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Authors: Morsy, Karim M, Mishra, Amrit K, and Galal, Mona M

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Karim M Morsy[1], Amrit K Mishra[2] and Mona M Galal[1]

[1]Department of Sanitary and Environmental Engineering, Faculty of Engineering, Cairo University, Giza, Egypt. [2]Marine Conservation Department, Bombay Natural History Society, Mumbai, India.

ABSTRACT: Nile Delta Lagoons have been formed 7000 years before the present. The lagoons were aqua-cultural and ecological keystones for the early Egyptian agricultural civilization. The water quality of Nile Delta Lagoons has been deteriorated with the economic development, population rapid increase, and the related industrialization, which exert high pressure on the surrounding environment. The 4 lagoons (1) Maryut, (2) Edku, (3) Burullus, and (4) Manzala are large is surface area, shallow in depth and located on the Nile Delta that receive great amounts of agricultural drainage, sewage, and industrial effluents before discharging into the Mediterranean Sea. The aim of this study is to monitor and assess the water and sediment quality of the lagoons. In light of this assessment, it was found that excessive nutrients are discharged into these lagoons causing severe eutrophication. In addition, relatively low values of dissolved oxygen were recorded causing fish mortality in the lagoons which amplifies in summer as the temperature increases. The article also examined the physical and biological parameters in addition to the chemical concentration of trace metals (Zn, Fe, Pb, Mn, Cr, and Cd) in the water and sediment samples that were collected from the 4 lagoons. High values of biological oxygen demand, chemical oxygen demand, total coliform, fecal coliform, fecal streptococci, ammonia (NH_3), total nitrogen, and total phosphorus were recorded. In addition, high concentrations of trace metals were found in the water and sediments of the 4 lagoons.

KEYWORDS: Water quality, sediment quality, Nile delta lagoons, trace metals, physical and biological parameters

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CORRESPONDING AUTHOR: Karim M Morsy, Department of Sanitary and Environmental Engineering, Faculty of Engineering, Cairo University, Giza 12613, Egypt. Email: kareemmorsy@ymail.com

Introduction

In Egypt, the main freshwater resource, the Nile River, divides into 2 branches, Rosetta and Damietta forming the Nile Delta. It provides 96% of the renewable water resources to fulfill the agricultural needs for food, urban, industrial, and environmental usage as per the Agreement on Full Utilization of the Waters of the Nile made between Egypt and Sudan in 1959.[1] Egypt receives 55.5 billion cubic meters (BCM) of water annually, which represents about 97% of the renewable water resources in Egypt as shown in Figure 1.[2] This is in addition to the groundwater, desalinated water, domestic wastewater, and rainfall. The Blue Nile, all of which rise in Ethiopia, contribute about 85% of the Nile waters that reach the Aswan High Dam (AHD).[3] From these water resources, 67% are used for industrial purpose and the Nile river receives 57% of the water as industrial effluents.[3,4] Consequently, the Nile River water quality has been steadily deteriorating over the last few decades due to discharge of these industrial effluents and various other untreated wastewater and anthropogenic inputs.[3,4] Moreover, the construction of AHD over the Nile River not only resulted in checking the flow of water downstream, it also led to drastic changes in the physico-chemical and biological parameters of the Nile ecosystem.[4] The AHD have also led to reduction in area of 3 critical lagoon ecosystem of the Nile Delta, such as Manzala lake area (in eastern delta lagoon), Burullus lake area (middle delta lagoon), Edku and Maryut lake area (western delta lagoon), and associated ecosystems.[5]

Water quality is a term used to describe the physical, chemical, and biological characteristics of water. However, the increase in water consumption to satisfy the different demands leads to rapid increase in the quantities of wastewater disposal.[4] The continuous wastewater disposal to the water body causes a serious impact on the water quality of the Nile River. In response to the growing concern about the environmental degradation of the ecological system and to recover the water quality, the governmental and nongovernmental organizations introduced some environmental regulations and awareness of the human activities negative impacts on surface water quality.

Deteriorating water quality of Nile Delta has both environmental and socioeconomic consequences. This degradation of water quality is based on 2 factors, ie, the increasing population inhabiting the upriver areas and various economic activities.[5] The combination of these 2 factors has led to huge anthropogenic pressure on the River Nile delta. The major anthropogenic activities that have led to degradation of water quality are the discharge of untreated sewage from open drains, agricultural return flows, domestic sewage, and industrial wastewater.[6] The agricultural pollutants include agrochemicals such as fertilizers, herbicides, and pesticides. It has also been recorded that the dissolved Oxygen (DO) concentrations in the 2 branches fail to fulfill the required standards.[7,8] The Damietta branch suffers from the pollutants that are discharged from fertilizers' factories and other industrial effluents that are disposed along the branch.[9] Moreover, 10 out of 67 various drains that discharge these contaminates and pollutants into the Nile Delta do not comply to the Egyptian standards. As a result of these industrial, agricultural, and domestic wastes, the trace element contamination of the Nile River and its Delta has

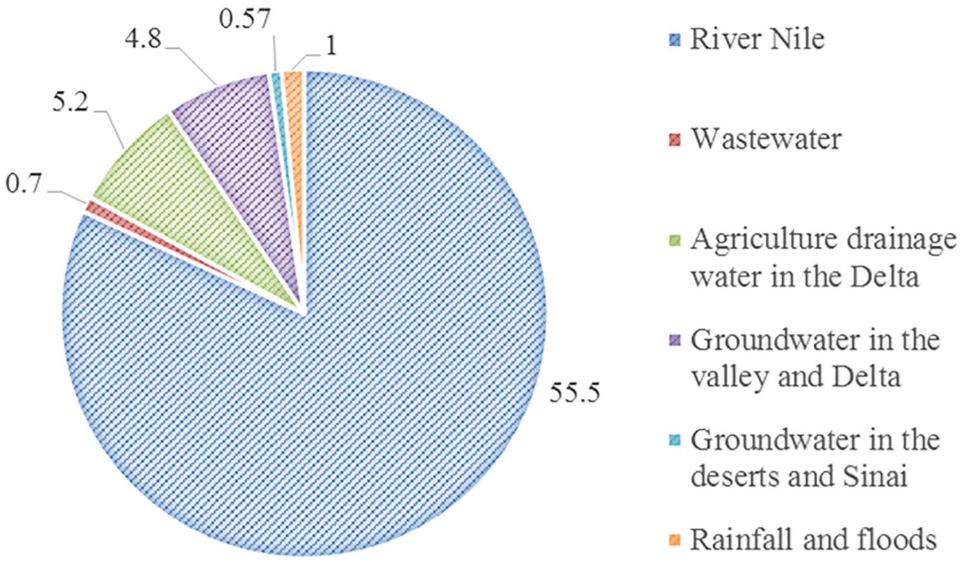

Figure 1. Egypt's main water resources.[2]

increased significantly over time. Element enrichment is a serious concern for water quality, associated biodiversity, and human health, as these elements are nonbiodegradable and can accumulate through food chain and ultimately reach humans through fish consumption.[10]

Periodic water quality evaluation of the Nile River is essential for maintaining feasible water standards for human activities and sustainability of the aquatic biodiversity and migratory birds.

Therefore, the aim of this study is to assess the water quality of the Nile delta at 4 important locations. At each of these locations, various physiochemical parameters of the water were quantified over a period of 1 year. Bacterial pathogenic organisms cell counts were used to derive the suitability of the water for human consumption. The sediment of these locations was used to quantify various trace elements such as Cd, Cr, Cu, Fe, Hg, Mn, Ni, and Pb and their respective contamination levels. Similarly, these trace elements were also quantified in the water column from the same study locations. These various parameters were used to assess the water quality of the main 4 Nile Delta Lagoons in Egypt to determine the pollution sources causing the deterioration of these lakes and their impact on the associated biodiversity and human health. Hence, pollution prevention and/ or control strategies were suggested to achieve environmental conservation for future sustainable development projects.

Materials and Methods

Study areas

The Nile delta lagoons are located in 3 different regions as shown in Figure 2. The lagoons locations can be divided as follows:

1. Eastern Delta Lagoon (Manzala): from Suez Canal to Damietta branch.
2. Middle Delta Lagoon (Burullus): between Damietta and Rosetta branch.
3. Western Delta Lagoons (Edku & Maryut): all canals and drains in the west of Rosetta branch.

Manzala lagoon. Manzala lagoon is considered as the largest lagoon in Egypt. It lies between latitude 31° 45′ to 31° 35′ N and longitude 31° 45′ to 32° 50′ E. It is located in the northeast of Nile Delta on the Damietta branch. The water salinity of the lagoon widely varies from saline water in the northern part to fresh water in the southern part. The lagoon is relatively very shallow with average depth of 1.3 m. It receives water from groundwater, fluvial, and seawater.[11] Annually, an average of 7500 million cubic meters of untreated domestic, industrial, and agricultural water are drained to Manzala lagoon, which resulted in the contamination of the lagoon and the richness of its sediments with trace metals.[12]

Edku lagoon. Edku lagoon is a shallow coastal wetland located in the north-west part of the Nile Delta on the Rosetta branch 30 km from the city of Alexandria. It lies between latitudes 30°12′N and 30°16′N, and longitudes 31°18′ and 32°09′E. Boughaz El-Maadyia channel connects the lagoon with the Mediterranean Sea. The total area of the lagoon is almost 65 km^2 which consists of 22 km^2 open water and 43 km^2 wetland area which is covered by aquatic vegetation and isles.[13] Edku Lagoon also receives large amount of untreated drainage water from El-Khairy drain with total annual discharge of 592 $\times 10^6 m^3$/year and Barsik drain total annual discharge of 348 $\times 10^6 m^3$. Seawater intrusion occurs at the western part of the lagoon where the outlet exists.[14]

Burullus lagoon. Burullus lagoon is the second largest lagoon in Egypt after Manzala lagoon. It lies between latitude 30°30′ to 31°10′ E and latitudes 31°35′ to 31°21′ N. It is located in the

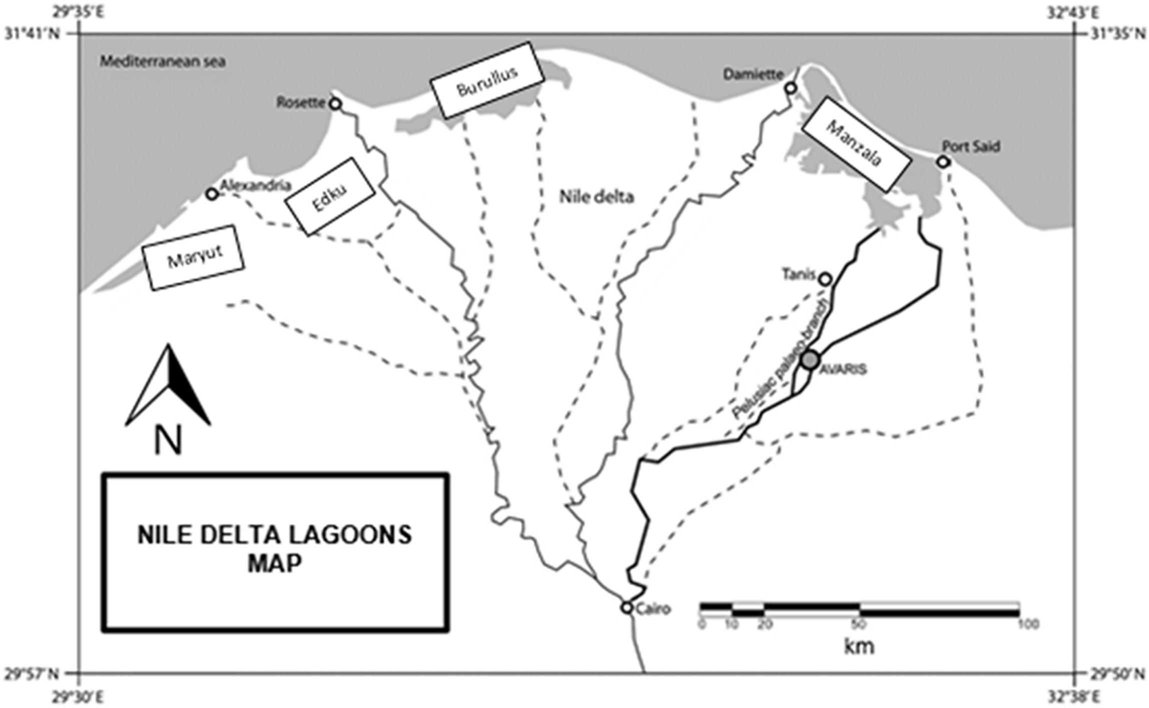

Figure 2. Distribution of the Nile Delta showing the 4 lagoons: (1) Manzala, (2) Edku, (3) Burullus and (4) Maryut.

central part of the northern shoreline of the Nile Delta.[15] It is considered a special site for the birds' migration and a valuable fish resource. It is a shallow lagoon with an average depth of 1.75 m of water and a surface area of 410 km^2. Burullus lagoon is also facing water quality challenges.[16] The lagoon is rich in trace metals contamination due to the industrial and agricultural discharge to its water body.[17,18]

Maryut lagoon. Lake Maryut is divided into 5 main areas separated by sand banks. It lies between latitude 29°30′ to 30°00′ E and latitudes 31°30′ to 31°10′ N. It is located 20 meters far from the Mediterranean Sea; however, it does not have any direct connection point out to the sea to aid in its natural purification process. It is deeper than the other lagoons with 4 m average depth of water. It is the most polluted lagoon in the Nile Delta not only because of the agricultural drains discharging to the lagoon but, also for the effluents from a petroleum refinery and other industries which are directly discharging into its water body. The Nubariyah Canal and Omum drain are the main water bodies connected to it.

Main factors affecting water quality of the Nile Delta lagoons

Pollution (domestic, agricultural, and industrial). The condition of the water quality in the Nile Delta is serious in both Damietta and Rosetta branches. The Dissolved Oxygen (DO) concentrations in the 2 branches fail to fulfill the required standards. The major sources of pollution of Rosetta branch are some drains in the southern part in addition to the industrial effluents. On the other hand, the Damietta branch suffers from the fertilizers' factories effluents that are disposed along the branch. Water quality in irrigation canals depends on the location point where the water is supplied along the Nile from which they draw their water. Mainly pollution along the canals can be measured based on 2 aspects:

- Quantity of domestic and industrial effluents.
- Quantity of flow in the canals based on the irrigation demands.

Climate change. Climate change rises the atmospheric temperature which leads to an increase in the water temperature, change in precipitation regimes, and occurrence of intensive storm events. This rise in water temperature leads to a complete loss of underwater vegetation in deep waters and the increase in the mineralization rate of the catchment sediments and soils accompanied by an increase in the nutrient loading. This increase causes a depletion of the dissolved oxygen in the lagoons which amplifies in summer as the temperature increases. Also, the increase in the storm intensity leads to an increase in the land erosion and the rate of nutrients delivery to the lagoons.[19]

Fish farms. Many fish farms are distributed in the estuaries of Rosetta and Damietta. Fish farming is a main contributor to poor water quality due to bio-deposits such as fish feces and uneaten feed, which produces H_2S and ammonia. The waste materials produced by the fish farms are not only affecting the physical and chemical properties of the aquatic ecosystems, but also have negative effects on the human health.[20]

Methods of monitoring the water quality

In this study, various water quality parameters were measured in situ in the 4 lagoons using YSI 6000 multiprobe (Xylem Inc, USA). Measurements took place during the year 2017 for the months of January, March, June, September, and December. At each location 4 points were fixed using a GPS for different depths (0.2, 0.5, 0.7, and 1.3 m). In each month, sampling was carried twice using the multiprobe to record several parameters such as (1) pH, (2) temperature, (3) dissolved oxygen, (4) turbidity, and (5) total suspended solids (TSS) of each study location. Five water samples were collected from each point for biological oxygen demand (BOD), chemical oxygen demand (COD), and nutrient [total nitrogen (N) and phosphorous (P)]. Also, from the collected water samples, laboratory tests and analysis were carried out to detect the concentration of trace metals in the different lagoons such as Zn, Fe, Cu, Pb, Mn, Cr, Cd, and Hg.

In addition, microbial contamination with pathogenic microorganisms is one of the most important indicators for water pollution. Pathogens are considered to be a main responsible for waterborne diseases. The presence of pathogens in water may be due to direct domestic discharge of untreated sewage or agricultural wastewater drainage. Fecal coliform bacteria, fecal streptococci bacteria, and total coliform bacteria are typically selected as microbial indicators for presence of pathogens in the water bodies.[21] Multiple fermentation tube technique was used for the analysis of total coliforms as a most probable number (MPN) index.

Methods of monitoring the sediment quality

Five sediment samples were collected for each location, from the same fixed points as water parameters were measured. The sediment was collected using a sediment grab and was packed into a ziplocked plastic bag and stored in a cool box and transported to laboratory. In the laboratory, the sediment samples were oven dried at 105°C for 24 hours, grinded and sieved. Then, 1 gram of the fine fraction (<0.65 microns) were digested with a mixture of concentrated acids by adding 60 mL of the acid in a ratio of 30 mL H_2O_2: 20 mL HCl: 10 mL HNO_3. After the acid was evaporated, the left-over solute was dissolved in 6 mL HCl, filtered and left in 2 N HCl solution for elemental measurements.[22] Thermo electron spectrometer was used to detect the trace metal (Cd, Cu, Cr, Fe, Hg, Mn, Ni, and Pb) concentration (mg/g) in the sediment.

Results

Water quality monitoring

Physical properties. The main physical parameters were monitored for water in the 4 lagoons. These parameters are pH, temperature, dissolved oxygen, turbidity, and total suspended solids (TSS) as shown in Figure 3.

The pH values of the water column in the 4 lagoons were ranging from 7.99 to 8.78 which indicates that the water in the 4 lagoons is alkaline. A general pattern of high pH values for each location was observed for the month of December. The pH values of Maryut and Edku lagoon were lowest in March, while that of Burullus and Manzalah lagoon were lower in June 2017. The water temperature levels were higher in June and September at the 4 locations, within a temperature range of 29.73°C to 34.45°C and lower in January and December of the year 2017, due to seasonal influence of summer and winter season of Egypt. The effect of high temperature was clearly observed on the DO content of the water. The months of June and September with high temperature were observed with low DO content at the 4 locations and vice versa. As the water temperature increases, it was noticed that a complete loss of underwater vegetation in deep waters and increase in the mineralization rate of the catchment sediments and soils accompanied by an increase in the nutrient loading. The dissolved oxygen decreases below the allowable limit (less than 4 mg/L) causing severe eutrophication and fish mortality in the lagoons which amplifies in summer as the temperature increases as mentioned in the US Environmental Protection Agency manual for the ambient water quality criteria for dissolved oxygen.[23] Also, in the winter season, specifically in December and January, when the temperature decreases, the dissolved oxygen in the water returns back to the accepted values. Similarly, the months with higher turbidity also resulted in lower DO content.

Total suspended solids (TSS) is a significant factor in identifying water clarity, the higher TSS, and the lower clarity of water.[24] These solids include all the floating and drifting sediment, silt and sand to plankton and algae in the water.[25] Although most suspended solids are made up of inorganic materials, bacteria and algae can also contribute to the total solid concentration.[26]

The TSS were directly affected by turbidity levels, with higher turbidity resulting in higher TSS content in the water column and vice versa. The TSS levels of the 4 lagoons were within the same range. TSS values were the highest in June and September during the summer season and lowest in January and December during the winter season, except for Manzala lagoon where the TSS values were high.

Suspended solids enter the water column in the form of small organic particles after the decomposition of algae, plants, and animal decay.[27] The turbidity of water can be measured based on the amount of light scattered by the particles exist in the water column. The turbidity of water was measured using a Sacchi desk. The presence of more particles, the more light will be scattered. Accordingly, there is a relation between turbidity and total suspended solids. However, turbidity is not a direct measurement of TSS. It can only give an indication of the changes in the total suspended solids concentration in water without providing an exact value of it.[27]

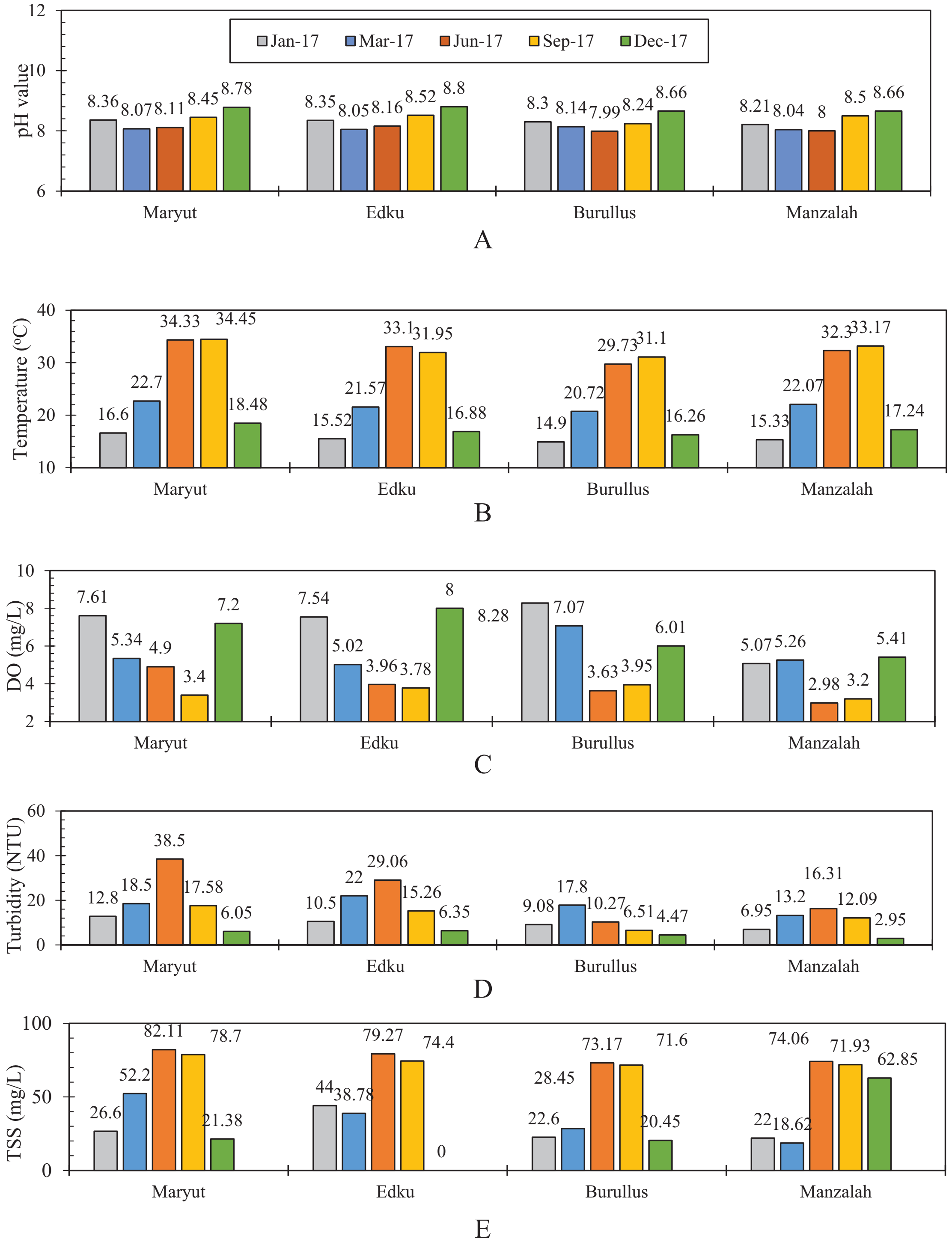

Figure 3. Water physical properties of Nile Delta lagoons during year 2017 where: (A) pH, (B) temperature, (C) dissolved oxygen (DO), (D) turbidity and (E) total suspended solids (TSS).

The water chemical and biological properties were also monitored in the 4 lagoons of the Nile Delta as shown in Figure 4. High values of BOD, COD, total coliform, fecal coliform, fecal streptococci, ammonia (NH_3), total nitrogen, and total phosphorus were recorded. The BOD recorded the highest values in Maryut lagoon with average 43.02 mg/L; however, Edku and Burullus lagoons showed relatively lower values with averages 15.3 and 16.6 mg/L, respectively. Accordingly, the COD recorded the highest values in Maryut and Manzala lagoons with averages 230 and 227 mg/L, respectively.

However, Edku and Burullus lagoons showed relatively lower values with averages 181 and 193 mg/L, respectively. It was noticed that during the summer season in the month of June when the temperature of water is high, the BOD and COD have shown higher values compared with the winter season in the months of January and December. This can be

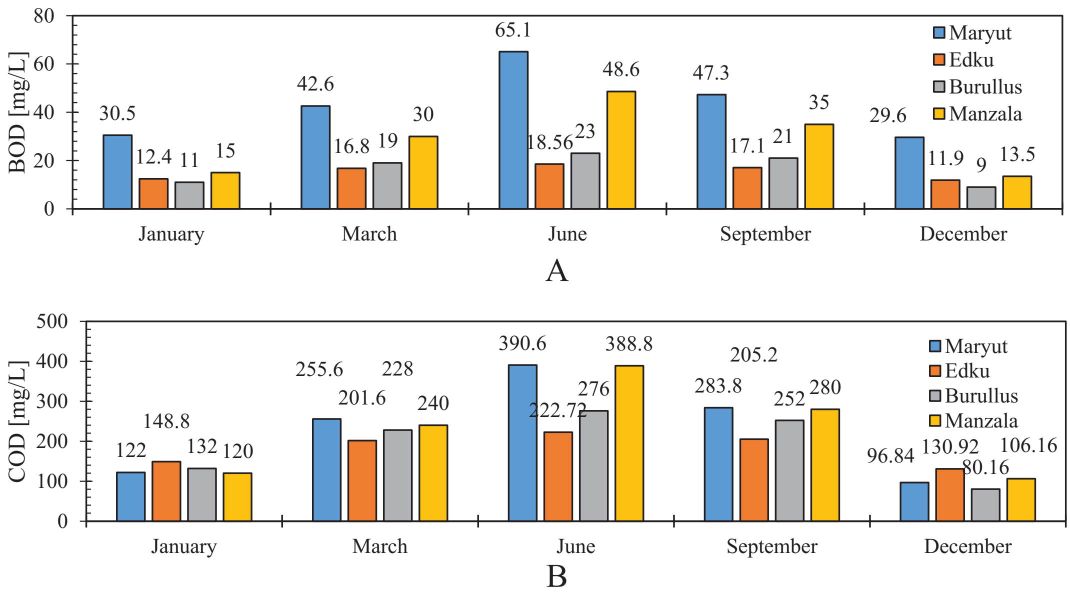

Figure 4. (A) Biological oxygen demand and (B) chemical oxygen demand.

because as the temperature of water increases, the photosynthesis rate made by the algae increases.[28] This accordingly fastens the bacterial rate of decomposition and results in higher levels of BOD as shown in Figure 4.

These values were compared against the records of the Egyptian Environmental Affairs Agency (EEAA), Central Department for Water Quality the national program for monitoring the Egyptian Lakes as shown in Figure 5.[29] This is intended to allow for a strong comparison and validation to be made between the analyses conducted herein and previous studies from the literature.

The excessive amount of nutrients such as nitrogen and phosphorus discharging to the water bodies of the lagoons are the main cause of eutrophication phenomenon, which results in undesirable disturbance to the balance of organisms and affects the water quality.[30] Eutrophication can take place in all types of water bodies such as lakes, rivers, seas, and oceans regardless their degree of salinity. Excess fertilizers and chemicals are being discharged into the aquatic ecosystem resulting in the presence of aquatic organic matter causing hypoxia and anoxia, which threat the beneficial, commercial, and recreational fisheries.[31] After analyzing the samples taken from the 4 lagoons, it was noted that all of them has high concentration of nitrogen and phosphorus as shown in Figure 6. The total phosphorus test measures all the forms of phosphorus in the sample (orthophosphate, condensed phosphate, and organic phosphate). Spectrophotometric method was used for determining total nitrogen in water sample. The method depends on oxidation and reduction steps, including persulfate digestion of nitrogen compounds into nitrate then spectrophotometric determination. This is the main cause of the eutrophication that takes place in the 4 of them. Maryut lagoon was found to be the most eutrophicated lagoon because it recorded the highest concentration of nutrients.

Microbiological analysis has been performed for water samples collected from the 4 lagoons. The values of fecal coliform bacteria, fecal streptococci bacteria, and total coliform bacteria were found to be high for the 4 lagoons, which indicates the presence of high amount of pathogens in water. Maryut lagoon has shown an extremely high level of contamination compared with the others and to the Egyptian Law allowable limits as shown in Table 1.

Trace metals. High concentrations of trace metals: Zn, Fe, Cu, Pb, Mn, Cr, Cd, and Hg were also observed in all the lagoons as shown in Table 2. Out of the 4 locations, the trace elements concentration in the water column of Maryut and Burullus lagoon were higher compared with the other 2 locations. Trace elements such as Cd, Cu, Fe, Pb, and Ni concentration were higher at the Burullus lagoon, whereas Cr and Mn levels were higher at the Maryut lagoon and Hg levels were similar between these 2 lagoons. Industrial discharges are considered the main source of trace metals existence in the water body of the Nile Delta Lagoons. Some other secondary sources are contributing in the increase of the existence of trace metals in the water body such as the fertilizers, Fe and Mn rock leaching. Also, it was noted that more than 60% of the metals found in the lagoons are due to the discharging of effluents from petroleum refining sites and associated chemical by-products into it.[32]

The concentration of Cadmium (Cd) showed a narrow range of variation ranging from 0.92 to 1.8 μg/L. Copper (Cu) and Chromium (Cr) were ranging from 13.96 to 24.9 μg/L and from 5.63 to 8.85 μg/L, respectively. The highest concentration for Cu was recorded in Burullus lagoon and the lowest one was recorded in Edku lagoon. Iron (Fe) showed the highest concentration of all trace metals ranging from 89.2 μg/L in Edku to 159.65 μg/L in Burullus. Manganese (Mn) concentration represented the second highest metals after iron, ranging from 16.95 μg/L in Edku to 32.85 μg/L in Maryut. These high levels of pollution can be attributed to the high pressure exerted from the rapid

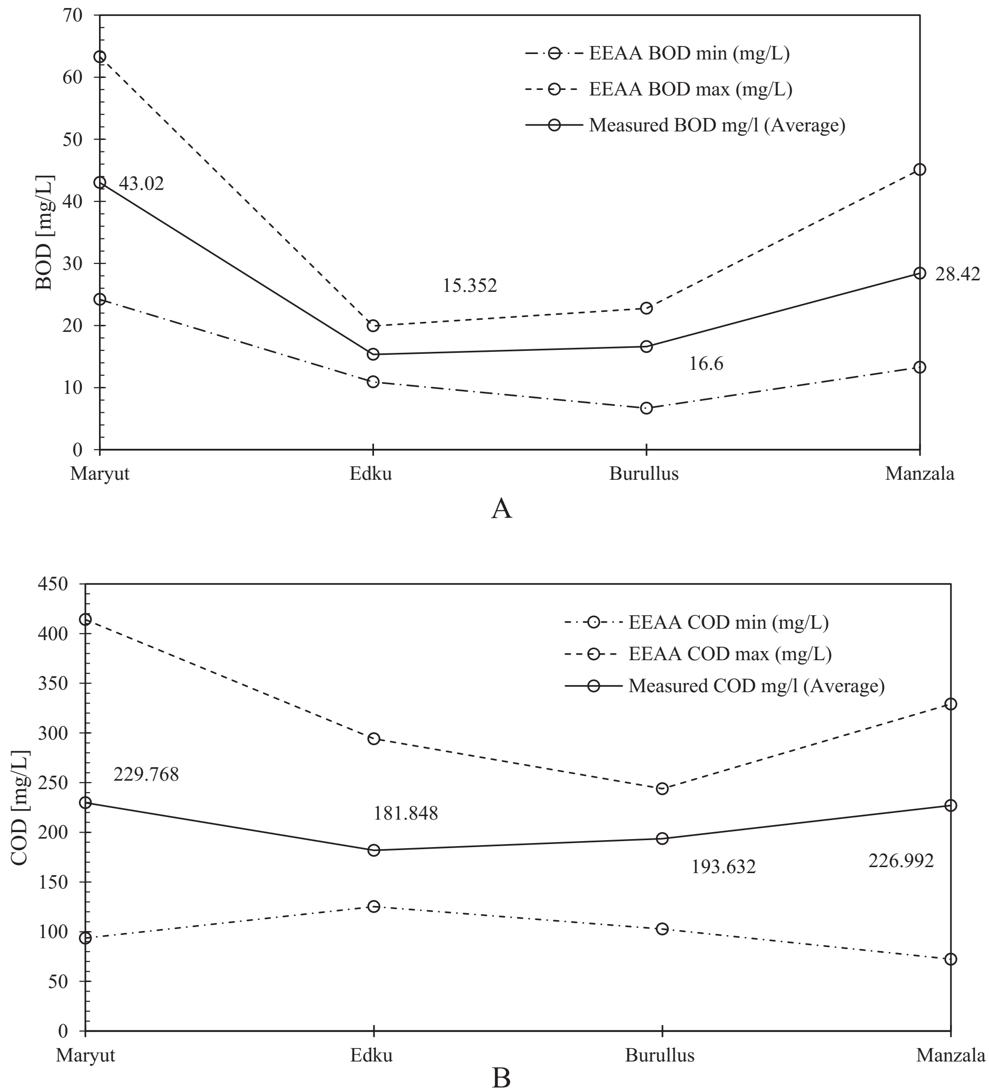

Figure 5. (A) Average BOD compared with EEAA and (B) average COD compared with EEAA. BOD indicates biological oxygen demand; COD, chemical oxygen demand; EEAA, Egyptian Environmental Affairs Agency.

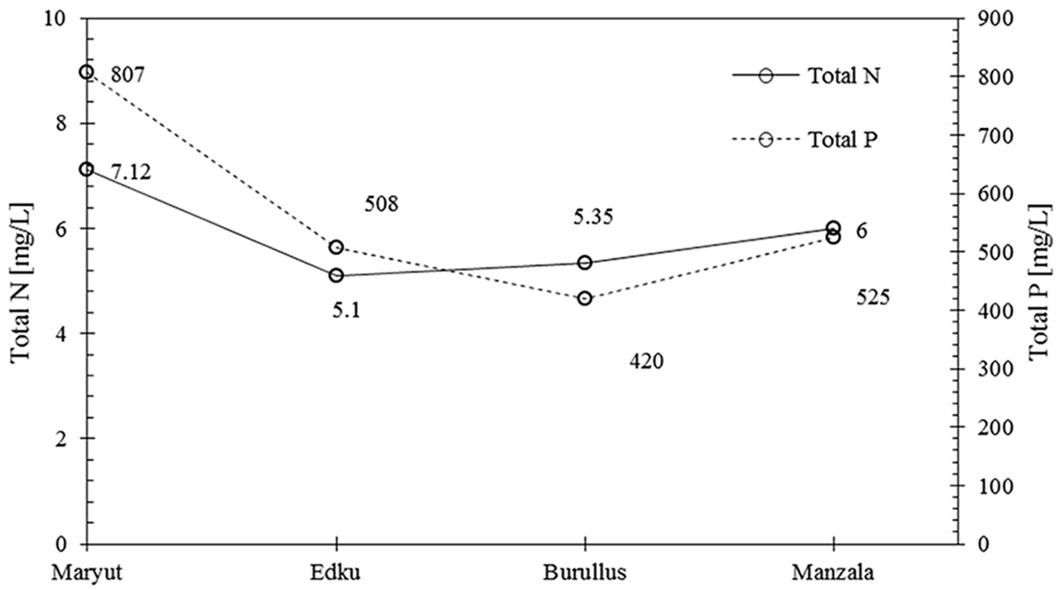

Figure 6. Concentration of nutrients in the Nile Delta lagoons.

Table 1. Fecal coliform, fecal streptococci, and total coliforms.

PARAMETER	UNIT	MARYUT	EDKU	BURULLUS	MANZALA	ALLOWABLE LIMIT
Fecal coliform	cells/100 mL	100 365	402	539	5210	100
Fecal streptococci	cells/100 mL	36 258	198	398	2403	1000
Total coliforms	cells/100 mL	143 698	683	1309	7205	100

Table 2. Trace metals in the Nile Delta lagoons.

PARAMETER	UNIT	MARYUT	EDKU	BURULLUS	MANZALA	EGYPTIAN LAW (48) LIMIT			FAO LIMIT
						ART. 60	ART. 61	ART. 65	
Cadmium (Cd)	µg/L	0.97	1.1	1.8	0.92	0.01	<1	0.01	–
Copper (Cu)	µg/L	18.94	13.96	24.9	23.07	1	<1	1	0.2
Iron (Fe)	µg/L	97.12	89.2	159.65	106.5	<1	<1	1	5
Lead (Pb)	µg/L	27.9	20.07	40.74	31.13	0.05	<1	–	5
Mercury (Hg)	µg/L	0.36	0.27	0.35	0.2	<1	<1	<1	<1
Nickel (Ni)	µg/L	7.07	5.3	9.73	7.02	–	<1	–	–
Manganese (Mn)	µg/L	32.85	16.95	25.3	19.5	0.5	<1	1.5	0.05
Chromium (Cr)	µg/L	8.85	5.63	7.3	6.26	0.05	<1	0.01	0.05

Abbreviation: FAO, Food and Agriculture Organization.

increase in population and the related industrialization. Industrial, agricultural, and domestic effluents are discharged into the Nile Delta Lagoons which lead to an increase in the trace metal and contamination in the lagoons. Values were compared against the Egyptian Law for protection of the River Nile and water ways from pollution, Article (60): water quality in River Nile and Article (61): discharge treated industrial liquid effluent into River Nile and Article (65): discharge drain water into River Nile,[33] in addition to the Food and Agriculture Organization (FAO) Guidelines[34] as shown in Table 2.

Sediment quality monitoring

The analysis of the sediments at the bottom of the water column can reflect the quality of the water system. Sediment analysis plays an important role to detect the nonsoluble contaminants discharged into the water body. Figure 7 shows the concentration of metal in the sediment samples taken from the 4 lagoons.

It was found that Pb, Mn, Fe, Zn, and Cd are the most dominant metals in the sediment of the Nile Delta lagoons. The existence of these metals with high percentage can lead to severe illness and pollution in the area.[35] These element concentrations are above the FAO limit that can also lead to degradation of the social growth.[36] However, Hg, Cr, and Cu were recorded in very low concentrations through the 4 Nile Delta lagoons. Such concentrations seem to be constant in all sites. The wide ranges of trace metal concentrations recorded for some metals may be attributed to variations in sediment grain size percent and increase in trace metals rich urban effluents draining into river. The results are compared against the allowable limits for trace metals in sediments according to the EEAA, Central Department for Water Quality the national program for monitoring the Egyptian Lakes as shown in Figure 7.[29]

In addition, contamination of shallow groundwater systems and soil–plant transfer of trace metals may take place as a result of surface water seepage to the ground. The movement of trace metals through the soil, plants, water, and even atmosphere is part of a complex biogeochemical cycling process in nature.[37]

Discussion

Water quality and healthy ecological systems are essential for better functioning of the Nile River Delta region. Through the monthly sampling of the various parameters such as physiochemical, biological, nutrients, and trace elements for a period of 1 year, it was observed that the continuous input of anthropogenic contaminants through drains and direct release of industrial effluents leads to deterioration of water and sediment quality. This anthropogenic contamination also increases pathogenic microbes in the water column that can be harmful

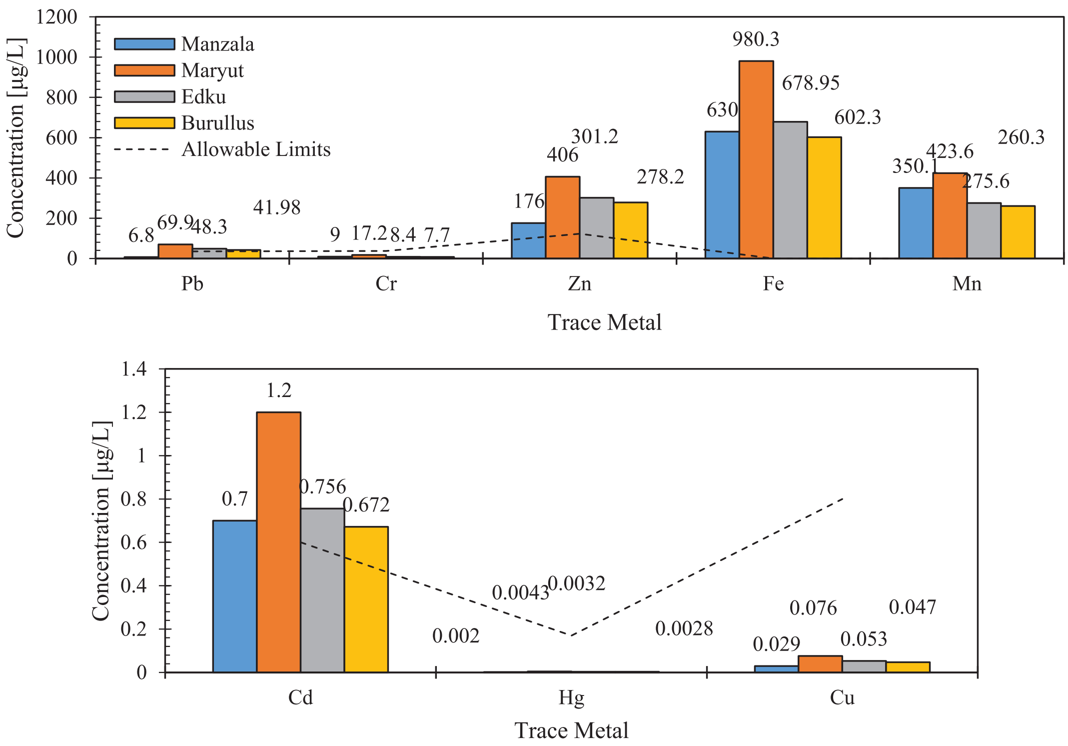

Figure 7. Concentration of trace metals in the sediments of the Nile Delta lagoons.

to human health. The results obtained in this study agree with previous findings that continuous monitoring of water and sediment quality in addition to the proper mitigation and management plans are needed to achieve better living standards.[4]

The physio-chemical parameters of the water column are the first line of indicators of water quality. Seasonal temperature fluctuations influence the physio-chemical parameters of the water column, such as pH and DO.[4] Also, a positive relationship for change in pH and DO with changing temperatures was observed in this study. The continuous input of domestic sewage and industrial effluents increased the nutrient concentration of the water, which lead to increase in eutrophication and higher concentration of microbial cells in the water column. This increase in microbial cells was affected by temperature, as temperature controls physiological functions of microbes, that leads to both increase in pH and decrease in DO levels.[4,38] The degradation of microbial cells can lead to release of various acids that can turn the sediment pore water and the water column above the sediment into acidic and a decrease in the pH value. However, the continuous input of domestic sewage and input of fresh water from the AHD dam maintain the water pH as alkaline. As the water temperature increases, it also leads to increase in the mineralization rate of the catchment sediments and soils accompanied by an increase in the nutrient loading. However, in the winter season, specifically in December and January, when the temperature decreases, the DO levels in the water returns back to ambient quality. With already higher nutrient levels due to the drainage loading and industrial effluents, increase in temperature, microbial cells, and decreased DO levels create an unfavorable environment for the local fish population, where most of the fish population die off due to hypoxia.[5,39] This die-off has a direct socioeconomic consequence on the local people, which depend on the productive Nile Delta for livelihood options.

The increase in nutrient levels due to anthropogenic pollution also increase microbial cell counts of total fecal Coliforms and Streptococci's, which decreases the water quality and the presence of these pathogens makes the water unsuitable for drinking purposes.[7] Seasonal water flow from the AHD and the continuous drainage of water from the surrounding urban population and industries bring inflow of various particulate and organic matters that affect the turbidity and TSS of the 4 study locations. Similarly, the eutrophication, algal bloom, and increased microbial cell count also contributes to the turbidity and TSS values of the Nile Delta.[4,6,35] The TSS are a significant factor in identifying water clarity; the higher TSS, the lower clarity of water and we show that there is a seasonal fluctuation and most importantly local anthropogenic influence on TSS.

Temperature, DO, microbial cell count, and high nutrient contents influence the BOD and COD of the water column.[31] As these chemical and biological parameters are interlinked, a change in any of the above factors affect BOD and COD, for example, increase in the water temperature and nutrients increases the photosynthesis rate of micro algae and microbes, which directly influence the increase of BOD,[4] while after the peak when the decomposition of micro-algae-bacterial cells start by decomposers, the COD increases.[4] BOD is part of COD, as COD measures all the oxidizable organic content while BOD measures only the biodegradable constituents of organic matter which also explains the higher COD concentration in water than BOD. Generally, both temperature and pH has no effect of direct relationship with COD. However, when there is a change in temperature (in our case seasonal influence) and pH (due to microbial decomposition), it leads to increase in COD levels. This increase or decrease in pH can simultaneously affect the trace element release from sediment. Most of the BOD and COD levels in our study was within the limit proposed by EEAA, which indicates about the self-balancing act of the Nile River Delta, though proper management and mitigation plans are necessary before threshold levels are reached.[31]

The presence of pathogenic microorganisms like fecal coliforms and fecal streptococci is an important indicator for water quality, with higher cell counts related to deteriorating water quality, as observed in this article. These pathogens are responsible for waterborne diseases and can affect human health. The main cause of increase in these pathogens in the Nile River Delta is due to direct domestic discharge of untreated sewage. However, the fertilizers run-off and nutrient enrichment can also lead to increase in the microbial pathogens as these provide suitable energy sources for microbial multiplication. This was evident as study areas like Maryut lagoon having high nutrient levels were found with 1000-fold higher microbial cells than the allowable limit,[40] which can have serious drinking water problems.[7]

The main source of trace metals existence in the water body of the Nile Delta Lagoons is through industrial discharges such as petro-chemicals and refining industries,[4,5,22] even though there is a significant contribution from wastewater and fertilizers. These continuous input of trace elements into the Nile River Delta regions may be the cause of abundance of elements in the water column. However, the trace element levels in water column were lower than the sediment, which is expected as trace elements require finer grain size particles for adsorption.[41] Other than sediment grain size, the pH also affects the trace element speciation and release from the sediment pore water into the water column and makes it bioavailable.[42,43] However, in the sediment redox stratification of trace element occurs with depth,[44,45] until resuspension occurs due to physical processes and bioturbation. Resuspension with oxygenated overlying waters results in metal speciation in the dissolved phase,[46] making the metals bioavailable in pore waters.[47] Once released from pore waters into water column, these metals are bioavailable to aquatic organisms till precipitation of these metals are initiated by the fine fraction (<63 micron) of the sediments suspended in water column.[48,49]

For the trace element levels in sediment, a seasonal pattern was not observed as there is a continuous input of these trace elements at the study regions and their trophic transfer and exit from the system is minimal. Though, the rapid increase in population and the related industrial, agricultural, and domestic effluents are discharged into the Nile Delta Lagoons play a major role in increased trace element levels in the sediments, other factors such as weathering, climate, soil type, pH, redox potential, and dilution capacity also influence the trace element concentration.[41]

Conclusion

The economic development, rapid population increase, and the related industrialization have their negative consequences on the water quality of the Nile Delta Lagoons. The poor water quality of the 4 lagoons (1) Maryut, (2) Edku, (3) Burullus, and (4) Manzala of the Nile Delta region was evidence of this industrial development related environmental damage. These environmental changes are altering the basic physico-chemical, biological, and trace metal chemistry of the Nile Delta region, which is having negative consequences on the food chain and associated human livelihood options. Degrading water quality is not healthy for the Nile River Delta biodiversity nor for the human civilization that depends on this Nile River for their water and food resources. The research provided evidence that a regular monitoring of various water quality parameters can provide real-time scenarios and changes in the water quality of Nile River and the various environmental management authorities of Egypt should come together to conserve and manage the life line of Egypt.

Author Contributions

KMM: Conceptualization, Methodology, Formal analysis, Validation, Investigation, Resources, Writing - Original Draft, Visualization, Project administration. AKM: Writing - Review & Editing, Validation, Resources, Formal analysis. MMG: Writing - Review & Editing, Supervision.

ORCID iDs

Karim M Morsy https://orcid.org/0000-0002-8661-6476
Amrit K Mishra https://orcid.org/0000-0002-9605-3865

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