The Nile Delta

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Abstract The Nile Delta, an area of about 22,000 km^2, accounts for two thirds of Egypt's agriculture. In the late Pliocene, the delta started to advance across a marine embayment and developed, especially in the Pleistocene, through major sea-level changes associated with glacial periods. The Nile Delta area is now the major oil and gas-producing area of Egypt. Chemical industry located in the Nile Delta is the main source of hazardous waste. Water pollution in the Nile branches as well as its lakes is caused by agricultural pesticides, raw sewage, and urban and industrial effluents.

The decision of the Egyptian government to reduce the Nile water discharged to the Mediterranean is not only affecting the quantity of discharge, but also its quality. Sewage from coastal lakes and other land run-offs became the substitution source of nutrients of coastal fisheries. The limited Nile nutrient-rich sediments and water reaching the delta negatively affect both the agricultural activities as well as the functioning of the ecosystems in the coastal area facing the delta.

This chapter highlights the main factors characterizing the Nile Delta: the geology, hydrology, and ecology of this delta-estuary-coastal marine system are described and illustrated. It also forecasts future trends in the development of the Nile Delta and uses numerical simulations as a tool to predict future variations within the coastal area of the delta.

Abbreviations AHD: Aswan High Dam; Ma: Million years of age; Mt: Metric tons

1 Geological Development of the Nile Delta

The Nile Delta is part of the Egyptian Mediterranean coast and extends for approximately 240 km from Abu Quir headland at Alexandria in the west, to Port Said in the east (Fig. 1). The most conspicuous features of its margin are the Rosetta

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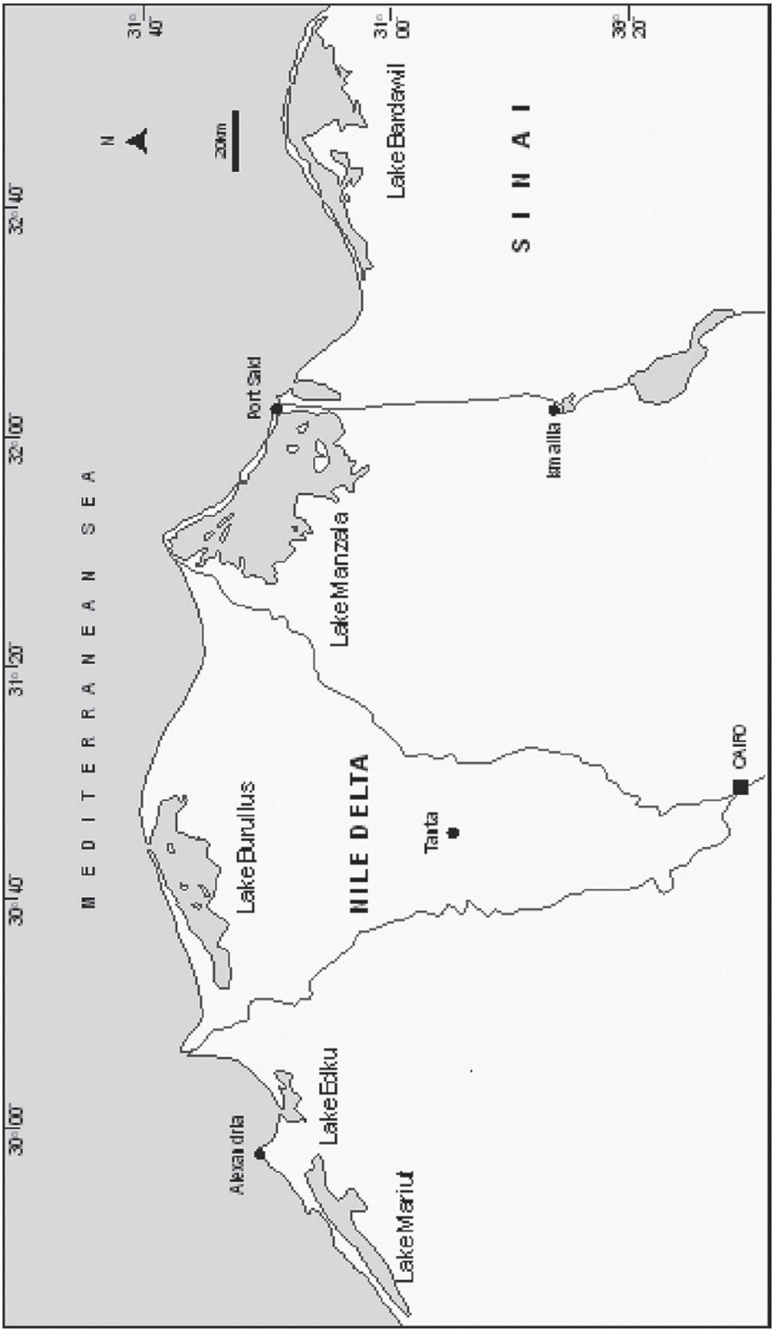

Fig. 1 The Nile Delta and its northern lakes connections with the Mediterranean Sea along the Egyptian coast

and Damietta promontories, which emanate from a point of bifurcation 23 km north of Cairo. Between these promontories lies a broad headland composed of Nile sediments deposited since 6,500 years ago (Stanley & Warne, 1994; Frihy & Dewidar, 2003; Hamza et al., 2003). The recent geological age of the delta has been noted in the literature (Goudie, 2005). The Nile negotiates its way through five regions, each differing in terms of history and structure: the great lake plateau of Central Africa, the Sudd and Central Sudan, the Ethiopian Highlands, the cataract tract from Khartoum to Aswan, and Egypt down to the delta and Mediterranean (Said, 1981). According to Issawi & McCauley (1992), Egypt was drained during the Cenozoic by a succession of three major drainage systems that competed for survival by means of gradient advantage (but see Talbot & Williams, 2009, for an alternative view). This competition took place in response to tectonic uplifts and sea level changes in the interval between the retreat of the Tethys Sea in late Eocene (40 Ma) and the birth of the modern Nile during the late Pleistocene (ca ~25 Ma). In his review, Goudie (2005) presented the three different drainage systems as follows:

1. Oldest: the Gilf system, which consisted of north-flowing consequent streams that followed the retreating Tethys Sea across the newly emerging lands of Egypt, and streams that formed on the flanks of the Red Sea region toward the end of the Eocene (Fig. 2a).
2. Intermediate: the Qena, where a major south-flowing stream developed down the dip slope of a zone of intensified uplift in the Red Sea range during the early Miocene. This stream flowed into the Sudan basin, and was limited in the west by the retreating scarp of the limestone plateau, and in the east by the uplifted Red Sea range (Fig. 2b).
3. Youngest: the Nile system, which came into existence as a result of the drop in the Mediterranean sea-level in the late Miocene. Formerly local drainage eroded headward into the limestone plateau. The Nile captured the Qena system and reversed its flow from south to north (Fig. 2c).

In the late Pliocene, the Nile began to advance across a marine embayment. It developed, especially in the Pleistocene, through major sea-level changes associated with glacial periods. During low sea-level stands, large quantities of sand and mud were dispersed far into the eastern Mediterranean, forming a large submarine fan (Sestini, 1991). Coastal changes can be followed from maps since the early eighteenth century and with more precision from topographic surveys since the early 1800s (UNDP/UNESCO 1978). Throughout the last century there was a steady advance of the Rosetta and Damietta promontories (Fig. 3), averaging 30 and 10 m year^{-1}, respectively, and accretion in all embayments towards the east. Around 1910, reduced monsoonal rainfall over eastern Africa resulted in an overall 25% decrease in Nile discharge that set the theme for present-day coastal instability and headland recession. From 1910 to 1965, the Rosetta promontory receded by 2.5 km and the Damietta promontory by about 2 km (Frihy et al., 1998; Frihy, 2001).

Although the Aswan High Dam (AHD), completed in 1964, was aimed to produce clean energy and to conserve and protect the agriculture in Egypt by

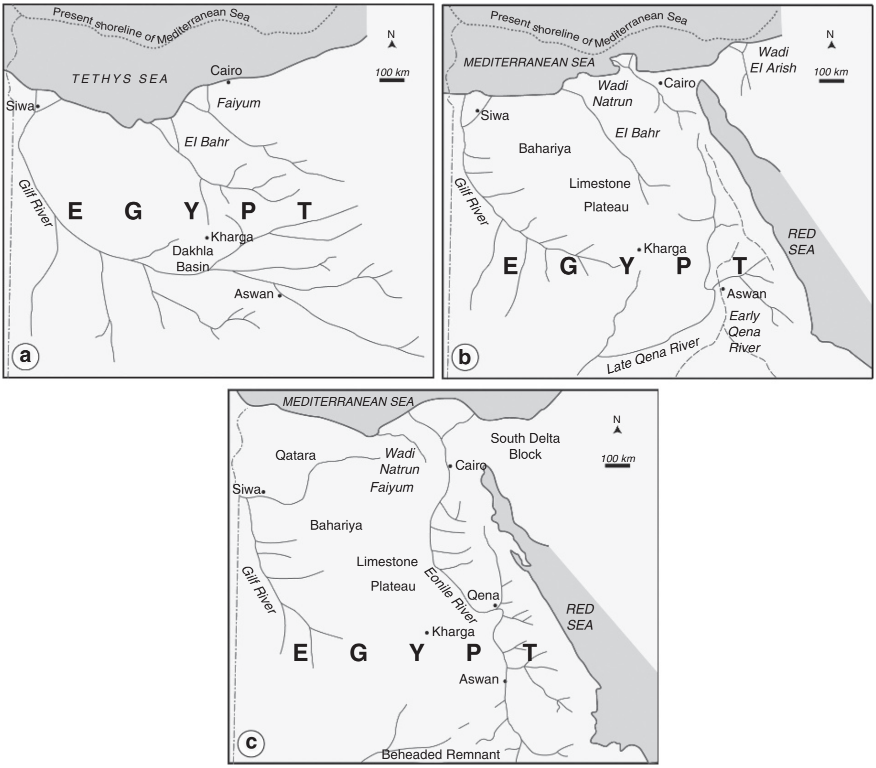

Fig. 2 Sketch showing (**a**) the oldest, (**b**) the intermediate and (**c**) the youngest formation of the Nile Delta (modified from Goudie, 2005 after Issawi & McCauley, 1992)

controlling the Nile flood, it had a dramatic negative effect on the sediment flux to the delta. Since that time the supply of sediment reaching the river mouth at Rosetta and Damietta has no longer been sufficient to stabilize the delta coastline and prevent coastal erosion. Alternatively, Stanley (1996) claims that neither the blockage of the Nile flow at Aswan and other large river control structures, nor additional influence of natural factors including subsidence, sea-level rise, and near shore current processes, fully explain the altered sedimentary regime currently prevailing along the Nile Delta coast. He finds that the trend of land loss along the delta margin is better explained by increased sediment entrapment in the delta proper, between Cairo in the south and the coast in the north. Retention of sediment on the delta plain is directly related to catchments by irrigation waterways, land reclamation structures and wetlands in the delta proper, rather than to blockage of the Nile by dams in upper, middle and lower Egypt (Fig. 4). Stanley (1996) concluded that near-complete entrapment of Nile sediment on the delta plain by canalization, coupled with strong coastal processes, account for the alteration of the delta shoreline.

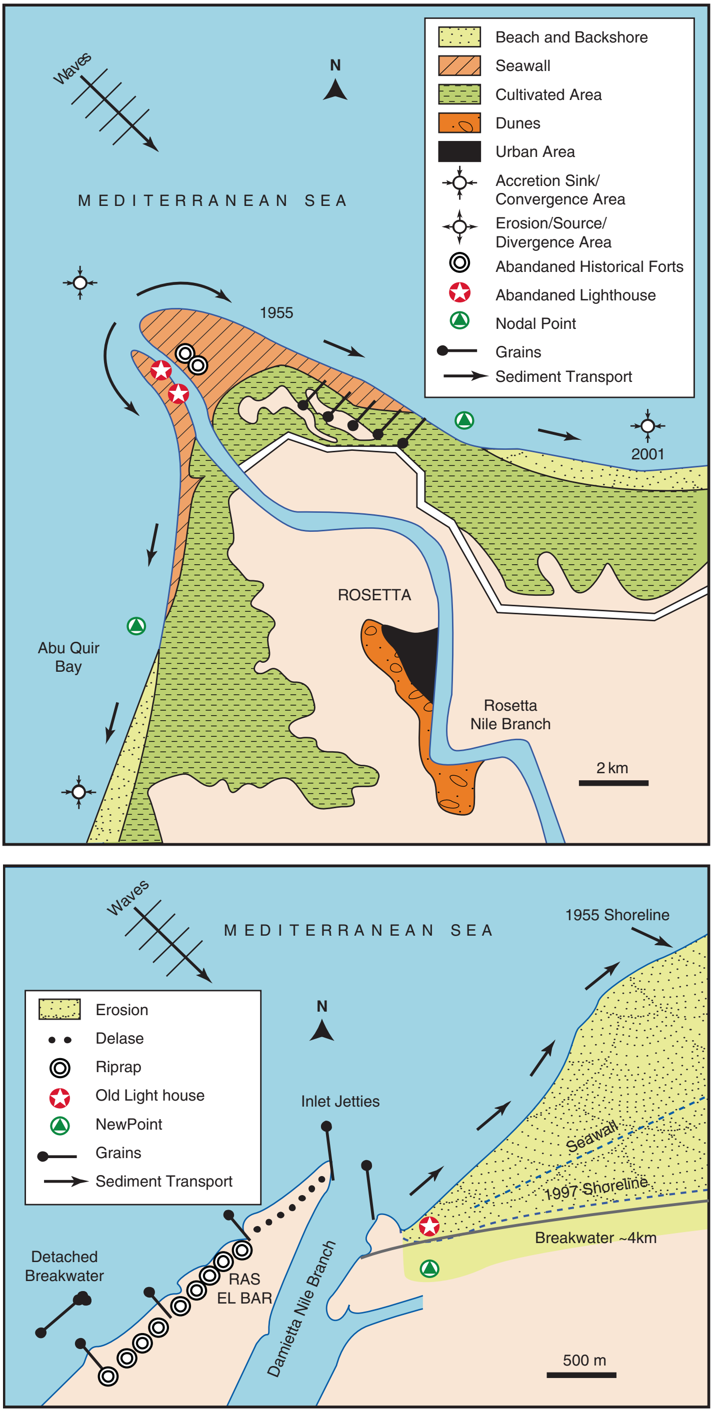

Fig. 3 Erosion and accretion features of the Rosetta (*upper*) and Damietta (*lower*) promontories and the developed protective measures (modified from Frihy et al., 1998 and 2001) (*see Color Plates*)

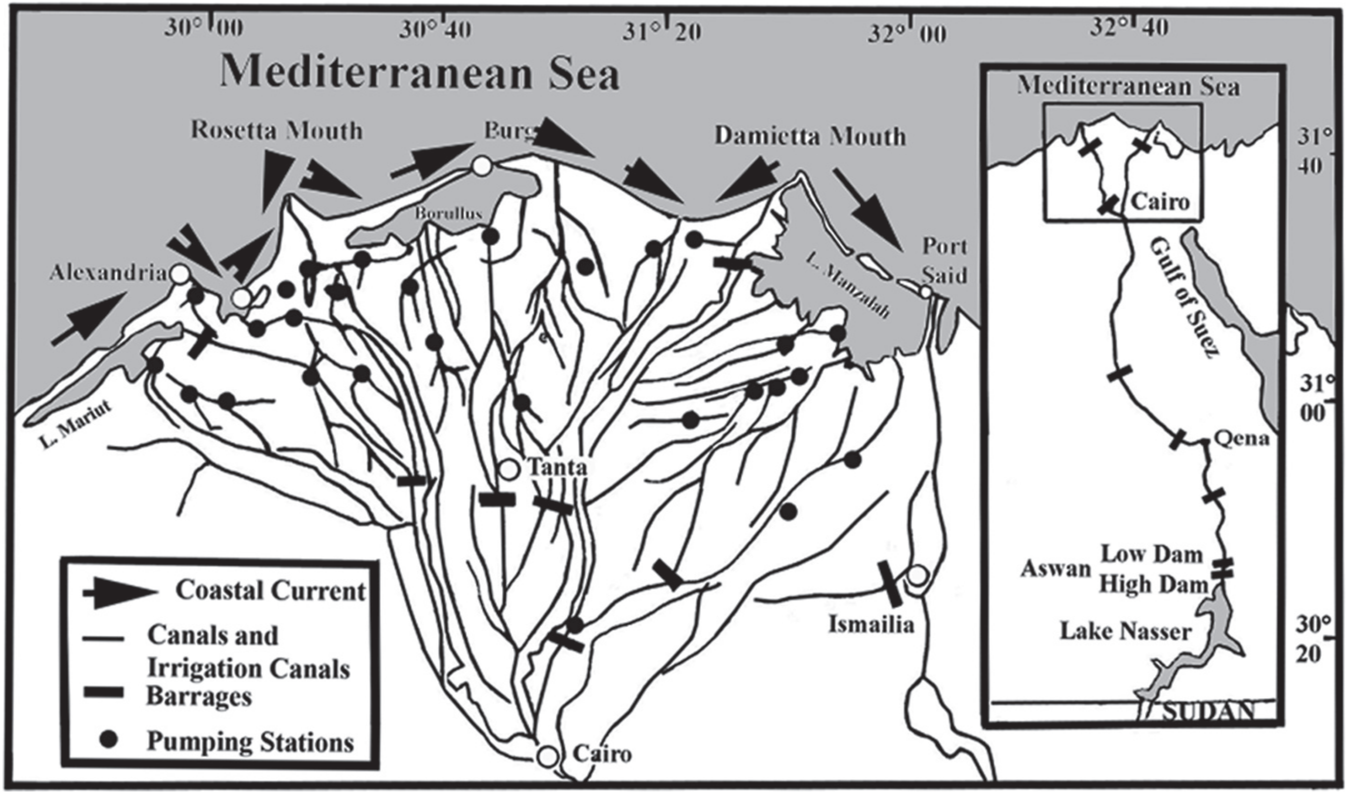

Fig. 4 Ancient and recent irrigation waterways, barrages, canals and wetlands which entrap Nile sediments at the Nile Delta before discharging to the coastal area (modified from Stanley, 1996)

2 Nile Branches Serving the Delta

Both the Rosetta and Damietta branches extend northwards from Cairo to the Mediterranean over distances exceeding 200 km. Along their course, they provide for the needs of agriculture, industrial activities, and they supply drinking water for the most populated area of Egypt. Water flowing through the Damietta and Rosetta branches accounts for less than half of the original total northward flow across the delta plain, that is now captured by artificial waterways comprising >10,000 km of canals, usually only 2–3 km apart. Some canals originally dug in Dynastic times have been expanded and enlarged over the years. The position of major canals and drains, compiled from charts held by the Defense Mapping Agency, is given by Stanley (1996). As shown in Fig. 5, drains and large irrigation and navigation canals flow past major urban centers. Most extend as far as the delta lakes and wetlands, including the southern margin of Manzalah Lake and its large poorly drained southern area to the southeast; the southern margin of Lake Borullus, and its southeastern marshy area; and Lakes Idku and Mariut. Most numerous are the small to moderate-sized canals that flow through hundreds of delta villages and criss-cross the deltaic plain. These are interconnected with large irrigation canals and drains and flow northwards (Stanley, 1996). They discharge to one of the Nile branches or to the northern delta lakes; some reach the Mediterranean Sea.

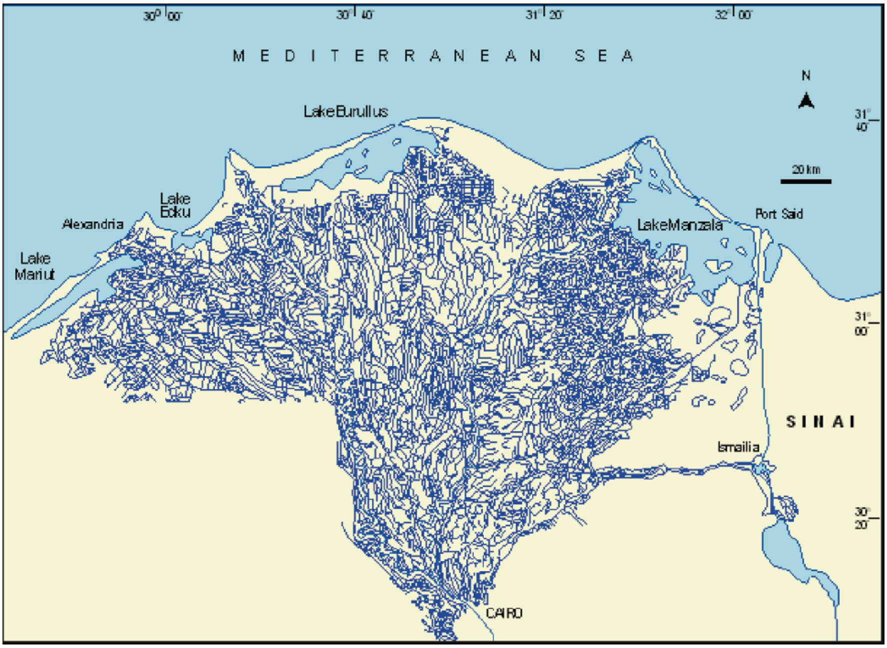

Fig. 5 Map showing >10,000 km of irrigation canals and drains forming the extensive waterway system in the Nile Delta (modified from Stanley, 1996) (*see Color Plates)*

Hamza (2006) stated that approximately 85% of Egyptian water resources (mainly supplied by the Nile) are committed to irrigation of the 3.4 million hectares of cultivated lands. About 65% of these agricultural activities are within the delta area. The dense agriculture in the delta as well as the available infrastructure have enhanced socio-economic growth in this area, with a consequent faster growth in population density in the delta than in other areas of the country. In addition to catering for agricultural needs, the Nile branches also serve industrial activities concentrated around the cities of Cairo and Alexandria. Although the demand for Nile water by the industrial sector is relatively small compared to that for agriculture, the waste discharge from the industrial sector has resulted in degradation of the water quality of the Nile branches. This discharge is supplementary to the domestic sewage making its way into the northern lakes, before it is discharged to the Mediterranean Sea (Hamza et al., 2004; Hamza, 2006).

Since the construction of the AHD in 1964, the Nile discharge to the Mediterranean has been restricted to the Rosetta branch. The Damietta branch is blocked 12 km upstream from its mouth by a dam at the city of Faraskur. The water flowing through the mouth of the Rosetta branch is controlled by the Edfina Barrage located 35 km south of the river mouth. Stringent control of the flow through the Nile branches to the Mediterranean is due to the almost total dependence of Egypt on the Nile (95% dependent) as the main freshwater source to satisfy the fast increase in its population growth. As a result of these controls the quantity of water released to the Mediterranean is no longer determined by Nile flooding, but is composed of wastewater considered unsuitable for recycling. In his review, Hamza (2006) indicated that the actual quantity of Nile surplus reaching the Mediterranean annually amounts to 2.5–4 km^3. Almost all of this water passes through the northern delta lakes and other land effluents connected to the sea, instead of flowing through the main Nile branches. According to El-Arabawy's (2002) water balance strategic model for the year 2017, an estimated 6–7 km^3 of return flow into the Mediterranean and northern lakes is required to mitigate salt-water intrusion and preserve the Nile Delta salt balance.

3 The Nile Delta Lakes

As the final reservoirs of Nile water before it flows into the Mediterranean, lakes Mariut, Edku, Borullus, and Manzalah are the last opportunity for Egyptians to use the Nile water (Fig. 1). The four lakes occupy an area of about 1,100 km^2. They are common shallow (average depth 1.10 m), and their salinity changes from fresh to brackish in seaward direction. They are connected to the Mediterranean Sea either directly or indirectly. The quantity and quality of water discharging to the lakes are determined by up-river activities, not by the requirements for activities within the lakes.

During the last 50 years the surface area of the four lakes has been reduced to ca 50% of their area during the 1950s (Table 1). Lake area was lost to highway construction, reclamation of land for agriculture, and in some cases for residential

Table 1 Gradual changes in the surface areas (km^2), of the northern Delta Lakes during the last 50 years (after Hamza, 1999)

Lake Years	L. Mariut km^2	L. Edku km^2	L. Burullus km^2	L. Mazalah km^2
1950s	136.9	150.1	571.8	1274.2
1970s	68.4	129.2	534.4	997.3
1980s	66.1	115.3	481.6	904.1
1990s	62.3	109.7	350.8	650.3

construction. Such unnatural use has certainly modified the ecosystem as a whole, beginning with hydrological changes and resulting in the reduction of their economical and natural value. Due to their position along the coast, the lakes are surrounded by or included within highly populated coastal cities. This is reflected, especially during the last 20 years, in different forms of human impact on these water bodies, such as industrialization and the construction of new infrastructure, responding to population density increase. Such impacts deteriorated water quality and reduced lake surface area (Hamza, 1999). One negative effect of human impact on the Nile Delta Lakes (NDL) ecosystems is the decline in fish production. Up to 1985, the annual fish production of the lakes accounted for >50% of the total annual yield for the country. Amongst these lakes, Lake Mariut was the most fertile (Aleem & Samaan, 1969). Now, Mariut as well as Manzalah are the least productive ones because of a continuous discharge of sewage and industrial waste into their basin (Siegel, 1995), causing algal blooms in all of the lakes. From their study on changes of zooplankton community structure in the NDL for the last seven decades, Dumont & El-Shabrawy (2008) concluded that the construction of AHD reduced the marine influence in the lakes and an elimination of some large grazers by freshwater fish took place. They also added that major changes to the Lake Borullus faunal community were caused by intensified agriculture at the delta region, especially during 1980s–1990s, responsible for eutrophication, and leading to the elimination of large to medium sized (micro)crustaceans.

The reduction of lake area has forced fishermen to harvest fingerlings and dredge the lake bottom in search for adult fish in their breeding grounds. Dredging the bottom sediments re-suspends particulate organic matter, which consumes oxygen and results in fish kills. Also, turbid water reduces the photosynthetic capacity of algal cells, making re-oxygenation more difficult. The removal of fingerlings alters the ecosystem balance and creates an imbalance between plankton and fish. Over-fishing is common, as is the practice of bottom dredging, despite the passing of laws aimed to protect the lake ecosystems.

As shown in Table 2, all lakes are eutrophic to hypertrophic, reflecting their high organic loads. Although the water residence time in the lakes is small (range 10–42 days), their trophic status is high. This phenomenon is consistent with high organic loads and a high binding capacity of the clayey sediments that have accumulated in the lakes over time. The lakes are fed by Nile water rich in phosphorus compounds, which are easily captured by clay deposits. The shallowness of these lakes

Table 2 Main geographic and hydrographic features of the Nile Delta Lakes (modified after Hamza, 2000)

	Location			
Parameters	L. Mariut	L. Edku	L. Burullus	L. Manzalah
Lon. (E)	29.28	30.20	31.00	31.48
Lat. (N)	31.20	31.33	31.62	31.46
Surface area (km^2)	62.00	109.00	350.00	650.00
Depth range (cm)	50–150	40–220	50–200	50–140
Av. water salinity (‰)	6.3	3.8	2.5	5.9
Annual discharging volume (×10^9 m^3)	2.37	2.06	3.2	6.7
Discharging rate (m^3 s^{-1})	74.0	60.0	80.0	165.0
Water residence time (days)	10	21	42	32
Trophic status	Hypertrophic	Eutrophic	Eutrophic	Hypertrophic
Water sources	A, I, S, G	A, S	A	A, I, S

A = Agriculture, I = Industrial, S = Sewage, G = Groundwater.

is an important factor in increasing the capacity of clay to bind with phosphorus compounds, because continuous agitation of the short water column by wind helps to keep bottom sediments in an oxic condition. This helps the clay particles to accumulate phosphorus to the limit of their binding capacity (Gachter & Meyer, 1993; Hamza et al., 1995) and explains the high phosphorus loads shown in Table 2.

4 Human Activities and Their Impact on the Nile Delta

The Nile Delta accounts for two thirds of Egypt's agricultural land (Stanley, 1996). Egypt covers an area of about 1 million km^2, but about 99% of the Egyptian population (now approaching 80 million) is concentrated in 5.5% of that territory, mainly located along the Nile valley (area = 2.7%, population = 36%) and delta (area = 2.8%, population 63%). The remaining 94.5% host only 1% of the population (Attia, 2002). Egypt is the most populous country in the Arab world, and the second most populous in Africa. It is a middle-income nation with a diversified economy. Agriculture accounts for about 17% of GDP. The principal export crops are cotton and winter vegetables. Cultivation of basic grains is also extensive. Egypt is a rapidly industrializing country with extensive use of chemicals in a wide spectrum of industrial sectors. The main industrial sectors are raw and fabricated metals, vehicles, pharmaceuticals, textiles, pesticides, fertilizers, petrochemistry, cement, paper and pulp, and food processing. About 50% of all industrial activity is concentrated in Greater Cairo and about 40% in Alexandria. The rest is in delta, upper Egypt, and new cities (Barakat, 2004).

With an arid landscape, little rain and 94.5% desert, Egypt is dependent on the Nile for its existence and faces a host of environmental problems. These are aggravated by a high population density, which places a strain upon resources. Since the Nile Delta is the most populated, cultivated and industrialized part of the Egyptian territory, it receives the highest quantities of contaminants derived from human activities. The sources of these contaminants and their release and ultimate fate may be summarized as follows:

4.1 Chemical Contaminants

The chemical industry located in the delta is the main source of hazardous waste. Frequent problems have been faced by these industries in the disposal of their waste. Water pollution in the Nile branches as well as the northern lakes is caused by agriculture pesticides, raw sewage, and urban and industrial effluents. Barakat (2004) noted that the use of organochlorine insecticides in Egypt began in the 1950s and lasted until 1981, to protect crops from insects, fungi and weeds, to remove undesired vegetation and for domestic household use in the control of insects. The reported total active ingredients include: toxaphene 45,000 Mt (1955–1961), endrin 10,500 Mt (1961–1981), DDT 13,500 Mt (1952–1971) and lindane 21,000 Mt (1952–1978) (El-Sebae et al., 1993). The main purpose of these insecticides is the control of cotton leafworm and bollworms. DDT is still in limited use as a rodenticide and termiticide. These compounds, released into drainage canals, reach the delta branches and lakes, which partially release their waters to the Mediterranean. According to the Ministry of Agriculture, the application of pesticides decreased from 20,500 tons in 1980 to 16,435 tons in 1995. Since chlorinated pesticides have been banned, the pesticides currently used are organophosphorus compounds (Barakat, 2004). Table 3 shows concentrations of PCBs, DDTs, HCB and lindane in waters of the delta region.

Table 3 Concentrations (ng l^{-1}) of HCB, DDTs, PCBs and lindane in freshwaters from different locations of the Nile Delta (modified from Barakat, 2004)

Location	Sampling	HCB	DDTs	PCBs	Γ-HCBs
River Nile					
Cairo	1993	<0.001	0.08–0.12	3–640	0.05–0.07
Rosetta Branch	1998	1–77	0.2–99	5–161	
Damietta Branch	1988	<DL–93	90–102	25–53	<DL–126
				7–21	
Nile Estuaries					
Rosetta	95–97	197–217	83–97	166–181	286–310
				390–430	
Damietta	95–97	195–240	109–128	270–330	312–352
				581–700	
Coastal Lakes					
Lake Manzala	1993	0.03–0.18	0.10–0.56		0.37–1.57
	92–93	0.84–2.28	26–55	18–48	8.6–12.1
			3–26	<DL–20	1–11

<DL: below detection limit.

4.2 Hydrocarbon Contaminants

The Nile Delta area harbors the major producing oil and gas fields in Egypt. Vandre et al. (2007) described how the geological history of northern Egypt generated multiple petroleum sources, reservoir and seal combinations of source rocks in the delta. Between 1966, when drilling for hydrocarbons began, and 2002, over 36 trillion cubic feet of gas have been discovered in northern Egypt (Dolson et al., 2002). Since oil and gas exploration activities are increasing dramatically in the delta area it is imperative to prevent the leakage of hydrocarbon contaminants to the environment, from exploration activities and other activities of the oil and associated petrochemical industries.

4.3 Sewage, Trace Metals and Nutrient Contaminants

Domestic and industrial sewage represent major sources of nutrient enrichment to waters of the Nile Delta. Sewage contributes to the development of eutrophication and the degradation of water quality. Often, municipal and rural domestic wastewater is discharged directly. It contributes pathogens, nutrients, trace metals, suspended solids, salts and oxygen-demanding materials (Hamza & Mason, 2004). Siegel (1995) reported that the nutrient base for aquaculture in Lake Manzalah is sewage carried by drains from as far away as Cairo, 140km to the south. He added that untreated or poorly treated industrial wastes, heavy metals and other pollutants are released into the Nile Delta drain network and are discharged along with sewage and agriculture wastes into the northern delta lakes and their associated wetlands. In an earlier study Siegel et al. (1994) measured sedimentary deposits in the southeastern sector of Lake Manzalah. They detected Hg (up to 822ppb), Pb (up to 110ppm), Zn (up to 635ppm), Cu (up to 275ppm), Cr (up to 215ppm), Sn (up to 14ppm) and Ag (up to 4.7ppm). They concluded that high concentrations of heavy metals in lake sediments contaminated fish, especially bottom feeders. This may be the case in the northern lakes, since all of them receive the sewage discharges of major cities. Unfortunately, with the dwindling of the natural nutrient-rich Nile water discharge into the Mediterranean, the sewage discharges from coastal lakes and other land run-offs have become the alternative source of nutrients for coastal fisheries (Hamza, 2006). Satellite images of discharges into the Mediterranean show the impact of the degraded water quality on the coastal lakes, which act as transitional basins for sewage (Fig. 6).

Dissolved humic substances of agricultural or industrial origin have been measured in Lake Edku (El-Sayed et al., 1993). The seasonal variation showed a minimum average of 1.93 mg l^{-1} during winter and a maximum average of 4.33 mg l^{-1} during summer. The total humic substance budget derived from an autochthonous source represented by primary production which contributed about $5,150 \times 10^6$ g year^{-1}; allochthonous (drains) sources contributed about 4328×10^6 g year^{-1}. About 65% of dissolved humic substance input is lost (trapped, transformed, or degraded) in the lake before being discharged to the sea.

Fig. 6 Eutrophication of Alexandria coast by sewage discharge from Lake Mariut (after Halim & Abu-Shouk, 2000) (*see Color Plates)*

5 Effects of the Nile Delta Effluents on the Coastal Ecosystem

The capricious Nile floods between the late 1970s and early 1980s, motivated the Egyptian Ministries of Irrigation and Public Works to adopt policies to face any future shortage of Nile water supply. Despite the fixed 55.5 km^3 of Nile water allotted to Egypt yearly, the rapid increase in its population during the last 30 years has resulted in more freshwater needed to satisfy the nation's demands. This circumstance forced policy makers to turn to non-conventional resources such as underground water accessible to drilling, water recycling and, to some extent, desalination. These sources of freshwater are not suitable to satisfy all needs and are always mixed with Nile water. The decision of the Egyptian government to reduce the discharge of Nile water to the Mediterranean not only affects the quantity of the Nile water discharge, but also its quality. That is mainly because the water undergoes a series of recycling before finally reaching the Mediterranean (Hamza, 2006). The discharge points to the sea have been identified by Stanley (1996) as El-Tabya and El-Maadiya (Lake Idku), El-Burg (Lake Burullus), El-Gamil (Lake Manzalah), Shibin drain at Gamasa (west of the Damietta branch), and Kitchener drain (east of lake Burullus). These are in addition to the El-Max pumping station, which pumps sediments and sewage water from Lake Mariut to El-Max Bay along the Alexandrian coast. Recent quantitative data on sediment

Table 4 Location and discharge water characteristics of the main land-runoffs and the winter season discharge percentages (after Hamza et al., 2003)

	Location					Nutrient loads	
	Lon.	Lat.	Discharge	Winter	Salinity	N	P
Sources	deg.	deg.	km^3 year^{-1}	%	S%	T year^{-1}	T year^{-1}
Lake. Mariut	29.82	31.20	2.3	40	6	90.85	11.41
Lake Idku	30.20	31.33	0.4	40	4	16.16	2.03
River Nile	30.37	31.50	3.5	90	2	138.17	17.35
Lake Burullus	31.00	31.62	2.2	40	5	87.14	10.94
Nile Delta drains	31.28	31.55	3.5	40	4	138.17	17.35
Lake Manzalah	31.48	31.46	5.2	40	5	205.44	25.80
Total	–	–		–	–	676.37	84.88

and water discharge from the above-mentioned effluents are lacking. Based on nutrient concentrations in the major effluents during 1986, a total of 676.37 tons of inorganic nitrogen and 84.88 tons of orthophosphate were discharged to the Nile Delta coastal area (Table 4). These quantities were carried in the total discharge, about 18 km^3 of Nile water, to the Mediterranean Sea at that time (Hamza et al., 2003). If the nutrient concentrations in the quantity of water actually discharged (ca 2–4 km^3) remain similar, a simple calculation shows an actual load of 112.73 tons of nitrogen and only 14 tons of orthophosphate released annually through the Nile Delta effluents to the Mediterranean. However, higher concentrations may be found in the coastal area of the Nile Delta, due to highly polluted water after its agricultural use, in addition to poorly treated sewage. Dumont & El-Shabrawy (2007) reported concentrations of dissolved nutrient salts measured in the water column of Lake Burullus during 2004. They found that the average concentrations of nitrogen ions NO_2, NO_3 and NH_3 were up to 147, 613, and 1120 µg l^{-1}, respectively. Concentrations of PO_4 ranged between 100–1647µg l^{-1}. These high concentrations could be measured at all the NDL, since their sources of water supply and its water quality are almost similar.

On the other hand organochlorine pesticide concentrations along the Nile estuary are high (Table 5), with some dilution due to mixing with marine coastal water. As shown in Table 4, about 40% of the discharge to the Mediterranean through the Nile Delta effluents and about 90% of the discharge through the Nile branches occurs during winter. This is due to the relatively high precipitation (200 mm cm^{-2}) over the delta during winter, and to the opening of the Nile branch barrages during this season. The release during one season of such a large portion of the total flow is the main cause of an algal bloom along the Egyptian coast in front of the Nile Delta (Dowidar, 1984, 1988; Hamza et al., 1998). This bloom is anomalous, considering the oligotrophic state of the Mediterranean in general and the Levantine basin in particular. Tselepides & Lampadariou (2004) stated that the eastern Mediterranean has one of the lowest meiofaunal standing stocks, reflecting the low productivity of this area. But they also concluded that the highest meiofaunal densities occur over the shallow continental shelf of the Nile Delta (340 ind cm^{-2}). This phenomenon is explained by the fact that the Mediterranean occasionally undergoes periods of

Table 5 Concentrations (ng l^{-1}) of HCB, DDTs, PCBs and lindane in seawater from different locations in Egypt (modified from Barakat, 2004)

Location	Sampling	HCB	DDTs	PCBs	Γ-HCBs
Mediterranean Sea					
Alexandria Coast		5–19	12–20	37–131	1–9
Abu Quir Bay		2–52		20–844	<0.1–60
			17–166	31–872	
El-Max Bay		6–32	16–88	40–153	9–39
			16–48	26–191	
Wastewater discharge (av. conc.)					
Edku Lake output	97–98	30	78	310	310
				410	
El-Max pump station	97–98	85	72	620	420
				810	
El-Amia Drain	97–98	37	61	420	410
				520	

increased nutrient availability, such as the effect of the Nile Delta effluents on productivity along the Egyptian Mediterranean coast.

6 Prediction of Future Variations in the Nile Delta

The Nile Delta is a complex environment, combining the effects of both natural and human factors. The reduction of Nile water flow through the delta branches, in addition to recent intensification of agricultural activities (Hamza & Mason, 2004), limit the ability of the nutrient-rich sediments to reach the delta agricultural lands. North of Cairo there have been marked increases in population and agriculture and industrial activities. These human activities and the shortage of freshwater resources have led to water recycling becoming a common practice before its release as waste and sewage to the northern lakes, and then into the Mediterranean as a polluted but complex nutritive discharge. Along the northern coastal area, the arrival of diminished quantities of Nile sediment have not been sufficient to combat coastal erosion due to long-shore coastal currents (Stanley, 1996; Frihy & Dewidar, 2003; Conway, 2005). There are also erosive effects from strong coastal wave action along the Nile Delta headland (El-Asmar & White, 2002).

To predict changes within the Nile Delta area and its coastal environment, it is necessary to assess the effects of various combinations of the above-mentioned parameters. Neither monitoring nor simple statistical analysis will reveal future characteristics of the Nile and its coastal ecosystem if these parameters remain unquantified. In an attempt to provide a quantitative tool, a 3D numerical model has been established to simulate, analyze and predict quantitative variations in the Egyptian-Mediterranean coastal area (Hamza et al., 1998). This model takes into account meteorological variations and their effects on the coastal area. For example, El-Asmar & White (2002) found that wave action along the Nile Delta coast is seasonal with high storm waves approaching from the NW-NNW during winter. These generate eastward long-shore currents with velocities up to 0.9 m s^{-1}. The 3D numerical model couples hydrodynamics and biological components in its calculations based on data collected along the Egyptian Mediterranean coastal area during the period 1982–1986. The model also considers nutrient inputs, and the full range of topographic features along the coast (Hamza et al., 2004). Based on the FinEst model of Tamsalu & Ennet (1995), the basic equations are as follows:

$$\boldsymbol{\partial c/\partial t + Lc = F} \tag{1}$$

where

$$\mathbf{c} = \left| \begin{array}{lllll} \mathbf{u} & & & & \\ & \mathbf{v} & & & \\ & & \mathbf{T} & & \\ & & & \mathbf{S} & \\ & & & & \mathbf{C} \end{array} \right| \quad \begin{array}{l} \\ \text{hydrodynamic parameters} \\ \\ \\ \text{ecosystem parameters} \end{array}$$

$$\mathbf{F} = \left| \begin{array}{lllll} \mathbf{-1/r0\partial p/\partial x + fu} & & & & \\ & \mathbf{-1/r0\partial p/\partial y - fv} & & & \\ & & \mathbf{1/(cp\ r0)\partial I/\partial z} & & \\ & & \mathbf{0} & & \\ & & & & \mathbf{G} \end{array} \right| \quad \begin{array}{l} \text{pressure + Coriolis} \\ \text{pressure + Coriolis} \\ \text{solar radiation} \\ \\ \text{biochemical reactions} \end{array}$$

$$\mathbf{Lc} = \mathrm{div}\mathbf{h}\ [\mathbf{Uc} + \langle \mathbf{U'c'} \rangle] + \partial/\partial \mathbf{z}[(\mathbf{w} + \mathbf{w})\mathbf{c} + \langle \mathbf{w'c'} \rangle]$$

Here, U is the horizontal velocity vector with components u and v; U' = fluctuation of the horizontal velocity vector with components u' and v'; w = vertical velocity; w' = fluctuation of the vertical velocity; T = temperature; S = salinity; p = pressure; ρ = density; ρ0 = mean density; b = buoyancy; g = acceleration due the gravity; f = Coriolis parameter; C = ecosystem parameter; c' = fluctuation of parameter C; G = biochemical reactions; F = linked reaction results of the model; Lc = spatial variations of the model parameter.

For calculations, the continuity equation is required:

$$\mathrm{div}\mathbf{h}\ \mathbf{U} + \boldsymbol{\partial w/\partial z = 0} \tag{2}$$

The hydrostatic equation is:

$$\boldsymbol{1/r0\partial p/\partial z = g(r = r0)r0 = b} \tag{3}$$

The components of the plankton community are autotrophs (photosynthetic plant organisms), heterotrophs (non-photosynthetic organisms), and detritus. Five categories of autotrophs (**Ai**) and heterotrophs (**Hi**) are classified:

Their evolution is governed as follows:

$$\boldsymbol{\partial A_i/\partial t + LA_i = Ga1_i - Ga2_i - Ga3_i - Gh5_i} \tag{4}$$

i = 1,…,4

$$\partial \mathbf{A}_5 / \partial \mathbf{t} + \mathbf{LA}_5 = \mathbf{Ga1}_5 - \mathbf{Ga2}_5 - \mathbf{Ga3}_5 \quad (5)$$

$$\partial \mathbf{H}_i / \partial \mathbf{t} + \mathbf{LH}_i = -\mathbf{Gh2}_i - \mathbf{Gh4}_i + \mathbf{b}(\mathbf{Gh5}_i + \mathbf{Gh6}_i) - \mathbf{Gh6}_{i-1} \quad (6)$$

i = 1,…,4

$$\partial D/\partial t + LD = \sum_{i=1}^{5} (Ga2_i + Gb2_i) - Gd3 \quad (7)$$

Here: Gd3 = detritus decay; $Ga1_i$ = autotrophs growth; $Ga2_i$ = autotrophs mortality; $Ga3_i$ = autotrophs respiration; $Gh1_5$ = bacterioplankton growth; $Gh2_i$ = heterotrophs mortality; Gh3 = - heterotrophs respiration, $Gh4_i$ = heterotrophs excretion; $Gh5_i$ = heterotrophs grazing; Gh2i = heterotrophs predation; b = efficiency coefficient.

All biochemical reactions are parameterized for autotrophs as follows:

$$\mathbf{Gaj}_i = \mathbf{ca}\ \mathbf{Ma}_i^{-1/4}\ \mathbf{cta}_i\ \mathbf{fj}_i\ \mathbf{A}_i\ \ \mathbf{i = 1,...,5;\ j = 1,...,3} \quad (8)$$

The biochemical reactions for heterotrophs may be written as follows:

$$\mathbf{Ghj}_i = \mathbf{ch}\ \mathbf{Mh}_i^{-1/4}\ \mathbf{cth}_i\ \mathbf{fj}_i\ \mathbf{H}_i\ \ \mathbf{i = 1,...,5;\ j = 1,...,6} \quad (9)$$

The model has four phosphate compounds and five nitrogen compounds. Although the hydrodynamic part of the model is established, the ecosystem equations are still in a developmental stage. Certain processes of the food-web interactions, such as fish competition and predation, can be included following the same mass dependent bases. Further details regarding the model and coefficients used are found in Hamza et al. (2003).

The results of simulations for the winter season demonstrate an effect of wind direction and intensity on the delta coastal area (Fig. 7). Biological simulations show that the effect of wind along the coastal area is variable. In certain areas near the

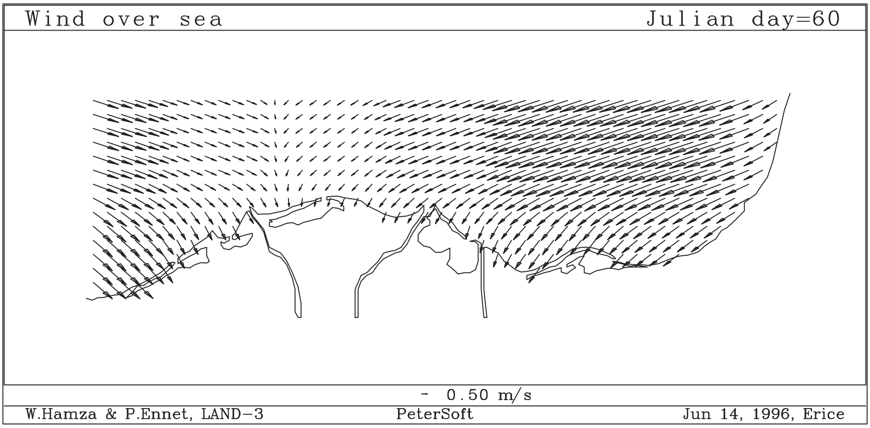

Fig. 7 Finest model simulation of wind components data obtained from Mars Archives over the Egyptian coast during the 60 Julian days (after Hamza et al., 2004)

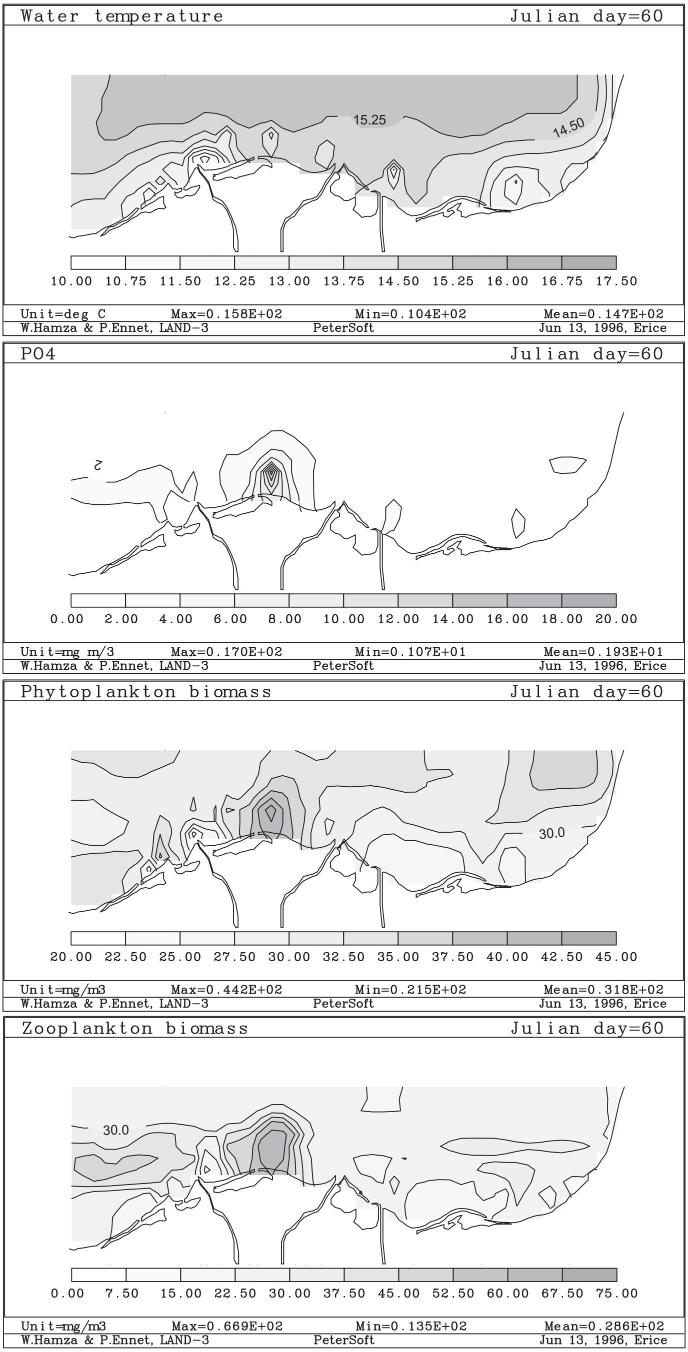

Fig. 8 Calculated water temperature, PO4-P, phytoplankton and zooplankton biomasses along the Egyptian Mediterranean coastal area (after Hamza et al., 2004)

Rosetta mouth, a calm condition develops during winter, when the Rosetta branch is discharging up to 90% of its annual load to the Mediterranean. Such circumstances may promote the development of a winter algal bloom that thrives on the nutrients in the delta effluent (Hamza et al., 2003). A summary of the environmental parameters along the Egyptian Mediterranean coast during winter is shown in Fig. 8.

In conclusion, it is evident that the accentuated erosion of significant stretches of Nile Delta shoreline results from the inferior supply of sediments presently reaching the sea, compared to the sediment removed by currents from the coast. The Nile Delta is an extreme example of human interference in the stability of a depocenter, which is no longer prograding. Maintaining a healthy Nile Delta region, capable of sustaining a dense population, requires reconciling support to agricultural intensification with the need to release sediments to the coast. Careful monitoring based on quantitative analysis is of extreme importance in future planning for sustainable development of the Nile Delta – a region vital to the national food supply of Egypt.

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