

# 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 socio-economic 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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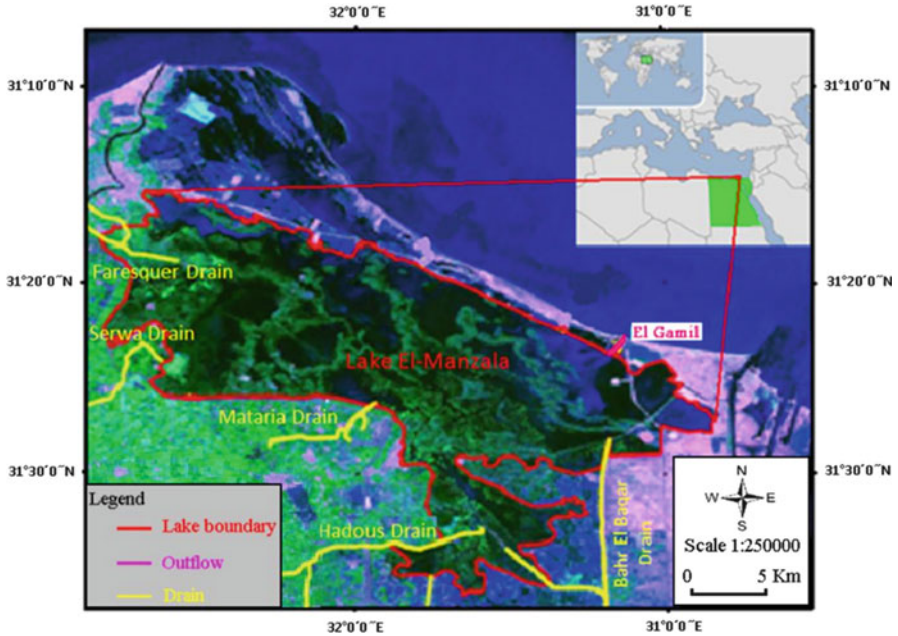
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## 1 Introduction

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  $31^{\circ} 45' - 32^{\circ} 15'$  east and latitudes  $31^{\circ} 00' - 31^{\circ} 30'$  north) has a total surface area of about  $700 \text{ km}^2$  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, Pelusiatic, 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<sup>2</sup> in 1907, 1,470 km<sup>2</sup> in 1949, and 1,260 km<sup>2</sup> in 1960 reaching 895 km<sup>2</sup> in 1979 [3]. In addition, it is reported that the total loss of water body of Lake Manzala was estimated at about 355 km<sup>2</sup> 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

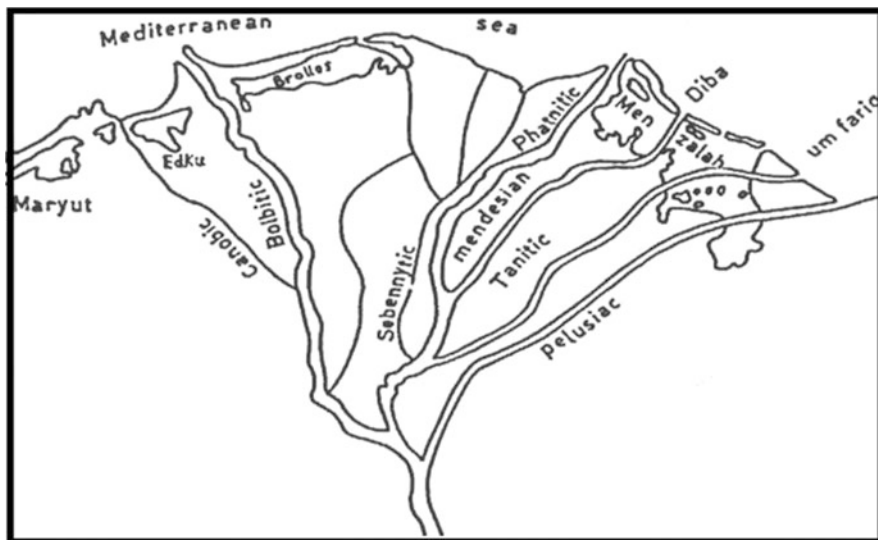


Fig. 2 Lake Manzala historically after [2]

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<sup>3</sup>. 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 <sup>2</sup>
Lake classification	Brackish
Average and maximum depth	1–3.5 m
Average sediment accumulation rate	1.9–2.2 kg m <sup>-2</sup> year <sup>-1</sup>
Annual precipitation	78.4 mm year <sup>-1</sup>
Annual evaporation	1,100.2 mm year <sup>-1</sup>
Annual mean temperature	21.4°C
Suspended particulate matter	129–261 mg m <sup>-3</sup>
Chlorophyll a	12.66–32.38 mg m <sup>-3</sup>
Zooplankton	1,212 × 10 <sup>3</sup> animals/m <sup>3</sup>
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 <sup>-1</sup>

## 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.

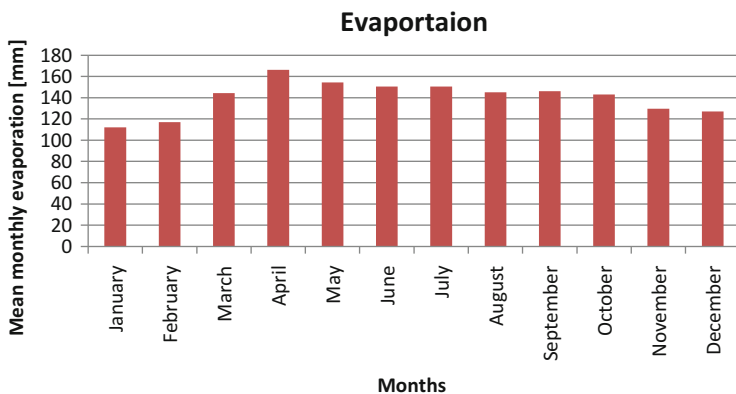


Fig. 3 Mean monthly evaporation after [18]

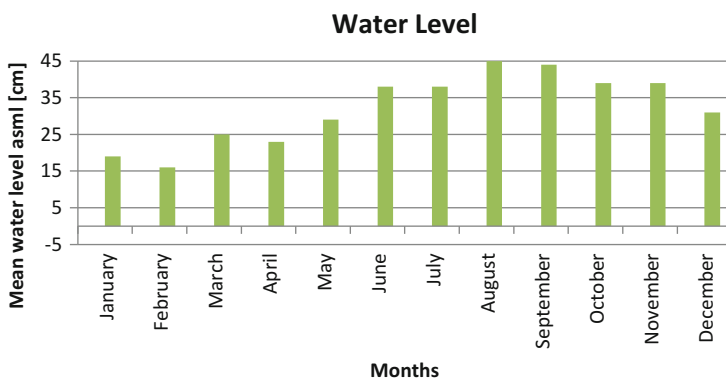


Fig. 4 Mean monthly water level fluctuations after [6]

### 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 ( $\text{NO}_3$ ) 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  $4,200 \times 10^6 \text{ m}^3$  annually [6]. However, it has recently increased to  $5,463 \times 10^6 \text{ m}^3 \text{ year}^{-1}$  according to [5]. The maximum inflow of water takes place in the summer season while the minimum rate is in winter.

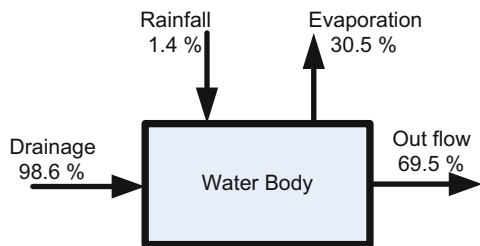
The Bahr El-Baqar drain is considered to be the largest contributor to the lake. The drain carries untreated and primary treated wastewater from the east Cairo region along the 170 km of its length [22]. The maximum flow volume occurs in summer from the beginning of July until the end of September, and its peak is reported in August at about  $200 \times 10^6 \text{ m}^3$  [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



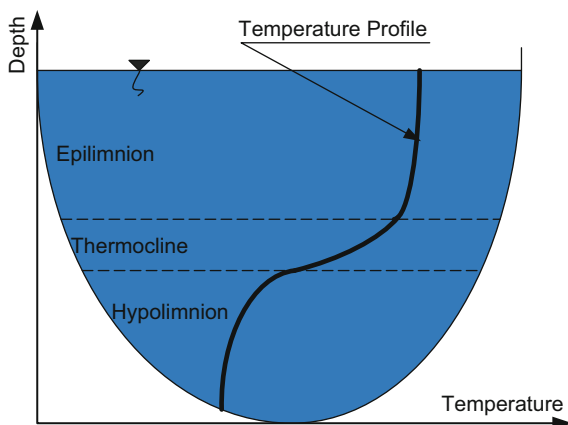
responsible for a loss of approximately 30% of the total water inflow to the lake with the balance being delivered to the Mediterranean Sea.

## 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.

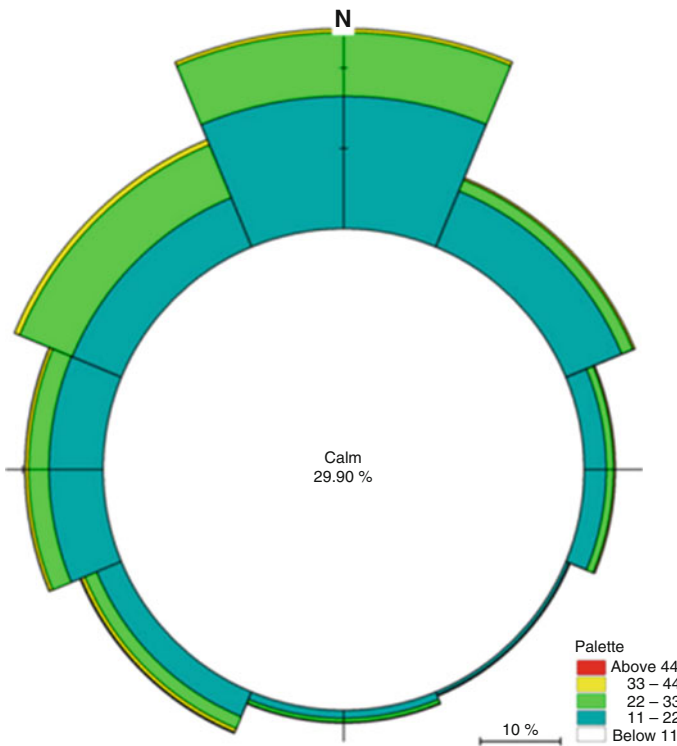
The flow patterns within the lake are dominated by the average surface wind speeds, which range from 6 m/s from in the north to 1.5 m/s in the south of the lake. The wind speeds are observed to be lower in July and August and to increase in magnitude progressively in November and January, reaching a 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  $-2.22$   $\mu$ g/L, 0.85 and  $-7.82$  mg/L, 353.66 and  $-1,395.62$   $\mu$ g/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. Submergent 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<sup>3</sup> [11]. However, it sharply increases to 1,000 mg chl/m<sup>3</sup> 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  $1,212 \times 10^3$  animals/m<sup>3</sup>. 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  $500 \times 10^3$  animals/m<sup>3</sup>, with a minimum loading period in February and August and a maximum of  $3,000 \times 10^3$  animals/m<sup>3</sup> 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<sup>2</sup> in 1977 [12] to only 700 km<sup>2</sup> in 2009 [5]. It is predicted that at the current land reclamation rates being practiced, this will leave the lake with only 450 km<sup>2</sup> 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

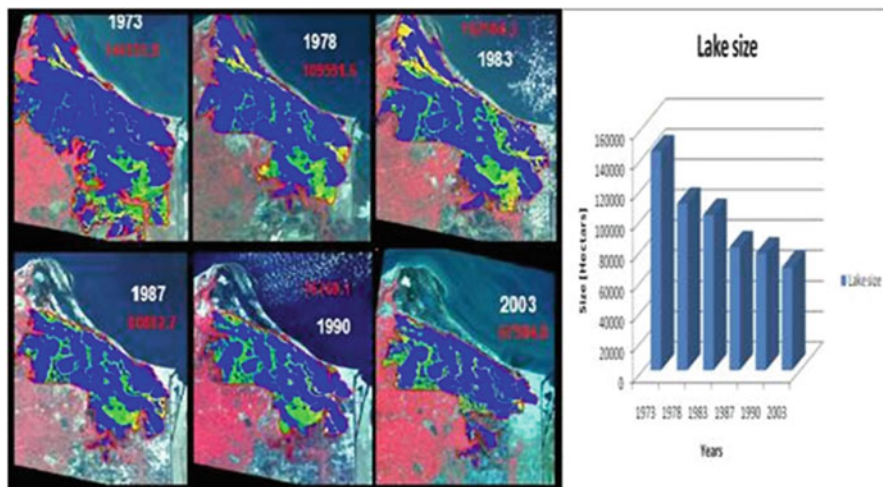


Fig. 8 Land reclamation during the past four decades after Donia and Ahmed [1]

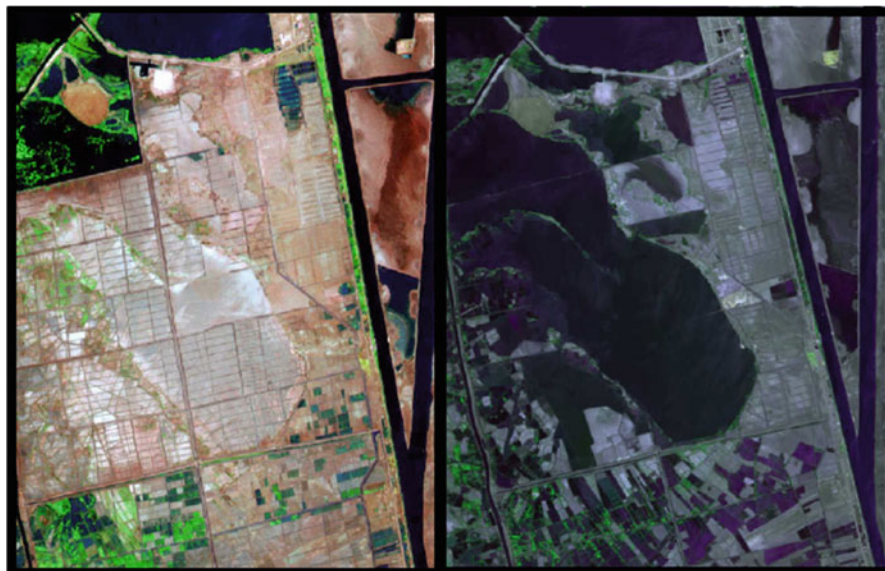


Fig. 9 Land reclamation in the southern region of Lake Manzala (On the left is the current situation, on the right the extent of the water before reclamation)

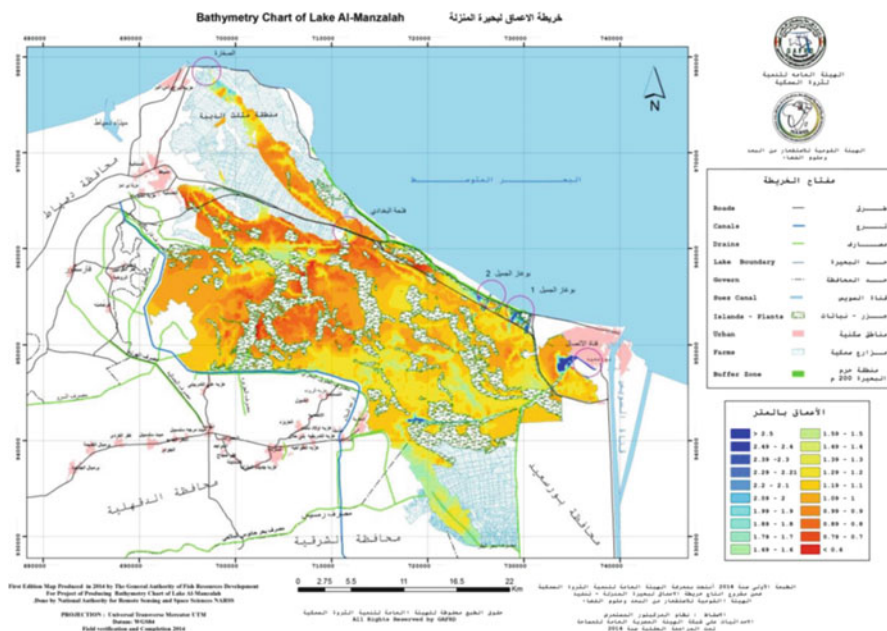


Fig. 10 Lake Manzala bathymetry 2014

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<sup>2</sup> 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<sup>3</sup> 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

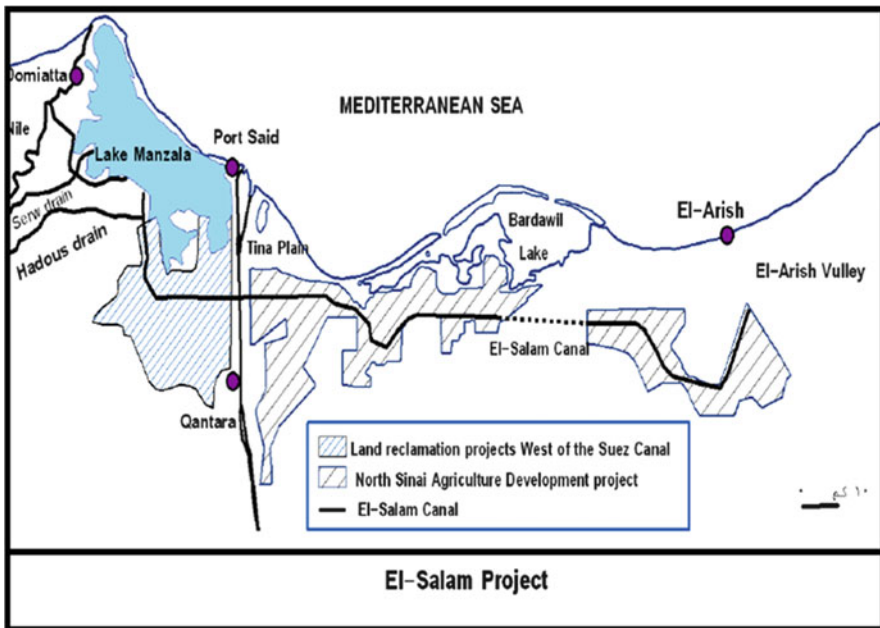


Fig. 11 El-Salam Canal project

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  $\text{SO}_4$  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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