and root anoxia [34, 35]. When the water table is very shallow, soil waterlogging limits the root growth of winter wheat due to the reduced oxygen concentration of the soil [36]. Due to the rapid discharge of drainage and industrial and untreated domestic water on these lakes, sodium is the dominant cation which leads to sodic or sodic-saline soils. Also, this enriches the soil with heavy metals and other pollutants which decrease soil quality. Moreover, drying parts of these lakes, that are originally saline or sodic soils and used for agriculture purposes, have negative impacts on agricultural production in these areas.

Continuous puddling may cause degradation of soil physical properties such as increasing bulk density and compaction [37–40] while decreasing infiltration rate and hydraulic conductivity [41–43]. These unfavorable soil physical properties cause a decrease in nutrient uptake efficiency, air and water movement, and root distribution which led to a significant reduction of crop yields.

Soil salinity and shallow water table could be solved through leaching and drainage projects; drainage is one of the most effective solutions to reduce waterlogging and salinity problems [28, 44–51]. While sodicity and unfavorable soil physical properties could be solved through the application of gypsum, soil conditioners and tillage practices maintain crop productions in the lakes surrounding areas.

6 Conclusions and Recommendations

Due to the essential role of the coastal lakes in Egypt's economy through fishing and salt production, in addition to the important wetland ecosystems, agriculture, urban and industrial activities, the continuous monitoring of land use/land cover changes along the north part of the Nile Delta is very important for the planner, management, governmental and non-governmental organizations, and the scientific community. This information is essential for planning and implementing policies to optimize the use of natural resources and accommodate development while minimizing the impact on the environment.

Decision-makers should introduce a law to protect the coastal lakes as a conserved natural region and forbid illegal practices such as drying, illegal fishing methods, overfishing, isolating water bodies, and untreated drainage discharge. Moreover, it is important to control land reclamation, aquatic vegetation, and high level of pollution to keep the wetland ecosystems of these lakes in favorable conditions.

Planners and policymakers should prepare the database for these lakes and introduce alternatives and innovative options to face the projected impacts of climate change on these lakes such as sea level rise, seawater intrusion, and changing of wetland ecosystems.

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Adaptive Management Zones of Egyptian Coastal Lakes

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Abstract Lakes are one of the most important characteristics of Egypt's coastal areas. However, deteriorating condition of these lakes due to industrialization, land reclamation, agricultural practices, overfishing, bird hunting, and coastal erosion is serious. Many challenges are faced by these lakes, some of which are the most polluted lakes in Egypt where they receive large quantities of agricultural, industrial, and municipal wastes through several drains and from factories around them. In addition, Egypt's Mediterranean coast and the Nile Delta have been identified highly vulnerable to climate change impacts. Adaptive management is the best approach for addressing this type of complex problem. The main objective of this chapter is to classify Egypt's lakes and depressions and to evaluate the land resources status of Egypt's coastal lakes. Also, the challenges facing the sustainable development of these lakes were identified. Adaptive management approach would facilitate the investigation and classification of Egypt's lakes and depressions.

Egypt has been distinguished into four adaptive management zones based on different factors such as the climatic conditions in combination with the agriculture, physiography, natural resources, and other issues affecting the socioeconomic activities. The country is endowed with four main zones as follows:

1. The North Coastal zone: including the coastal area stretching eastward from the northwestern coast to the northern coastal area of Sinai. The northern lake group includes Northern Delta Lakes and Lake Bardawil.
2. The Western Desert zone: encompassing oases and remote areas, including Wadi El- Natrun, Qattara Depression, Siwa Oasis, and Toshka Lakes.

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3. The Nile Valley zone: encompassing the fertile alluvial land of Middle and Upper Egypt, the Nile Delta region, and the reclaimed desert areas on the fringes of the Nile Valley. This group includes Nasser Lake, Qarun Lake, and Wadi El-Rayyan Lakes.
4. Inland Sinai and the Eastern Desert zone: including Great Bitter Lake and El-Timsah Lake.

In the northern lakes, the levels of pollution in these lakes are Mariut > Manzala > Edku > Borollus > Bardawil. The most polluted lakes are Lake Mariut and Lake Manzala. Lake Mariut receives agricultural drainage and domestic and industrial wastewater from agricultural drains. However, Lake Manzala serves as a final repository for many of the municipal and agricultural wastewater of the eastern Delta, including the wastewater of most of Cairo. The main contributors to the lake are the Bahr El-Baqar drain, Hadous drain, and drainage water delivered by Mataria, lower Serw, and Faraskour pumping stations. Bahr El-Baqar drain carries sewage effluent from Cairo and the drainage water of more than 200,000 ha of agricultural lands.

The result of the case study on the Lake Manzala showed the land use and land cover change that has occurred during the period 1986–2016. The highest positive changes areas are showed in crop vegetation areas (+16.44%) and bare land areas (+15.43%), while the highest negative changes areas are displayed in natural vegetation areas (−23.91%) and fish pond areas (−10.77%).

Keywords Adaptive management, Climate change, Coastal lakes, Egypt, Land resources, Nile Delta

Contents

1 Introduction

Coastal zone "describes the area under the influence of coastal processes, such as coastal erosion and inundation. The offshore limit of the coastal zone may extend to several kilometers until the continental shelf, whereas the landward limit may be several kilometers in sedimentary beaches and tens to hundreds meters in rocky and cliffy beaches" [1]. The Egyptian coast is connected to the Mediterranean through the southern Levantine sub-basin, which extends from 25°E in the west to 34.5°E in the east.

On the one hand, northern lakes are considered the frontline defense to Egypt against possible Mediterranean sea level rise. Egyptian coastal lakes, which represent about 25% of the Mediterranean total wetlands, are considered vulnerable to the impacts of climate change, in particular, the expected sea level rise (SLR). Egypt's Mediterranean coast and the Nile Delta have been identified highly vulnerable to climate change impacts. An investigation of the climate change impacts, especially sea level rise and temperature change, on coastal lakes is addressed in limited publications [2]. There are some studies that are addressed to assess the impact of sea level rise on the Egyptian coastal zone and its protection works [3]. It is expected that temperature would change with a range between 1.8°C and 4.0°C and, consequently, sea level would rise with a range from 18 to 59 cm by the end of the current century [4]. This coastal zone is considered one of the five regions expected to experience the worst effects of a sea level rise (SLR) of 1.0 m [5]. El-Raey [6] estimated that even with a SLR of only 0.5 m, nearly all the Nile Delta beaches and approximately 30% of the city of Alexandria and Port Said would be eroded and damaged. Cazenave et al. [7] demonstrated that "except in the northern sub-basin, the sea level increased throughout the Mediterranean Sea between 1993 and 1999, and the authors expect this trend to increase in the future." Criado-Aldeanueva et al. [8] found that the mean sea level (MSL) changed but, insignificantly, over the 1999–2005 period. More recently, Tsimplis et al. [9] found that the MSL rose significantly from 1993 to 2011 by approximately 3.0 cm decade^{-1}. Finally, Shaltout et al. [10] supported Tsimplis et al. [9] finding that throughout the 1993–2010 period, the MSL displayed a significant positive trend of 2.6 cm decade^{-1}. The authors stated that 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.

On the other hand, numerous of Egypt's lakes are located in the Delta, where their proximity to large populations and industrial centers makes them vulnerable to environmental transgressions. Egypt drives its fish yield from three main resources: marine (Red and Mediterranean Seas), inland (lakes and the River Nile with its tributaries), and aquaculture. The Egyptian Mediterranean coast has six lakes or lagoons (Manzala, Borollus, Edku, and Mariut; Northern Delta Lakes and Port Fouad and Bardawil; east of the Suez Canal). All of them, with the exception of Lake Mariut, are directly connected to the sea. The northern lakes provide a rich habitat for marine fish and their regeneration, which have always been major areas of fish production in Egypt. At the end of the eighteenth century, maps show that large areas were covered by water as an extension of Lake Mariut in the northwest of the Beheira province to Abu Al-Matamir in the south. Another lake, called the ferry, extends from the east of Mariut to Lake Edku. There is a strip extending from the small sea from Mansoura to Lake Manzala and the large Dakahlia pool that extended to San Al-Hajar and Lake Borollus with the vast extension with the time in most of the present Kafr El-Sheikh. The Egyptians turned all these lakes and marshes into agricultural land in Dakahlia, Kafr El-Sheikh, and Beheira during continuous efforts throughout the nineteenth and in the early twentieth century.

However, the deteriorating condition of these lakes has been noticed and triggered a number of studies for reaching sustainability [11]. Its environmental damage is serious. This severe damage is due to industrialization, land reclamation, innovative agricultural practices, overfishing, bird hunting, and coastal erosion. Many challenges are faced by these lakes, some of which are the most polluted lakes in Egypt, where they receive a large quantity of agricultural, industrial, and municipal wastes through several drains and from factories around them [12–14]. Adaptive management is the best approach for addressing this type of complex problems, in which various definitions are available in the literature (e.g., [15, 16]). To be able to properly address these problems, detailed information about land resources are important. Adaptive management accepts the fact that management must proceed even if not all the information is complete. It views management not only as a way to realize the goals but also as a procedure of probing to find out more about the resource or system being managed [17]. Thus, learning is an essential objective of adaptive management to adapt our policies and to be more responsive to future conditions. Despite the presence of the few studies that have been conducted to investigate the northern lakes [18–20], this chapter has two main objectives. The first is to classify Egypt's lakes and depressions based on adaptive management zones. The second objective focused on the evaluation of land resources of the Egypt's coastal lakes. All challenges facing the sustainable development of these lakes are identified.

2 Adaptive Management Zones of Egypt's Lakes

Adaptive management zone is an attempt to improve the traditional mapping technique. Specific criteria are employed to define management zones, other than soil maps, and vary depending on available tools, their costs, and how they adapt to the particular conditions of the region.

Three-hourly 3B42.v6 Tropical Rainfall Measuring Mission (TRMM) that provides global data on rainfall was used for precipitation data from 1998 to 2007 [21]. TRMM provides global (50°N–50°S) data on rainfall using the microwave and visible-infrared sensors. Instantaneous rainfall estimates are obtained every 3 h with a $0.25° \times 0.25°$ footprint and continuous coverage from 1998 to the present. The average annual precipitation is 9 mm, 13 mm, and 70 mm over the Western Desert, Eastern Desert, and Sinai, respectively (Fig. 1).

Egypt has been distinguished into four adaptive management zones based on the climatic situations in combination with the physiography, natural resources, agriculture, and other factors affecting the socioeconomic activities. This approach would facilitate the investigation and classification of Egypt's lakes and depressions [22].

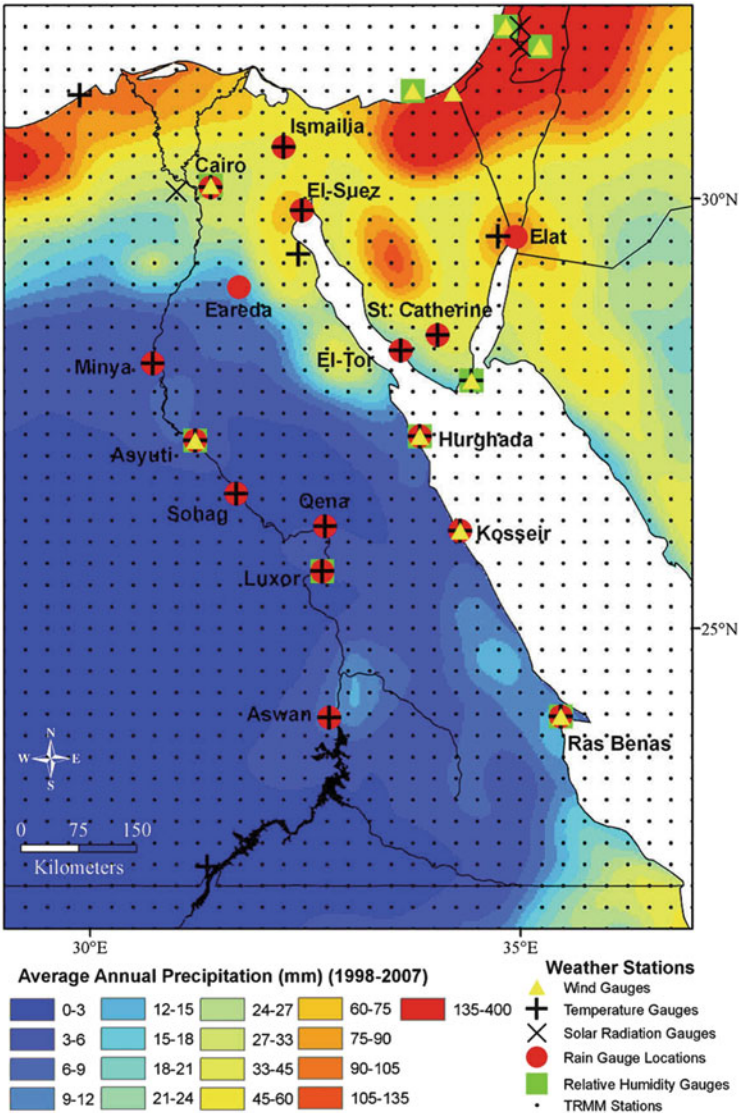

Fig. 1 Average annual precipitation (mm) derived from TRMM 3B42.v6 three-hourly (1998–2007) [21]

2.1 North Coastal Zone

This zone is made up of two major subzones: northwestern coast and northeastern coast of Sinai. Such zone represents the arid province under the maritime influence of the Mediterranean with a shorter dry period (attenuated). The northwestern coast

(NWC) is characterized by a dry Mediterranean climate with an average high and low temperature of 18.1 and 8.1°C in the winter and 29.2 and 20°C in summer seasons, respectively. Rainfall on the northwestern coast ranges between 105.0 mm/year at Salloum and 199.6 mm/year at Alexandria. The greatest intensity of rainfall in Egypt (300 mm/year) occurs on the far northeast of North Sinai (at Rafah). The NWC area has the highest average wind speed in Egypt in the winter, which can reach up to 18.5 km/h and drops gradually inland [22]. Northern coastal areas of Sinai are also characterized by the Mediterranean climate with relatively rainy, cool winter and dry hot rainless summer. Air temperature is similar to those of the NWC. Generally, about 70% of rains along the North Coastal zone occur in winter (November to February) months, and 30% fall during the transitional months.

2.2 The Nile Valley and Delta Zone

This zone is distinguished into two sectors: The first is the Nile Delta and its vicinities, with latitude 29°N as the southern boundary. Except for the north coastal belt, the area corresponds roughly to the accentuated arid province with 20 to 100 mm annual rainfall. The second is the Nile Valley and the surrounding reclaimed areas, which are almost rainless, roughly belongs to the hyperarid province.

2.3 The Inland Sinai and Eastern Desert Zone

The inland Sinai and Eastern Desert zone is characterized by the hyperarid conditions, with a mild winter and a hot summer. Exceptional being the coastal belt along the Gulf of Suez and the highlands of South Sinai, which represent the hyperarid province with a cool winter and hot summer [22].

2.4 The Western Desert Zone

This zone is characterized by hyperarid climatic conditions with rare rainfall and extremely high temperature. The northern and northwestern winds extend from the Mediterranean over the Western Desert with falling speed southward. These winds are the main factors of erosion and deposition [22].

The country is endowed with four main zones (Fig. 2) having specific characteristics of various resources (climatic features, terrain characteristics, land use

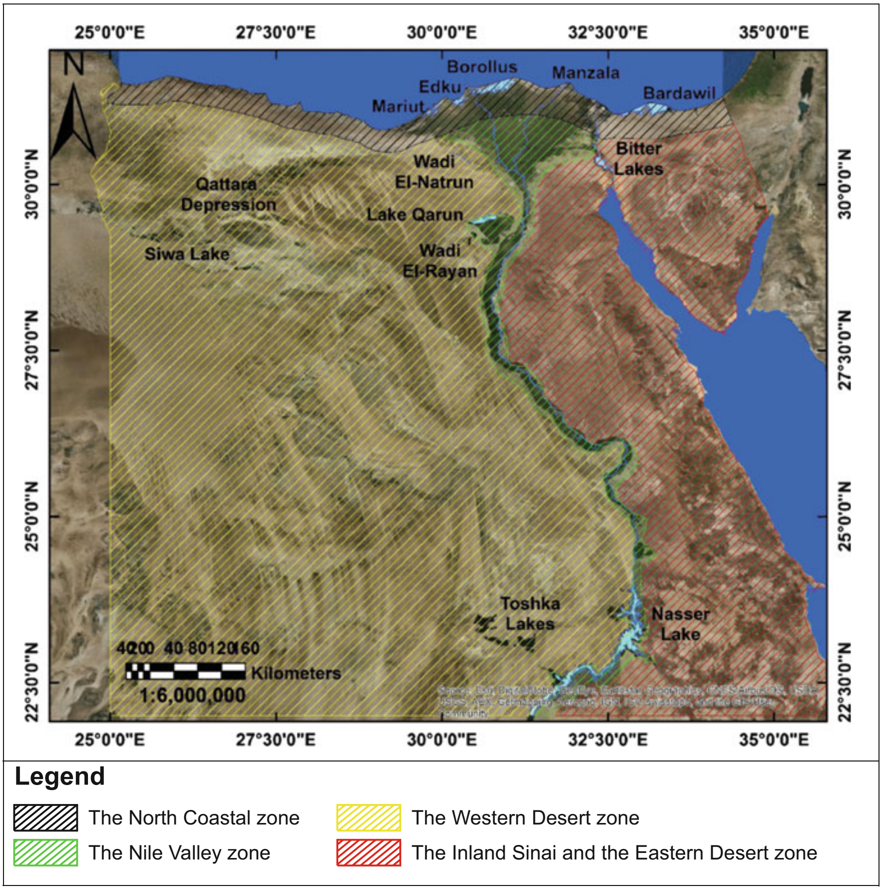

Fig. 2 Adaptive management zones of Egypt's lakes and depressions

patterns, and socioeconomic implications). Therefore, Egypt's lakes in these four zones are distinguished as follows:

1. North Coastal zone: including the coastal area stretching eastward from northwestern coast to a northeastern coastal area of Sinai. The northern lake group includes Northern Delta Lakes and Lake Bardawil [22].
2. The Western Desert zone: encompassing oases and remote areas, including Wadi El-Natrun, Qattara Depression, Siwa Oasis, and Toshka Lakes.
3. The Nile Valley zone: encompassing the fertile alluvial land of Middle and Upper Egypt, the Nile Delta region, and the reclaimed desert areas on the fringes of the Nile Valley. This group includes Nasser Lake, Qarun Lake, and Wadi El-Rayyan Lakes.
4. Inland Sinai and the Eastern Desert zone: including Great Bitter Lake and El-Timsah Lake.

3 North Coastal Lakes

3.1 The Nile Delta History

Herodotus since about 500 BC was the first one to name the Delta, because of the Latin delta (▼) character [23]. The Nile basin by nearly 10,000 years has nine branches and then reduced to seven branches, then five, then three, and finally the existing branches of Damietta and Rosetta. Toussoum [24] collects and archives much information about the branches of the Nile. Ancient maps and manuscripts show that the seven branches (Pelusiac, Tanitic, Mendesian, Phatnitic, Sebennytic, Bolbitine, Canopic) were formed during the period leading up to the big increase that happens in the sea level (5,000 years BC), in which the surface of the sea was low. These branches have been silting in times where the river was acting a little bit, and therefore the rate of deposition of silt over these branches was high. As for the failure silting of Damietta and Rosetta branches it may be due to the branches that were ending directly into the sea, which are destined to inflation and survival. However, the one which was aimed at the lakes are those which have as much atrophy and silting [25]. Figure 3 shows the oldest branches of the Nile, which were drawn by geographers and ancient historians.

3.2 Northwestern and Eastern Coastal Lakes

Five natural lakes lie adjacent to the Mediterranean Sea (Fig. 4): Lake Mariut, Edku, Borollus, Manzala (deltaic section) [27] and Bardawil (North Sinai). These lakes are kept separated from the sea by narrow splits and are not more than 2 m deep. They provided fish and recreation, and part of Lake Mariut was once used as a landing place for seaplanes. These lakes are the most productive lakes in Egypt, which have fresh, brackish, and saline or hyper-saline water. The depth of these lakes is ranging from 50 to 180 cm. In addition, they are internationally important sites for wintering of the migrating birds, providing valuable habitat for them, and an important natural resource for fish production in Egypt [28].

The current pattern of these lakes is changing rapidly, due to natural developments and, commonly, to man's activities (e.g., fishing and agricultural practices). Unfortunately, most of these lakes have deteriorated sharply over the last 20 years due to the wastewater being discharged into them. Three types of wastewater contributed to the problem [27]: domestic sewage, untreated industrial effluents, and agricultural drainage water. The first used to be discharged directly into the sea. The second has increased dramatically due to the growth of new industries. The third has also increased after the building of the High Dam because the agricultural land has been switched to produce more than one crop a year. The construction of the Aswan High Dam in 1964 is the driving force for a continuous evolution of the Delta lakes. The morphometry of the five northern lakes is represented in Table 1 [29].

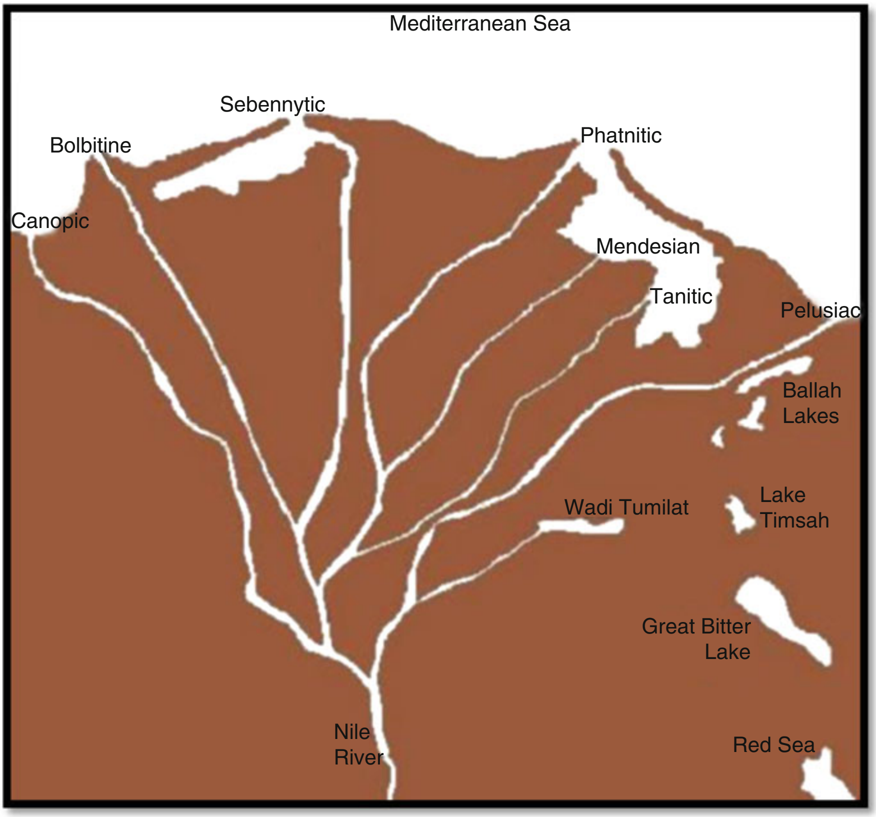

Fig. 3 Ancient branches of the Nile, showing Wadi Tumilat and the lakes east of the Delta [26]

Fig. 4 Map showing the five Egyptian northwestern and eastern coastal lakes

Table 1 Morphometry of the five Mediterranean lakes [29]

Lake	Latitude (N)	Longitude (E)	Area (km²)	Depth (m)	Length (km)	Width (km)
Bardawil	31° 03′–31° 14′	32° 40′–33° 30′	650	1.0	75.0	22
Manzala	31° 00′–31° 30′	31° 16′–32° 20′	1,200	1.1	64.5	49
Borollus	31° 25′–31° 35′	30° 30′–31° 10′	410	1.02	64.0	16
Edku	31° 13′–31° 16′	30° 07′–30° 14′	126	1.0	21.0	6.0
Mariut	31° 12′–31° 2′	29° 55′–29° 55′	63	1.2	8.8	7.7

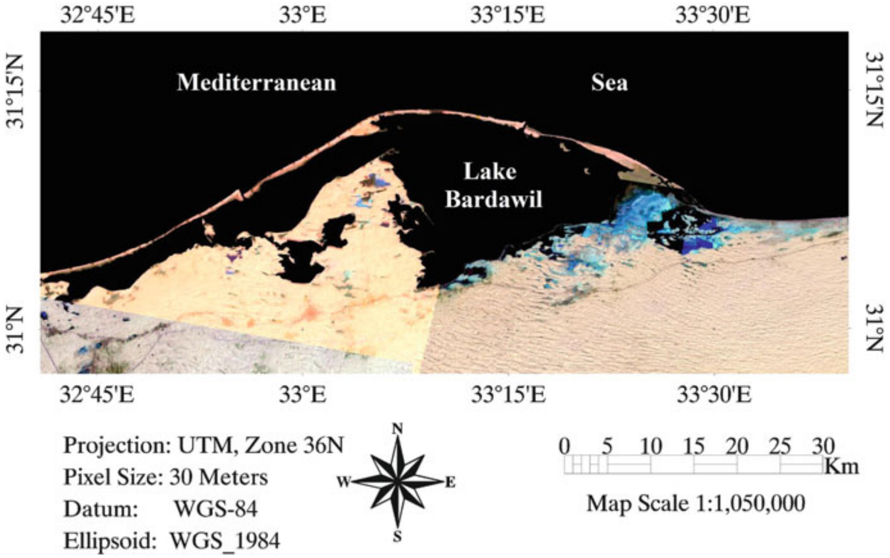

Fig. 5 Bardawil lagoon as one of the largest saltwater lagoons along the northern coast of Sinai

3.2.1 Lake Bardawil

The Bardawil lagoon is one of the largest saltwater lagoons along the northern coast of Sinai, Egypt. It is a natural shallow saline lagoon on the north coast of the Sinai, embedded in sandy dunes whose colors change from brown to yellow to pink as the day progresses. It is separated from the Mediterranean Sea by a narrow sandbar. Lake Bardawil covers an area of about 650 km^2. Bardawil lagoon is extending from latitude 31° 03′ to 31° 15′N and longitude 32° 40′ to 33° 32′E (Fig. 5). It is a tectonic origin compared to the other Mediterranean Egyptian lagoons. For example, Edku, Borollus, and Manzala are of deltaic origin. Bardawil lagoon represents a transitional zone between land and the Mediterranean Sea, which is separated from the sea by a narrow curved sand barrier. Around Bardawil lagoon, there are many sabkhas, which can be divided into flat and dune sabkhas. The water quality of the Bardawil lagoon is mainly governed by tidal water-level variation. “Due to the relatively small tidal range (i.e., 40 ~ 50 cm) along the northern coast of Sinai, the water exchange between the Bardawil lagoon and the Mediterranean Sea is relatively poor." In addition, the inlets are subjected to morphological changes due to coastal sediment motion that might lead to the closure of the inlet on some occasions. This may cause changes in the lagoon ecosystem, environmental degradation, and shortage in fish catch.

3.2.2 Lake Manzala

Lake Manzala (Fig. 6) is one of the most vulnerable lakes and is the largest natural lake of the northern Egyptian lakes along the Mediterranean coast. Lake Manzala in northeastern Egypt on the Nile Delta is a brackish lake that covers a surface area of 1,200 km^2 and reaches a maximum depth of 1 m. It is located between longitudes 31° 45′ and 32° 22′ E and latitudes 31° 00′ and 31° 35′ N. There are narrow outlets at El-Baghdadi, El-Gamil, and El-Qaboti at the northern side of the lake. The lake is linked to Damietta branch through El-Inaniya canal. Therefore, the southwestern corner of the lake receives its freshwater from the Serw and Faraskour pumping stations and the Inaniya canal.

Six main agricultural drains flow into Lake Manzala and affect its water quality. Drainage water contributes about 98% of the total annual inflow to Lake Manzala. Six drains are carrying the fresh and drainage water to the lake [31]: Hadous drain, which contributes about 25% of the total inflow, Serw drain (13% of the total inflow), Ramsis drain (4% of the inflow), Faraskour drain (4% of the inflow), Bahr El-Baqar drain (25% of the total inflow), and Matariya drain (2% of the inflow).

3.2.3 Lake Burullus

Lake Burullus (Fig. 7), the brackish water lake, is located on the northern shore of the River Nile Delta at a western corner in Kafr El-Sheikh Governorate, east of Rosetta. Beneath its waters lies the historical settlement of Paralus. Lake Borollus has lost an estimated of 37% of its open-water area and 85% of its marsh area in the past 40 years, because of the ongoing drainage and reclamation of the lake's eastern, western, and southern margins.

3.2.4 Lake Edku

A large lagoon (Lake Edku) is one of the less polluted lakes of the five northern lakes of Egypt. Lake Edku is situated about 30 km east of Alexandria in Beheira Governorate. It is situated west of the River Nile Delta between longitudes 30° 8′ and 30° 23′ E and latitudes 31° 10′ and 31° 18′ N (Fig. 8). The lake is connected to the adjacent Abu Qir Bay through Boughaz El-Maadiya, a 20-m-wide, 100-m-long, and 2-m-deep channel. The actual surface area of the lake has been decreased since 1964 due to the reclamation of a large area on the eastern side for cultivation purposes. It has an area of about 126 km^2. Lake Edku has been reduced to less than half its original size since 1950 until now [32]. Its area diminished from 336.4 km^2

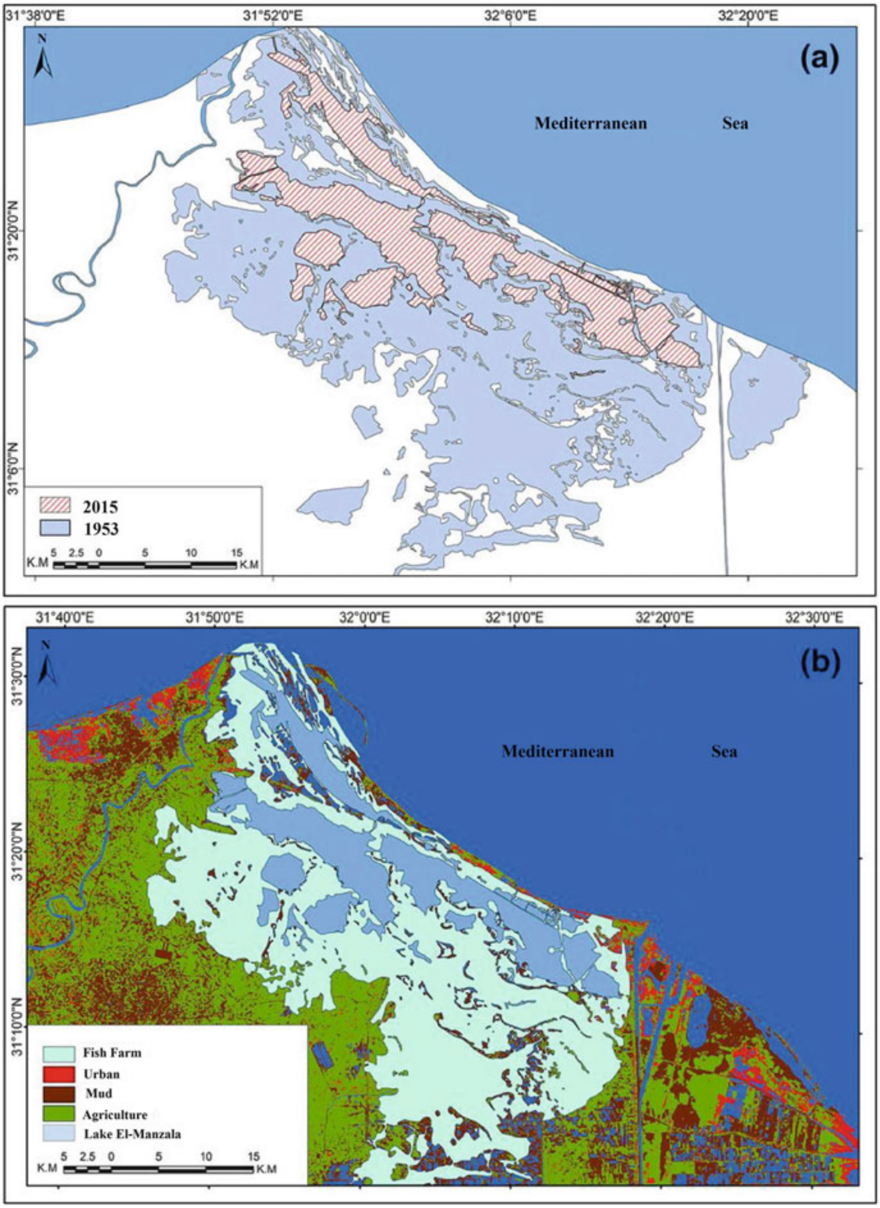

Fig. 6 Lake Manzala as one of the largest natural lakes of the northern Egyptian lakes along the Mediterranean coast; degradation of Lake Manzala between 1953 and 2015 (**a**); current fish farms, housing, and cultivated land around the lake (**b**); note that almost all these areas were parts of the water body until 1953 [30]

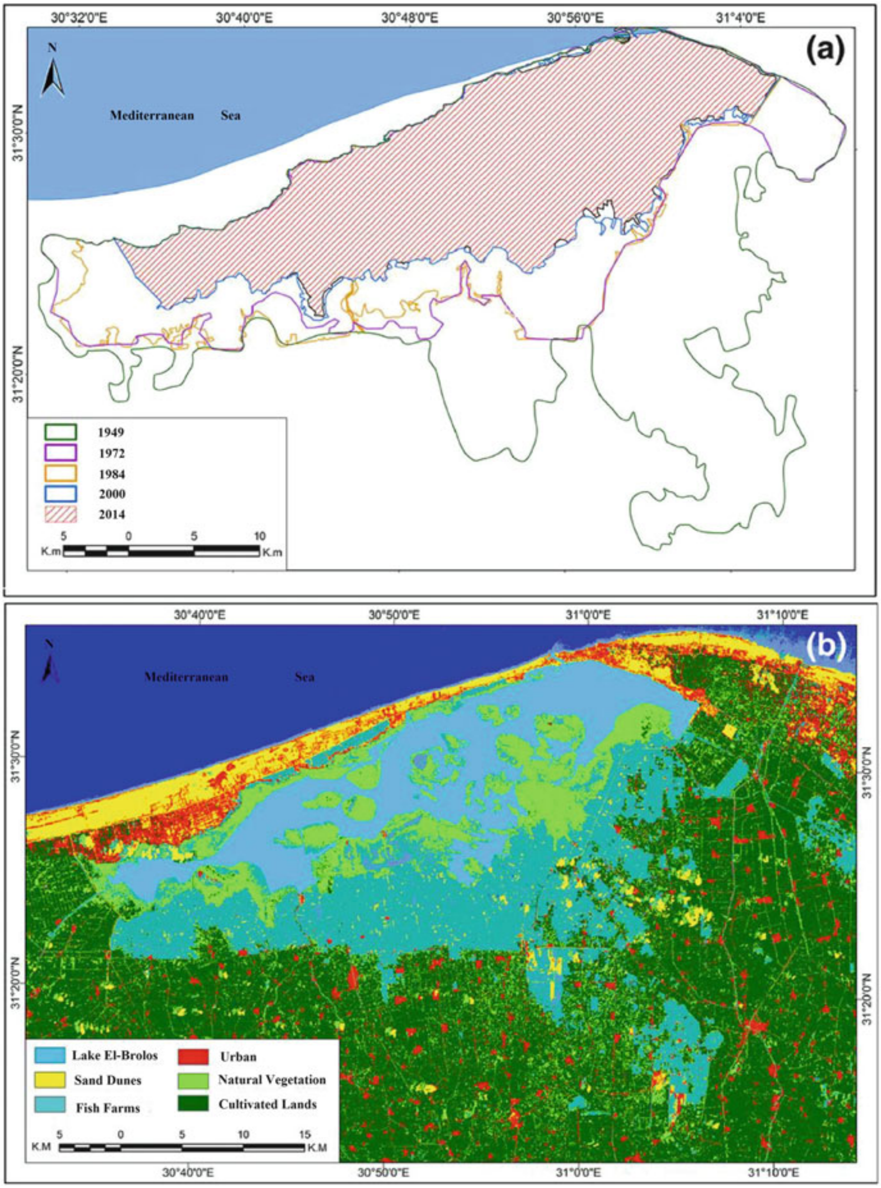

Fig. 7 Lake Burullus as the brackish water lake located in the northern shore of the River Nile Delta; degradation in surface area of Lake Burullus between 1949 and 2014 (**a**); current fish farms, housing, and cultivated land around the lake (**b**) [30]

in 1800 to 17.1 km^2 in 2010 (Fig. 8), so it lost 319.3 km^2 in 210 years, with an annual average of 1.735 km^2.

Lake Edku – a shallow coastal wetland west of the Rosetta Nile branch – has also suffered from drainage and land reclamation policies. The lake receives water from

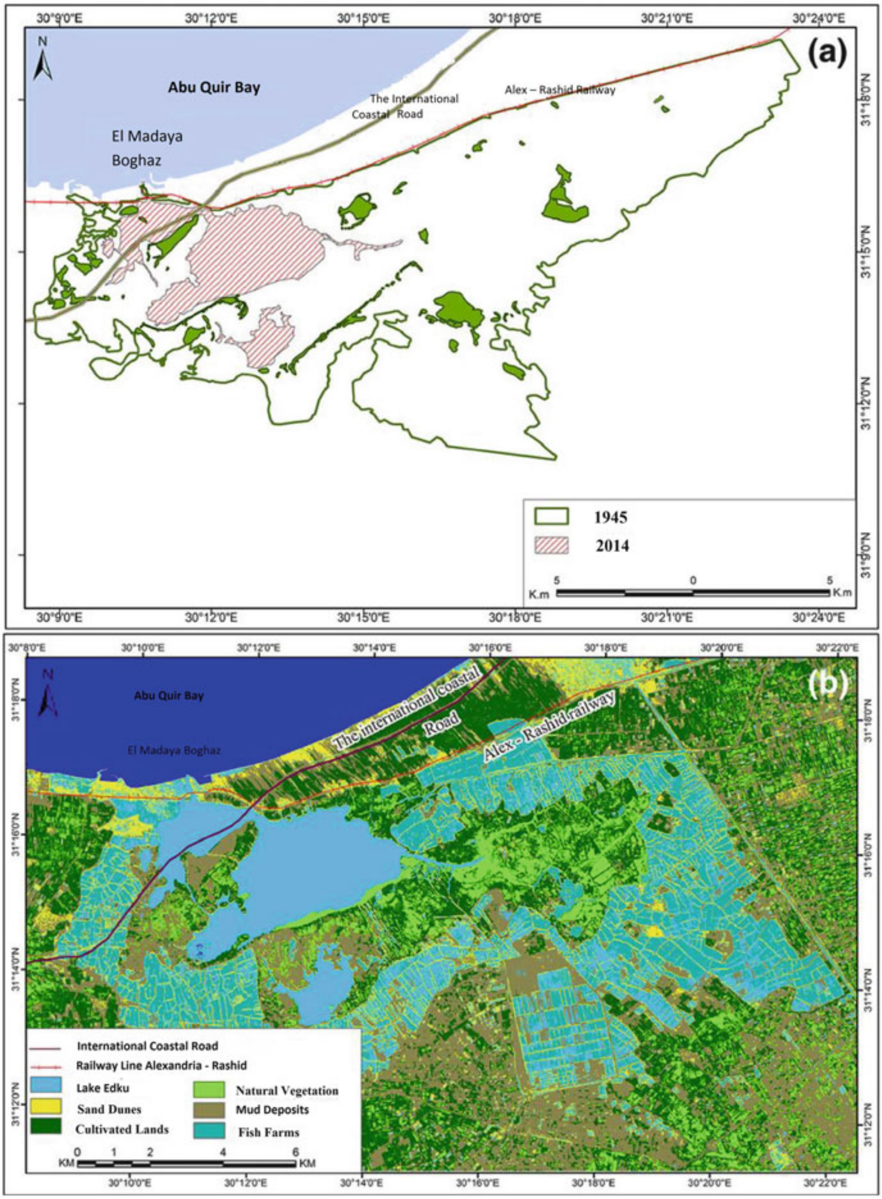

Fig. 8 Lake Edku as one of the less polluted lakes of the five northern lakes of Egypt; lake degradation between 1945 and 2014 (**a**); current fish farms, housing, and cultivated land around the lake (**b**); note that almost all these areas were parts of the water body until 1945 [30]

three drains along the southern and eastern sides. Lake Edku has been exposed to different sources of pollution. The agriculture drainage water is loaded with fertilizers, pesticides, and untreated industrial wastes of several factories. Aggregated boats at Boughaz El-Maadiya (i.e., the entrance of the lake) would release the oil wastes and other discharges.

Seawater is mainly affecting the western side of the Lake Edku near the outlet. Annual drainage in the lake has increased, after the construction of the Aswan High Dam. This has caused an increase in the lake level and prompted flow from the lake into the sea; hence, the lake became less influenced by saltwater from the sea. In the past, the region has been suffering from various aspects of mismanagement and problems such as neglect, deterioration, coastal erosion, water resource pollution, urban encroachment in agricultural land, vulnerability to sea level rise (e.g., [33]), and lack of urban and environmental planning. Loss of marine biodiversity was due to the increased load of dumped waste in the bay and loss of agricultural and bird biodiversity due to deterioration of soil and water quality. The climate change impact including saltwater intrusion is an important hazard to the region. Resource losses in the region have caused large-scale socioeconomic deterioration.

3.2.5 Lake Mariut

Lake Mariut is a salt lake in northern Egypt, between Alexandria and Beheira governorates. Lake Mariut (Fig. 9) has been decreased by more than 75% and is still shrinking. The fundamental driver is urban encroachment and solid waste dumping from the quickly developing city of Alexandria. Lake Mariut's area secured 200 km^2 at the beginning of the twentieth century, but at the beginning of the twenty-first, it covers only about 50 km^2 [35]. Lake Mariut has experienced serious contamination, despite the fact that at one time, it was a profoundly profitable lake [34]. This contamination increment with time; because of the progressive increment in population and industry around the lake, different types of untreated toxins (sewage and industrial wastes and agricultural runoff), going into the lake, transformed it into a profoundly eutrophic state. This alongside reclamation of great areas from the lake has influenced dramatically its fish production.

3.3 *Northern Lake Soils*

Elmaaz [36] studied some soils adjacent to lakes at the north of Egypt and found the soils of recent Nile alluvium, marine alluvium, and desert plain have mainly heavy texture (clay), whereas the others of sub-deltaic and sandy beaches are lighter (loam). These soils are of non- to moderate saline, and total carbonate content differs widely. Many lime concretions and broken shells are existing especially in the lower layers of profiles south of Lake Mariut. The different statistical size parameters indicated that the most soil materials of recent Nile alluvium, marine

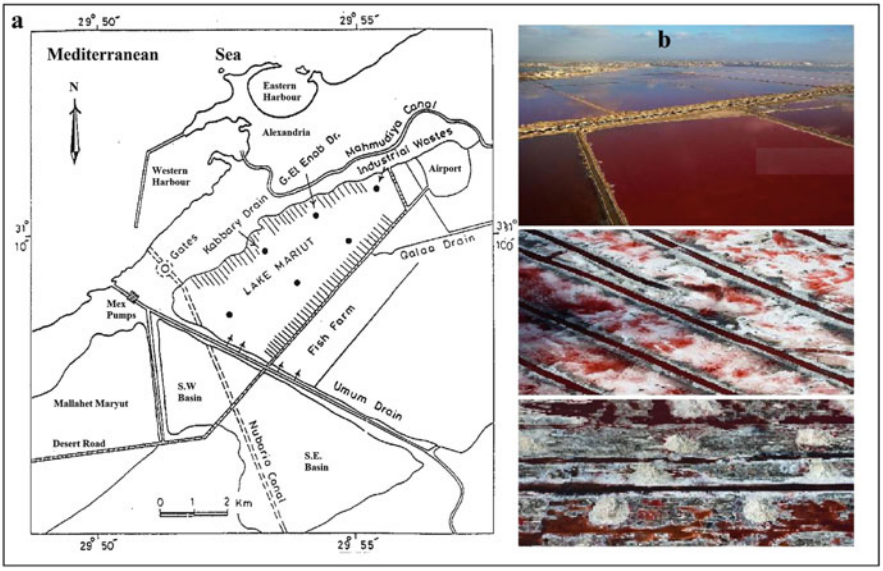

Fig. 9 Lake Mariut as a salt lake in northern Egypt, between Alexandria and Beheira governorates [34] (**a**); Salt evaporation ponds of Lake Mariut (**b**)

alluvium, and desert plain deposits are poorly sorted with platy to the very platykurtic pattern. This indicates that the water is the main factor responsible for transportation and formation of soil materials of these deposits. The cumulative curves of these soils are nearly similar and symmetrical reflecting almost uniform and homogenous soil materials. However, results of sub-deltaic and sandy beaches deposits indicate that their soil materials are formed under a combined effect of water and wind action. Their soil materials are nearly heterogeneous and formed under different depositional regimes. Most soils are considered young from the pedological point of view. The majority of recent Nile alluvium, marine alluvium, and desert plain are formed under similar depositional regime. The soils of other landforms are deposited under multi-depositional regime.

The salt-affected soils, in the northern part of the Nile Delta, were investigated in governorates of El-Beheira (Ferhash & El-Lakana), Alexandria (Abees), Kafr El-Sheikh (Burg Megasal & Shalma), Damietta (Kafer Soliman El-Bahri), El-Dakahlia (Mear Meraga salcil), and Sharqia (El-Monaga El Kobra & El-Tal El-Kebir) [37]. The results showed the significance of the Mediterranean Sea water, lakes, and groundwater as sources of salinity to adjacent soils. However, the action of seasonal wetting and drying under the arid climatic environment and the low elevation from surrounding areas add some extra salts to these soils. Soils were classified as saline soils, saline-alkali soils, and alkali soils. Generally, most of the salt-affected soils of the Nile Delta are of the saline-alkali nature [38]. The study of soil morphology and sedimentation pattern showed that these soils vary in their components in different locations based on soil relief, the Nile, sea, lakes, and Western and Eastern Desert deposits. Accordingly, the different sediments of these parent materials interfere with each other but in different deposit rates in the different locations [37].

Abo El-Ennan et al. [39] studied the genesis of clay minerals in some saline and alkaline soils in the northern part of the Nile Delta. They stated that the clay minerals of the investigated soils could have been carried either by the River Nile from its upper sources or formed in situ by the weathering of primary silicates. Smectite, kaolinite, and illite minerals may have been transported in the suspended matter carried by the Nile. The presence of interstratified clay minerals in some soil samples may be explained by pedogenic formation and transformation processes. An inadequate drainage system and a high water table possibly promoted such a transformation. The soils are affected by saline water and relatively high temperature, which allows the alteration of the lattice framework of the clay minerals. These soils have high Mg/Ca or Na/Ca ratios because of the inadequate drainage system and seepage of saline water from the Mediterranean Sea and the northern lakes. Seawater rich in Mg ions leads to the transformation of hydrous mica into montmorillonite, whereas the K ions between the layers have been replaced, and due to this, the attractive forces were weakened, and water molecules entered the lattice resulting in its expansion.

Abu-Agwa and Amira [40] stated that the soils adjacent to Burullus and Manzala salty lakes differ from sandy loam to clay texture affecting mainly by natural sedimentation pattern and circumstances of each area. The soils situated close to the lakes have moderate horizontation, which may be due to the intermixing between recent alluvium and lacustrine deposits in these areas.

3.4 Northern Lakes: Degree of Pollution

Human activities will not only cause the loss of important habitats in northern lakes but will also create new ecosystems [28]. These lakes cover about 6% of the non-desert surface area of Egypt. They are separated from the Mediterranean Sea by sand bars that are very narrow in several places and connected with the sea through narrow straits. These straits are either remnants of the mouths of old deltaic branches or merely gaps in the weak sections of the bars known as tidal inlets [41]. Pollution levels of these lakes are Mariut > Manzala > Edku > Burullus > Bardawil [42]. The most polluted lakes are Lake Mariut and Lake Manzala. Lake Mariut receives agricultural drainage and domestic and industrial wastewater from agricultural drains [27]. Lake Mariut is the most polluted wetland in Egypt, which suffers from contamination due to its closeness to Alexandria. Contaminated agricultural drainage water and huge quantities of largely untreated municipal and industrial wastewater are again the culprits. Environmental consultant describes the damage to the wetlands, particularly those in the north of Egypt, as “one of the greatest environmental crimes – it is a truly tragic environmental tale.” The outlook for the future of this wetland is rather grim [35].

However, Lake Manzala serves as a final repository for many of the municipal and agricultural wastewater of the eastern Delta, including the wastewater of most of Cairo. The main contributors to the lake are the Bahr El-Baqar drain, Hadous drain, and drainage water delivered by Mataria, lower Serw, and Faraskour pumping stations. Bahr El-Baqar drain carries sewage effluent from Cairo and the drainage water of more than 200,000 ha of agricultural land.

The situation is aggravated by the way that the water quality in what stays of these lakes has been truly compromised through the systematic release of waste into them. While the seriousness of the contamination fluctuates among the different water bodies, the primary driver in all cases is the release of untreated or in part treated industrial and household wastewater (mainly sewage) and the dumping of agricultural drainage stacked with fertilizer, pesticide, and herbicide residues. In Lake Manzala, the contamination issue is exceptionally extreme and is caused by many factors. Municipal wastewater is, maybe, the most serious source of contamination, as a significant part of the crude and treated sewage from Cairo, Port Said, and Damietta ends up in Manzala.

Industrial wastewater is additionally released into the lake from different sources. 65% of the industries situated in Alexandria are disposing of their wastewater in this lake. In addition, it is contaminated by agricultural drainage with high fertilizer and pesticide concentrations, while solid waste from urban centers is regularly dumped into the lake, which is used for landfill [35]. Similarly, in Lake Mariut and Lake Edku, industrial waste and chemicals used to spur agricultural productivity nearby are severely damaging fish habitats.

Lake Burullus is the least polluted of the Northern Delta Lakes, but it is subject to increasing quantities of agricultural drainage, which contributes significantly to eutrophication – a harmful vegetation bloom – and pollution.

3.5 Case Study: Lake Manzala

Changes in the land use and land cover (LULC) of southern Manzala are evaluated from the differences between 30 years of the period from 1986 to 2016 [43]. Six categories of land use are identified (Fig. 10) as the following: bare land, crop vegetation, natural vegetation, fishpond, saline land, and water body (Table 2). It is estimated from the table that in the year 1986, the region is dominated by natural vegetation areas (35.08%), followed by fishpond (22.89%), water body (22.39%), bare land (13.44%), crop vegetation (5.52%), and salt land (0.68%). In the year 2006, the percentages of land use are majored by bare land (28.30%), water body (24.75%), natural vegetation (24.32%), fishpond (11.5%), crop vegetation (10.62%), and salt land (0.51%). In the year 2016, bare land (28.89%), water body (25.64%), crop vegetation (21.95%), fishpond (12.12%), natural vegetation (11.19%), and salt land (0.24%) are the dominate land use classes.

LULC maps of years 1986, 2006, and 2016 images (Fig. 10) were produced. Positive change (increased) areas are displayed in supervised classes of LULC as

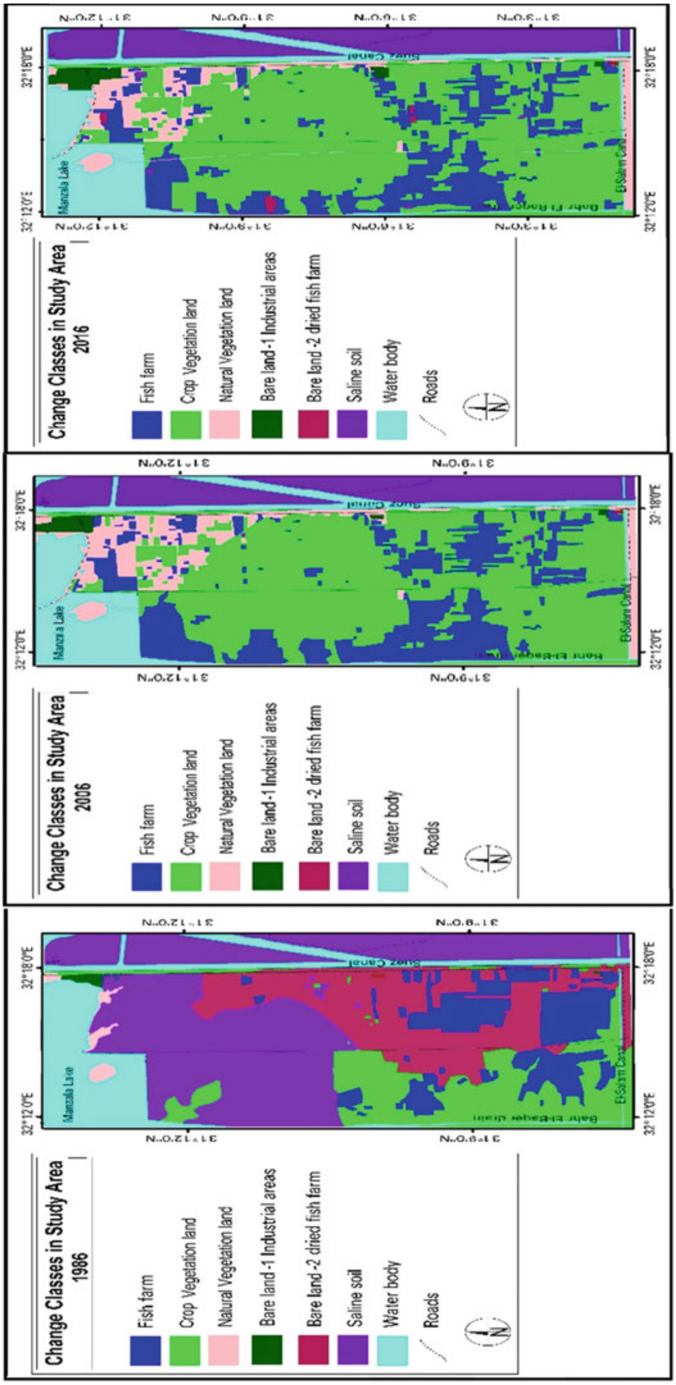

Fig. 10 Land use and land cover (LULC) change class map from 1986 to 2016

Table 2 Digital elevation model (DEM) classes and risk area in southern region of Manzala

DEM classes		Area (km^2)	Area (%)	Risk area (%)
C1	−4–(−0.1) m	62.58	18.13	34.29% waterlogged soils
C2	−0.1–0 m	55.79	16.16	
C3	0–0.8 m	56.78	16.44	44.67% medium depth soils
C4	0.8–1.7 m	54.59	15.81	
C5	1.7–2.2 m	42.87	12.42	
C6	2.2–3.1 m	25.75	7.46	21.04% depth soils
C7	3.1–4.6 m	21.99	6.37	
C8	4.6–6 m	24.89	7.21	
Total area		345.24	100	–

follows. Crop vegetation areas (+56.76 km^2) were covered about +16.44% with rate of change about +4.93% and per years about +1.892. Bare land areas (+53.26 km^2) were covered about +15.43% with rate of change about +4.63% and per years about +1.775. Water body areas were covered about (+11.22 km^2) were covered about +3.25% with rate of change about +0.97% and per years about +0.374. While negative change areas (decreased areas) are displayed in classes of LULC as follows. Natural vegetation areas (−82.54 km^2) were covered about −23.91% with rate of change about −7.17% and per years about −2.751. Fish pond areas (−37.18 km^2) were covered about −10.77% with rate of change about −3.23% and per years about −1.239. Salts areas (−1.52 km^2) were covered about −0.44% with rate of change about −0.13% and per years about −0.051.

The areas of study are about 345.24 km^2 in the southern region of Manzala. Bare land area class was covered about 46.38 km^2 in the year 1986 and was increased to 97.68 km^2 in the year 2006. The bare land area increased around 51.3 km^2 may be gaining from drying fish farms and/or Lake Manzala area through 30 years, with an average rate of change of +2.565 km^2 year^{-1}. The crop vegetation areas were covered about 19.03 km^2 in the year 1986, which were increased to 36.68 km^2 by the year 2006. The increased area of around 27.65 km^2 maybe due to changing natural vegetation area, with an average at a rate of change about +0.883 km^2 year^{-1} through 20 years. The study area of natural vegetation area was shrunk over the entire study period from 1986 to 2006 from 121.13 km^2 to 83.97 km^2, respectively, with an average at a rate of change about −1.858 km^2 year^{-1}. Fishpond areas were shrunk from 79.04 km^2 (in 1986) to 39.69 km^2 (in 2006) with an average at a rate of change about −1.968 km^2 year^{-1}. The total water body areas (deep and shallow water) were expanded from 77.32 km^2 in the year 1986 to 85.45 km^2 in the year 2006, with an average at a rate of change about +0.477 km ^{2} year^{-1}. On the last class, salt areas were shrunken from 2.34 km^2 to 1.77 km^2 between 1986 and 2006 periods of images, with an average at a rate of change about −0.029 km^2 year^{-1}.

The anticipated sea level rise resulting from global climate change may threaten many soils. It is difficult to predict exactly how much sea level will rise, but there is agreement that coastlines, deltas, and small islands are particularly vulnerable. Because of the geography of Egypt’s Nile Delta, a rise nearly that high (say 1 m in sea level) could inundate 2,000 km^2 of land [44]. The terrain analysis (Table 2) revealed that 34.29% of the area is waterlogged areas under sea level (that area under high risk by sea waterlogged covered), whereas 44.67% is ranged between 1.7 and 2.2 m a.s.l (this class is medium level of a.s.l for depth of soils), and 21.04% is up to 2.2 m a.s.l. The analysis of the digital elevation model (DEM) revealed that the present elevation gives sea intrusion risk at 118.37 km^2 (waterlogged soil areas). The increase of 80 cm rises in sea level will put about 175.15 km^2 under risk that will increase to 229.74 km^2 and to 272.61 Km^2 by sea level rise more 80 cm or 100 cm, respectively.

The DEM analysis map (Fig. 11) and topographic map revealed that 34.29% of the area is under sea level, whereas 44.67% is 1.7 m a.s.l, and 21.04% is up to 2.2 m a.s.l. The analysis of the DEM revealed that the present elevation gives sea intrusion

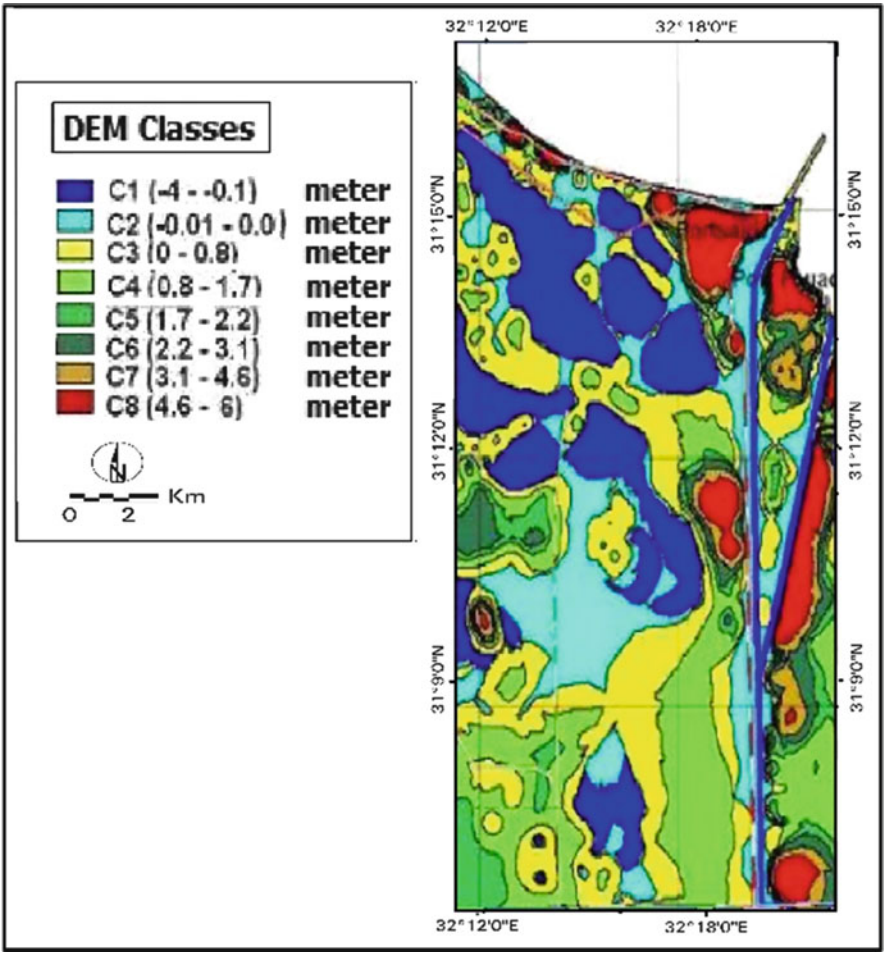

Fig. 11 Digital elevation model (DEM) class map in the southern region of Manzala

risk at 118.37 km^2. The increase of 30 cm in sea level will put 175.15 km^2 under risk, which will increase to 229.74 km^2 and to 272.61 km^2 by a sea level rise in the area southern Port Said government from 80 to 100 cm, respectively.

4 Conclusions and Outlook

Adaptive management approach facilitates the investigation and classification of Egypt's lakes and depressions. Egypt has been distinguished into four adaptive management zones based on the climatic conditions in combination with other natural and socioeconomic resources. The northern coastal zone (the focus of this chapter) includes Northern Delta Lakes and Lake Bardawil. The most polluted northern lakes are Lake Mariut and Lake Manzala. Lake Mariut receives agricultural drainage and domestic and industrial wastewater from agricultural drains. However, Lake Manzala serves as a final repository for many of the municipal and agricultural wastewater of the eastern Delta, including the wastewater of most of Cairo. The main contributors to the lake are the Bahr El-Baqar drain, Hadous drain, and drainage water delivered by Mataria, lower Serw, and Faraskour pumping stations. Bahr El-Baqar drain carries sewage effluent from Cairo and the drainage water of more than 200,000 ha of agricultural lands.

The result of the case study on the Lake Manzala showed the LULC change that has occurred during 30 (1986–2016) years of period. The positive changes (increased) areas are displayed in crop vegetation areas (+16.44%), bare land areas (+15.43%), and water bodies areas (+3.25%), while the negative changes (decreased) areas are displayed in natural vegetation areas (−23.91%), fish pond areas (−10.77%), and salts areas (−0.44%).

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Sediment Contaminants in Northern Egyptian Coastal Lakes

L. I. Mohamedein, M. A. El-Sawy, and M. A. Bek

Abstract Mariout, Edku, Burullus, El-Manzala, and Bardawil lakes are the five northern lakes connected to the Mediterranean Sea. They suffer from different types of serious problems because they receive contaminants from drains. Consequently, those lakes are under increasing threat from eutrophication, pollution, and destruction of surrounding wetlands. Sediments of lakes deposit small particles because of the relatively unmoving waters in them. Sediments in these lakes are considered to be the sink of these different contaminants. The inorganic contaminants like heavy metals had been determined in the sediments of the lakes. The organic contaminants like polycyclic aromatic hydrocarbons (PAHs) and polychlorinated biphenyls (PCBs) are found to bind strongly to sediments. In Lake El-Manzala, Hg showed the highest values and alarming toxicity levels, and it is considered as one of the most hazardous. Lakes Burullus, Edku, and Bardawil recorded highest values of some heavy metals, while Lake Mariout got the highest ranged values for the organic contaminants. Continuing observing and monitoring of northern lakes is very important to resolve the existing contamination problems and to avoid its complication in the future.

Keywords Biodiversity, Contaminant, Drain, Egyptian, Heavy metals, Lakes, Northern, Sedimentations

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Contents

1 Introduction

Pollution is defined as the introduction of harmful substances into the environment. The environment has been revealed to have many adverse effects on the human health, agriculture productivity, and natural ecosystem [1]. Pollution is a serious issue of all environmental problems and causes a major threat to the health and safety of millions of people and global ecosystems. Additional major environmental problems are also partly caused by pollution; these include global warming, climatic change, and the loss of biodiversity through the extinction of many species. The dramatic increase in public awareness and concern about the state of global and local environments which has occurred in recent decades has been accompanied and partly prompted by an ever-growing body of evidence on the extent to which pollution caused server environmental degradation. Water pollution is mainly due to main pollutant elements which include organic pollutants such as polycyclic aromatic hydrocarbons (PAHs), polychlorinated biphenyl (PCBs), and farans (PCDFs) by aerial and other inputs [2] and inorganic pollutants such as heavy metals [3]. Currently, the coastal zone of Egypt and its lakes suffer from a number of serious problems, including a high rate of population growth, land subsidence, excessive erosion rates, saltwater intrusion, soil salinization, extensive land use, pollution and degradation, and lack of appropriate institutional management systems. Therefore, these lakes are under increasing threat from water withdrawal for human use and secondarily from eutrophication, pollution, and destruction of surrounding wetlands [4].

Lake sediments are normally the final pathway of both natural and anthropogenic components produced or derived to the environment because they play an important role in the aquatic environment. They are transporting a significant proportion of many nutrients and contaminants. Sediment pollution commonly occurs when contaminated sediments are supplied directly to waterbodies. However, pollution can also occur when contaminants are applied to soils, which are subsequently eroded and delivered to waterbodies as sediment, or when contaminants are introduced directly to water that contains sediments. Deposition of smaller sediments requires relatively unmoving waters and so is most likely to occur in lakes, reservoirs, estuaries, bays, and harbors. Contaminants become attached to sediments simply by coating the sediments or by various sorption forces that depend on the nature of the sediment and the contaminant as well as the chemistry of the water. Most contaminant sorption and desorption occur on the smaller clay size sediments less than about 4 μm (0.004 mm) in size. Sediment pollution may also occur from natural contaminants such as heavy metals in sediments derived from mine ores and may be found in sediments of considerably larger sizes [5, 6].

The Egyptian coastal lakes can be classified according to its location to the north lakes and east lakes. North lakes connected to the Mediterranean Sea are Mariout (or Mariut), Edku, Burullus, El-Manzala, and Bardawil lakes (see Fig. 1). The lakes represent highly dynamic aquatic systems that have been undergoing continuous and pronounced changes through the late Holocene to the present time, particularly after the construction of the Aswan High Dam in 1965 [7].

High concentrations of trace organic and inorganic pollutants were recorded along the Egyptian Mediterranean coast and its corresponding coastal lakes. The lakes receive different types of contaminants from different sources as land-based and maritime activities. Sediments in these lakes are considered to be the sink of these different contaminants. This review will highlight some recent studies' concerns with the major contaminants in the Egyptian lakes.

Fig. 1 General locations of the Egyptian northern coastal lakes

2 Environmental Drivers Influencing Sediment Contamination

Egyptian northern lakes receive contaminations from drains. Different types of drains drive different types of contaminants which affect the sediment inside it.

Lake Mariout receives agricultural drainage water (at least six million m^3/day) loaded with agrochemicals, trace metals, industrial wastes and untreated domestic waste were they discharged into the lake [8]. There are three main inflows to the Lake Mariout: the Qala drain located at the northeast part of the lake, the Omum drain or Mogama drain located at the east of the lake which discharges industrial effluents of eight factories (Salt and Soda, Extracted Oils, National Paper, Starch and Yeast, Nile Matches, South Alexandria Mills and Alexandria Foundry, and the raw sewage of Kabbary and Gheit Enab Drain), and the Nubaria navigational canal located at the south of the lake. Also, there are two minor inflows: one from the West Nubaria drain and, the second, from the West wastewater treatment. The only outflow from the Lake Mariout is El Mex pumping station which consists of two buildings, each housing six pumps with nominal capacities of 12.5 m^3/s [9].

Lake Edku receives huge amounts of drainage water from three main drains, namely, Berzik, Edku, and El-Boussili, which open into the eastern basin of the lake [10]. Kom Belag drains at the east and Berzik at the south-central part of this lake [11]. An amount of 3.3×10^6 m^3 per day of brackish water is introduced into Abu Qir Bay from Lake Edku through Boughaz El-Maadiya [10–18]. The lake receives 2.62 million m^3 of agricultural drainage which has very bad effects on the chemical characteristics of its water.

Lake Burullus, one of the Mediterranean eutrophic lakes, is one of the major disposal areas for agricultural drainage water in Egypt. It receives approximately 4 billion m^3 of drainage water per year from the Nile Delta agricultural lands [19], which accounts for 97% of the water inflow [20, 21]. The lake receives discharges through drains, namely, West El-Burullus, Nasser (in the eastern side of the lake), Gharbia drain, El-Kashaah Drain, Tirrah Drain, Drain 7, Drain 8, Drain 9 (drains 7, 8, and 9 found in the southern side of the lake), El-Hoks Drain, and Brimbal Freshwater Canal (in the western extremity of the lake) [22]. Drainage water is discharged into the lake through a group of pumping stations at the end tail of the drains except for Gharbia drain which discharges its water freely without pumping [22]. The lake is connected to the Mediterranean Sea via Boughaz El-Burullus at the northeastern part of the lake [23].

El-Manzala Lake is one of the most polluted lakes in Egypt. The lake's hydrological and water quality status has been degraded due to the progressive increase of industrial and agricultural wastewater discharge. The most widely recognized issue is that the agricultural drains, industrial and domestic waste as Hados, Bahr El-Baqar Ramses drains were open into the southern part of the lake. Also, Fareskour, Elserw, Mataria [24–26].

3 Bottom Sediment in Lakes

3.1 Lake Mariout

Lake Mariout also spelled Mariout or Mariut or Maryut is a brackish lake in northern Egypt between Alexandria and Al-Buhira (see Fig. 2). It is located on the west side of the delta between latitude 31° 07′ N and longitude 29°57′ E along the Mediterranean coast of Egypt. It is the smallest of the northern lakes and maybe the most threatened. The lake is shallow with a depth of approximately 1.5 m [27]. The lake was formed at least 6,000 years ago. The present lake represents the ruminant of a huge ancient prehistoric Lake Mareotis. Canals divide the lake waterbody into several basins. There are three main inflows to the Lake Mariout: the Qala drain located to the northeast part of the lake, the Omum drain located at the east of the lake, and the Nubaria navigational canal located at the south of the lake. Besides, there are two minor inflows: one from the West Nubaria drain and, the second, from the West wastewater treatment plant [28, 29] (see Fig. 2).

The main basin (MB) of Lake Mariout is affected by the discharge of effluents from a primary wastewater treatment plant, direct discharge of industrial effluents, domestic wastes, and agricultural effluents.

The physical and chemical characteristics, as well as elemental concentrations in sediment, were studied by Hassan and Badran [30]. The results of the study revealed that the lowest metal pollutions are in the northeastern end of the lake and tend to increase toward the other end. Al, Fe, K, Mn, Na, B, and Cr are more likely to exist in

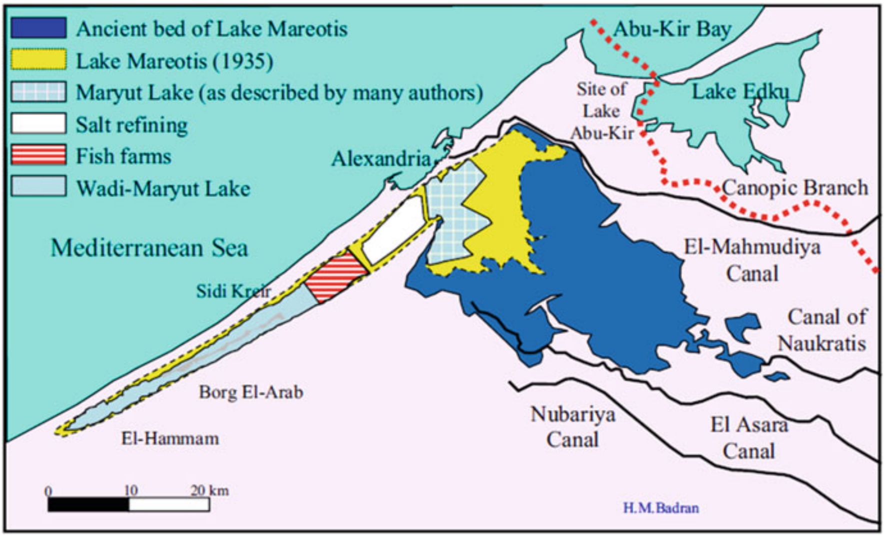

Fig. 2 The present-day waterbody including the main basin of the lake described by many authors as Mariout Lake, salt land, fish bonds, and the western arm (Wadi Mariout Lake) superimposed on the map of Lake Mareotis and its ancient bed according to [30] (original source [31])

the insoluble form in the southwestern part and in soluble form in the northeastern part. The geoaccumulation index suggests that two locations have the low anthropogenic influence of Pb, and the enrichment factors and the degree of contamination indicate that Co and Pb may be enriched in the sediment of some locations. Comparisons with consensus-based sediment quality guidelines revealed that no sample exceeded the probable effect concentration for Cr, Cu, Ni, Pb, and Zn. In Khalil et al. [32] study, the geochemistry of some major and trace elements in sediments of Mariut had been determined. “The metal concentrations inside Lake Mariout varied from 0.29 to 1.13%, 0.08 to 0.32%, 8.4 to 16.3%, 1.9 to 6.7%, 17.92 to 116.40 μg/g, 68.59 to 309.79 μg/g, 0.63 to 17.19 μg/g, 0.34 to 35.67 μg/g and 0.04 to 4.92 μg/g for Na, K, Ca, Mg, B, Li, Co, Bi and Se, respectively” [32]. Sediments were contaminated with Se and Bi which might be affected by municipal discharges, industrial development, agricultural drainage, and fish farms. Soliman et al. [33] investigated the phosphorus (P) fractions and their bioavailability in the sediments from Lake Mariout. Summation of the bioavailable P fractions did not exceed the sediment quality guidelines, and, therefore, P does not represent a danger to marine organisms. Correlation coefficients showed no apparent relations between total P (TP) and iron (Fe), aluminum (Al), and calcium (Ca) in the sediments. Fe:P ratio was less than 15 indicating that there was not enough Fe in surface sediments to bind to P at most of the sampling sites. The positive correlation between TP and organic matter (OM) for Lake Mariut sediments indicated that the organic matter content of the sediment was a useful predictor of the total phosphorus content.

“Hydrophobic organic compounds, such as polycyclic aromatic hydrocarbons (PAHs) and polychlorinated biphenyls (PCBs), bind strongly to sediments. They can thus serve as a long-term source of contaminants in waterbodies and biota long after the original source has been removed. Advances in analytical techniques make it possible to measure even the smallest amount of anthropogenic contaminants present in sediment” [34]. Organochlorine compounds (OCs) had been investigated by [35] in the sediment samples collected from Lake Mariout. The highest concentrations of OCs were found at stations close to discharge point of sewage and near the industrial areas. Contamination levels of sedimentary PCBs and DDTs can be categorized as moderate to high compared to other urbanized regions worldwide. Concentrations of PCBs and DDTs were higher than other OCs, ranging from 3.06 to 388 and from 0.07 to 106 ng/g dry wt., respectively. The distribution of DDT and its metabolites suggest no recent inputs into the lake environment. Temporal trends in OCs levels were influenced by input pathways at two sites. Detection of the levels of phenolic compounds (chlorophenols, methylphenols, and nitrophenols) in sediments was carried out by [36] in Lake Mariout. Chlorophenols (CPs) were the major group detected in the lake sediments followed by methylphenols (MPs) and nitrophenols (NPs). CPs were dominated by 2-, 4-, and 3-chlorophenols, and they were higher at the north and northwestern parts of the main basin of the lake which is affected by the direct discharge of industrial effluents, domestic wastes, and agricultural effluents from Qala drain (QD). On the other hand, NPs’ higher concentrations were observed in the south and southwestern parts of the main basin which are affected by the discharge of agricultural and domestic effluents. The risk assessment revealed that phenol, cresols, 2,4-dinitrophenol, 4-NP, 2-CP, 2,3,4,6-tetrachlorophenol, and 2,4-dimethylphenol are contaminants of concern and that adverse ecological effects could occur to benthic species from the exposure to these pollutants in Lake Mariout [36].

Although the inorganic contaminants in the lake sediment did not exceed the permissible guidelines, it has to be monitored continually. On the other hand, the organic contaminants discharged from the industrial effluents, domestic wastes, and agricultural effluents will have adverse ecological effects on the benthic species due to its exposure to these pollutants in Lake Mariout.

3.2 *Lake Edku*

"Lake Edku lies in the north of the Nile Delta, west of the Rosetta branch between Long. 30° 8′ 30″ & 30° 23′ 00″ E and Lat. 31° 10′ & 31° 18′ N (see Fig. 3). It is one of four coastal deltaic lakes that are connected to the Mediterranean Sea. Its area has decreased from 28.5×10^3 to about 12×10^3 Feddans (is an area unit equals 4,200 m^2) as a result of agricultural reclamation. The lake can be divided into three ill-defined basins; eastern, central and western. Lake Edku receives huge amounts of

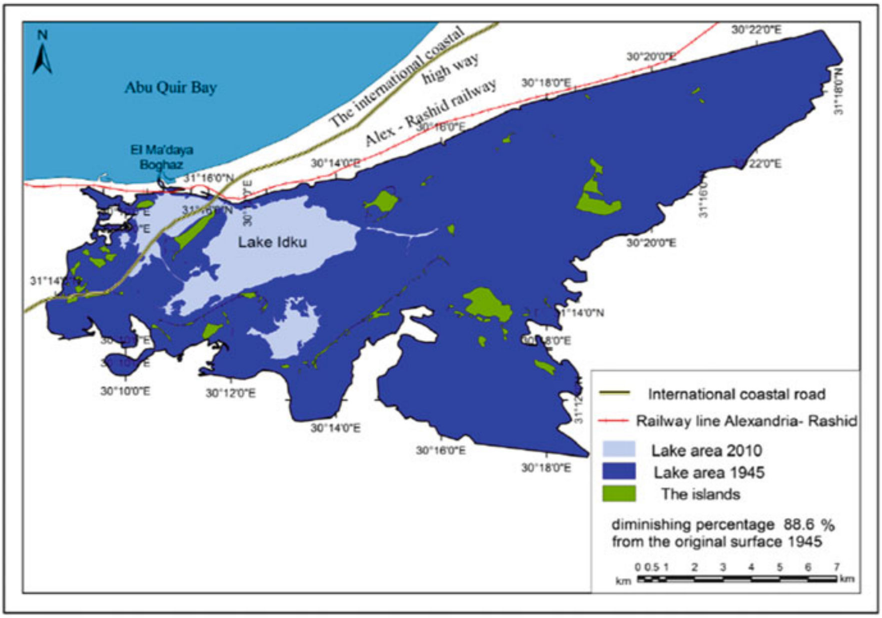

Fig. 3 Change of spatial boundaries of the environmental system of Edku Lake between 1945 and 2010 [39]

drainage water from three main drains, namely Berzik, Edku, and El-Boussili, which open into the eastern basin of the lake" [37, 38].

Edku is one of the northern Nile Delta lakes in Egypt that receives input from numerous anthropogenic activities in addition to agriculture wastes through several huge drains. The drainage water came from three main drains, namely, Berzik, Edku, and El-Boussili, which open into the eastern basin of the lake [10].

The distribution of organic matter, carbonate, phosphate, calcium, magnesium, and the heavy metals (Fe, Mn, Cu, Zn, Pb, Cd, Cr, Co, Ni) in the sediments of Lake Edku was studied by [40]. Organic matter, carbonate, phosphate, and studied metals were affected by the agriculture and domestic effluents. Organic matter precipitated in the surface sediment, and it had an irregular trend. In spring, percentage of carbonate, levels of Fe, Zn, Mn, Cu, and Cr were increased. Saeed and Shaker investigated Fe, Zn, Cu, Mn, Cd, and Pb in sediments from Lake Edku [41]. Mn in sediment samples recorded higher values than the sediment quality guidelines. Khalil et al. [32] studied the geochemistry of some major and trace elements in sediments of Edku. The metal concentrations varied from 0.30 to 1.19%, 0.13 to 0.38%, 4.9 to 16.8%, 1.8 to 7.9%, 21.95 to 66.22 μg/g, 61.00 to 145.94 μg/g, 7.43 to 24.79 μg/g, 5.99 to 13.40 μg/g, and 0.12 to 1.39 μg/g for Na, K, Ca, Mg, B, Li, Co, Bi, and Se, respectively. The sediments were contaminated with Se and B which might be affected by man's activities [42]. In [43], they evaluated the fractionation of metals (Fe, Zn, Cu, Pb, Cd, and Ni), volatile acid sulfide (AVS), and simultaneously extracted metals (SEM) in Edku lagoon sediments. Five stations near the drains exhibited 10% toxic probability according to the interim sediment quality guidelines (ISQG), but the evaluation of USEPA showed all sediment samples $\sum$SEM/AVS < 1 and ΣSEM–AVS < 0, and this indicates that Edku lagoon sediments did not cause any adverse effects. The calculations of the global contamination factor (GCF) and the individual contamination factors (ICF) using fractionation technique gave values of 111.644 and 84.555 in El Bosily drain and station I near the cages of the fish farm, respectively, due to possible contamination. Waheshi and his colleagues determined and assessed heavy metal content (Fe, Mn, Zn, Cu, Ni, Cr, Co, and Pb) in the sediment of Lake Edku [18]. The metal content in the lake sediments had a descending order of Fe $>$ Mn $>$ Cr $>$ Co $>$ Zn $>$ Cu $>$ Ni $=$ Pb, while the enrichment factor of the study area (EF mean values) has the order of EFCo $>$ EFMn $>$ EFPb $>$ EFCu $>$ EFCr $>$ EFZn $>$ EFNi. The study area may be practically unpolluted with Fe, Zn, Ni, and Cr (*Igeo ranged from* -2.15 to -0.41) according to the geoaccumulation index (*Igeo* classification). On the other hand, the *Igeo* of Co ranged from moderately to strongly polluted area. Also, a lower degree of pollution was found in the sediments by the other heavy metals: Pb and Cu (unpolluted to moderate). The pollution load index (PLI) indicated that station IX was characterized by low level of PLI with a value of 1.25, while the other stations ranged from 1.50 to 1.67. Interestingly, the collected data refer that the mobility and bioavailability of heavy metals in Edku lagoon sediments posed a low risk of adverse biological effects due to cadmium, copper, lead, nickel, and zinc in all evaluated studies.

As the geochemical studies are very important in environmental legislation because it recommends limits for heavy metals in contaminated areas and other surficial materials as defined by environmental authorities, the study of the persistent organic pollutants is also considered to be very important for the same reason. Abdallah and Elmagd Morsy [44] evaluated the persistent organochlorine pollutants and metal residues in sediment. Residues of persistent organochlorine (OC) pollutants, polychlorinated biphenyls (PCBs), 1,1,1 -trichloro-2,2-di (4-chlorophenyl)ethane (DDT), total cyclodienes (TC), hexachlorocyclohexanes (HCHs), and heavy metals (Cu, Cd, and Pb) were detected in the sediment samples. In all sediment samples, PCBs were found in higher concentrations than pesticides. The mean concentrations of PCBs and pesticides in sediments are 539.66 ± 48.8 and 259.17 ± 81.2 ng/g dry weight, respectively. As for the concentration of the studied metals in sediments of Edku lagoon, results showed that copper had the highest concentration (2.2 ± 0.37 μg/g) in the lake sediment.

3.3 *Lake Burullus*

Lake Burullus (or Burullus Lagoon) is a protected area located toward the east of the Rosetta branch of the River Nile in Egypt (see Fig. 4). "Around the early 1900s, it

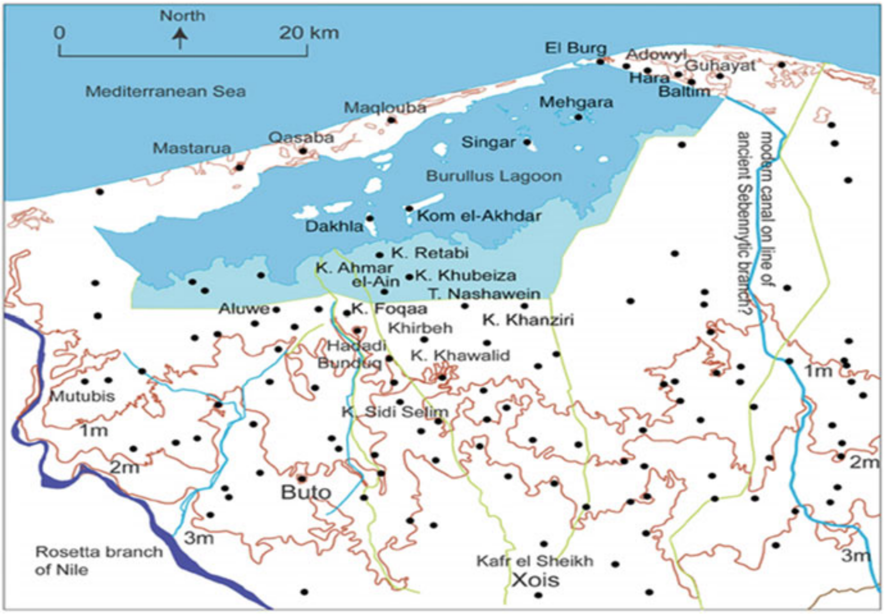

Fig. 4 Lake Burullus boundaries and min surrounding cities

had a surface area of about 600 km^2, by 1974, land reclamation for agriculture in its southern sector had caused it to decline to about 460 km^2, and this decline continues today Its long axis" [45]. The lake is rather elongated, and there are around 50 islands scattered over it. It is situated between the River Nile branches and is separated from the Mediterranean Sea by a strip of sandy land (see Fig. 4). The lake is about 60–70 km in length, and its width is between 6 and 16 km, with the average being 11. The lake is extremely shallow, and water depth varies from 0.4 to 2.0 m from west to east. The deepest part is in the western sector, which is also the freshest, while the eastern sector, which contains a 250-m-long canal connecting Burullus to the sea (Bughaz), is shallow and saline [46].

Distinguishing physical features of lakes, which include relatively low flow velocities, often qualifies lakes to act as sinks for nutrients, toxicants, organic matters, and other substances that produce significant water quality problems.

Several sediment samples in Lake Burullus have been affected by the discharges of organic and inorganic contaminants through different drains.

Sediments of Lake Burullus were derived mainly from one source which is dominated by mafic components. They are most probably derived and related to the Quaternary Nile sediments. The heavy mineral assemblage recorded from Lake Burullus sediment was particularly enriched with unstable minerals (pyroxenes and amphiboles and epidotes) accompanied by lower contents of ultrastable minerals (zircon, tourmaline, and rutile), reflecting a provenance dominated by basic igneous rocks. The clay mineral suit detected in Lake Burullus was uniform in most of the lake. It is dominated by smectite with a subordinate amount of kaolinite and lesser illite contents. Owing to a wide variety of grain sizes and organic matter, metals showed the order of abundance: Fe $>$ Mn $>$ Zn $>$ Cu $>$ Cd $>$ Pb. There was a significant correlation between iron with clay, organic carbon, and manganese which gives an idea about the association of iron and manganese as main compositions of clays. On the other hand, there was an insignificant relation with total carbonate and all phosphorus forms [47, 48]. "The spatial distribution of pollutants within the lake indicated that the highly polluted areas are located close to the drains, whereas as the less polluted areas were close to El-Boughaz" [49]. The eastern and eastern southern parts of the lake have higher concentrations of heavy metals than the western and middle one. Cd and Pb were the common pollutants in lake sediments. Cadmium was the most enriched element in the lake sediments due to industrial and agricultural wastes drained into the lake [23, 50].

The concentrations of individual PAH recorded in sediment ranged from non-detectable levels to 17,556 ng/g dry weight and were much lower than the ERM values. High concentration of DBA (above the ERM value) at some locations of the lake were observed. PCB concentrations ranged from 4.6 to 213.9 ng/g with an average of 47.2 ng/g dry weight. Total pesticides were higher than PCBs for mostly all sediment samples of Lake Burullus [51, 52].

3.4 Lake Manzala

El-Manzala Lake is one of the most important lakes in North Delta of Egypt. Lake Manzala is located in the northeastern extremity of the Nile Delta (see Fig. 5). Its northern border is a narrow sandy fringe which separates the lake from the Mediterranean Sea. It is bordered by the Suez Canal to the east, Damietta Branch of the Nile to the west, and cultivated lands to the south. It is the largest shallower lakes which is located between latitudes (31E10″ to 31E40″ N) and longitudes (31E50″ to 32E25″ E). It covers an area of approximately 100,000 ha and has a maximum length of 64.5 km, a maximum width of 49 km, and a total shoreline length of 293 km. The lake is shallow ranging between 20 and 200 cm. It contains numerous islands which consist of former shorelines, sand dunes, and clay hummocks. Fresh and drainage water flows to the lake via seven main sources (Fig. 5). The total annual input from these is approximately $6,657 \times 10^6$ m^3. Bahr El-Baqar and Hados drains contribute about 75% of the total inflow. Bahr El-Baqar drain (Fig. 5) carries the partially treated sewage of Cairo. Sewage from Port Said, Damietta, Matariya, Manzala, and Gamaliya is also discharged into the lake. These flows constitute an important source of nutrients to the lake, which in turn promote the high level of fish productivity [53, 54].

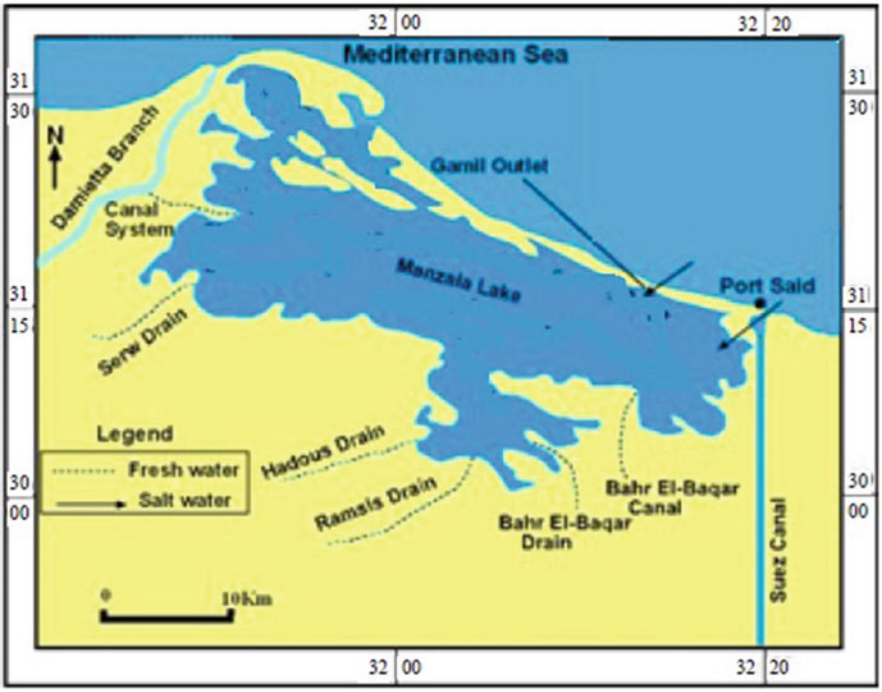

Fig. 5 Lake Manzala outlines with sources of fresh and drainage water

Manzala lagoon is a tectonically subsiding basin, receiving increased wastewater discharge from the south and seawater driven across the eroded coastal ridge system in the north. However, instead of becoming deeper, the lagoon Delta has become a sediment sink of reduced area and depth, with increased contaminant due to increasing sedimentation rates into a decreasing lagoon area [55]. The predominant type of sediment was intercalation of silt and clay. The highest concentration of organic matter in sediments is found in cores 1 and 7. The highest concentration of calcium carbonate in sediment is recorded in core 1 [56].

The highest concentrations of heavy metals were observed in the northeastern and the southern parts of the lake nearby drains. Industrial, agricultural, and municipal wastes coming through the drains especially Bahr El-Baqar drain also industrial wastes coming from Port Said drains to the same drain. In many studies, high level of metals (Cd, Zn, Pb, Fe, Mn, and Cu) is found above the permissible limits except Pb, but the geoaccumulation index (Igeo) results revealed that the lake was polluted with Cd and Pb. High levels of Cd can be attributed to the use of phosphate fertilizer [25, 56–58]. The Hg showed the highest values and alarming toxicity levels, and it is considered as one of the most hazardous. El-Badry and Khalifa found the arsenic content ranges from 4.6 to 22 ppm, averaging 12 ppm, about eightfold the average Earth's crust [54]. Selenium concentrations range from 3 to 5 ppm averaging 4 ppm, about 80-fold the average Earth's crust. Tin in studied lake ranged from 25 to 90 ppm with an average of 46 ppm, about ninefold the average Earth's crust. The highest values for arsenic selenium and tin are extended toward the industrial area in Port Said Governorate. It is found that the MI and PI values confirm that most sites of aquatic utilizations are highly polluted with the mentioned metals (Fe^{+2}, Mn^{+2}, Cu^{+2}, Zn^{+2}, Pb^{+2}, and Cd^{+2}), and this is attributed to discharging of the effluents of different industrial wastes into the lake [26].

Persistence of the residue of organochlorine pesticides (OCPs) and polychlorinated biphenyls (PCBs) became a great danger to our environment long ago. Geographical distribution indicates that levels of contaminants were significantly higher in areas which are mainly influenced by municipal discharge, indicating significant sources of these compounds in urbanized areas. Generally, the data of many studies proved that the sediment layer plays a sourcing role in OCP persistence in the aquatic ecosystem. The profiles of $\sum$OCPs and $\sum$PCBs in a core from the sites heavily impacted by sewage discharge had highest concentrations in the surface core section indicating recent inputs and confirm that OCP contamination in the Manzala Lake ecosystem had an external source. The residues of OCPs in the sediment samples were significantly high. A relatively high concentrations of chlorpyrifos, $\sum$DDT, and HCB were found, particularly at the Bahr Al Baqar drain station, which has uncontrolled inputs of untreated domestic, agricultural, and industrial wastes. Sediment from the Bahr Al Baqar drain exceeded the probable effect level (PEL) for DDT isomers 2,4′ and 4,4′. Ratios of DDT to its metabolites suggest that the source of $\sum$DDT was from past usage of technical DDT in the regions surrounding the lake which mean that the composition of DDT and its metabolites were the old input of

DDT. Sediment quality guidelines were exceeded in 88, 75, and 42% of sediments for the effect range low (ERL) for ∑PCBs, ∑DDT, and *4,4′*-DDE, respectively [59–61].

The levels of PAHs were significantly lower compared to the values reported in several coastal/estuarine areas (e.g., in Spain, Italy, the USA, and Egypt) receiving substantial anthropogenic inputs from urban and industrial activities. The highest values corresponding to urban hot spots with high anthropogenic input coming from wastewater discharges and combustion activities and decreasing offshore. Source ratios indicated that the PAHs were mainly from petrogenic sources in near-shore urban hot spots, with higher contributions of pyrolytic sources in coastal and offshore areas which are little influenced by human activities. Sediment quality guidelines (SQGs) showed that except at the stations heavily impacted by sewage discharge, the total and individual PAH concentrations were below effect range low (ERL) concentrations that are not likely to adversely affect benthic biota [62]. Assessment of ecotoxicological risk indicated that sediments in the lake were likely to pose potential biological adverse impact.

3.5 Lake Bardawil

Bardawil Lagoon in North Sinai, Egypt, is a unique Mediterranean semi-enclosed coastal waterbody that is listed among the Ramsar Wetlands of International Importance. It was also known as “Sabkhat El-Bardawil,” due to the intermittent connection with the Mediterranean. Previously, it was also known as “Lac Sirbonis” [63] that seems to be an old Roman name [64]. In 1953, two artificial inlets (Boghaz I and Boghaz II) had been dug, connecting the Sabkha with the Mediterranean Sea to secure its permanent connection to the Mediterranean, decrease the salinity of the lagoon, and allow the natural immigration of fish into it [65, 66]. Bardawil Lake protrudes into the Mediterranean with a smooth convex coastal barrier that extends for 85 km from east to west. On the contrary, the southern shores are irregular due to the effect of pre-lake topography, of which sand dunes of North Sinai Sand Sea are the most effective (Fig. 6). Based on satellite image interpretations and GIS techniques, the lake has a maximum width of 20.5 km from north to south along the longitude 33,100 E, covering an area of 629 km^2, and the length of its inner shores is 611 km. Using solid model surface analysis (true 3D models), the average volume of the lake was estimated as 193 $\times$ 10^6 m^3. Generally, the lake is very shallow, with a mean depth of around 1.5 m and a maximum of 7.5 m. Maximum depth in Boghaz (II) is 5.75 m due to dredging. Areas with depths less than 1 m occupy about 20% of the lagoon area, whereas areas with depths between 1 and 1.5 m constitute 65% of the lagoon area, and those deeper than 1.5 m cover 15% only of the lagoon. The results of a survey of depths of the lake showed that the shallowest parts lie in the extreme eastern and western parts and the southern shores of the lagoon basin (The Maritime French Company for the Survey of Bardawil Lake, 1982). Islands

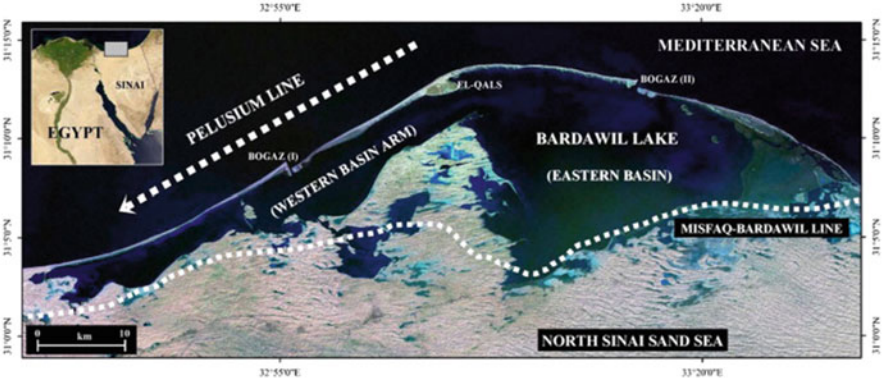

Fig. 6 Enhanced ETM mosaic shows the location of Bardawil Lake and the general structure (Dashed lines approximately show major lineaments after [64, 67])

represent one of the prominent features of the lagoon, with about 50 islands, covering an area of 2.1% of the total area of the lagoon [57].

The lake sediments are mainly characterized by ultrastable minerals such as zircon, tourmaline, and rutile. In addition, minor component of pyroxenes and amphiboles, minerals of metamorphic affinity such as staurolite and garnet constitute a recognizable part of the total non-opaque fraction [68]. Lake Bardawil clay minerals were a mixture of kaolinite, smectite, and illite. The mineral contents were different from location to another one reflecting variability in source rocks. The smectite was in the western area, while illite increases in the eastern part of the lake; however, kaolinite was notably found as a part of the sediment [68, 69]. Bardawil Lake sediments reflect derivation from more than one source; they originated mainly from reworked sediments especially Nubian sandstone and high-rank metamorphic and basic igneous rocks derived from the neighboring sand dunes. Fluvial Neolithic sediments must also be considered as an important additional source [48]. Higher $CaCO_3$ percentage was found in Bardwell Lagoon sediments at the salt pans where there are biogenic calcareous components and carbonate rock fragments in sufficient quantities [70, 71]. Based on high C/N ratios, the organic carbon fraction of surface sediments is dominated by the terrigenous material. The distribution of Al, Fe, Mg, and Ti is essentially controlled by the mineralogy of the sediments. The ratios of Ba, Sr, Cu, Mn, Pb, and Mo to Al are all high in the salt pans and reflect changes in mineralogy and sediment texture [66]. High levels of Cu, Pb, and Cd were observed in the western sector of the lagoon which is affected by seawater through Boughaz I, while Fe, Zn, and Mn were observed in the eastern area, which is highly affected by seawater through Boughaz II [72]. The different metal concentrations could be arranged in descending order as follows: Ca $>$ Na $>$ Fe $>$ Mg $>$ K $>$ Mn $>$ Cu $>$ Zn $>$ Pb $>$ Cd [73]. Metal concentration in the exchangeable and carbonate fractions was found in the following order: Fe $>$ Pb $>$ Cu $>$ Cd, whereas they follow the order of Fe $>$ Cu $>$ Pb $>$ Cd in the oxide fraction. In the organic form, metals had the sequence of Fe > Pb ≈ Cu > Cd. The sequences of metal concentration in the residual fraction were as follows: Fe > Pb > Cu > Cd. The results of Pb and Cd fractionation reflect the dangers of these metals which more than 75% are associated with the non-residual fractions [71].

4 Conclusions

Sedimentation plays an important role in the recognized changes in the aquatic vegetation and the increase of organic productivity. Also, the situation of the lake sediments reflects the severe contaminations they suffer from the organic contaminants that enter the lakes and affect the marine life. Therefore, the sediment properties are considered an acceptable indicator of the water status and can be used as an indicator for pollution of the lakes. Recently, it can be noticed that Lake Burullus recorded the highest values of Cu, Zn, and Pb. However, Lake Edku found to have the highest values of Fe, Mn, and Cr. Co and Ni got the highest records in Co and Ni values, while Bardawil had the highest value of Cd. Lake Mariout got the highest range values for the organic contaminants, and Lake Manzala recorded the highest values of Pb. Although the inorganic contaminants in the lake sediment did not exceed the permissible guidelines, it has to be monitored continually.

4.1 Recommendations

- It is very important to identify the key influencing factors that control the sedimentation rate and the sediment properties to protect and enhance the status of the shallow deltaic coastal lakes in Egypt.
- It is advised to establish spatial monitoring framework (surface sediment grab samples). Following the data collecting process, it is important to establish effective networking, information exchange, and coordination among concerned parties.
- It is essential to encourage the scientific community to engage in the development process of increasing the public awareness and participation in monitoring programs.
- Because agriculture is the main source of heavy metals, nutrients, and other pollutants, substantial changes may be required in the use of fertilizers in agriculture.

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Physical and Chemical Properties of Egypt's Coastal Wetlands; Burullus Wetland as a Case Study

Magdy T. Khalil

Abstract Egypt's coastal wetlands are located along the Mediterranean coast; four in the northern part of the Nile Delta (Manzala, Burullus, Mariout and Edko) and one in the northern part of the Sinai (Bardawil). According to the map of the world distribution of arid areas, northern Egypt belongs to the Mediterranean arid region. The climatic conditions are warm summer (20–30°C) and mild winter (10–20°C). The aridity index ranges between 0.03 and 0.2 in the northern areas and less than 0.03 in the south (hyperarid region).

In the Delta wetlands, the annual mean water temperature is 22.3°C, while the annual mean water transparency and water depths are 31.0 and 115.8 cm respectively. The annual mean water chlorosity is 1.9 g l^{-1}, while in Bardawil salinity ranges between 38.5 and 74.5‰. Water in these wetlands is alkaline throughout the year. The annual mean pH is 8.6. On the other hand, the annual mean alkalinity was 257.8 mg l^{-1}.

The annual mean dissolved oxygen (DO), chemical (COD) and biological (BOD) oxygen demands are 8.6, 4.6 and 3.6 mg l^{-1}, respectively. The concentrations of dissolved salts have the following sequence: $SiO_2 > NO_3 > PO_4 > NO_2$, with annual means of 41.7, 2.8, 1.2 and 1.1 µg-at. l^{-1}. The concentrations of heavy metals have the following sequence: Zn > Fe > Cu > Cd > Pb, with annual means of 8.5, 6.2, 5.9, 3.8 and 3.6 µg-at. l^{-1}. Most of the estimated heavy metals of the water near to the southern shores were higher than those near the northern shores due to pollutants of drainage water. The comparison of the dissolved salts in the water of Delta wetlands in 2015, with those of the 1980s, indicates a tremendous increase due to an increases of agricultural drainage waters that are rich in fertilizers and discharge into these wetlands from the southern drains.

Keywords Burullus, Chemical characteristics, Mediterranean coast, Physical properties, Wetlands

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Contents

1 Introduction

Egypt has an extensive surface area of coastal wetlands (roughly 2,500 km^2); the most characteristics of these are found in Delta region (Fig. 1). Manzala, Burullus and Edku Wetland are similar in that they are permanently connected to the open sea by a narrow natural channel (Boughaz). The Mariout Wetland, on the contrary, is permanently cut off from the sea by the Mex pumping station; its surface level being maintained at up to 3 m below sea level. All these wetlands are shallow (<3 m deep), fluctuating seasonally and varying in salinity from 2.5 to 28.5%. Physical, chemical and biological characters are similar in these wetlands. Therefore, we will focus on the most important wetland, i.e. the Burullus one.

The Burullus Wetland has rich productivity; sources and transformers of numerous biological, chemical and genetic materials and valuable habitats for wildlife and fisheries. Moreover, it is an internationally important wetland for wintering water birds. Consequently, Bird Life International has designated it as an Important Bird Area (IBA).

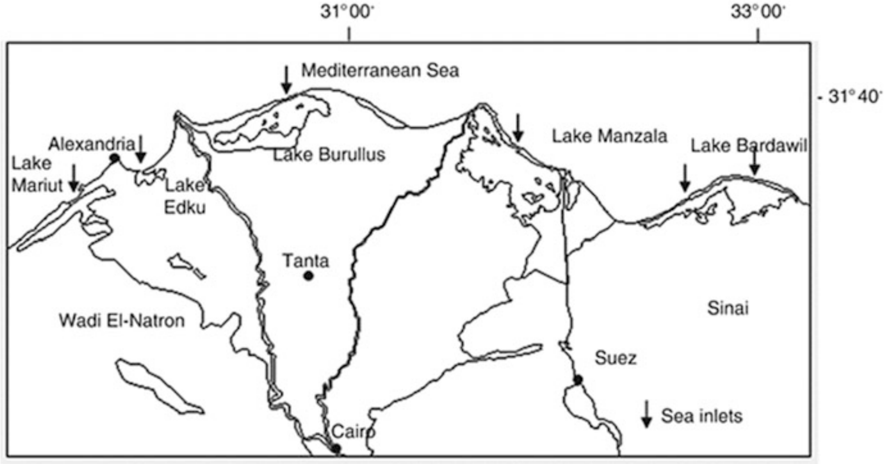

Fig. 1 Northern part of Egypt showing the coastal wetlands

Therefore, Conservation associations worldwide have noted and described the alarming changes in these important habitats. This led to the Convention on Wetlands known as RAMSAR Convention in 1971, and it was declared as a natural protectorate in 1998.

The Burullus Wetland is formed along the Mediterranean coast in the northern part of the Nile Delta. It is bordered from the north by the Mediterranean Sea and from the south by the agricultural lands of the north Nile Delta. The Burullus Wetland belongs administratively to Kafr El-Sheikh Governorate. It lies centerally between the two branches of the Nile: Damietta to the east and Rosetta to the west. Its coordinates are 31° 36′ N and 30° 33′ E in north-west, 31° 36′ N and 31° 07′ E in the north-east, 31° 22′ N and 30° 33′ E in the south-east, 31° 22′ N and 31° 07′ E in the south-east. It has a total area of 460 km^2, which includes the entire area of Burullus open area with numerous islets insides it, as well as the sandbar separating the lake from the Mediterranean Sea, with a shoreline of about 65 km (Fig. 2).

1.1 Shape and Dimensions

The shoreline of Burullus Wetland takes several forms related basically to its formation, origin, and evolution. It has an oblong shape that extends for a distance of 47 km along NE-SW axis (Fig. 1). The width of the wetland from north to south varies from one site to another. The western sector has the least width which does not exceed 5 km, then its increases in the middle sector to reach an average of 11 km. As the area of the wetland changed with time, its dimensions changed also. It is obvious that the lake size had decreased from 502.7 km^2 in 1984 to 410 km^2 in 2015 (i.e. 18.4% reduction), the maximum length from 56 to 47 km (16.1% reduction) and the maximum width from 15 to 14 km (6.7% reduction). It is clear that Burullus

Fig. 2 Burullus Wetland at the Mediterranean Sea coast

Table 1 Evolution of the size of Burullus Wetland during the period from 1802 to 2015 [2]

	Year						
Character	1801	1913	1959	1962	1972	1984	2015
Area (km^2)	1,092	556.5	546.3	592.9	502.7	440	410
Reduction (%)	–	49.0	50.0	45.7	54.0	59.7	62.5

Wetland lost about 49% of its size during 112 years from 1801 (1,092 km^2) to 1913 (556.5 km^2), and about 62.5% by 2015 (410 km^2) (Table 1 and Fig. 3).

The change in the size of the wetland basin is associated with changes in the prevailing natural phenomena. The rate of these changes was assessed using the GIS and remote sensing techniques [1]. The human impact in reduction of the size was represented by removal of sand dunes in some parts of the marine bar between the Mediterranean sea and the wetland and cultivation of some crops in the dried parts of the wetland (e.g. grapes and watermelons). Moreover, increase of the swamps and salt marshes particularly along the south-east and south-west areas and increase of the cultivated lands and human settlements contribute to this reduction.

1.2 Wetland Depth

Burullus Wetland is a shallow ecosystem; its depth varies between 40 cm near the shores and 200 cm near the sea outlet (Boughaz El-Burullus). Its main basin is classified into three sectors (eastern, middle and western), each with some homogeneity in hydrology, biology, and geomorphology. Remote sensing studies indicate that the deepest parts were in the middle sector of the wetland, where the depth

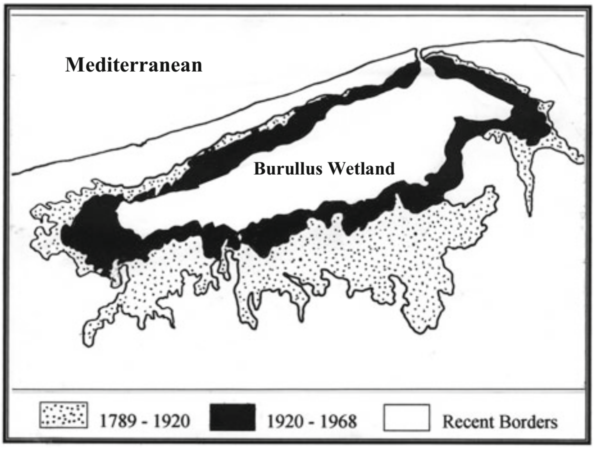

Fig. 3 The lost area from Burullus lake during the period from 1789 to 2015 [2]

reached 2 m, and also the southern parts of the western sector. The eastern sector is the shallowest where the depth does not exceed 20 cm near the shore but increases westwards until it reaches about 70 cm. Due to the continuous morphological and water budget changes, particularly after constructing many irrigation and drainage projects, and silting of Boughaz El-Burullus, the depth of the wetland changes from time to time. The changes that happened during the period from 1984 to 2015 were studied using GIS. The hypsographic analysis indicated that the contour line zero (i.e. the shoreline of the wetland) is about 143.5 km. The area between the shoreline and 75 cm depth approximates 58% of the total area of the wetland (236.6 km^2 out of 410 km^2). Thus, it seems that the wetland lives its senility stage particularly with the continuation of drying and silting up processes which lead to the increase of shallow areas; the areas deeper than 130 cm have already decreased to about 20.6 km^2 (5% of the wetland size) [2].

Being so shallow, there is a rather broad ecotone between the dry land and the wetland; most of which is overgrown with *Phragmites* reeds. There are also several large and countless small islands, and large parts of the wetland are invaded by floating, emergent, and submerged water macrophytes.

A canal (Brimbal), connecting Burullus to the Rashid branch of the Nile, used to supply up to half the fresh water of the wetland; after 1964, this amount of water rapidly declined to 5% because the Rosetta (Rashid) branch of the Nile was largely inactivated. This small amount of brackish water has only a negligible influence on the wetland. Agricultural drains are the main source of fresh water in the wetland, and they have now taken over the function of Brimbal.

The year 1964 was the last one with an unregulated Nile flood, and by 1967, all water reaching the Nile delta area was used for irrigation purposes. The contribution from the Nile via the Brimbal canal rapidly dropped, and the southern sector of the wetland started receiving a steady inflow of agricultural and domestic drainage water through eight drains, instead of a flood waters. These are Drain 7, Drain 8, Drain 9, Teira drain; El-Khashaa drain, Burullus drain west, Burullus drain east and Huksa drain.

2 Physical and Aggregate Properties

2.1 *Climatology*

According to the map of the world distribution of arid regions [3], the northern part of Nile Delta belongs to the Mediterranean arid region. The climatic conditions are warm during summer (20–30°C) and mild during 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). Long-term climatic averages of three meteorological stations distributed within Burullus Wetland were used to draw their climatic profile.

In general, January is the coldest month, while July and August are the hottest. The annual mean maximum temperature varies between 24°C at Baltim and 27.4°C at Sakha, and the minimum temperature varies between 12.9°C at Sakha and 17.3°C at Baltim. The annual mean wind speed varies between 2.9 knots at Sakha and 6.6 knots at Baltim. The annual mean relative humidity, evaporation and sky cover exhibit narrow ranges of variation among stations. The total annual rainfall has a maximum value at Rosetta (190.8 mm year^{-1}) and a minimum at Sakha (69.6 mm year^{-1}). The isohytes of the mean annual rainfall in Egypt [4] indicates that Burullus Wetland is among the isohyte 200 mm at its northern border and the isohyte 150 mm at its south (Fig. 4). In general, the distribution of the mean annual rainfall in this region shows a maximum close to the Mediterranean coast and then decreases rapidly toward the south. More than 80% of the rain falls during the winter, and less than 10% falls during the spring.

The mean annual evaporation is 1,583.3 mm. This value approximates about 646.5 million m^3 of water loss from Burullus Wetland. Maximum evaporation takes place during May–September, while the minimum occurs during December–February [5].

2.2 *Water Balance*

A water balance is often used to estimate the magnitudes of unknown hydrologic components such as outflow and change in storage within the wetland. To evaluate the change in storage for Burullus Wetland, the water budget was estimated as follows: $\mathrm{d}S/\mathrm{d}t =$ Inflow–outflow, where $\mathrm{d}S/\mathrm{d}t$ represents the change of storage within the wetland over a specified time interval, inflow represents water bodies contribution to the wetland, and outflow represents water losses and water interaction with the sea.

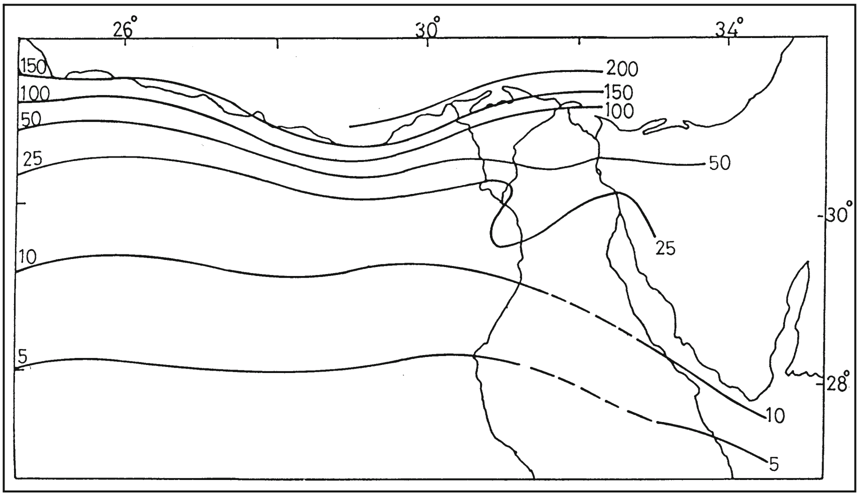

Fig. 4 The isohytes of the mean annual rainfall in Egypt (after Griffiths 1972)

Results of the annual water balance indicate that the drainage water contributes about 97%, while the contribution of rainfall is less than 2% and groundwater is less than 1% of the total water resources in the wetland ecosystem (Fig. 5). On the other hand, evaporation losses represent about 16% of the total water resources in the system, while the drainage system discharges about 3.2 billion m^3 to the sea through the wetland. This amount represents, in addition to the change of storage in the reservoir, about 84% of the total water resources in the system.

To re-establish the equilibrium status of salt balance in the wetland, 84% of the water resources should be discharged outside the lake. This represents about 3.4 billion m^3 annually. This volume of excess water resources within the system makes water level in the wetland during the whole year above the mean sea level. Accordingly, the salt balance in Burullus Wetland has been deteriorated. To make use of this huge amount of drainage water, it is recommended to convert this water to the areas of development projects at the east of the lake and to make use of Al-Moheet Drain to discharge water outside the wetland [5].

Volumes of outflow and change of storage represent monthly excess water to be used in developing plans. Due to the winter closure in January, the water level in the wetland becomes below the sea level with about 26 cm. This case allows sea water to move into the wetland with a volume of about 110 million m^3.

2.3 Water Temperature

The annual mean surface water temperature was 22.3 ± 5.2°C, with a minimum value of 21.8°C at the middle sector and a maximum of 23.3°C at the western sector.

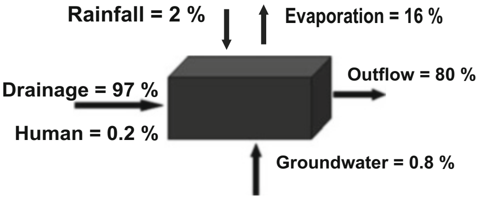

Fig. 5 Water balance in Burullus Wetland [5]

Regarding the variation from the eastern to the western sectors of the wetland, the annual mean was 22.9°C at the east, 22.2°C at the middle and 23.0°C at the west. On the other hand, the annual mean was 22.4°C at the north and 22.6°C at the south. The monthly surface water temperature ranged from a minimum of 16.0°C during February and a maximum of 29.4°C during June.

2.4 Water Transparency

In general, the transparency of the wetland water is affected by inflowing water from sea outlet (Boughaz Al-Burullus) and drains, wind action, and suspended matters [6]. The annual mean water transparency is 31.0 ± 11.1 cm, with a minimum value of 22.3 cm in the eastern sector and a maximum of 49.6 cm at the western sector. Regarding the variation from the eastern to the western sectors of the wetland, the annual mean is 26.3 cm at the east (the most turbid), 31.3 cm at the middle and 41.4 cm at the west (the clearest). On the other hand, the transparency decreases from north (39.7 cm) to south (25.1 cm). The monthly mean ranges between a minimum of 25.3 cm during March and a maximum of 40.0 cm during October.

2.5 Salinity

The salinity distribution in the water of Burullus Wetland, as noted in electrical conductivity measurements, is heterogeneous. This depends on the water drained by the drains and the fresh water of Berembal Canal, the water invading the wetland from the sea (Boughaz El-Burullus) and the degree of mixing. The annual mean water salinity was 5.4 ± 4.8 mS cm^{-1}, with a minimum of 1.6 mS cm^{-1} in the western section and a maximum of 16.8 mS cm^{-1} at the eastern sector (the nearest to the sea outlet). Regarding the variation from the eastern to the western sectors of the wetland, the annual mean decreased from the east (8.4 mS cm^{-1}) to the west (2.4 mS cm^{-1}), and from the north (5.7 mS cm^{-1}) to the south (4.2 mS cm^{-1}). The salinity decreases during March (3.9 mS cm^{-1}), and increases during January and February (6.6 and 6.7 mS cm^{-1}, respectively). Figure 6 shows how the average salinity levels of Burullus decreased dramatically from 14‰ in 1966 to 3‰ in 2015, due to increasing of drainage water discharge into the wetland [2].

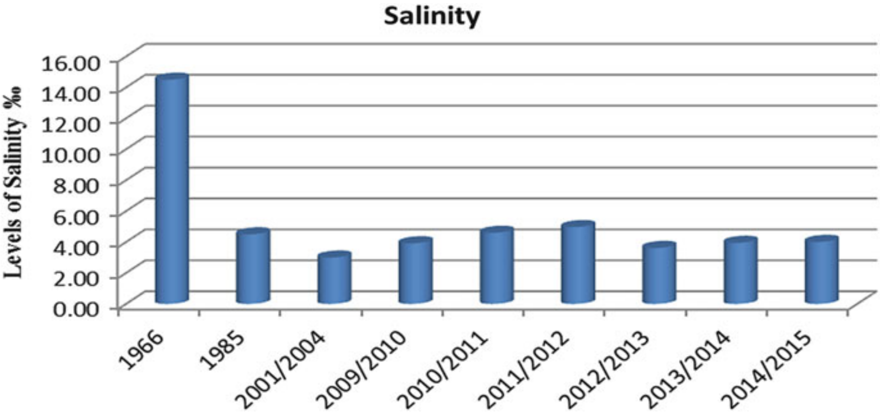

Fig. 6 Salinity levels in the Burullus Wetland during the period 1966–2015

2.6 *Chlorosity*

The annual mean chlorosity is 1.9 ± 1.8 g l^{-1}, with a minimum of 0.6 g l^{-1} in the western sector and a maximum of 6.6 g l^{-1} in the eastern sector. Regarding the variation from the east to the west, the annual mean was the highest in the eastern sector (3.1 g l^{-1}), and the lowest in the western sector (0.7 g l^{-1}). On the other hand, the chlorosity is slightly higher at the north (2.0 g l^{-1}) than the south (1.5 g l^{-1}). Temporally, chlorosity had the same trend of salinity where it decreased during March (1.3 g l^{-1}), and increased in January and February having 2.1 and 2.3 g l^{-1}, respectively [7, 8].

2.7 *The pH*

Water in Burullus Wetland is alkaline throughout the year. The annual mean pH is 8.6 ± 0.6, with a minimum of 8.4 in the western sector and a maximum of 8.9 in the middle sector. The variation from the eastern to the western sectors of the wetland indicated an annual mean 8.7 at the eastern and middle sectors and 8.5 in the western sector. On the other hand, pH was 8.7 at the north and 8.6 at the south. The monthly annual mean ranged between 8.0 during June and 9.2 during November [2].

2.8 *Alkalinity*

The annual mean alkalinity is 257.8 ± 53.7 g l^{-1}, with a minimum of 188.0 g l^{-1} in the western sector and a maximum of 309.6 g l^{-1} in the middle sector. Regarding the variation along the east-west axis, the middle sector had the highest alkalinity (274.4 g l^{-1}), followed by the eastern (266.9 g l^{-1}), while the western sector had the lowest one (208.9 g l^{-1}). On the other hand, the annual mean alkalinity increased from the north to the south (240.0 g l^{-1} at the north, 258.2 g l^{-1} at the middle and 272.4 g l^{-1} at the south of the wetland. This variable increased during August (272.0 g l^{-1}) and October (279.6 g l^{-1}) and decreased during March (213.7 g l^{-1}).

3 Oxygen Properties

These properties include dissolved oxygen (DO), chemical oxygen demand (COD) and biological oxygen demand (BOD). DO levels in natural and waste waters depend on the physical, chemical and biochemical properties. The analysis of DO is a key test in water pollution and waste treatment process control [9]. On the other hand, BOD is an empirical test used to determine the relative oxygen requirements needed for the biochemical degradation and oxidation of organic and inorganic materials. COD is a measure of the oxygen equivalent of the organic matter content of a water sample that is susceptible to oxidation by a strong chemical oxidant. For water samples from a specific source, COD can be related empirically to BOD, organic carbon or organic matter [2].

3.1 Dissolved Oxygen (DO)

The annual mean dissolved oxygen was 8.6 ± 2.3 mg l^{-1} [2], with a minimum of 6.6 mg l^{-1} in the eastern sector and a maximum of 10.4 mg l^{-1} the western sector. Regarding the variation from the eastern to the western sectors of the wetland, the maximum dissolved oxygen was observed in the middle and western sectors (9.1 and 9.0 mg l^{-1}, respectively), while the minimum was recorded in the eastern sector (8.1 mg l^{-1}). On the other hand, the dissolved oxygen decreased from north (9.5 mg l^{-1}) to south (8.0 mg l^{-1}). This trend may be related to the oxidation-reduction processes, as well as photosynthetic activities, which in turn correlated with a load of organic matters discharged into the wetland through the drains. The monthly mean dissolved oxygen varied between 10.2 mg l^{-1} in June and 7.5 mg l^{-1} in August.

3.2 Chemical Oxygen Demand (COD)

The annual mean chemical oxygen demand was 4.6 ± 1.7 mg l^{-1}, with a minimum of 3.6 mg l^{-1} in the eastern sector and a maximum of 5.4 mg l^{-1} in the eastern sector [2]. COD is slightly higher in the eastern and western sectors (4.7 mg l^{-1}) than the middle one (4.3 mg l^{-1}). On the other hand, COD is lower in the north (4.5 mg l^{-1})

than the south (5.0 mg l^{-1}). It had the highest value during August (6.4 mg l^{-1}) and the lowest during November (2.4 mg l^{-1}).

3.3 Biological Oxygen Demand (BOD)

The annual mean biological oxygen demand is 3.6 ± 1.6 mg l^{-1} with a minimum of 2.7 mg l^{-1} in the middle sector and a maximum of 4.6 mg l^{-1} in the same sector [2]. Regarding the variation along the east-west axis, BOD was similar to the chemical oxygen demand, where it was higher in the eastern and western sectors (3.7 and 4.0 mg l^{-1}, respectively) than the middle one (3.2 mg l^{-1}). On the other hand, it was lower in the north (3.4 mg l^{-1}) than the south (4.0 mg l^{-1}). Comparable to COD, BOD had a maximum value during the August (5.4 mg l^{-1}) and a minimum during November (1.7 mg l^{-1}).

4 Dissolved Salts

The contents of dissolved salts in the water of Burullus Wetland have the following sequence: $SiO_2 > NO_3 > PO_4 > NO_2$ [2]. The presence of silicate may be due to the nature of the sandy bottom sediments of the lake, while the presence of nitrite, nitrate, and phosphate may be due to the drainage of fertilizers from the agricultural land into the drains which discharge water into the wetland. In general, the nutrient concentrations in Burullus relate to the input of all domestic, industrial and mainly agricultural wastes from the reclaimed lands surrounding the lake.

4.1 Phosphate (PO_4)

The annual mean phosphate content in Burullus Wetland is 1.2 ± 1.1 μg-at. l^{-1}, with a minimum of 0.6 μg-at. l^{-1} at the eastern and the middle sectors; and a maximum of 2.7 μg-at. l^{-1} at the eastern sector [2]. The mean phosphate content was higher in the eastern sector of the wetland (1.6 μg-at. l^{-1}) than both in the middle and western sectors viz (1.0 and 1.1 μg-at. l^{-1}, respectively). It was lower in the north (0.8 μg-at. l^{-1}) than in the south (1.9 μg-at. l^{-1}). On the other hand, the monthly fluctuation indicated a minimum value during January (0.6 μg-at. l^{-1}) and a maximum during March (1.8 μg-at. l^{-1}). Figure 7 shows phosphate levels in Burullus Wetland during the period 1985–2015 [2].

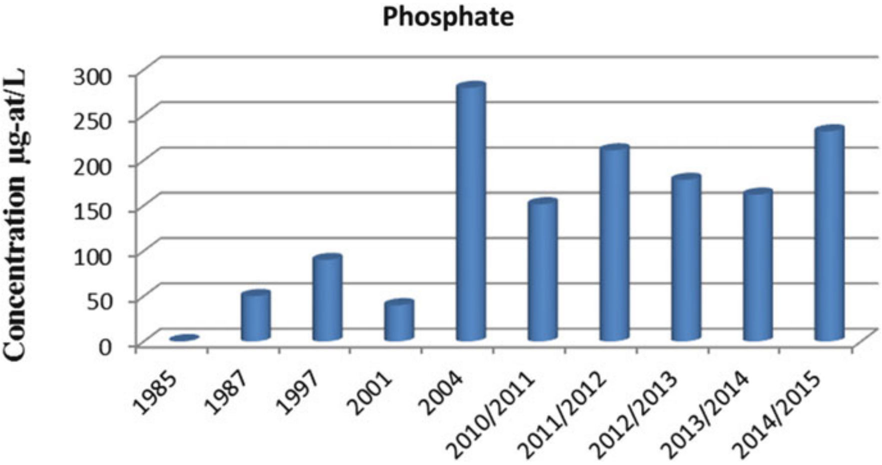

Fig. 7 Phosphate levels in the Burullus Wetland during the period 1985–2015

4.2 Nitrate (NO_3)

The annual mean nitrate in the water of Burullus Wetland is 2.8 ± 2.3 µg-at. l^{-1}, with a minimum of 0.8 µg-at. l^{-1} at the eastern sector and a maximum of 6.5 µg-at. l^{-1} at the same sector [5]. The mean nitrate content in the eastern and western sectors of the wetland (3.2 µg-at. l^{-1}) was higher than in the middle sector (2.0 µg-at. l^{-1}). On the other hand, it increased from the north (1.8 µg-at. l^{-1}) to the south (4.3 µg-at. l^{-1}). Regarding the monthly variation, the minimum value was recorded during January (1.6 µg-at. l^{-1}) and the maximum during March and May (4.7 and 4.6 µg-at. l^{-1}, respectively). Figure 8 shows nitrate levels in Burullus Wetland during the period 1987–2015 [2].

4.3 Nitrite (NO_2)

The annual mean nitrite in Burullus Wetland is 1.1 ± 0.8 µg-at. l^{-1}, with a minimum of 0.3 µg-at. l^{-1} at the eastern sector and a maximum of 2.0 µg-at. l^{-1} at the same sector. Regarding the variation from the eastern to the western sectors of the wetland, mean nitrite was higher in the western sector (1.4 µg-at. l^{-1}) than the eastern and middle sectors (1.0 and 0.9 µg-at. l^{-1}, respectively). On the other hand, the nitrite increased in the north (0.9 µg-at. l^{-1}) than the south (1.4 µg-at. l^{-1}). The monthly mean had a minimum value during April (0.7 µg-at. l^{-1}) and a maximum during February (1.4 µg-at. l^{-1}). Figure 9 shows nitrite levels in the Burullus Wetland during the period 1985–2015.

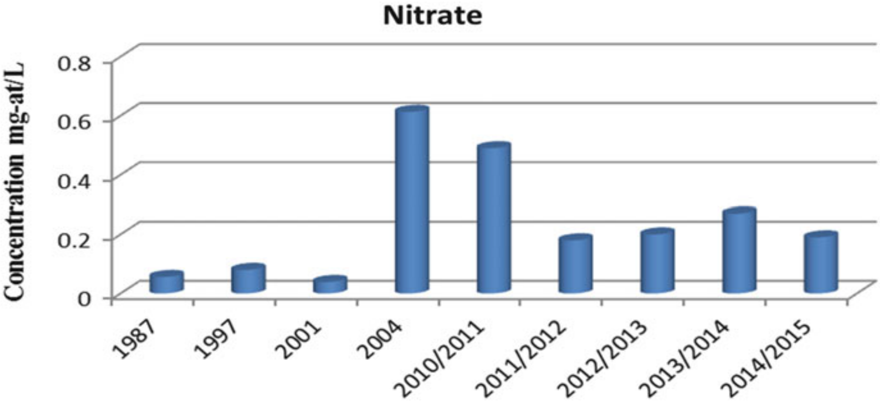

Fig. 8 Nitrate levels in the Burullus Wetland during the period 1987–2015

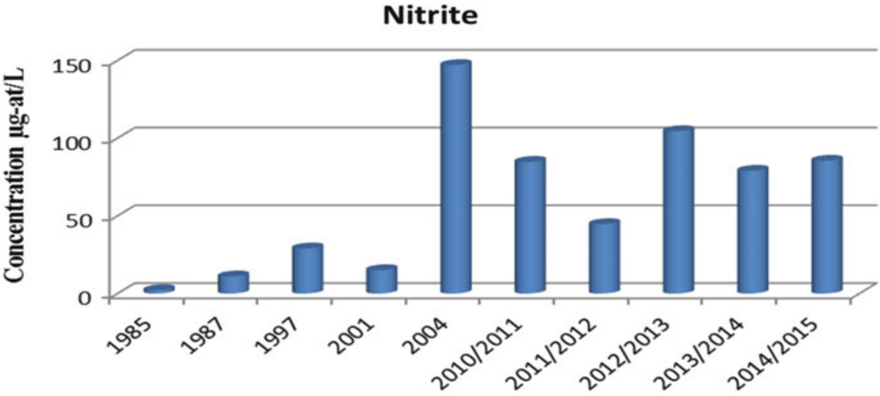

Fig. 9 Nitrite levels in the Burullus wetland during the period 1985–2015

4.4 Silicate (SiO_2)

The annual mean silicate in Burullus Wetland is 41.7 ± 25.1 µg-at. l^{-1}, with a minimum of 29.8 µg-at. l^{-1} at the eastern sector and a maximum of 51.9 µg-at. l^{-1} in the western sector. It increased from the east (36.9 µg-at. l^{-1} to the west (50.3 µg-at. l^{-1}), and decreased from the north (45.6 µg-at. l^{-1}) to south (39.5 µg-at. l^{-1}). On the other hand, the minimum value was obtained (19.5 µg-at. l^{-1}) during July, while the maximum (81.9 µg-at. l^{-1}) was during April. Figure 8 shows silicate levels in Burullus Wetland during the period 1985–2015 [2] (Fig. 10).

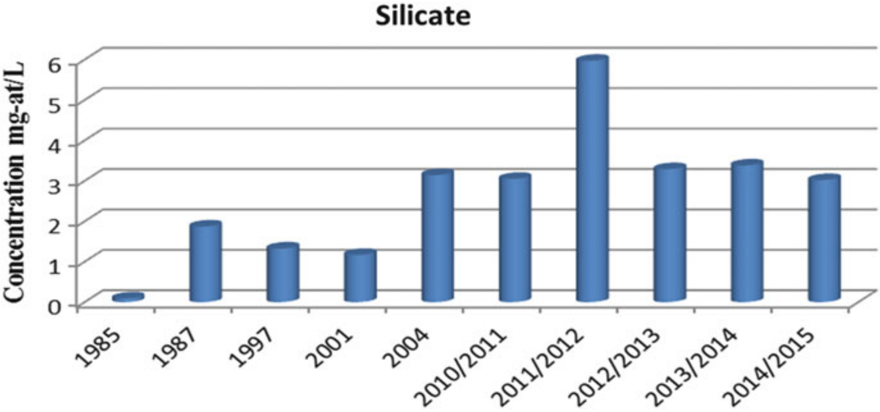

Fig. 10 Silicate levels in Burullus Wetland during the period 1985–2015

5 Heavy Metals

The content of heavy metals in the water of Burullus Wetland had the following sequence: Zn > Fe > Cu > Cd > Pb [5]. Most of the estimated heavy metals of the water near to the southern shore of the wetland were higher than those near the northern shore. This trend could be attributed to the effect of sewage effluents from the drains at the south particularly at the locations near to the mouths of drains with increasing levels of organic matter and the clay nature of the sediments. Also, the trend of variation along east-west axis is as follows: eastern sector > western sector > middle sector for all the estimated heavy metals except Zn (east > middle > west). On the other hand, the period from February to May showed heavy metals increase, while the period from June to September was characterized by a remarkable decrease in heavy metals [2].

5.1 Copper (Cu)

The annual mean copper was 5.9 ± 4.0 μg-at. l^{-1}, with a minimum of 2.6 μg-at. l^{-1} at the middle sector and a maximum of 8.8 μg-at. l^{-1} in the eastern sector. Regarding the variation from the eastern to the western sectors of the wetland, the mean values were 7.2 μg-at. l^{-1} at the east, 3.8 μg-at. l^{-1} at the middle and 6.3 μg-at. l^{-1} at the west. On the other hand, the copper increased from the north (4.7 μg-at. l^{-1}) to the south (7.4 μg-at. l^{-1}). The monthly mean copper ranged between 3.6 μg-at. l^{-1} during June and August and 11.5 μg-at. l^{-1} during May.

5.2 *Iron (Fe)*

The annual mean iron was 6.2 ± 6.2 μg-at. l^{-1}, with a minimum of 1.9 μg-at. l^{-1} at the middle sector and a maximum of 13.7 μg-at. l^{-1} in the eastern sector [5]. Regarding the variation from the east to the west, the mean values were 8.7 μg-at. l^{-1} in the east, 3.1 μg-at. l^{-1} in the middle and 5.7 μg-at. l^{-1} in the west. On the other hand, the iron, similar to the other heavy metals, increased from the north (4.6 μg-at. l^{-1}) to the south (8.6 μg-at. l^{-1}). The monthly mean iron ranged between 0.7 μg-at. l^{-1} during June and 13.2 μg-at. l^{-1} during May.

5.3 *Cadmium (Cd)*

The annual mean cadmium was 3.8 ± 3.2 μg-at. l^{-1}, with a minimum of 1.6 μg-at. l^{-1} at the middle sector and a maximum of 8.4 μg-at. l^{-1} in the eastern sector. Regarding the variation from the east to the west, the mean value in the east (5.5 μg-at. l^{-1}) was higher than that of the middle (2.2 μg-at. l^{-1}) and west (2.4 μg-at. l^{-1}). On the other hand, the cadmium, similar to the other heavy metals, increased from the north (3.1 μg-at. l^{-1}) to the south (4.4 μg-at. l^{-1}). The monthly mean ranged between 1.7 μg-at. l^{-1} during August and 6.6 μg-at. l^{-1} during March.

5.4 *Lead (Pb)*

The lead had the lowest value of all the estimated heavy metals in Burullus Wetland, with an annual mean 3.6 ± 3.2 μg-at. l^{-1} (it approximates the annual mean cadmium). It had a minimum value of 1.1 μg-at. l^{-1} at the middle sector and a maximum of 6.3 μg-at. l^{-1} in the western sector. Regarding the variation along the east-west axis, the mean value in the east was 4.4 μg-at. l^{-1}, that in the middle was 1.9 μg-at. l^{-1} and that of the west was 4.3 μg-at. l^{-1}. On the other hand, the lead increased from the north (2.5 μg-at. l^{-1}) to the south (4.8 μg-at. l^{-1}). The monthly mean ranged between 1.2 μg-at. l^{-1} during July and 6.2 μg-at. l^{-1} during April.

5.5 *Zinc (Zn)*

Zinc has the highest values of heavy metals in Burullus Wetland, with an annual mean 8.5 ± 5.7 μg-at. l^{-1}. It had a minimum of 3.5 μg-at. l^{-1} in the western sector and a maximum of 17.2 μg-at. l^{-1} in the eastern sector. Regarding the variation along the east-west axis, the mean value decreased from 12.1 μg-at. l^{-1} in the east to 4.9 μg-at. l^{-1} in the west. On the other hand, it increased from the north (7.1 µg-at. l^{-1}) to the south (9.4 µg-at. l^{-1}). The monthly mean ranged between 4.3 µg-at. l^{-1} during July and 12.7 µg-at. l^{-1} during March.

In conclusion, most of the estimated heavy metals of the water near to the southern shore were higher than those near the northern shore. In addition, the trend of variation along east-west axis was as follows: eastern sector > western sector > middle sector for all metals except Zn (east > middle > west). The spatial ranges in µg-at. l^{-1} were 3.5–17.2 (Zn), 1.9–13.7 (Fe), 2.6–8.8 (Cu), 1.6–8.4 (Cd) and 1.1–6.3 (Pb). On the other hand, the period extended from February to May had the peak of heavy metals increase, while the period from June to September had the reverse. The monthly ranges in µg-at. l^{-1} were 4.3–12.7 (Zn), 0.7–13.2 (Fe), 3.6–11.5 (Cu), 1.7–6.6 (Cd) and 1.2–6.2 (Pb).

6 Long-Term Changes in Water Chemistry

The comparison of the dissolved salts in the water of Burullus Wetland in 2015, with those of 1987, 1997 2001 indicated an increase of nitrate, nitrite, and phosphate from 1987 to 1997, but a decrease in 2001 and 2015. On the other hand, silicate had a decreasing pattern from 66.8 µg-at. l^{-1} in 1987 to 47.3 µg-at. l^{-1} in 1997 and 41.7 µg-at. l^{-1} in 2001. Regarding the heavy metals, there was a continuous increase in Cu, Zn, Pb and Cd contents from 1987 to 1997 and then to 2001 and 2015 (Table 2).

7 Correlations Between Water Properties

The simple linear correlation analysis of the water properties in Burullus Wetland indicates that the salinity and chlorosity are positively correlated with each other ($r = 0.99$, $P < 0.001$). In addition, Cd and Zn are positively correlated with each other on one hand ($r = 0.94$, $P < 0.001$), and with the salinity and chlorosity on the other hand ($r = 0.84$–0.86, $P < 0.001$). These correlations indicate that a

Table 2 Changes in water chemistry in Burullus Wetland

Year	NO_3	NO_2	PO_4	SiO_2	Reference
(a) Dissolved salts (µg-at. l^{-1})					
1987	4.0	0.8	1.6	66.8	[11]
1997	5.7	2.1	2.9	47.3	[7]
2001	2.8	1.1	1.3	41.7	[5]
2015	1.9	7.7	2,3	13.5	[12]
Year	Cu	Zn	Pb	Cd	Reference
(b) Heavy metals (µg-at. l^{-1})					
1987	2.3	5.5	1.9	1.6	[11]
1997	3.5	6.8	2.7	1.9	[7]
2001	5.9	8.5	3.6	3.0	[5]
2015	14.1	21.1	6.7	3.1	[12]

considerable portion of the Cd and Zn in the water of Burullus Wetland is due to the sea water (the main source for increasing water salinity in this wetland). The pollution from detergents that come mainly from the sea may partially interpret the increase of Zn. No doubt that the drains which carry the liquid industrial wastes are among the main sources of heavy metal pollution in Burullus [10].

Phosphates, nitrates, and nitrites that are used as fertilizers for the agricultural land in the catchment area of Burullus Wetland are positively correlated with each other (they are washed with the agricultural drainage into the wetland). Also, Cu, Fe, and Pb are positively correlated with each other on the one hand, and with the previously mentioned dissolved salts on the other hand. This may indicate that the main source of pollution with these heavy metals in the agricultural drainage water. This conclusion is supported by the fact that the levels of these heavy metals are much higher in the south (where all the drains pour their drainage water into the wetland) than the north.

8 Conclusions

It is concluded that most of the estimated heavy metals of the water near to the southern shores of Burullus and other Delta wetlands [13, 14] are higher than those near the northern shores due to pollutants of drainage water. The comparison of the dissolved salts in the water of Delta wetlands in 2015, with those of the 1980s, indicates a tremendous increase due to an increase of agricultural drainage waters that rich with fertilizers and discharge into these wetlands from the southern drains.

Moreover, coastal wetlands in Egypt, including Burullus and its surrounding areas are subject to ecological constraints that relate to excessive use of resources and overwhelming flow of polluted drainage water. To this may be added the likely impacts of future climate change including sea-level rise. As well as, these wetlands are unique amongst Egypt's ecosystems areas because they are home to a substantial human population.

9 Recommendations

Authorities should propose a management plan for these wetlands and should not be conducted in isolation from the local inhabitants. Management objectives must take into consideration the fact that they are fully utilized wetlands with many human activities taking place and should seek to optimize their benefits to the local community, and in the meantime fulfill its role environmental quality, ecological equilibrium. The ideal or "principal" long-term objectives of this management plan have been proposed after accurate field studies and thorough evaluation:

1. Restoring ecological and landscape values which have been lost or damaged,
2. Maintaining and enhancing the ecological values of the site,
3. Improving socio-economic opportunities for local people, and
4. Developing public awareness for nature conservation for the Coastal Lakes.

To achieve each of the above objectives, some measures and tasks are required. Each of these needs its own "operational objective" to ensure that it complies with the general tenure of the plan, that the outcome or result can be assessed and that it relates directly to one or more of the principal objectives. Once the operational objectives have been determined, a series of measures or "projects" can be developed to achieve them. Thus there is a step-wise progression in devising a management plan from principal to operational objective and onto identification of projects or measures.

Decision-makers need to restore ecological and water quality values which have been lost or damaged, by:

1. Restoring salinity to a safe level.
2. Initiating and establishing a well-working network for monitoring water quantity and quality.
3. Treatment of the incoming water to the lake to fulfill the water quality standards.
4. Monitoring climate variables related to climate change to take the needed mitigation/adaptation measures.

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Lake Manzala Characteristics and Main Challenges

M. A. Bek, I. S. Lowndes, D. M. Hargreaves, and A. M. Negm

Abstract This chapter presents an extensive background on Lake Manzala, Egypt, in the form of a literature review. It covers the lake's physical, chemical, and biological characteristics to date. In addition, the main challenges for the lake water body are land reclamation, nutrient enrichment, and pollution, especially from the Bahr El-Baqar drain. In addition, the spread of aquatic plants, such as water hyacinth, has occurred in most parts of the lake, which affects the movement of water in the lake, and hence the quality of both water and fish health. A summary of relevant research that has been conducted during the past four decades are presented. These investigations include a wide range of research investigations that have considered the chemical, physical, geological, and biological facets of the lake. In addition, the numerical models and recent studies from the literature are presented. It is concluded that a quick action for the lake remediation is initially to allow the law to take action over any type of stakeholder's violence toward the lake. A socioeconomic study for Lake Manzala is recommended. Moreover, increased numerical modeling would provide further benefit.

Keywords Biological characteristics, Chemical, Lake Manzala, Physical

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Contents

1 Introduction

Lake Manzala (Fig. 1) is the largest of the northern Egyptian coastal lakes and is located in the northeastern edge of the Nile Delta. The lake is the most important national freshwater aquaculture resource producing half the total fish production of the northern delta lakes and almost one-fifth of the Egyptian nonmarine fish productivity [1].

The lake lies within five Egyptian local government districts. It is bordered by the Nile's Damietta River branch to the west, the Suez Canal to the east, the Mediterranean Sea to the north, and major tracts of agricultural land to the south. Lake Manzala (which is located between longitudes 31° 45′–32° 15′ east and latitudes 31° 00′–31° 30′ north) has a total surface area of about 700 km^2 and has a maximum length of about 50 km parallel to the Mediterranean Sea.

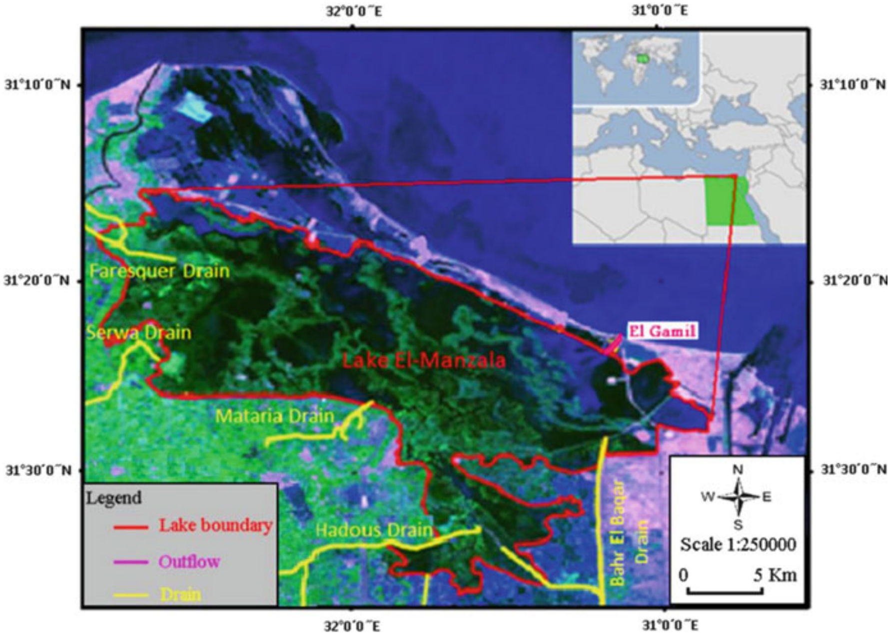

Fig. 1 The location and extent of Lake Manzala

Historically the lake was known as Lake Tanis (Fig. 2). Three of the seven historic Mediterranean river Nile branches, Pelusiac, Tanitic, and Phatnitic, passed through the lake body. The remaining two branches, Damietta and Rosetta, were named Phatnitic and Bolbitine, respectively. A feature of the lake is a large number of islets, consisting of sand or clay and which vary in shape and size. These islets divide the lake into about 30 basins. The lake contains 1,022 of these islands, which represents about 10% of the lake area. Most of these islets support human activities. The lake's high nutrient content allows aquatic plants to grow excessively. The subsequent sediment accumulating around the roots of the plants effectively subdivides the lake and affects the water circulation. The lake area has reduced markedly during the last few decades. The lake area was 1,709 km^2 in 1907, 1,470 km^2 in 1949, and 1,260 km^2 in 1960 reaching 895 km^2 in 1979 [3]. In addition, it is reported that the total loss of water body of Lake Manzala was estimated at about 355 km^2 between 2003 and 2012. It is expected that the lake water body will decrease by 84.67% in 2030. Which may lead to a variety of negative environmental impacts and may endanger the ecosystems in the area of the lake [4].

The lake is currently exposed to unregulated land reclamation which threatens to further reduce the available water surface area by a third over the next 10 years. The depth of the lake is remarkably shallow in relation to its areal size, with 50% of its area at an average depth of between 0.5 and 1 m. The lake is approximately

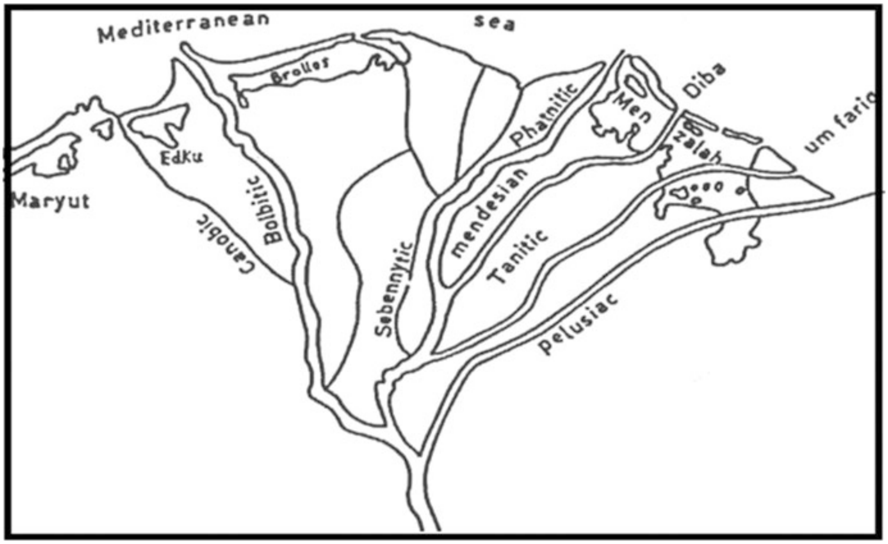

Fig. 2 Lake Manzala historically after [2]

rectangular in shape and separated from the Mediterranean Sea by sandbars that are 1–2 m in height above sea level and up to 2 km in width [5].

The main water inflows to the lake are six large drainage discharges from urban and industrial wastewater and agricultural runoff. The six major drainage channels (drains) contribute an annual flow rate of approximately 4,170 million m^3. The Bahr El-Baqar drainage channels, located at the southeast corner of the lake, discharge untreated urban domestic and industrial wastewater from Cairo, which is located 170 km away. This drainage channel of wastewater is highly polluted with heavy metals, nutrients, and toxic organics. The other water sources are the Hadous, Serwa, and Faresquer drains which discharge agriculture water to the lake. The Mataria drain, which is located in the middle of the southern part of the lake, is responsible for discharging sewage wastes [6–13]. The lake is connected to the Mediterranean Sea through a narrow main sluice channel [14] which is approximately 4 km long. It cuts through the sandbar [15] and is 200 m wide [3]. The channel is located to the northeast of the lake and responsible for the exchange of water between the lake and the Mediterranean Sea. A second connection is located in the middle of the lake at El-Boghdady. The main freshwater lake is connected to a saltwater buffer lagoon (Mussallas) located at the northwest corner of the lake. The Mussallas saltwater lagoon is then connected to the Mediterranean Sea. The Mussallas lagoon is characterized by high water salinity content.

The aforementioned information and other useful data about Lake Manzala are summarized in Table 1.

Table 1 Lake Manzala data [16–19]

Location	31°45′–32°15′ E 31°00′–31°30′ N
Area	600 km^2
Lake classification	Brackish
Average and maximum depth	1–3.5 m
Average sediment accumulation rate	1.9–2.2 kg m^{-2} $year^{-1}$
Annual precipitation	78.4 mm $year^{-1}$
Annual evaporation	1,100.2 mm $year^{-1}$
Annual mean temperature	21.4°C
Suspended particulate matter	129–261 mg m^{-3}
Chlorophyll a	12.66–32.38 mg m^{-3}
Zooplankton	$1,212 \times 10^3$ animals/m^3
pH	7.8
Salinity	3,000–3,500 mg/L
Range of water temperatures	30.5°C max. 11.3°C min
Conductivity	3.1–9.4 S m^{-1}

2 Hydrology and Hydrodynamic Description

2.1 Evaporation

Lake Manzala loses approximately 30% of its annual water inflow to the lake through evaporation; the remainder passes through to the Mediterranean Sea. As can be seen in Fig. 3, the peak period for evaporation occurs in the summer when the relative humidity is low, and the wind speed is high. The degree of evaporation experienced varies across the lake, with the evaporation in the north of the lake being lower than that in the south due to the lower humidity and the higher inland temperatures.

Lake Manzala is located in a low rainfall area. The mean annual rainfall is 78.4 mm [20] and ranges from 47 to 88 mm [17]. The amount of rainfall decreases across the lake as the rain clouds move away from the northern coast bordering the Mediterranean Sea. The peak rainfall occurs during the winter season, while July and August are dry.

2.2 Water Levels

The mean water level fluctuation occurs in a range between 19 and 45 cm above sea level (Fig. 4). The high water level observed may be attributed to the maximum inflow to the lake during the summer season.

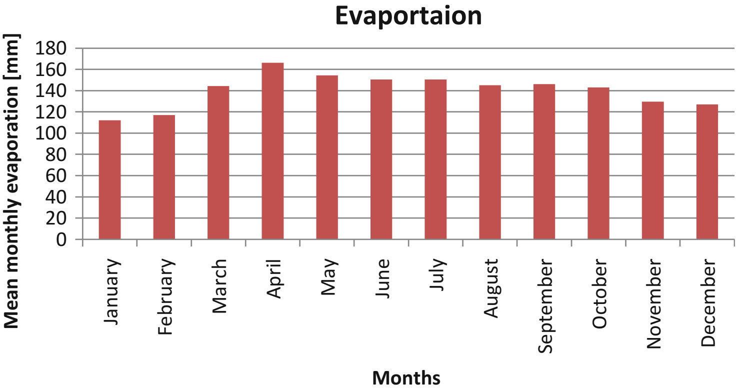

Fig. 3 Mean monthly evaporation after [18]

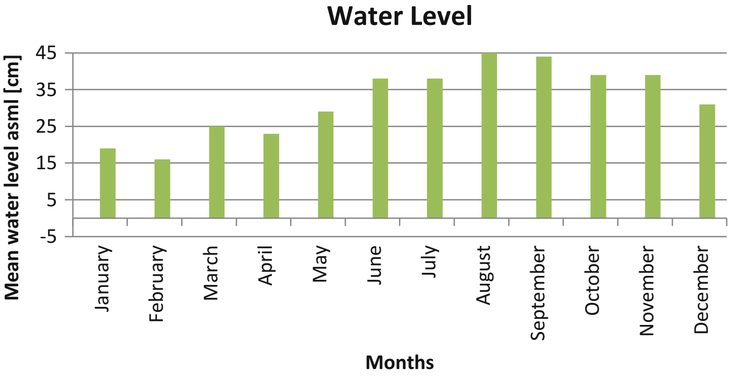

Fig. 4 Mean monthly water level fluctuations after [6]

2.3 Hydroperiods and Water Depth

The hydrologic character of shallow waters and similar wetlands is one of the attributes by which they may be defined. The residence time is the key factor that controls the lake water quality status [21]. For example, the nitrate (NO_3) removal is largely controlled by the residence time. So identifying the water discharge and the water budget is essential before conducting our study as they are main motivation and controllers of the residence time.

2.4 Discharge

The six major drains feeding Lake Manzala are responsible for providing the lake with 4,200 × 10^6 m^3 annually [6]. However, it has recently increased to 5,463 × 10^6 m^3 $year^{-1}$ according to [5]. The maximum inflow of water takes place in the summer season while the minimum rate is in winter.

The Bahr El-Baqar drain is considered to be the largest contributor to the lake. The drain carries untreated and primary treated wastewater from the east Cairo region along the 170 km of its length [22]. The maximum flow volume occurs in summer from the beginning of July until the end of September, and its peak is reported in August at about 200 × 10^6 m^3 [5]. This high volumetric flow is related to the Egyptian agricultural drainage system where the high crop demands occur at summer. The freshwater delivered to the lake through Bahr El-Baqar is 25% of the total discharge that enters the lake annually [23]. The remaining portion is split approximately equally between Hadous drain and the remaining drains (Mataria, Serwa, and Faresquer).

The Bahr El-Baqar drainage water is under anaerobic conditions with high biochemical oxygen demand (BOD) values, ranging from 30 to 60 mg/L. In addition, the high ammonia concentrations range from 2.8 to 5.2 mg/L [6]. It is reported that the drain also carries high concentrations of heavy metals such as cadmium, copper, and zinc [8, 12, 14, 16, 24–26] which partially settle and accumulate in the bottom sediments of the lake [10]. The drain discharges its contents in the southern part of the lake which explains the existence of high concentrations of heavy metals such as cadmium in this area.

2.5 Hydrological Budget

A water budget is a systematic procedure that summarizes the relationship between gains and losses within any water system. The annual water balance for Lake Manzala is presented schematically in Fig. 5. The freshwater inflows through the different drainage channels around the lake contribute approximately 98.6% of the total volumetric inflow. The remaining portion of the inflow is from precipitation which occurs mainly in the winter period. As described above, evaporation is

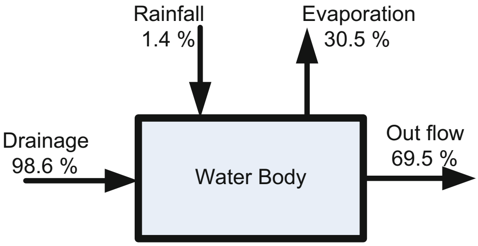

Fig. 5 The volumetric water budget for Lake Manzala

responsible for a loss of approximately 30% of the total water inflow to the lake with the balance being delivered to the Mediterranean Sea.

2.6 Thermal Stratification

One of the most significant factors that are responsible for the mixing and vertical gradients in the lake is thermal stratification. Generally, lakes are not well mixed because the warm water, heated by incoming solar radiation, stays at the top and the cold water sinks to the bottom. A temperature profile in a typical lake is sketched in Fig. 6 and shows the three main thermal layers. The main thermal layers are as follows: epilimnion which is the upper surface layer where the temperature is relatively uniform with depth. It is well mixed as wind shear stress is directly applied to its upper surface. The second layer, the thermocline, is the transition zone between the upper warm layer and the bottom cold one. This layer features a minimum amount of vertical mixing and a maximum rate of temperature decrease. The lower cold layer is the hypolimnion and is characterized by cold dark water. Thermal stratification is seen in deep lakes and also in some relatively shallow lakes.

Lake Manzala is classified as a shallow well-mixed brackish water body or wetland. The well-mixed water body can be attributed to two reasons: the lake shallowness and the wind circulation. Falconer et al. [27] indicate that the wind leads to strong vertical mixing in shallow water. Thermal stratification is not observed nor reported in any related published materials. Lakes with thermal stratification are fundamentally different from those without thermal stratification. Shallow lakes without thermal stratification tend to have higher phytoplankton biomass than deep lakes with similar levels of nutrients [28]. This may explain the high phytoplankton biomass in Lake Manzala.

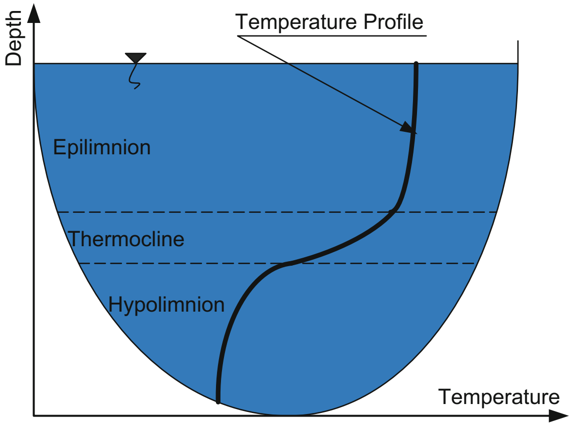

Fig. 6 Temperature profile in the thermally stratified lake

3 Hydrodynamics

There are a number of physical factors that may influence the hydrodynamics within shallow water lakes such as Lake Manzala such as the wind, inflows and outflows, the seasonal variation of thermal stratification, gyres, and seiches.

3.1 Winds

Wind plays an important role in the limnological properties of the Egyptian northern delta lakes especially in Lake Manzala. It has a mixing action reducing any chemical or physical stratification due to the shallowness of the lake. It also affects the lake by agitating of the bottom sediments. The absorbed and regenerated nutrient salts such as nutrients (ammonia and nitrite) and phosphorus may be released from the sediment layer by this stirring process. Wind actions assist in dissolving the atmospheric oxygen that is required for the metabolic activities of various organisms. The strong northerly winds that blow steadily from March to September drive the flow of the seawater along the coast. Consequently, it raises the level of the sea and may, in some cases, contribute to the transport of seawater into the lake. This phenomenon, termed locally as the "Noaa," occurs in the winter season and is considered to be the main reason why high salinity measurements are recorded near the sea connection channels within the lake.

The flow patterns within the lake are dominated by the average surface wind speeds, which range from 6 m/s from in the north to 1.5 m/s in the south of the lake. The wind speeds are observed to be lower in July and August and to increase in magnitude progressively in November and January, reaching a maximum in April. The wind speed and direction change smoothly from season to season. The directions and speeds of winds blowing on Lake Manzala during the four seasons can be briefly indicated in Table 2 and presented in Fig. 7. Generally, the wind tends to blow NW most of the year [30]. However, in winter it tends to be seawards, SW. Although the wind is moderate and varies from a minimum of 0.5–4 m/s in summer, there are some strong winds that reach a maximum of 8 m/s in winter.

4 Physical and Chemical Parameters

The water's physical parameters produce strong effects on both chemical and biological parameters. Factors such as the flow velocity, volume of the water body, depth, bottom roughness, light penetration, and temperature are controlling

Table 2 Lake Manzala wind speed and direction

Season	Magnitude (m/s)	Direction	Reference
Winter	2–8	SW and NW	[5]
	2–4	SW, NW, and NE	[6]
	2–6	SW and E	[29]
Spring	2–6	NW	[5]
	1–2	NW, less from SE/S	[6]
	1–4	NW, less from SW	[29]
Summer	0.5–4	NW and N	[5]
	1–2	NW and NE	[6]
	1–3	NW and NE	[29]
Autumn	1–6	NW and W	[5]
	2–5	NW and NE	[6]
	2–4	NE	[29]

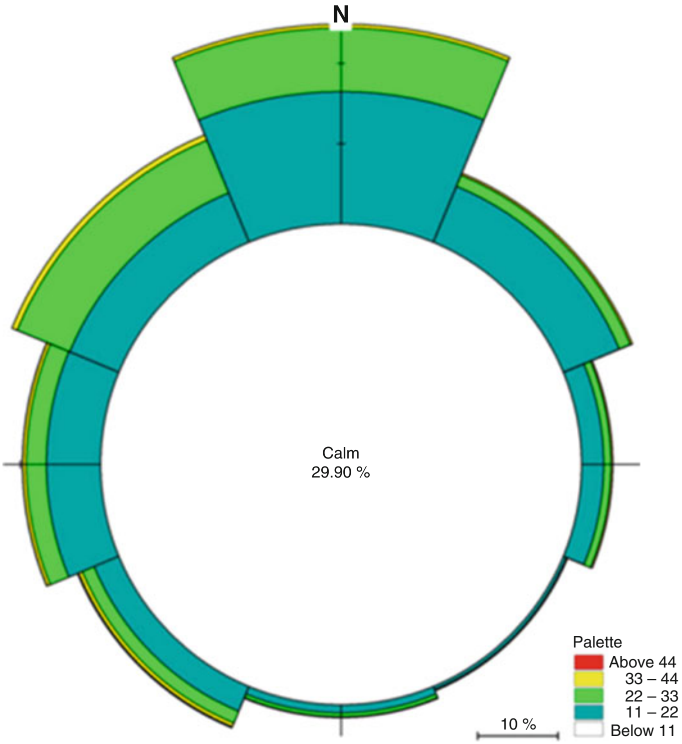

Fig. 7 Wind rose after [30]

the ability of the lake to receive and store pollution. There are several physical and chemical parameters that are important when discussing Lake Manzala.

4.1 Temperature

Due to the shallowness of the lake water and the significant wind on the surface of the lake, it is difficult to establish thermal stratification in the water body of Lake Manzala. The water is well mixed, and the variation in the water temperature between the surface and bottom water layer lies in a very narrow range. The recorded water temperatures made by previous researchers at various locations within the water domain demonstrate this [9–13, 16, 31]. The minimum water temperature was observed during January with an average of 12°C and a water temperature range between 11 and 13°C. The maximum water temperature was recorded during July ranging between 27 and 30°C with an average of 29°C. The water temperature was observed to gradually increase from February to reach this maximum in July. The temperature then was observed to gradually decrease reaching the aforementioned minimum in January. The difference in average water temperature values did not change significantly from one measurement station to another [18]. In addition to the water temperature potentially influencing the chemical and physical characteristics of the water environment, it can have a major effect on the vital activities of the living organisms. It can influence the total crop of phytoplankton which is observed to significantly decrease during the milder winter temperatures and increase the phytoplankton crop during the warmer spring and summer months. A temperature increase in the lake water is observed to decrease the dissolved oxygen content of the lake water [32].

4.2 Relative Humidity

The mean monthly relative humidity of the air above the lake free surface varies from between 60% in the dry season to 75% in the wet season with a mean value of about 72% [24]. The maximum relative humidity reading, 75%, occurs in January and the lowest is observed in April, May, and July. The wind direction is also concluded to be an important contributor to the relative humidity readings of the air above the lake. During the summer months when the dry El Khamsin wind blows from the west, the relative density humidity above the lake surface decreases. However, when the wind comes from the north, it is humidified with water evaporated from the Mediterranean Sea water which consequently increases the relative humidity readings of the atmosphere above the lake. The surface area of the lake is so large that a small difference in the humidity between the northern edge (the coast) and the southern part of the lake is observed.

4.3 Transparency

Transparency is a water quality indicator for the penetration of the light passing through the water body. The delta lakes in the north of Egypt are generally known to possess a low water transparency due to their shallowness and the continuous disturbance and resuspension of the sediment and debris from the mud layer at the bottom of the lake by the circulation currents created predominantly by the wind shear effect. The recorded Secchi depth readings indicate that the most transparent area of the lake occurs in the middle of the lake in the eastern sector. The high transparency may be the result of the higher water depth in this location compared to other areas. During the month of May, the Secchi depth reading indicates a high transparency index when compared to the rest of the year. The stormy winds experienced in winter are responsible for an agitation of the lake sediments that in turn raises the turbidity of the water body. Therefore, January has the minimum Secchi reading starting from 40 cm before reaching a depth of 120 cm. It is also observed that the Secchi depth is a minimum in the spring due to the maximum growth of suspended phytoplankton which decreases the visibility of the water within the shallow lake [33]. However, recently the readings indicate higher transparency in summer than winter time [16]. Accordingly, Lake Manzala may be classified as a Eutrophic lake dependent on its average Secchi depth reading [34].

4.4 Conductivity

A number of recent research studies have attempted to measure the electrical conductivity of this shallow water lake. As an example, Bertonati and colleagues [35] recorded high values of electrical conductivity (EC) during the hot seasons, spring and summer, especially in August, while lower values were recorded during cold seasons, autumn and winter, especially in February [16]. The northwestern sector of the lake had the highest conductivity measurement with the maximum reading being recorded during August. The lowest EC was recorded in the southern sector of the lake during February, and this was due to the combination of the low temperature and the low salinity of the freshwater in this area of the lake. These readings support the conclusions drawn by another independent study [36] that the observed increases in measured conductivity were accompanied by corresponding increases in the measured total dissolved solids and the water temperature.

4.5 Salinity

The salinity of lakes plays an important role in the aquatic organism life. Historically, the salinity of the lake was high described as “marine type.” However, it now has a low salinity and has turned into a eutrophic lake. Lake Manzala can be classified as a brackish lake. Its salinity readings have dramatically decreased during the past 20 years – “declined by about 82.7% since 1921, from 16.7% to 2.9% during 1985” [9]. This change in the salinity affects both the existence and distribution of fish [12]. Fish species that were more closely associated with the marine aquatic environment were present, but currently, they are hardly found. The northern portion of the lake has high salinities ranging from 7 PSU to 35 PSU due to the influence of the Mediterranean Sea and the lack of freshwater, while the low salinity level is found in the southern area [26, 30]. Low salinity is a result of the freshwater, which is almost 90% of the total freshwater amount, coming through the southern drainage channels. The lake can be divided into three main regions depending on the salinity of the lake. The first one is the northern part which has high salinity, and the second one is in the middle part of the lake which is of medium salinity and finally the high salinity region on the western side of the lake. Also, it is noticeable but understandable that the low salinity regions are near the mouths of the drains. From the sampling stations locations in [6, 19], the circulation of the freshwater can be described as weak. The stations which were located in the middle part of the lake give low measured salinity readings and are almost close to the drainage inflow readings. This implies that the flow moves directly from south to north with very little change in its direction.

4.6 Total Dissolved Solids

The total dissolved solids (TDS) in water are useful chemical parameters. TDS in the water is affected by several factors. The main factors are the discharge of drainage water, seawater reaching the lake through the sea-lake connections, rainfall, and evaporation [6]. TDS measured readings can be summarized as follows. The northern area is the highest in TDS due to the connection with the Mediterranean Sea, while the lowest TDS values were in the southern area. The highest readings were in summer while the lowest in the winter season. The decreased values of TDS can be attributed to the discharge of drainage water inflow from Bahr El-Baqar drain. Generally, the highest recorded TDS value (2,012.6 mg/L) was recorded at Bahr El-Baqar drain and the lowest (840 mg/L) was recorded at Lotfi et al. [37].

4.7 Hydrogen Ion Concentration

In the aquatic environment, the hydrogen ion concentrations play an important role in many life-supporting processes. Water pollution and biological activity are commonly indicated by pH levels. The pH values recorded at the different measurement stations across the Lake Manzala indicate low pH values within the southeastern sector of the lake due to a large amount of polluted water discharge. The higher rates of wastewater discharge from the drains located in the southern sector of the lake decrease the recorded pH values. However, at these low recorded pH levels, fish are still able to survive. By performing a comparison of the measurement readings of [6, 16, 19], it may be concluded that the average measured pH value was observed to decrease with time. This indicates the lake is under pressure due to the very polluted water.

4.8 Dissolved Oxygen

Dissolved oxygen (DO) is a very important factor for the support of aquatic plant and animal life. Low DO levels are unable to support fish and other aquatic life. In shallow lakes such as Manzala, the levels of DO may be affected by several important factors, including air and water temperature, wind mixing, and photosynthetic activity [33].

The analysis of DO data of Lake Manzala reveals that DO levels were found to be highest during the cold season, particularly in November. The lowest DO values were recorded in the hot season, especially during the month of July, which confirms the earlier discussion on the effects of temperature. Low DO levels were found near the southern sector of the lake due to the high amount of wastewater discharges in this region and the high BOD associated with these.

4.9 Biochemical Oxygen Demand and Chemical Oxygen Demand

BOD is a chemical procedure for determining how fast biological organisms use up oxygen in a body of water. However, the COD test is commonly used to measure the amount of organic matter indirectly which indicates the mass of oxygen consumed per liter of the solution [38]. The data collected during 2005 reveals that the higher values were recorded during spring period in the northern part near the fish farms [24]. It is mainly attributed to the photosynthetic activity and the abundance of phytoplankton. According to the data analysis, the lower values were in August in the northwestern part of the lake. The COD highest recorded value was recorded near the industrial compound in Port Said city, while the lowest values were recorded in the northern part far from factories or discharge of pollutants.

4.10 Heavy Metals

Heavy metals are very important chemical factors for the public health. Heavy metals affect water quality, sediment, and the whole aquatic environment.

Consequently, the fish became heavy polluted, therefore badly affecting the Egyptian health. Heavy metals are bioaccumulated in the fish and then accumulate in the humans and affect the public health as reported in [14, 39, 40]. The heavy metal reading of [8, 41] indicates that the maximum polluted area is the northwest and occurs during the month of July. It gives another indicator that the heavy metals accumulate in the water and sediments in this area due to the low water circulation. The variation of the heavy metals values varies from month to month according to the drain inflow properties. The highest levels of heavy metals were found during winter, while the lowest values occurred during summer [16]. The main heavy metal components are as follow:

Iron The minimum recorded average value of (5.41 mg/g) was during autumn. Then it was increased gradually during winter (5.83 mg/g). The iron values reached a maximum value of (5.86 mg/g) during spring [25]. The iron concentration is varying from drain to other. The maximum value (1.8 mg/g) was recorded at Bahr El-Baqar drain in winter, and the minimum value (0.82 mg/g) was recorded at Faraskour drain in winter.

Manganese Similarly the highest average value of (0.5 mg/g) was recorded during winter and reached its minimum value of (0.25 mg/g) during summer. The results illustrated in Hamed et al. [26] show that the Mn level reaches a maximum value of 0.72 mg/g near Bahr El-Baqar drain. This may be attributed to industrial activities which take place in summer.

Zinc, Lead, and Copper The highest average value of 0.08, 0.02, and 0.2 mg/g was recorded during summer, spring, and summer, respectively. However, the lowest average value of 0.06, 0.033, and 123.5 mg/g was recorded during winter, autumn, and spring, respectively [25].

4.11 Nutrients

The concentration of dissolved nutrients in the lake plays an important role in changing the lake status to eutrophic. The main source of the nutrients is the sewage water entering the lake through the southern drain discharges. The concentrations of these nutrients are documented in [19]. Ammonia, nitrites, nitrates, silicates, and phosphates were found in high concentration near the outlets of drains in the southern region of Lake Manzala. The average values fluctuated between 1.32 and −357.43 mg/L, 0.29 and −2.22 μg/L, 0.85 and −7.82 mg/L, 353.66 and −1,395.62 μg/L, 22.61 and −357.43 mg/L, 280.47 and −821.13 mg/L, 12.12 and −44.39 mg/L, and 30.46 and −135.22 mg/L for nitrite, nitrate, silicate, total phosphorus, sulfate, sodium, potassium, and calcium, respectively [42]. The cause may be attributed to the fertilizers used in the agricultural lands served by the major land drains flowing into the lake. A recent study [32] recommends that substantial changes should be enacted in the use of such fertilizers to stop the enrichment of the runoff waters flowing into these drains. An unusual observation, unlike the other nutrients parameters, was that high silicate concentrations were measured in the middle of the lake.

5 Biological Parameters

Biological parameters are used to determine the impact of human activities on the aquatic community. Changes in these can highlight water quality problems that other methods may miss. Plankton (phytoplankton and zooplankton), macrophytes, benthic macroinvertebrates, aquatic plants, and fish are the most commonly used in assessing biological integrity. In lakes, algae are often the most common parameter used to measure lake eutrophication.

5.1 Algal Groups

The main inflow stream, Bahr El-Baqar drain, in particular, contains high concentrations of nutrients which increase the growth of phytoplankton. Consequently, the water quality of the lake deteriorates near this drain. A study by El-Naggar et al. [43] identified 157 species of algae: 59 Chlorophyta, 37 Bacillariophyta, 30 *Cyanophyta* (*Cyanobacteria*), 28 Euglenophyta, 1 Pyrrophyta, and 2 Cryptophyta. Ten years after this initial study, an additional six new freshwater algae-type species were identified in the lake [44]. As a consequence of the increase in nutrients reported above, it was observed that green algae blooms became dominant. The peak occurrence of these blooms occurs during the summer season. This may be attributed to the excess of nutrients, particularly phosphorus which is used in fertilizer applied to land for agriculture purposes.

5.2 Macrophytes

Macrophytes are aquatic plants, growing in or near water ecosystems. In lakes, macrophytes produce oxygen, act as food, and provide cover for some fish and wildlife. They can be grouped on the basis of their water requirements and habitats. Macrophyte groups can be described as submergent, floating, or emergent. Submerged macrophytes are those which are completely covered with water. They have leaves that tend to be thin and finely divided adapted for the exchange of nutrients with water. Floating macrophytes are split into two types: floating leafed macrophytes which are rooted but have floating leaves. The second floating type is the free-floating which floats on the water surface. The last group is the emergent macrophytes. Emergent macrophytes are rooted plants with their principal photosynthetic surfaces projecting above the water. The aquatic macrophytes could be a potential source for the accumulation of heavy metals from water and act as biomarkers for metals, so that macrophyte readings could be used in sustainable development, management, and pollution assessment for shallow coastal lakes [45].

There are several factors controlling the macrophyte characteristics and establishment including depth of water, topography, water turbidity and currents, and the wind. In Lake Manzala, the classification of 100 stands revealed 8 vegetation groups which indicated 11 dominant communities. These are *Potamogeton pectinatus*, *Najas armata*, *Ceratophyllum demersum*, and *Ruppia maritima* as dominant submerged macrophytes, *Eichhornia crassipes* and *Azolla filiculoides* as floating macrophytes, and *Phragmites australis*, *Typha domingensis*, *Scirpus maritimus*, *Echinochloa stagnina*, and *Ludwigia stolonifera* as emergent macrophytes [46, 47]. The northern part of the lake is characterized by the low depth and relatively high salinity and has low species diversity (mainly emergent species). Species diversity increases with decreasing salinity and increasing eutrophication near the mouths of the drains in the western and southern parts of the lake. The most dominant species is the water hyacinth which appears extensively in the southern part. The recent changes in species distribution can be attributed to the effects of salinity, water depth, and drainage water. An inventory of macrophytes in the lake can be found in [45, 47].

5.3 Chlorophyll

Chlorophyll is vital for photosynthesis, which allows plants to obtain energy from light. The average chlorophyll in the surface water is about 32.38 mg chl/m^3 [11]. However, it sharply increases to 1,000 mg chl/m^3 as can be seen in [48]. This increment can be attributed to the enhanced nutrient loading from agriculture and the sewage drains. Also, it proves the quick transformation of the lake condition from eutrophic phase to the hypereutrophic one in a very short period of time.

5.4 Zooplankton

Zooplankton plays an important role in the aquatic food web. They consume and process phytoplankton. The results of a recent investigation [3] concluded that the average annual number of zooplankton in the lake was 1,212 × 10^3 animals/m^3. The peak occurrence was recorded in April while the lowest loadings were recorded in October and November. A more recent study by Ramdani and his coworkers [44] indicated a high increase in the standing crop to 500 × 10^3 animals/m^3, with a minimum loading period in February and August and a maximum of 3,000 × 10^3 animals/m^3 during April.

6 Issues in Lake Manzala

6.1 Land Reclamation

Land reclamation is one of the major challenges that affects the sustainable future of Lake Manzala. The available free water surface area of the lake has been dramatically reduced over the last four decades from 1,700 km^2 in 1977 [12] to only 700 km^2 in 2009 [5]. It is predicted that at the current land reclamation rates being practiced, this will leave the lake with only 450 km^2 surface area within 10 years.

Land reclamation affects the water quality of the lake as it directly affects the residence time of water within the lake [7]. Hence, several factors which control the water quality are disturbed. Land reclamation (Fig. 8) has contributed to a significant deterioration of water quality and to the disappearance of several important species of fish which are not able to survive in the poor water quality. Also, the reduction of the surface of free water reduces the available fish productivity. Unfortunately, the reclamation of the land from the lake is often unregulated and usually executed by growing communities adjacent to the lake. Since the construction of the High Dam and the consequent complete arrest of sedimentation, the coasts of the eastern delta have been affected by erosion. The rapid erosion of the coast of Lake Manzala and encroachment of the sea in the northern region are expanding at an average rate of about 10 m per year. On the other side of the lake, within the southern sector of the lake, a rapid growth of tourist amenity projects has placed additional impacts that reduce the effective lake area. Figure 9 illustrates how a large part of the lake has dried up and has been converted to land for various purposes. Figure 10 shows the most recent bathymetry of Lake Manzala. The figure confirmed that it is still

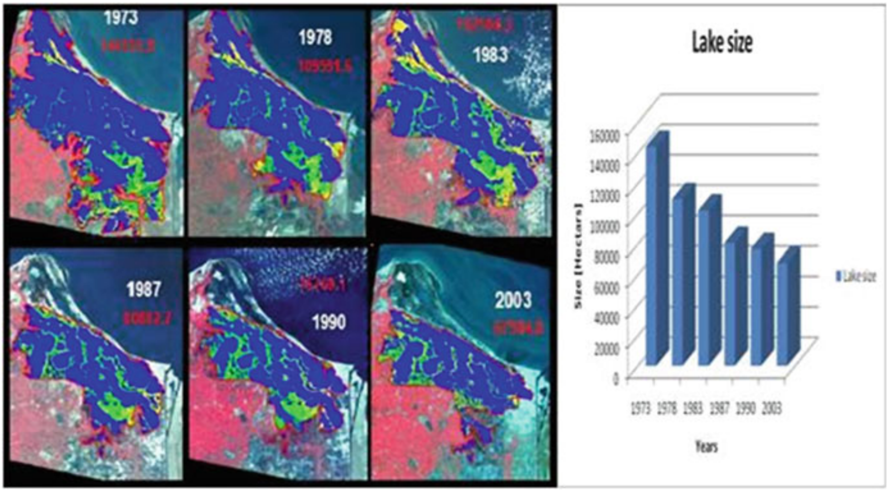

Fig. 8 Land reclamation during the past four decades after Donia and Ahmed [1]

Fig. 9 Land reclamation in the southern region of Lake Manzala (On the left is the current situation, on the right the extent of the water before reclamation)

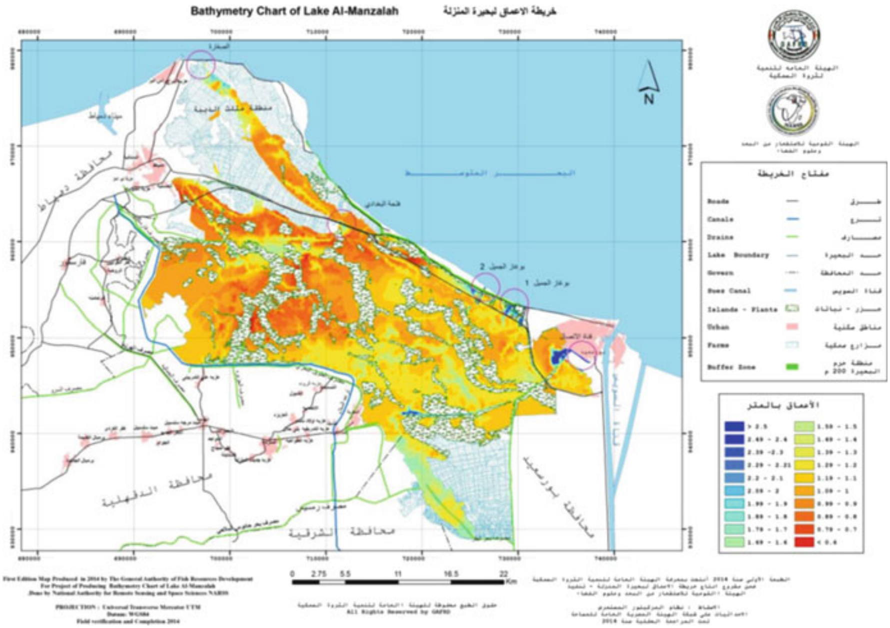

Fig. 10 Lake Manzala bathymetry 2014

subjected to huge land reclamation in a quick manner. The quick land reclamation process is expected to lead to bad water circulation. From our point of view, it is proposed to investigate the response of the lake water circulation after expanding the radial (narrow) channels. In addition, the available bathymetry data will give a good guide to select the best location where the expansion process will take place.

6.2 Nutrient Enrichment and Pollution

Water quality and eutrophication are dependent on a number of complex contributory physical, chemical, and biological processes. These processes depend on the interaction between several parameters such as the nutrients loading within the drainage channels entering the lake, the wind, precipitation levels, etc. The water quality of Lake Manzala is characterized by:

1. High concentration loads of nutrients
2. High biological productivity
3. High concentration of algae and vegetation
4. Low DO levels
5. Contaminated sediments

These features are typical symptoms of the eutrophication process and taken together form a clear picture of the prevalent poor water quality and the need to develop sustainable water quality management solutions. Good ecosystem water quality is characterized by small concentrations of nutrients. When the nutrients exceed the normal level (mesotrophic) with a trophic index (TI) reading from 40 to 50, it disturbs the lake balance [49]. With high nutrient concentration, algal blooms and intensive plant growth reduce the DO level in the lake, which may be responsible for the high fish mortality observed in the southern sectors of the lake. Another consequence of these floating plants is to block the free water circulation within the lake which in turn reduces the dilution exchange of water to remove localized pollutant loads as found in fish ponds within the lake. Currently, the fishing communities use these natural vegetation barriers to divide the lake into small fish farms. This may, in turn, divide the lake into semi-closed fish pond basins with a reduced circulation and water quality.

Currently, the lake produces about 30% of the national fish catch. The average annual production of the lake is 6,000 tons, and the number of the fisherman community exceeds 100,000 with 6,000 registered boats. Lately, Lake Manzala fish quality has a bad reputation as it is heavily polluted. The lake water and its fish are considered as a source of some diseases such kidney and liver diseases [50, 51].

6.3 Diversion of Freshwater Inflows: El-Salam Canal Project

In 1987, the Egyptian government commissioned an ambitious water irrigation project known as El-Salam Canal or the “Peace canal” (Fig. 11). The canal is located south of the lake in the north of the Sinai Peninsula.

The canal project is planned to supply enough irrigation water to support about 450 km^2 of potential agricultural development in the northern part of Sinai. The El-Salam canal project is designed to divert $1,270 \times 10^6$ m^3 of water currently destined for Lake Manzala to the new agricultural development area in Sinai. The project is expected to make a significant ecological impact on the lake’s ecosystem and lead to a notable change in the lake water quality.

The planned diversion of this amount of freshwater is approximately 40% of the current total freshwater inflow delivered to the lake annually. It is anticipated that the water salinity of the lake may rise significantly. This may lead to the loss of low-saline-tolerant fish stocks to be replaced by high-saline-tolerant species. Therefore, the balance of the distribution of the types of fish species found in the lake may be expected to change. This diversion of fresh water may also be expected to reduce the lake water level which directly plays an important role in turning parts of the lake into the brackish marsh. That may, in turn, lead to the disappearance of several plant species and their associated avifauna. It is, therefore, worthwhile to conduct a

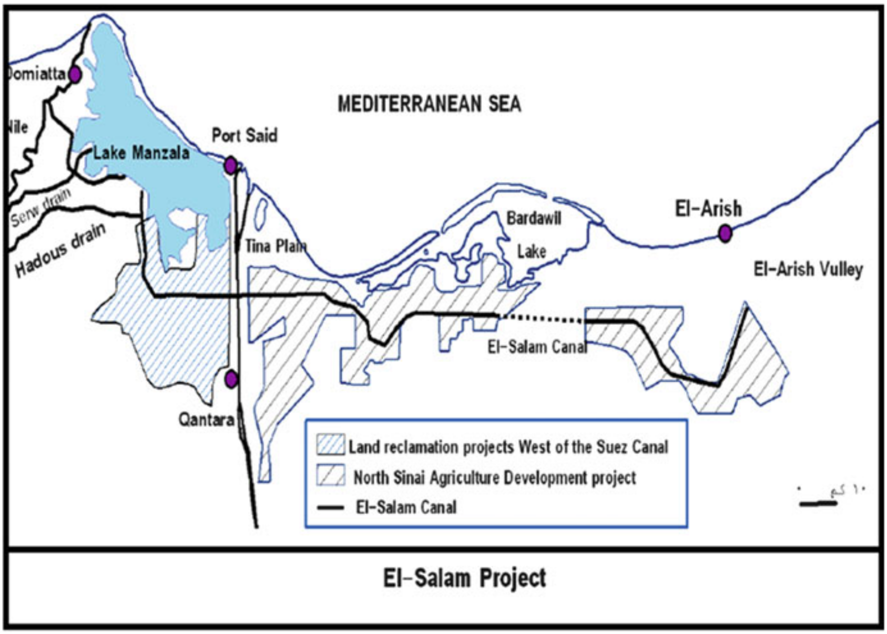

Fig. 11 El-Salam Canal project

research study to determine the potential ecological effects of the project and to propose some engineering solutions that may sustain the ecology of the lake.

7 Previous Studies of Lake Manzala

Lake Manzala has been the subject of a wide range of research investigations that have considered the chemical, physical, geological, and biological facets of the lake. The objectives of many of these studies were to benchmark the current environmental condition of the lake.

Over the past few decades, Lake Manzala has experienced accelerated eutrophication due to excessive nutrients loads entering the lake mainly from agriculture runoff [8]. The nutrients load distribution on the water surface of the lake has been studied by Dowidar and Abdel-Moati [52]. They identified Bahr El-Baqar drain as the largest contributor of nutrients to the water body. Abdel-Moati and Dowidar [10] investigated the concentration of heavy metals in the lake sediments, while Abdel-Satar and Geneid [53] examined the heavy metal loadings in the sediments, plant, and fish of the lake. These studies concluded that heavy metal contamination is a major problem in the lake. El-Wakeel and Wahby [2] investigated the chemistry of the water during the period of 1962–1963 before the opening of the Aswan High Dam project.

It was anticipated that the lake water quality would change after the opening of the High Dam as the irrigation system will be changed accordingly. This was the motivation for El-Hehyawi [13] to conduct a study to identify the change in the water type and distribution inside the lake domain. Some physical and chemical water characteristics were traced to identify the change of the water type within the lake water body. Three main water types were found: maximum chlorosity, drainage, and polluted water types.

Further studies were conducted by Wahaby and Bishara [12] to determine the tolerate limits of some physical and chemical parameters for different fish species. In addition, the change of the fish distribution in the lake according to the prevailing water quality condition associated with the increase in the volume of the drainage water has been highlighted. The full detailed physical and chemical characteristics of the lake can be found in [6, 9, 18] through their field data collection studies.

Said and Abel-Moati [54] examined the variation in mean water temperature and the heat content recorded in the lake. Based on the lake volume and the freshwater inflow quantity, the author calculated 48 days to be the time in which the lake replaces its water. However, according to [18, 55] residence time is 35 days. This inconsistency illustrates the huge area impacted by land reclamation projects during the intervening period.

The lake water environment exhibited high levels of Ca, Mg, and SO_4 and heavy metals Zn, Pb, and Cd which exceed the safety baseline world levels [14, 56]. The authors found the dark polluted water increases stress on the fish and affects its hypophysical-gonadal activity. The accumulation of these heavy metals is found in tilapia organs [40]. Gad [15] relates the reduction of the total protein and lipid contents in the fish muscles and its bad meat quality to the high water pollution. Also, the pollution affected the enzymatic activities and the physiological functions.

El-Sherif and Gharib [34] studied the spatial and temporal distribution of phytoplankton community. Ramdani et al. [44] found the relatively high inflows of both freshwater and nutrients into Lake Manzala produced a rich phytoplankton community dominated by green algae. The lake water salinity has been dramatically reduced during the past three decades [9]. This change has affected the fish species present in many regions of the lake and, in particular, has led to a disappearance of some marine species types and the existence of new freshwater fish types. Mageed [3] investigated the distribution and long-term historical changes of zooplankton assemblages in the lake during the past four decades. The author reported significant increases in the species composition of zooplankton and its numbers. Twenty new zooplankton taxa were found for the first time in his study. All the new species were of the freshwater type which confirms and indicates the low salinity condition of the lake.

Donia and Ahmed [1] demonstrate the importance of using the geographic information systems (GIS) as analytical tools. They use a GIS database as a visualization technique for quick understanding of the water quality condition and to serve as a lake data archive. The technique is applied to determine the overall trend of water quality inside Lake Manzala. The conclusion of water quality and its distribution were consistent with [55, 57].

A series of papers that describe the hydrological [5] and environmental characteristics [18] of the lake are issued in special edition of the *Hydrobiologia* journal. These papers are the outcome of a large project called MELMARINA. MELMARINA is a multidisciplinary project funded from the EUINCO_MED. The project aims are to effectively manage the coastal lagoons and develop adaptive designed strategies to minimize the nutrient enrichment and other environmental effects such as climate change and sea level rise. One of the motivations and goals of MELMERIN project is to model the hydro-ecological processes for three important lagoons on North Africa.

In the most recent studies, Lake Manzala is still representing a high risk for human and stakeholder as its fish is heavy polluted [24]. And it has been advised that the fish is not suitable for humans. However, people there still eat it which in turn will produce a major health problem. This finding is confirmed by Abdel-Gaber et al. [57] who use fish as useful bioindicators when evaluating the environmental pollution of aquatic ecosystems by heavy metals. A full analysis of the lake's most recent water quality was presented in [24, 58]. Remote sensing techniques were utilized to investigate the lake water quality [4]. Remote sensing technique may be a viable option to combine with the numerical simulation work of [24, 30, 58, 59].

8 Lake Manzala Modeling

During the past decade, the Egyptian government has promoted a series of research studies to improve water resources management in the northern Egyptian shallow water lakes. These lakes are under the pressure of water pollution, land reclamation, and vegetation. Lake Manzala is the largest among those and is considered as one of the major sources of fish and economic resource.

The condition of Lake Manzala is a high priority issue for the Egyptian government [20]. A quick resolution of the current environmental and water management problems is essential to allow the lake to survive. The use of CFD models will provide a good tool to develop a better fundamental understanding of the cause and effects of aquatic pollution problems. Also, it will permit the investigation of potential engineering solutions and support water quality management and decision making. The necessity for a hydrodynamic model of the lake was first raised during the past 7 years [32].

Numerical modeling of Lake Manzala is very limited. In 2009 Rasmussen et al. [19] developed the first hydrodynamic model to represent Lake Manzala. The hydrodynamic one-layer model used in this study was MIKE 21 FM. The model was combined with an ecological model to identify the conditions required to enable the propagation of vegetation throughout the lake. This study investigated different general scenarios when nutrient loads were reduced to 25, 50, and 75% of its normal load. The model ignores the impact of the 40% freshwater diversion of the lake inflow. This reduction may change the water hydrodynamic and quality of the lake. A detailed study of the lake hydrodynamics using the Finite Volume Coastal Ocean Model (FVCOM) hydrodynamic/oceanographic model [59] can be found in [60]. The FVCOM model was employed to simulate the hydrodynamic and water quality processes of Lake Manzala system and to estimate the effects of alternative operations scenarios on the system. In 2016 another numerical simulation using MIKE 21 model was conducted [30, 60, 61].

The model is developed in order to investigate the impacts of future climatic changes on hydrodynamic and water quality characteristics of the lake. Khadr and Elshemy [61] investigated the capabilities of adaptive neuro-fuzzy inference system (ANFIS) to predict water quality parameters of drains associated with Lake Manzala. In order to have a full insight view for the lake statues, all scattering researchers should work under one umbrella of the Egyptian government of one integrated project [62].

9 Conclusions

Lake Manzala is an important economic resource for the Egyptian government. The lake has been subject to intensive observation studies that well described its physical, chemical, and biological status. These studies highlighted the serious water quality condition of the lake and described its bad impact on the surrounding environment. The main challenges for the lake water body are land reclamation, nutrient enrichment, and pollution, especially from Bahr El-Baqar drain. In addition, the spread of aquatic plants, water hyacinth, in most parts of the lake, which affect the movement of water in the lake, affects the quality of both water and fish. A quick action for the lake remediation is initially to allow the law to take action over any type of stakeholder's violence toward the lake. Perhaps socioeconomy study for Lake Manzala became essential. The available studies indicated the essential need for better understanding of the lake hydrodynamics through numerical models. These models will be used to relieve some of the pressure and allow quick lake remediation of choosing the best-proposed scenario.

10 Recommendations

The authors highly recommend the following:

1. Lake Manzala needs full surveys and monitoring programs to examine the themes of hydrology, water, sediment quality, and aquatic ecology.
2. Numerical investigation of the lake water circulation in response of expanding the radial (narrow) channels.

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Phytoplankton Ecology Along the Egyptian Northern Lakes: Status, Pressures and Impacts

Mostafa El-Sheekh, Elham Ali, and Hala El-Kassas

Abstract The northern lakes, particularly the delta ones (Manzala, Burullus, Edku and Mariout), were among the richest and most diverse ecosystems in Egypt 40 years ago. They are the important natural resource of fish production in Egypt. Besides, they are internationally important sites for the migrating birds, providing them with the suitable habitat. Water discharges into the lakes are mainly agricultural drainage water (containing pesticides, fertilizers) and effluents of industrial activities and runoffs. In addition, sewage effluents supply the lake water body and sediment with huge quantities of inorganic anions (such as phosphates, nitrates and ammonia), combined organic nitrogen and heavy metals. Such nutrient enrichment to the lakes' ecosystem is mostly followed by alterations in phytoplankton community structure. The phytoplankton represents the main group of primary producers and hence is considered as the main food source for fish in these lakes. In addition to the four mentioned delta lakes, Lake Bardawil is located North Sinai, and it is a saline lake which is considered one of the most important lakes in North Egypt. Lake Bardawil environment differs from that of the other Mediterranean Egyptian lakes in terms of climatic factors, geomorphology and salinity. The northern lakes provide a rich and vital habitat for estuarine and have always been major areas of fish production in Egypt, where they contribute to the economy of Egypt. The alteration in environmental conditions together with other human-induced pressures and interferences has played an important role in lake

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deterioration and water quality and accelerates all the biological productivity along the lakes. In nature, thousands of years are required for oligotrophic water body to become an eutrophic one. Water quality of the northern lakes is largely influencing phytoplankton growth, the structure of their community and the trend of species succession. Therefore, the pattern processes and dynamics of phytoplankton community assembly along the five lakes should be studied in order to understand the status of the water quality of the lakes. For example, Lake Edku was classified among the oligotrophic lakes several years ago because it receives huge amounts of drainage water; however, it is currently described as eutrophic lake with a tendency to hypertrophy. In this chapter, we discuss the phytoplankton ecology along the Egyptian northern lakes with special reference to status, pressures and impacts.

Keywords Biodiversity, Biological indicators, Egyptian northern lakes, Phytoplankton, Water quality

Contents

1 Introduction

Globally, water quality of inland lakes is of great importance, particularly in countries of the arid region. This makes the majority of these inland lakes of a great public interest for recreational activities, some industries as well as water supply and support to most of the local communities. The Egyptian northern Mediterranean coast extends from Sallum to Rafah, for about 970 km. This coast occupies about 6% of the surface area of Egypt (the nondesert area) with five natural lakes along, named (1) Mariout (western section), (2) Edku, (3) Burullus, (4) Manzala (deltaic section) and (5) Bardawil (North Sinai) Fig. 1 [1]. The northern lakes, particularly the deltaic ones (Manzala, Burullus, Edku and Mariout), were among the richest and most diverse ecosystems in Egypt 40 years ago. They are considered as the important natural resource of fish production in Egypt. Lake Edku, for example, has an average production of 500 kg fish/feddan (i.e. 8,500 tones fish/year) contributing with about 8.8% to the total national agricultural income in 2014 [2].

During the last decades, the national production of fisheries resources in Egypt has been greatly changed (see Fig. 2) with dramatic diminishes in lake production [3]. The four deltaic lakes were providing approx. 35% of Egypt's fish catch during the 1970s although this rate is currently reduced only to 17%. According to [4], this is mainly attributed to several factors including the accelerating developmental

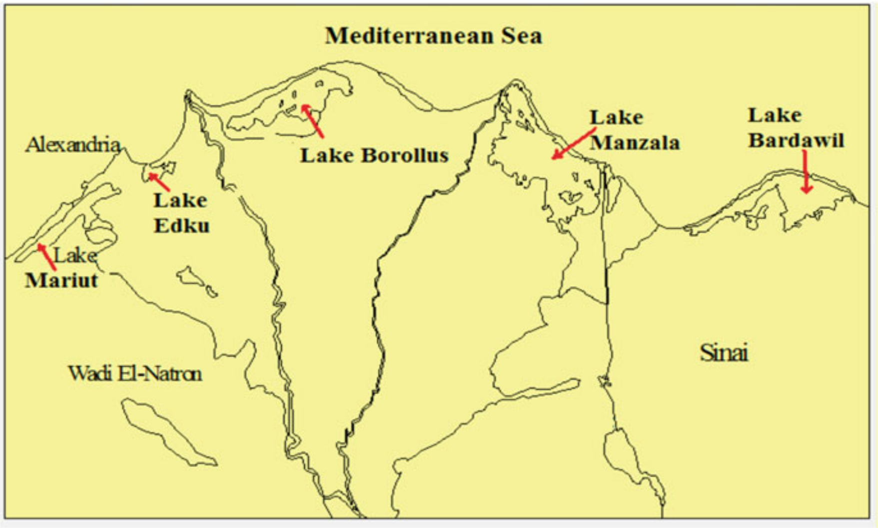

Fig. 1 Location map of the five northern lakes of Egypt [1]

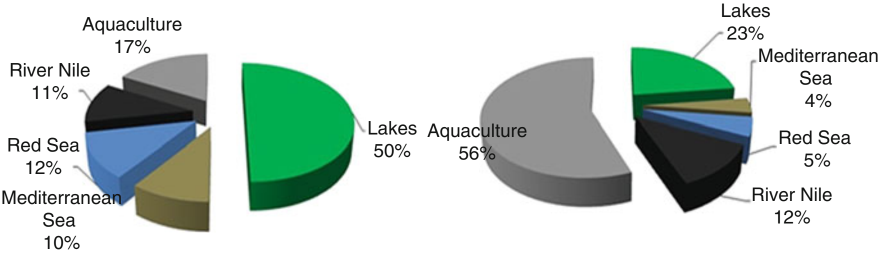

Fig. 2 Changes in fisheries resources in Egypt from 80th and 2007. Modified from [3]

activities, overfishing activities, clarification practices and, most importantly, the continuous deterioration of lakes.

As a response of such aggressive impacts on these lakes, generating a management plan with rehabilitation process and adequate policies/regulations is urgently recommended. This is prior requiring an improved monitoring strategy, measures and advanced techniques for the lakes and their changeable attributes. This would certainly depend on the typical conventional water quality measurements that based on in situ water sampling and laboratory measurements, which surely give accurate values and recently depend more on other advance earth observation methodologies – such as satellite images – that give the synoptic view with a complete and wide spatial coverage of various water quality parameters. Chlorophylls – the universal measure for aquatic biological activates – are among the major attributed that can be optimally monitored by remote sensing. Regular monitoring of chlorophylls could give some good insights on phytoplankton existence, growth and distribution at both special and temporal scales which in turn reflect the ecosystem health and vitality.

The main aim of this chapter was to provide information about overall phytoplankton diversity and how phytoplankton characteristics differ between the Egyptian northern lakes. The water quality and the seasonal and spatial differences in the quantitative and qualitative composition of the phytoplankton communities at each lake will be considered. The relevance of phytoplankton data and information to the assessment process of lake status will be addressed. Also recommendations to improve lake status and water as well as future monitoring preferable will be considered.

2 Phytoplankton Community Assembly Along the Five Lakes: Pattern, Processes and Dynamics

2.1 Phytoplankton Standing Crop and Food Chain

Phytoplanktons are known to be the primary producers in aquatic environments and are represented at the bottom level of the food chain. Also they are able to absorb and assimilate metals from their aqueous environment [5]. Thus, the amount and diversity of phytoplankton in a water body reflect the average ecological condition and, therefore, may be used as an indicator of water quality. Phytoplankton are one of the bioindicators that including algae, macrophyte, zooplankton, insect, bivalve molluscs, gastropod, fish, amphibian and others are enumerated in practical bio-monitoring of aquatic metal pollution. Abd El-Monem and Kanswa [6] indicated that phytoplankton comprises the base of the food chain in the aquatic environment and constitutes the main group of primary producers. Sautour et al. [7] studied the significance of the trophic relationship between phytoplankton and zooplankton in estuarine ecosystems. Any increase in nutrient loading can cause an increase in phytoplankton productivity and standing stocks [8], especially in the large-sized phytoplankton [9]. Several previous studies have indicated that large phytoplankton cells are more likely to be ingested by mesozooplankton communities dominated by copepods [10–12]. In addition, elevated nutrient loadings may cause a change in the ratio of macronutrients, which may alter the species composition, dominance and succession of zooplankton [8, 13]. When phytoplankton presented in high numbers, their presence appears as dramatic discoloration of the water. This population growth can be rapid and typically occur when temperature and nutrient levels rise, usually in late spring and autumn [14]; it is commonly known as an algal bloom. Blooming phytoplankton can have environmentally detrimental effects either by causing oxygen depletion or toxic poisoning. Oxygen depletion effects occur when respiration by blooming phytoplankton (usually non-toxic species) and by other organisms feeding on the phytoplankton decreases oxygen to low enough levels to cause animal mortalities [14]. Any change in their composition, density and spatial distribution will affect the secondary producers, consumer and decomposer characteristics [15]. It is well known that phytoplankton has an important and main role in primary production and food chain in aquatic ecosystems of the lakes [16]. Phytoplankton in the northern lakes is affected by pollutants and nutrient load. El-Sheekh [17] stated that lake systems in northern Egypt are affected by drainage of polluted water, and this affects the diversity of fish, phytoplankton and other microorganisms. Also, El-Sheekh et al. [18] found that oil pollution decreased phytoplankton standing crop in polluted locations.

2.2 *Dynamicity of Phytoplankton Growth and Replication*

The regulation of algal population dynamics in lakes and reservoirs has become of a broad interest in order to protect water quality and economic expediency and also to reduce costs of drinking water treatment. This approach became important after the large development of phytoplankton in lakes and reservoirs and hence has broadened the interest in the regulation of algal population dynamics [19]. They also stated that the growth in the availability and power of personal computers had widened the opportunities for building models which simulate the phytoplankton development. Jørgensen [20] has published a model for predicting extrapolations of phytoplankton development in specific water bodies. His model is suitable for the behaviours of the individual species (or, rather, their biological properties) to meld into an assembly of species functioning simultaneously.

Several studies have discussed the effects of environmental factors on phytoplankton dynamics, for example [21–25]. ‘Several factors are known to affect phytoplankton species coexistence at a local scale, such as productivity’ [26], nutrient supply/ratios [27] and the underwater light conditions [28]. The influence of various factors on the seasonal appearance of phytoplankton differs significantly, with physical factors such as temperature and light intensity being the most important and chemical factors (e.g. dissolved oxygen, pH, salinity, total hardness, EC and nutrient level) which being of lesser importance [21].

Many attempts have been done by researchers to build models for predicting and regulate the growth and distribution of phytoplankton in water bodies. The models should be accurate in representing the way that phytoplankton populations modulate their activities so as to achieve the fastest sustainable growth rate. The rapid development in computing has opened great new possibilities to modellers of limnological systems and the plankton they support [18, 23]. The estimation of in situ cell replication rate can be attained from the direct observation of phased cell division in natural populations. For example, cell separation in certain genera of dinoflagellates and desmids is sufficiently distinctive and protracted for it to have been possible substantiate the direct linkage between the rate of population increase and the number of cell divisions required daily to sustain it [29, 30]. Reynolds [31] used the frequency of distinctive reproductive daughter colonies of *Volvox*, as a sensitive indicator of growth conditions. Pinckney et al. [32] used the photopigment biomarker application for quantifying microalgal community composition and in situ growth rate. They used mesocosm bioassay to quantify the short-term responses of phytoplankton. The data obtained showed that the growth rates were higher under static conditions in N-amended cultures, while the biomass of most algal groups studied was higher under N addition condition. The environmental conditions and nutrient availability affect the dynamics and distribution of phytoplankton. The dominance of Bacillariophyceae was attributed to the high concentration of silica, while the high amount of nitrate, phosphate and sulphate caused the abundance of Chlorophyceae, Cyanobacteria and Desmidiaceae [33]. In addition, genus *Euglena* tops a list of 60 most tolerant genera to pollution [34] and is generally considered as a biological indicator of organic pollution. The increase in water temperature and nutrients is an important factor that cause increasing of phytoplankton abundance and diversity in winter. In summer, water temperature increasing, nutrient consumption by phytoplankton and grazing by zooplankton cause decrease in phytoplankton abundance and diversity [35]. Eutrophication of water in lakes and reservoir due to the overload of nutrients, especially from waste water disposal, causes some toxic algae and Cyanobacteria to flourish. This may affect the water quality and human, animal and fish health. Therefore, the predictive models based on microbial and ecological processes in freshwater bodies are useful for developing management responses aimed at reducing the negative consequences of algal blooms to the community [23].

2.3 Temporal and Spatial Distribution

Phytoplankton flora in the 5 northern lakes of Egypt includes 867 species that belong to 9 algal divisions, 102 families, and 203 genera. The recorded names are in bold, italic types, and their synonyms are in italic type. The nine recorded algal divisions are arranged descendingly as follows: Bacillariophyta > Chlorophyta > Cyanophyta > Dinophyta > Euglenophyta > Cryptophyta > Chrysophyta > Phaeophyta > Rhodophyta [36].

Khairy et al. [37] studied the phytoplankton populations of five Egyptian northern lakes. They analysed their species composition, diversity, behaviour and abundance of the common species characterizing each lake. The obtained phytoplankton list comprised 867 species related to 9 algal divisions, 102 families, and 203 genera. Bacillariophyta (diatoms) was the most dominant group, while Cryptophyta, Rhodophyta (red algae) and Phaeophyta (brown algae) were represented by only one species. They arranged descendingly the species diversity of the five lakes as follows: Manzala (383 spp.) > Mariout (376 spp.) > Bardawil (333 spp.) > Burullus (247 spp.) > Edku (183 spp.). The highest number of unique species was recorded in Bardawil (208 spp.) followed by Manzala (128 spp.), then Mariout (85 spp.), Burullus (76 spp.) and Edku (6 spp.). The highest number of unique species was recorded (208 spp.) in Lake Bardawil (62.4% of the total species). They attributed the high number in Lake Bardawil to its hypersaline nature and the low level of polluted water compared to the other oligotrophic lakes.

2.3.1 Lake Mariout

Lake Mariout is the smallest lake in northern Egypt (63 km^2). Lake Mariout is the only lake that has no natural connection with the Mediterranean Sea [1]. Therefore, it differs from the other coastal Egyptian lakes in being disconnected from the sea and freshwater. According to El-Wakeel and Wahby [38], the lake becomes brackish since the Napoleon's Campaign in 1801 when the British Forces cut the dykes of the freshwater canal that separated Lake Mariout from the sea and allowed the sea water to flow in and flood a vast area around the lake.

The high input of nutrients through sewage, agricultural and industrial wastes has considerably increased the phosphorus and nitrogen load in the lake. This resulted in a high degree of water eutrophication along the lake accompanied with a heavy bloom of phytoplankton, particularly blue-green algae [39]. In summer 1971, Saad [40] observed a thick layer of green phytoplankton covering the surface water of the Lake Mariout, which reduced the transparency of the lake. Toxic cyanobacterial species were recorded in the lake water such as *Microcystis aeruginosa* and *Anabaena* spp. [41, 42].

Salah [43] recorded six classes of phytoplankton in Lake Mariout, and, from them, Bacillariophyta formed more than 70% of the total standing crop. Aleem and Samaan [41] identified 33 species of Bacillariophyta, 35 species of Cyanophyta, 20 species of Chlorophyta, 5 species of Euglenophyta as well as few species of Cryptophyta and Dinophyta. Cyanophyta species were identified. They noticed that the flagellated forms of Chlorophyta flourished in winter. However, Bacillariophyta showed a maximum density in spring and to a lesser extent in autumn. Chlorophyta comprised the species from the order Chlorococcales and Volvocales. The flagellated forms of Chlorophyta (e.g. *Chlamydomonas* and *Carteria*) flourish best in winter. The most dominant green algae species were *Ankistrodesmus*, *Kirchneriella* and *Scenedesmus* species. Cyanophyta comprises the genera *Merismopedia*, *Microcystis*, *Spirulina* and *Oscillatoria*. Bacillariophyta is represented by the genera *Cyclotella*, *Nitzschia*, *Cocconeis* and *Mastogloia*.

Abdalla et al. [44] reported that phytoplankton community in Lake Mariout is characterized by low species diversity and regular pattern of blooms and was dominated by pollution-tolerant species such as *Merismopedia tenuissima*, *Spirulina platensis*, *Cyclotella meneghiniana*, *Crucigenia tetrapedia*, *Oocystis borgei*, *Kirchneriella* spp. and *Euglena granulate*. Koussa [45] identified a total of 93 algal taxa and species in Lake Mariout. These taxa are belonging to four divisions: Cyanophyta (21 taxa), Bacillariophyta (57 taxa), Chlorophyta (12 taxa) and Euglenophyta (3 taxa). Regarding their percentage frequency to the total phytoplankton standing crop, Cyanophyta species constituted about 80% of the total density. Bacillariophyta formed 17%, Euglenophyta about (2%) and Cyanophyta only (1%). The algal assemblages were dominated by *Spirulina platensis*, *Oscillatoria tenuis* (Cyanophyta) and polluted indicator species (*Euglena gracilis*).

2.3.2 Lake Edku

Lake Edku covers an area of about 124 km^2. It is connected to the Mediterranean Sea at its north eastern edge through Boughaz El-Madaya inlet. The lake is very shallow, with a maximum depth of about 200 cm [46].

Soliman [47] found that phytoplankton community in Lake Edku consisted mostly of Bacillariophyta that comprised 54 species. Chlorophyta and Cyanophyta were also observed, including 33 and 16 species, respectively. Other classes of phytoplankton were rarely represented with six species of Euglenophyta and one species of Dinophyta. Among the Bacillariophyta, *Cyclotella meneghiniana*, *Nitzschia* spp., *Navicula* spp., *Synedra* spp., *Cocconeis placentula* and *Bacillaria paradoxa* are the widely distributed taxa. The dominant chlorophytes were *Pediastrum tetras*, *Scenedesmus* spp., *Spirogyra* spp. and *Closterium acutum*. The most predominant blue-green algae in the lake are *Oscillatoria* spp., *Lyngbya aestaurii*, *Merismopedia punctata*, *Anabaena* spp., *Spirulina* spp. and *Phormedium* spp. Gharib and Gorgham [48] studied the phytoplankton structure and abundance of Boughaz El-Madaya which connect the Lake Edku with the Mediterranean Sea. The majority of the recorded species were fresh or brackish water forms, while 39 species were marine. Diatoms were the most diversified group (77 spp.), followed by green algae (46 spp.), blue greens (30 spp.), Euglenophyceae (16 spp.) and dinoflagellates (13 spp.). *Cyclotella meneghiniana*, *Nitzschia palea* and *Closterium* were the most dominant diatoms, while *Scenedesmus quadricauda*, *Sc. bijugatus*, *Sc. acuminatus* and *Crucigenia rectangularis* dominated among the green algae.

Fathi et al. [49] identified a total of 31 genera in Lake Edku during the whole period of study. Out of these 10 genera belong to Chlorophyta, 11 to Bacillariophyta, 4 to Euglenophyta, 5 to Cyanophyta and only 1 to Chrysophyceae. In terms of a total number of different species of all groups, the highest count was found to be in winter 1997, followed by spring, and the lowest count was harvested in autumn.

Bacillariophyta and Euglenophyta represented the main algal groups during the study period. It can be clearly seen that all over the period of investigation, Bacillariophyta was the most dominant group. Chlorophyta ranked second, Euglenophyta the third, Chrysophyceae the fourth and Cyanophyta come in the fifth group in the order of dominance. The epiphytic diatom *Cocconeis placentula* has a maximum abundance at most sampling sites in Edku Lake but is also common in some samples in Burullus and Manzala lakes. Furthermore, the mesohalobous taxa *Pleurosira laevis* and *Planothidium hauckianum* are common and characteristic species in Edku Lake [50].

Algal species with the high occurrence were *Cyclotella meneghiniana*, *Cyclotella ocellata*, *Scenedesmus bijuga*, *Euglena acus*, *Euglena proxima*, *Stephanodiscus invisitatus* and *Rhodomonas ovalis*. *Cyclotella* spp. was the only species demonstrated with relatively high density, contributing 34.8% of the total count. Zalat and Vidary [50] attributed the predominance of epiphytic taxa, of diatoms compared to other benthic and planktonic forms, may be due to the shallowness of the lake and the development of macrophytes, because of high inputs of nutrient-rich effluents in Edku Lake from the southern and eastern drains. The results of Fathi et al. [49] indicated that few cyanobacterial species were recorded in the lakes during the investigated period especially *Microcystis aeruginosa* and *Spirulena platensia*. There was a significant seasonal difference in quantitative and qualitative composition of the phytoplankton.

2.3.3 Lake Burullus

Burullus is the second largest of the Egyptian lakes along the Mediterranean coast. It is located in the central part of the northern shoreline of the Nile Delta. It covers an area of about 568 km^2 and has a maximum length of nearly 64.5 km, with a maximum width of about 16 km. The lake is very shallow, with a maximum depth of about 175 cm in the middle and western parts [50]. Lake Burullus is connected to the Mediterranean Sea through Boughaz El-Burullus opening. It is a shallow brackish water basin. It is one of the Nile Delta lakes located between the two main delta promontories, Rosetta and Damietta.

The phytoplankton population and biological characters in Lake Burullus were investigated by many researchers [51–61].

Phytoplankton community of Lake Burullus is considered rich, both in density and species richness, but most of the species are fresh and brackish water forms. From the survey of the literature on phytoplankton assemblages of the lake, there is a large variation among the researches in the species composition and density depending on the surveyed stations, sampling depth, sampling season, water quality, environmental conditions and of the lake [36, 37]. Kobbia [51] recorded 49 species belonging to 6 algal divisions during 1980 at 3 stations and different depths; 14 species of Chlorophyta, 19 of Cyanophyta, 12 of Bacillariophyta, 2 of Cryptophyceae and 1 species of each Chrysophyta and Dinophyta. On the other hand, El-Sherif [62] recorded 113 species distributed among algal divisions as follows: 52 species of Bacillariophyta, 41 of Chlorophyta, 15 of Cyanophyta, 2 of Euglenophyta, 2 of Dinophyta and 1 Cryptophyta. Radwan [55] recorded and identified 65 species of phytoplankton belonging to 5 classes, namely, Bacillariophyceae (28), Cyanophyceae (15), Chlorophyceae (15), Euglenophyceae (5) and Dinophyceae (2). Okbah and Hussein [57] recorded a total of 170 species, represented mainly by Bacillariophyta (47.49% of the total standing crop) comprising 68 species; the main diatoms comprised *Cyclotella meneghiniana* and *Synedra ulna*. Chlorophyta was represented by 39.44% with 54 species; *Oocystis borgei*, *Geminella minor* and *Dictyosphaerium pulchellum* formed the bulk of Chlorophyta and Cyanophyta (8.46%) 16 species; the most dominant blue-green algae species were *Microcystis aeruginosa*, *Lyngbya limnetica*, *Anabaena* spp. and *Oscillatoria limnetica*, *Euglenophyta* (3.96%) 15 species, Dinophyta (0.64%) 6 species and silicoflagellates (0.01%) 1 species. Okbah and Hussein [58] identified a total of 170 taxa, comprising 68 Bacillariophyceae, 54 Chlorophyceae, 26 Cyanobacteria, 15 Euglenophyceae, beside 6 species Dinophyceae and 1 silicoflagellate. Bacillariophyceae was the most dominant group, forming 44.826% of the total phytoplankton count. Radwan [55] also concluded that the maximum number of phytoplankton species counted belonged to class Bacillariophyceae which represents the first productive one.

Ali and Khairy [60] stated that a total of 156 phytoplankton taxa were identified out of which 64 Bacillariophyta, 52 Chlorophyta, 24 Cyanophyta, 12 Euglenophyta and 4 Dinophyta. Data showed that phytoplankton species succession widely varied along the lagoon with Bacillariophyta the mostly abundant community. Phytoplankton was then dominated by blue-green algae and dinoflagellates. Euglenophyta and/or Chlorophyta, however, occurred as a transition stage, and the overdominant green algae species was *Scenedesmus* sp. El-Kassas and Gharib [61] recorded a total of 163 taxa from 5 classes; diatoms were the most diversified group. The main three dominant classes are Chlorophyceae, Bacillariophyceae and Cyanobacteria. They also showed that Chlorophyceae was the dominant group, followed by Bacillariophyceae in the eastern and western basins, while Cyanobacteria followed chlorophytes in the middle basin. The recorded phytoplankton in the lake 2009 to spring 2014 was shown in Table 1.

Table 1 Number of species and genera observed in each algal division in Burullus Lagoon from summer 2009 to spring 2014 [61]

	[65]								[61]	
Period	2009–2010		2010–2011		2011–2012		2012–2013		2013–2014	
Taxonomic groups	Species	Genus	Species	Genus	Species	Genus	Species	Genus	Species	Genus
Chlorophyceae	31	N.R.	62	23	49	17	46	18	46	21
Bacillariophyceae	35	N.R.	72	30	53	22	50	20	61	27
Cyanobacteria	18	N.R.	35	13	27	11	27	13	25	11
Euglenophyceae	7	N.R.	21	2	20	3	20	3	19	3
Dinophyceae	3	N.R.	4	4	4	2	5	4	12	7
Chrysophyceae	1	N.R.	1	1	1	1	0	0	0	0
Xanthophyceae	0	N.R.	0	0	1	1	0	0	0	0
Total	95	55	195	73	155	57	148	58	163	69

N.R. not recorded

2.3.4 Lake Manzala

This lake is the largest of the Egyptian lakes along the Mediterranean coast. It covers an area of about 1,275 km^2 and has a maximum length of nearly 64.5 km, with a maximum width of about 49 km. The lake water is generally brackish. The lake is very shallow with a maximum depth of about 250 cm and has recently decreased further in size, due to land reclamation effects [50].

The changes of algal communities are most commonly a response to the increase of water pollution and the influence of season. Therefore, the excessive algal population (eutrophication) is a problem having a worldwide central concern, and the degree of water pollution can be evaluated by characterizing the aquatic communities in the habitat [63]. Khalil [64] investigated the phytoplankton abundance and distribution from June 1985 to June 1986. He means phytoplankton abundance ranged from 32.7×10^7 to 76.1×10^7 cells m^{-3} with a mean value of 48×10^7 cells m^{-3}. Diatoms were the predominant phytoplankton group comprising 52–90% by number. The most predominant genera were *Synedra*, *Nitzschia*, *Melosira* and *Coscinodiscus*. The green algae *Tetraspora*, *Scenedesmus* and *Pediastrum* were predominant. Two genera of blue-green algae (Cyanobacteria) recorded (*Spirulina* and *Anabaena*) representing 1–23% by numbers for all stations. El-Sherif and Gharib [66] stated that Bacillariophyta was the most important algal group in Lake Manzala during winter and spring (1992–1993). Chlorophyta were mainly observed during autumn, while Cyanophyta favour summer season. Their study indicated high levels of eutrophication. The phytoplankton diversity varied widely in the areas neighbouring the outfall of discharged water and within a narrow range in areas far from the effect of drainage water. Salah El Din [67] identified 57 algal species in Lake Manzala; out of these 18 species belong to Chlorophyta and 18 species to Bacillariophyta, representing a percentage of (31.58% of the total phytoplankton) each, 14 species to Cyanophyta (24.56%), 6 species to Dinophyta (10.53%) and only 1 species to Euglenophyta (1.75%). Bacillariophyta were predominantly by *Nitzschia* spp., *Navicula* spp. and *Amphora ovata*. Chlorophyta was the second greatest group represented mostly by *Ankistrodesmus falcatus*, *Scenedesmus bijuga*, *Scenedesmus* spp., *Oocystis* spp. and *Crucigenia* spp.; however, Cyanophyta was considered the third predominant group. Abd El-Karim [68] found that the dominant classes in Lake Manzala were also Chlorophyta, Bacillariophyta and Cyanophyta. The three groups altogether constitute more than 90% of the total phytoplankton abundance. Other groups were marginally present like Prasinophytes, Cryptophytes, Chrysophytes, Euglenophyta and Dinophyta. On the biovolume basis, Bacillariophyta dominated the phytoplankton communities, whereas, based on cell number, the Chlorophyta exclusively dominated the phytoplankton communities year round. The dominant classes were dominated by the single-celled *Dictyosphaerium pulchellum* (Chlorophyta), *Cyclotella meneghiniana* (Bacillariophyta), *Microcystis aeruginosa* and *Tetrachloride merismopedies* (Cyanophyta).

2.3.5 Lake Bardawil

Bardawil lagoon is the most saline (hypersaline) and oligotrophic of the Egyptian northern lakes [69]. It is one of the largest (650 km^2) Mediterranean coastal lagoons and is located on the northern Mediterranean shore of the Sinai Peninsula of Egypt. Phytoplankton population in Lake Bardawil were studied by [70–75]. Phytoplankton diversity in Lake Bardawil is as other oligotrophic lakes and is characterized by high species diversity compared to eutrophic water bodies. As recorded by Toulibah et al. [70], both the Cryptophyta and Euglenophyta were recorded, and each represented by a single species during 2000. It is noticed that species diversity of phytoplankton is higher near the inlets if compared with the centre of the lake; this decrease is obviously related to the increase in salinity [76]. El-Kassas et al. [74] recorded a total of 186 phytoplankton taxa from 95 genera, and 7 classes, namely, Bacillariophyceae, Dinophyceae, Chlorophyceae, Cyanobacteria, Euglenophyceae, Rhodophyceae and Chrysophyceae were recorded. Phytoplankton community was dominated by Bacillariophyceae followed by Dinophyceae. Bacillariophyceae was quantitatively the predominant division (73.12%) (Fig. 3).

Konsowa [74] found that in the hypersaline Bardawil lagoon, Bacillariophyta and Dinophyta were the main classes of phytoplankton, constituting 96% of the total phytoplankton cell counted. A bloom of *Chaetoceros* spp. occurred in the middle region of the lagoon during June and July 2005. Bacillariophyta densities were relatively higher than those of Dinophyta near the two artificial inlets from the Mediterranean Sea, especially near the western one. The western basin of lagoon maintained the highest density of Dinophyta, comprising 74% of the total phytoplankton cells counted. Phytoplankton abundance increased with raising temperature and salinity during the summer season. He also indicated the presence of 114 species, of which Bacillariophyceae represented 56.6% of the total counts,

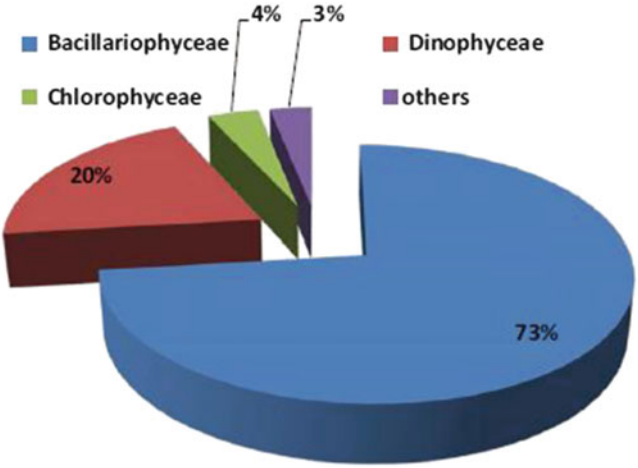

Fig. 3 Community composition of total phytoplankton in Bardawil lagoon during 2013–2014 [75]

where *Chaetoceros*, *Bacteriastrum*, *Leptocylindrus*, *Skeletonema*, *Thalassionema* as well as *Thalassiothrix* and *Campylostylus* were the most dominant genera, while Dinophyceae represented 39.5%, and *Prorocentrum*, *Exuviella*, *Diplopsalis*, *Ceratium*, *Hermesium*, *Peridinium*, *Oxytoxum* and *Dictyocha* were also dominant genera. The data collected from 1985 to 2002 by Shaltout and Khalil [73] indicated that 241 species were recorded in Lake Bardawil and Bacillariophyta were represented by 154 species followed by Dinophyta with 53 species. Cyanophyta, Chlorophyta and Chrysophyceae were lesser recorded and represented by 15, 8 and 4 species, respectively. Among the 241 recorded species, only 12 species were common and documented in all investigations, while 56 ones were considered as new species that invaded the lagoon. El-Kassas et al. [75] concluded that the overall average of phytoplankton abundance in Lake Bardawil was 2.44×10^4 cells L^{-1}, this average being about nine times lower than the abundance recorded during 2005 by Konsowa [74]. It is evident that phytoplankton community obviously changed from 1985 to 2014, and these changes were more pronounced in density rather than in species number. These changes should be taken into consideration for further studies in the lagoon to explore the reasons for these changes.

2.4 Phytoplankton Biodiversity and Species Dominance

From the available collected data [36, 37], the algal flora in the 5 northern lakes of Egypt includes 867 species that belong to 9 algal divisions, 102 families and 203 genera. The recorded nine algal divisions arranged descendingly as follows: Bacillariophyta > Chlorophyta > Cyanophyta > Dinophyta > Euglenophyta > Cryptophyta > Chrysophyta > Phaeophyta > Rhodophyta (Table 2). With regard to the species/genus ratio (S/G), Bacillariophyta had the maximum ratio of 5.7; however, Chrysophyta has the minimum of 1.5. On the other hand, Cyanophyta achieved the maximum genus/species (G/F) ratio with a value of 2.8 followed by Bacillariophyta with a value of 2.1. As presented in Table 3, the highly represented families of Bacillariophyta are Naviculaceae, Bacillariaceae, Fragillariaceae, Rhobalodiaceae and Stephanodiscaceae. The highly represented families of Chlorophyceae are Scenedesmaceae, Oocystaceae, Selenastraceae, and Chlorellaceae. The most diverse cyanophytic families are Oscillatoriaceae, Nostocaceae, and Chrococcaceae. The most diverse dinophytic families are Peridiniaceae, Ceratiaceae and

Table 2 Taxic diversity of the major algal divisions along the five Mediterranean lakes of Egypt (modified after [37])

Divisions	Bacillariophyta	Chlorophyta	Cyanophyta	Euglenophyta	Dinophyta	Chrysophyta	Cryptophyta	Rhodophyta	Phaeophyta
S/G	5.7	3	3	4.7	3.3	1.5	0	0	0
G/F	2.1	1.7	2.8	4	1.7	1.3	0	0	0

Table 3 Number of the highly represented families, species and genus for the common algal divisions of the five Mediterranean lakes (modified from [37])

Divisions	No. family	No. species	No. genus
Bacillariophyta	5	197	21
Chlorophyta	4	74	20
Cyanophyta	3	67	18
Dinophyta	3	33	4
Total	15	371	63

Table 4 Algal species richness and number of unique species along the five Egyptian Mediterranean lakes (modified from [37])

	Divisions				Unique species		
Lake	Bacillariophyta	Chlorophyta	Cyanophyta	Dinophyta	No.	%	Total
Mariout	*255*	65	43	1	85	1.2	**364**
Edku	87	48	33	2	6	16.9	**170**
Burullus	126	66	36	7	76	15.1	**235**
Manzala	253	*70*	*49*	4	128	25.4	**376**
Bardawil	238	14	22	*53*	*208*	*41.3*	**327**

N.B. italicized numbers represent the maximum values of each division

Gymnodiniaceae. Dinophyta were represented by the families Peridiniaceae, Ceratiaceae and Gymnodiniaceae.

The species diversity of the five lakes can be arranged descendingly as follows: Manzala (383 spp.) > Mariout (376) > Bardawil (333) > Burullus (247) > Edku (183). Bacillariophytes have the following sequence: Bardawil (238 spp.) > Mariout (255) > Manzala (253) > Burullus (126) and Edku (87), while chlorophytes sequence is Manzala (70 spp.) > Burullus (66.) > Mariout (65) > Edku (48) > Bardawil (14). Cyanophytes sequence is Manzala (49 spp.) > Mariout (43) > Burullus (36) > Edku (33) > Bardawil (22). Dinophytes sequence is Bardawil (53 spp.) > Burullus (7) > Manzala (4) > Edku (2) > Mariout (1) species, while Euglenophytes sequence is Burullus (11 spp.) > Edku and Mariout (10 for each one) > Manzala (7) > Bardawil (1) (Table 4).

The highest number of unique species was recorded in Bardawil (208 spp.) followed by Manzala (128), then Mariout (85), Burullus (76) and Edku (6) (Table 4). It is determined [37] that the general sequence of Bacillariophyta is as follows: Bardawil (141 spp.) > Manzala (74) > Mariout (61) > Burullus (27) > Edku (2). However, the sequence of chlorophytes is Burullus (33 spp.) > Manzala (26) > Mariout (12) > Bardawil (4) > Edku (1), while cyanophytic sequence is Manzala (27 spp.) > Bardawil (12) > Burullus (11) > Mariout (9) > Edku (3); dinophytic sequence is Bardawil (46 spp.) > Burullus (1), and euglenophytic sequence is Burullus (3 spp.) Mariout (2) > Manzala (1).

3 Environmental Drivers/Pressures Influencing Phytoplankton Growth

The northern lakes in Egypt have subjected to an extensive process of developments and human interventions during the twentieth century [36, 77]. These include (1) land reclamations and transformation into farmlands, (2) changes in lakes' hydrology, (3) excessive fishing efforts, (4) imbalanced shoreline processes (i.e. accretion/erosion) [56] and (5) overgrowth of aquatic vegetation [78]. All the above-mentioned processes and/or activities dramatically impacted the lakes' ecosystem and influenced most of the inhabitant biota.

As the base of the food chain in the aquatic environment, phytoplankton constitutes the main group of primary producers [6] and the sensitive community that reflects the system environmental conditions [79]. There are various factors that affect phytoplankton species existence at any aquatic system, including productivity [26], nutrient supply and ratios [27] and light climate [28, 80]. Seasonal appearance of phytoplankton varies significantly, with physical factors such as temperature and light intensity being the most important followed by chemical factors in the second level of importance (e.g. dissolved oxygen, pH, salinity, total hardness, EC and nutrient level) [21]. Next section will focus on the major factors influencing phytoplankton existence.

3.1 Water Properties

Water quality of the northern lakes is largely influencing phytoplankton growth, the structure of their community and the trend of species succession. Environmentally, these lakes are highly structured with an obvious gradient in system conditions that affect vigorously diversity and structure of the phytoplankton-existent community (i.e. species type, numbers and distribution). The ecosystem of the northern lakes is highly variable physically and chemically due to the surrounding activities that are changed continuously and affect the biological interactions along the lake systems.

Air and water temperature are among the factors that regulate the seasonal distribution and dominance of specific species based on their temperature favour tolerance limits. Temperature among the Mediterranean northern lakes varied widely with a unique seasonal pattern that belongs to the dry arid zone according to Koppen's classification quoted by Trewartha [81]. The mean annual temperature varies from 20.5 to 21.1°C from Al-Arish to Port Said, respectively. The maximum range of hot season is 27–27.3°C (mainly August), while the minimum in the cold season is 13.6–14.2°C (in January). In specific, minimum water temperatures are 11.6, 16.1 and 17.2°C for Lake Bardawil [82], Burullus [56] and Edku [78], respectively. However, their maximum hot ranges are 33.2, 29.4 and 31.4°C. Salinity distribution along the five lakes is widely varied and could be described as heterogeneous. It is mainly changed with changing the water inflows into lakes' body as well as the mixing degree. Water transparency is a function of clarity that influenced mainly by properties of the water inflowing into the lakes from the sea outlet (Bughazes) or drains or both [56]. Water transparency is varying due to the amount of suspended matters and phytoplankton concentration and highly changeable with changing lake water depth. Water depths of the northern lakes varied between a minimum of <0.5 m and a maximum of ~4 m. Water depth varied from one lake to another due to the amount of water entering either from the surrounding drainage system or from the water exchange of the Mediterranean Sea. For instances, water depth varied from 50 to 400 cm, 42 to 207 cm and 20 to 300 cm for Lake Edku [36], Lake Burullus [78] and Lake Bardawil [82].

Pollution of shallow water ecosystems is a worldwide problem that imposes hazardous effects on the health of the local community besides its vigorous impacts on the national economy as a major threat to most aquatic organisms. Inorganic pollution particularly is one of the major threats to aquatic organisms including fishes. Normally, phytoplankton grows suspended within the water column using up nutrients (from water and/or sediments) and energy (from sunlight) and forms blooms on increasing nutrient levels and suitable temperature [14], i.e. in late spring and autumn. Nutrient profiles of each lake control the existent community of phytoplankton with regard to their quantity (standing crop) as well as quality (dominance and succession of species).

Changes in phytoplankton community composition, density and/or their spatial distribution will certainly affect the secondary producers, consumer and decomposer characteristics [15] via their critical role in the primary production, nutrient cycling and food webs. Such nutrient richness creates good habitats not only for phytoplankton but also for submerged plants as well which certainly have an essential structuring and functioning influences on the entire ecosystem [83].

Levels of dissolved oxygen along the northern lakes are generally well above the concentration below which most fishes die (<2 mg DO/L) [84]. However, it sometimes declined below the threshold, particularly during bloom periods. Oxygen status in aquatic environments is typically a result of the imbalance between system processes of photosynthesis, degradation of organic matter, re-aeration [85] and physicochemical properties of water [86]. However, the biological oxygen demand (BOD) gives an indication of the existence and level of organic pollutants. High levels of DO are recorded along the Egyptian northern lakes during cold seasons [77, 78], and this could be explained by the reduced activities of living organisms. On the other hand, minimum DO levels are recorded at the systems on increasing organic pollution as it needs high rates of oxygen consumption [87]. See Fig. 4 for DO and BOD levels in Lake Edku as an example.

Ali and Khairy [88] state that eutrophication of the lake is responsible of increasing phytoplankton density during summer with the dominance of Bacillariophyceae followed by chlorophycean taxon. They evaluated the water quality of the Lake Edku through the application of five indices. Diversity index (DI) indicated slight to light pollution along all sites, while saprobic index (SI) indicated slight pollution with acceptable oxygen conditions and an availability of sensitive species.

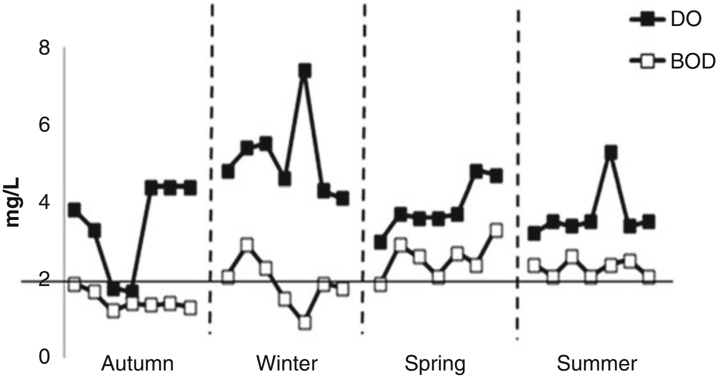

Fig. 4 Annual levels of DO and BOD along Lake Edku during 2012 [88]

In a recent study on Lake Mariout, a hydrodynamic and water quality model was used to evaluate the current status of the response to the pollution loadings from the surrounding agricultural drains and other discharging point sources [89]. The study suggested many scenarios that would improve the lake water circulation and hence its quality with applying several pilot interventions, such as upgrading the east and west water treatment plants. This upgrade helped to achieve about 5% reduction in pollution loads entering the Mediterranean Sea through Lake Mariout.

With regard to heavy metals, various types of heavy metals are found in the northern lakes, among which copper, lead and cadmium are the most common traces [90]. Generally speaking, industrial and petroleum contamination and sewage disposal are the most anthropogenic sources of metals in aquatic environments, water and sediments [91, 92]. For the northern lakes in Egypt, agricultural and sewage effluents supply the lake water and sediments with huge quantities of heavy metals that contribute significantly to the eutrophication and pollution status of these lakes [78, 93, 94]. Regardless, the great role and importance of heavy metals for aquatic organisms and the entire ecosystem, high levels of heavy metals dramatically impact most aquatic biota, mainly fishes, and phytoplankton.

Several extensive research programs have been carried out to investigate heavy metal distribution along the lakes' water [95–98], in sediments [98–101] and in tilapia tissues [102–104]. As a case of study, [93] determined concentration levels of 3.14–7.31 μg/L; 1.91–4.4 and 2.16–5.54 μg/L for copper, lead and cadmium, respectively, in Burullus. A comparison of five heavy metal concentrations along three deltaic lakes is summarized in Table 5.

3.2 *Drainage System*

The development of complex irrigation and drainage systems in the catchment area of the northern lakes together with other human-induced pressures and

Table 5 Heavy metal concentration (mg/L) in water (modified from [36])

Lake	Metals						Source
	Fe	Zn	Cu	Mn	Cd	Pb	
Edku	1.30	0.08	0.17	–	0.01	0.21	[96]
	0.57	0.016	0.011	0.024	0.007	0.028	[36]
	3.30	0.04	0.11	–	Nd	Nd	[96]
Burullus	0.24	0.19	0.05	–	–	0.06	[97]
	0.43	0.039	0.006	0.194	Nd	Nd	[36]
	–	7.94	0.08	–	0.11	0.064	[95]
Manzala	3.20	1.37	0.19	–	Nd	0.11	[96]
	1.42	0.463	0.513	0.513	0.044	0.099	[36]
	–	0.311	0.055	–	0.020	0.022	[105]
Bardawil	–	0.03	–	–	0.01	0.01	[106]
	0.444	0.166	0.011	0.04	–	0.016	[107]
Mariout	0.019	0.010	0.004	0.026	0.062	–	[108]

Note: *Nd* means not detectable

interferences is within the great influences on system deterioration and status of water pollution [109]. This would accelerate the biological productivity (e.g. net production) along the lakes.

The drains surrounding the northern lakes transport huge amounts of agricultural (containing pesticides, fertilizers), industrial (effluents), runoffs and fishing wastes in addition to sewage effluents into the lakes' water and their sediments supplying them with huge quantities of inorganic anions (phosphates, nitrates, ammonia, combined organic nitrogen and/or heavy metals) [56, 110]. Consequently, this brings the receiving water bodies into unpleasant levels of eutrophication with high inputs of nutrients of various types (i.e. terrigenous and anthropogenic), especially nitrogen and phosphorus [111–114]. Nutrient enrichment is mostly followed by vigorous alterations in phytoplankton species composition and community structure [60, 79, 88]. This is mainly attributed to their greater opportunity for nutrient recycling and hence the better and direct availability to primary producers, especially phytoplankton [115, 116]. Such drain inflows increasingly impact the water quality of these lakes [77, 93] and their circulation [117] and alter its water chemistry [118]. This is the case for most North African coastal lakes, such as Lake Burullus [78], Lake Manzala [119] and Lake Edku [88] in Egypt, lake Merja Zerga in Tunisia and Ghar El Melh lake in Morocco [120].

As studied cases, Lake Burullus receives the water of various properties from different sources with an annual rate of about 3.9 × 10^9 m^3 through nine drains and one fresh-brackish water canal (Brimpal) (Fig. 1). The monthly average discharge volume is estimated at ~240 × 10^6 m^3 (in winter) and 420 × 10^6 m^3 (in summer) [93, 121] with the drains D9, drain D11 and D5 (see Fig. 1) being the most important ones with 20, 18.5 and 15.6% contribution to the total annual inflow volume (Table 6). In addition to the sea waters entering the lake through Boughaz El-Burullus to the eastern north (Fig. 1), an average of 50–70 million m^3 of water

Table 6 Mean monthly and total annual water volume (million m^3) discharged into Lake Burullus from three main drains in 2008–2009 (personal communications with the Drainage Research Institute, National Water Research Center, Egypt)

	Monthly discharge rate (million m^3/month)											
	2008					2009						
Drain name	August	September	October	November	December	January	March	April	May	June	July	Mean
Drain no. 7	71.61	78.49	50.71	43.95	39.03	31.01	34.37	41.48	44.67	45.51	62.51	58.801
Drain no. 8	55.79	43.86	38.72	33.27	27.52	22.30	27.32	28.59	37.37	47.65	59.25	45.901
Drain no. 11	81.13	74.96	50.24	45.62	46.19	34.72	46.15	53.60	61.57	81.57	98.22	73.554
Total	136.92	118.82	88.96	78.89	73.71	57.02	73.47	82.19	98.94	129.22	157.47	119.455

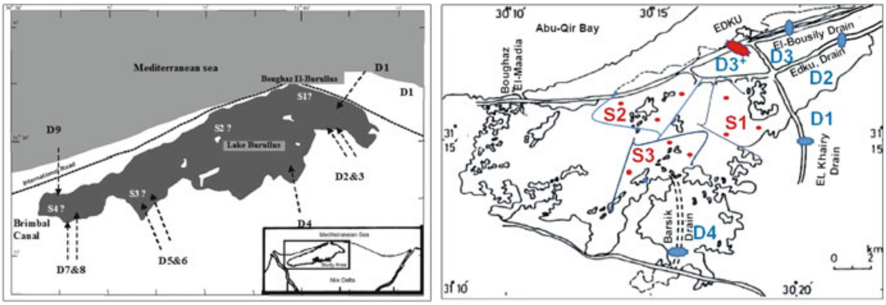

Fig. 5 Lake Burullus: D1 = Brimpal Canal, D2 = Burullus West Drain, D3 = Burullus Drain, D5 = El-Gharbia Drain, D6 = Nasir or Tira Drain, D7 = Drain No. 7, D8 = Drain No. 8, D9 = Drain No. 9, D11 = Drain No. 11 (Source: [79]). Lake Edku: D1 is El-Khairy Drain; D2 is Edku Drain; D3 is El Bouseily Drain; and D4 is Barsik Drain (Source: [88])

enters the lake annually from the south which is slightly saline and nutrient rich [122]. The western part of the lake receives freshwater carrying nutrients from the Brimpal irrigation canal (Fig. 1) [58, 93, 94].

Lake Edku is another good example as it receives huge amounts of drainage water from four main drains with a monthly rate of about 2.06×10^9 m^3 [101, 123] (Fig. 5). As a result, both lakes became sinks for several inflows with increasing levels of nutrient and pollutants from several kinds (domestic origin, sewage land disposal, sludge and/or solid wastes) [78, 88, 93, 121]. Table 7 gave an insight about the mean monthly and total annual water volume discharged into Lake Edku from the main two drains (Edku and Barsik drains) during 2012 and 2013 [124].

3.3 *Human Activities and Interventions*

Human activities seriously impacted the ecosystem biodiversity in several ways, among which the conductivity change process is the most important as it led to biodiversity reductions [125, 126]. Unplanned human activities lead to a growing loss of important and unique wetland habitats and also will create new artificial unbalanced ecosystems [127]. For instance, after the construction of the Aswan High Dam, considerable changes have been observed in the morphology, water characters and biotic composition of the northern lakes [128–130]. In addition, a gradual shrinkage in lake size was occurring due to land reclamation and land transformation into fish farms and aquatic vegetation outgrowth. This would reduce the entrance of open sea water into the lake which speeds up the process of land transformation [77] and limits water movement that provides habitats that suit the growth of parasite hosts (such as snails) [110]. Moreover, the unhealthy manners of fishing are one of the influencing processes of most coastal lakes in Egypt.

Table 7 Mean monthly and total annual water volume (million m^3) discharged into Lake Edku from the main two drains (Edku and Barsik drains) during 2012 and 2013 [124]

Drain name	Monthly discharge rate (million m^3/month)												
	January	February	March	April	May	June	July	August	September	October	November	December	Mean
	2012												
Edku Drain	75.64	73.20	146.40	141.52	73.20	146.40	151.28	75.64	77.23	75.64	73.20	75.64	105.19
Barsik Drain	342.24	165.6	165.6	320.5	331.2	165.6	171.12	171.12	165.6	171.12	331.2	171.12	236.47
Total	417.88	238.8	312	462.02	404.4	312	322.4	246.76	242.83	246.76	404.4	246.76	341.65
	2013												
Edku Drain	78.33	70.76	146.4	146.4	73.2	68.2	73.2	75.64	146.4	151.28			117.621
Barsik Drain	342.24	320.16	331.2	165.6	165.6	513.36	331.2	513.36	165.6	171.12			318.504
Total	420.57	390.92	477.6	312	238.8	581.56	404.4	589	312	322.4			436.125

Originally, the northern lakes were considered as oligotrophic water bodies [131] and partially mixed of fresh, brackish and saline or hypersaline water according to the interactions with adjacent water systems. All the above-mentioned conditions accelerate the biological productivity along the northern lakes changing them towards hypereutrophy [113, 114]. Similarly, the excessive effluents from the urbanized Bangalore city (India) have similarly changed the oligotrophic nature of Bellandur Lake into an artificial reservoir with domestic sewage and industrial effluents [132].

3.4 Grazing Activities

Zooplankton consumption of bacteria and Cyanobacteria was extensive in the eutrophic subtropical lake, despite previously published taxonomic designations of feeding preference [133, 134]. Work and Havens [135] indicated that all planktonic taxa, including a wide range of flagellates, ciliates, rotifers, cladocerans and copepods, can graze bacteria and that all macrozooplankton can graze Cyanobacteria; however, diatoms may be preferred. Different mechanisms may be contributed to the consumption of heterotrophic bacteria and Cyanobacteria. First, zooplankton sometimes are unable to avoid consuming either bacteria or Cyanobacteria or both particularly with dense existence, i.e. consumption may be incidental, rather than intentional. Secondly, a paucity of food resources is usually considered as ‘edible’, e.g. small chlorophytes and cryptophytes, and requires zooplankton as diet supplements. Thirdly, the co-existence of zooplankton with Cyanobacteria dense population would be rather better to digest cyanobacterial cells than unexposed zooplankton [136].

4 Phytoplankton as Biological Indicators for Water Quality

4.1 Environmental Biological Indicators

Environmental indicators reflect trends of environment state and monitor the progress made in realizing environmental policy targets. Environmental indicators have taken on such importance due to their role providing signals of a complex message in a simplified manner [137] that could be a guide in decision-making as well as monitoring and evaluation of the environment [138]. These indicators are important to provide a complete description of the aquatic ecosystem that could be integrated into a conceptual framework for decision-makers during formulating restoration plans. A wide variety of environmental indicators, including physical, chemical and biological indicators, are in use, of which biological ones are much indicative as they reflect information about the system biota but also about the interactions and integrations between the biological components and all other components. Therefore, it helps in defining the system functionality and behaviour. Various bio-related parameters and attributes could be used efficiently as biomarkers/indicators. The presence of faecal coli forms (for freshwater), information about phytoplankton seasonal and spatial distribution, the percentage of endangered species, an abundance of selected key species and abundance of invasive/alien species are among the biological indicators crucial for better understanding of aquatic systems [139].

Phytoplankton is one good tool for water ecosystem assessment and has been used relevantly used as water quality indicator for the northern lakes in Egypt [60, 78, 88, 140]. Phytoplankton density, changes in total population, the percentage of specific groups, diversity of genera/species, dominance status and the presence of specific indicative species are among the phytoplankton-based indicators for lake water quality assessment. Information about phytoplankton concentration, structure and/or succession of phytoplankton community could be used as good indicative, in a way for nutrient levels in aquatic systems [141]. In a similar way, information of biological oxygen demand (BOD) also indicated high levels of organic and inorganic matters along the lakes' system.

4.2 Phytoplankton Community Structure and Species Composition

Generally, information about phytoplankton standing crop could describe the level, ratio and availability/limitation in nutrients. Any fluctuation in N/P ratio is severely influencing the structure and composition of the existent phytoplankton community [142, 143]. For instance, the N-limited condition is an advantage to some toxic species (e.g. N-fixing Cyanobacteria) [21, 144]. Monitoring and delineation of phytoplankton distribution along the northern lakes at both levels, seasonal and spatial, would successfully define their system health and toxicity.

For instance, the overdominance of Bacillariophyceae (Diatoms) is fairly indicated in the excessive existence of silicates, with the availability of which is, in turn, controlled by biological removal of phytoplankton (mainly diatoms and silicoflagellates) [86, 145] and other factors [86, 146–148]. In a similar way, bloom formation of some specific species like *Microcystis aeruginosa* with big numbers ($>$100 cell/mL) is an indicative of poor water quality with high ammonia and low oxygen concentrations [77, 78, 149].

Tolerant species could be used as potential indicator organisms, and they can be used in the environmental assessment and monitoring with some other water parameters [150]. For example, the pollution-tolerant diatoms, such as *Cyclotella* spp. (e.g. *C. comate*, *C. glomerata* and *C. meneghiniana*), were among the phytoplankton good indicator species for the northern lakes [60]. Similarly, the dominance of *Scenedesmus* spp. among other chlorophyceans is another pollution indicative, particularly for excessive phosphate levels and organic pollution [121]. This is a repeated scenario for most aquatic systems in Egypt, e.g. the coastal lakes (e.g. Lake Burullus; [60], the River Nile [151] and other similar systems (e.g. Sawa Lake in Iraq)) [152].

4.3 Biological Indices

Several pollution indices could be applied to evaluate the pollution status of the water ecosystem. Some of which are mainly chemical based, e.g. water quality index (WQI), and others are biologically dependent, e.g. trophic state index (TI), diversity index (DI), saprobic index (SI), pollution index (PI) and generic diatom index (GDI). These indices and several others would reveal strong evidence about the lakes' nutrient richness, saprobity level, pollution type/level, phytoplankton community structure, species dominance, bacterial existence, etc. WQI is a 100-point scale that is created by the National Sanitation Foundation, USA, and is used to summarize results of some measured physicochemical and biological measurements along water systems using a computer program created. Nine parameters are used for WQI estimation; each has a definite weighting factor. These parameters are temperature, pH, turbidity, dissolved oxygen, biological oxygen demand, nitrates, total phosphates, total dissolved solids and faecal coliforms. This index transforms huge amount of data to a single number, which is then used to rank water into one of five descriptive categories of water qualities ranged from very bad conditions (0–25) to excellent conditions (90–100). This index transforms huge amount of data to a single number, which corresponding to the general descriptive quality classes [153]. Full details about the index with a free calculating program are available at the following website http://www.waterresearch.net/watrqualindex/waterqualityindex.htm.

The other biologically based indices are mainly used to describe the existent phytoplankton community in any aquatic systems; however, each index is using different inputs and hence provides different information. For example, diversity index [154] provides information about phytoplankton species diversity; saprobic index relates the existent biological composition to the level of pollution [155]; the trophic diatom index [156] is indicative of the system trophic status (4). The diatomic index (Id) which is based on the weighted average equation of Zelinka and Marvan [157] estimates the degree of water pollution. Also, the Generic Diatom Index (GDI) assesses the water quality, but it is mainly based on the diatom genus level [158]. Much specifically, the Pollution Index (PI) determines the status and level of organic pollution [34]. It assigns an index factor from 1 to 5 for each of the 20 most tolerant species to organic pollution, where five is given to the more tolerant species and vice versa.

Application of those pollution indices (e.g. TI, DI, SI, PI and GDI) for Lake Edku [88] showed a level of nutrient richness along the drains and lake waters that ranged from high to very high levels (Table 8). However, some indices (e.g. DI)

Table 8 Environmental indications of using environmental/biological indices in Lake Edku during 2012–2013 (Source: [88])

	S1	S2	S3	Idku Drain (D1)	Boseily Drain (D2)	Khairy Drain (D3)	Barsik Drain (D4)
	Autumn						
TI	High – very high nutrient conc						
DI	Slight – light pollution						
SI	B-mesosapropic			Oligosaprobic to B-mesosapropic			B-mesosapropic
PI	No or very low organic pollution						
GDI	Strong pollution						
	Winter						
TI	High nutrient conc						
DI	Slight – light pollution						
SI	B-mesosapropic			Oligosaprobic to B-mesosapropic			B-mesosapropic
PI	No – very low organic pollution						
GDI	strong pollution						
	Spring						
TI	High nutrient conc						
DI	Slight pollution						
SI	Oligosaprobic						
PI	No – very low organic pollution						
GDI	Strong pollution						
	Summer						
TI	High nutrient conc						
DI	Slight – light pollution			Medium – high pollution			
SI	Oligosaprobic			Oligo-B mesosaprbic			Oligosaprobic
PI	Medium – high organic pollution			Low – medium organic pollution			
GDI	strong pollution			Average pollution			

showed that the lake is not highly polluted the whole year long, except during summer season. Saprobic index (SI) is normally used to describe the saprobic level within the aquatic system as it measures the degree to which the decomposition of organic material is occurring within the system. Lake Edku, for example, was described as an oligo–B-saprobic system, which means the lake has a middle level of self-purification. On the other hand, application of the PI gave an indication of no or low organic pollution along the lake and the drain systems.

5 Mortality and Loss Processes in Phytoplankton

It rarely occurs that growth rates could alone control phytoplankton dynamics. Combined physical, chemical and biological forces act on both growth and loss process, and both are important [159]. The loss of photosynthate produced in excess of the cell's ability to incorporate in biomass is necessary as the term 'loss rates' was applied collectively to the dynamics of almost all measurable photosynthetic production that did not find its way into increased producer biomass [160]. It had been supposed by many workers at the time that the realized shortfall was attributable to grazing and sedimentation of biomass. However, with the demonstration that, very often, production in some systems was almost wholly and precisely compensated by simultaneous bulk loss rates [161], when the grazing rates or sedimentation rate explain the disappearance of the equivalent day's new product, it became clear that some further separation of the 'losses' was necessary, together with some refinement of the terminology. Additionally, dramatic changes in certain low trophic level conditions in lakes (e.g. water clarity, phytoplankton composition) have been linked to changes in the upper food web interactions [162, 163].

5.1 Wash-Out and Dilution

The hydraulic displacement and dispersion of phytoplankton are best approached by considering the case of algae in small lakes or tidal pools in which the volume is vulnerable to episodes of rapid flushing. Inflow is exchanged with the instantaneous lake volume, and embedded plankton cells are removed in the outflowing volume that is displaced. In this instance, the algae thus removed from the water body are considered 'lost'. It may well be that the individuals thus 'lost' will survive to establish populations elsewhere. Indeed, this is an essential process of species dispersal. The balance of the original population that remains is, of course, now smaller and, occupying the similar volume of the lake, on average, less concentrated [164].

The dilution method is the main in situ method to evaluate microzooplankton grazing rates; grazing, as the only mortality process, is considered by the theoretical models and used to underline the interpretation of in situ experiments [165]. Zooplankton grazing is thought to be one of the dominant drivers of plankton mortality [166]. However, other processes such as nutrient limitation, sinking and viral lysis compete and interact with grazers as sources of plankton mortality [167, 168]. Understanding the dynamics of microbial food webs is, therefore, the key to understanding their role in biogeochemical fluxes [169, 170].

Partitioning between the losses was found to vary interspecifically between a complete removal by grazers (e.g. for nanoplankton) and a complete elimination by sinking (e.g. for some diatom populations). Such variation is critically influenced phytoplankton community structure and the seasonal dominance of species. Zooplankton controls phytoplankton biomass, and blue-green algae (Cyanobacteria) dominate by virtue of being 'ungrazed'.

5.2 Consumption Susceptibility to Pathogens and Parasites

Over the past decade, it has become increasingly apparent that phytoplankton is not immortal on encountering adverse environmental conditions they often die spontaneously. Indeed, substantial cell death by lysis has been documented in field populations, with some estimates exceeding 50% of phytoplankton growth [171, 172]. These observations indicate that important loss processes independent of grazing by heterotrophs must exist and might explain how an average of ~50% of global primary production is consumed by bacteria [173].

Viruses are known to infect and lyse a wide range of autotrophs [174]. Because viral lyses can affect the carbon fixation rates of eukaryotic and prokaryotic primary producers, this suggests a significant effect of viruses on primary production-mediated carbon cycling [175]. Modelling exercises have estimated that between 6 and 26% [176, 177] of primary production may bypass higher trophic levels because of the viral-induced transformation of phytoplankton cells to dissolved organic matter (viral shunt). However, although viruses are predicted to have a significant impact on primary production, viral-induced mortality rates from natural waters are scarce.

The exogenous infection by viruses is the main mechanism used to explain the high rates of lysis in phytoplankton populations by most microbial ecologists. The process works when any lytic viruses infect a host cell and it propagates, the viral progeny is subsequently released and dissolved, and the organic matters from the lysed microbial cell translocates it into the surrounding water. The virus-like particles (VLPs) were observed in thin section ultrastructure studies of marine phytoplankton in the 1970s [178–180], but it was almost two decades before their importance to microbial mortality was realized [181, 182]. Viruses are now known to be ubiquitous and crucial components of marine ecosystems, reaching an abundance of 107–108 VLPs mL^{-1} of surface sea water, which exceeds bacterial and phytoplankton abundances by at least an order of magnitude. Viral infection can influence the population dynamics of bacterioplankton and phytoplankton communities either through bloom demise or ‘trimming’ of host cell populations to nonbloom levels [183].

The recent discovery of autocatalytic cell death which is induced by environmental stresses, such as cell age, nutrient deprivation, intense light, excessive salt concentrations or oxidative stress in phytoplankton (i.e. prokaryotic and eukaryotic), provides another mechanism explaining the high lysis rates. This mechanism of the cellular self-destruction is analogous to PCD or apoptosis in multicellular organisms. PCD is accompanied by distinct morphological changes that include cell shrinkage, chromatin condensation and fragmentation [184] and involves the expression and biochemical coordination of specialized cellular machineries such as receptors, adaptors, signal kinases, proteases and nuclear factors [185]. PCD is often compared with necrosis, which is a passive, indiscriminant, degenerative form of cell death that follows irreversible injury, is not characterized by de novo protein synthesis and ends in immediate rupture and lysis of the cells [186]. Here, we define phytoplankton PCD as a form of autocatalytic cell suicide in which an endogenous biochemical pathway leads to apoptotic-like morphological changes and, ultimately, cellular dissolution.

Evidence of PCD in phytoplankton was found after monitoring physiological responses to nutrient stress. Among the diatoms, which are abundant and can dominate primary productivity in a variety of oceanic systems, autolysis in *Ditylum brightwellii* was an important cause of mortality in laboratory cultures that were subjected to nitrogen and phosphorus limitation [187]. Phytoplankton blooms in lake Kinneret, Israel, were mostly dominated by the dinoflagellate *Peridinium gatunese*. Populations of this species (naturally exist or cultured) were shown to initiate PCD in response to the limited inorganic carbon (CO2) and the consequence stress of reactive oxygen [188]. Cysteine proteases are the central to the PCD response because treatment with the cysteine protease inhibitor E-64 was found to suppress autolysis and resulted in cyst formation. *Anabaena* spp., the freshwater cyanobacterium, was shown to initiate PCD on exposure to univalent cation salts with an increase in the protease activity [189].

5.3 Sedimentation, Death and Decomposition

Most phytoplankters are normally heavier than the water in which they are dispersed and, therefore, tend to sink through the adjacent medium [190]. However, over the past decade, it has become increasingly apparent that phytoplankton is not immortal on encountering adverse environmental conditions they often die spontaneously. The exact mechanisms controlling phytoplankton bloom termination in natural ecosystems are not well understood. This lack is mainly because few studies have focused on phytoplankton mortality compared to other organisms, such as bacteria, protozoa, fungi and multicellular land plants and animals. However, a large body of evidence has accumulated on cell-death mechanisms in. These mechanisms include viral infection, necrosis, programmed cell death (PCD), apoptosis and paraptosis, each of which is supported by both cytological and biochemical evidence and occurs under disparate circumstances. In this review, we analyse whether these processes occur in phytoplankton and their contributions and relevance to phytoplankton ecology.

The balance of phytoplankton biomass was studied during spring and early summer 1986 and 1987 in lake Müggelsee, a eutrophic polymictic lake. It is assessed as the result of biomass changes, gross primary production (^{14}C–method) and physiological and ecological or any other external losses. Some estimates have been measured in situ, such as biomass changes, primary production, grazing, dark carbon losses and exudation; however, others were conducted through the phytoplankton balance of the lake such as light carbon losses and net sedimentation rate [178].

A value of 80.5% of the primary production was estimated as physiological losses of algae in 1986 compared to 72% in 1987. On the other hand, the dark carbon losses through respiration ranged between 15% in 1986 and 20% in 1987, and grazing losses was 24.5% and 21.9% of gross primary production, respectively. The remaining percentage (i.e. 16.6 and 23.6%) of primary production for both years is mainly attributed to sedimentation [178].

In spite of high intraspecific temporal variability of the sinking velocity, there is a clear hierarchy from the pinnate and centric diatoms sinking the fastest to the cryptomonads, not affected by sedimentary losses. The temporal variability of the sinking velocity is mainly related to the ‘physiological state’ of the species as the high velocities always occurring during the stationary or decline phases of growth. Analysing of the role of sedimentary losses for some species reveals some positive correlations between both sedimentation rate and cell mortality [190].

High mortality of *S. dorsidentiferum* due to cell lysis caused by fungal parasitism may explain the contradictory observations reported in Lake Biwa, where zooplankton eliminated a large part of primary production [191] in spite of the fact that large less edible phytoplankton species dominated. The parasitic fungus can be grazed by zooplankton when it is in the zoospore stage [192]. In addition, cell lysis of phytoplankton stimulates the growth of microorganisms [193], which in turn can be grazed by zooplankton [191]. Thus, although zooplankton cannot always utilize the production of large phytoplankton directly, they may use a large part indirectly by grazing on fungal zoospores and heterotrophic organisms in the microbial food web [194]. Because of such indirect processes, the sedimentation rate was low in Lake Biwa [195] when large inedible phytoplankton species dominated during summer. Other than fungi, viruses may also contribute to cell lysis of algal species [196]. In addition to cell and colony size that relates functionally to sinking velocity and vulnerability to zooplankton grazing, other species-specific features, such as vulnerability to fungal and viral infections, should be taken into account when the function of phytoplankton community structure in the material flow is considered.

5.4 Aggregated Impacts of Loss Processes on Phytoplankton Composition

Phytoplankton is currently responsible for 50% of global primary production [197]. In aggregate, these stressors will modify phytoplankton community structure and have cascading consequences on marine food web dynamics and elemental cycling [198, 199]. To improve predictions of marine ecosystem responses to environmental and climate change, plankton physiologists and ecologists need to determine how to quantify and parameterize the key physiological responses of plankton that will, in turn, affect marine food webs and the carbon-climate system. Phytoplankton cell size, cell growth requirements and cellular composition are the potential physiological traits that impose fundamental constraints on the acquiring rate [200, 201] and processing energy and materials from the environment [202], to influence evolution [203–205], food web structure [206, 207] and biogeochemical cycling [206, 208].

6 Conclusions and Recommendations

The coastal region of Egypt on the Mediterranean Sea occupied about 1,200 km. The coastal region extended between Matruh and Alexandria has tens of tourist villages, which are often heavily occupied by visitors especially in summer. Such activities coupled with from the huge amounts of nutrients, especially nitrogen and phosphorus, entering the marine ecosystem through the land runoffs accelerated the eutrophication level of the Egyptian Mediterranean coast. This is certainly led to abnormal phytoplankton blossoms. Increment of both factors (phytoplankton and nutrients) is the main reason for degeneration of the coastal waters and deterioration of the ecosystem. So, it became crucial to think of solutions or mitigation measures.

Phytoplankton plays an important role in the structure and functioning of aquatic ecosystems, particularly lakes. Phytoplankton, including eukaryotic algae and Cyanobacteria, contribute with a large proportion to the primary production. The distribution and abundance of the phytoplankton are mainly dependent on the nutrient load and other environmental factors. Therefore, phytoplankton was used for water quality assessment in lakes especially the structure of the phytoplankton community. Flourishing of specific algae species may indicate the water status and can be used as an indicator for pollution of the lakes.

Appreciating the great value of the northern lakes in Egypt, it becomes crucial to think of applicable and efficient ways to prevent any future deterioration. Doing so, we need priory to identify the key influencing factors that protect and enhance the status of aquatic ecosystems in Egypt which require achieving 'good surface water status' for the lakes [88]. Therefore, there is a growing demand for proposing a national water framework directive. According to the European commission report for Water Framework Directive in 2010, elements of surface water status (ecological status and chemical status) (Fig. 6) must attain an acceptable quality before a water body can be identified as having good surface water status [209].

This framework could be an inspiring initiative that could greatly support the national vision Sustainable Development Strategy (SDS) for 2030. The Egyptian vision focused on enhancing the local economical and societal issues with great

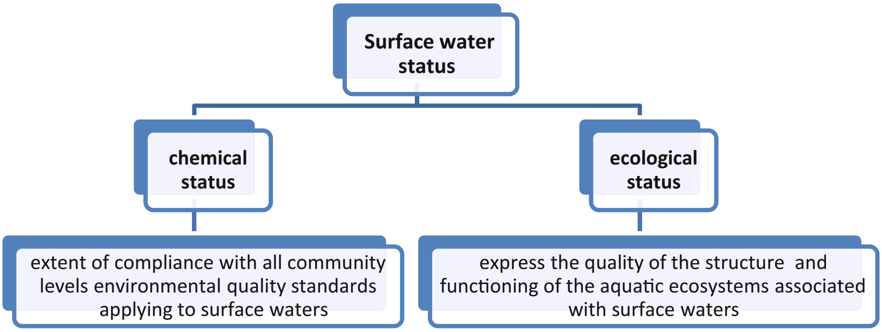

Fig. 6 Elements of surface water status

consideration to the environmental status. Globally, the standard usage and acquisition of lakes as one of the main water resources is among the main 17 goals of the recently defined Sustainable Development Goals (SDGs) that target to change to better world towards 2030 after enhancing the Millennium Development Goals (MDGs) declared in 2015.

To improve the ecosystem of lakes, it is recommended to simulate the standard conditions and propose applicable mitigation measures with good alternatives for their restoration. The "optimal" strategy, according to Ansari and Khan [210], should adopt an effective (decreasing the loading with a sufficient number of tons) and cost-effective (at the lowest possible cost) manners.

The operational management of water quality of aquatic ecosystems requires a methodology that can provide precise information on cycles and trends in water quality in an objective and reproducible manner. Such information can be provided by monitoring lake geomorphological features, water quality variables with the adoption of a water quality indexing system with special reference and consideration to phytoplankton distribution and abundance in lakes. This needs to firstly define standard measures for the local ecosystem of lakes in Egypt.

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Macrobenthos Diversity of Egypt's Coastal Wetlands

Magdy T. Khalil

Abstract Different studies have revealed that Egypt's coastal wetlands have become more dulcitude, eutrophic, and productive ecosystems, owing to remarkable increase in amount of discharging agricultural drainage, loaded with nutrients, into the wetlands via the southern drains. Decreasing salinity and nutrients loading have led to significant impacts on biodiversity and abundance of macrobenthos in these wetlands, such as in Burullus. Thirty-four macrobenthic species, belonging to three main groups (Arthropoda, Annelida, and Mollusca) were recorded in this wetland during 2013. There was no sign of occurrence of eight marine species, which have been previously recorded in this ecosystem during the 1970s and 1980s of the last century. It is worth mentioning that 17 species (freshwater in origin) were recorded for the first time in the Burullus wetland during 2003.

On the other hand, the macrobenthic community in the saline Bardawil Wetland during the last decade hosted 51 species belonging to five phyla: Arthropoda, Annelida, Mollusca, Echinodermata, and Coelenterata. The abundance of macrobenthic species was closely correlated with the nature of bottom sediments, organic matter, and salinity. The long-term changes in the macrobenthos density of the Bardawil Wetland were attributed to changes in the fish community structure.

Keywords Bardawil, Biodiversity, Burullus, Macrobenthos, Mediterranean coast, Wetlands

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Contents

1 Introduction

Benthic invertebrates in aquatic ecosystems play an important role in the transformation of the organic matter sediment on the bottom to its base elements and subsequently contribute to the basic nutrition of fish. Macrobenthic invertebrates in Lakes are frequently used to evaluate the overall ecosystem "health," because these communities are important to material cycling and secondary production and are sensitive to environmental contaminants. To fully understand the reasons of disturbances that affect benthic community and distribution, it is important to measure the environmental factors that provide the basic ecological template structuring the benthic community. The macroinvertebrates of coastal wetlands are important food resources and contribute to the widespread use of wetlands as fish spawning and waterfowl breeding areas.

The composition of the benthic fauna has largely been considered as a good indicator of water quality because, unlike planktonic species, they form relatively stable communities in the sediments which do not change over long time intervals and reflect characteristics of both sediments and upper water layer. Despite the apparent importance of macroinvertebrates, comparatively little is known of their distribution and ecology in coastal wetlands in general.

The few studies, which specifically deal with benthic fauna in coastal wetlands, include Aboul-Ezz [1], who stated that the most important bottom dwellers inhabiting the wetland are *Gammarus*, *Corophium* (Amphipoda), *Mesenthura* (Isopoda), *Chaetogaster* (Oligochaeta) and *Corbicula* (Bivalvia). Samaan et al. [2] mentioned that the highest biomass of benthos appeared in the western region of the wetland and decreased gradually eastwards. Samaan et al. [3] studied the general ecology and periodicity of the different changes in community structure, abundance, and biomass of macrobenthos in relation to changes of wetland hydrographic regime. Khalil and

El-Shabrawy [4] studied the biodiversity, density, and population dynamics of macrobenthic invertebrates in Burullus in relation to salinity and eutrophication changes of this wetland. Bedir [5] studied the ecological aspects of zooplankton and macrobenthos communities in relation to physical and chemical properties of wetland water.

2 Biodiversity of Macrobenthos

In a 2002 survey (Fig. 1), 33 benthic species belonging to three main groups (Arthropoda, Annelida, and Mollusca) were recorded [4]. The benthic community consisted of 3 common species, 13 moderately common species, 11 rare species, and 6 very rare species (Table 1). There was no sign of the occurrence of eight marine species which have been previously recorded in Burullus by Aboul-Ezz [1]. These are three of Arthropoda (*Mesanthura* sp., *Sphaeroma* sp., and *Balanus improvisus*), two of Annelida (*Chaetogaster limnaei* and *Ficopomatus enigmaticus*), and three of Mollusca (*Cerastoderma edule*, *Cerastoderma glaucum*, and *Abra ovata*).

Seventeen benthic species (freshwater in origin) were recorded for the first time in the wetland during 2002 (Fig. 2). The majority of these species were highly associated with the wetland macrophytes and these were: seven of Arthropoda (Nymph of *Neurocordulia* sp., Nymph of *Ischnura* sp., Nymph of *Enallaga vansomerni*, *Micronecta plicata*, *Lethocerus niloticus*, *Sternolophus solieri*, and aquatic spiders), seven of Annelida (*Branchiura sowerbyi*, *Limnodrilus hoffmeisteri*, *Limnodrilus udekemianus*, *Limnodrilus claparedeianus*, *Potamothrix hammoniensis*, *Helobdella conifera*, and *Salifa perspicax*), and three of Mollusca (*Bellamya unicolor*, *Hydrobia ventrosa*, and *Succinea cleopatra*).

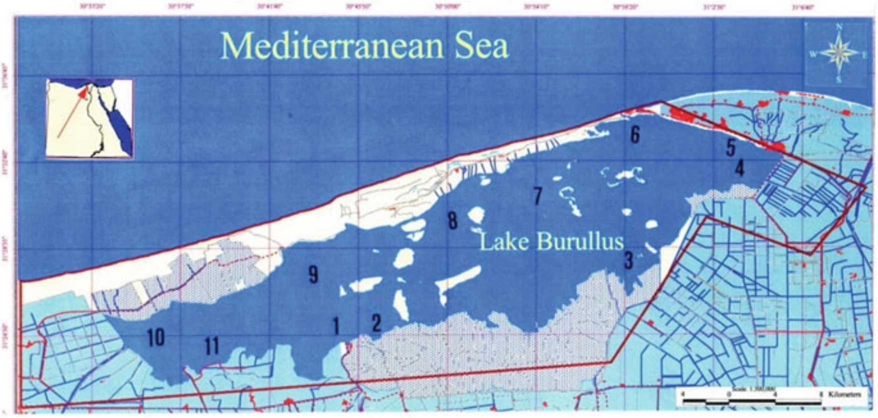

Fig. 1 Map of Burullus Wetland showing the location of sampling sites by number [4]

Table 1 Checklist of benthos species recorded in Burullus Wetland during different time periods (1978–2002)

Species	1979	1982	2002	2005	Habitat	Location
Arthropoda						
Corophium volutator (Pallas)	+				M.W.	Sediment
Corophium orientale (Schellenberg)		+	+	C	F. and M.W.	Sediment
Gammarus lacustris (Fabricius)	+				F. and M.W.	Macrophytes associated
Gammarus aequicauda		+	+	MC	F. and M.W.	Macrophytes associated
Gammarus orinicornis		+			F. and M.W.	Macrophytes associated
Mesanthura sp.	+				F. and M.W.	Under rocks
Sphaeroma sp.		+			M.W.	Macrophytes associated
Balanus improvisus		+			M.W.	Macrophytes associated
Palaemon elegans		+	+	MC	F. and M.W.	Macrophytes associated
Pasiphaeidae sp.		+			M.W.	Sediment
Mysis relicta (Loven)	+		+	R	M.W.	Macrophytes associated
Tandipos tentans (Meigen)	+	+	+	R	F. and M.W.	Macrophytes associated
Nymph of *Neurocordulia* sp.			+	VR	F.W.	Macrophytes associated
Nymph of *Ischnura* sp. (Pinhey)			+	VR	F.W.	Macrophytes associated
Nymph of *Enallaga vansomerni*			+	R	F.W.	Macrophytes associated
Micronecta plicata (Costa)			+	MC	F.W.	Macrophytes associated
Lethocerus niloticus (Stal)			+	R	F.W.	Macrophytes associated
Sternolophus solieri (Lapouge)			+	R	F.W.	Macrophytes associated
Decapod zoeae		+	+	MC	F. and M.W.	Macrophytes associated
Aquatic spiders			+	VR	F.W.	Macrophytes associated
Annelida						
Branchiura sowerbyi (Beddard)			+	MC	F.W.	Sediment
Limnodrilus hoffmeisteri (Claparede)			+	C	F.W.	Sediment
Limnodrilus udekemianus (Claparede)			+	MC	F.W.	Sediment

(continued)

Table 1 (continued)

Species	1979	1982	2002	2005	Habitat	Location
Limnodrilus claparedeianus (Ratzel)			+	MC	F.W.	Sediment
Potamothrix hammoniensis (Mich)			+	C	F.W.	Sediment
Chaetogaster limnaei (K. Von Beak)	+				F.W.	Sediment
Nereis limnoicola (Johnson)	+				F.W.	Sediment
Nereis diversicolor		+	+	R	M.W.	Rocks
Ficopomatus enigmaticus		+			M.W.	Rocks
Helobdella conifera (Moore)		+	+	VR	F.W.	Rocks
Salifa perspicax (Blanchard)			+	VR	F.W.	Rocks
Glossiphonia sp.		+			F.W.	Rocks
Mollusca						
Melanoides tuberculata (Muller)	+	+	+	MC	F.W.	Macrophytes
Theodoxus niloticus (Reeve)	+	+	+	MC	F.W.	Macrophytes
Bulinus truncatus (Audouin)		+	+	R	F.W.	Macrophytes
Gyraulus ehrenbergi (Beck)		+	+	R	F.W.	Macrophytes
Physa acuta (Draparanud)		+	+	VR	F.W.	Macrophytes
Cleopatra bulimoides (Olivier)		+	+	MC	F.W.	Macrophytes
Bellamya unicolor (Olivier)			+	MC	F.W.	Macrophytes
Lanistes carinatus (Olivier)		+	+	R	F.W.	Macrophytes
Biomphalaria alexandrina (Ehr.)		+	+	R	F.W.	Macrophytes
Hydrobia ventrosa (Montagu)			+	MC	F.W.	Sediment
Succinea cleopatra (Pallary)			+	MC	F.W.	Sediment
Corbicula consobrina (Cailliaud)	+				F.W.	Macrophytes
Corbicula fluminalis (Muller)		+	+	R	F.W.	Sediment
Abra ovata		+			M.W.	Sediment
Cerastoderma glaucum		+			M.W.	Sediment
Cerastoderma edule	+				M.W.	Sediment

C common, *MC* moderately common, *R* rare, *VR* very rare, *F.W.* freshwater, *M.W.* marine water. 1979: [1]; 1982: [6]; 2002: [4]; 2005: [7]

3 Seasonal Variations of Common Species

3.1 Arthropoda

3.1.1 *Corophium orientale*

Corophium orientale is the most common and dominant benthic species in most northern wetlands, especially Burullus, forming 87.4% and 72.1% of the total arthropod number and biomass, respectively [4]. Two density peaks with standing

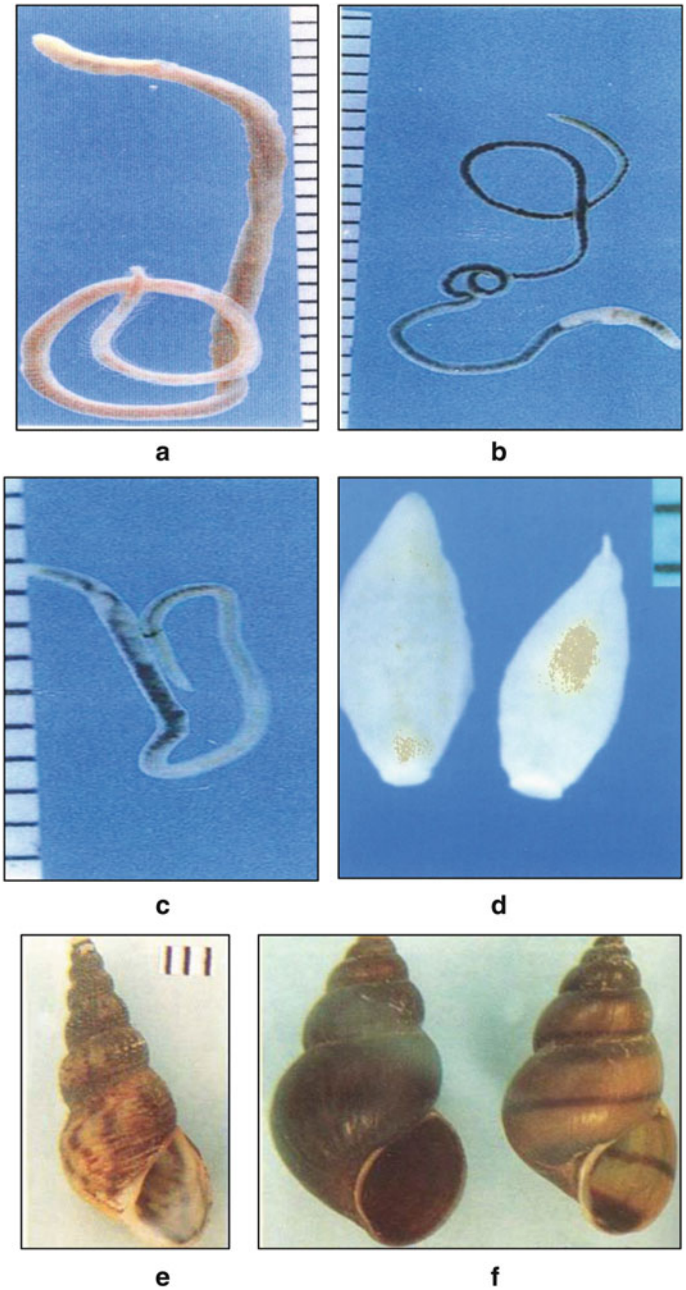

Fig. 2 Photos of some benthos of coastal wetlands [6]. (**a**) *Branchiura sowerbyi*, (**b**) *Limnodrilus udekemianus*, (**c**) *Limnodrilus hoffmeisteri*, (**d**) *Helobdella conifera*, (**e**) *Melanoides tuberculata*, and (**f**) *Cleopatra bulimoides*

crop of 1,427 and 1,407 ind. m^{-2} were observed in autumn and spring, respectively. The lowest average abundance of 29 ind. m^{-2} was reported in summer. In reference to species biomass, it was more or less following its standing crop, except during spring when heavy biomass individuals were present. The highest biomass value of *C. orientale* was 43.63 g wet wt. m^{-2}, recorded at station IV in spring, while it was infrequently recorded at the western sector of the wetland. *C. orientale* seems to have two generations in Burullus. Shaltout and Khalil [6] recorded three density peaks of *C. orientale* in Wadi El-Rayan lakes during April, August, and November. Anderson [8] mentioned that *Corophium* in general inhabits sediments predominantly of silt-size particles, while Gee [9] advocated that this genus was found in mud or muddy sand, containing approximately 37% silt or clay. They also reported that it was not found in heavily polluted areas.

3.1.2 *Gammarus aequicauda*

Khalil and El-Shabrawy [4] recorded a few individuals of this species at station IV in spring and at stations I, III, VII, and XI during summer. *Gammarus aequicauda* was common in the macrophytes belt in Burullus Wetlands. They stated that *Gammarus* mainly lived among the leaves of macrophytes and fed on the epiphytes growing on them.

3.2 Annelida

3.2.1 *Limnodrilus hoffmeisteri*

Limnodrilus hoffmeisteri, numerically, is the most predominant bottom animal inhabiting coastal wetlands. Khalil and El-Shabrawy [4] recorded it at all sampling stations during the entire period of their study. *L. hoffmeisteri* contributed 72.7 and 45.8% of total annelids count and biomass, respectively, with annual average of 1,173 ind. m^{-2}, weighing 1.51 g fresh wt. m^{-2}. The flourishment of this species has been recorded in spring with a major peak of 9,450 ind. m^{-2} at station VIII. The lowest abundance of this species was during autumn. Its biomass was generally proportional to its numbers. Qi Sang [10] mentioned that *L. hoffmeisteri* is dominant and favored in organic polluted water, and it is known for its ability to tolerate low oxygen levels. Milbrink [11] stated that *L. hoffmeisteri* inhabits polluted lakes together with *L. udekemianus* and *L. claparedeianus.* The same association of species was generally found to occur at grossly polluted sites of the Guangzhou Reach, which is located in the subtropics [10] and the Burullus wetland. Verdonschot [12] stated that this species has a positive relation with pH, nitrate, and bicarbonate; it has been defined in the literature as an eutrophic species [11].

3.2.2 *Potamothrix hammoniensis*

Potamothrix hammoniensis occupied the second predominant position among annelids, contributing 13.7% of the total number of annelids and 7.9% of its biomass [4]. This species is widespread in Burullus, but not abundant anywhere. The highest standing crop of 401 ind. m^{-2} weighing 0.47 g wet. wt. m^{-2} occurred in winter, while the least yield of 78 ind. m^{-2} weighing 0.04 g was recorded in summer. Verdonschot [12] mentioned that this species has a positive linear correlation with pH and water depth. Milbrink [11] stated that *P. hammoniensis* is one of the commonest species in shallow eutrophic lakes all over Europe; it is a moderate pollution indicator.

3.3 *Mollusca*

3.3.1 *Melanoides tuberculata*

Melanoides tuberculata is the most common gastropod in coastal wetlands and occupies the first position, regarding standing crop of total molluscs, forming 42.2% of its total numbers [4]. The share of this species in molluscan biomass was relatively low (23.4%). Summer showed the highest abundance of this species (avr. 180 ind. m^{-2} weighing 8.68 g wet wt. m^{-2}), while it was poorly represented during the rest of year [6]. The biomass of this species followed the same general trend as its count. It lives in stagnant and slowly running waters, can tolerate a moderate salinity, and is highly associated with aquatic macrophytes [13, 14]. In Burullus Wetland, *M. tuberculata* was recorded in sediments as well as associated with macrophytes.

3.3.2 *Theodoxus niloticus*

The perennial occurrence of this species is restricted to the western sectors of the Burullus Wetland [4]. It collectively contributed 17.1 and 6.5% of the total molluscan standing crop and biomass, respectively. Autumn was relatively rich with this species with an average standing crop of 59 ind. m^{-2}. *T. niloticus* lives in all types of freshwater bodies. It usually occurs in colonies over and under rocky limestone and associated with many macrophytes [14].

4 Benthos as Indicator Species

4.1 *Eutrophication-Indicator Species*

The composition of benthic fauna has long been considered as a good indicator of the water quality because, unlike plankton organisms, they form relatively stable communities in and on the sediments, which integrate changes over long time intervals and reflect characteristics of both sediments and the upper water layer [2].

Macrobenthic chironomids were used as indicators of Lake type (trophic state) and macrobenthic oligochaetes [12] were similarly used. Goodnight and Whitley [15] used the percentage of oligochaetes in benthic samples to indicate water quality. Brinkhurst [16, 17] proposed that the number of tubificids present together with the proportion of *Limnodrilus* to all other species might provide a useful index of organic enrichment. Finogenova [18] mentioned that *L. hoffmeisteri* and *Aulodrilus japonicus* are eutrophic indicator species that prefer sediment with a large amount of allochthonous organic matter. Timm et al. [19] stated that *L. hoffmeisteri* is a tolerant species which preferred more eutrophic habitats.

In coastal wetlands, such as Burullus, Oligochaeta is represented only by the naidids of *C. limnaei* in 1979 [1]. As a result of a continuous load of nutrient to the wetland through the agricultural wastewater drains, the eutrophication process increased progressively and became more favorable for the establishment of tubificid oligochaetes species. Six tubificid species dominated mainly by *L. hoffmeisteri* were recorded during 2002. All of these species are considered as indicators of increasing eutrophication of Burullus wetland.

The gradual increase in fish yield production of Burullus wetland, which is concurrent with increasing benthos and zooplankton standing crop reflects another sign of the progressive increase of eutrophication of the Burullus wetland.

4.2 Salinity-Indicator Species

The hydrographic condition of coastal wetlands changed a few years ago (i.e., the amount of agricultural drainage wastewater increased obviously and led to decreasing the water salinity). The total missing of all marine species, previously recorded by Aboul-Ezz [1] and Shaltout and Khalil [6], confirmed this phenomenon. These species are *A. ovata*, *C. glaucum*, *Nassarius cuverii*, *C. edule*, *Mytilus edulis*, *B. improvisus*, and *F. enigmaticus.* Khalil and El-Dawi [20] and Bedir [5] reported the disappearance of both marine zooplankton species and fishes from Burullus wetland during the last decade due to decreasing of salinity.

5 Macrobenthos of Bardawil Wetland

The Bardawil Wetland is the only saline ecosystem of the five northern lakes in Egypt. It is bordered from the north by a convex sand barrier that separates it from the Sinai Mediterranean coast and from the south by the sand dune belt, which extends inland to the region of the fold and anticlinal hills. This wetland is a Ramsar site, while Zaranik area, the extreme eastern part of it, has been declared as a natural protectorate in 1985. Bardawil has an elliptical shape representing a major

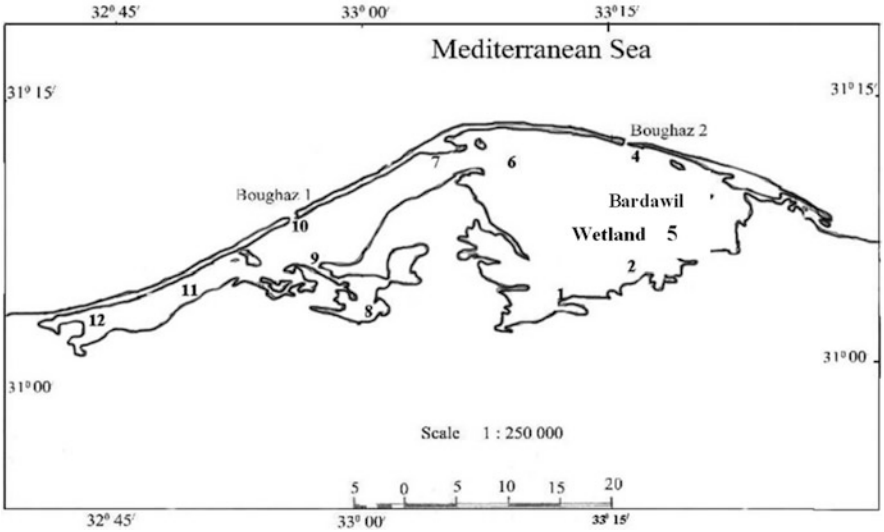

Fig. 3 Map of Bardawil Wetland showing the sampling locations [24]

morphological feature along the North Sinai coast. Its area is about 164,000 acres (c. 685 km^2) and extends for a distance of 80 km along N-S axis. Its maximum width is 20 km and the maximum depth is 3 m. Zaranik has an area of about 58,000 acres, of which Zaranik pond occupies about 10,000 acres.

The available data dealing with the macrobenthos in the Bardawil Wetland is scarce. Fouda et al. [21] included macrobenthos in their study on the ecology of the Bardawil lagoon. They listed 39 species of benthic fauna and flora of the lake. Aboul-Ezz [22] mentioned that the benthic community consists mainly of members of Annelida, Arthropoda, and Mollusca. El-Shabrawy and Khalil [23] studied community structure, biodiversity, biomass, and abundance of macrobenthos in the lagoon in relation to changes in some abiotic and biotic variables. The latest study on macrobenthos of the wetland was carried out by Fishar [24]. He surveyed a monthly sampling of macroinvertebrates from 12 sites during 2004 (Fig. 3).

5.1 *Community Composition and Relative Abundance*

The annual average density of the macrobenthic community recorded by Fishar [24] in Bardawil Wetland was 359 organisms/m^2. This value is lower than that recorded in the Manzala wetland [25, 26], Lake Nasser [27], and Lake Qarun [28].

A total of 52 species of living bottom invertebrates were identified in the collected benthic samples during 2004. Of these, 19 arthropods, 16 molluscs, 14 annelids, 2 echinoderms, and 1 species of Coelenterata were recorded. The species are listed in Table 2 and Mollusca occupied the highest population density (P.D.) of total

Table 2 Abundance of macrozoobenthic species in Bardawil Wetland in different years

		Sampling year			
		1984	1986/1987	2002/2003	2004
Group	Species	[21]	[22]	[23]	[29]
Coelenterata	*Rhizostoma pulmo*		+		+
	Actinia equine			+	
Nematoda	*Thornella teres*	+			
	Rhabditis marina	+			
	Enoplus meridionalis		+		
Nemartina	*Cerebratulus fuscus*			+	
Annelida	*Tubificidae* sp.			+	
	Nereis pelagica	+		+	+
	Lumbriconeries funchalenais			+	+
	Cirratulus cirratus			+	+
	Ophelia sp.			+	
	Hydroides elegans			+	+
	Amphitrite affinis			+	+
	Syllis variegata			+	+
	Myxicola infundibulum			+	+
	Polydora ciliate			+	+
	Polydora sp.			+	
	Augeneriella bagunaria	+			
	Polychaete spp.			+	
	Spirorbis borealis	+		+	+
	Filograna implexa	+		+	+
	Hydroides norvegica		+		
	Sabella fabricia		+		
	Glycera rouxii		+		
	Capitella capitata		+		+
	Nereis diversicolor		+		
	Heteronereis sp.		+		
	Polygordius lacteus		+		
	Eupolymnia nebulosa		+		+
	Raphidrilus sp.		+		
	Dadecacera sp.		+		
	Cucumaria pseudocurata		+		
	Aemotryama autegaster		+		
	Eunice torquata		+		+
	Styiarioides plumose		+		
	Dolichoglossus sp.		+		
	Arenicola marina		+		
	Autolytus sp.		+		
	Dasybranchus caducus		+		
	Phoronopsis viridis		+		

(continued)

Table 2 (continued)

		Sampling year			
		1984	1986/1987	2002/2003	2004
Group	Species	[21]	[22]	[23]	[29]
	Physcosoma sp.		+		
	Amphitrite sp.		+		
	Boronia clavata		+		
	Protula tubularia		+		+
Arthropoda	*Orchestia gammarella*	+		+	+
	Concahecia spp.	+			
	Cypridina mediterranea	+			
	Ampithoe remondi	+		+	+
	Gammarus locusta		+	+	+
	Corophium sp.	+	+	+	+
	Mysis relicta		+		
	Anchialina agilis	+			
	Neptunus pelagicus	+			
	Ocypode saratan	+			
	Dynamena bidentata			+	
	Idotea baltica			+	+
	Balanus perforatus	+		+	
	Balanus amphitrite		+		
	Lupa pelagicus			+	
	Anthura gracilis		+		
	Caprella acanthifera			+	+
	Sphaeroma serratum			+	+
	Sphaeroma walkeri				+
	Dynamene bidentata				+
	Nymphon gracile			+	
	Lepas sp.	+	+		
	Palaemon sp.		+		
	Cancer sp.		+		
	Cricotopus mediterraneus	+	+		+
	Cancer pagurus				+
	Geryon longipes				+
	Ceibbula sp.				+
	Penaeus monoceros				+
	Penaeus japonicus			+	+
	Penaeus semisulcatus				+
	Penaeus kerathurus *Metapenaeus stebbingi*				+
	M. stebbingi	+			+
Mollusca	*Brachidontes variabilis*	+	+	+	+
	C. glaucum			+	+

(continued)

Table 2 (continued)

Group	Species	Sampling year			
		1984	1986/1987	2002/2003	2004
		[21]	[22]	[23]	[29]
	Cerastoderma sp.		+		
	Cerastoderma edule	+	+		
	Donax trunculus		+		+
	Tellina edentula		+		+
	Dosinia lupinus	+		+	+
	Gari depressa	+		+	
	Mactra coralline	+	+	+	+
	Arca lacteal		+		
	Mytilus galloprovincialis		+		+
	Patella sp.			+	+
	Barnea candida		+		
	Hydrobia ventrosa			+	
	Murex tribulus	+	+		+
	Rissoa ventrosa				+
	Gibbula ardens				+
	Thais haemastoma				+
	Pirenella conica	+		+	
	Cerithium vulgatum		+	+	+
	C. reticulatum		+		
	Cerithium scabridum	+			
	Cerithium kochi	+			
	Bulla sp.				+
Echinodermata	*Patiria miniata*		+		
	Psammechinus sp.	+			
	Ophiothrix fragilis				+
Stomatopoda	*Squilla desmaresti*	+			
	Squilla massawensis	+			
	Squilla mantis				+

macrobenthic fauna as represented by 60.79% followed by Annelida (24.05%) and then Arthropoda (14%) of the total number of macrofauna in the wetland (Fig. 4). Individuals of Echinodermata and Coelenterata appeared in the wetland with low numbers representing 1.01% and 0.15% of the total macrobenthos, respectively.

Regarding the temporal distribution of macrofauna, the highest density was recorded during April with an annual average value of 630 organisms/m^2. A remarkable decrease was recorded during the next few months to reach 250 organisms/m^2 during June. The P.D. increased again to form the second peak (383 organisms/m^2) during September. The lowest average value (126 organisms/m^2) was recorded during November (Fig. 5).

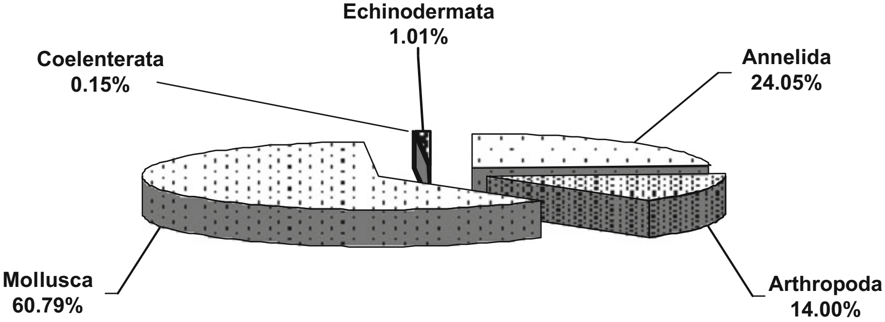

Fig. 4 Percentage composition of macrofaunal community in Bardawil Wetland [24]

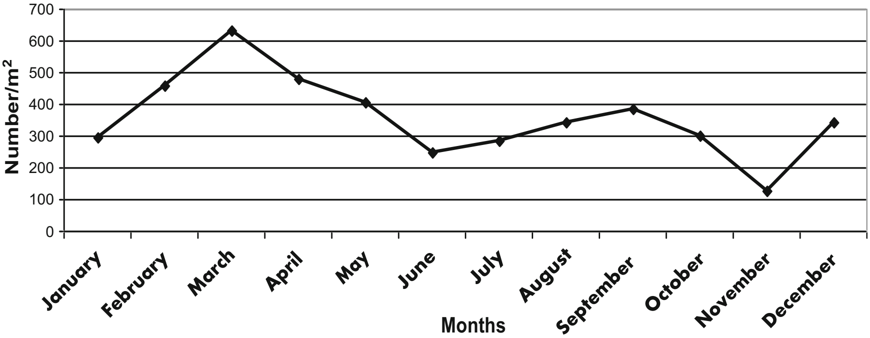

Fig. 5 Monthly variations of total macrobenthos in Lake Bardawil [24]

5.2 *Long-Term Changes of Macrobenthos*

Four sampling programs reflecting long-term changes of macrozoobenthos in the Bardawil Wetland were carried out during 1984 [21], 1986–1987 [22], 2003 [23], and 2004 [24].

5.2.1 Density Fluctuation

As shown in Fig. 6, the standing crop of total benthos during 1984 was 4,164 organisms/m^2. P.D. showed a remarkable decrease (3,711 organisms/m^2) during a survey in 1986–1987 and continues their decrease in 2003 (2,230 organisms/m^2) followed by a sharp drop during 2004 (359 organisms/m^2).

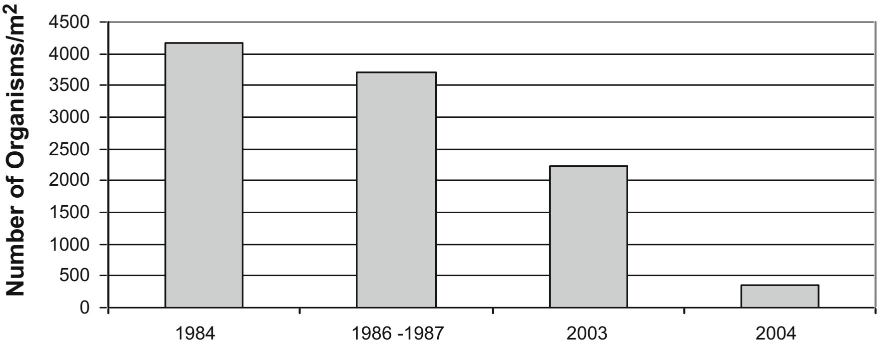

Fig. 6 Annual fluctuation of macrobenthos density during four periods (1984–2004) [24]

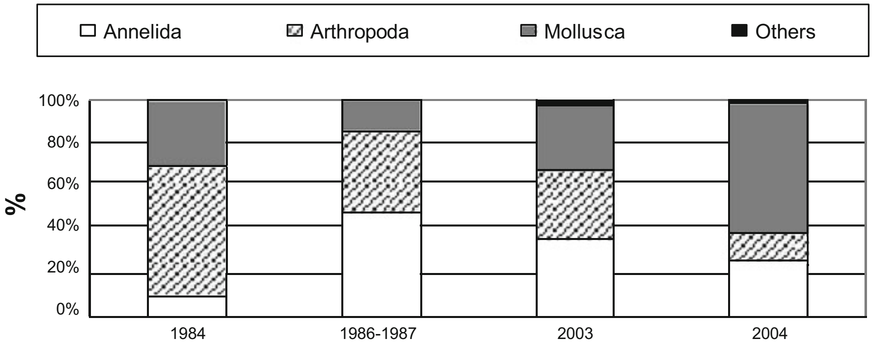

Fig. 7 Annual fluctuation of percentage composition of macrobenthic groups for different surveyed years [24]

5.2.2 Variations in Species Composition

The community composition of macrobenthos in Lake Bardawil showed remarkable changes from one survey to another. In 1984, Arthropoda was the most common group followed by Mollusca and Annelida. In 1986/1987, Annelida was the most predominant group in the lake, forming 41% of the total P.D. of benthos followed by Arthropoda (32.7%), then Mollusca (12.6%). In 2003, the same trend was observed but with different percentages (Fig. 7). In 2004, Mollusca occupied the first position, with 60.79% of P.D. followed by Annelida (24.05%) and Arthropoda (14%).

5.2.3 Variations in Biodiversity

As shown in Fig. 8, 33 macrobenthic species were recorded during 1984, including 4 annelid species, 9 molluscs, 14 arthropods, 1 nematode, and 2 echinoderms. This number increased to 47 macrobenthic species during 1986–1987. Annelids were the

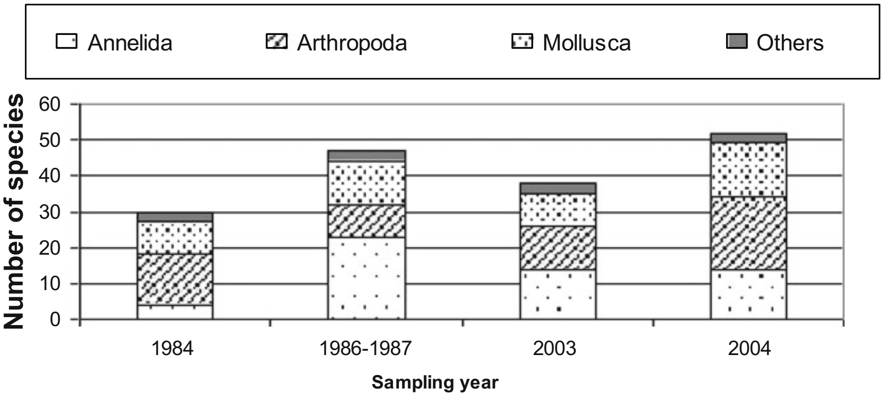

Fig. 8 Annual fluctuation of macrobenthos diversity (number of species recorded) during different surveyed years [24]

most predominant in the lake with 23 species. Mollusca occupied the second position of benthos and was represented by 12 species, followed by Arthropoda represented by 9 species. Echinodermata, Coelenterata, and Nematoda were represented by only one species for each, namely: *Patiria miniata*, *Rhizostoma pulmo*, and *Enoplus meridionalis*, respectively.

In 2003, the species composition changed dramatically. The disappearance of nine annelids and three Molluscs species was accompanied by the appearance of three arthropods, beside one nemartine species, one echinoderm, and one coelenterate species, see Figs. 9, 10 and 11.

In 2004, the macrobenthic fauna increased to 52 species. The numbers of species recorded were 19 Arthropoda, 16 Mollusca, 14 Annelida, 2 species of Echinodermata, and 1 species of Coelenterata.

6 Conclusions and Recommendations

The previous results showed that macrobenthic community composition changed over time. During 2003, only two molluscan species of 1986–1987 survey were recorded. At the same time, 24% of species recorded were previously recorded during 1986–1987 and 43% of such species were previously recorded during 2003 [24]. The population density of total macrobenthos has dramatically declined from one year to another, especially in 2003 and 2004. Since 1995, fisheries catch composition has also changed. The contribution of the most economic species such as the sea bream and sea bass has sharply declined from 56.5%, in 1982–1988, to about 8.6% in 2003, of the total catch. Change in the fish community certainly affects macrobenthos assemblages, since the fish species decline are mainly bottom feeders. As an instant, Mollusca comprised the highest volume of *Sparus aurata*

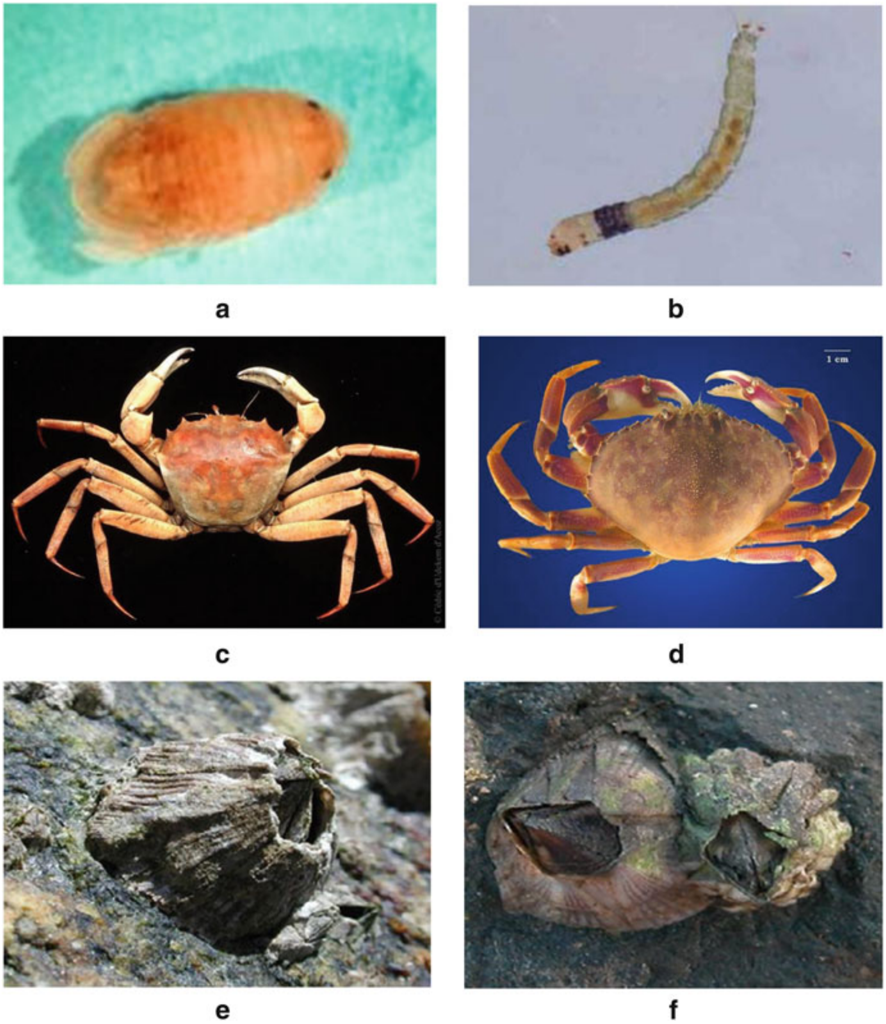

Fig. 9 Photos of some macrobenthos of Bardawil Wetland [6]. (**a**) *Sphaeroma* sp., (**b**) *Cricotopus mediterraneus*, (**c**) *Geryon longipes*, (**d**) *Cancer* sp., (**e**) *Balanus perforatus*, and (**f**) *Balanus amphitrite*

diet. It formed up to 33.24% and was found in 89.63%, while Crustacea constituted about 8.11% by volume [30]. Accordingly, the decrease in the predators leads to a reduction of the grazing pressure upon the prey, and in turn increases the population of the prey. That could logically explain the increase in the diversity and abundance of Mollusca during the last study.

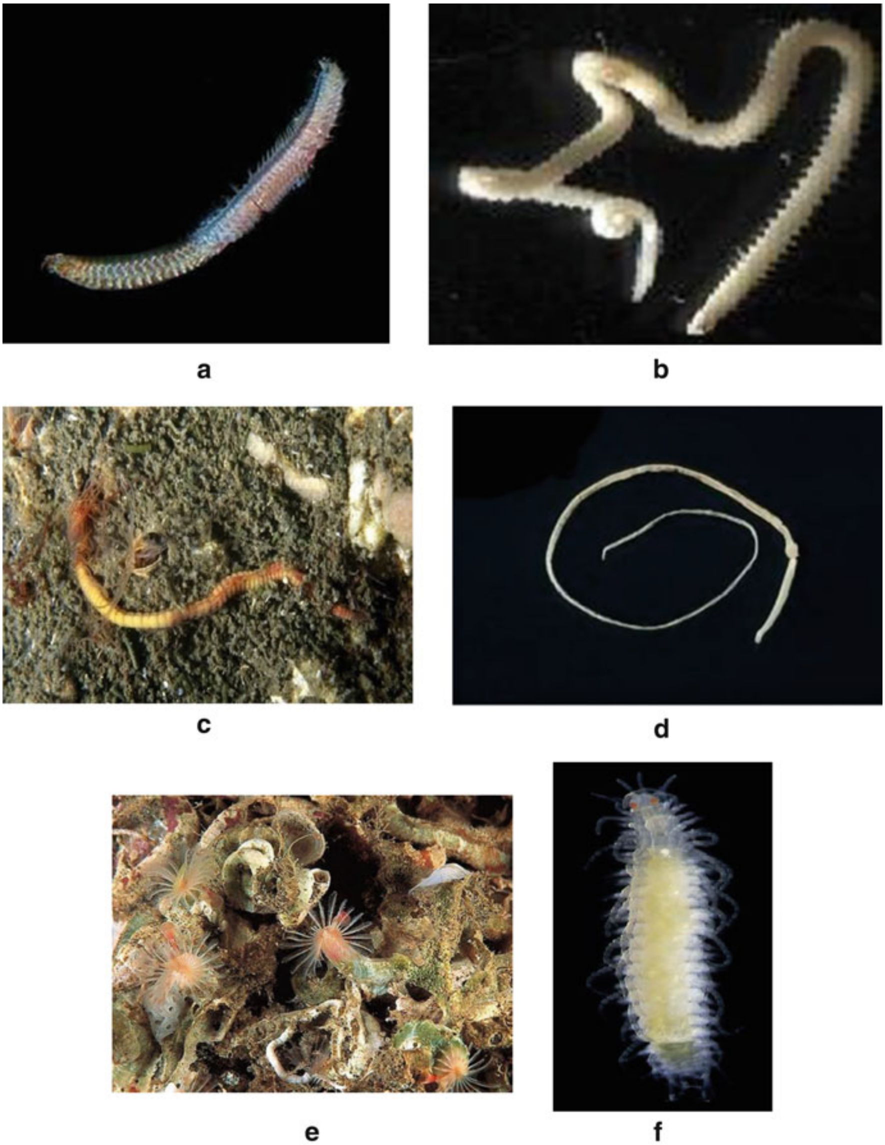

Fig. 10 Photos of some macrobenthos of Bardawil Wetland [6]. (**a**) *Nereis pelagic*, (**b**) *Lumbriconeries funchalenais*, (**c**) *Cirratulus cirratus*, (**d**) *Dolichoglossus* sp., (**e**) *Hydroides elegans*, and (**f**) *Syllis variegata*

This change in the fish community, which consequently changes the whole ecosystem of the wetland, encourages us to recommend establishing a monitoring program to follow up on the changes in the wetland ecosystem, especially the benthic fauna. This will improve the management ability of such important wetlands.

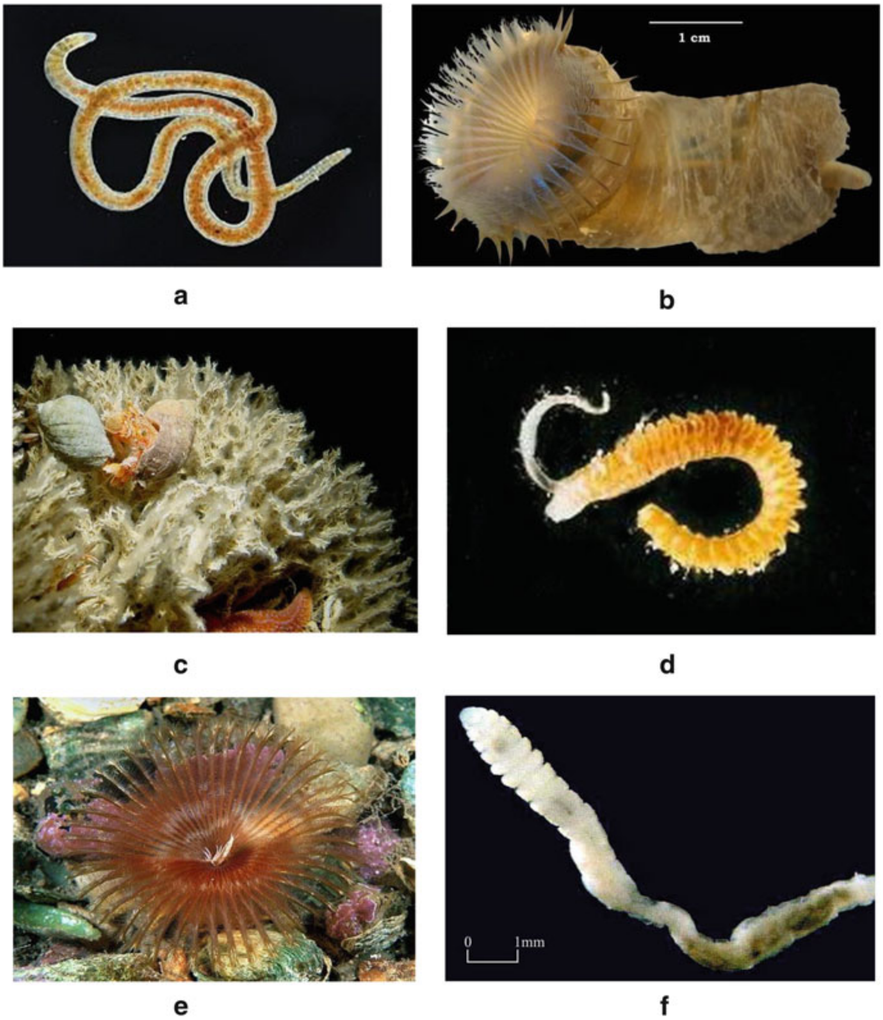

Fig. 11 Photos of some macrobenthos of Bardawil Wetland [6]. (**a**) *Tubificid* sp., (**b**) *Myxicola infundibulum*, (**c**) *Filograna implexa*, (**d**) *Polydora* sp., (**e**) *Sabella fabricia*, and (**f**) *Capitella capitata*

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Lakes and Their Hydrodynamics

M. A. Bek, I. S. Lowndes, D. M. Hargreaves, and A. M. Negm

Abstract This chapter is split into two broad sections. The first deals with lakes – more specifically their categorization, their characteristics, and the quality of their water. The chapter briefly presents the seven main different formation processes, as tectonic activity, volcanic activity, glacial activity, fluvial action, Aeolic action, anthropogenic action, and marine action. The lakes are characterized by low flow velocity and relatively low inflows and outflows. Vertical stratification appears in deep lakes, while shallow lakes are considered well mixed in the vertical axis. Lakes act as a sink for all types of nutrients, toxins, and all organic suspended materials from different types of sources. The second section focuses on the hydrodynamics within lakes, dealing with the very specific nature of flow that is peculiar to these large bodies of what often appears to be still water. The main hydrodynamic processes in lakes are inflows and outflows, wind shear, vertical circulation, thermal stratification, and gyres and seiches.

Keywords Eutrophication, Hydrodynamic process, Lake pollution, Lakes

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Contents

1 Introduction

Lakes are one of the most easily available and exploitable water resources. They are defined as “a mass of stillwater placed in a depression of the ground without direct communication with different water bodies” [1]. Lakes are extremely varied in terms of their origin, occurrence, size, shape, depth, water quality, and other features. Lake surface areas can be thousands of square kilometers (great lakes) or less than a square kilometer (small lakes). Timms [2] considered lake depth as the most important geomorphic parameter of a lake. Lakes are categorized into deep or shallow lakes. Normally, deep lakes are formed through glacial, volcanic, and tectonic activities. On the other hand, shallow lakes, which are less than 7 m deep [2], are usually formed by wind or on floodplains. Lakes can be nearly uniformly round, or they can be irregularly shaped. Their water can be highly acidic, nearly neutral, or highly alkaline. According to Smit [3], lakes can be low in nutrients (oligotrophic), moderately enriched (mesotrophic), highly enriched (eutrophic), or extremely enriched (hypertrophic). Lake salinity varies, from the freshwater type that contains less than 1 Practical Salinity Unit (PSU) = 1 g/l to the hypersaline that contains more than 250 PSUs. In general, most of the world’s largest lakes are freshwater, with some exceptions such as the Caspian Sea. For comparison, seawater contains about 35 PSUs. In addition to lakes, the wetland is defined as a land area which is saturated either permanently or seasonally with water [4]. It is distinguished from other water bodies by the unique characteristic vegetation of aquatic plants. In addition, it is featured with distinct soil conditions (hydric soil). Wetlands are important as they play an important role in the environment. They contribute to the water purification process where they absorb excess nutrients, sediments, and other pollutants before they reach other water bodies. It provides flood control and shoreline stability. Globally it is considered as the home of a wide range of plant and animal life and serves as a rest zone for birds during their annual winter immigration trips. The wetlands are classified into five main types: marine (ocean), estuarine (estuary), riverine (river), lacustrine (lake), and palustrine (marsh). The Convention on Wetlands, called the Ramsar Convention, is the intergovernmental treaty that provides the framework for the conservation and wise use of wetlands and their resources. According to Ramsar, Egypt is gifted with four important wetland sites, Lake Bardawil, Lake Burullus, Lake Qarun Protected Area, and Wadi El Rayan [5].

2 Categorization of Lakes

Lakes and the related shallow water bodies cover millions of square kilometers of continental area and form part of the regional and global water balances. Lakes are normally subcategorized as either natural or artificial. Natural lakes can be categorized based on lake origins. Llames and Zagarese [6] summarized the seven main different formation processes, including tectonic activity, volcanic activity, glacial activity, fluvial action, Aeolic action, anthropogenic action, and marine action. These processes might act alone or in combination with others.

2.1 Tectonic Activity

The Earth's exterior layer is composed of a network of rigid crustal plates. These plates form a shell around the planet. The boundaries of these plates are tectonic movement zones of active slip, collision, and separation that generate tectonic forces. These tectonic forces are transformed upward to the Earth's surface, which deforms bedrock through the fracture, rifting, separation (as illustrated in Fig. 1), and warping resulting in the formation of mountains, ocean basins, and some of the world's largest, deepest, and oldest lake basins. Tectonic lakes, such as Lake Baikal in Russia and Lake Tanganyika in Malawi, are extremely large, covering thousands of square kilometers, deep at hundreds of meters, and old, existing from 10,000 to 30,000 years ago. Other crustal movements, such as uplift of the seafloor, formed the Caspian Sea [8].

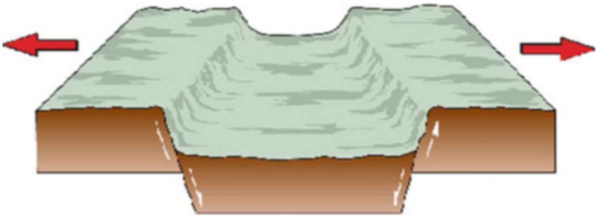


Fig. 1 Schematic diagram of tectonic movement. Adapted from [7]

2.2 Glacial Activity

Glaciers are large bodies of ice that form on land as a result of the accumulation and compaction of snow. Glaciers' advance and retreat over the Earth's surface is responsible for carving out massive valleys, depressions, and deep basins. This process is known as the glacial erosion process, which takes place during ice ages. The most recent ice age, in the Pleistocene Epoch, occurred thousands of years ago and had contributed to at least 70% of all the existing lakes during this era. When the ice melts, it fills these depressions resulting in the formation of great lakes, as can be seen in Fig. 2.

The largest glacial lakes are the Great Lakes of North America (Superior, Huron, Michigan, Erie, and Ontario) and also Canada's Great Slave Lake formed after the melting of the Laurentide ice sheet during the most recent ice age. This type of lake tends to be large, deep, and most abundant in high-latitude areas in the northern hemisphere that were occupied by such glaciers. The glacial lake water budget is highly dependent on the distribution of glaciated area in the past geological times.

There are several types of lakes formed through glacial activities. Kettle lakes, illustrated in Fig. 3, were formed as ice blocks melted in place within the glacial sediment. In this process, the dimensions, shape, and bathymetry of the kettle lake depend on the extent of the ice block. Normally, kettle lakes are deeply relative to their surface area. They might be formed as multi-basins, where some blocks of ice were adjacent to one another. Another type of glacial lake was formed when glacial sediment remained, creating a natural dam (Moraine dam) that interrupted rivers and streams.

Fig. 2 Glacier Lake. Adapted from [9]

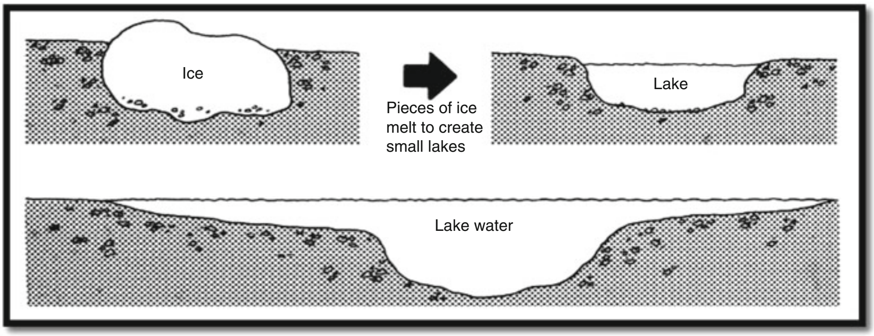


Fig. 3 Kettle lake formation process. Adapted from [10]

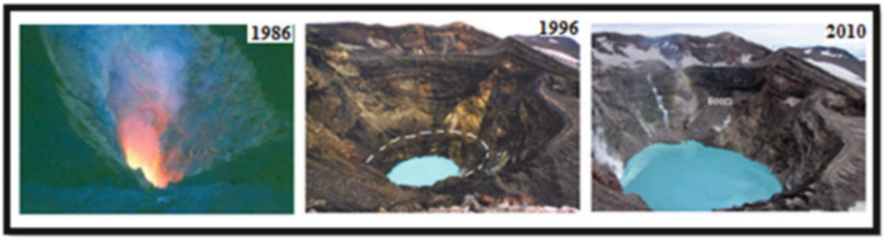


Fig. 4 Volcanic lake formation process. Adapted from [11]

2.3 Volcanic Activity

Volcanic activity is responsible for a variety of lake basin types, which are classified into two groups. The first group, the volcanic crater lake, may be formed directly in the volcanic chamber, where the magma was ejected in an active but a quiet volcano, as illustrated in Fig. 4. These volcanic crater lake basins are relatively small, and the lake has a characteristically small ratio of maximum width to maximum depth, which reduces the lake mixing processes. Lake Nyos in Cameroon is a good example of how this type of lake may interact with the surrounding environment. The lake remained partially unmixed for a long time and therefore became supersaturated with carbon dioxide gas [10]. The sudden release of an enormous volume of trapped carbon dioxide explains the sudden death by suffocation of 2,000 citizens in 1986. Le Guern et al. [12] proposed to pump and degas the lake's deep water to prevent the accumulation of carbon dioxide.

The other group, volcanic dam lakes, includes basins that result from drainage that is obstructed by the volcanic mountain itself or the expelled magma. Volcanic lakes are generally small but are often deep and comprise some of the world's most aesthetically pleasing, for example, Lava Lake, British Columbia, Canada.

Fig. 5 General process of oxbow lake formation. (**a**) Erosion and deposition processes. (**b**) River takes shortest course. (**c**) Oxbow lake. Adapted from [13]

2.4 Fluvial Action

Running water, such as a river, plays a role in sculpting the Earth's surface. This natural process assists in forming new lakes. Figure 5 describes the general process of an oxbow lake basin formation. Initially, the river cuts a newer direct path through the bank (Fig. 5b). Then, the old river course is sealed at both ends with sediment deposits leaving a new forming lake (Fig. 5c). Almost all these types of lakes are small and shallow. They are commonly crescent-shaped which refers to their position on the old river bank.

2.5 Aeolic Action

Deflation lake basins originate through the erosive force of wind that excavates a depression. The process is associated with an arid climate and a lack of vegetative cover. Deflation lakes may become dry if the precipitation and runoff are unable to maintain their evaporative losses. They are common throughout arid regions, such as Australia, Africa, and North America [10]. Deflation lakes are generally shallow, less than 5 m and normally 1 m deep, with a relatively small size, often 1 km^2, and have sandy shores [2].

2.6 Human Activity

Artificial lakes are excavated or formed by engineers often by the construction of dams across natural river valleys to form water storage reservoirs, which are the result of the flooding of the land behind the dam. They are generally built for purposes of flood control, water supply, power generation, and fish production. Modern highly engineered reservoirs are capable of retaining enormous volumes of water and controlling its passage at the outlet with great precision. Lake Nasser in Egypt may be considered a good example of how these human-made lakes can control water flow, which saved Egypt from the severe drought that affected Africa during the low rains of the 1990s (Fig. 6).

Fig. 6 Artificial lakes. Adapted from [14]

2.7 Marine Action

The formation of coastal lakes and lagoons generally results from the movement of sandbars along the shoreline between a land mass and a sea or ocean. Where the lake becomes separated from the ocean, they may be fed by freshwater from rivers and/or groundwater. The resulting mixture of seawater and freshwater is defined as brackish water. These coastal lakes or lagoons are usually brackish and may be classified into three main categories [15], which depend on the nature of the connecting channel between the lagoon and the bounding coastal oceans:

Chocked lagoons: are characterized by high wave energy, significant littoral drift, and long flushing time. The connecting sea channel acts as a dynamic filter, which reduces the tidal currents and water level fluctuations.

Restricted lagoons: are oriented parallel to the shoreline. They are usually connected to the sea by one or more inlets. They are large shallow bodies of water with a high surface area in which the prevailing winds play a major role in driving the internal water circulation. The salinity of these lakes ranges from brackish to hypersaline marine.

Leaky lagoons: have many ocean-connecting entrance channels. Salinity is close to the marine level. The internal circulation of these lakes is dominated by strong tidal-driven currents. Lake Nabugabo in Uganda is an example of a freshwater coastal lake, which was cut off from Lake Victoria.

Fig. 7 Egyptian northern lakes. Adapted from [16]

The Egyptian northern lakes represent a very valuable resource not only for the Egyptian but also for the humankind. Egypt has five shallow coastal lakes. These lakes are Lake Manzala, Lake Burullus, Lake Edku, Lake Mariout, and Lake Bardawil (Fig. 7). Lake Bardawil and Lake Burullus are considered as protected wetlands. Egyptian northern lakes are varying in their characteristics and mean features. Lake Manzala is the largest of the Northern Delta lakes with a total area of about 90,000 feddan with an average depth of 0.5 m. The lake is considered as the most productive lake with the mean annual fish production of 60,000 ton. The lake suffers from major problems including degradation, pollution, and a high level of eutrophication. Similarly, Lake Burullus is the second largest delta lake, with the mean water level of 0.25 m. Lake Edku and Lake Mariout are located in the western part of Alexandria. Lake Edku is classified as a shallow eutrophic lake. The mean annual fish production from the lake is 9,000 ton. However, Lake Mariout is the smallest of the Delta lakes with an approximate area of 17,000 feddan. The lake is ally isolated from the open sea. The depth ranges from 0.6 to 2.7 m and the mean annual production is 5,000 ton.

3 Characteristics of Lakes

Lakes are characterized by a low flow velocity and relatively low inflows and outflows. Vertical stratification appears in deep lakes, while shallow lakes are considered well mixed in the vertical axis [17]. Lakes act as a sink for all types of nutrients, toxins, and all organic suspended materials from different types of sources.

Nutrient enrichment is an important feature in characterizing lakes. Lakes with low nutrient levels exhibit high water clarity, which is often accompanied by low vegetation within the water domain. The higher the level of nutrients, the poorer the water clarity, and the higher the vegetation concentration observed. Eutrophic states are used to describe moderate nutrient enrichment, where the possibility of good plant growth and algal blooms exists. However, if there is very high nutrient enrichment, the lake state is considered as hypertrophic. A hypertrophic lake features poor water clarity with extensive plant growth. Moreover, the whole surface area could be covered with plants, which consume a large amount of water and affect the water circulation.

3.1 Key Factors Controlling Lake Hydrodynamics and Water Quality

The hydrodynamic and water quality characteristics of a lake depend on several factors, including formation and history, human activities, size and shape, climate conditions, and the lake's main physical features.

The two most important indices of lakes are the depth and hydraulic residence time. Residence time less than 1 year is classified as short and more than 1 year as long. The morphometry of the lake is responsible for the water residence time. The residence time is defined as the required time to empty the lake water through its outlet. It is equal to the lake volume divided by the outlet flow rate. Residence time plays an important role in lake water quality. For short residence time, the availability of plant growth is reduced and results in less biomass. On the other hand, if the residence time is long, nutrient enrichment increases, and algae may have a better chance to grow [18].

3.2 Biological Zones in Lakes

The depth to which various wavelengths of light penetrate into lake water is a major determinant of the distribution of organisms. The light should be included in any limnological analysis. It is the source of energy for the photosynthetic reaction and plays an important role in algae concentration, where diatom growth rate is a function of radiation levels. Transparency is the indicator for the penetration of light. A simple tool, the Secchi disk, is used to measure the light penetration depth. Lake biological zones are separated into three main regions, according to light penetration depth [19]. As illustrated in Fig. 8, the euphotic zone (Secchi disk zone) is the upper layer from the water surface down to the depth where only 1% of the surface sunlight can reach. Generally, the euphotic zone is two to three times that of the Secchi depth. Secchi depth is measured using a circular plate, known as a

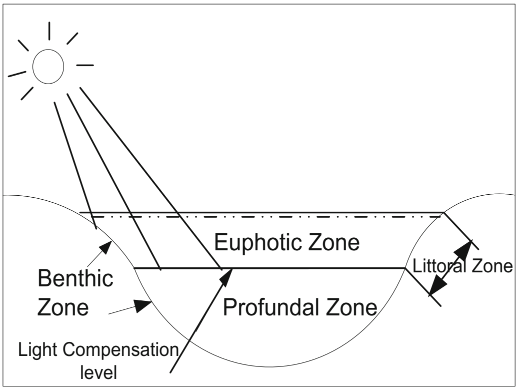


Fig. 8 Biological zones in a lake. Adapted from [19]

Secchi disk, which is lowered into the water until it is no longer visible. The second is the littoral zone, which can be described as the shallow water near the shoreline in which rooted water plants can grow. This cannot extend deeper than the euphotic zone, as more than 1% of the surface sunlight is required for plant growth. This yields the growing of emerged, submerged, or floating plants. Hence, it provides a food source for fish. The third is the profundal zone, which is the layer that lies below the euphotic zone. The transition between the euphotic and profundal zone is called the light compensation level. Finally, there is the benthic zone, which is the bottom sediment zone.

3.3 Lake Pollution and Eutrophication

Due to their long residence time, lakes and reservoirs can hold water for a long time. Hence, pollutants can accumulate in the water body from both point (feeder rivers, streams, or effluent pipes) and nonpoint sources (surface runoff). This accumulation process disturbs the ecosystem and allows algal growth, thus accelerating the eutrophication of the lake. The eutrophication process is mainly caused by agricultural runoff and untreated industrial and urban discharge. The prevention of lake eutrophication needs good planning and management of the associated watershed. It needs a better understanding of the relation between nutrient sources and the eutrophic process in lakes. Each trophic state describes a different water quality; the oligotrophic state describes water, which features low nutrients, high water clarity, and the low existence of algae. In the mesotrophic state, medium nutrients and algal blooms exist, while the eutrophic state describes a high nutrient load and intensive algal blooming. In the worst cases, the term, hypereutrophic, is used to describe a severely high nutrient load and algal condition as can be seen in Fig. 9.

Fig. 9 Algal blooms at surface

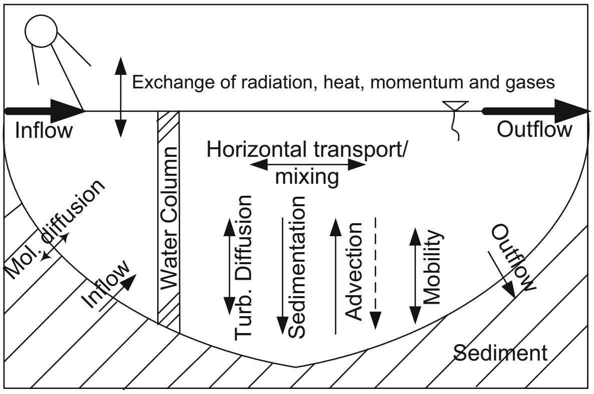


Fig. 10 Important transport and exchange processes in a lake

4 Hydrodynamic Processes

Hydrodynamic processes, such as inflows and outflows (Fig. 10), wind shear, vertical circulation, thermal stratification, and gyres and seiches, play an important role in the lake's hydrodynamics. It is expected that some or all these processes will be present depending on the nature of the lake or in similar water bodies, such as wetlands and reservoirs.

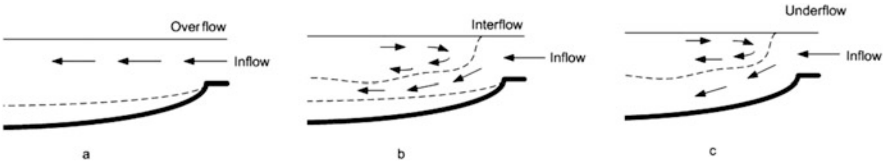


Fig. 11 Water inflows: (**a**) overflow, (**b**) interflow, and (**c**) underflow

4.1 Inflow, Outflow, and Water Budget

There are several types of water inflow, including river flows, runoff, groundwater baseflow, and discharge from wastewater treatment plants. One of the main factors controlling water movement is water density. The lower the density variation is between the lake and the inflow, the more rapid is the mixing. If the density of the inflow water is low, the inflow will move as a density current and will take the form of overflow as illustrated in Fig. 11a. For inflow of similar density, interflow may be seen, and for a more dense inflow, an underflow may occur.

Outflow is the natural release of the water from the lake and depends on the type of connection between the lake and other water bodies.

The water budget is a result of the water entering and exiting the water body. Mathematically, the water budget is the difference between the water entering the lake through inflow sources, such as inflow, precipitation, and inlet groundwater, and the outflow sources, such as outflow, evaporation, and leakage to groundwater.

4.2 Wind Forcing and Vertical Circulation

In shallow lakes, reservoirs, and the coastal zone, flows are driven by several key processes. These processes are presented in Sladkevich et al. [20] as shear stresses imparted to the free water surface by the wind, by radiation stresses caused by waves, by tide-induced water level variations at the boundaries, and by the atmospheric pressure gradient. Also, water density stratification caused by temperature and salinity contributes to large-scale flows. Kocyigit and Falconer [21] added bottom topography and roughness, shore configuration, and vertical eddy viscosity as extra parameters that control the hydrodynamics of shallow lakes, associated with complex bathymetry. Among all these parameters [22], considered that the primary external driving force creating motion in the lake is the wind, which is responsible for a good deal of vertical mixing.

The water movement observed on the surface of lakes on a windy day demonstrates the effects of the shear force imparted by the surface wind. Although this shear stress is very small, it has a large effect, when integrated over a large water domain [23]. The wind shear stress exerted on the water surface can be estimated using one of the several mathematical formulations found in the literature. The most commonly used formulas are those introduced by Van Dorn and Wu [24, 25]. Dean and Dalrymple [23] presented Wu's equation as follows:

$$\tau = \rho_{\text{air}} k_w W^2 \tag{1}$$

where τ is the wind stress exerted on the water surface by the wind, ρ_{air} is the density of air (0.001226 g/cm^3 at STP), and

$$k_w \equiv \left\{ \begin{array}{ll} \dfrac{125}{(W/100)^2} \times 0.001 & \text{if } W \text{ less than } 100\ \text{cm/s} \\ \dfrac{(W/100)^{0.5}}{2} \times 0.001 & \text{if } 100\ \text{cm/s} \leq W \leq 1,500\ \text{cm/s} \\ 0.0026 & \text{if } W \text{ greater than } 1,500\ \text{cm/s} \end{array} \right\} \tag{2}$$

where W is the wind speed in cm/s at a 10 m elevation above the water surface.

Van Dorn's formula [24] was the first formula proposed and is considered as the departure point for all following researchers. Van Dorn's formula can be presented as follows:

$$\tau = \rho_{\text{water}} \kappa_{\text{vd}} W^2 \tag{3}$$

where τ is the wind stress (N/m^2) exerted on the water surface by the wind, ρ_{water} is the mass density of water = (~62.3 lbm/ft^3 = 998 kg/m^3 at 68 F°, 0 ppt salinity). (~64.0 lbm/ft^3 = 1,025 kg/m^3 at 68 F°, 35 ppt salinity). W is the sustained wind speed in (m/s) at a 10 m height above the water surface, and

$$k_{\text{vd}} = \begin{cases} 1.2 \times 10^{-6}, & W < W_c \\ 1.2 \times 10^{-6} + 2.25 \times 10^{-6} \left(1 - \frac{W_c}{w}\right)^2, & W > W_c \\ \text{where } W_c = 5.6\ \text{m/s} \end{cases} \tag{4}$$

These empirical equations were developed for the case where there was no obstruction to the wind. So care should be taken when using this formula, as in the actual case, some barriers may be found. For example, tall trees along the lake bank could affect the wind speed, direction, and distribution [26]. So, some calibration is required before using the equation.

The wind shear effect on the water body is introduced as described below. The water surface layer is accelerated in the direction of the prevailing wind. Once it has gained velocity, a stress is exerted on the next layer. This process is repeated until the velocity profile development reaches the bed. This process takes a period of time and depends on the level of turbulence, which depends on other factors, such as wind speed, radiation stresses caused by waves, and tide-induced water level variations at the boundaries [27]. This process is demonstrated in Fig. 12. Meanwhile, a second wind-generated process – water surface setup development (drawn in red) – occurs, while the velocity profile is developed. This phenomenon is in the opposite direction of the shear stress. When the two generated currents are superimposed, the fully developed velocity is achieved as illustrated (green color) in Fig. 12.

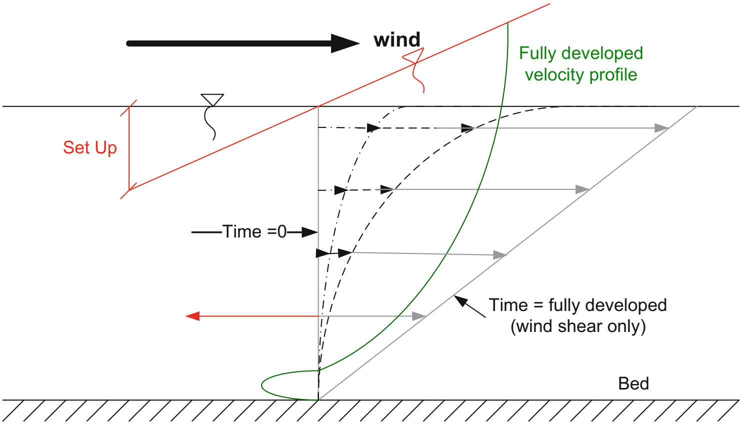


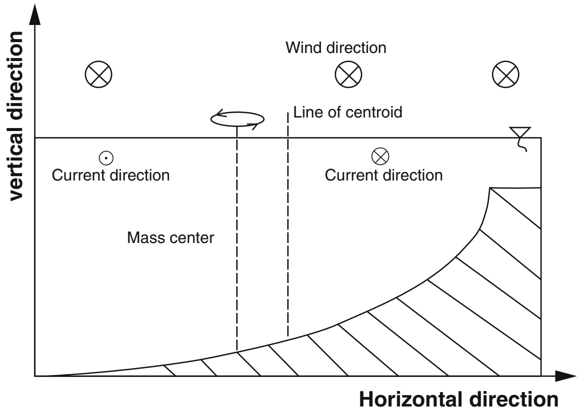
Fig. 12 Development of velocity profile due to wind stress

In the early 1980s, two-dimensional hydrodynamic mathematical models were widely used. These two-dimensional models are computationally efficient and easily implemented and were successfully employed in a number of situations. However, it was soon recognized that these models are not appropriate to simulate wind-induced currents due to their incapability of describing the detailed three-dimensional characteristics of wind-induced currents [28]. Kocyigit and Falconer [21] constructed a three-dimensional numerical model for a shallow homogenous lake with a complex bathymetry similar to the geometry of Egyptian coastal lakes. This model may be considered as the state-of-the-art in the field. The model was used to simulate wind-induced circulation patterns. The circulation patterns gave satisfactory results and showed close agreement between the predicted and the analytical solutions. The authors concluded that the non-hydrostatic pressure distribution did not have a noticeable influence, except in the nearshore regions in the circulation patterns. So, the necessity of using three-dimensional modeling is rising when the investigated area is near the shoreline.

4.3 Gyres

In oceanography, gyres are circular, rotational circulation patterns, established by wind movement. Gyres are caused by the Coriolis effect along with horizontal and vertical friction, which determine the circulation patterns from the wind torque. The term can be used to refer to any type of vortex in the air or sea but is most commonly used in oceanography, to refer to the major ocean systems. Gyres are prominent features of lakes and are responsible for the transport of sediments, nutrients, and algae in the horizontal direction.

Fig. 13 A schematic of a gyre. ⊙ represents flow out of the plane of the paper and ⊗ into the plane of the paper. Adapted from [29]



The gyres in the lake and the relationship between the wind forcing as a primary driving force and the lake circulation are illustrated in Fig. 13. The shallow lake presented is featured as shallower on the right side and deeper on the left side. When a uniform wind blows over the lake, the line of action of the wind is forcing through the centroid of the water surface. Since the lake is deeper and contains more water on the left, the center of the mass of the lake water is shifted toward the deeper side, to the left of the line of the centroid. Therefore, the center of the mass line and the line of centroid do not coincide. Hence, a torque is produced. This torque makes the lake water rotate, flowing into the paper on the right and flowing out of the paper on the left as shown in Fig. 13 [30].

4.4 Seiches

In lakes and reservoirs, internal waves are more important than surface waves for vertical mixing. Internal waves are produced by wind forcing, withdrawals, hydropower releases, thermal discharges, and local disturbances. One of the most important internal waves is seiches.

Seiches are standing waves, which can be considered as the sum of two traveling waves moving in opposite directions [30]. This phenomenon occurs in closed or semi-closed water bodies, such as lakes, estuaries, and harbors. Extended wind forcing on a lake produces a surface gradient. Therefore, the water level rises in the downwind sector (wind setup). Oscillations take place when the wind force suddenly reduces or changes direction. Because the solid barrier of the lake boundary reflects waves, the superposition of the original and reflected waves gives rise to standing waves called seiches.

4.5 Coriolis Effect

The rotational motion of the Earth has consequences for the large-scale dynamics of the ocean and the atmosphere. The resultant effect is known as the Coriolis effect (force). The Coriolis parameter, f, is a function of the angular velocity, Ω, and the latitude, φ, thus:

$$f = 2\Omega \sin \varphi \tag{5}$$

In oceanography, the Coriolis force is an important factor, and an extra term representing it is added to the momentum equation. The importance of this parameter is evaluated by Rossby number. A small Rossby number indicates a system that is strongly affected by Coriolis forces, and a large Rossby number signifies a system in which inertial forces dominate. The Coriolis parameter is positive in the northern hemisphere and negative in the southern.

5 Conclusion

Generally, lakes are formed through seven main different formation processes which might act alone or in combination with others. Lakes formed due to glacier activities are the largest and deepest and are mainly located in the northern hemisphere. The lake depth is the most important geomorphic parameter. Lakes are classified as shallow if they are less than 7 m deep. At the moment eutrophication is considered as the major problem that faces lakes. This process takes place when there are excessive nutrient enrichment and long residence time. The inflow, outflow, tide, wind shear, vertical circulation, thermal stratification, gyres, Coriolis effect, and seiches play an important role in lake hydrodynamics. In shallow lakes, the wind shear is the dominant factor in controlling the lake's hydrodynamic process, while inflow and lake geometry are important but come next.

6 Recommendations

- The Egyptian northern lakes need a full monitoring program.
- The Egyptian government should encourage the scientific community to investigate and offer solutions to the lake's problems.

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Basics of Lake Modelling with Applications

M. A. Bek, I. S. Lowndes, D. M. Hargreaves, and A. M. Negm

Abstract This chapter presents a review of previous studies related to the numerical modelling of the hydrodynamics of coastal lakes with emphasis on Egyptian coastal lakes. Also, related applications, such as water quality management and sediment transport scenarios in lakes, are presented. The focus is primarily on existing, well-established, numerical models and their applications to shallow water systems. The chapter starts with a general introduction to lake modelling followed by the techniques and assumptions that are commonly used. A summary of the available hydrodynamic models categorised based on whether they are one-, two-, or three-dimensional is presented. Previous hydrodynamic modelling of lakes is reviewed under a separate section within this chapter as well as those studies related to water quality management.

Keywords Coastal lakes, Egyptian, Evaluation, Hydrodynamics, Lakes, Modelling, Models

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Contents

1 Introduction

In general, modelling is a mixture of science and experience. It requires a detailed understanding of the physics to make a good judgment in terms of the trade-offs between those processes of secondary importance and keeping the problem as simple as possible [1]. There are several model formulations for oceans, estuaries, lakes, and bays. However, the basic equations and the assumptions of these models are similar. In this chapter, the objectives and history of lake modelling are briefly introduced, and the model assumptions and approaches are presented. Following this description of the model assumptions, the approximations, and turbulence closure schemes in the more important models will be presented, with a consideration of their applicability to the Egyptian coastal lake.

2 Objectives of Lake Modelling

The main objectives of conducting lake modelling are summarised as follows:

1. To develop a better understanding of the physical, chemical, and biological processes of the lake ecosystem.
2. To support lake ecosystem management.
3. To summarise the knowledge on the lake ecosystem.

Lake models play an important role in investigating different hypotheses adopted by the modeller, and in checking their reliability and applicability. The comparison between the predicted model data and the measured field data allows one to make a judgment about any new theories that try to describe any of the lake processes.

Field-validated lake models are essential and offer an excellent tool to support water quality management and decision-making. They allow insight into what will occur under different scenarios. These models increase the awareness of the major problems of the lake, and how these may be treated.

3 Numerical Modelling Approaches and Approximations

There are several modelling approaches and approximations that are commonly used in most hydrodynamic models.

3.1 Governing Equations

The governing equations that comprise the conservation of momentum, mass, and energy (collectively known as the Navier–Stokes equations) in three dimensions incur too large and computational cost to be solved numerically over a large domain for a long simulation time. Therefore, simplifications are often needed. In particular, the case where the horizontal length scale is much greater than the vertical length scale (the depth), the shallow water assumption is often employed. This assumption is widely used in the studies of rivers, lakes, estuaries, and coastal water bodies. The hydrostatic approximation, the Boussinesq approximation, and the quasi-3D approximation are different aspects of the shallow water assumption, which are intensively used in the studies of lake hydrodynamic simulations.

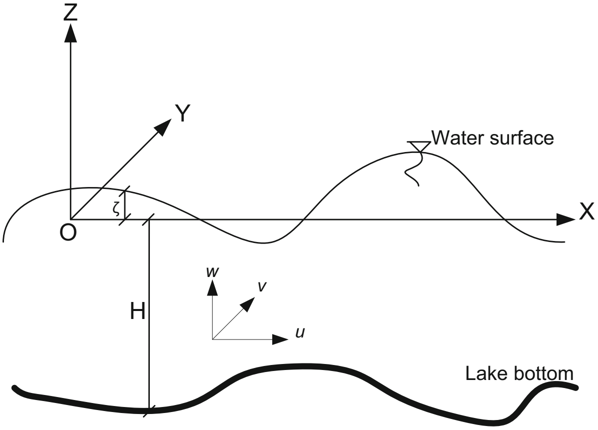
3.2 Hydrostatic Approximation

The hydrostatic approximation is applied when the characteristic length in the horizontal direction is several orders of magnitude larger than the characteristic vertical dimension. This assumption is valid for lakes and reservoirs. In particular, in shallow lakes where the vertical accelerations are small compared to the gravitational acceleration, the hydrostatic approximation is valid and desirable [1]. The assumption results in a huge saving in computational time. The hydrostatic equation is shown below (Eq. 1):

$$\frac{1}{\rho}\frac{\partial p}{\partial z} = -g \tag{1}$$

The hydrostatic approximation is a simplification of the equation governing the vertical component of velocity. It simply says that the pressure at any point in the ocean (atmosphere) is due to the weight of the water (air) above it, omitting the vertical acceleration.

Fig. 1 Cartesian coordinate system for a water body



In Fig. 1, x, y, and z are the east, north, and vertical axes of the Cartesian coordinate system; u, v, and w are the velocity components (m/s) in x, y, and z directions, respectively. H is the bottom depth (relative to $z = 0$) (m) and ζ is the height of the free surface (relative to $z = 0$) (m).

Integrating Eq. (1) from z to the free surface ζ which is presented in Fig. 1 gives:

$$\frac{\partial p}{\partial x} = \frac{\partial p_a}{\partial x} + \rho_s g \frac{\partial \zeta}{\partial x} + \int_z^{\zeta} g \frac{\partial \rho}{\partial x} dz \tag{2}$$

where ρ_s is the surface density. Equation (2) represents the horizontal pressure gradient as the summation of the atmospheric gradient term, a barotropic (water surface gradient) term, and a baroclinic (density gradient) term. Usually, in shallow lakes, the atmospheric pressure gradient is neglected, as it is small when compared to the wind stress.

This assumption is no longer valid in cases when the horizontal motion scale is similar to the vertical motion scale. Cases such as convective wastewater plumes and flows associated with high-frequency internal waves cannot be modelled using the hydrostatic approximation.

Global atmospheric models, such as Princeton Ocean Model (POM), Regional Ocean Modelling (ROM) system, and Finite Volume Coastal Ocean Model (FVCOM), are employing the hydrostatic assumption, whilst regional models, such as Coupled Ocean–Atmosphere Mesoscale Predicted System (COAMPS), are not using it. Although most ocean circulation models utilise the hydrostatic approximation, there are some models under development that tries not to use it. For example, FVCOM is undergoing an upgrade to a new non-hydrostatic version, to resolve vertical convection and internal waves.

3.3 Boussinesq Approximation

Density variations within the water body are small and approximately of order 10^{-3}, resulting in a negligible effect on the barotropic term [2]. So, ρ_s can be replaced by a constant reference density ρ_o. On the other hand, the effect of buoyancy arising from differences in fluid density along the horizontal surface is not negligible, where it appears in the terms multiplied by g, the acceleration due to gravity. As a result, the effect of the density variation is only retained in the baroclinic term. This called the Boussinesq approximation and is demonstrated in Eq. (3).

$$\frac{\partial p}{\partial x} = \frac{\partial p_a}{\partial x} + \rho_o g \frac{\partial \zeta}{\partial x} + \int_z^\zeta g \frac{\partial \rho}{\partial x} dz \tag{3}$$

3.4 Quasi-3D Approximation

Most three-dimensional (3D) hydrodynamic models used in rivers, lakes, and estuaries are quasi-3D models. This approach eliminates the momentum equation in the vertical direction and treats the system as a set of horizontal layers that interact via source and sink terms, which represent the water exchange between adjacent layers. Models with the quasi-3D approximation are not suitable for simulations where turbulence occurs, resulting in strong vertical mixing.

3.5 Equations in the Cartesian Coordinate System

Natural water bodies are three-dimensional. Hence, the hydrodynamics and water quality have spatial variations over length, width, and depth. However, some simplifications of the governing equations are permissible. The governing equations can be reduced from 3D to 2D or even to 1D. This reduction in dimensionality results in savings in development, simulation, and analysis costs [3].

Zero-dimensional (whole lake) models assume a well-mixed water body without any spatial variations in all directions. This model is suitable for small lakes or ponds that are completely mixed in all directions [3]. It is considered as a useful tool for preliminary estimate of the water quality conditions.

One-dimensional models assume that the spatial change is only over a single dimension. Such models are often used to simulate the hydrodynamics of rivers. For example, the change is considered to be in the longitudinal direction for rivers. To investigate the stratification of a small lake, a 1D model in the vertical direction is sufficient.

Two-dimensional models consider spatial variations in the horizontal plane in the case of shallow water lakes or in a vertical plane for narrow reservoirs. Normally, two-dimensional models are used to simulate the water circulation without stratification in the x–y plane.

Three-dimensional models describe changes that occur over all three dimensions and provide the most detailed assessment of hydrodynamic parameters. There is an inverse relationship between the number of dimensions used and the time required to run the simulation. So, it is preferable to use a model of sufficient dimension to retain accuracy and reduce the computational costs.

4 Horizontal and Vertical Grids

4.1 Horizontal Grid

Horizontal grids are classified into: structured (Cartesian or curvilinear) and unstructured grids. The structured grid is where each cell typically has four sides and, in the interior of the grid, four neighbours (Fig. 2a). The Cartesian grid is a simple representation of the domain in the horizontal direction and is commonly used in large-scale applications. It is simple to code but with key disadvantages, as it cannot resolve curved boundaries well. They can be easily refined and improved by using a non-uniform Cartesian grid spacing or nested grid spacing [4].

Curvilinear grids are similar to Cartesian grids; however, their quadrilateral elements are distorted throughout the horizontal space (Fig. 2b). Although curvilinear grids allow the user to combine coarser and finer resolution in the same horizontal discretisation, it needs to be a gradual process, which may lead to computational waste [4] in terms of excessive numbers of cells.

Unstructured grids are commonly composed of triangular or quadrilateral elements in some applications or n-sided polygons. These are widely used in coastal water hydrodynamic models. The unstructured grid can easily resolve complicated topography and has the greatest geometric flexibility that gives accurate fitting to the irregular coastal boundary (Fig. 2c). Moreover, it offers different resolution types in

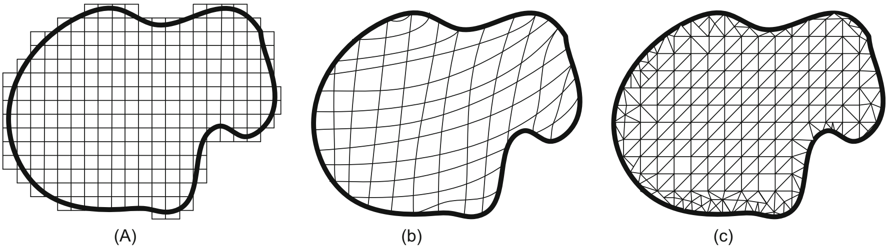


Fig. 2 Plane view illustrated different horizontal grid layouts. (**a**) Cartesian grid, (**b**) a curvilinear grid, and (**c**) an unstructured grid

the same horizontal domain, i.e. fine resolution in particular areas of interest and coarse resolution in others. So, the unstructured mesh is the best technique to resolve for lake water bodies with complicated coastal regions.

4.2 Vertical Grid

In the vertical direction, the most common discretisation used is *z*-level grids, sigma coordinates, and isopycnal coordinates. The simplest among these is the *z*-level grid which uses a Cartesian coordinate system, where it has a uniform, most of the time equally thick layers which span the horizontal plane (Fig. 3a). The layer thickness may vary but should be changed by no more than 10% from one layer to the next adjacent one. Although the *z*-level grid is a simple discretisation approach, the change of bottom slopes is represented as discrete stair steps, which distort the along-slope flow, which is far from realistic, although this effect can be mitigated when the grid spacing is very small. The *z*-level grid is simple, but the lake modelling community still uses it to simulate the two- and three-dimensional water hydrodynamics of deep lakes.

The disadvantage of this technique is the difficulty in resolving the water column equally well and equally effective in both shallow and deep regions of a basin simultaneously. Moreover, the user may sacrifice details of near-surface or deep regions.

In shallow water, turbulent mixing plays an important role in the circulation process in the entire water column. So, it is important that both the surface and bottom mixing layers be resolved correctly. The sigma-coordinate system results in a terrain-following vertical computational domain with irregular vertical spacing, but an equal number of computational points (Fig. 2b). Thin layers appear at the shallow zones and thick ones at the deep zones. It is a widely adopted method. The advantages of adopting the sigma-coordinate system are smoothing the bottom irregularities and better modelling of boundary layers [5].

The third approach is to use isopycnal coordinates, which are composed of layers of uniform density with temporally and spatially varying thickness (Fig. 3c). This approach is common for 1D lake models to allow for the tracking of stratification. This approach is rarely used and is mainly for one-dimensional models.

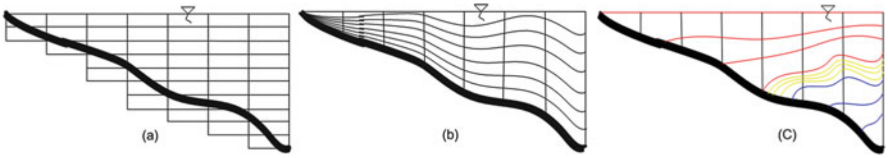


Fig. 3 Elevation view illustrated different vertical grid. (**a**) *Z*-level, (**b**) sigma coordinates, and (**c**) isopycnal coordinate – warm water in red, thermocline in yellow, and cooler hypolimnetic near the bottom in blue. Adapted from [4]

5 Review of Numerical Models

In the past four decades, the hydrodynamic and water quality models have developed from initially 1D steady-state models to sophisticated 3D unsteady models. These models are now very general and have been used to investigate hydrodynamics, pollution, sediment transport, toxins, and eutrophication. The availability of powerful, high-performance PCs and clusters has transformed the usage of three-dimensional complex models from a research area into a practical engineering field.

Numerous hydrodynamic models are available for application to coastal lakes. These include, but are not limited to, those presented below. These models are presented briefly, and the rationale is explained for choosing the most suitable one for the present Egyptian coastal lakes. The selected models are recognised as widely used and well-tested by hydrodynamic modellers and researchers.

Generally, hydrodynamic models are classified into two categories: the first are the advective–diffusive models, and the second category is based on the turbulence closure scheme [6]. The first category needs little input data, such as Minnesota Lake (MINLAKE) [7], whilst the second needs more detailed input data. The second group includes models based on a turbulence closure scheme, in which the vertical transport is related to the turbulent kinetic energy, such as DYRESM [8]. Despite this classification, models are usually organised according to their dimension as described in the following.

5.1 Availability, Dimensionality, and Capabilities

One approach for distinguishing hydrodynamic and the water quality models is based on their corresponding dimensionality [3].

5.1.1 Examples of 1D Models

Minnesota Lake

MINLAKE was developed in the early 1980s at the University of Minnesota [7]. It is a one-dimensional model, maintaining variation in the vertical direction, created to investigate lake eutrophication and proposed management scenarios. The model can simulate lake stratification and water quality changes caused by external forcing, including weather, inflow, outflow, exchange processes at the sediment interface, and in-lake processes. The dynamics of all state variables in a horizontal water layer whether dissolved or suspended can be expressed by the same one-dimensional advection–diffusion equation:

$$A\frac{\partial C}{\partial t}+\omega\frac{\partial (CA)}{\partial z}=\frac{\partial}{\partial z}\left(KA\frac{\partial C}{\partial z}\right)\pm \text{Source/Sinks}$$

where C is concentration property of the fluid; ω, vertical settling velocity of the substance (=0 for dissolved substances and temperature); z, vertical coordinate measured positively downward; K, vertical turbulent diffusion coefficient (assumed to be identical for each state variable); and A, horizontal area of the control volume. The computer model is divided into five basic sections: input, heat budget, biological-nutrient kinetics, inflow–outflow subroutines, and user-defined function. MINLAKE first solves the physical processes of heat flux, wind mixing, inflow, outflow, and conservative suspended and dissolved substances and then treats the biological processes of nutrient uptake and depletion, growth, and oxygen depletion.

DYnamic REServoir Simulation Model

DYnamic REServoir Simulation Model (DYRESM) is a 1D hydrodynamic model for predicting the vertical distribution of temperature, salinity, and density in lakes and reservoirs [8]. Imberger developed a Lagrangian model using variable grid spacing to represent the vertical distribution of the water quality parameters. Imberger built his model based on the hypothesis that the strong stratification found in small reservoirs and medium size lakes inhibits vertical motions and reduces the turbulence. So, he considered variations in the transverse and longitudinal directions to have a secondary role. The elements of the model were discussed in detail in [9]. The model is being regularly developed and used intensively in stratified aquatic environments. The model can be used for hydrodynamic studies or coupled to the Computational Aquatic Ecosystem Dynamics Model (CAEDYM) for investigations involving biological and chemical processes.

Although the work of Imberger was mainly focused in stratified fluids and its related phenomenon, he and his colleagues have played an important role in both theoretical and modelling development in the coastal engineering field since he started 30 years ago. The group has made major contributions to the understanding of the transport and mixing processes in stratified lakes, estuaries, and coastal seas. They used and developed DYRESM in several applications [10–12]. The group became interested in the internal wave and its mixing. Imberger [13] referred the vertical transport of mass, momentum, and energy to the wind and showed that most of momentum and energy which passes through the surface boundary layer and enters the interior is transferred into basin-scale internal wave motion [14]. Antenucci et al. [15] stressed for the necessity to accurately model the internal wave [16]. Hodges et al. [17] successfully modelled the internal wave of Lake Kinneret, Israel [18].

5.1.2 Examples of 2D Models

Resource Management Associates

RMA2 (Resource Management Associates) are two-dimensional depth-averaged finite element hydrodynamic and contaminant transport models. The models were developed by the US Army Corps of Engineer. The models compute water surface elevations and horizontal velocity components for subcritical, free-surface flow. It is suitable for well-mixed water bodies in which vertical accelerations are negligible (hydrostatic), and velocity vectors generally point in the same direction over the entire depth of the water column.

RMA2 uses the Reynolds-averaged form of the Navier–Stokes equations; turbulence is defined by eddy viscosity coefficients. The model can simulate wetting and drying and is therefore suited to computing hydrodynamics in tidal flats and wetlands. RMA2 and its new version, RMA4, which incorporates the 1D option beside the original 2D one, are not public domain models.

CE-QUAL-W2

CE-QUAL-W2 is water quality and hydrodynamic two-dimensional model. The model is suitable for two-dimensional applications such as rivers, estuaries, lakes, and reservoirs. The model is developed by Portland State University. The model was originally published in 1975 under the name LARM (Laterally Averaged Reservoir Mode). The model is handling eutrophication processes such as temperature-nutrient-algae-dissolved oxygen-organic matter efficiently. However, the model has some limitations, as it is not suitable for well-mixed in the lateral direction.

MIKE 21

MIKE 21 is a commercial software package for 2D modelling. The software is utilised for water hydrodynamics, waves, sediment dynamics, water quality, and ecology. The software is intensively used for various applications. It has been used in modelling of tidal flows, storm surge, advection–dispersion, oil spills, water quality, mud transport, sand transport, harbour disturbance, and wave propagation. The software has an easy interface with productive tools aimed at preparing input and interpretation as well as the presentation of results.

5.1.3 Examples of 3D Models

RMA10

RMA10 is a three-dimensional hydrodynamic and transport model (USACE-WES, 1997). RMA10 needs permission and cooperative agreement with the US Army Engineer Research and Development Centre (USACE-ERDC). The disadvantage of this model is that it does not allow users to run in parallel on multiprocessors.

TELEMAC

TELEMAC is a two-, or three-dimensional, finite-element, hydrodynamic model [19]. The model was developed by the Laboratoire National d’Hydraulique et Environnement of the company, Electricité de France (EDF). It offers extra modules for sediment transport, waves and water quality studies in rivers, estuaries, and coastal and oceanic zones. The model has the flexibility of an unstructured grid of triangular elements, which can be easily refined in areas of special interest. The model is not public domain.

H3D

H3D is a three-dimensional, finite-difference, hydrodynamic, and transport model based on a model called GF8 [20]. The model features extra modules, which are used to simulate sediment and pollution transport, and sediment settling processes. The model solves for the three velocity components and scalar quantities, such as temperature, salinity, and water level. The model is fully unsteady so that it responds to time-varying river inputs, wind stress and salinity, and water level forcing. The model is subject to limited distribution and has not been tested extensively within the oceanography community. Moreover, model documentation is limited.

Regional Ocean Modelling System

ROM is a three-dimensional, finite-difference, free-surface, terrain-following ocean model. The model solves the Reynolds-averaged Navier–Stokes equations using the hydrostatic and Boussinesq assumptions. The model uses Cartesian or orthogonal curvilinear horizontal coordinates and sigma vertical coordinates. Initially, the model was based on the S-coordinate Rutgers University Model (SCRUM) described by Leon et al. [21]. ROMS provides several methods for turbulence closure: (1) by user-defined analytical expressions for K_H and K_M; (2) by Brunt–Väisälä frequency mixing, in which the level of mixing is determined based upon the stability frequency; and (3) by the K-profile parameterisation, (4) the Mellor–Yamada level 2.5, and (5) the Generic Length Scale methods. The model includes biological modules and is widely used in the oceanographic simulation. ROMS is widely used by the scientific community for a diverse range of applications. The model Cartesian or curvilinear horizontal grid makes the refinement in particular areas of interest computationally costly.

MIKE 3

MIKE 3 is a three-dimensional, finite-difference, and a commercial package developed and marketed by the Danish Hydraulic Institute [22]. The model simulates water hydrodynamics, cohesive sediments, water quality, and ecology in rivers, lakes, estuaries, bays, and coastal oceans. The model allows users to choose between two adopted assumptions: hydrostatic pressure and generalised sigma-coordinate transformation, and the non-hydrostatic pressure with z-level coordinate. The model includes a wide range of turbulence closures: constant eddy viscosity, Smagorinsky model, a k one-equation model, the k-ε model, and the combination between the zero equation (Smagorinsky) model for the horizontal and the k-ε model for the vertical direction. Minh Hang et al. [23] have applied MIKE 3 to study the dynamics of phytoplankton and nutrients in the Ariake Sea, west coast of Kyushu, Japan [24].

A newly developed version of MIKE 3 is MIKE 3 FM, where FM denotes flexible mesh. This new version uses finite-volume unstructured mesh techniques. Only one study has been found in the literature using MIKE 3 FM [25]. MIKE 3 FM typically applies the same assumptions and techniques used in FVCOM. The only exception is that MIKE 3 FM uses the standard k-ε, whilst FVCOM employs the Mellor and Yamada level 2.5 turbulence closure in the vertical direction. MIKE 3 source code is not open, which restricts any code development.

Estuary and Lake Computer Model

The Estuary and Lake Computer Model (ELCOM) is a three-dimensional, finite-difference hydrodynamic model employing the hydrostatic assumption and the Cartesian horizontal coordinates. The model is used for predicting the velocity, temperature, and salinity distribution in natural water bodies and allows several external environmental forcings. Hodges et al. [17] developed ELCOM in the Centre for Water Research, University of Western Australia, as a 3D version of the legendary DYRESM model under the direct supervision of Imberger. The model is intensively used in stratified lakes and reservoirs.

Princeton Ocean Model

POM [26] is a three-dimensional, finite-difference, sigma-coordinate, free-surface ocean model. The model includes turbulence closure sub-model and uses curvilinear orthogonal geometry. The finite differences consist of external and internal modes solved using two split time steps technique. In the early 1990s, POM became one of the first ocean model codes that was provided free of charge to users. It began with few users in the USA, mostly researchers. Then, the number of users increased sharply to 2,000 in 2000 and has doubled in the last 10 years. Chen et al. [27] refer the new understanding of a number of physical phenomena to POM and consider it as the first core model for coupled physical–biological modelling [28]. The model has been used extensively in modelling of lakes, estuaries, coasts, and oceans. The model has proven ability to simulate the hydrodynamics for different types of water bodies. The need for modelling sediment processes in the second phase of the current study restricted its use, since it does not have a sediment transport model.

Environmental Fluid Dynamics Code

Environmental Fluid Dynamics Code (EFDC) is a three-dimensional, finite-difference, curvilinear grid, hydrodynamic model, water quality, and sediment transport model developed by Hamrick in [29]. The model can simulate the hydrodynamics of rivers, lakes, reservoirs, wetlands, estuaries, and coastal oceans. The model is maintained by Tetra Tech Inc. and is supported by the US Environmental Protection Agency (EPA). The computational schemes implemented in EFDC model are equivalent to those used in POM. The model uses Cartesian or curvilinear–orthogonal horizontal coordinates and vertical sigma coordinates and implements the modified Mellor and Yamada level 2.5 version of Shilton [30], the turbulence closure scheme. EFDC is capable of simulating cohesive and non-cohesive sediment transport, discharge dilution from multiple sources, eutrophication processes, the toxic contaminant transport in the water and sediment phases, fate and the transport of various life stages of finfish and shellfish [31]. Although the hydrodynamic model is used intensively within the oceanography modelling community, especially in the USA, water quality model has not yet been fully tested.

Estuarine, Coastal and Ocean Modelling System

Estuarine, Coastal and Ocean Modelling System (ECOM-si) is three-dimensional, finite-difference, estuarine, and coastal ocean model. ECOM-si is similar to and is considered an updated version of POM, described in [26]. The model incorporates an implicit scheme developed in [32]. As in EFDC, the model uses the Mellor and Yamada turbulence closure model, and the semi-implicit external and implicit internal mode solutions. ECOM-si allows the use of Cartesian or orthogonal curvilinear grids in the horizontal direction and is based on the sigma-coordinate system in the vertical, making it suitable for coastal applications. It can simulate rivers, lakes, reservoirs, and coastal ocean. ECOM-si can use larger time step than POM for the same model problem. In the second half of the 1990s, ECOM-si was the most advanced coastal ocean model that was widely used by the scientists in the coastal community. The ECOM-si code is not optimised for parallel computing.

Finite Volume Coastal Ocean Model
FVCOM is a three-dimensional, finite-volume, unstructured grid, coastal ocean model [33, 34]. FVCOM includes biological and water quality sub-models. A simple three-dimensional sediment suspension and tracer tracking model with settling, sedimentation, and resuspension processes is included. The model uses unstructured grids in the horizontal direction, a number of layers for the vertical direction, and implements the Mellor–Yamada 2.5 level [30], for parameterisation of vertical eddy viscosity. The model is a new promising model that has become well-supported in the international research community since being launched in 2003. FVCOM uses non-overlapping unstructured triangular meshes. The triangle is composed of three nodes, a centroid and three sides. All scalar quantities, such as salinity, temperature, density, etc., are stored in the nodes. However, the two horizontal velocity components are stored at the centroid. The triangle-based horizontal grid allows FVCOM to have much more flexibility to represent the complex coastline and bathymetry of coastal regions. Also, a refined grid can be used in areas of special interest, without affecting the rest of the grid. Practically, it is easier to set up a model run with FVCOM, due to a more modular design and configuration. There is also less manual involvement and therefore less chance for error. The model has been used to simulate the water circulation and transport process in many different water body types, i.e. estuarine, coastal waters, and open oceans. The tidal flushing in Mount Hope Bay and Narragansett Bay can be considered as a good application to examine FVCOM reliability. The model shows high accuracy in capturing the complex physics of the bay [35]. Chen et al. [26] illustrate the accuracy of finite-volume techniques over finite-difference techniques [36]. POM and ECOM-si were chosen to represent the models, which use the finite-difference method. These two models were widely used in the past 20 years and have a good reputation in the oceanography community. The comparison shows that the finite-volume method used in FVCOM provides more accurate simulation than the two finite-difference models in cases with complex geometry and steep bottom slope.

In general, the flexibility of the unstructured triangular grid in approximating the complex coastal water domain makes FVCOM more suitable for use in coastal regions with irregular geometry. FVCOM model predicted the results when compared to the results of ROM model that demonstrate the ability of FVCOM to easily make local grid refinements. FVCOM shows better ability to achieve higher numerical accuracy accompanied with higher computational efficiency when local grid refinement is applied [37]. This merit is what the modelling community was seeking and may be considered as the most recent state of the art.

FVCOM is like POM composed of external and internal mode time steps. However, the distinct advantage of FVCOM over other models is that FVCOM is numerically solved in the integral form. This ensures that the total mass is conserved in the individual cells of the grid as well as over the whole computational domain.

POM, ECOM-si, and EFDC have the same hydrodynamic solvers and use sigma coordinate in the vertical and curvilinear grid in the horizontal. FVCOM is advantageous over those models, because of unstructured horizontal grids, multiple turbulence closure schemes, the fact that it runs in parallel, and because it is an open community ocean model with support by the UMassD/WHOL development team.

6 Model Selection

Candidate Models

Following the model reviews presented earlier, Ji [1] considered that the correct selection for the most suitable model is the first step in the modelling application. Although a variety of models are available, which are capable of meeting most of the Egyptian coastal lakes objectives, if not all, electing the model that best matches our objectives is a major decision. The suitable candidate models should meet at least one of the following requirements:

- The model has capabilities for simulating hydrodynamics, water quality, and transport processes.
- The model is available as open source and documented through manuals, publications, and user guides.
- There should be an availability of appropriate data and technical expertise.

6.1 Model Evaluation

Four essential requirements for the software were identified:

1. 3D hydrodynamics, so that the spatial distribution of the field variables could be resolved over the entire lake. Included in this requirement is the ability of the software to include turbulent mixing in the vertical direction.
2. Wetting and drying module is necessary for the Egyptian coastal lakes.
3. A water quality module, so that the effects of salinity and pollutants can be modelled during the calibration of the lake model and subsequent investigations into different water management scenarios.

4. The software should be freely available at a minimum and open source as a bonus.

Two further desirable requirements were identified:

1. Graphical pre- and post-processing software should be freely available. This should include mesh generation, boundary condition identification on the pre-processing side and contour, vector, and *xy* plotting functionality on the post-processing side.
2. The software should come with up-to-date and reliable documentation and support. It was feared, however, that this would be in contradiction of the fourth essential requirement.

An overview of the candidate models is presented in Table 1.

With reference to Table 2, the following classification were used:

● Two points in the essential and one in the desired

O One point in the essential and half point for the desired

○ zero point

Two points were awarded for every essential criterion met and one point for each desirable feature. If the model is deemed to only partially fulfil one of the criteria, half marks were awarded. Using this scoring system, it boiled down to four models. These models are FVCOM, POM, ROM, and RAM10. To give an example of how to utilise one of these models, FVCOM was chosen to conduct a numerical study for one of the Egyptian coastal lakes, Lake Bardawil. FVCOM has two major advantages when compared with the remaining models. It uses an unstructured grid to represent the horizontal domain, allowing a better fit to the curvature of the coastline and the complex geometry of the water body. Moreover, it is a finite-volume, public domain, fully open-source code model.

7 Historical Overview of Lake Modelling

7.1 *Previous Modelling Effort in Lakes*

Improvements in numerical algorithms and computer processing power have increased the reliability and use of advanced hydrodynamic models. These include advances in water quality, sedimentation, and ecological sub-models. The driver behind these advances is that increasing water pollution and eutrophication have been considered to be the major problems facing lakes. To solve these problems, hydrodynamic models coupled to one or more sub-models were introduced.

Meselhe in [15] used H3D to predict the water level variation and salinity fluctuation in the Brown Lake of the Calcasieu–Sabine basin. Their model was based on the one used successfully [38] to simulate the hydrodynamics of the Calcasieu–Sabine estuary. The new model was validated and calibrated against the observed water levels and salinity data. The comparison showed good agreement

Table 1 Candidate models overview

	Model name	Hydrodynamic model	Assumption	Grid	Water quality module	Study area	Source code availability	Types of platforms
1	RAM10	RAM10	F-Element	Sigma	CE-QUAL-ICM	Rivers	Yes	PC or Unix
2	TELEMAC	TELEMAC	F-Element	Sigma	Del WAQ	Lakes, reservoirs, wetlands, and estuaries	No	Unix
3	H3D	H3D	F-Difference	Cartesian	N/A	Lake	Yes	Unix
4	ROM	POM	F-Difference	Cartesian or orth. curvilinear	ROM wq	Ocean, lakes	Yes	PC or Unix
5	MIKE 3	DELFT-Flow	F-Difference	Sigma	MIKE ECO LAB	Estuary and lakes	No	PC or Unix
6	EFDC	EFDC	F-Difference	Curvilinear	WASP	Lakes, reservoirs, wetlands, and estuaries	Yes	PC or Unix
7	ELECOM	ELECOM	F-Difference	Cartesian	No	Lakes	Yes	Unix
8	POM	POM	F-Difference	Sigma	Modified WASP5	Ocean	Yes	PC or Unix
9	ECOM-se	POM	F-Difference	Cartesian or orth. curvilinear	Modified WASp5	Estuarine	No	PC or Unix
10	FVCOM	FVCOM	F-Volume	Unstructured	NPZD	Lakes, wetlands, and coastal	Yes	PC or Unix

Table 2 Preliminary evaluation results

	Essential req.				Desirable req.		
Model	3D	WD	WQ	OP	PP	DT	Degree of suitability
RAM10	●	●	●	●	**O**	●	Perfect
H3D	●	●	●	●	**O**	**O**	Mostly suitable
TELEMAC	●	●	●	**O**	●	**O**	Mostly suitable
ROM	●	●	●	●	**O**	●	Perfect
MIKE 3	●	●	●	○	●	●	Suitable
EFDC	●	●	●	●	**O**	**O**	Mostly suitable
ELECOM	●	●	○	●	**O**	●	Less suitable
POM	●	●	●	●	**O**	●	Perfect
ECOM-si	●	●	●	○	●	●	Suitable
FVCOM	●	●	●	●	**O**	●	Perfect

Model selection criteria and evaluation, where *3D* 3D hydrodynamics, *WD* wetting and drying, *WQ* water quality/transport module, *OP* open-source code, *PP* pre-/post-process, *DT* documentation and technical support

between the model's predicted results and the observed data. The validated model has been used to investigate the wetland response to a proposed reduction of tidal fluctuation, flooding duration, and salinity level. Antenucci et al. [15] applied the H3D model to access the impact of the proposed "West Pointe a la Hache Outfall Management Project" in Barataria Basin. The project's primary objective was to reduce the wetland loss rate by enhancing the sediment and nutrients distribution and to reduce the saltwater inflows to the basin through a new hydraulic structure. The model again showed good agreement between results and field data for both water levels and salinity. However, the authors did not give explanations for the deviations existing between model results and field measurements during some periods of the simulation. The model was validated with two additional datasets which contributed to the model reliability, and then the proposed scenarios were conducted. Marques et al. [39] simulated different oil spill scenarios then recommended better tactics and strategies response. They concluded that oil spill recovery could be improved by adequate assets, a quick, timely response, and access to good environmental and spill information.

A two-dimensional vertically averaged flow model has been already discussed as the most suitable technique for shallow lakes if computational resources are limited. Jin et al. [40] used a two-dimensional vertically averaged model to investigate the effect of the wind on the circulation in a shallow lake. They used the model to simulate the water circulation for Lake Belau, Germany. They illustrated that lake flow field is dramatically changed if a spatial variation of wind was applied. The predicted simulation showed two gyres when a constant wind was applied. However, a single gyre was formed when varying wind was applied which is in good agreement with the field measurements.

Jozsa is a well-known name in the field and is a specialist in modelling wind-induced flow and sediment transport in shallow lakes. Like most of the shallow lake modellers, he used models with a fixed rectangular grid in the horizontal plane.

However, as previously illustrated this technique is highly inaccurate and computationally costly if there is interest in a particular area. To overcome this disadvantage under his supervision, quadtree grid technique was introduced in [41]. This technique was applied to simulate the water circulation of a large shallow lake, Lake Balaton, Hungary. The lake dimension is nearly 80 km long, 10 km wide, and 3 m deep on average. The two-dimensional depth-averaged model was simplified with the following assumptions: the water is incompressible, isothermal, and isotropic. The predicted results illustrate the potential technique ability to capture the water circulation with reasonably low computational cost. Quadtree grid techniques associated with dynamic mesh adaption were used to investigate the wind induced in Lake Neusiedl, Hungary [42]. The velocity gradient was used to determine the level of mesh adaptation. The results indicate an improvement in the model accuracy compared with fixed coarser mesh.

Podsetchine and Huttula [12] simulated the thermal dynamics of Lake Kinneret with a newer version of DYRESM. Despite the fact that the newer version predicted better results, than the older one, the authors reported that the seasonal variation in light extinction due to the phytoplankton population was not modelled. The results of this study were used as the driver for an extended water quality study [43]. They estimated the impact of changes in nutrients loading on the Lake Kinneret ecosystem. Similar studies were conducted by Romero and colleagues [44]. They investigated the water quality response to physical events, such as flooding or desertification using the 3D hydrodynamic model ELCOM, instead of the 1D model DYRESM. Yang et al. [45] checked the ability of ELCOM–CAEDYM to reproduce the oxygen cycle and related biogeochemical variables, to access the nutrient management in a stratified lake, Lake Erie. Following the recent trend in using 3D hydrodynamic models for all types of waters, even shallow lakes, ELCOM–CAEDYM in combination were implemented to simulate the water quality parameters of a shallow lake, Lake Minnetonka [46].

Haralampides et al. [47] applied ECOM-si to investigate the low DO concentration that had been observed in the Satilla River estuary by developing a 3D physical and water quality model. The predicted results did not capture the spatial structure correctly. Hence, the necessity for a better modelling approach was identified. However, Chen [48] successfully modelled the estuary hydrodynamics accurately. The model captures the estuary currents correctly, although at great computational cost, which is essential for coastal engineering studies. The comparison between the predicted results of two different models for the same case gives the opportunity to evaluate their performance fairly.

Liu and Huang [36] used FVCOM to investigate the hydrodynamics of the same case study, Satilla River estuary. The comparison between the results of both models indicates the better accuracy of FVCOM over ECOM-si.

Lakes exert considerable influence on regional climate systems and vice versa. To account for the effect of the lake, which is known to have large seasonal lags in temperature and fluxes compared to other landscape types, the Canadian Foundation for Climate and Atmospheric Science tried to find a suitable hydrodynamic model to couple with the Canadian Regional Climate Model (CRCM). Leon in [49] developed the 3D hydrodynamic model, ELCOM, to simulate the hydrodynamics of the Great Slave Lake. The validated model was used to evaluate the model performance, using: (a) observed data, and (b) the output of CRCM as forcing data. The comparison showed large errors in both horizontal and vertical temperature patterns. This finding highlighted the necessity of including the lake's behaviour in regional climate models.

There were limited trials to use commercial packages to investigate the 3D flow structure. These studies mainly focused on studying the 3D flow structure of wastewater stabilisation ponds based on their hydrodynamic features [50–52]. Many of these studies were aimed at improving the short-circuiting stagnation and improving the poor mixing in ponds or lagoons. These commercial packages are restricted in use, as these were developed for general flows. Therefore, they may be not suitable for shallow waters, where small aspect ratios of depth to horizontal grid resolution are found; this is computationally expensive and may lead to excessive computational time, instability, and high storage requirements. However, such limitations may be overcome in the future, as computer speed and efficiency rise sharply.

According to Fischer et al. [53], the complex ecological model of Lake Erie was constructed using CE-QUAL-W2, two-dimensional hydrodynamic and water quality model (version 2.0), developed by the US Army Corps of Engineers. They investigated the effect of dreissenid mussels on the large lake's plankton population. They found a weak relationship between the dreissenid mussels and the algae biomass growth rate. Moreover, a large amount of ammonia and phosphate excreted from the dreissenid mussels has a strong impact on algae grazing.

The developed POM model was used to simulate the water circulation and thermal structure of Lake Michigan [54]. The model accurately predicted the temperature profile at two locations. They pointed out that the model failed to simulate the temperature in the thermocline area, and the internal waves were less than those observed. They concluded that the model generated excessive vertical diffusion that resulted in a smaller vertical temperature gradient than was measured. When they excluded the horizontal diffusion for the simulation, no improvement in the results was observed. Imberger [13] integrated POM model with a 1D biological model. This model showed that stratification was controlling the phytoplankton growth and distribution. In early summer, the phytoplankton biomass increased significantly in the subsurface layer and then decayed quickly in the mixed region. However, the small phytoplankton population subsequently grew in mid and late summer under a phosphate-limited environment and then fell rapidly in the autumn and winter. Another interesting finding was that of Fischer et al. [53]. They addressed the relationship between the contaminant source and their resultant concentration in the water body of the lake. The model results indicated that air–water exchange and interaction between the water column and sediment are the most important processes controlling the concentration of a contaminant in the water and sediments of Lake Michigan.

Hodges et al. [17] used ROMS to study the winter wind-driven circulation in the thermally stratified Lake Kinneret, Israel. The author applied various wind regimes to investigate the lake's hydrodynamic response. A double-gyre circulation pattern was formed in response to the applied wind shear stress. The authors pointed out that a shift in the topographic wave frequency is observed if various wind forcing regimes were applied to the lake. The currents predicted by ROMS agreed well with measured data.

Salter et al. [31] used EFDC and a sediment transport model to predict the wind-induced circulation and sediment transport process in the shallow estuary of Apalachicola Bay. The author identified wind as the most important factor that drives the movement of suspended sediment, which consequently releases nutrients to the water column. The released nutrients change the water clarity [55]. The calibrated model was used by Galland et al. [55] in a probability analysis approach to assess the long-term effects of changing river inflows on the estuarine ecosystem. The probability analysis technique demonstrated its advantage in the risk assessment process to support the water resource management. This step took the developed hydrodynamic–sediment–water quality model into a new area, where mathematical modelling contributed to the selected solution. 3D hydrodynamic and water quality model for Lake Yilong, China was developed to investigate the serious eutrophication threat [16]. The model validated and calibrated with observed water surface elevation, water temperature, and nutrient and algal conditions. The authors indicated that algal bloom intensity in the lake could be significantly depressed under the vegetation restoration condition than under the condition where aquatic vegetation diminished.

Most of the studies presented addressed the necessity of lake hydrodynamic modelling to enhance understanding of the complicated interaction processes, and to improve the lake condition by coupling the lake model with other sub-models. This shows the need for these models to be linked with other climate models to improve its reliability. It was noted that commercial packages, which solve the full Navier–Stokes equation, are rare. Perhaps, the situation may change, given the development of computer processing power.

Despite the knowledge accumulated about deep lakes, shallow lake modelling has developed only over the last decade or so. Numerical modelling approaches offer a good tool to understand and describe the water circulation, mixing, etc. These can affect the water quality and transport of pollutants within a shallow water body. However, these models vary in specification, yet usually share the same principles and assumptions. The shallow lake hydrodynamic models developed are usually used in conjunction with other sub-models, i.e. sediment, water quality or eutrophication models, depending on the aims of the particular study. These auxiliary models were mainly employed to study the contaminant dynamics, and to evaluate alternative water quality management scenarios associated with nutrient removal processes and other biological processes. The complexity of water quality models, for example, also varies according to the applications and the hydrodynamic models used. The following section provides an overview of the modelling efforts during the past 10 years for shallow water hydrodynamics. In most cases, the driving forces for the flow are: shear stress imparted to the water surface by the wind, waves (radiation stress), tides, and the atmospheric pressure gradient [56]. These flows are responsible for the transport and dispersion of pollutants.

The general description of shallow water circulation is well-described using both the 2D depth-integrated approach in the horizontal plane, where the length scale of the vertical direction is much smaller than the horizontal, and 3D models. The 3D modelling approach is always preferable if interest is focused on the vertical circulation.

The TELEMAC3D model was used to investigate the dynamics of the Patos Lagoon plume [57]. The predicted results showed that the amount of freshwater is the primary physical forcing mechanism controlling the plume formation. Also, the wind also played a role in controlling the behaviour of the plume. The Coriolis effect and tide effects were responsible for the northward transport over the shelf, and the vertical and horizontal mixing, respectively.

DHI [58] developed the EFDC 3D model to compute the water surface elevation, horizontal velocities, and temperature for the large (1,730 km^2) shallow (mean depth 2.7 m) Lake Okeechobee. The model included heat transport and long-wave radiation. The results were improved after adding the wind-induced wave and vegetation resistance algorithms to the model. The model then correctly reproduced the water circulation trends.

The FVCOM model has been extensively tested, documented, and applied in more than a hundred modelling studies worldwide. The model has been used by universities, government agencies, and environmental consultancies and is considered to be a state-of-the-art coastal and ocean circulation model.

Applications of the FVCOM hydrodynamic model include examining the tidal dynamics in Mount Hope Bay [35]. The model captured a cyclonic eddy that was never predicted before by other coastal models. This finding highlighted the benefit of using the unstructured grid that is implemented in FVCOM. In addition, the unstructured grid was not only fine enough to capture the weak eddies but was also coarse enough in regions of low flow gradients to prevent the grid from becoming too large. The author described the horizontal resolution as a key factor in the bay hydrodynamics. Minh Hang et al. [23] benefited from the merits of the unstructured mesh and developed the first 3D model to simulate the circulation and exchange of Kinston basin and Lake Ontario. The model reproduced the water circulation accurately. The model has been used to simulate the circulation and physical processes in estuaries, to investigate wind effects on circulation and transport processes, to explain the freshwater plume dynamics on the Skagit estuary [59], to investigate nearshore restoration and the accompanying salinity intrusion [27, 60], and to investigate physical and biological interactions [61].

In each of these studies, the hydrodynamic model is used to drive other sub-models. The following is a review of some studies, in order to present how shallow lake models are developed and integrated with other models.

Lake Pontchartrain is shallow and mostly well-mixed [62]. The water circulation is mostly wind driven and was investigated several times using different types of models. In Mellor and Yamada [62], EFDC model was used to simulate the hydrodynamic and transport processes in Lake Pontchartrain. The author related the errors in the predicted contaminant concentration results in the model's numerical diffusion. The unstructured grid employed in the study required excessive computational run time.

Following the first attempts to simulate the water circulation of Lake Okeechobee with an EFDC model, described by DHI [58]. Jin in his work [63] presented a development of the original model, named the Lake Okeechobee Environmental Model (LOEM). The model's initial results indicated that sediment was resuspended primarily by wind–wave action and then transported by lake circulation. The addition of a bottom shear stress induced by the wind was added to the model, which improved the predictions. The new results were better and proved the model's ability to be used as a management tool. The LEOM model was used to investigate the lake response to different nutrient management scenarios [64]. The final step towards the ultimate goal of developing a 3D hydrodynamic–sediment–water quality model was achieved by adding a water quality module [65]. 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.

Chung et al. [66] 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 [11, 67]. 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. The approach used in [65] and that presented here may lead to the importance of integrating a full model, including both water quality and the sediment resuspension models, which would yield better results than if these were investigated separately.

8 Conclusions and Recommendations

The overall conclusion from the review presented is that integrated, sophisticated 3D hydrodynamic models for shallow lakes, coupled with sedimentation, water quality, and ecological models have been developed over the last 5 years. This may be attributed to the development of powerful, yet affordable, computers, in combination with fast numerical algorithms, which had previously limited shallow lakes hydrodynamic modelling from three dimensions to two dimensions. The review for shallow lake modelling indicates that most of the studies conducted and discussed in this section involve the modelling of lake hydrodynamics, sedimentation, and water quality management. This review revealed that different approaches were adopted for the different applications. Although many models for the hydrodynamics of shallow lakes were reported in the literature, the top suitable models for the Egyptian coastal lakes are FVCOM, MIKE 3D, POM, and ROM in our opinion. It is worth mentioning that the launch of the Delft3D Flexible Mesh Suite 2016 (Delft3D FM) took place during the Delft Software Days (DSD-INT 2015) presented a new valuable tool worth to be considered.

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Hydrodynamic and Water Quality Modeling of Lake Mariout (Nile Delta, Northern Egypt)

Naglaa A. El-Naggar and Ahmed E. Rifaat

Abstract Egyptian coastal lakes, which represent about 25% of the Mediterranean total wetlands, are not only one of the most valuable ecosystems in the world but also some of the most threatened as they receive the wastewater discharged from the watershed. Lake Mariout was one of the most important shallow coastal lakes north of the Nile Delta of Egypt that produces between 50 and 70% of the total fish production of the coastal lakes, but it was widely used to drain industrial wastes, sewage, and agriculture drainage. As a consequence of the environmental degradation, it has changed from being the most productive fishery resource of the four major Egyptian brackish water lakes to the least productive in a couple of decades. Over the past few years, water quality and hydrodynamic modeling of lakes, lagoons, and rivers has become an important tool for managing water resources, especially in modeling the dispersion of pollutants. The objective of the study is to build a hydrodynamic and water quality model of Lake Mariout, to show the current status of the lake which is subject to pollution from the agricultural drains and the point sources discharging directly to the lake. That objective is achieved through simulating the flow circulation inside the main basin of the lake and the transport and advection of the pollutants and then identifies and develops the most critical surface drainage water quality indicators to simulate and predict the temporal and spatial variation of pollution. The model proved to be an effective tool for the water dynamics, water quality simulation, and evaluating different scenarios of such shallow lake.

Keywords Coastal lakes, Egypt, Hydrodynamic modeling, Lake Mariout, Water quality

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Contents

1 Introduction

Over the past few years, hydrodynamic and water quality modeling of lakes, lagoons, and rivers has become an important tool for managing water resources, especially in modeling the dispersion of pollutants and morphological analysis [1]. Mathematical modeling of lakes' water quality started to receive high attention in the 1960s. According to [2], mathematical models of lakes have evolved along two different lines. First, there was the extension of the zero-dimensional model to one-, two-, and three-dimensional models. Then, there were the modeling activities that focused primarily on a better and more detailed description of the chemical and biological processes [3]. "Several physical factors combine to make the coastal systems complex and unique in their hydrodynamics, and the associated physical transport and dispersal processes of the coastal flow field are equally complex" [4].

Shallow lakes have recently received enhanced attention all over the world. Their unique value and multipurpose utility have been more and more recognized, which has led then to misusing a number of them, thus worsening their ecological state even to an alarming extent at places. Furthermore, the recent changes in the global climate or, at least the fact that extremes seem to grow, changed also the boundary conditions for these vulnerable water bodies [5].

From the survey of the literature, many lake models have been applied in various regions, and as a result of several applications, models have become more and more complex. Some studies recently discussed the hydrodynamics of the coastal lakes in Egypt [6–10]. For example, Donia designed a model to simulate the hydrodynamic and water quality of Lake Mariout using Delft 3D [6, 7]; also, El-Adawy et al. [8] developed the hydrodynamics and flow patterns in Lake El-Burullus. Moreover, El-Naggar et al. [9] implemented a hydrodynamic water flow model within Lake El-Manzala using AQUASEA, while Bek and Lowndes [10] applied the ocean model (FVCOM). However, Amel developed 2D hydrodynamic, water quality and eutrophication screening models for the Edku Lake [11]. Modeling of hydrodynamics and water quality in lakes involves the representations of hydrodynamic behavior of the lake, effluent quality, mixing pattern, and physical, chemical, and biological processes.

Applying a hydrodynamic and water quality numerical modeling at Lake Mariout will help to give some answers to both planning and technical questions of water quality managers, decision-makers, and technical engineers working on the sampling, monitoring, and analysis of water quality parameters.

The objective of this chapter is to illustrate the technique of building a hydrodynamic and water quality model as an application on Lake Mariout.

The objectives of the hydrodynamic and water quality numerical model study can be summarized as follows:

1. Studying the current status of Lake Mariout using the available data and simulating the hydrodynamic flow within the main basin of the lake that is subjected to discharges from the agricultural drains and the other input sources
2. Investigating the flow circulation inside the main basin and its effect in minimizing the negative impacts on the water quality of the lake
3. Investigating the transport and advection of the pollutants due to the effluent discharges from drains and other sources of pollutants to simulate the pollutant dispersion process within the lake domain
4. Simulating and predicting the temporal and spatial variation of pollution by identifying the most critical surface water quality indicators
5. Calibrating and validating the hydrodynamic model over the range of conditions typically experienced seasonally in 1 year
6. Examining potential scenarios by decreasing the pollutant loads entering the lake, to improve the institutional mechanisms for sustainable coastal zone management in Alexandria, in particular, and to reduce land-based pollution to the Mediterranean Sea

2 Lake Mariout

The Egyptian northern Nile Delta lakes adjacent to the Mediterranean Sea are the principal depository for Nile drainage and wastes before its outflow in the sea [12]. They are Edku, Burullus, Manzala, and Lake Mariout. They are economically the most important fishing ground, and they provide a rich and vital habitat for estuarine and marine fish and their regeneration. Moreover, they have always been major areas of fish production in Egypt, since more than 75% of the Egyptian lake production are harvesting from them [13, 14]. Lake Mariout is one of the four shallow lakes in the northern Nile Delta of Egypt. It is the smallest and most polluted of these lakes. It is situated along the Mediterranean coast of Egypt south of Alexandria city between latitude 31°07′ N and longitude 29°57′ E. It has a surface area of 60 km^2 and ranges in depth from 1 to 3 m. The lake has no direct connection to the sea, and its surface is maintained at 2.8 m below mean sea level by pumping water from the lake to the sea at El-Mex Bay [15]. The lake environment was continuously subjected to quality degradation due to human pressure as well as land reclamation reducing the area of the lake over the years.

Over the last 65 years, the lake has lost approximately 71% of its area, decreasing from 59,000 feddans in 1935 to about 15,000–17,000 feddans today [16]. From the 1940s to 1960s, land reclamation was mostly conducted for agriculture and series of roads, and drainage and navigation canals were constructed. As a result, the lake is currently subdivided into four basins, namely, 6,000 feddans basin (main basin), 5,000 feddans basin (south basin), 3,000 feddans basin (west basin), and 1,000 feddans basin (aquaculture basin) [17], as shown in Fig. 1a.

- *The southern basin* covers 33.77 km^2 and is partially divided by El-Noubariyah canal. Breaks in the canal embankments allow water to pass from one subbasin to the other. The basin is very shallow, and the average water depth is 0.68 m. The main sources of water are El-Omoum drain and El-Noubariyah canal. Along the length of the El-Omoum, a series of breaches allow flow to leave the drain and enter the basin. Along the western boundary, a series of breaches allow the exchange of water between the basin and El-Noubariyah canal. The basin consists of heavily vegetated areas and fish farms. Also, considerable wetland loss in this portion of the basin was recorded. Many petrochemical and petroleum companies, such as Amria and Misr Petroleum companies, are discharging their wastes into the north part of the basin [7].

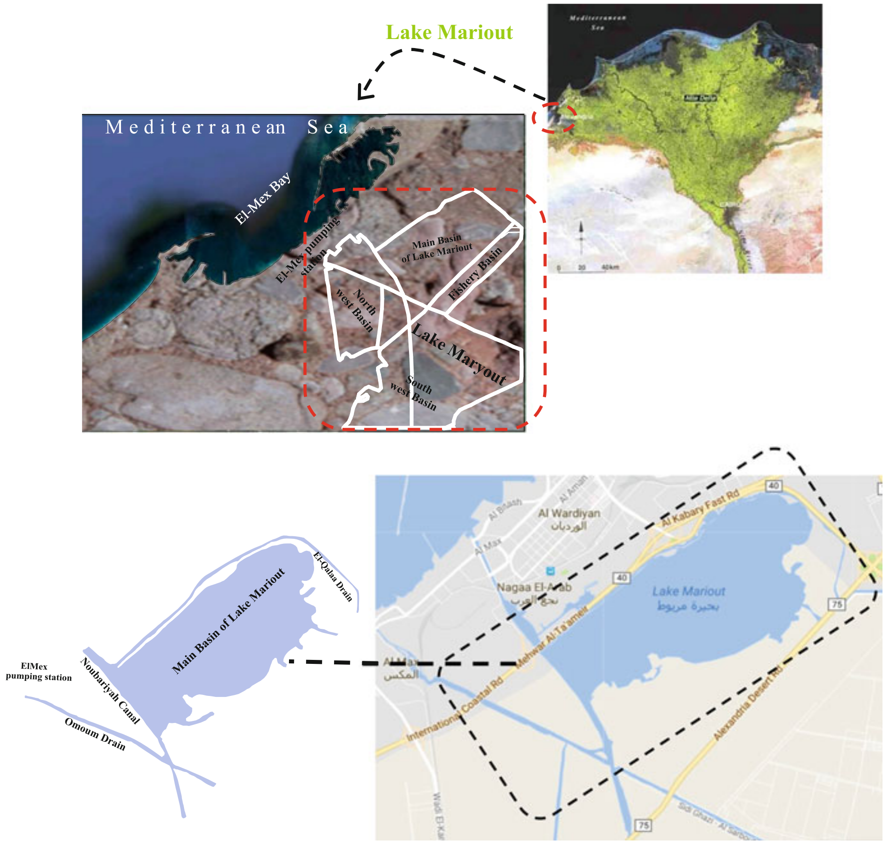

Fig. 1 (**a**) Lake Mariout map [7] (**b**) the location and layout of the main basin of Lake Mariout

- *The western basin* is about 11.59 km^2. The average water depth is about 0.7 m. Adjacent to this basin, salt marshes are located and are producing 1,000,000 kg of unrefined salt per year. They are surrounded by many industrial and petrochemical companies.
- *Aquaculture basin* (fisheries) covers 9.44 km^2 (849 feddans). It consists of a series of small basins which are separated by earthen berms. This facility acts as a research center for fish farming and is operated by the 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 openings from El-Omoum drain.
- *The main basin* is about 14.77 km^2. The average depth of water is about 0.8 m. This basin, since 1993, receives water from El-Noubariyah canal, El-Omoum, and El-Qalaa drain. El-Qalaa drain is heavily polluted water by industrial wastes and untreated sewage from municipal and industrial outfalls [18]. West wastewater treatment plant (WWTP) effluent is 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. The main basin is bisected by the El-Noubariyah canal, and the triangular area between this canal and El-Omoum drain that is considered as part of the main basin, which holds a huge amount of wastewater in the delta and El-Noubariyah canal which supplies the west of Nile Delta by irrigation water [19]. In general, El-Omoum drain and El-Noubariyah canals are less polluted drains; El-Qalaa drain is considered the major source of pollution in the lake [20]. Therefore, the main basin is the heavily polluted part of the lake, as it receives most of its water from heavily polluted drains. Most recently, the main basin (6,000 feddans), which fishermen regard as the most productive area, was reduced to approximately 4,000 feddans as shown in Fig. 1b.

These ponds are dissected by roads and canals that have blocked the movement of water, fish, and fishermen, making each basin functions independently (Fig. 1a). As a result, each basin has unique characteristics that require specifically tailored management activities [16]. In the early 1980s, about 1,400 feddans were dried for several projects that included the sewerage facility, electricity plant, and an international park. Since then, other parts of the lake have been filled in with garbage [7].

From the above, Lake Mariout is considered a major source of pollution to the Mediterranean Sea through El-Mex Bay that receives a huge amount of polluted water from the following three major sources on a daily basis (see Fig. 2):

1. Industrial effluents where various industries discharge their effluents directly into the lake.
2. Domestic effluents: Two wastewater treatment plants discharge their primary treated effluents into the lake.
3. Drainage water from agriculture: The lake receives an important part of agricultural drainage water coming from secondary drains and agricultural activities upstream, nutrients along with organic matter from animal farming and domestic wastewater of nearby villages.

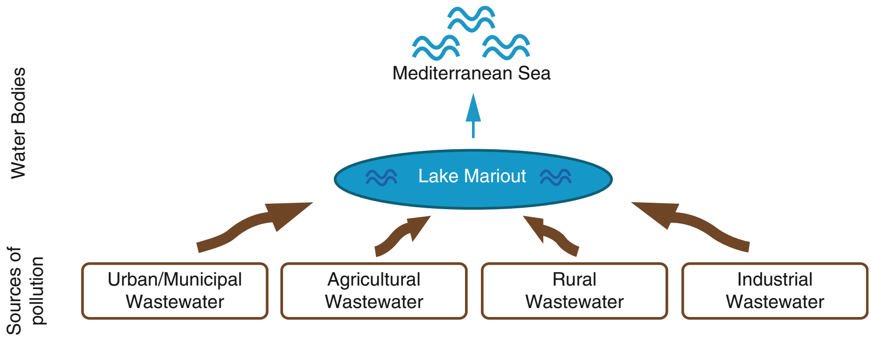

Fig. 2 Different sources of pollution of Lake Mariout [21]

"As a consequence of the environmental degradation of the lake Mariout over time, it has changed from being the most productive fisheries resource to the least productive in a couple of decades" [21].

3 Model Development

3.1 Overview of the AQUASEA Model

AQUASEA is a software package developed by Vatnaskil Consulting Engineers to solve the shallow water flow and transport equations using the Galerkin finite element method. The program was first developed in 1983 to solve two-dimensional problems, and since 1992, it has been continuously upgraded and tested in use worldwide on the most difficult modeling problems. The AQUASEA [22] model consists of the following two models:

Hydrodynamic Flow Model

The flow model can simulate water level variations and flows in response to various forcing functions in lakes, estuaries, bays, and coastal areas. The water levels and flows are approximated in a numerical finite element grid and calculated using the information on the bathymetry, bed resistance coefficients, wind field, and boundary conditions. The basic equations of flow model that are used in this study are given below as: The equation of continuity is given by Kolar et al. [23]:

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

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

As the continuity equation includes three unknown variables u, v, and h, thus two more equations are needed to complete the solution of the problem. These are given by the momentum equations in two directions [22]:

$$\frac{\partial u}{\partial x}+u\frac{\partial u}{\partial x}+v\frac{\partial u}{\partial y}=-g\frac{\partial \eta}{\partial x}+fv-\frac{g}{HC^2}\left(u^2+v^2\right)^{1/2}u+\frac{k}{H}W_x|W|-\frac{Q}{H}(u-u_0)$$
$$\frac{\partial v}{\partial t}+u\frac{\partial v}{\partial x}+v\frac{\partial v}{\partial y}=-g\frac{\partial \eta}{\partial y}+fu-\frac{g}{HC^2}\left(u^2+v^2\right)^{1/2}v+\frac{k}{H}W_y|W|-\frac{Q}{H}(v-v_0)$$

The Coriolis parameter, f, is defined as follows:

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

where ϕ is the latitude and ω is the Earth's rate of rotation equal to $7.2722 \times 10^{-5}\ \mathrm{s}^{-1}$.

The wind shear stress parameter, k, is defined as follows [22]:

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

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

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

Transport-Dispersion Model

The transport-dispersion model simulates the spreading of a substance in the environment under the influence of the fluid flow and the existing dispersion processes. The substance may be a pollutant of any kind, conservative or non-conservative, inorganic or organic salt, heat suspended sediment, dissolved oxygen, inorganic phosphorus, nitrogen, and other water quality parameters [22].

AQUASEA solves the equation for transport of mass or heat. The transport equation is given by:

$$\frac{\partial}{\partial x}\left(HD_x\frac{\partial c}{\partial x}\right)+\frac{\partial}{\partial y}\left(HD_y\frac{\partial c}{\partial x}\right)-\frac{\partial}{\partial x}(Hcu)=\frac{\partial}{\partial t}(Hc)+S-Qc_o$$

Or if we substitute it from the continuity equation:

$$\frac{\partial}{\partial x}\left(HD_x\frac{\partial c}{\partial x}\right)+\frac{\partial}{\partial y}\left(HD_y\frac{\partial c}{\partial y}\right)-Hu\frac{\partial c}{\partial x}=H\frac{\partial c}{\partial t}+S-Q(c_o-c)$$

c is concentration, excess suspended sediment or excess temperature; u is velocity within each element taken from the solution of the flow problem, ms^{-1}; D_x is longitudinal dispersion coefficient, m^2 s^{-1}; D_y is transversal dispersion coefficient, m^2 s^{-1}; H is total water depth, m; S is the mass flux term in kg/m^3; Q is injected water, m^3 s^{-1}; and c_o is concentration, excess sediment concentration/temperature of the injected water.

3.2 Model Setup

Figure 3 shows the main steps in developing the hydrodynamic and water quality model.

The basic input data for the model include lake topography (bathymetry), drains' and outlets' streamflow, water quality records (physical, chemical, and biological) as well as meteorological information. Three main drains were considered as the

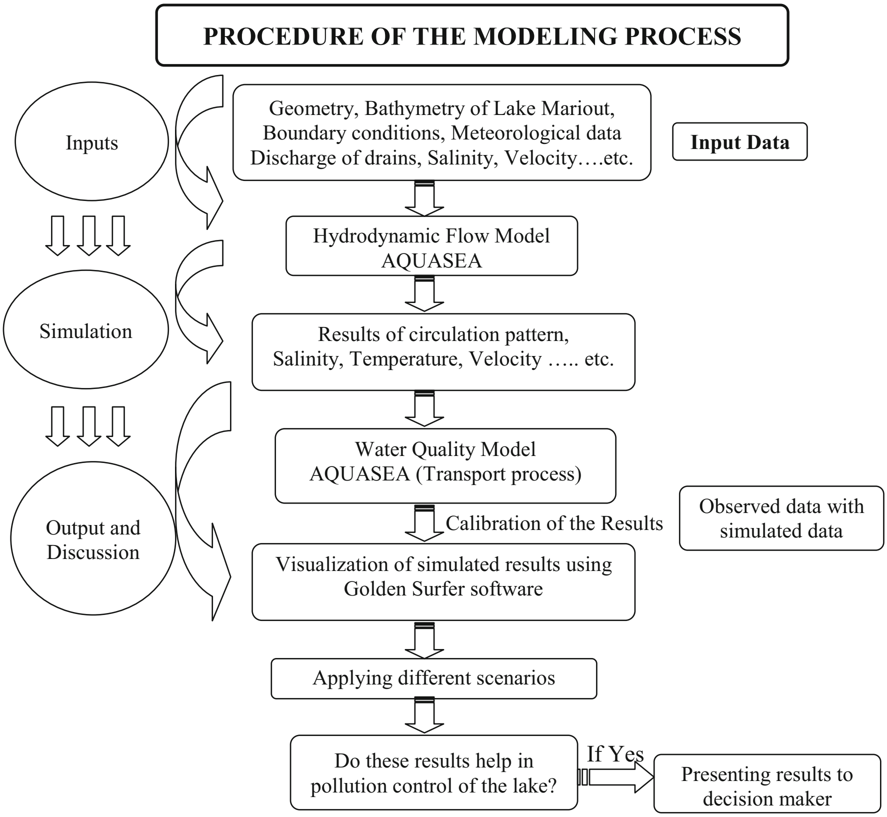

Fig. 3 Procedure of developing the hydrodynamic and water quality model

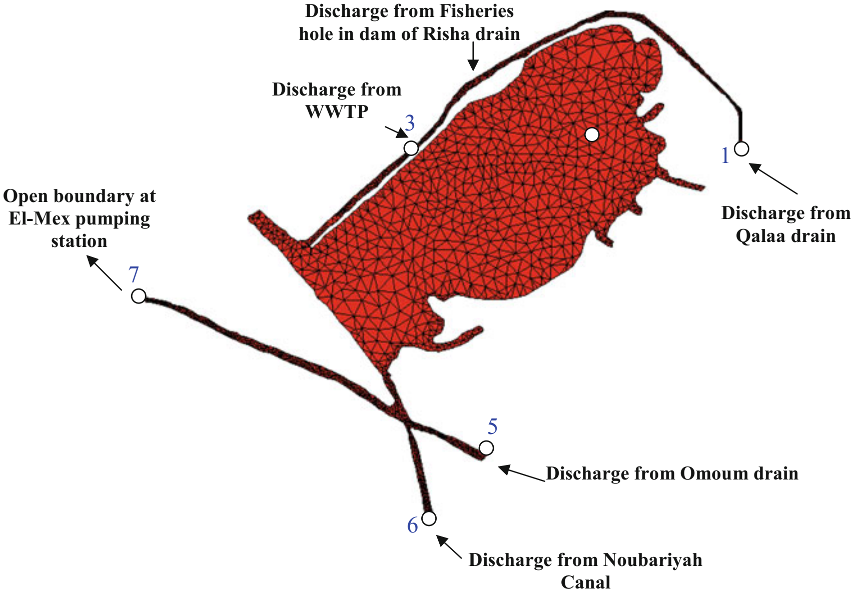

Fig. 4 Grid used in the model with different sources of discharges (the measurement stations used to validate the model are marked with a white dot)

freshwater source of the lake, according to their discharges, namely: El-Qalaa and El-Omoum drains and El-Noubariyah canal; also, west waste water treatment plant and fisheries' hole in the dam of Risha drain were simulated as source point discharge in the main basin of the lake. El-Mex pumping station is selected as an open boundary to El-Mex Bay (Fig. 4). The following sections present the steps of development of Mariout hydrodynamic and water quality model.

3.2.1 Grid Development

The bathymetry of the main basin of Lake Mariout was designated using GEBCO Digital Atlas and DXF files, which is produced by CAD packages and contouring programs. The area of study is divided into small regions of finite elements consisting of 2,141 nodes. The mesh is generated on the triangular formation by inserting nodes manually. The mesh is composed of triangles, the edges of which are defined by model nodes. Each triangle is an element, and calculations are carried out for each element. Boundary conditions on closed internal boundaries are also generated (Fig. 4). The mesh density was also greater inner parts of the region than open external boundary (Fig. 4). The conditions defined in external boundaries are "no slip" $u = v = 0$ for solid surfaces and time-dependent values for the open external boundary. Nodes on the boundary can subsequently be assigned sine wave/fixed values. Non-zero flow boundary conditions are most readily defined by applying a source/sink on nodes at the boundary [22].

3.2.2 Defining Substances and Parameters

The setup and application of a lake model of hydrodynamics and water quality require a variety of different datasets to specify boundary or input conditions and also for model calibration and verification. The average water depth across the lake is 1.5 m; wind data of Lake Mariout during measuring days were obtained from the Internet (www.wunderground.com). Field measurements were provided by El-Shorbagi [24] during four successive cruises, summer (June) and autumn (October) 2013 and winter (January) and spring (April) 2014. The samples were taken from seven sites representing the main basin and discharge points of El-Qalaa, El-Omoum drains, El-Noubariyah canal, west waste water treatment plant, fisheries' hole in the dam of Risha drain, and El-Mex pumping station as shown in Fig. 4.

The measurements comprised the following:

- Water flows ($m^3\ s^{-1}$) which determines the inflow and outflow in the main basin
- Basic physical parameters: salinity, temperature
- Chemical parameters: dissolved oxygen, pH, and NH_4^+ of the lake

Results of field measurements of hydraulic parameters are shown in Table 1, and results of field measurements of average water quality parameters are shown in Table 2.

Table 1 Water flow measurements (June 2013–April 2014)

Location	Average water discharges ($m^3\ s^{-1}$)	Cross-sectional area (m^2)	Flow direction
El-Qalaa drain	7.67	31	10
Fisheries' hole in the dam of Risha drain	0.47	1.6	179
West waste water treatment plant	4.20	3.4	137
El-Omoum drain	40.74	97	290
El-Noubariyah canal	53.47	122	330
El-Mex pumping station	80.00	24	290

Table 2 Field measurements of water quality parameters

Station no.	Location	Salinity (‰)	*T* (°C)	DO (mg/L)	NH_4^+ (mg/L)	pH
1	El-Qalaa drain	1.8	25.0	0.0	64.6	7.26
2	Main basin 1	2.5	23.9	6.3	14.1	8.19
3	WWTP	1.9	25.1	0.0	82.4	7.4
4	Main basin 2	2.4	24.4	2.1	14.8	7.94
5	El-Omoum drain	2.5	23.8	1.9	19.2	7.73
6	El-Noubariyah canal	0.4	24.5	8.9	14.0	8.76
7	El-Mex pumping station	3.3	24.7	0.6	79.1	7.11

The input parameters were a period of sinusoidal forcing (12 h), the most common wind direction (315° NW), average wind speed (3.9 ms^{-1}), and the Chezy coefficient (57 $m^{1/2}\ s^{-1}$). Other essential required characteristics were collected from the international publications on the lake. The averaged seasonal drain inflow data were used to specify model boundary flow conditions (Table 1). According to the collected data, the lake was modeled for a typical simulation year (June 2013–April 2014). The time step was selected for the model simulations based on the grid size and the Courant number. Time step of 1 min (60 s) was used in the simulations. This time step fulfills the numerical criteria and the Courant number requirements; final time is 24 h for each day. The output of the AQUASEA application is presented using the computer application Surfer 11 from the Golden Software company.

3.2.3 Model Calibration

Four different data were used to build, calibrate, and validate the model to accurately simulate the lake water quality. All constants were calibrated by trial and error, based on these data. The model was spatially calibrated against measured salinity, pH, DO, and NH_4^+.

3.2.4 Applying Scenarios to Control Lake Pollution

The final step in the study is to test various scenarios to assess different engineering solutions to control pollution in Lake Mariout. The first set of developed scenarios involves equal reduction factors of loads coming from all drainage points to the lake. The second set of scenarios involved only the reduction of pollutants coming from El-Qalaa drain and El-Omoum drain which contributes by higher amounts of wastes to the lake water.

4 Results and Discussion

AQUASEA [22] was utilized to develop a hydrodynamic and water quality model of Lake Mariout. The hydrodynamic model simulates the flow pattern in the main basin vicinity. The velocity magnitude and direction pattern are shown in Fig. 5. The velocity vectors indicate that water movement from El-Noubariyah canal is predominantly directed toward the main basin of the lake that circulation occurs and then changes toward the outlet of El-Noubariyah canal to the western harbor direction. Inside the main basin, the velocity is low that is between 0 and 0.08 ms^{-1} and mainly affected by wind direction. Water that comes from El-Omoum drain inflows either toward the west where the main coastal outlet exists (El-Mex pumping station) or changes toward El-Noubariyah canal that enters the lake. The high velocity at the lake outlet (2.8 ms^{-1}) is due to the confluence of the various

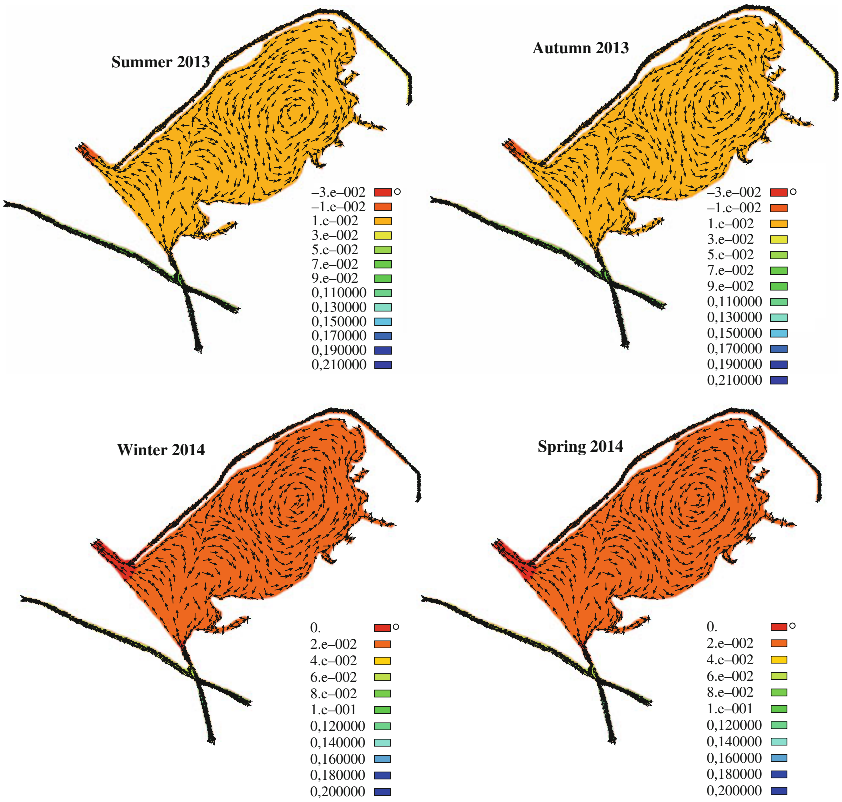

Fig. 5 The velocity magnitude and direction pattern in the main basin of the lake

exiting flows. There are different water pattern directions with time inside the main basin, while other water domains almost remain constant. It also should be noticed that the effect of drains' discharges on velocity vectors is limited to the areas near their inlets and flow velocity in the narrow El-Noubariyah canal, and El-Omoum and Qalaa drains are faster than that of inside the basin; this conforms with the physical truth of the research area. Velocities during summer, autumn, winter, and spring seasons are the same, but some differences in velocities' direction occurred (see Fig. 5).

Donia [7] designed the same model on Lake Mariout using Delft 3D program, but considered El-Noubariyah canal and El-Omoum and El-Qalaa drains as part of the main basin of the lake, and this is not correct as shown in Fig. 1a.

First, El-Qalaa drain does not enter the main basin except through an opening close to El-Noubariyah canal to the north. Second, the main basin is bisected by the El-Noubariyah canal through the triangular area between this canal and El-Omoum drain that considered as an inlet to the basin, and therefore different parents occur through it. Donia [7] neglected all these and considered that water plumes begin from drain inlets and dispersed inside the basin then carried into the outlet of El-Omoum drain (El-Mex pumping station) to El-Mex Bay.

4.1 Validation of Hydrodynamics

Four different data were used to build, calibrate, and validate the model to accurately simulate the lake's hydrodynamics. It is practiced to use salinity for hydrodynamic calibration in case of insufficient flow velocity monitoring data. As a conservative substance, salinity as is only subject to transport but, unlike decayable substances, is not subject to water quality processes. Salinity level can isolate the effect of transport and thereby help to distinguish between the effect of transport and processes for other substances. While simulating salinity, a velocity-dependent horizontal dispersion process is added as an active process.

The model calibration was carried out by visual comparison of simulations and measurements in graphs, together with the calculation of the statistical error values such as mean relative error (MRE), correlation coefficient (*r*) to examine the performance of the model. The simulated and measured salinities at the seven monitoring stations during June, October 2013 and January, and April 2014 within Lake Mariout are shown in Fig. 6. The average water salinity is varied between 0.27 and 3.47‰. The highest simulated salinities are at the station closest to the El-Mex pumping station marine connections (stations 7). Statistical analysis results for the simulated and observed values of salinity are shown in Table 3.

In general, the salinity measurements are close to the simulated results with an RME value of 6.68%, 4.25%, 8.01%, and 9.17% for June, October 2013 and

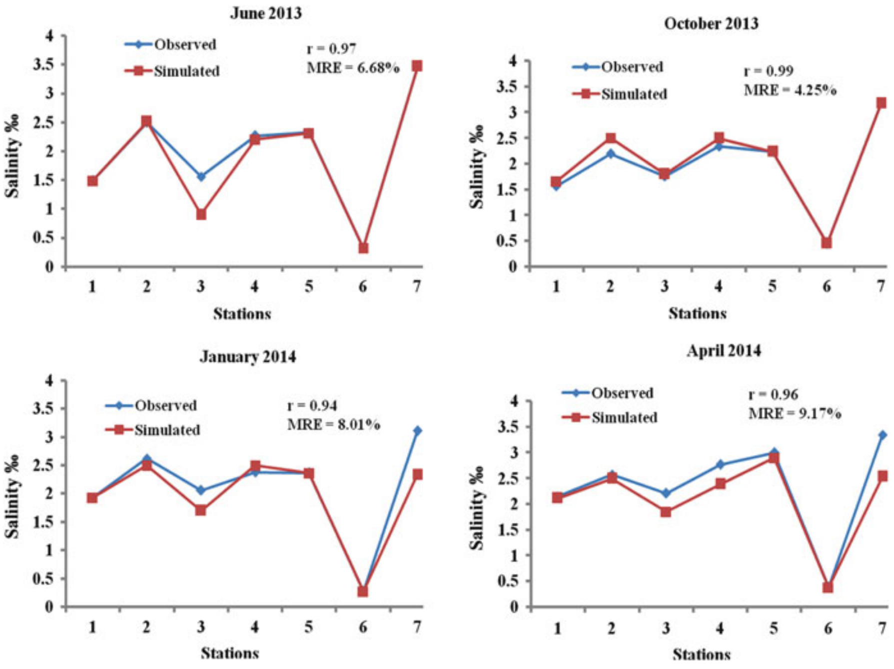

Fig. 6 Comparison between measured and modeled salinity

Table 3 Statistical analysis results for simulated and observed salinity values

Station no.	Location	Relative error (RE) (%)			
		June 2013	October 2013	January 2014	April 2014
1	El-Qalaa drain	0.26	5.73	0.00	1.40
2	Main basin 1	0.36	13.95	4.58	2.72
3	West waste water treatment plant	42.31	2.56	17.48	16.29
4	Main basin 2	3.08	6.84	5.04	13.72
5	El-Omoum drain	0.43	0.00	0.42	3.33
6	El-Noubariyah canal	0.31	0.67	3.57	2.56
7	El-Mex pumping station	0.00	0.00	24.95	24.18
Mean relative error (MRE) (%)		6.68	4.25	8.01	9.17
Correlation coefficient (r)		0.97	0.99	0.94	0.96

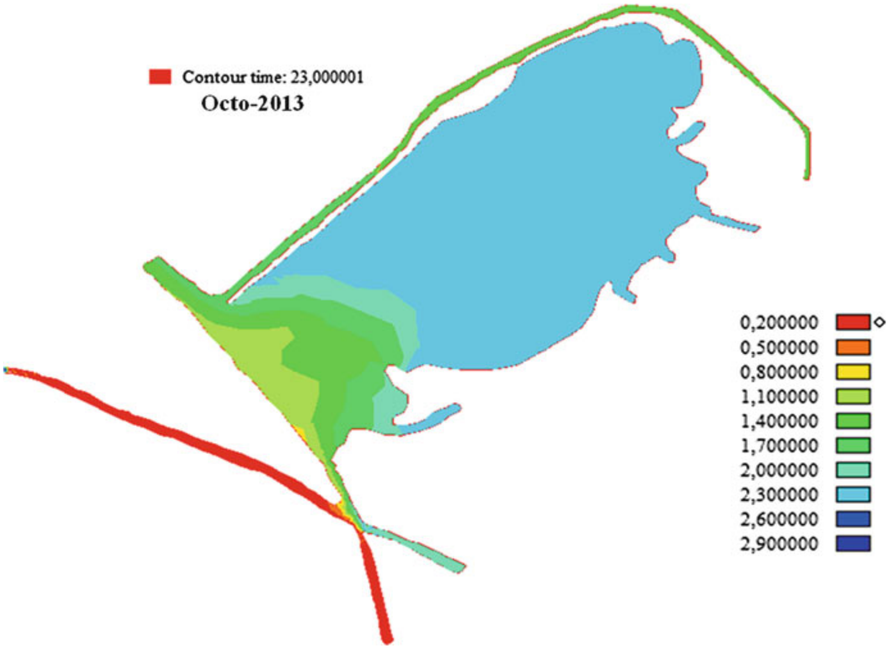

Fig. 7 Simulation of salinity in the main basin of the lake

January, and April 2014, respectively. Figure 7 shows the simulation of salinity in the lake as an example of output from the model during October 2013.

The results were in good agreement with the measurements, which confirms that the model simulates the flow pattern in the main basin of the lake in the right way.

4.2 Validation of Water Quality

Dissolved oxygen is an important and useful parameter for identification of different water masses. It has been used as basic water criteria in assessing the degree of pollution in any aquatic environment and is critical to the health of biota. The oxygen saturation level depends on water temperature, among other variables [25].

Hydrogen ion plays an important role in many life processes in the aquatic environment, where the living organisms are sensitive to pH values. It is one of the most important and frequently factor used to test water chemistry. Practically, every phase of water supply and wastewater treatment (e.g., acid-base neutralization, water softening, precipitation, coagulation, disinfection, and corrosion control) is pH dependent [26].

Figure 8 shows the simulation of dissolved oxygen and pH in Lake Mariout as an example of output from the water quality model during June 2013.

In the present study, low value of pH and complete depletion of DO were recorded in the northeast part of the main basin (El-Qalaa drain and west waste water treatment plant); and this agrees with the studies reported by Saad et al. [27]. Smith [28] pointed out that the decrease in the pH value coincides with the drop in oxygen content.

The complete depletion of DO was associated principally with the presence of high load of organic pollutants in the water of the eastern side of the main basin which in turn consumed DO during oxidation processes, in addition to the numerous adjacent animal farms which directly discharging their untreated effluent to drain [29, 30].

The opposite trend was observed at the western side of the main basin which was almost toxic especially in and near El-Noubariyah canal [29].

Water quality model calibration is done on the conventional oxygen group (DO), nutrient group (NH_4^+), and pH. The simulation results were assessed via mean relative error (MRE) and correlation coefficient (r) to examine the performance of

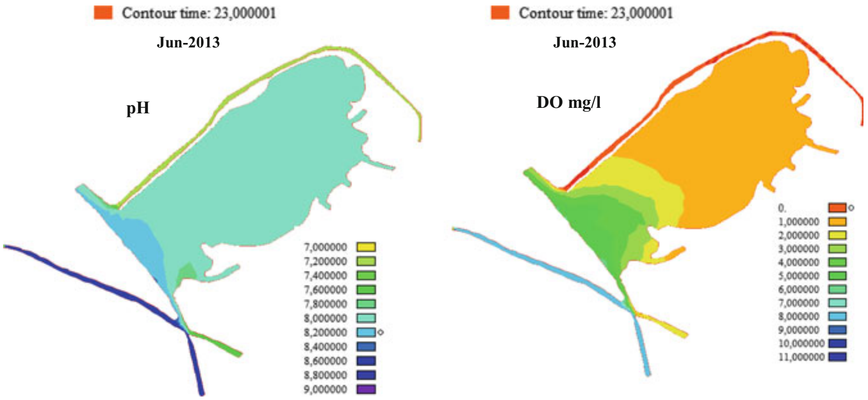

Fig. 8 Spatial distributions of simulated dissolved oxygen and pH in June 2013

Table 4 Calibration for important parameters in water quality processes

Parameters		June 2013	October 2013	January 2014	April 2014
DO	Mean relative error (MRE) (%)	1.8	8.5	14.7	9.1
	Correlation coefficient (*r*)	0.996	0.995	0.973	0.978
pH	Mean relative error (MRE) (%)	2.5	0.5	1.5	1.2
	Correlation coefficient (*r*)	0.86	0.98	0.75	0.85
NH_4^+	Mean relative error (MRE) (%)	8.7	8.2	13.5	26.5
	Correlation coefficient (*r*)	0.987	0.996	0.998	0.996

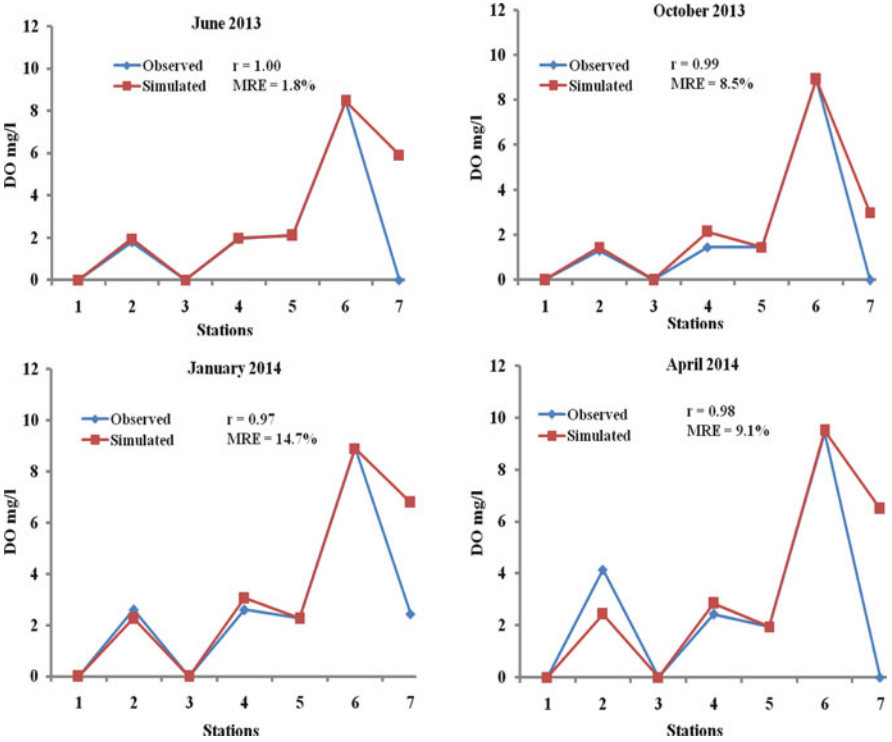

Fig. 9 Comparison between measured and modeled dissolved oxygen

the model. Table 4 presents the statistical analysis results for the simulated and observed values of DO, pH, and NH_4^+.

Figures 9 and 10 compare the measured and simulated values of DO and pH, showing low values in the area around El-Qalaa drain and high value at El-Noubariyah canal.

In general, the simulated DO and pH results are very close to the measured values at most locations within the lake, and the MRE value is around 1.8, 8.5, 14.7, and 9.1% for DO and 2.5, 0.5, 1.5, and 1.2% for pH. As a whole, variation trends of those two values are in good agreement.

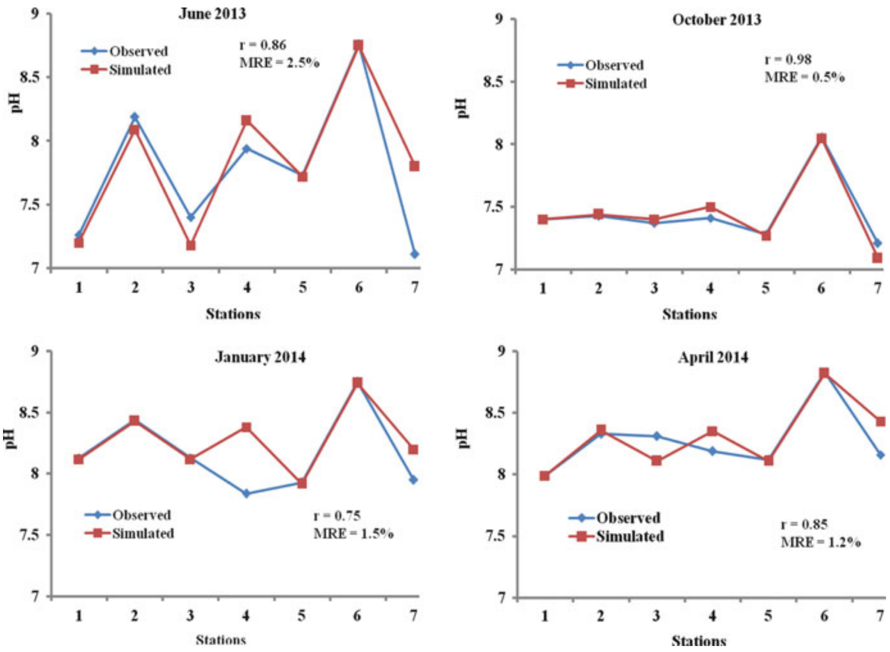

Fig. 10 Comparison between measured and modeled pH

4.3 Analysis of Model Response to Suggested Engineering Scenarios

Different model scenarios have been tested to assess the spreading and mixing of the discharge effluents and its impact on the water quality of the main basin.

4.3.1 Scenario of Load Reduction from All Drainage Points to the Lake

To reduce the pollutant loads to the lake and to prevent more deterioration of lake water quality, a set of planned scenarios for load reduction is developed and tested. Consequently, this will imply strategic planning actions to be taken at the upstream of the watershed.

The drainage points contributing to the lake pollution are El-Qalaa and El-Omoum drains, El-Noubariyah canal, west waste water treatment plant, and fisheries' hole in the dam of Risha drain, so the reduction of loads coming from these sources was investigated for pollution control. A series of scenarios were simulated in which loads to the main basin of the lake were reduced by 25, 50, and 75% at all drainage points to the lake. The comparison between all scenarios has been conducted at a monitoring station in the west part of the lake as shown in Fig. 11.

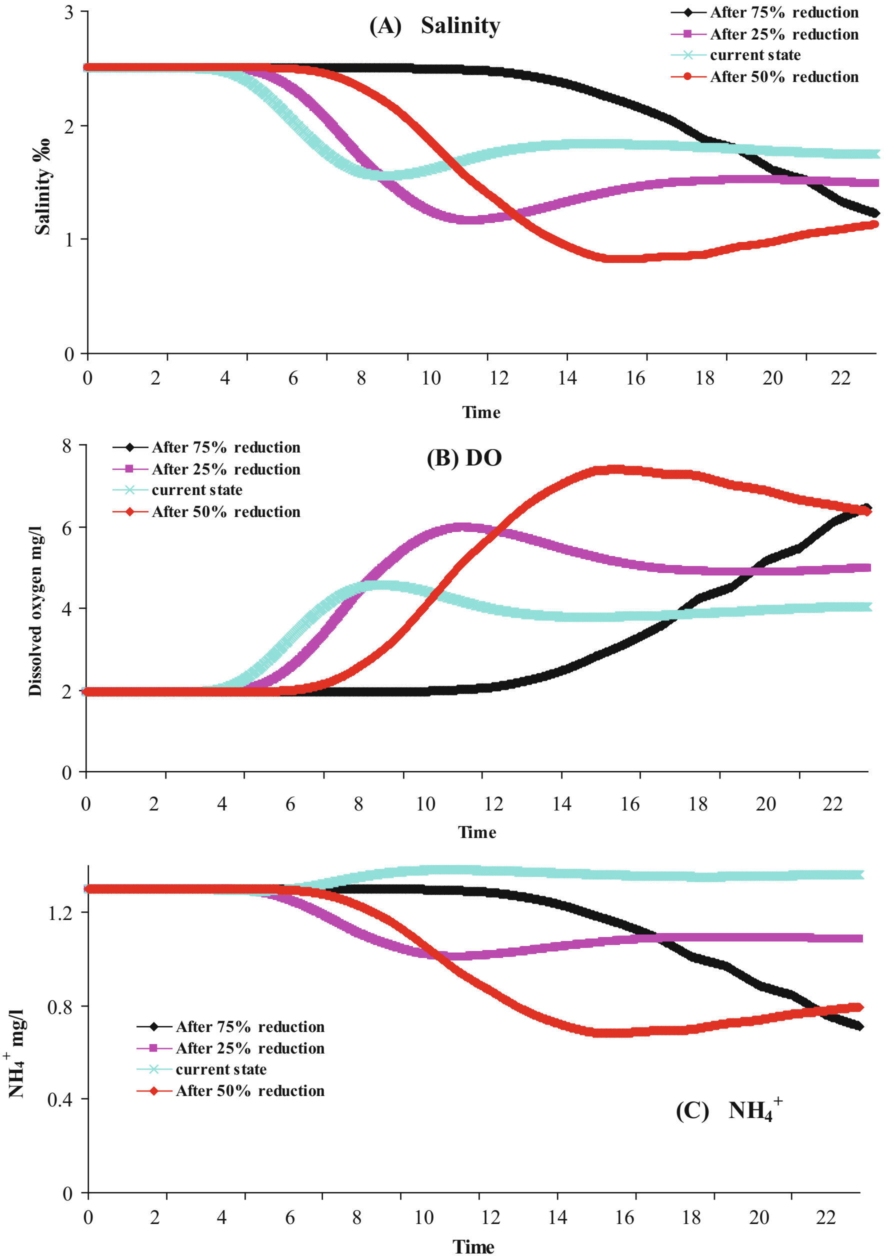

Fig. 11 (**a**) Simulated results of salinity. (**b**) Simulated results of DO. (**c**) Simulated results of ammonium under different load reductions from all drainage points to the lake “scenario 1”

Figure 11 shows the decrease in salinity and ammonium and increase in DO after 25, 50, and 75% reduction, respectively, at a monitoring station in the west part of the lake due to the reduction in pollutant loads entering the lake.

4.3.2 Reduction from El-Qalaa Drain to the Lake

El-Qalaa drain is considered the major source of pollution in the lake [20]. A scenario is developed to reduce the load from the drain by 50% reductions. The simulation results predict that load reduction from El-Qalaa drain did not affect water velocity and water quality parameters. This is due to water discharges from El-Qalaa drain which does not enter the main basin except through an opening close to El-Noubariyah canal to the north and directed toward the western harbor as shown in the flow pattern (Fig. 5).

4.3.3 Load Reduction from El-Omoum Drain to the Lake

A scenario is developed to reduce the load at El-Omoum drain boundaries by 50% reductions due to the fact that El-Omoum drain is the main source of water supply to the lake. It carries different pollutants to the lake characteristic for agricultural drainage water. These pollutants include pesticides and various nutrients along with organic matter from animal farming and domestic wastewater of nearby villages.

Figure 12a, b shows the effect of load reduction from El-Omoum drain on the spatial distribution of salinity and DO. The simulation results predict that load reduction from El-Omoum drain would help in a decrease of salinity with 1‰ in the lake and increase DO, which will reach 7.5 mg/L with an average increase of approximately 2 mg/L.

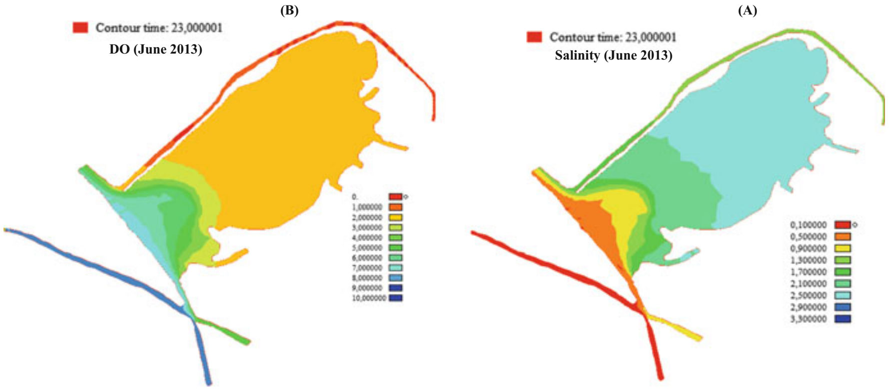

Fig. 12 Spatial distribution of salinity (**a**) and DO (**b**) "scenario 02"

Figure 13a, b shows the decrease in salinity and increase in DO at a monitoring station in the west part of the lake. Figure 13c shows the decrease in ammonium due to the reduction in pollutant loads entering the lake.

5 Summary and Conclusions

The present study presents an up-to-date two-dimensional hydrodynamic and water quality model of Lake Mariout that is one of the Egyptian coastal lakes suffering from almost all possible environmental impacts. Many datasets (2013–2014) from different sources are used to achieve that goal. The calibration was conducted using a partial set of the collected data to compare the model results with the observed data at the different locations for both the hydrodynamic and the water quality models. The model results and calculations are in reasonable agreement with the measured concentrations.

First, the 2D hydrodynamic model was developed to simulate the hydrodynamic behavior of the lake through simulating the water velocity and flow within the main basin of the lake. The developed, well-structured hydrodynamic model was also capable of describing the physical and hydrodynamic processes of the water system.

Second, hydrodynamic results were successfully used as inputs to water quality model. The basic water quality modeling component simulates the main water quality parameters including ammonia, DO, pH, and salinity.

The model also proved to be an effective tool for evaluating different scenarios of such shallow lake. Some factors should be considered in future modeling of Lake Mariout, such as suspended sediment concentrations, COD, BOD, chlorophyll-a, and phosphorous compounds.

6 Recommendations

The following recommendation could be stated:

1. To improve the water quality and minimize the environmental deterioration, it is suggested to enhance the water circulation in the lake through reed removal and speed up the rate of water discharge into the Mediterranean Sea by increasing the water pumping rate.
2. Reduction of the pollutants load from El-Omoum drain (the main source of pollutants to the lake), through water treatment facilities, is highly recommended.
3. It is highly recommended to conduct a permanent monitoring system to get continuous records of both hydrodynamic and water quality parameters and should cover all parts of the lake.

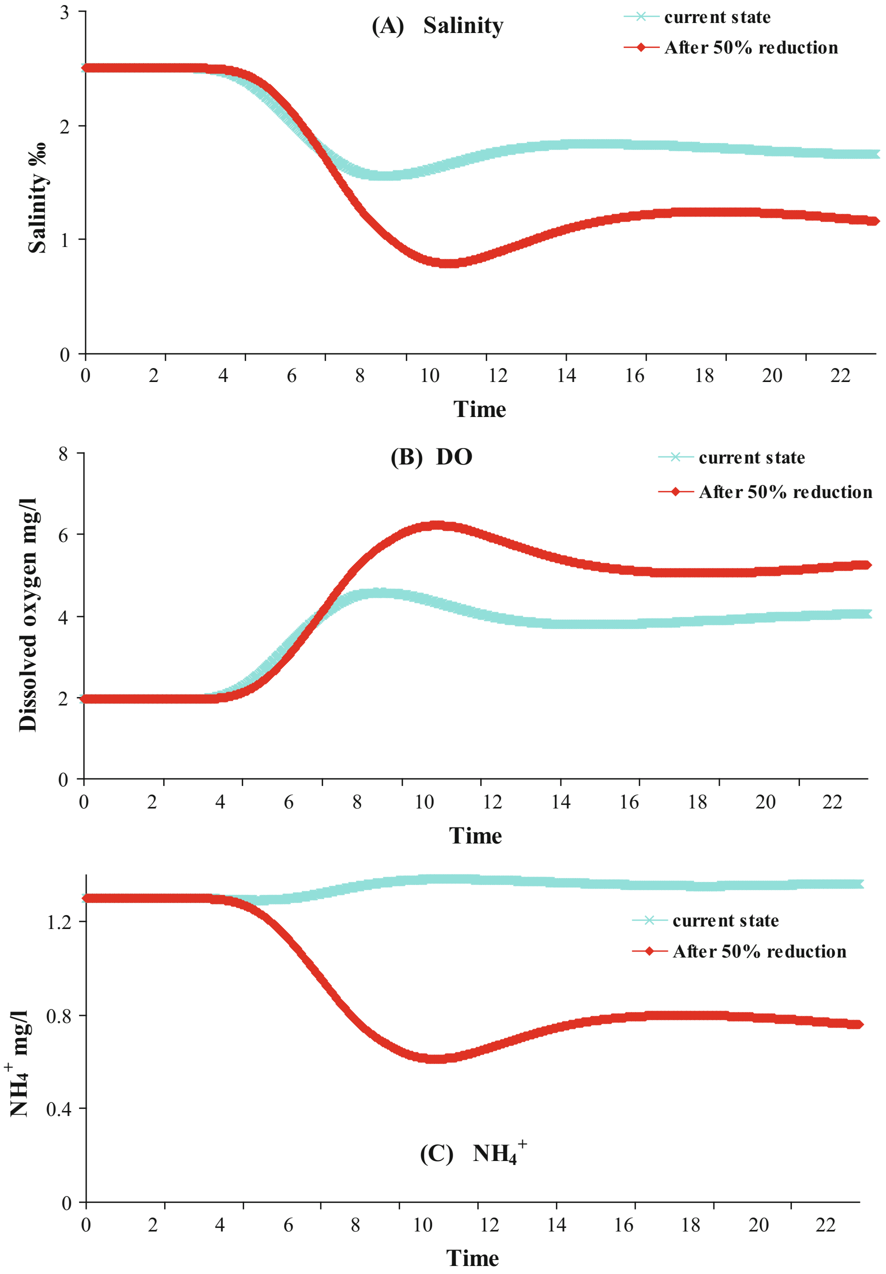

Fig. 13 (**a**) Simulated results of salinity. (**b**) Simulated results of DO. (**c**) Simulated results of ammonium under loads reduction from El-Omoum drain to the lake “scenario 3”

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A Three-Dimensional Circulation Model of Lake Bardawil, Egypt

M. A. Bek and G. W. Cowles

Abstract Lake Bardawil is an important hypersaline lake located in Egypt on the coast of the Sini Peninsula adjacent to the Mediterranean Sea. The lake is host to several industries which provide critical contributions to the regional economy including farmed and wild-caught fisheries and salt extraction. The lake also has significant ecological importance, serving as a rest stop and overwintering location for a numerous waterfowl. To date, only limited studies of circulation and water properties have been performed leaving lake managers without the information needed to make strategic decisions needed to mitigate long-term threats to the lake stemming from regional infrastructure projects, expansion of industry, and natural processes such as inlet shoaling. The present chapter presents a numerical model of Lake Bardawil which can be used to study dynamic processes and predict the outcome of management actions. The approach predicts the three-dimensional circulation using an unstructured grid approach which enables resolution of the complex coastline and wide range of spatial scales associated with the lake. In a validation study, the model was found to reproduce the annual variation and magnitude of monthly averaged salinity at ten measurement stations but significantly overpredict salinity at the two stations in the shallow far western section of the lake. The model demonstrates that evaporation, wind forcing, and tidal exchanges all play important roles in lake forcing. The present work represents a critical step toward the longer-term goal of establishing an operational circulation model for Lake Bardawil which can be employed as a tool by managers to assist and accelerate the decision-making process.

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Keywords Egypt, FVCOM, Lake Bardawil, Numerical simulation, Water hydrodynamics

Contents

1 Introduction

Lake Bardawil is an oligotrophic hypersaline shallow lake located along the Mediterranean shore of the Sinai region, Egypt (Fig. 1). The lake is bordered from the north by a curved sand barrier that separates it from the Mediterranean coast and from the south by the sand dune belt. The lake is approximately 80 km long (west-east) and 20 km wide, has an average depth of ~1 m, and covers an approximate area of 685 km^2 or 13% of the Sinai Peninsula (Fig. 1). Lake Bardawil is connected to the Mediterranean through two artificially constructed inlets. The western inlet is ~150 m wide, and the eastern inlet is ~100 m wide. Historically, a third inlet has existed intermittently in the far eastern end of the lake but is currently closed due to infilling from longshore drift. The responsible Egyptian authority must regularly maintain the two existing inlets. Navigation channels are dredged to depths of 4–7 m. Bardawil has no riverine input and receives freshwater only through the scarce winter precipitation. This lack of freshwater and limited exchange with the Mediterranean is combined to make Lake Bardawil the most saline of the northern Egyptian lakes [2].

The lake is home to several key industries. Salt extraction has grown around the hypersaline areas, particularly along the eastern shore (Fig. 2). Aquaculture production is about 22% of the Egyptian northern lakes [3]. The lake is also well known for its wild caught of natural fishery which is comprised of many high-value saltwater species including *M. cephalus*, *L. ramada*, *L. saliens*, *C. labrosus*, and *L. aurata*

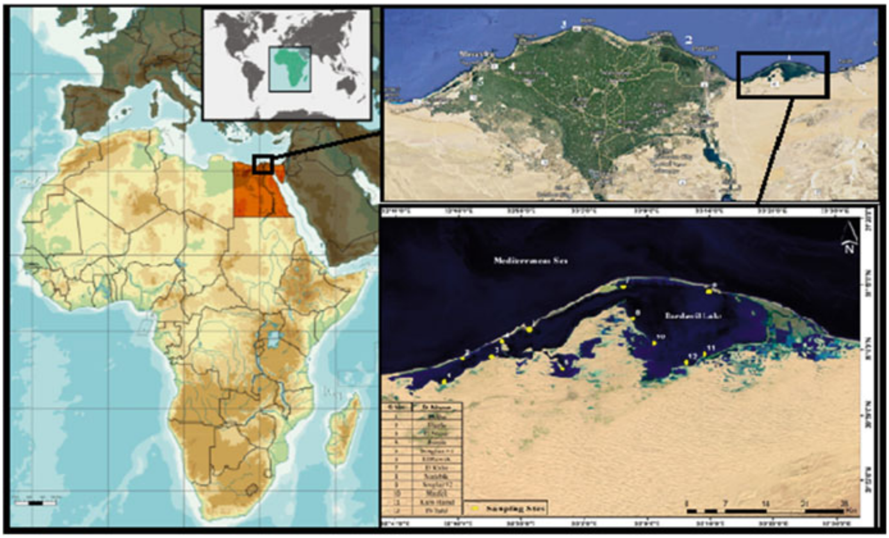

Fig. 1 Lake Bardawil location after [1]

Fig. 2 Salt extraction industry in Lake Bardawil

(Mugilidae) [4]. They contributed about a third of the total catch. Minor species include *S. aurata* (Sparidae), *S. solea*, *S. aegyptiaca*, *D. labrax*, and *D. punctatus* (Moronidae). The harvest also includes crustaceans such as shrimp and native crabs like *Portunus pelagicus*. Fishers harvest between 2,200 and 5,000 tons of fish from seven species each year, contributing approximately 5.5 M USD to the economy [5]. In addition to the regional importance, Lake Bardawil is regarded by the international scientific community as a critical ecological resource. In 1985, UNESCO designated a 250 km^2 zone in the far eastern part of the lake as a Ramsar site. Known as the Zaranik Protectorate, this area serves as a valuable stopover and winter home for a variety of migrant Palearctic waterfowl including *Spatula querquedula* (Garganey) and *Calidris alpine* (Dunlin) [6].

Lake Bardawil faces two primary concerns related to the hydrodynamics. The first is the stability of the inlets. Sediment fluxes associated with longshore drift along the Sinai shore generates inlet infilling which must be addressed on a regular basis. Reductions in the exchange between the lake and the Mediterranean Sea due to the partial or total closure of one or more inlets would have drastic effects on both the salinity and water quality. This would, in turn, affect the water quality and lake ecosystem and likely have a negative impact on the local fisheries. Another primary concern is the potential impacts of a proposed large-scale regional irrigation project aimed at increasing the extents of arable land in the Sinai. A comprehensive impact study concluded that the project would lead to increased fluxes of contaminated groundwater in Lake Bardawil [7]. The fate of these contaminants, timescale of their residency in the lagoon, and impact on the ecosystem require a thorough understanding of the lake circulation and biogeochemistry.

This chapter presents a hydrodynamic model of the lake that resolves the critical physical and hydrographic processes associated with these concerns. Such a model could be used as a decision-making tool for managers that may be employed for examining approaches to resolving these concerns. These include a current proposal to construct a new inlet in the western region of the lake. The numerical model developed in the present work could enable a study of the impact of this additional inlet on lake circulation and salinity and enable management to decide whether or not to proceed. Such model-based approaches to resource management leverage the rapid growth in computing power to provide critical information needed to make difficult decisions involving complex conflicts among various stakeholders [8].

2 Physical Forcing

The water circulation within Lake Bardawil is primarily driven by the surface wind stress, tides from the Mediterranean, and evaporation [9]. The regional characteristics of these fields as well as the data sources used to drive the model are presented in this section.

2.1 Tides

Tidal forcing in the lake is established by the tidal characteristics of the eastern Mediterranean along the north Sinai coast. Tides in this region are primarily a result of the equilibrium tide with minor influence from the Atlantic tidal wave [10]. The main tidal constituents along the north Sinai coast in the far eastern Mediterranean are the M_2 and S_2. At the nearest tidal gauge (Port Said, from [10]), the M_2 has an amplitude of 11.2 cm and phase of 241°G, and the S_2 has an amplitude of 6.9 cm and a phase of 254°G. The resulting elevation is weakly diurnal with a diurnal variation of approximately 1.5 (Fig. 3). The tide range varies from ~40 cm during neap to ~15 cm during spring tides with a mean annual range of 25 cm.

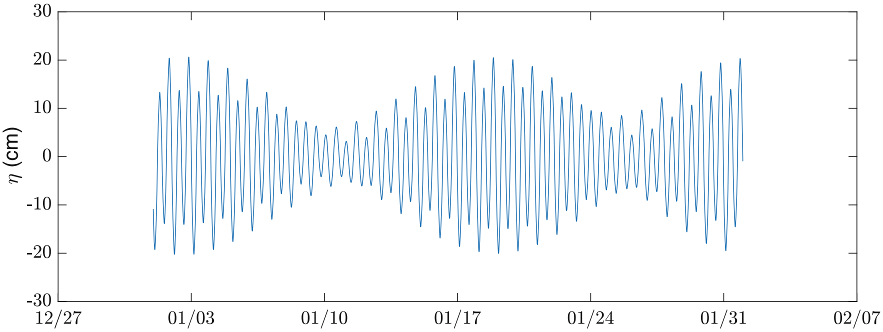

Fig. 3 Tidal elevation near Port Said, Egypt for the first 2 months of 1999 constructed from tidal harmonics

2.2 *Wind Forcing*

The wind plays an important role in the limnology properties of the Egyptian northern delta lakes including Lake Bardawil. The wind field induces mechanical mixing of the water column which, combined with the shallowness of the lake, can nearly eliminate the stratification of the hydrographic and other biogeochemical quantities. The wind can also influence the lake through agitation of bottom sediments. These sediments may be transported by the large-scale circulation within the lake and be deposited in the deeper channels near the inlets, causing them to shoal and reducing the flushing rate. The wind field can also generate large-scale setup in the Mediterranean Sea leading to additional transport of seawater into the lake. For this work, the primary source of wind data was the Egyptian national weather surface station at Port Said, approximately 40 km to the west of the lake. The archived data included hourly wind magnitude and direction at a 10-m height. Additional long-term data was acquired from the Egyptian national weather station at El Arish, approximately 20 km to the east of the lake. This data included daily averaged 10 m wind magnitude for the years 1985–2014.

The dominant regional wind direction is NW and is characterized by magnitudes of ~5 m/s (Fig. 4). Stronger events with magnitudes greater than 10 m/s are associated with W and SW winds. Previous studies found that NW winds can be characterized as a sea breeze having a notable diurnal variation with peak strengths of 6–7 m/s in the afternoon (12:00–17:00 local time) and lesser strengths of ~2 m/s in the evening [11]. These winds blow offshore with respect to the Mediterranean coast and thus do not contribute strongly to wave forcing on the shoreline. However, they may play an important role in the mixing and circulation of the lagoon water. The seasonal variation of the wind constructed from the 30-year time series from El Arish exhibits stronger winds in winter with a maximum monthly mean magnitude in March of 5.3 m/s and weaker winds during the summer with the minimum monthly mean magnitude of 3.3 m/s occurring during August (Fig. 5).

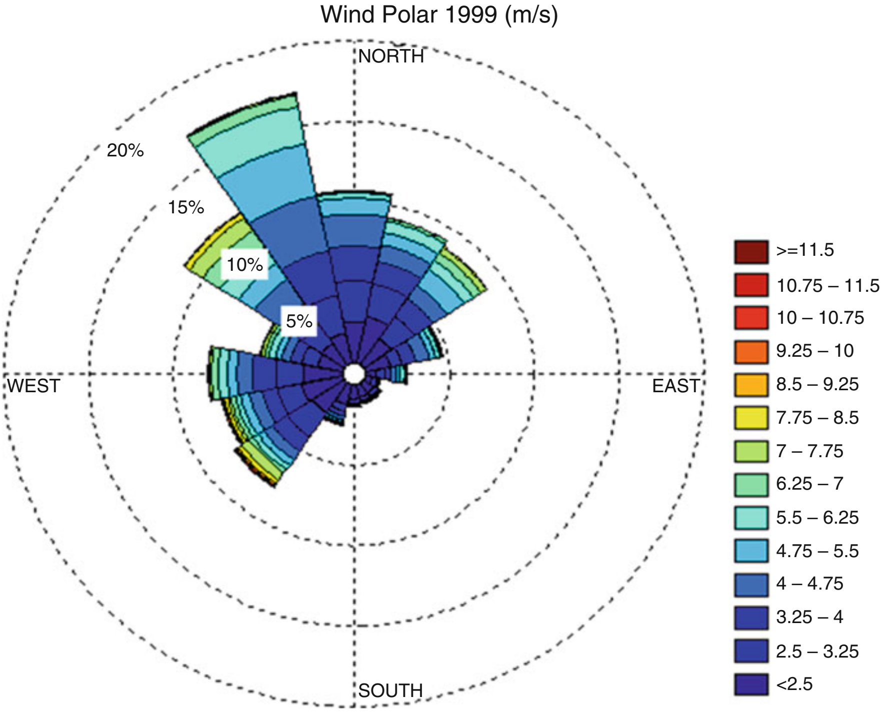

Fig. 4 Wind statistics from Jan 1, 1999, to Jan 1, 2000, from the Port Said meteorology station. Wind speeds in m/s. The upper left quadrant denotes NW winds

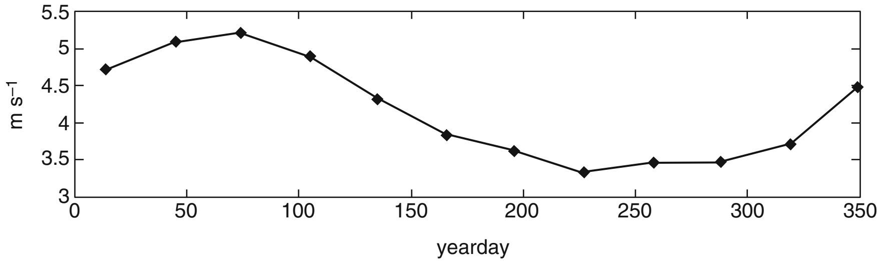

Fig. 5 Monthly mean wind magnitude [m/s] derived from a 30-year time series from the El Arish meteorological station

2.3 *Precipitation and Evaporation*

The average annual precipitation and evaporation for Lake Bardawil are estimated to be about ~100 mm year^{-1} and ~1,750 mm year^{-1}, respectively [12]. The largest monthly rainfall occurs in the winter, with the maximum amount being recorded in January (0.9 mm/day). The rainy period of the year lasts from November to March with a peak monthly rainfall occurring in January (0.9 mm/day). The dry period of the year lasts from April to October with nearly no precipitation on average from June to August. Evaporation also experiences a significant seasonal variation. During winter, the rates of evaporation are lower with a minimum monthly minimum rate of 3.2 mm/day occurring in January. Rates of evaporation during summer are significantly greater with a peak of 5.9 mm/day occurring in July. The annual average evaporation rate is 4.8 mm/day.

3 The Unstructured Grid Circulation Model for Lake Bardawil

Lake Bardawil has been the subject of several prior numerical studies. El Bagoury [13] employed the 2D version of the RMA model to assess flushing time. RMA employs a mixed-element mesh, and in this work, quadrilaterals were employed with local refinement in the inlets and narrow passageways. Linnersund and Mårtensson [14] used both the ADCIRC unstructured grid finite element solver and the structured grid solver CMS-flow to examine renewal rates in the lake. Both solvers were used to solve the 2D vertically averaged flow using the shallow water equations.

In the present work, the primary objective is to develop a model which can resolve the key physical processes in the lake to be suitable for use in a wide range of management decisions. A key requirement of the model is the ability to resolve the density-driven salt flux associated with reverse-estuary circulation. For this, a three-dimensional (3D) model with sufficient resolution of the water column coupled to a turbulence model suitable for stratified flows is needed. A second key requirement is the ability to resolve the wide scales of circulation generated by the narrow inlets and complex coastlines. For this, an unstructured grid approach was determined to be necessary. The model selected for the work is the Finite-Volume Coastal Ocean Model (FVCOM). This section presents an overview of the model selected for the work and the application to Lake Bardawil.

3.1 The Finite-Volume Community Ocean Model

FVCOM was developed under the leadership of Changsheng Chen of the University of Massachusetts Dartmouth, USA [15, 16]. The FVCOM coding is an open source and has been distributed to over 3,000 registered users. The hydrodynamic kernel of FVCOM discretizes the 3D hydrostatic primitive equations (HPEs) using a finite-volume formulation on an unstructured horizontal grid. The finite-volume, unstructured mesh approach combines the advantages of the finite-difference approach (computational efficiency) and the finite-element approach (geometric flexibility). It is well-suited to applications such as the Egyptian coastal lakes with irregular coastlines, islands, and complex bathymetry. The spatial fluxes of momentum are discretized using a second-order accurate finite-volume method [17]. A generalized terrain-following transform is used to discretize the vertical coordinate. The General Ocean Turbulence Model (GOTM; [18]) is coupled to FVCOM to compute the vertical eddy viscosity and diffusivity. The model is parallelized using the MPI standard library that scales efficiently on distributed memory clusters [19].

FVCOM has been used for numerous applications ranging from embayment to global scale. These include efforts relevant to the present work such as the hydraulic modeling of multiple-bay-inlet systems on Great South Bay, NY [20] and a targeted study of discretization errors with complex salinity fields [21]. In addition to the hydrodynamic kernel, FVCOM is coupled to several modules to resolve other processes including ice, waves, water quality, biogeochemical processes, and both cohesive and non-cohesive sediment transport. These modules enable the potential for directed studies of the impacts of various management scenarios on the water quality and ecosystem in the lake.

3.2 Model Domain and Mesh

The unstructured grid was constructed using the Surface-Water Modeling System (SMS) version 12.2 commercial software. This software produces grids with elements of high quality. The interior lake domain was defined using shoreline data acquired from the NOAA National Geophysical Data Center (NGDC). Shoreline features with scales smaller than 50 m were trimmed. The domain extended through the inlets into the Mediterranean a distance of 30 km to reduce the influence of the open boundary and allow for larger scale setup/setdown due to the wind forcing. The interior was meshed using a paving algorithm and evaluated to ensure the quality of the elements was suitable for computation with FVCOM. The resulting horizontal grid is comprised of 5,015 elements and 2,897 vertices (Fig. 6). The mesh resolution within the lake ranges from 100 m along the coastline and inlets to 1,000 m in the interior of the lagoons. Outside the lake, the mesh resolution extends from 100 m at the inlets to 5,000 m at the open boundary.

Lake bathymetry is derived from a dataset collected during repeat field surveys during 2015–2016 conducted in cooperation with the Egyptian General Authority for Fish Resources Development. The survey scientists employed a commercial depth sounder/GPS device, the LMS-240 model manufactured by Lowrance International, to collect the bathymetry data (Fig. 7). The vertical height of the seabed, z, is calculated by adjusting for the height of the free surface above mean level and subsequently shifted to the standard NAVD88 vertical datum. The resulting dataset contains 14,300 points and sufficiently resolves the lake bed boundary including important features such as the navigation channels. The data is interpolated onto the model grid in the lake using SMS. In the Mediterranean portion of the model

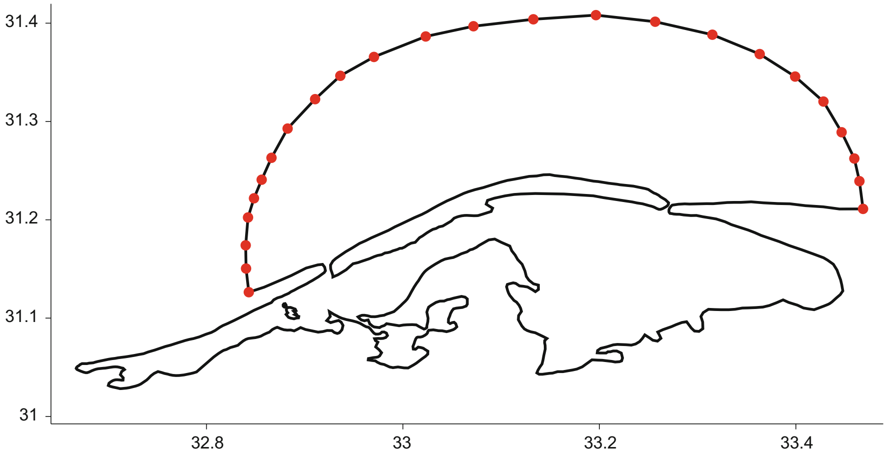

Fig. 6 Unstructured horizontal grid for Lake Bardawil with open boundary nodes (red circles)

Fig. 7 Lake Bardawil bathymetry survey (2015)

domain, the Mediterranean bathymetry data were extracted from [22]. The resulting bathymetry in the model grid ranges from a minimum of 20 cm along the perimeter to 1–2.5 m within the interior of the lagoons and 4–6 m in the vicinity of the inlets (Fig. 8).

3.3 Model Parameters

The horizontal turbulent eddy diffusivity (k_m) was computed using a Smagorinsky closure scheme [23] with a background diffusivity of 10 m^2/s. To resolve vertical processes, ten layers equally spaced in the σ-coordinate were used, providing ~10 cm resolution in the vertical in the lake interior. The vertical turbulent eddy diffusivity (k_h) was computed using the standard two-equation k-epsilon scheme implemented in GOTM. A uniform hydraulic roughness $z_0 = 0.0015$ was used in the entire domain with the exception of the east inlet where an enhanced hydraulic roughness of $z_0 = 0.015$ was found to provide improved comparison with salinity observations (see Sect. 3.6). This hydraulic roughness corresponds to a drag coefficient $C_d = 0.0025$ in 1 m of water. The split mode explicit scheme was selected for model integration. The time step used in the external (2D barotropic) mode is bounded by a Courant-Friedrich-Levy (CFL) condition, which can be approximated as

$$\Delta t_E \leq \frac{\Delta L}{U + \sqrt{gD}},$$

where Δt_E (s) is the external mode time step, ΔL is the shortest edge of an individual triangular grid element (m), U is the local horizontal velocity magnitude (m/s), g is the gravitation acceleration, and D is the local depth (m). Due to the fine mesh used

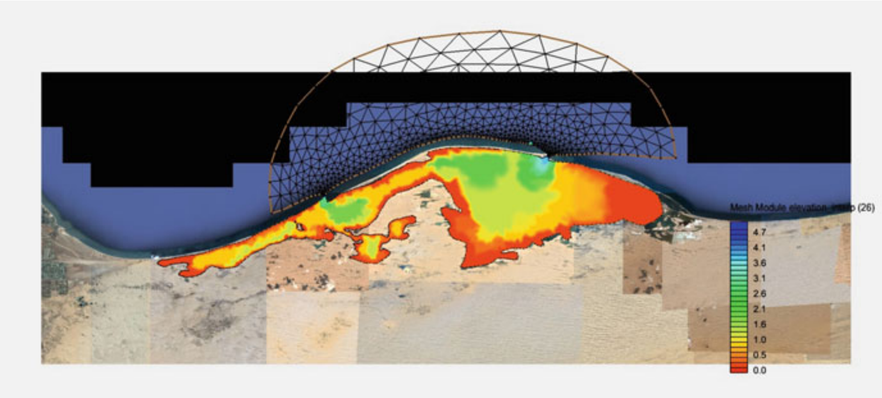

Fig. 8 Lake Bardawil model bathymetry (m). Values not shown outside the lake for clarity

in the inlets and their relatively high current speeds, Δt_E is conservatively constrained to 0.5 s. For studies of this nature, the time step of the internal (3D) mode (Δt_I) is typically set to $10\Delta t_E$ and thus for the present work $\Delta t_I = 5$ s.

3.4 Model Forcing

At the open boundary, the sea surface elevation is forced using height reconstructed from the eight principal regional tidal harmonics (M_2, S_2, N_2, K_2, K_1, O_1, P_1, Q_1). The amplitude and phase for these harmonics are interpolated onto the open boundary nodes from the TPX08 1/30° Mediterranean tidal atlas [24, 25]. Salinity at the open boundary is relaxed to a constant value of 39 PSU with a timescale of 4 h. Surface forcing consists of wind stress and evaporation. Wind stress is computed using the Large and Pond [26] formula from hourly observed wind speed and direction for the year 1999 measured at the Port Said meteorology station. Evaporation is set using a time series reconstructed from monthly averaged evaporation rates [12]. Both wind stress and evaporation were considered to be spatially uniform over the domain.

3.5 Circulation Model Integration

The model starts from rest with the free surface set to mean sea level. Salinity in the domain is set to a constant value of 39 PSU. The model is integrated at a time step of 5 s for a period of 4 years for the period Jan 1, 1996, to Jan 1, 2000. The goal is to model a typical annual cycle of the lake, and thus the surface forcing (evaporation and wind stress) is repeated each year. The tidal elevation is continuous to ensure the model does not undergo abrupt transitions. This approach is reasonable as tidal periods are much smaller than a year. Approximately, 2 years of the simulation are required to establish the spatial variation of salinity in the lake, and thus 3 years are used in the present work to ensure the model reaches a quasiperiodic annual response. In the last year of integration (1999), hourly fields of velocity, hydrography, and sea surface elevation are archived for post-processing. The simulation requires approximately 120 core hours to complete the 4-year integration using Intel Haswell CPUs. Typically, the model was run in parallel on 12 cores, enabling overnight runs.

3.6 Validation

The available data for validation consists of point measurements of salinity acquired from 12 stations within the lake every month during the period 1999 to 2000. This observation program has very broad coverage of the lake and captures the wide range of salinities in the lake. Stations are located in the hypersaline region in the far western end (ST1, ST2), near the western inlet (ST5), in the isolated embayment in the southern portion of the lake (ST6), on the perimeter of the eastern lagoon (ST7, ST8, ST10-ST12), and in the eastern inlet (ST9) (Fig. 9 and Table 1).

Time series of surface salinity were extracted from the model-computed fields, and monthly mean values were computed for comparison with the measurement data (Fig. 10). The locations of the measurement stations used to calibrate the model are shown in Fig. 10. At these stations, the salinity measurements were made at a regular monthly interval. These salinity measurements were used to assess the model skill and to establish key model parameters such as the bottom roughness.

Overall, the model is able to reproduce the significant spatial variation of salinity on the lake (Fig. 10). The strongest agreement is found at stations 4 and 9 which are the measurement locations closest to the west and east inlets, respectively (refer to Fig. 9 for locations). In these locations, the salinity largely reflects that of the Mediterranean water. In the eastern lagoon, the model captures well the salinity magnitude and variation at stations 7, 8, and 10. These stations are all toward the interior of the lagoon, away from the strong salinity fronts. These stations are also significantly influenced by the wind-driven flow associated with the dominant NW breeze which carries water from the west to the east lagoons (see Sect. 2.2). At all three sites, the model captures the seasonal cycle of salinity with the exception of the winter values at station 7 where the model-computed salinity is found to be greater

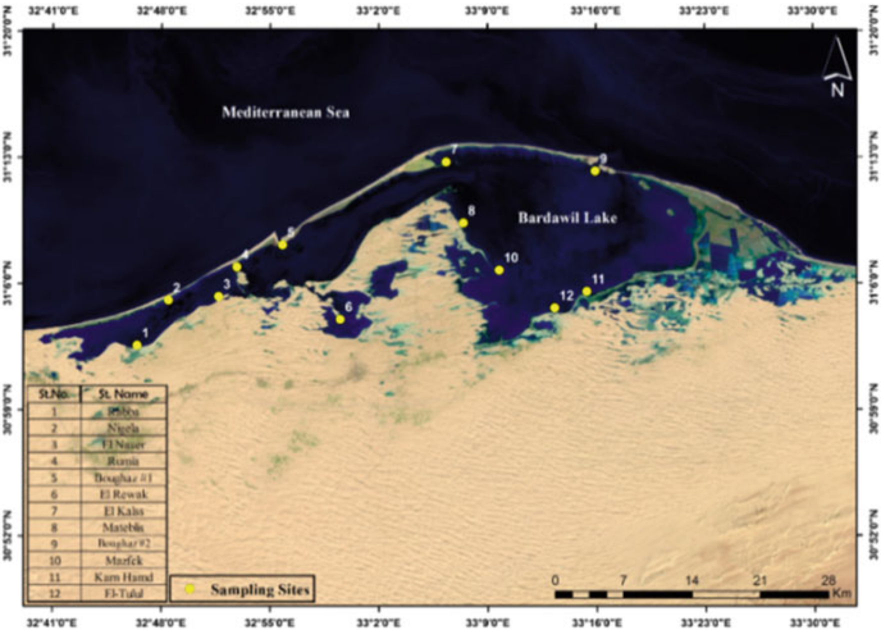

Fig. 9 Lake Bardawil salinity measurement locations and IDs

Table 1 Locations of salinity measurements

Station number, ST	Name	Latitude	Longitude
1	Rabaa	31° 03′ 51″	32° 46′ 75″
2	Negela	31° 04′ 20″	32° 48′ 36″
3	El Nasar	31° 05′ 67″	32° 51′ 18″
4	Rumia	31° 06′ 12″	32° 53′ 30″
5	Boughaz 1	31° 08′ 11″	32° 55′ 75″
6	El Rewak	31° 05′ 35″	32° 59′ 18″
7	El Kalas	31° 11′ 78″	33° 06′ 24″
8	Mateblis	31° 08′ 96″	33° 07′ 92″
9	Boughaz 2	31° 12′ 27″	33° 15′ 43″
10	Mazfck	31° 05′ 81″	33° 13′ 65″
11	Kam Hamd	31° 09′ 18″	33° 19′ 25″
12	El Tulul	31° 04′ 50″	33° 10′ 13″

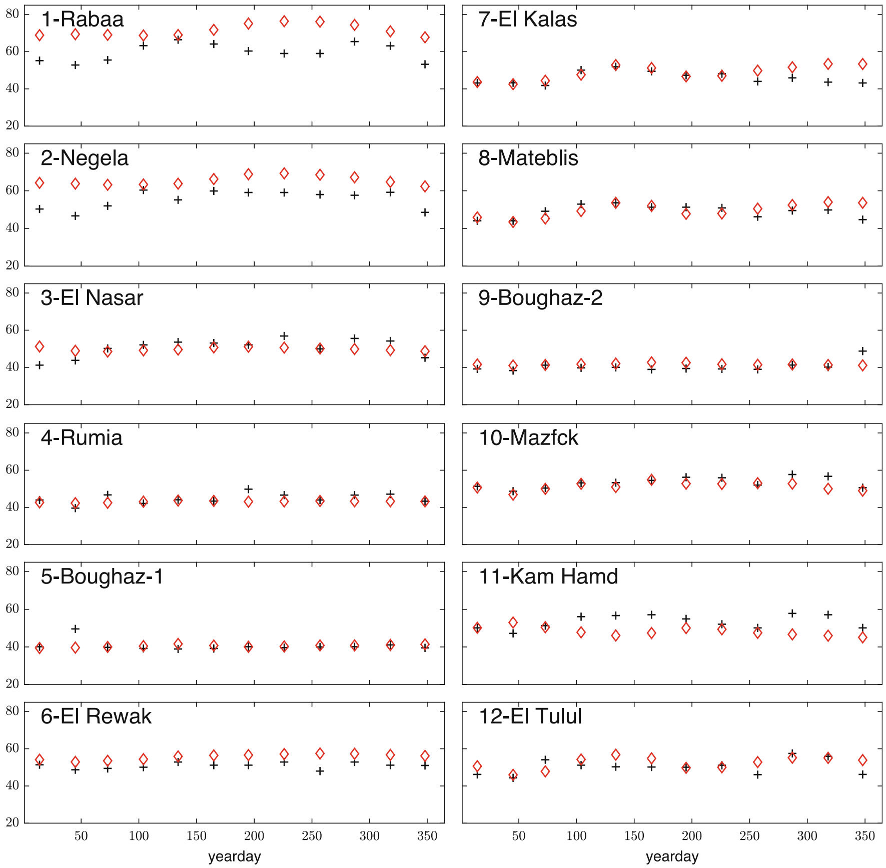

Fig. 10 Comparison of model-computed (red diamonds) and observed (black +) monthly average surface salinity at 12 stations in Lake Bardawil

than observed. This is important because the seasonal cycles at stations 7 and 8 are found to be out of phase with the other stations which have seasonal cycles which follow that of evaporation. At stations 7 and 8, the maximum salinity is observed in spring, prior to peak evaporation. This is likely linked to the seasonal wind fields as summer NW breezes tend to introduce stronger flushing at these locations, contributing to reduced salinity. The model is able to capture these important trends. At the remaining locations in the eastern lagoon (11,12), the model-computed and observed annual mean salinities match well with the observations, but the model fails to predict the variation in the monthly mean. This may be due in part to the limited number observations which do not represent well the monthly averages in locations that are in the vicinity of strong salinity fronts and thus subject to significant variation due to short-term changes in wind forcing as well as the spring-neap cycle. In the western lagoon, the model-computer predictions agree well with observations at stations 3 and 4 which, similar to 7, 8, and 10, are in the interior of the lagoon. At stations 1, 2, and 6, the model-computed salinity is greater than observed during all months. The model bias at stations 1 and 2 in the shallow, far western portion of the lake is particularly strong. In these locations, the contributions to the salinity field from tidal mixing and baroclinic pressure gradient are weaker than that of the wind stress and the evaporation process.

4 Results

4.1 Monthly Average Surface Salinity

The model-computed monthly averaged surface salinities are shown in Fig. 11. The spatial variation is greater than the temporal variation on this timescale. Model-computed salinity ranges from 39 PSU near the inlets to 80 PSU in the hypersaline far western reaches of the lake where the tidal exchange is limited by frictional losses, and the dominant NW wind cannot induce significant mixing. Salinity increases during summer and decreases during winter in response to the seasonal fluctuation in evaporation rates. This is particularly notable in the isolated embayment of the western lagoon.

4.2 Wind-Driven Circulation

To examine the influence of the dominant wind field on the lake circulation, an idealized model run was executed. Forcing consisted of Mediterranean tides, a constant 5 m/s NW wind, and annually average evaporation rate of 4.8 mm/day. The model was run for 4 years to reach a quasi-stable response in the salinity field. The model-computed vertically averaged velocities over the last 60 days of the run were extracted and low-pass filtered using a 33-h cutoff to produce the subtidal

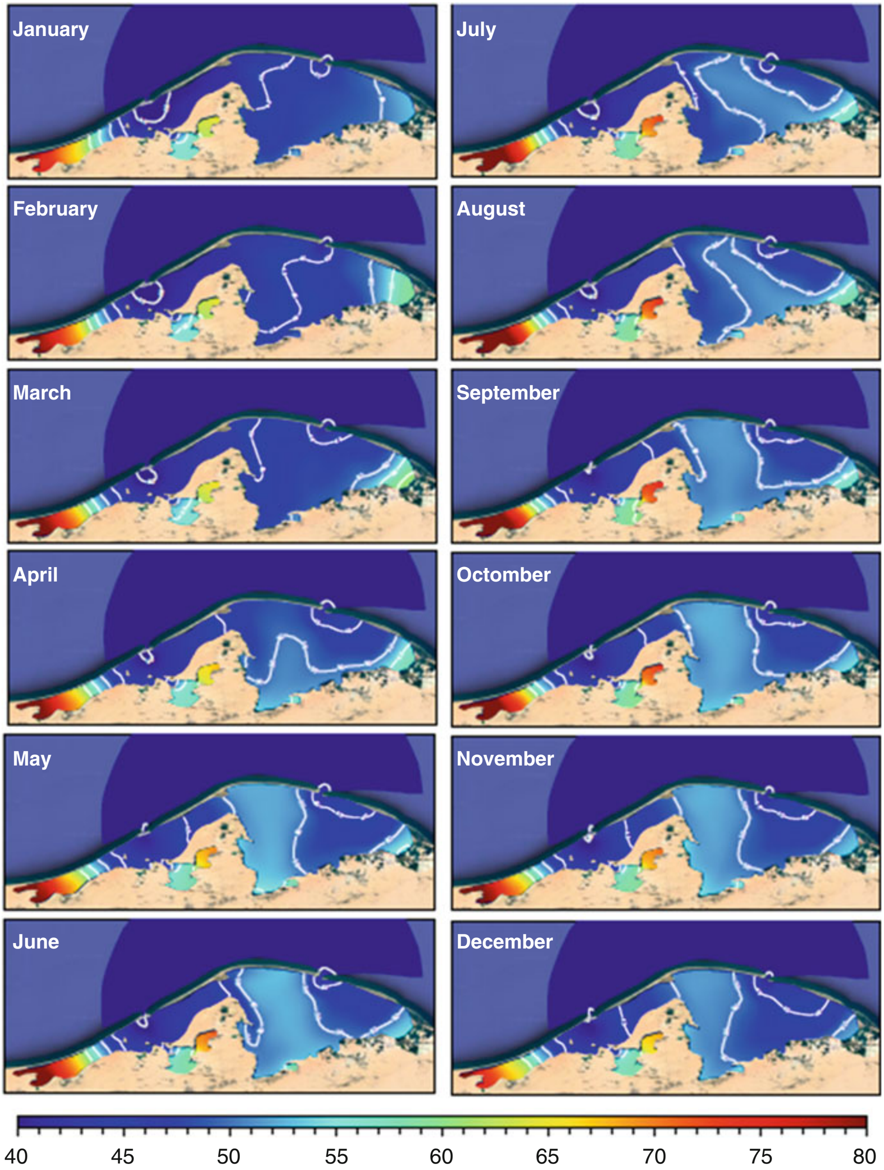

Fig. 11 Monthly averaged model-computed surface salinity (PSU) in Lake Bardawil

residual circulation. The resulting flow pattern indicates a general flow from west to east with net inflow in the west inlet and outflow in the east (Fig. 12). The subtidal velocity magnitude is enhanced along the western perimeter of the east lagoon, reaching values of ~5 cm/s. The circulation within the eastern lagoon consists of two broad recirculating cells, a counterclockwise gyre in the western portion of the

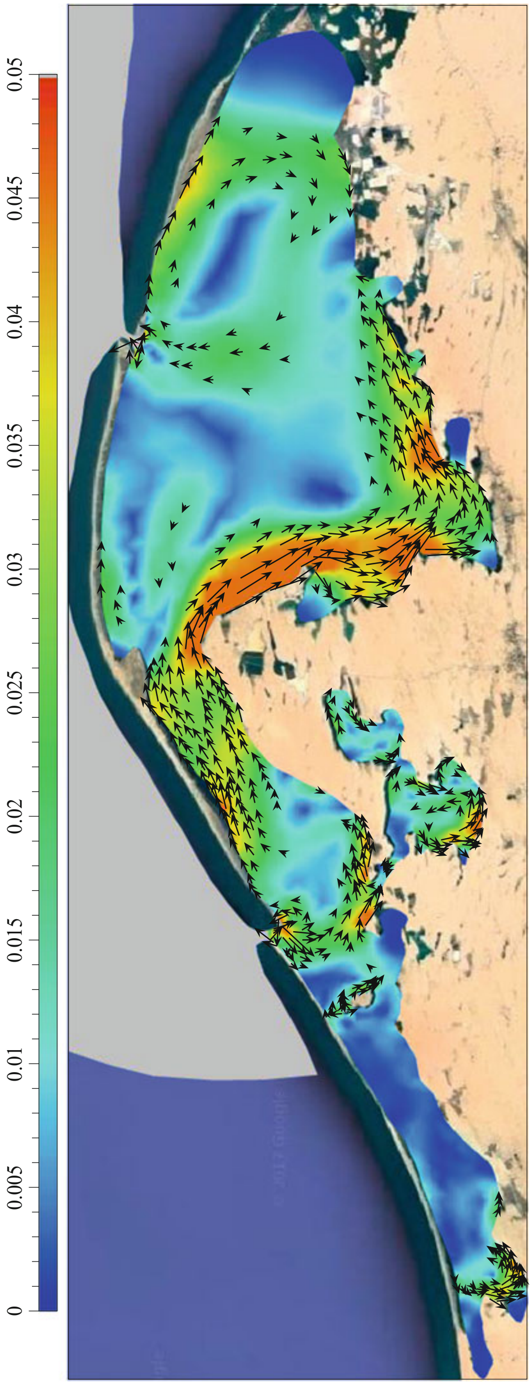

Fig. 12 Subtidal vertically averaged velocity magnitude (m/s) for idealized NW wind experiment. Vectors at locations where the magnitude was less than 1.5 cm/s are not shown. Vectors are sparsified to improve figure clarity

lagoon and a clockwise gyre in the eastern portion. This experiment indicates the importance of the wind field in generating circulation that links the west and east lagoons.

5 Discussion

One of the challenges of developing a model for Lake Bardawil is the lack of observations needed for calibration of model parameters and validation of predictions. In particular, time series of water level in the interior of the lake would be useful for looking at the attenuation of the tidal wave and assisting the parameterization of bottom friction. Several numerical experiments were performed to examine the over prediction of salinity at stations 1 and 2. It was determined that unrealistic values of bottom roughness and/or horizontal diffusivity were required to reduce the salinity values within the observed range. This indicated that the discrepancy may be due to the model forcing or bathymetry. To test the latter, a static increase of 25 cm in the bathymetry in the western reaches of the of the lake was applied, and this led to increased exchanges of salt in the western reach of the lake. The position of the salinity front moved approximately 5 km shoreward, resulting in a significant improvement in the skill at the two problematic salinity measurement locations. Datasets needed for model improvement as well as for the greater context of lake management are discussed in the next section.

In view of the fact that simulations were performed with spatially and temporally uniform climatically monthly atmospheric forcing, the results are acceptable so far. This exploration is considered an intermediate step toward the longer-term goal of an operational unstructured grid three-dimensional model for Lake Bardawil. As additional field data becomes available, further improvement in accuracy may be possible with local refinement of model grids and additional analysis of model parameters.

6 Conclusions

In this chapter, a three-dimensional hydrodynamic model of the circulation of Lake Bardawil was presented. The model is based on the Finite-Volume Community Ocean Model which employs unstructured grids to solve the hydrostatic primitive equations in the finite-volume formulation. The unstructured grids enable small-scale features like the inlets to be resolved while maintaining a reasonable number of elements in the model domain. The model is able to reproduce annual variation and magnitude of monthly averaged salinity at ten measurement stations but significantly overpredicts salinity in the two stations in the shallow far western section of the lake.

7 Recommendations

Further acquisitions of data are needed to improve the model skill, to provide baseline values for long-term studies, and to complement simulation-based studies of lake dynamics and water quality.

1. A full monitoring program for the lake physical, chemical, and environmental parameters with sufficient stations to resolve the spatial variability.
2. Annual shipboard ADCP measurements in the inlets to enable a direct skill assessment for calculation of the volume exchange and to monitor long-term changes in flushing rate.
3. A meteorological buoy moored in the central eastern lagoon to provide quantities need to establish the surface forcing components of wind stress, heat flux, and net precipitation-evaporation driving the momentum, salinity, and temperature fields at fine temporal scale (<1 h). At a minimum, these would include measurements of wind speed and direction, air and water surface temperature, humidity, photosynthetic active radiation (PAR), and rainfall.
4. Additional bathymetry be acquired to ground truth and improve the existing dataset and reflect current lake-wide topography and inlet conditions. Ideally this data would be acquired using LIDAR, should the water clarity be deemed sufficient.

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Update, Conclusions, and Recommendations of Egyptian Coastal Lakes: Characteristics and Hydrodynamics

M. A. Bek, Abdelazim M. Negm, and Sommer Abdel-Fattah

Abstract This chapter aims to provide a summary of the major conclusions and recommendations presented in this volume. It provides a brief conclusion and recommendations for lakes' better management. Also, it contains some findings from the few recently published work related to the Egyptian coastal lakes. The chapter contains the main background of the Egyptian coastal northern lakes' physical, chemical, and biological properties. These lakes include Bardawil, Manzala, Burullus, Edku, and Mariout. Moreover, a set of recommendations for future research work is extracted to direct the researcher community toward sustainability of the lake's ecosystem.

Keywords Bardawil, Burullus, Current status, Edku, Egyptian coastal lakes, Future, Management, Manzala, Mariout, Modeling

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1 Introduction

The coastal lakes in Egypt are very important not only for the Egyptian but also globally. They contain five of the most productive wetland ecosystems in the world. The Nile deltaic lakes are located along the southern Mediterranean coast. They are a vital economic resource because of fish production and industry. The current production makes up nearly 40% of Egypt's production. The lakes have a significant contribution to wildlife habitat. The lakes are considered as one of the crucial stations (rest point) for birds during the annual winter journey. However, these lakes are suffering from degradation and environmental stress. These stresses are mainly attributed to several factors including discharging of polluted drains, the accelerating development activities, overfishing activities, reclamation practices, and adverse impacts of climate change. These challenges should be seriously considered to remediate the lakes' bad condition and to move forward to sustainable management and development. Hence, generating a management plan with rehabilitation process and adequate policies/regulations is urgently recommended. This is at least prior requiring an improved monitoring strategy, measures, and advanced techniques for the lakes and their changeable attributes. The next section will present a brief of the important findings of some of the recently published studies on the Egyptian northern lakes. This will be followed by the main conclusions and recommendations of the book chapters.

2 Update

The Egyptian coastal lakes have natural fish production, natural aquaculture plants, commercial fishing, agriculture in dried and reclaimed areas, and huge fishing industrial activities. The lakes are suffering from several severe problems [1]. Foremost among these are the negative impacts of sea level rise on these lakes. There are several studies that utilized numerical simulation to investigate the climate change impact on the water bodies. These research studies cover Lake Manzala and Lake Burullus [2, 3]. These studies revealed the need for better management plans. Similar results are expected from sea level rise on the other delta lakes. However, the effect of sea level rise on different parts of the lakes may be influenced by various interrelated factors. Therefore, more studies are required to understand the vulnerability of the fishing sector and possible adaptation options to climate change [4, 5]. One of the dramatic losses of water areas is due to drying and reclamation for agriculture. This hazard is recognized in all lakes but clearly observed in Lake Burullus as the lake area decreased by 30% in the last 10 years. Also, the urban has doubled during the 1984–1997 period. The pollution of the water bodies is due to the receiving of the huge amount of agricultural drainage, municipal sewage, and industrial wastewater. The polluted water supplied the lake with heavy metals, which in turn affected every aspect of marine type. The good news is that these wetlands become top priorities to the Egyptian authorities as reported in the National Biodiversity, Strategy and Action Plan (NBSAP) for the years (2015–2030). The main conclusions from this volume on the main features and characteristics of the Egyptian northern lakes will be summarized in the next section followed by a set of recommendations for future considerations.

3 Conclusion

The following conclusions which are mainly extracted from the chapters presented in this volume are presented under the main themes of the volume. Therefore, the word “chapter” in the next sections means a chapter in this volume.

3.1 Overview, Opportunities, Challenges, and Adaptive Management

This volume of the Egyptian Coastal Lakes and Wetlands consisted of several parts. Part I is one chapter titled “An Overview of Egyptian Northern Coastal Lakes” which provides a detailed description, origin, and current status of the Egyptian coastal lakes. However, part II consisted of two chapters. In the chapter “Land Use in Egyptian Coastal Lakes: Opportunities and Challenges,” the authors discussed the northern lakes’ future opportunities and current challenges. The authors highlighted the lakes’ essential role in the Egyptian economy, where they provided about 39% of harvested fish in Egypt [6]. These valuable resources got the attention of the Egyptian government. The Egyptian Ministry of Environmental Affairs (MENA) updated the National Biodiversity, Strategy and Action Plan (NBAP) for the years (2015–2030) with the important objective of reducing the rate of wetland loss by 50%. This is expected to increase based on the Egyptian authorities’ strategy. The deltaic lakes are promising areas because they contain valuable nature ecosystems and industrial activities and energy resources [7]. The authors discussed in details the main challenges as continuing decrease in the open water area, high level of lakes’ water pollution, and the negative effect of climate change. The second chapter of part II is titled “Adaptive Management Zones of Egypt’s Lakes and Depressions” which introduces the adaptive management as a suitable approach for addressing this type of complex Egyptian lake problems. The authors classified the lakes and evaluated the land resource status of it. The authors indicated that the most polluted northern lakes are Lake Mariout and Lake Manzala. As for Lake Mariout, this is due to receiving agricultural drainage and domestic and industrial wastewater from agricultural drains. Among them, Lake Manzala serves as a final repository for many of the municipal and agricultural wastewater of the eastern Delta, including the wastewater of most of Cairo. The main contributors to the lake pollution are the Bahr El Baqar drain, Hadous drain, and drainage water delivered by Mataria, lower Serw, and Faraskor pumping stations. The sewage effluent from Cairo and the drainage water of more than 200,000 ha of agricultural lands were carried to the Lake Manzala by Bahr El Baqar.

3.2 Chemical and Physical Properties of Coastal Lakes

The chapter "Sediments Contaminations in Egypt's Northern Coastal Lakes" provides a comprehensive review of the sedimentation process and its environmental drivers, drains, in the Egyptian coastal lakes. The authors investigated the lake's sediment property as it is considered as a good indicator of the severe contaminations it suffers. The results show that Lake Burullus recorded the highest values of Cu, Zn, and Pb. However, Lake Edku was found to have the highest values of Fe, Mn, Co, and Cr. While Bardawil had the highest value of Cd, Lake Mariout got the highest ranged values for the organic contaminants, and Lake Manzala recorded the highest values of Pb. The authors indicated the high concentrations of heavy metals in the deltaic lakes' nearby drains. Industrial, agricultural, and municipal wastes coming through the drains are the main source of the existence of metals high level (Cd, Zn, Pb, Fe, Mn, and Cu). These levels are found above the permissible limits. It is worth to mention that the high levels of Cd can be attributed to the use of phosphate fertilizer [8–10]. Hence it is recommended to control the use of this type of fertilizers. Lakes Manzala and Mariout showed the highest values and alarming toxicity levels, and it is considered as one of the most hazardous. The organic contaminants discharged from the industrial effluents, domestic wastes, and agricultural effluents will have adverse ecological effects on the benthic species due to its exposure to these pollutants in deltaic lakes. Although the inorganic contaminants in the lake sediment did not exceed the permissible guidelines, it has to be monitored continually.

The chapter titled "Chemical and Physical Properties of Egyptian Shallow Coastal Lake" provides a full background of Lake Burullus' physical, chemical, and biological properties. The results indicate the heavy metals of the water near to the southern sector of the lake are higher than those near the northern sectors which are attributed to pollutants of drainage water [11, 12]. The author highlighted the current tremendous increase of the dissolved salts in the water of the lake compared to the 1980s measurements data. The southern drains are the main source of such pollutants as it feeds the lake with agricultural drainage waters that are rich with fertilizers. Based on the available observations, the lake annual mean water temperature is 22.3°C, while the annual mean water transparency and water depths are 31.0 and 115.8 cm, respectively. The annual mean water chlorosity is 1.9 g l^{-1}, and the lake is alkaline throughout the year with annual mean alkalinity of 257.8 mg l^{-1}. The annual mean dissolved oxygen (DO) and chemical (COD) and biological (BOD) oxygen demands are 8.6, 4.6, and 3.6 mg l^{-1}, respectively. The concentrations of dissolved salts have the following sequence, SiO2 > NO3 > PO4 > NO2, with annual means of 41.7, 2.8, 1.2, and 1.1 μg-at. l^{-1}. The concentrations of heavy metals have the following sequence, Zn > Fe > Cu > Cd > Pb, with annual means of 8.5, 6.2, 5.9, 3.8, and 3.6 μg-at. l^{-1}. The observed heavy metal readings were higher near to the southern part of the lake than those near the northern part. The annual mean water salinity was 5.4 ± 4.8 mS cm^{-1}. The salinity levels were low in the western part while they were higher in the eastern part. The author reported how the average salinity levels of Burullus decreased dramatically from 14‰ in 1966 to 3‰ in 2015, due to increasing of drainage water discharge into the wetland [13]. The salinity and chlorosity are positively correlated with each other and with Cd and Zn. The seawater is the main source of Cd and Zn in the water of the lake. The agricultural fertilizers (phosphates, nitrates, and nitrites) are positively correlated with each other. Similarly, the heavy metal (Cu, Fe, and Pb) are positively correlated with each other. Consequently, the major challenges facing the lake and its surrounding areas are the overwhelming flow of polluted drainage water and the climate change impact.

The chapter "Lake El-Manzala Characteristics and Main Challenges" documented that Lake Manzala is considered as the most important Egyptian freshwater aquaculture resource producing half the total fish production of the northern Delta lakes and almost one-fifth of the Egyptian nonmarine fish productivity [14]. It is noted that the land reclamation severely affected the sustainable future of Lake Manzala. It affects the water quality of the lake as it directly affects the residence time of water within the lake [15]. So that, several important species of fish vanished as they are not able to survive in poor water quality. The authors propose to expand the radial channels to improve the water circulation. The massive nutrient enrichment increases the algal blooms and increases the plant growth, which reduces the DO level in the lake. The consequence of the low level of DO causes the high fish mortality observed in the southern sectors of the lake. Moreover, the fishing communities strangely benefit from the existence of vegetation to divide the lake into small fish farms. This leads to increase the number of semi-closed basins with a reduced circulation and water quality. Finally, the third main challenge is the expected salinity level increment due to the freshwater diversion of El-Salam Canal Project. The physical, chemical, and biological properties of Lake Manzala are as follows:

- Lake average water temperature is 22°C with a minimum water temperature of 12°C during January and maximum water temperature of 30°C during July.
- The minimum observed Secchi were in Spring with a reading starting from 40 cm before reaching a maximum depth of 120 cm [16].
- The annual mean water salinity was 6 PSU during summer and 1.8 PSU during winter [17]. The salinity levels were low in the southern part, while they were higher in the northern part near the lake openings with an average of 7 PSU to 35 PSU. The water type changed from marine to be brackish during the past four decades. It declined by "about 82.7% since 1921, from 16.7% to 2.9% during 1985" [18].

- The annual mean dissolved oxygen (DO) and chemical (COD) and biological (BOD) oxygen demands are 5.6, 4.6, and 30.1 mg l^{-1}, respectively [17].
- The concentrations of the ammonia, nitrites, nitrates, silicates, and phosphates were found in high concentration near the outlets of drains in the southern region of Lake Manzala. The average values for nitrite, nitrate, silicate, total phosphorus, sulfate, sodium, potassium, and calcium, respectively, were fluctuated between 1.32–357.43 mg/l, 0.29–2.22 μg/l, 0.85–7.82 mg/l, 353.66–1395.62 μg/l, 22.61–357.43 mg/l, 280.47–821.13 mg/l, 12.12–44.39 mg/l, and 30.46–135.22 mg/l [18].
- The concentrations of heavy metals have the following annual mean values of Zn, Pb, and Cu of 0.07, 0025, and 0.2 mg/g. The observed heavy metal readings were higher near to the polluted southern part of the lake. It was concluded that a quick action for the lake remediation is initially to allow the law to take action over any stakeholder's violence toward the lake. Moreover, increased numerical modeling would provide further benefit.

3.2.1 Phytoplankton and Macrobenthos in Coastal Lakes

The phytoplankton is a key factor player in structuring and functioning the lakes' ecosystem. The chapter titled "Phytoplankton Ecology Along the Northern Egyptian Lakes: Status, Pressures, and Impacts" investigated the pattern, processes, and dynamics of phytoplankton community along the five northern lakes. The authors documented the phytoplankton flora in the five northern lakes of Egypt. The phytoplankton flora includes 867 species that belong to 9 algal divisions, 102 families, and 203 genera. The recorded names are in bold, italic types, and their synonyms are in italic type. The nine recorded algal divisions are arranged descendingly as follows: Bacillariophyta > Chlorophyta > Cyanophyta > Dinophyta > Euglenophyta > Cryptophyta > Chrysophyta > Phaeophyta > Rhodophyta [19]. Moreover, the chapter investigated the overall phytoplankton diversity and how phytoplankton characteristics differ between the northern Egyptian lakes. The authors discussed the main drivers that influence phytoplankton growth. The main drivers for this were surmised as water properties, drainage system, human activities and interventions, and grazing activities. They concluded that the species diversity of the five lakes could be arranged in descending order as follows: Manzala (383 spp.) > Mariout (376) > Bardawil (333) > Burullus (247) > Edku (183). However, bacillariophytes have the following sequence: Bardawil (238 spp.) > Mariout (255) > Manzala (253) > Burullus (126) and Edku (87). Chlorophyte sequence is Manzala (70 spp.) > Burullus (66.) > Mariout (65) > Edku (48) > Bardawil (14). Cyanophyte sequence is Manzala (49 spp.) > Mariout (43) > Burullus (36) > Edku (33) > Bardawil (22). Dinophyte sequence is Bardawil (53 spp.) > Burullus (7) > Manzala (4) > Edku (2) > Mariout (1) species, while euglenophyte sequence is Burullus (11 spp.) > Edku and Mariout (10 for each one) > Manzala (7) > Bardawil (1). To conclude, the chapter highlighted the success of using phytoplankton community as good indicative, in a way for nutrient levels in aquatic systems [20]. In particular, flourishing of specific algae species may indicate the water status and the pollution level of the lakes. Therefore, the increment of both factors (phytoplankton and nutrients) is the main reason for the degeneration of the lake ecosystem. So, it became crucial to think of quick solutions or mitigation plans.

On the other hand, in chapter “Status and Trends of the Egyptian Coastal Lakes Macrobenthos,” the author investigated the macrobenthos community in deltaic lakes and in Lake Bardawil. A discussion of the seasonal variations of common species was well presented. The usage of macrobenthos as indicators of the trophic state, water quality, and salinity of the water body is documented. The previous results confirmed that macrobenthic community composition changed during the past four decades in the northern lakes. The macrobenthos population density has dramatically decreased especially in 2003 and 2004. For example, only two molluscan species of 1986–1987 survey were recorded. At the same time, 24% of species recorded were previously recorded during 1986–1987, and 43% of such species were previously recorded during 2003 [21]. Since 1995, fisheries catch composition has also changed. The contribution of the economic species such as the sea bream and sea bass has sharply declined from 56.5%, in 1982–1988, to about 8.6% in 2003, of the total catch. The author reported the detailed background of Lake Burullus macrobenthos community as a case study of the deltaic lakes. Also, a good background of Lake Bardawil macrobenthos community was presented. Concerning Lake Burullus (brackish water), it hosted 34 macrobenthic species, belonging to three main groups (Arthropoda, Annelida and Mollusca) as recorded during 2013. The results showed no sign of occurrence of eight marine species, which have been previously recorded in this ecosystem during the 1970s and 1980s of the last century. It is worth mentioning that 17 species (freshwater in origin) were recorded for the first time in the Burullus wetland during 2003. This may be attributed to the increase in amount of discharging agricultural drainage, loaded with nutrients, into the wetlands via the southern drains. Decreasing salinity and nutrient loading have led to significant impacts on biodiversity and abundance of macrobenthos in this lake. However, Lake Bardawil, hypersaline water, hosted macrobenthic community of 51 species belonging to 5 phyla, Arthropoda, Annelida, Mollusca, Echinodermata, and Coelenterata, during the last 10 years. The abundance of macrobenthic species was closely correlated with the nature of bottom sediments, organic matter, and salinity. The observed long-term change in the macrobenthos density may be attributed to changes in the fish community structure. The author concluded that the northern deltaic lakes became more eutrophic and productive ecosystems. This leads to change in the fish community, which consequently affects macrobenthos assemblages, since the fish species decline is mainly bottom-feeders.

3.2.2 Hydrodynamics and Modeling with Applications

Generally, modeling is a mixture of science and experience. It requires an insight understanding of the physics to make a good judgment in terms of the trade-offs between those processes of secondary importance and keeping the problem as simple as possible [22]. There are several models for different applications with various approaches and assumptions. In this section, the lake formation, categorization, and their water hydrodynamic process were presented. The objectives and history of lake modeling were briefly introduced and the model assumptions and approaches presented. Two case studies of the Egyptian shallow lakes' water hydrodynamic simulation were presented.

In the chapter titled "Lakes and Their Hydrodynamics" a summary of the lakes' categorization, characteristics, and the quality of their water was presented. The lakes' main seven different formation processes were summarized as tectonic activity, volcanic activity, glacial activity, fluvial action, Aeolic action, anthropogenic action, and marine action. Also, the main characteristics of the lakes were highlighted as low flow velocity and relatively low inflows and outflows. The presences of vertical stratification of deep lakes where its depth is more than 7 m compared to the well-mixed shallow lakes were presented. The major nature of the lakes' hydrodynamics such as inflows and outflows, wind shear, vertical circulation, thermal stratification, and gyres and seiches was discussed. The authors identified eutrophication as the major problem that lakes face. This process associates with the excessive nutrient enrichment and long residence time where it appears clearly in the major Egyptian deltaic lakes. Lake Burullus and Lake Manzala suffer from such phenomena and need a quick action plan to remediate the lakes' characteristics.

On the other hand, the chapter "Basics of Lake Modelling with Applications" provides the audiences with the important basics of the numerical modeling and the most popular models with some of its applications. The chapter starts with a general introduction to the modeling field and the reasons to use numerical models. This is followed by a brief introduction to the techniques and assumptions that are commonly used. The authors summarized the assumptions as hydrostatic, Boussinesq, and quasi-3D approximations. Then the different types of horizontal and vertical grids were presented. A selected list of the top important models of the available hydrodynamic models was listed. The selected models are recognized as widely used and well tested by hydrodynamic modelers and researchers. These models were evaluated according to certain requirements in order to select the most suitable ones for the Egyptian coastal lakes. The authors recommended a few models for the hydrodynamics of shallow lakes, the Egyptian ones in particular. These models include but are not limited to FVCOM, MIKE3D, Delft3D FM, POM, and ROM in our opinion. The authors presented a good review of the previous hydrodynamic modeling of lakes. The review for shallow lake modeling indicates that different approaches were adopted for the different applications. The authors concluded that integrated, sophisticated 3D hydrodynamic models for shallow lakes, coupled with sedimentation, water quality, and ecological models, had been developed and intensively used over the last decade.

In the chapter "Numerical Simulation of Lake Mariout, Egypt," the authors develop a 2D hydrodynamic model to simulate the water hydrodynamic behavior of Lake Mariout, Egypt. The model successfully simulates the water velocity and flow circulation within the lake main basin. The model was calibrated using a partial set of collected recent data sets (2013–2014) from different sources. The comparison between the predicted and measured data at different locations showed good agreement. Moreover, the produced hydrodynamic model replicates successfully the main physical and hydrodynamic process. As a good level of model confidence of the hydrodynamic model accuracy was achieved, the model was used as a driver for the water quality model. The water quality model includes the main water quality parameters such as ammonia and DO. The water quality model was validated and then used to evaluate different water quality management scenarios of Lake Mariout. The authors' investigated several scenarios include load reduction from all drainage points to the lake by 25, 50, and 75% of its total amount. Also, they investigated the load reduction from El-Qalaa drain, the main source of pollution, by 50%. Although El-Qalaa drain is the main source of pollution in the lake, the proposed 50% reduction of its pollutant load has no effect on the lake salinity or water quality levels. However, a reduction of 50% pollutant load from El-Omoum drain increases the DO levels and slightly decreases the salinity level. Moreover, the authors reported the needs for including suspended sediment concentrations, COD, BOD, chlorophyll-a, and phosphorous compounds in future models. Also, they proposed to conduct a permanent monitoring system to get continuous records of both hydrodynamic and water quality parameters in all parts of the lake. An action is urgently needed to restore the healthy environment of the Egyptian coastal lakes to allow them to share in the development and growth of the national income of the Egypt. Fortunately, the Egyptian government started to implement the sustainability agenda 2030 and one of its important sections is about developing and maintaining the coastal lakes.

Additionally, in the chapter titled "A Three-Dimensional Circulation Model of Lake Bardawil, Egypt," the numerical modeling technique was applied using the coastal ocean circulation model FVCOM to simulate Lake Bardawil water circulation. The three-dimensional validated model predicted the salinity levels within the water body. The model was validated against available oceanographic field data. The model predicted results were in good agreement with the measured salinity levels at the 12 sampling stations. The results showed that the water circulation is governed mainly by physical forcings such as tide and wind. The Coriolis effect and tide effects are responsible for the northward saline water transport to the lake and the mixing, respectively. The chapter reported the essential needs for more accurate field data through the national network for the spatial monitoring program. This will lead to better improvement in the results of such models. The produced model showed the importance of this technique to help in providing information and scenarios for better management and conservation of the Egyptian lakes.

4 Recommendations

The Egyptian authorities should propose a management plan for these valuable water resources. These quick plans should be integrated with the whole community. The community including academic, stakeholder, local community, and the fisheries industry should be involved. The ultimate goals of the management and development plans should consider the lakes' water quality and ecological equilibrium as well as the full economic benefit. The following proposed plans are essential and could greatly support the national vision sustainable development strategy (SDG) for 2030.

1. Initiating and establishing a well-working nation network for spatial monitoring and assessment of water quantity and quality. This important program should cover but not limited to the following parameters: physical, chemical, and biological. Also, the program needs to monitor climate variables related to climate change to take the needed mitigation/adaptation measures.
2. The key influencing factors that control the sedimentation rate and the sediment properties should be monitoring.
3. The full updated bathymetry data is not available, so it is recommended to launch campaigns to collect an updated set of data.
4. The wind is one of the main controllers of the lakes' water hydrodynamics. Therefore, the availability of hourly base accurate wind data will significantly improve the understanding of the water circulation when using numerical simulation tools.
5. Following the monitoring program and data collecting process, it is important to establish effective networking, information exchange, and coordination among all concerned parties.
6. The monitoring program should utilize new technologies such as remote sensing and geographic information system (GIS) to collect and upgrade available data.
7. Monitoring of land use/land cover changes in the boundaries of the lake is essential for the planner, management, governmental and nongovernmental organizations, and scientific community.
8. The monitoring program at certain points needs some measures, statistical analysis, and firm follow-up of the process.
9. The socioeconomic opportunities should be improved especially for local communities around the water bodies.
10. The public awareness is essential regarding the nature conservation of the coastal lakes. The scientific community needs to be engaged in the development process of increasing the public awareness and participation in monitoring programs.
11. The massive amount of polluted water should be treated through water treatment facilities before entering the water body to fulfill the water quality standards.
12. The academic community needs to be encouraged to prepare the full database for the lakes in order to introduce alternatives and innovative options to face the projected impacts of climate change.

The law should be enforced to protect the coastal lakes as a conserved natural region and forbid all illegal practices such as drying, illegal fishing methods, overfishing, isolating water bodies, and untreated drainage discharge. Moreover, decision-makers need to restore ecological, water quality, and landscape values which have been lost or damaged. The restoration process of salinity levels to a safe level should be priorities. Restoring ecological system which have been deteriorated through controlling the use of fertilizers in agriculture, as they are the primary source of heavy metals, nutrients, and other pollutants.

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