THE NILE DELTA-ALEXANDRIA COAST: VULNERABILITY TO SEA-LEVEL RISE, CONSEQUENCES AND ADAPTATION

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Abstract. Like many delta systems, the coastal zone of the Nile delta has been designated as a vulnerable zone to a rising sea level as a consequence of expected climate changes combined with geological and human factors. In view of the understanding of these factors, a degree of vulnerability analysis has been carried out to better locate which sectors need to be assessed and adapted to possible sea level rise (SLR) for the Nile delta-Alexandria region of Egypt. Results reveal that not all of the coastal zones of the Nile delta are vulnerable to accelerated sea-level rise at the same level. Based on multiple criteria the Nile delta-Alexandria coast can be categorized into vulnerable (30%), invulnerable (55%) and artificially protected coastal stretches (15%). These criteria include: local subsidence or uplifting, relative sea-level rise (RSLR), land topography, width of lagoon barriers, beach-face slope, high-elevated features such as dunes and ridges, eroding and accreting coastlines and protection works. Moreover, this study evaluates the long-term relative sea-level rise and subsidence rates along the Nile delta and Alexandria coasts. Statistical analysis of long-term tide gauge data recorded at Alexandria, Burullus and Port Said yields values of 1.6, 1.0 and 2.2 mm yr^{-1}, respectively. These values of relative sea-level rise and long-term subsidence rate obtained from age-dated sediment core sections are inconsistent: long-term subsidence appears to be larger (maximum of 7 mm/ yr). This discrepancy might be explained if the subsidence is episodic, and occurs rather abruptly during major earthquakes that occur every few hundred years associated with fault trend lines. Rising sea levels could have significant longterm impacts on the Nile delta, including the distribution of ground water salinity and erosion of the narrow and low-lying barriers of the Burullus and Manzala lagoons. Adaptive measures along the study area particularly those related to coastal protective structures are also evaluated.

Keywords: beach erosion, climate change, littoral cells, protective works, subsidence

1. Introduction

The Nile delta-Alexandria coast is located on the Egyptian Mediterranean coast at the northeast Africa. The shoreline of the Nile delta, from Abu Quir to east of Port Said, 275 km long, is a gently arcuate coast consists of protruding promontories separated by embayments and saddles (Figure 1). The delta beach and its contiguous coastal flat are backed partially by coastal flat, dunes or by brackish lagoons. Three lagoons (Idku, Burullus and Manzala) are separated from the sea by narrow barriers leaving artificial inlets. The delta was built by seven distributaries and subsequently silted up and replaced by the present day Rosetta and Damietta

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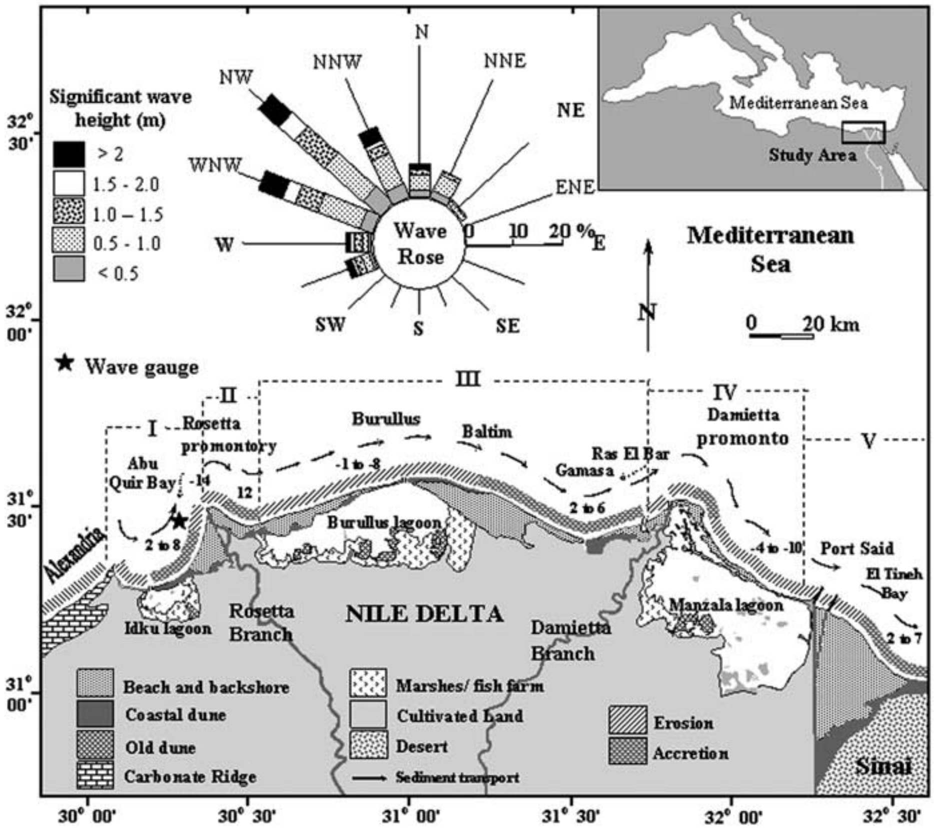

Figure 1. Map of the Nile delta and Alexandria showing the main geomorphologic units and the position of the five sub-cells identified by Frihy et al. (1991) and Frihy and Lotfy (1997): I= Abu Quir sub-cell; II= Rosetta sub-cell; III= Burullus sub-cell; VI= Damietta sub-cell; and V= Port Said sub-cell. Also, shows values of rate of erosion and accretion (m/yr) (Frihy et al. 2003a) and wave rose (average wave direction-height distribution) measured at Abu Quir Bay (modified from Frihy et al. 2003a). Wave rose shows dominant north and northwest frequencies associated with significant northeast reversals.

branches (Toussoun 1934; Said 1981). The beach and backshore are composed of loose quartz sand and feldspars with significant amount of heavy minerals and minor amount of shell fragments (UNDP/UNESCO 1978). Like many other deltas, the coastal zone of the Nile delta is presently undergoing extensive changes caused by both natural and anthropogenic influences. Natural factors affecting changes of the Nile delta coast include sediment supply, coastal processes, tectonic activities, climatic and sea level fluctuations (UNDP/UNESCO 1978; Stanley and Warne 1993).

Like many other deltas, main changes have attributed to river regulations. The sediment supply to the coast has been cut off due to the construction of dams

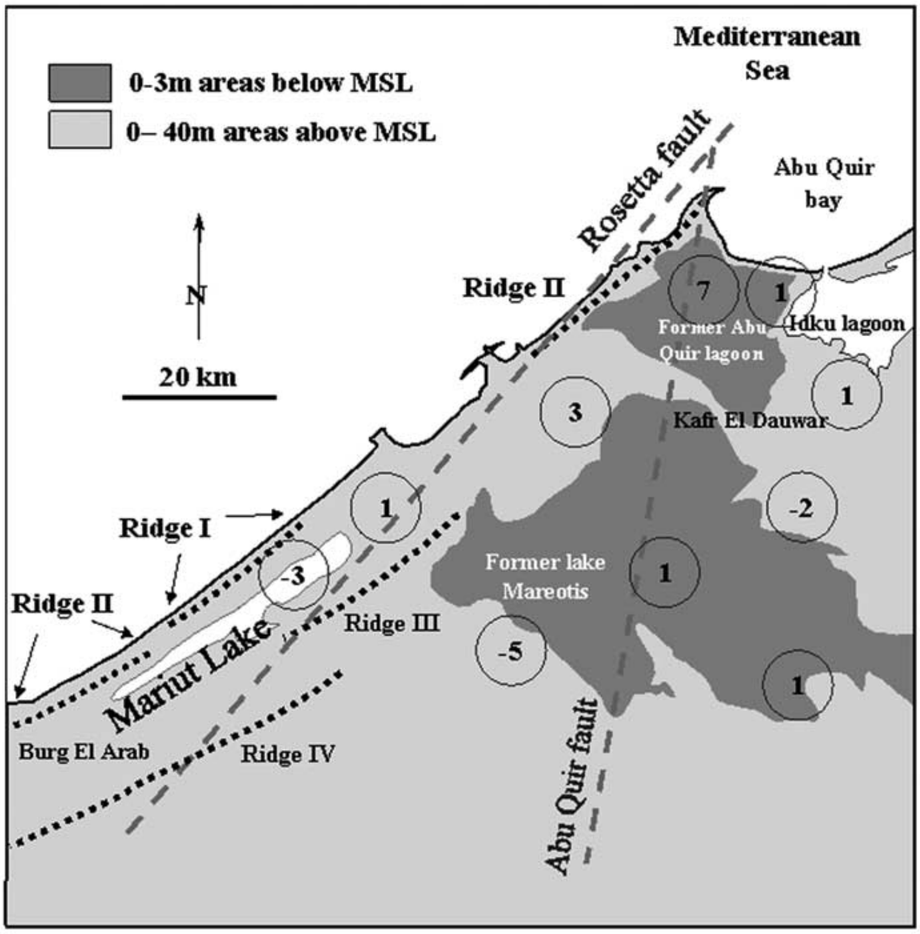

Figure 2. General topographic map of Alexandria region showing values of vertical land motion (mm yr^{-1}). Areas with overall land submergence and emergence (in circles) are denoted by positive and negative numbers, respectively (modified after Warne and Stanley 1993). The Rosetta and Abu Quir faults are delineated from Zaghloul et al. (1999).

and barrages on the Nile River. This is accompanied by the historical fluctuation in the Nile floods due to changes in climate over the Nile basin in the equatorial east Africa. In the absence of sediment supply to the coast, coastal processes mainly waves and currents act together with the SLR to induce beach changes (UNDP/UNESCO 1978).

The Nile delta, as in other world deltas, sea level was low at ~20,000–18,000 years BP and then rose rapidly during much of the period from ~16,000–9,000 years BP. Formation of the Nile delta started when sea level began to decelerate, from ~8000 to 6500 years BP. The delta coastal margin migrated northward by as much as 50 km during the past 5000 years (Stanley and Warne 1994). Alexandria is built on a narrow coastal plain of Pleistocene carbonate sand ridges of 8–10 m elevation (Figures 1 and 2). These ridges extend westward parallel to the present coast (Butzer 1960). The coastline is backed to the south by a series of different landuse/land cover units including carbonate ridges, Mariut lake, inland depression, drain, desert, urban, industrial centers, agriculture land and archaeological sites.

The aim of the present study is to integrate main factors acting on the Nile delta and Alexandria (erosion/accretion patterns, topography, subsidence and relative sea level rise) to determine the degree of vulnerability to coastal erosion including SLR. Another aim is to provide updated measurements of relative sea-level changes at Alexandria and the Nile delta. These measurements are correlated with the long-term subsidence rates previously measured using dated cores along the delta coast. Possible consequences of sea-level rise and corresponding mitigations are also discussed.

2. Physical and Socio-Economic Settings

2.1. Erosion/accretion patterns

The Nile delta is a typical wave-dominated (or perhaps more accurately termed wave- and current-dominated) environment. A recent study by Frihy et al. (2003a) on waves measured at Abu Quir Bay (1988–1990) has postulated that the predominant wave directions are mainly from north and northwest sectors. Location of the wave gauge (S4DW) used in their study is shown in Figure 1. Their results indicated that the degree of exposure to wave energy varies with coastline orientation in the relation to the incident waves. Measurements revealed that waves dominate from the N-W sector (81%) with small components from the N-E quadrant (14%) and from the S-W (5%) (Figure 1). Of the 13 months examined, 9 reveal N-W waves and 4 record a N-E wave component. Only three months show waves from S-W quadrant. Maximum significant wave height recorded west of the Rosetta promontory is 5.4 m approaching from the WNW direction in December 1988. On average, wave height and period are 1.2 m and 5.6 sec, respectively.

Studies of the shoreline position and sediment budget along the coastline of the Nile delta and Alexandria show that coastal areas can be divided into a series of discrete sedimentation compartments called ‘littoral cells’ (Frihy et al. 1991, Frihy and Lotfy 1997). Each cell contains a complete cycle of littoral transportation and sedimentation, including sources and sinks of sediment and transport paths (Figure 1). Previous studies along the nearshore zone of the Nile delta and contiguous Sinai coast have identified self-contained sub-cells. These littoral sub-cells are Abu Quir sub-cell, Rosetta Sub-cell, Burullus Sub-cell, Damietta Sub-cell and Port Said sub-cell. These sub-cells are part of the regional Nile littoral cells extends from Alexandria to Akko on the northern part of Haifa Bay, Israel (Inman and Jenkins 1984). The principal sources of sediment for each littoral sub-cell are the eroded headlands that supply large quantities of sand to the coast (Figure 1). The pattern of erosion versus accretion reflects the natural processes of wave-induced longshore currents and sediment transport. Seasonal variability of wave approach produces converging and diverging current pattern along the delta coast. The eroded sand is transported along the coast by wave and currents until it is intercepted and terminated in the downcoast direction by adjacent sinks including promontory saddles, embayments and long breakwaters. Based on Bruun's Rule (Bruun 1962) the beach erosion contributing to the expected SLR ranges from 4.3 to 9.6% of the long-term coastline retreat of the Nile delta (Frihy 1992b).

2.2. Land topography

Surprisingly, most previous studies that have dealt with the assessment of SLR have used different sea level scenarios projected on old topographic map surveyed during 1950s. In this study an updated topographic map is constructed for the coastal zone from Alexandria to 25 km east of Port Said and up to 65 km south of the coastline (Figure 3A). This map was constructed from a recent topographic map dated 1995 at scale of 1:50,000 and is integrated with land leveling data measured during beach profile surveying of the foreshore zone (Frihy et al. 2003a). The survey was carried out using a Digital GeoPositioning System and a Total Station, with an accuracy of ± 1 m (coordinate) and ± 1 cm (leveling), respectively. The leveling (above and below mean sea level) data are adjusted to local measured Mean Sea Level datum using fixed survey benchmarks located behind the beach area. The constructed map was processed using digitizer and Surfer software.

The lower Nile delta has a large area between zero and 1 m elevation, with parts below sea level (Figure 3A). Areas below mean sea level include coastal lagoons, the former Abu Quir/ Mareotis lagoon south of Alexandria and the aquacultures bordering the southern margins of the coastal lagoon. The delta lagoons form a transition zone between land and the sea, in most places separated from the sea by narrow and low-lying sand barriers. A great part of the beach and coastal flat lies between zero and 2 m above mean sea level. Areas above 3 and 4 meters lie within the coastal dunes at the backshore of Abu Quir Bay, Gamasa, and in the southern part of the lower delta plain, corresponding to about 35 km from the shoreline (Figure 3A).

2.3. Socio-economic setting

The population of Egypt has increased from 10 to nearly 65 million in the past 100 years, with a growth rate that approximates 1 million per year (World Bank 1990). Highest population centers ($\sim$25 million, i.e. 38% of the total population) are found at the coastal zone of Alexandria and Nile delta (Figure 3B). The Nile river delta contributes 30–40% of agricultural production and 60% of fish catch

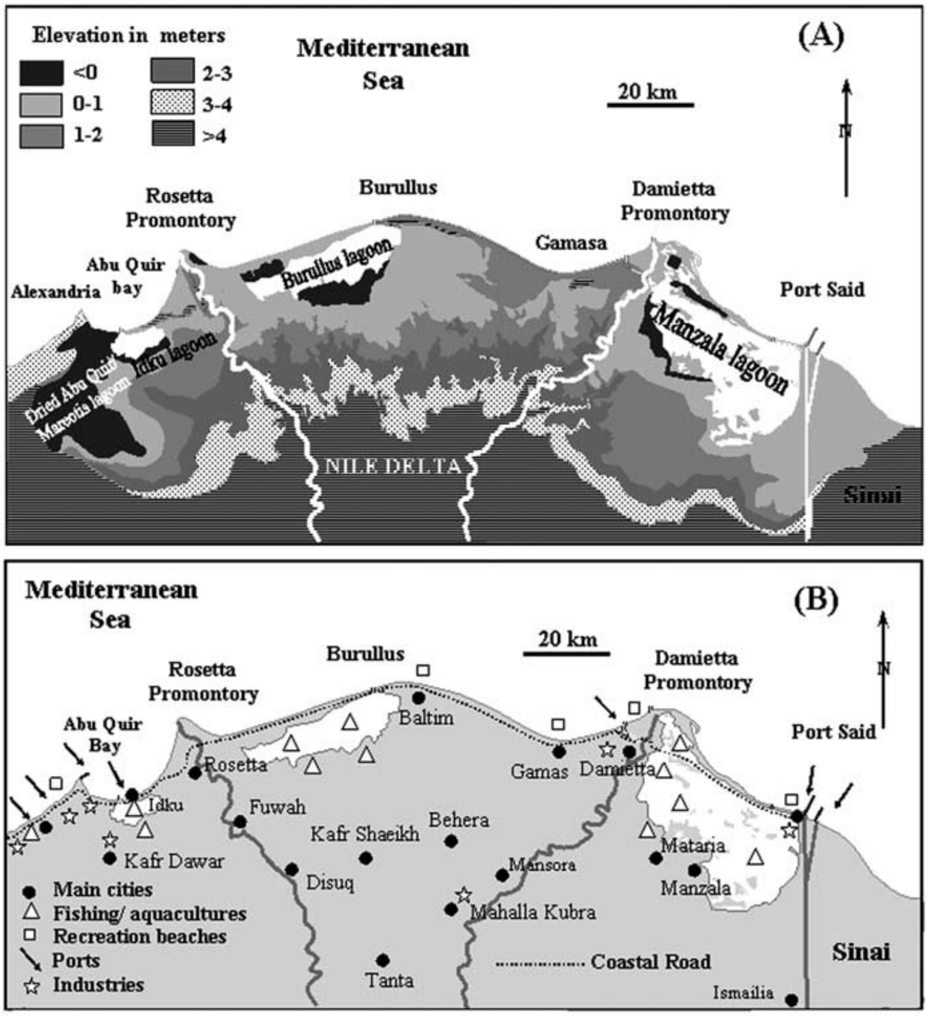

Figure 3. Map of the lower Nile delta showing (A) main topographic features below and above mean sea level up to 4 m contour and (B) distribution of main socioeconomic elements across lower Nile delta coastal plain. Agriculture land is depicted in Figure 1.

(marine and lagoonal). Most of the fertile soils of the Nile delta are used for agriculture, irrigated by the water supplied from the Nile system. Lands near the lagoon margins, especially at locations with low elevation, have been reclaimed for the purpose of agriculture and fish farms exist. Half of Egypt's industrial production comes from the delta, mainly from Alexandria. Main commercial ports are located at El Diekhila, Alexandria, Abu Quir, Idku, Damietta, Port Said and east of Port Said (Figure 3B). The beaches of the Nile delta are little used whereas Alexandria coast is totally used as public resort summer beach. Main delta resort beaches are located at Gamasa, Baltim, Ras El Bar, El Gamil and Port Said. A coastal road was recently completed to connect the delta region with west of Alexandria and Sinai. In the Nile delta few people live below 1 m contour, whereas populations are usually concentrated on ground more than 2 m above sea level, especially on the raised present or past alluvial channels (Sestini 1990). Commercial and industrial centers are situated above the 3 m-contour line. Economic activities in the coastal zone include agriculture, industry, fishes/aquaculture and recreation beaches are denoted in Figure 3B.

3. Factors Controlling Sea Level Fluctuations

Studies on long-term changes in SLR in the Mediterranean region indicate that it is mainly controlled by the interaction of global, regional and local factors. These factors are 1- Eustatic SLR due to global SLR climatic oscillations accompanying greenhouse warming, 2- local tectonism: subsidence/ emergence (uplift) of land (compaction, neotectonism, oil or groundwater pumping), and 3- seasonal oceanographic/ meteorological processes (wind, storm surge, wave set-up, standing waves).

A number of worldwide investigators have developed chronologies of eustatic sea-level variations for the last 50,000 years (worldwide) (Curry 1965, Milliman and Emery 1968). The results generally agree that about 15,000 to 20,000 years ago, the sea was approximately 100 m lower than at present. With the melting of glaciers and thermal expansion of seawater, there was initially a rapid rise in sea level, averaging about 8 mm yr^{-1}, until approximately 7,000 years ago when it slowed to 1 to 2 mm yr^{-1}. The eustatic rise has been estimated to be on the order of 1 to 2 mm yr^{-1}, but other predictions suggest that it could increase to 2.5 mm yr^{-1} (i.e. 25 cm) during the 20th century and this rate is expected to accelerate during the 21st century due to the human-induced global warming (Nicholls and Klein 2000). The UN Intergovernmental Panel on Climate Change (IPCC 1994) estimated that the global rise from 1990 to 2100 would be between 23 and 96 cm, with a mid estimate of 55 cm (Nicholls and Klein 2000).

The vertical motion of land, subsidence or emergence refers to the lowering or emerging of the land surface relative to a geodetic datum. Vertical motion varies locally depending upon rates of isostasy, tectonism, compaction and anthropogenic influences (groundwater or oil withdrawal) or combination thereof. Subsidence and emergence is generally independent on world (eustatic) sea-level changes. Measurement of subsidence requires removing the effects of changing sea level, which has been rising during much of the past $\sim$18,000 years. Land subsidence and emergence due to neotectonism play an essential part in increasing or decreasing sea level.

The following is a brief description of the main factors contributing to the coastal vulnerability of Nile delta and Alexandria. These factors are integrated

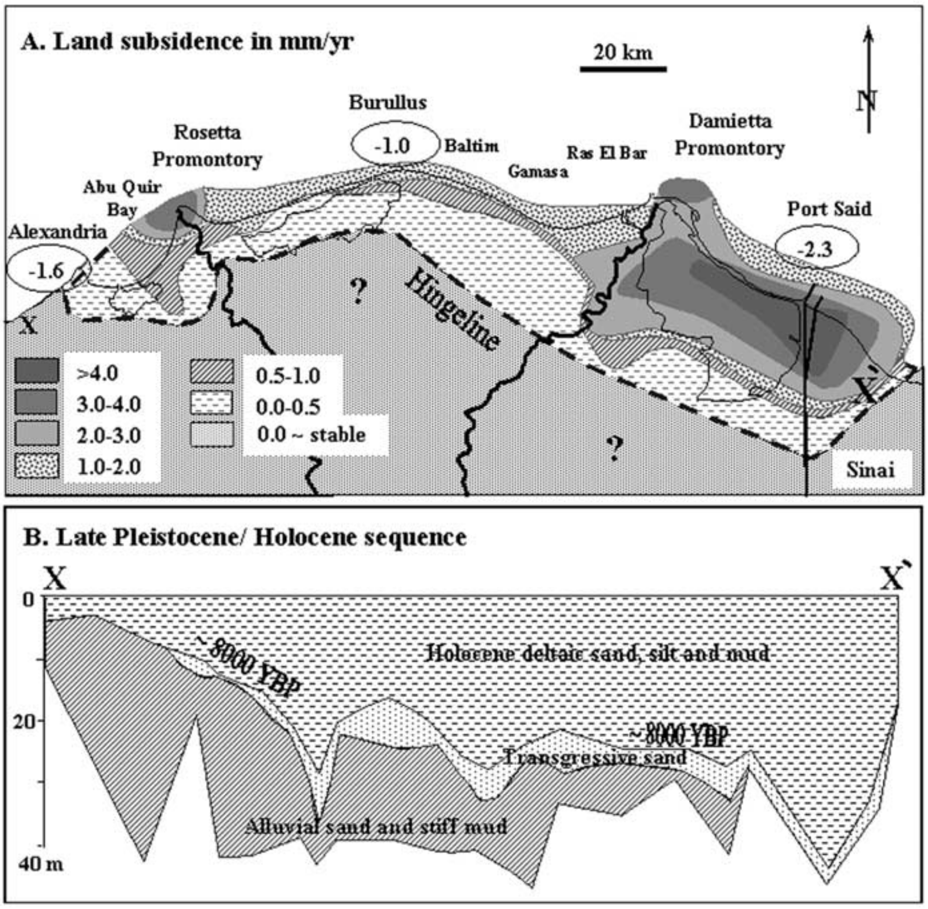

Figure 4. (A) Spatial distribution of land subsidence rates in the northern delta with values ranging to 5 mm/year (modified from Stanley and Warne 1993). Ellipses show values of relative sea level in mm calculated from tide gauge records in this study. (B) East-west stratigraphic cross section in the Nile delta and Alexandria region, simplified from numerous core sections, depicting late Pleistocene alluvial sequences overlain by Nile delta Holocene deposits (modified from Stanley and Warne 1993).

to characterize zones of vulnerability. Understanding of such factors will help in locating areas that might need to be assessed to the impacts and adaptations to SLR.

3.1. Land subsidence of the Nile delta coast and Alexandria

Along the Mediterranean coast of Egypt, long-term land subsidence or emergence has been calculated using archaeological and radiocarbon-dated sediment cores. There is a complex pattern of land subsidence on the Alexandria coast due to its tectonic setting. Based on carbon-dated sediment cores, previous studies of Alexandria have indicated diverse values of land emergence or subsidence ranging from –0.5 to 7.0 mm yr^{-1} (Warne and Stanley 1993; Chen et al. 1992) (Figure 2). Based on their studies, land subsidence at Alexandria is significantly higher than that at the Nile delta in spite of the absence of the soft fluviomarine deltaic mud underlying Alexandria region. The subsurface Pleistocene carbonate rocks and stiff mud of lagoon facies characterized this region, could not allow such higher rates of subsidence (Figure 4A) (Warne and Stanley 1993). Generally, land subsidence at Alexandria are attributed to is evidenced from: (1) the existence of submarine Ptolemaic and Roman archaeological remains and coastal structures, (2) disappearance of sandy beaches, and disappearance of emerged islands, submerged and disappearance of the former Nile distributary channel the Canopic, that once flowed across Abu Quir Bay about 2500 years BP. and (3) the major earthquakes which shook Alexandria in the fourth century A.D., and (4) from the documented fault mapped system (Figure 2).

The variability of emergence and subsidence of Alexandria land (ranging between –5 mm and 7 mm yr^{-1}) as calculated by Warne and Stanley (1993) may be attributed to the impact of tectonic activities. Tectonic activities in Alexandria were evidenced from the observations on submerged Roman and Greek ruins in the Eastern harbor and Abu Quir Bay (Toussoun 1934; El Sayed 1988; Warne and Stanley 1993). Ancient ruins as old as 2,500 years had submerged 2 to 5.5 m. The Hellenistic city of Canopus ($\sim$500 BC) in Abu Quir Bay was originally as much as 3 m above sea level, which may imply that it has been submerged as much as 8 m during the past 2,500 years. The tectonic activities are also confirmed from the major earthquakes, which shook Alexandria in the fourth century A.D. and from the documented fault/fold mapped system as well (Figure 2).

Further to the east and based on age-dated sediment core sections, Stanley (1988), Stanley (1990) and Stanley and Warne (1993) have estimated long-term average subsidence rates across the Nile delta region (Figure 4B). The processes of compaction and dewatering of the thick accumulated deposits of fluviomarine deltaic mud sequence formed in the Holocene has induced higher rates of subsidence ranging from 1 to 5 mm yr^{-1} (Stanley 1990; Chen et al. 1992). Subsidence has been considerably lower in a westerly direction, ranging from 5 mm yr^{-1} at Port Said in the east to $\sim$1 mm yr^{-1} farther to the west at Alexandria region (Warne and Stanley 1993; Figure 4A). Thickness of Holocene strata beneath the modern delta plain is a direct function of subsidence, which ranges from 50 m at Port Said and tends to decrease or be nearly absent westward below the Alexandria coastal plain (Figure 4A). Quaternary subsurface stratigraphy of the northern Nile delta and Alexandria records three main sequences (Warne and Stanley, 1993; Figure 4A). These sequences, from bottom to top: alluvial sand and stiff mud (older than $\sim$12.000) unconformably overlain by shallow marine to coastal transgressive sand ($\sim$12,000 to 8,000); this sand is, in turn, unconformably overlain by a variable sequence of Holocene deltaic sand, silt, and mud as old as $\sim$7.500 yr. Stanley and Warne (1993) have attributed the regional thickness of the Holocene deltaic sequence, from west to east, to the differential subsidence, that is, accelerated lowering of the land surface by isostatic depression and faulting. They also attributed the absence of marine prodelta and delta front facies of Holocene age in the west at Alexandria to emergence of that region. The spatial distribution of subsidence indicates that the delta plain is subsiding with a preferential northeastward tilting of the delta plain surface and consequent thickening of the Holocene section (Figure 4A). This thickening trend reflects the easterly increasing in subsidence values. This could be a response to land motion due to tectonic and tilting of the delta plain to the northeast (Stanley, 1988). This tilting may be related to the dominant SW-NW trending faults, recently active along the NE delta margin (Said 1981; Sestini 1989). For example, two major strike-slip faults were mapped off the Manzala-lagoon Port Said region (Neev et al. 1985). Based on the comparison made by Stanley (1997), the subsidence of the Nile delta is relatively lower than that of the other Mediterranean deltas (Rhone, Po and Ebro). These deltas have an average land subsidence rates varying between $\sim$3 and 10 mm yr^{-1} (Milliman et al. 1989).

3.2. Relative sea-level changes of the Nile delta coast and Alexandria

The local change in sea level or 'relative sea level' depends on the sum of two components, the eustatic SLR 'global' and local factors (Nicholls and Leatherman 1996). The local effects are caused by the change in the land with respect to the sea, i.e., subsidence or uplift of the land with respect to a geodetic datum. The RSL measured by the tide-gauge at a particular site is the product of the general worldwide (eustatic) rise in sea level plus any land-level changes.

The continuation of sea-level rise is indicated by tide-gauge records, the year-to-year averages of these records yielding measurements of the ongoing rise in sea level (Hicks 1972; Gornitz et al. 1982). Previous tide gauge analysis indicate that Alexandria sea-level history has a moderate value ranging from 2 to 2.9 mm /yr (El Fishawi and Fanos 1989; Sharaf El Din et al. 1989, Frihy 1992b). On the contrary, Emery et al. (1988) reported an uplift of Alexandria using a short time series of annual tide gauge records by a rate of –0.7 mm yr^{-1} due to neotectonic uplift. The Nile delta exhibits a relatively higher RSL ranges from 2.2 mm yr^{-1} (El Fishawi and Fanos 1989) to 4.8 mm yr^{-1} (Emery et al. 1988). In this study the RSL rates, including land subsidence, are estimated from updated discontinuous tide gauge data recorded at Alexandria and Port Said harbors. In addition, new data records measured at Burullus are also presented. These data comprise the monthly average tide gauge records calculated from the hourly heights of the sea level taken at Alexandria (1944 through 2001; 55 years), Port Said harbors (1926 through 1986; 48 years) and the Burullus (1972 through 2001; 26 years). The yearly average data are subjected to linear regression analysis to calculate the RSL trend (Figure 5). Results indicate that the mean sea level at Alexandria, Burullus and Port Said has risen 1.6, 1.0 and 2.3 mm/year, respectively. On comparison with the data

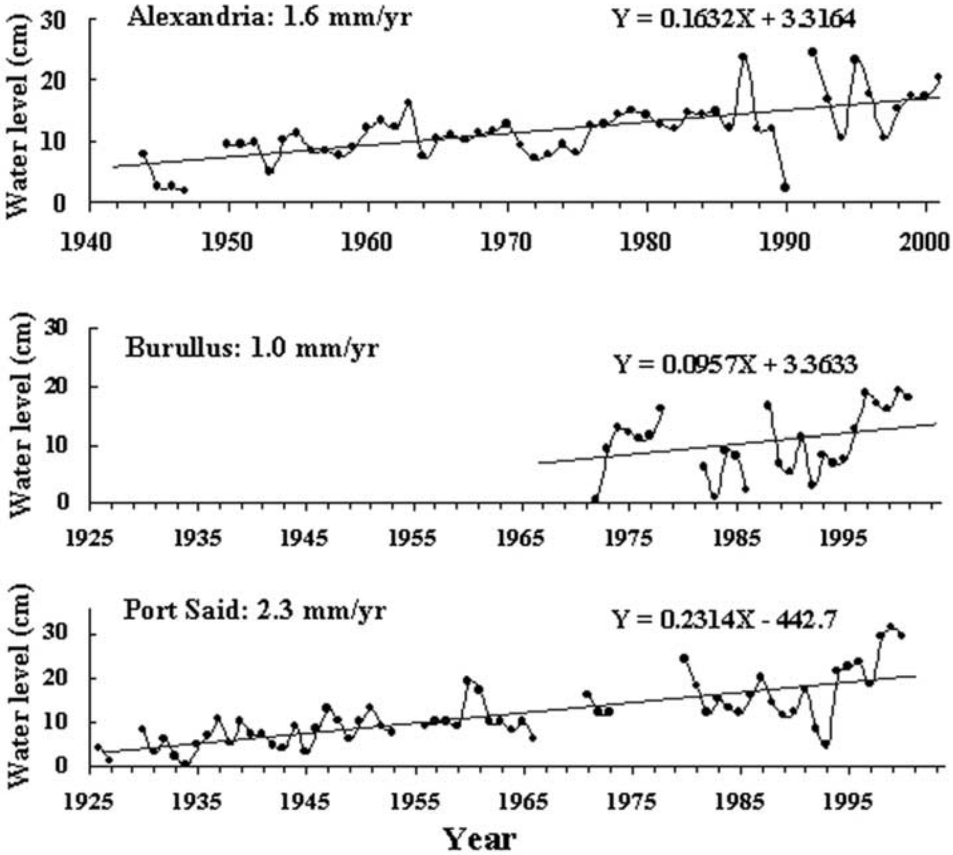

Figure 5. Longterm sea-level rise based on mean annual sea levels measured by tide gauges located at Alexandria, Burullus and Port Said.

reported by Milliman et al. (1989) on other low-lying deltas, it has been noticed that the expected sea-level rise at the Nile delta and Alexandria is considerably lower than that in Bangladesh (1.0 cm/yr), the Mississippi (1.5 cm yr^{-1}) and New Orleans (2.0 cm yr^{-1}). Generally, values calculated in the present study yield a very modest rise in sea level, approximately equal to what is generally believed to be the global eustatic rise in sea level. This would imply that there is essentially no subsidence of the delta, a surprising result in that deltas typically have very high rates of subsidence. In contrast, Stanley and Warne 1993 have reported significant amount of subsidence at the Nile delta (Stanley and Warne 1993; Figure 4B). A maximum subsidence of 5 mm yr^{-1} was estimated, which implies the sum of the eustatic SLR plus the rate of subsidence. Accordingly, this yields an amount of $\sim$ 7.5 mm yr^{-1} RSL, i.e., $\sim$2.5 mm yr^{-1} eustatic sea level (Nicholls and Klein 2000; Gornitz 1995) plus 5 mm yr^{-1} land subsidence; (Stanley 1988). My explanation of this discrepancy is that the subsidence is episodic occurring abruptly during

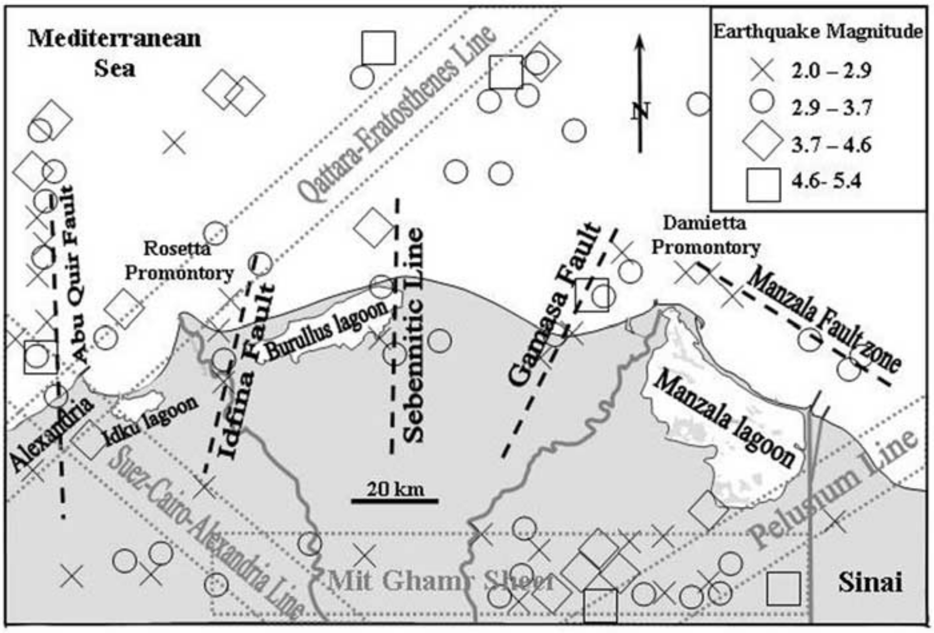

Figure 6. Map showing epicentral distribution of instrumental earthquakes recorded in the lower Nile delta between 1900 and 1997 together with major active 'fault' trends delineated by Zaghloul et al. (1999).

major earthquakes every few hundred years. This would account for the absence of subsidence indicated by the tide gauge records (maximum of 55 years), since those records span a time without a major earthquake. On the other hand, the core sediments studied by Stanley (1988) span approximately 30,000 years, and would integrate the effects of quiet periods without earthquakes plus the effect of the periodic earthquakes.

Of the 83 historical and recent earthquakes documented in Egypt, most of these earthquakes have affected the Nile delta (Ambraseys 1961; Ibrahim and Marzouk 1979; Poirier and Taher 1980; Savage 1984; Kebeesy 1990; El Sharkawy 1992 and Al Abiary 1999). Earthquake activity is also associated with tectonic movements through Holocene to Cretaceous (Figure 6). The geographical distribution of the instrumental earthquakes in historical time and significant seismicity trends across the offshore and the lower part of the delta is shown in Figure 6, (Zaghloul et al. 1999). In this map, major and minor seismicity trends include: the Pelusium trend (Neev et al. 1982); Suez-Cairo-Alexandria trend (Kebeesy 1990); Quattara-Eratosthenes trend (Neev 1977); Mit Ghamr shear zone (Zaghloul et al. 1999); Gamasa fault zone (Neev et al. 1985); Sebennitic fault zone (Gvirtzman and Buchbinder 1977); Abu Quir, Idfina and Manzala faults (Mamoun and Ibrahim 1978).

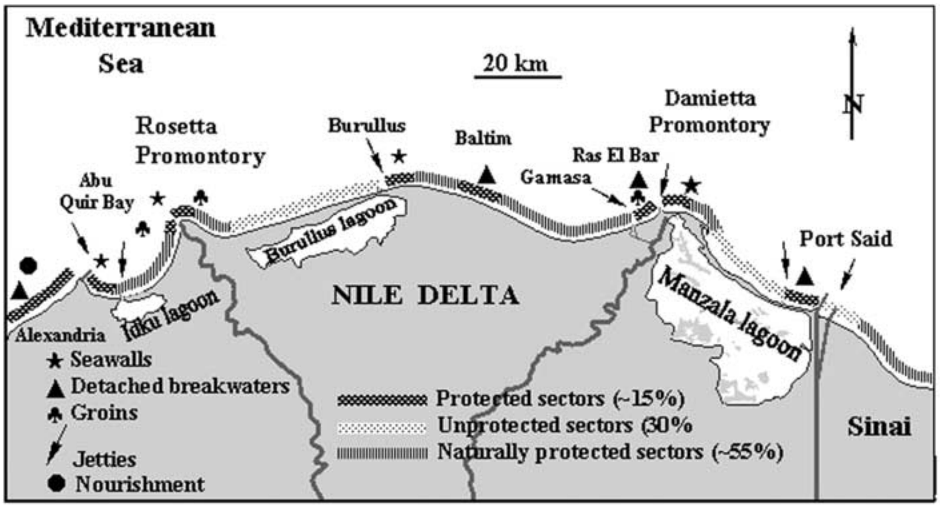

Figure 7. Map of the Nile delta shows main vulnerability degree (15% artificially protected sectors, 30% unprotected sectors and 55% naturally protected sectors) and the existing structural mitigations along the Nile delta coastal zone.

3.3. Seasonal oceanographic variations

Annual and seasonal variations can be produced by a variety of local oceanographic and climatic processes, including changes in water temperature, variations in the strength of coastal currents, atmospheric pressures, and winds blowing either in the longshore or cross-shore directions (Komar 1983). Although the study area is a microtidal environment, storm surges in association with spring tides (high tides) raise water levels by 60 cm above normal MSL (Hamed and El Gindy 1988). Maximum wave height of 5.4 m was recorded at Abu Quir Bay in the winter storm of 1988 (Frihy et al. 2003a). These stormy waves have accelerated beach erosion, flooding across the low-lying areas and large overtopping. Occasionally, high tides occur in combination with storm surges sea level can produce wave set-ups of 1.5 m over winter storm waves of 1.5–3 m height (Nafaa et al. 1991).

4. Degree of Vulnerability

In this study three main criteria are used to categorize levels of vulnerability and high-risk areas of the coastal zone of the Nile delta and Alexandria. Vulnerability, as used in this study, refers to areas vulnerable to beach erosion including climate change. The criteria contributed in defining degree of vulnerability are: local subsidence or uplifting, RSLR, land topography, width of lagoon barriers, beach-face slope, high-elevated features such as dunes and ridges, eroding/accreting coastlines and protection works. Based on these criteria coastal stretches of varying vulnerability are schematically presented in Figure 7. Of the 310 km shoreline length, the average percentages of the vulnerable, invulnerable (naturally protected) and artificially protected coastal stretches are approximately 30%, 55% and 15%, respectively. These vulnerable areas are described below:

I) Vulnerable areas

Vulnerable coastal areas or ‘seriously eroding areas’ are:

- Narrow sand barriers separating the Mediterranean from the coastal lagoons, such as parts of the Burullus and Manzala lagoon barriers.
- The flat and low-lying coastal plain (0–1 m above MSL), such as the western backshore zone of Abu Quir Bay and El Tineh plain (Figure 1).
- Deltaic coastal plain areas affected by subsidence such as Manzala-Port Said area (Figure 4A).
- Shores characterized by gentle slopping beachface and covered with very fine sand will under go a much broader area of flooding for a given rise such as Ras El Bar beach (Figure 1).

II) Invulnerable areas

Invulnerable coastal areas or ‘naturally protected safe areas’ are:

- Beaches and coastal plains backed by high-elevated features such as coastal dunes and shore-parallel carbonate ridges which act as a natural defense system against beach erosion and SLR. The Pleistocene carbonate ridges, fronting the western beaches of Alexandria and the local rocky limestone islets off the waterfront of Alexandria, are effectively protected and combat possible consequences of SLR. The rocky carbonate ridges (nos. 1, 2 and 3) are acting together to protect the low-lying areas south of the city and west of Abu Quir land (Figures 2 and 8A). Similarly, the coastal dune defense system fronting the backshore of Abu Quir Bay, Burullus-Baltim sector and part of Gamasa embayment. Preservation and fixation of these dunes might involve them in the processes of mitigation of the Nile delta (Figures 1 and 8B and C).
- Areas experiencing land uplifting such as part of Alexandria will not be affected by the SLR, if the tectonic uplift exceeds the global SLR. The uplifting of Alexandria (3 mm/year) is balancing the rate of worldwide rise of sea level including the global warming (eustatic). This would yield a nearly stationary state of RSLR.
- Prograding (accreting) coastal zones even they are subsiding. These zones are not vulnerable to SLR if the rate of accretion exceeds or at least balances erosion induced from other factors including SLR. Shore parallel-accretion sandy ridges exist at some localities along the Nile delta coast particularly along the Rosetta saddle, the central part of Abu Quir Bay, Gamasa embayment and the El Tineh plain (Figures 7 and 8D, E, F and G). Shoreline of these

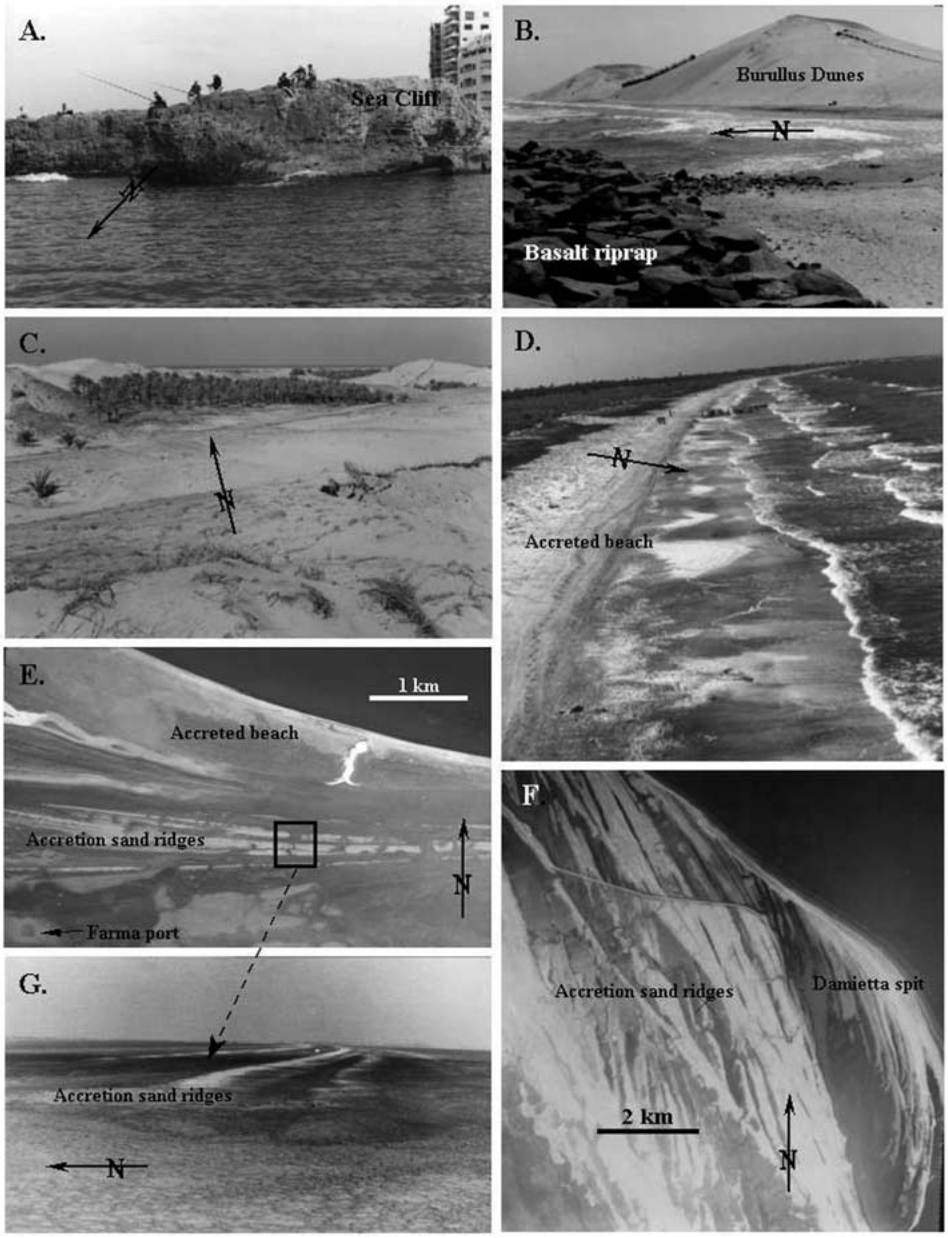

Figure 8. Photographs of selected invulnerable coastal areas: (A) Rocky cliff coastline at Alexandria, (B) coastal dunes at Burullus, (C) coastal dunes behind Abu Quir Bay, (D) accreted beach along the central part of Abu Quir Bay, (E) aerial photograph showing accreted sand ridges along El Tineh coastal plain, (F) Damietta spit backed by accretion sandy ridges east of Damietta promontory and (G) ground photo of sandy ridges along El Tineh coastal plain at north Sinai.

zones is seaward protruding with an average rate between 2 and 12 m/yr (Frihy et al. 2003a). In El Tineh plain, Sneh and Weissbrod (1973) delineated a series of accretionary beach ridges of shelly sand, extends 35 km along El Tineh coastal plain and to 12 km inland (Figure 1). By the 12th century, the Farma port (port of Pelusium) on the former Pelusiac branch was deserted as a result of the formation of these accretion ridges (Figure 8E and G), (Goodfriend and Stanley 1999).

III) Artificially protected areas

Artificially or mitigated areas with relevant structures that can adapt to future SLR even if such areas are experiencing subsidence or relative SLR. Several protection works have been intensified along beaches of Alexandria and the vulnerable delta shores to combat beach erosion. These measures include inlet lagoon and harbor jetties, groins, seawalls, detached breakwaters, revetment as well as beach nourishment (Figures 7 and 9). In all of these erosion control devices, the principle is to prevent waves from attacking the shore by interposing energy-absorbing structures.

Mitigation measures, which started as early as 1780 are in progress and others, are planned for the future. They have been built to combat beach erosion, and also to reduce shoaling processes in the lagoon inlets and navigation channels of the Nile estuaries and ports. Modifying and reinforcing some of these structures are being continued. Positions of these structures are given in Figure 7. The physical and geological processes affecting sea level as well as the driving forces are considered as a design criteria during implementing these structures, the height and the lifetime in particular. At Alexandria several beach nourishment projects were completed between 1987 and 1995 to mitigate shore erosion. Some of these projects were implemented with short groins (Figure 9A). Beach nourishment along Alexandria coast is the preferred response to mitigate erosional problems and to maintain wide recreational beaches.

Along the Nile delta coast, the oldest structure is Abu Quir seawall with an elevation of 1.4 m above mean water level and 10 km in length. It was initially built in 1780 to protect the low-lying cultivated land behind it from sea flooding (Figure 9B and C). In 1980, this wall was reinforced; its sea front slope was enhanced to 1:2 by placing an armor layer of modified cubes of 0.5 ton. In addition the wall crest was elevated to be 2.5 above mean sea-level to combat possible sea level rise (Figure 9D).

The Rosetta promontory on the western coast of the Nile delta is the area that has been subjected to the most severe erosion (UNDP/UNESCO 1978; Frihy et al. 1991). The annual rates of shoreline change demonstrated that higher erosion occurs along the outer margin of the Rosetta promontory; totaled approximately 100 m/yr before protection (Frihy et al. 2003a). To reduce shoreline losses along this area, two dolos seawalls (4 and 7 tons) were constructed between 1989 and 1991 on both sides of the Rosetta distributary (Figure 9E and F). The two seawalls

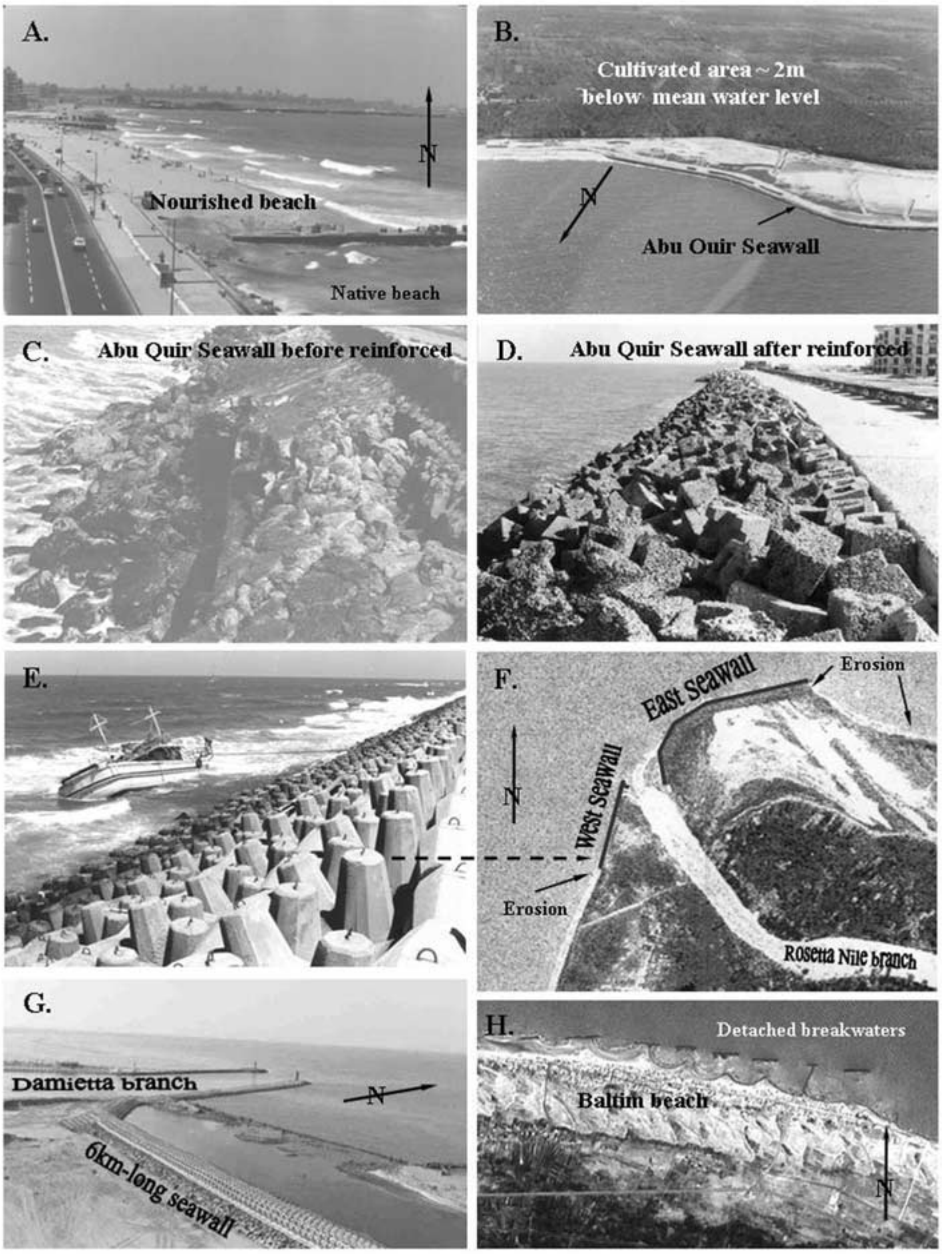

Figure 9. Photographs of selected mitigation measures at the Nile delta and Alexandria coast: (A) beach nourishment at Alexandria, (B) oblique aerial photograph of Abu Quir seawall fronting the low-lying cultivated land, (C) Abu Quir Bay before reinforcement, (D) Abu Quir Bay after reinforcement, (E) Rosetta dolos seawall on the western side of the Rosetta estuary, (F) the western and eastern seawalls protecting the outer margin of the Rosetta promontory, (G) Damietta dolos seawall and the inlet jetties at the Damietta estuary, and (H) Spot satellite image of the detached breakwaters at Baltim resort beach.

were constructed inland and extend alongshore to a length of 1.5 km and 3.35 km at the western and eastern shores, respectively. The seawalls stand 6.75 m above MSL, and have a width varying from 48 to 70 m. Five groins were built to protect the downdrift beaches on the eastern seawall. A similar dolos seawall (6 km-long) has been built to protect the tip of the Damietta promontory east of the Nile mouth (Figure 9G). This wall is extending straightly in the east-west trend up to the accretion area at Damietta spit. Both the Rosetta and Damietta seawalls have been effective in protecting the upland areas from wave attack and sea-level rise as well.

A series of emerged detached breakwaters have been constructed along Baltim, Ras El Bar and El Gamil resort beaches. Presently, they totaled 10, 8 and 6 breakwaters respectively at Baltim, Ras El Bar and El Gamil beaches and expected to be expanded (Frihy et al. 2003a). The breakwaters are built at a water depth between 3 and 4 m. Each breakwater extended approximately between 250 and 350 m parallel to the beach and is spaced 320 to 400 m apart (Figure 9H). They are armored by 4 to 7 ton dolos units with a crest level of 2.0 m above mean sea level. They represent a classical case of interruption of the longshore sediment transport system with accumulation of sand as tombolo or salient associated with severe erosion of adjacent downdrift beaches.

5. Possible Consequences of Sea-Level Rise

Previous studies have indicated that parts of the coastline of the Nile delta and Alexandria have been designated as vulnerable to a rising sea level as a consequence of expected climate changes. A number of studies have qualitatively assessed the impact of climate change on the Egyptian coast (Broadus et al. 1986; Milliman et al. 1989; Sestini 1990; El Sayed 1991; Delft Hydraulics/ CRI 1991; Sestini 1990 and 1992; El Raey et al. 1995; El Raey et al. 1999). Theses studies indicated that SLR would have physical, biological and socio-economic impacts. These include impacts on beaches, residential areas, agriculture, municipal services, commercial facilities, salt-water intrusion, and tourism and industrial activities. Brackish lagoonal areas will experience increased salinity. The socioeconomic impact of sea-level rise on coastal lowlands varies because of the degree of land use and development activities. Unfortunately, no national mitigation and adaptation strategy for global change has been outlined in Egypt. An attempt has been made by El Raey et al. (1999) to assess an adaptation to the impact of sea-level rise at Alexandria and Port Said using the methodology of Carter et al. (1994).

Like other low-lying deltas worldwide, beach erosion will accelerate as a result of sea level rise (Bruun 1962, 1988). The shoreline retreat due to sea-level rise has been investigated on the Nile delta using the ‘Bruun rule’ (Frihy 1992a). Accordingly, the predicted sea-level rise of 1 m by the year 2200 will cause maximum shoreline retreat of 0.9 km at the coastal zone of Manzala lagoon. The lower coastal plain of Manzala lagoon is characterized by large areas under 1 m elevation with

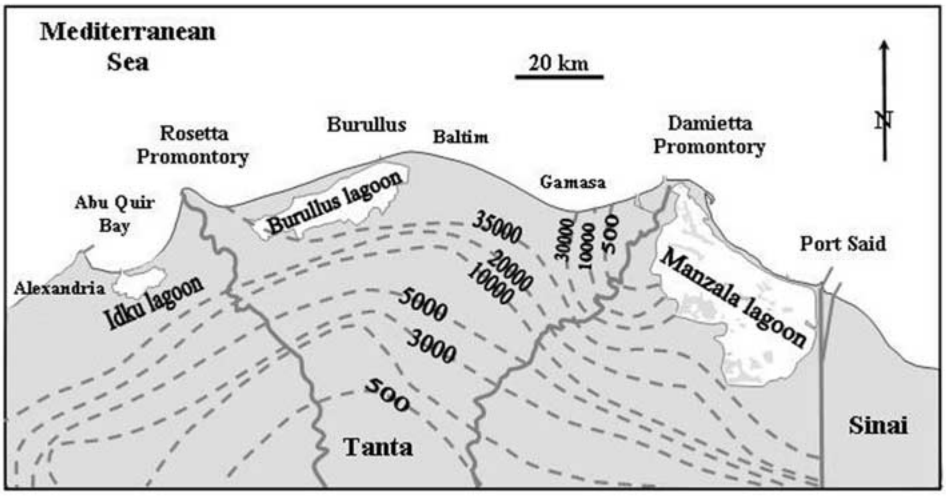

Figure 10. Distribution of groundwater salinity in ppm in the lower Nile delta for 50 m depth, showing incursion of saline water into the northeastern part and brackish water in the northwestern part including Alexandria (modified from Gaamea, 2000).

parts below sea-level including the lagoon itself. A comparable estimation was given by Milliman et al. (1989), a maximum value of 26 cm and 10 cm are projected at the Nile delta margin and Alexandria by 2100, respectively. On a global scale, the most likely rise is about 50 cm by 2100 being possible (Wigley and Raper 1992).

Surprisingly, the shoreline retreat projected at the Nile delta margin and Alexandria in this study is substantially lower than that estimated by Stanley (1988) based on land subsidence rate (5 mm yr^{-1}) estimated from dated core sections. According to his estimation, a relative rise in sea-level of 1 m would submerge much of the delta region within 30 km of the coast during the next 100 years. The gradual tendency of beaches to adjust their plan or horizontal configuration to the new water level due to a sea-level rise as described by Bruun (1962) has not been considered in his estimation. These horizontal adjustments will be caused due to the interaction of wave climate, depth of closure, berm height, beach width and mean grain size of the nearshore zone Bruun (1962). The application of the 'Bruun Rule' by Frihy (1992a) has indicated that only 9.6% of shoreline retreat of the Nile delta coast is account for sea-level rise, the remaining is caused by other factors such as wave induced littoral currents and sediment input deficiency.

In addition, the most serious effect of subsidence/ rise of RSL could be the incursion of the sea onto the low-lying, vulnerable outer margin of deltas (Stanley 1997). Hefny and Shata (1995) have indicated that the Nilotic aquifer system in the northern Nile delta to Tanta has a thickness of about 1000 m, overlying the thick Pliocene clay. The aquifer increases in thickness from about 250 in the south to about 900 m at the coast. The recharge of the aquifer is mostly from the Nile and irrigation canals (the contribution of rainfall is minimal). Hydrogeological studies have recorded distinct distribution of fresh, brackish and saline waters that underlie the delta plain (Gaamea 2000). According to Shata and El Fayoumi (1970) a safe and limited amount of fresh water is being extracted from the upper parts of the delta (1.6 billion m^3/yr) for the agriculture, domestic and industrial uses. The distribution of groundwater salinity in the lower Nile delta for the 50 m depth below the land surface is shown in Figure 10, which shows a large belt of saline water near the coast followed by a brackish groundwater to south (Gaamea, 2000). This map reveals that iso-contours of saline water from <35000 to <700 ppm is progressively shifted southward starting from Alexandria in the west to the east at Manzala lagoon-Port Said area, extending 50 m from the coast.

Stanley (1997) has attributed the wider and more extensive groundwater salinity pattern in Manzala lagoon, extending 130 km from the coast, to the higher subsidence rates in this area, providing evidence that marine water intrusion toward the south and southwest is a function of subsidence. In theory, a rising of RSL would unbalance the ground water salinity pattern; probably will shift the salt water wedge inland even in coastally protected areas and this in turn may increase salinization of soil profile and affect the agriculture landuse system in the lower delta (Delft Hydraulics/CRI 1991). The lagoon ecosystem, and hence fish resources, would probably adjust to gradually changed conditions of salinity and water temperature (Sestini 1990 and 1992).

Alexandria appears to be least vulnerable to sea level rise owing to the high land elevation of the coastal road which ranges between 2.4 and 12.3 m, relative to the mean sea level (Frihy et al. 2003b). This elevated features of the back-beach act as a natural defense barrier against beach erosion, and possibly against consequences of SLR. Nevertheless, local low-elevated spots <2.41 m are vulnerable to wave overtopping and flooding under the combination of surges and storm waves. Although this high elevated features, the city is surrounded to the south by low land. This indicates that not all of the coastal plain of Alexandria will be vulnerable to the impacts of future sea level rise. Planning and development of the southern low-lying region must take into consideration possible impacts of sea water intrusion including water logging and water bogging in case of higher SLR.

6. Conclusions

The objective of this paper is to summarize knowledge of delta processes allows determination of vulnerability, which in turn is of great help to assess consequences and adaptation to impacts of accelerated sea-level rise. Evaluation of current coastal processes, erosion/ accretion pattern, land topography, RSL and the newly built protective measures has revealed that not all of the coastal plain of the lower Nile delta and Alexandria are vulnerable to be impacted by future SLR. Therefore, the impact of sea-level rise on the Nile delta and Alexandria has to be assessed on the basis of such vulnerability evaluation. Vulnerability analysis has indicated that the coastal zones of the study area can be categorized into three main stretches, varying from high-risk areas to safe ones. Of the 310 km shoreline length, the safe areas include the artificially (15%) and the naturally protected sectors (55%). The high risk areas (30%) are the narrow and low-lying sandy lagoon barriers of the Burullus and Manzala lagoons. These barriers are eroding partially during storms, particularly in case of slight rising in sea level.

In terms of impacts, coastal erosion due to sea-level rise is expected with its attendant negative consequences for sectors categorized as high risk areas. This phenomenon occurred at a time of curtailed fluvial sediment-supply and diminished replenishment of delta coast. As a result, both beach erosion and saltwater incursion in groundwater would be increased. Saltwater intrusion would also disrupt the freshwater aquifer underlying the delta as well as the brackish water wetlands including the coastal lagoons and fish farms. This may have a serious impact on agriculture and drain conditions, and potentially on available groundwater resources in the upper Nile delta. The lagoon ecosystem, and hence fish resources, would probably adjust to gradually changed conditions of salinity and water temperature. Changes in the salinity conditions of the coastal lagoons may lead to impacts on lagoon ecology and fisheries. Strengthening shoreline defenses against beach erosion is an effective way to mitigate possible consequences of sea-level rise. The newly coastal structures, especially those fronting the new coastal road and development areas, an optimum height of these structures has to be considered to adjust the future SLR. This consideration involves the sum of local RSLR, elevation of sea-level due to storm surge and the maximum wave height in the region.

The nonstructural adaptive responses could be landward retreat of areas of small populations to areas above 2 m contour and little investment to save localities may be the most effective and economic response to sea level rise particularly in vulnerable areas of high risk. This is particularly effective when retreat is viewed as a long-term process that can be implemented as part of a program of coastal zone management decisions. Preserve the coastal dunes by fixation probably by water-tolerant plants and prohibiting sand quarrying as well. Other adaptive options include adapting new agricultural practices with improved efficiencies for using freshwater and developing salt-tolerant plants.

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