

Alexandria-Nile Delta coast, Egypt: update and future projection of relative sea-level rise

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Abstract Previous studies have indicated that the Nile River deltaic plain is vulnerable to a number of aspects, including beach erosion, inundation, and relatively high rates of land subsidence. This issue motivates an update and analysis of new tide-gauge records, from which relative sea-level changes can be obtained. Estimated rates from five tide gauges are variable in terms of magnitude and temporal trend of rising sea level. Analysis of historical records obtained from tide gauges at Alexandria, Rosetta, Burullus, Damietta, and Port Said show a continuous rise in mean sea level fluctuating between 1.8 and 4.9 mm/year; the smaller rate occurs at the Alexandria harbor, while the higher one at the Rosetta promontory. These uneven spatial and temporal trends of the estimated relative sea-level rise (RSLR) are interpreted with reference to local geological factors. In particular, Holocene sediment thickness, subsidence rate and tectonism are correlated with the estimated rates of relative sea-level change. From the relatively weak correlation between them, we presume that tectonic setting and earthquakes, both recent and historical ones, contribute more to accelerated RSLR than that of dewatering and compression/dewatering of Holocene mud underlying the Nile Delta plain. As a result, large areas of the coastal plain have been subsided, but some sectors have been uplifted in response to tectonic activities of thick underlying older strata. Projection of averaged sea-level rise trend reveals that not all the coastal plain of the Nile Delta and Alexandria is vulnerable to accelerated sea-level rise at the same level

due to wide variability of the land topography, that includes low-lying areas, high-elevated coastal ridges and sand dunes, accretionary beaches, and artificially protective structures. Interaction of all aspects (tectonic regime, topography, geomorphology, erosion rate, and RSLR rate) permitted to define risk areas much vulnerable to impacts of sea incursion due to accelerated sea-level rise.

Keywords Sea-level changes · Land subsidence · Tectonically active areas · Holocene sedimentation · Nile Delta · Mediterranean Sea

Introduction

In deltaic areas of low-lying coastal plains climate change, particularly sea-level rise, is already considered as an issue of great importance, while on high elevated land this issue is minor. Sea level curves for the Mediterranean are commonly presented as relative sea-level (RSL) curves (Pirazzoli 1991) because they incorporate absolute world (eustatic) sea-level rise (~ 1 mm/year), local land motion and compression/dewatering of prodelta, and delta-front sediments. Relative sea level could be inferred from the interaction of global sea-level component (eustasy), tectonic uplift or down-warping, subsidence that results from natural sediment compaction, and subsidence-caused withdrawal of subsurface fluids such as groundwater, oil, and natural gas (Morton et al. 2002). In the Mediterranean, sea level rose rapidly from -120 m below mean sea-level at $\sim 18,000$ year B.P., to about -16 m at $\sim 8,000$ year BP (Stanley and Warne 1994). The effects of sea-level rise tend to be spatially non-uniform, with some areas subjected to uplift and others to subside (Gornitz 1991). Church et al. (2001) concluded that the range of eustatic

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sea-level rise in the twentieth century was between 1 and 2 mm/year.

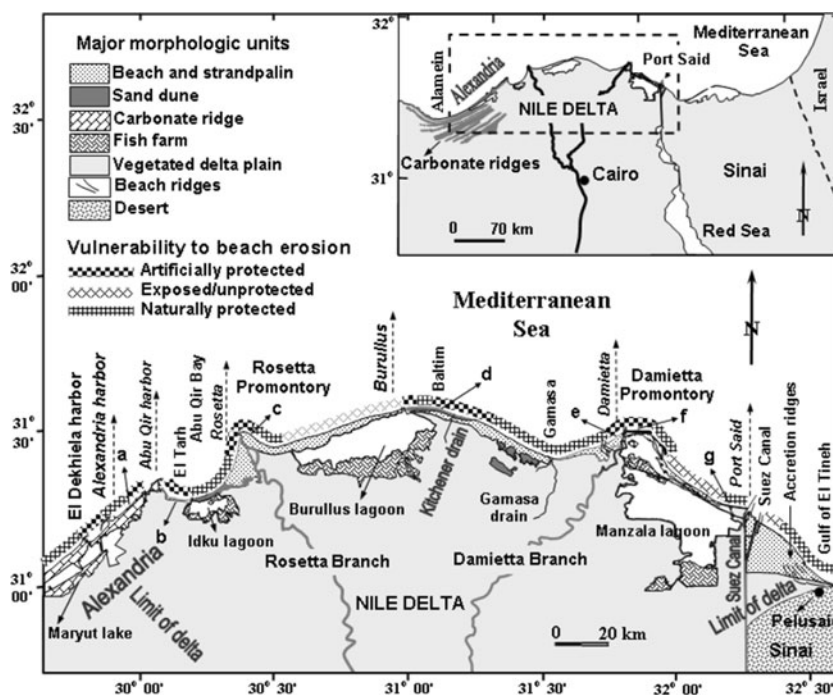
In modern delta plains, eustatic sea level tends to be the overriding process in the development of the late Pleistocene to Holocene deltaic sediment sequences. In a local level, variable processes such as climate, tectonism, fluvial and sediment discharge, tides, coastal processes, and regional slope would not have been the dominant long-term factors (Warne and Stanley 1995). It has been established that the weight of sediment sequences deposited at coasts by major rivers and concentrated as thick deltaic wedges has generally resulted in subsidence of the underlying crust (Kuenen 1950; Coleman 1982). Perhaps the more important factor for local sea-level rise is generally the effect of subsidence or uplift within a coastal area. For example, an area with tectonic uplift equal to the eustatic rise of sea level will experience no change in relative sea level (RSL), whereas an equal rate of subsidence will result in a “doubled” sea-level rise (Milliman et al. 1989). This indicates that subsidence and emergence are generally independent of global “eustatic” sea-level change. The compression/dewatering of Holocene sediment acting in conjunction with faulting of subsurface strata contributes to sinking of the Nile Delta surface and its contiguous continental margin (Ross and Uchupi 1977; Said 1981; Stanley 1988, 1990; Sestini 1989). This Holocene cover is only a thin layer above the greater 5 km of underlying sedimentary sequence of Tertiary Mesozoic age. In this study, we evaluate the relative contribution of each of the aforementioned factors to the estimated sea-level changes at the Nile Delta coastal plain.

Our approach differs from previous attempts to determine sea-level rise from tide gauge records. Rather than determining sea-level rise from tide gauge records as exemplified by the studies of Emery et al. (1988), El Fishawi and Fanos (1989), Sharaf El Din et al. (1989) and Frihy (1992b), we use as many gauges as possible to estimate the regional distribution of sea level between Alexandria to the east sector of Port Said (Fig. 1). Rates obtained are related to the spatial variability of various geologic characteristics of the region, acting in the region, including Holocene sediment thickness, subsidence rate, tectonism, and land topography. Also, we examine the vulnerability of the coastal plain of Alexandria and the Nile Delta to the coastal impacts of climate change, including accelerated sea-level rise. Vulnerable areas at risk are also identified. This has led us to measure and map land topography, grading from high elevated dunes to low-lying areas of -3 m below sea-level, generated from recent satellite images in conjunction with field observations. The study also considers the range of protective measures that may face the likely coastal erosion due to accelerated sea-level rise.

Study area

The coastline of the study area from Alexandria to the sector east of Port Said and the Suez Canal, 260 km long, is backed by a plain surface of coastal plain area of $\sim 13,610$ km² (Fig. 1). This coastal plain is backed by

Fig. 1 Map of the Nile Delta and Alexandria region showing major geomorphologic units and coastal sectors vulnerable to beach erosion (updated from Frihy et al. 2003). *Dashed vertical arrows* show locations of the tide gauges discussed in the text. *Small arrows* with letters **a–g** show positions of protective structures enlarged in Fig. 2



topographic features lying below and above the mean sea-level up to the 4-m contour that include coastal wetlands which range from small ponds to large lagoons; these lagoons are also referred as lakes. Previous studies have indicated that the study area is particularly vulnerable to beach erosion and inundation combined with relatively high rates of land subsidence (Stanley 1990; Stanley and Warne 1993a, b). Local subsidence in the Nile Delta coastal plain, ranging from ~ 1 to 5 mm/year, was estimated from numerous radiocarbon-dated cores recovered at the coastal plain of the Nile Delta (Stanley 1990). The sector of greatest annual mean subsidence (4–5 mm/year) is the area closely to the Manzala lagoon and the north-eastern sector of the delta (Stanley 1988). So far, no attempts have been made to determine local subsidence from precise leveling of benchmarks. However, a number of studies have discussed a number of aspects of climate change on the Egyptian coast (Broadus et al. 1986; Milliman et al. 1989; El Sayed 1991; Delft Hydraulics/CRI 1991; Sestini 1990, 1992; Frihy 1992a; El Raey et al. 1995, 1999).

Unlike using tide gauge records, sea-level change along the study area has been evidenced by comparing the elevation of submerged archeological remains (submerged cities, coastal roads, harbors, and other structures) with present mean sea level (Ibrahim 1963; El Sayed 1988; Stanley 2006). Such comparison is a useful tool for determining trend and rate of relative change of sea (or land) level. The settlements considered here (Greek/Ptolemaic and Roman to Byzantine and early Arabic) were, for the most part, constructed at, or near, the delta's coast between $\sim 2,500$ and 1,300 years ago (Stanley 2005a). Submergence of archeological sites to depths of 5–7 m is recorded in Abu Qir Bay, and higher values (lowering to 5 mm/year) are recorded along the NE corner of the Nile Delta across Manzala lagoon area. At Alexandria, tectonic aspects are evidenced from the following: existence of submarine (Greek/Ptolemaic, Roman to Byzantine) archaeological remains, disappearance of sandy beaches and emerged islands, submerged of the former Nile distributary channel, namely the Canopic, that once flowed across Abu Qir Bay about 2,500 years BP, and the major earthquakes which shook Alexandria in the fourth century A.D. (Frihy 2003).

Artificial and natural sea-defense system

Interaction between shoreline geomorphology, backshore topography, erosion/deposition events, subsidence, coastal processes, and engineered structures along the study coastline were analyzed by Frihy (2003) to determine the degree to which the Nile deltaic plain is susceptible or

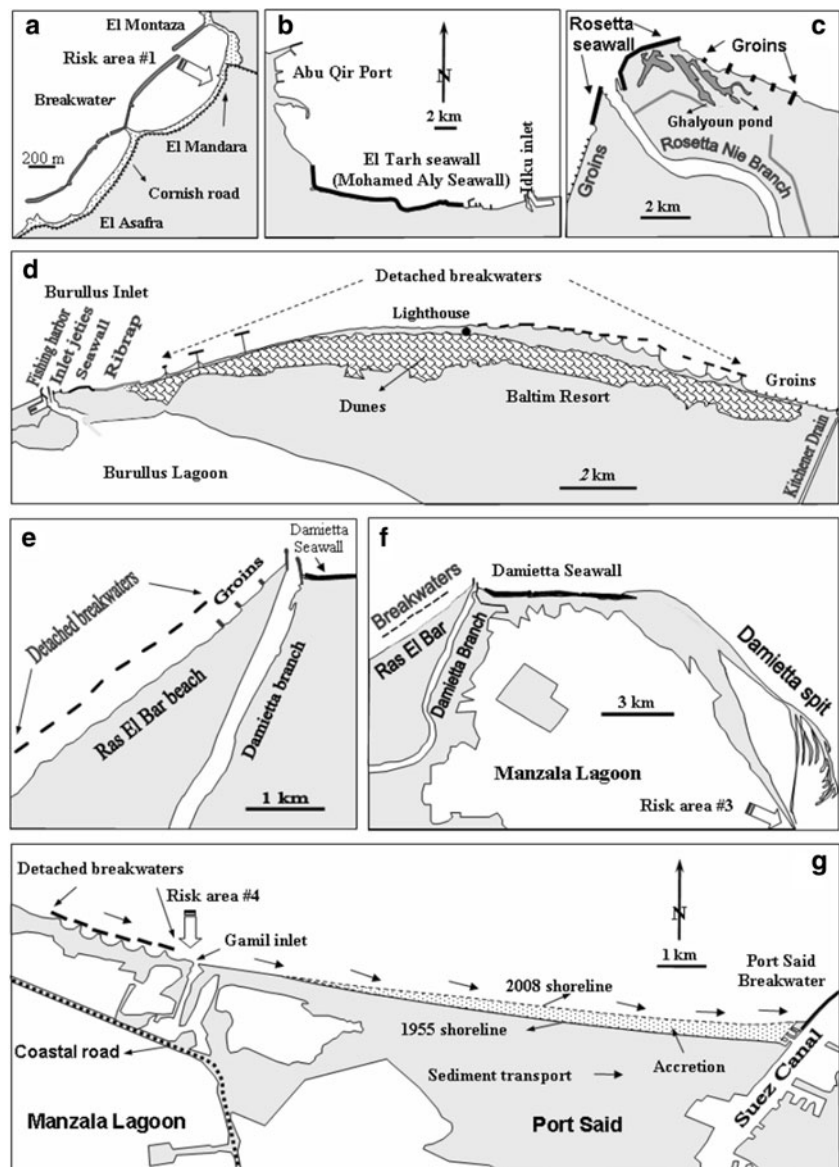
vulnerable to sea-level rise and erosional processes. According to this study, 15% of the delta coastline is artificially protected by engineering structures, 30% is exposed with no protection, and 55% is naturally protected by coastal dunes and accreted beaches along embayments and promontory saddles. These three types of coastal areas are schematically shown in Fig. 1.

The Nile Delta is a good example of a coastal region where human and natural stresses are increasing with time. Like other low-lying deltas, the coast of the Nile Delta has been designated as a vulnerable zone to beach erosion as a consequence of ongoing coastal processes and accelerated sea-level rise, in addition to human influences. Following the practical termination of sand delivery to the coast from the Nile as a result of dam constructions in the river basin in 1964, wave-driven longshore currents continued to transport beach sand to the east, resulting in a major adjustment of the Nile Delta coastline. As the Nile Delta is a typical wave- and current-dominated delta area, extensive beach erosion occur along the outer margins of the Nile delta-promontories, while some accretion has occurred mainly in the saddles or embayments between these promontories (Frihy et al. 1991; Blodget et al. 1991; Inman et al. 1992; Frihy and Komar 1993). This general erosion/accretion pattern has been interrupted by protective engineering structures.

Most Alexandria shoreline is considered to be relatively stable since the majority of the coastline is hard rock which constitutes the coastal limestone ridge (Frihy et al. 2004a, b). In order to maintain wide recreational sandy beaches, Alexandria beaches were protected in 1934 from further erosion by a ~ 20 -km-long vertical wall, known as the “Corniche” highway. In addition, breakwaters were constructed to protect four harbors at El Dekhiela, Alexandria (Western and Eastern harbors), and at Abu Qir (Fig. 1). Moreover, several artificial beach nourishment projects were executed using desert sand at some eroded beaches (Frihy and Dean 1992). More recently, during 2004–2007, two submerged shore-parallel breakwaters were built along Mandara-Asafra to mitigate the effects of wave overtopping that negatively affects the relatively low-lying coastal road (2.4 m elevation) during winter storms (Figs. 2a, 3g).

Man-made coastal structures at the Nile Delta started in 1830, when the government of Mohamed Aly (Ruled Egypt between 1805 and 1840) decided in 1820 to build a 10-km-long quarry stone barrier at El Tarh on Abu Qir bay to dry up the Abu Qir lake behind it (Figs. 1, 2b, 3b). Prior to the complete dryness of this lake, sea flooding had caused incursion of salt in the Mahmudiyah Canal, which had been diverting fresh-water to Alexandria (El Rafeay 1948). In 1980, this barrier was reinforced to act as a seawall and its crest was elevated to 2.5 above mean sea-level to face possible sea-level rise and wave overtopping.

Fig. 2 Vector maps showing major protective structures constructed to mitigate effects of beach erosion and sea-level rise along the study coastline. Their positions (a–g) are illustrated in Fig. 1. They are generated from ETM Satellite images 2006, 2007, and Ikonos 2006. **a** El Asafra-Mandara breakwater. **b** Mohamed Aly seawall. **c** seawall and the five groins constructed at Rosetta promontory. **d** Burullus-Baltim detached breakwaters fronted a dune belt. **e** Ras El Bar detached breakwaters. **f** Damietta seawall. Photographs of most of these protective structures are presented in Frihy (2003)



In 1980 up to now, extensive engineering structures were emplaced along the Nile Delta coastline to modulate effects of beach erosion, including revetments, jetties, groins, detached breakwaters, and seawalls (Fig. 2a–g). Among these protection works, the shore-parallel structures of Rosetta seawall, Burullus seawall, Burullus-Baltim detached breakwaters, Damietta seawall, and El Gamil detached breakwaters. Information on these protective structures and their impacts on beach morphology have been reported by others, including Fanos et al. (1995), Frihy (2003), Frihy et al. (2004b), Dewidar and Frihy (2008).

In order to face the diachronic shoreline losses at the outer margin of the Rosetta promontory, where erosion rates were higher, two seawalls comprised of artificial embankment covered by dolos concrete blocks weighing 4–7 tons were constructed between 1988 and 1991 to the west and

east of the Rosetta mouth (Fig. 2c). The two seawalls were constructed inland and extend alongshore to a length of 1.5 km and 3.35 km at the western and eastern shores, respectively. They stand 6.75 m above mean sea level, and have a width varying from 48 to 70 m. As a consequence, erosion is terminated at the tip due to construction of this seawall, which originally was 106 m/year prior to construction of the seawall (Frihy and Komar 1993). Despite this structure, wave runup bypassed to frequently flood the low-lying (0–1 m) area behind the western seawall. Additional erosion control structures were then built to face erosion at the eastern and western edges of the seawalls. These included five groins constructed east of the Rosetta estuary in 2003, their length ranging between 400 and 500 m seaward, spaced 800–900 m apart (Fig. 2c). Subsequently in 2005, another ten short groins (80–150 m long)

Fig. 3 **a** Locations of selected photographs and satellite images taken along the Alexandria-Nile Delta region; **b** El Tarh Seawall protects the low-lying cultivated and industrial areas (former Abu Qir lagoon and lake Mareotis depression) from the Mediterranean Sea. **c** High elevated Corniche road at Stanley. **d** Accretionary or prograding beach at the central part of Abu Qir Bay, **e** Remnant of limestone coastal ridge exposed at Alexandria waterfront. **f** Shore-parallel detached breakwater system backed by barchan dunes between Burullus inlet and Kitchener Drain (Ikonos 2006). **g** Lowest point at El Mandara Corniche Road of Alexandria. **h** Degraded longitudinal dunes lined the coastal plain of Gamasa embayment (ETM Satellite image 2006)



with spacing between 500 and 600 m were constructed at the lee side of the western seawall (Frihy et al. 2008).

Further east, a concrete 600-m-long seawall was built in 1950 to protect the eroded beach downstream of the Burullus inlet jetties (Fig. 2d). To the east of this wall a basalt riprap of ~1.3 km in length was constructed. The Burullus-Kitchener drain sector (10 km long) is artificially protected by a series of shore-parallel detached breakwaters and nine short groins. The detached shore-parallel breakwaters, 17 units, were built in various stages between 1993 and 2007 (Figs. 2d, 3f). Each individual breakwater extends from 250 to 350 m parallel to the beach, at a distance of 220 m from the shore and spaced 320 to 400 m apart. The breakwaters were constructed parallel to the beach in the active surfzone at a depth between 3 m and

4 m. These breakwaters have contributed to protecting the beach and dune belt by forming a series of accretionary tombolos and salient formation (Fig. 3f).

Another series of eight shore-parallel breakwaters were built during 1991–2002 along Ras El Bar resort; beach erosion was 10 m/year earlier (Fig. 2e,f; Frihy et al. 2004a, b). A dolos seawall of 6-km-length has been constructed, using 4–7 ton dolos similar to those at Rosetta, to protect the tip of the Damietta promontory east of the Nile mouth (Fig. 2f). This wall is extending straightly in the east–west trend up to the accretionary spit. Both the Rosetta and Damietta seawalls have been effective in protecting the upland areas from wave attack and sea-level rise as well.

In addition to the aforementioned man-made engineering structures, a natural defense system provides a natural

mechanism for protecting the coastal plain of the Nile Delta and Alexandria against beach erosion and SLR. This system includes accreting/advancing coastlines, high-elevated topographic features such as sand dunes and limestone ridges. Both natural and artificially protected coastal stretches are schematically presented alongshore in Fig. 1. In some sectors, beaches are backed by high-elevated features such as coastal dunes or shore-parallel carbonate ridges. The Pleistocene carbonate ridges on which Alexandria was built is effectively protecting the low-lying areas south of the city and west of El Tarh on Abu Qir Bay (Figs. 1inset, 3e). Theoretically, the coastal dune systems cover the backshore of the Burullus/Baltim sector, Abu Qir Bay and Gamasa embayment could prevent rising sea level from invading the interior of this region (location in Fig. 1). It is unfortunate that large areas of Gamasa dunes has been dredged for various uses, including land reclamation, land filling, fish farming, and road construction (El Banna and Frihy 2009).

In a similar manner, prograding or accreting coastlines can be part of the natural sea defense system when its prograding rate exceeds erosion induced from coastal processes and sea-level rise. Commonly, convex shores such as bays and embayments have a higher tendency toward accretion than either straight or concave coasts (Lakhan and Pepper 1997). Sectors that experienced significant shoreline accretion exist, particularly along the Rosetta east saddle at Abu Khashaba, the central part of Abu Qir Bay (Fig. 3d), Gamasa embayment, and Gulf of El Tineh plain (Fig. 1). These zones are not vulnerable to SLR if the net rate of accretion exceeds or at least balances erosion induced from other factors including SLR. Fortunately shoreline of these zones are seaward protruding with an average rate between 5 and 12 m/year (Frihy 2003). Along El Tineh Gulf at 23 km east of the Suez Canal, Sneh and Weissbrod (1973) and Goodfriend and Stanley (1999) identified a series of accretionary beach ridges of shelly sand, which extends 35 km along the coastal and to 12 km inland (Fig. 1). According to their studies, continued accretion of the strand plain, which began in the first century A.D., was responsible for the dramatic geographic changes, including degeneration of the Pelusiac Nile distributary, and silting up the port of Pelusium city (Tel Farama) (Fig. 1 for location).

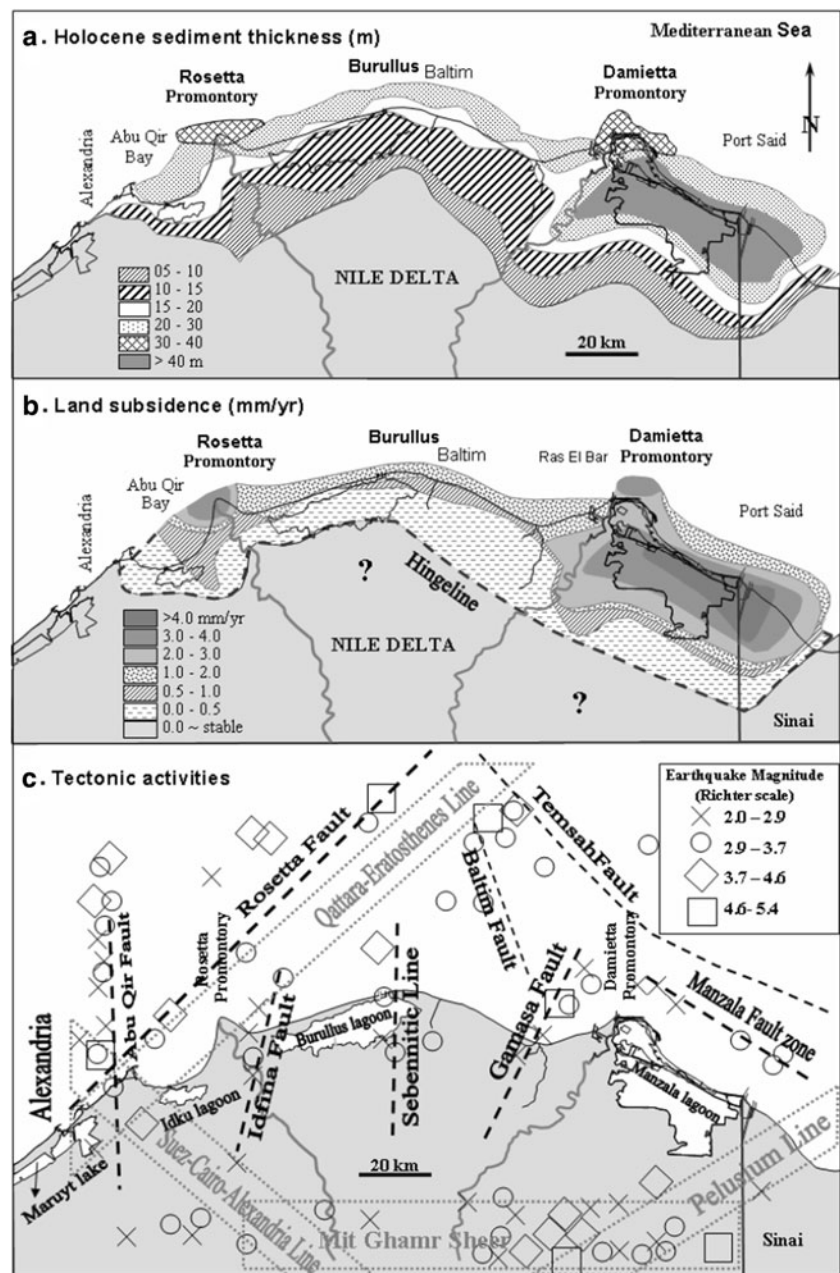
Factors controlling sea-level changes

This section focuses on discussing different factors that control sea-level fluctuations in the study area. Previous studies have indicated that significant components of present sea-level changes are the vertical motion of land surface induced by isostatic lowering, neo-tectonic activity,

compaction, and dewatering (Stanley 1997). Subsidence varies locally depending upon rates of lowering caused by isostatic fluctuation, faulting, compaction, or combinations of them. Subsidence refers to the lowering of land surface relative to a geodetic datum, which is generally independent of sea level changes. An isopach map depicting the thickness of the Holocene sequence above the basal transgressive sand unit (Fig. 4a), has been constructed by Stanley (1990) in the Nile Delta based on numerous radiocarbon-dated cores. Early Holocene sediments are comprised of basal shell-rich sands identified as transgressive deposits from shallow marine to littoral origin. These are overlaid by a thick (>40 m), typical Holocene deltaic offlap sequence. As seen in Fig. 4a, isopach contours of the outer Damietta and Rosetta promontories reveal markedly thick (>30 m) accumulations of Holocene deposits. The north-central part between these promontories has a modest Holocene thickness ranging from 10 to 15 m. Further east, a maximum thickness of Holocene deposits occurs beneath Manzala lagoon—Port Said region (>40 m). More specifically, Stanley and Goodfriend (1997) reported thick Holocene sediments of 46.5 m and 42 m in cores recovered at Port Said and Port Fuad, respectively, that indicate similar subsidence rate of ~ 3.98 mm/year and annual relative sea-level of ~ 5 mm/year, from 8,540 years ago up to present.

Stanley (1990) has applied the isopach map data in Fig. 4a in subsidence calculations across the coastal plain of the Nile Delta as presented in Fig. 4b. His calculation was made from numerous core sections ranging in length from 30 to 50 m recovered from the coastal plain of the Nile Delta (Stanley 1988, 1990) and basal muds above the transgressive sand unit and was dated to 7,000 year BP. Subsidence rates in this region vary spatially due to differential compaction and varying thicknesses in the Holocene layers. Therefore, it is difficult to define an average rate of land subsidence for the study area as a whole. Accordingly, most of the Nile Delta plain northward of a coast-parallel hingeline (flexure zone) is subsiding (Warne and Stanley 1993). The well-defined zone of higher subsidence coincides with the Manzala lagoon area and is related to the Manzala fault zone (Fig. 4c). Rates of subsidence across the northern delta range from <1 to >4 mm per year in the northeastern sector. As expected, values of Holocene sediment thickness closely coincide with the subsidence rates (Fig. 4a, b). Subsidence rates at the Rosetta and Damietta promontories are higher, ranging from 2.5 to 3.5 mm/year. Rates increase markedly east of Damietta promontory, with values approaching 5 mm/year in the Manzala lagoon-Port Said region (Stanley 1988). Subsidence has been considerably lower in the westerly direction, ranging from ~ 1 mm/year near Baltim resort on the north-central coast, to 0.5 mm/year farther to the west,

Fig. 4 Geological components contributing to changes of RSL along the Nile Delta and Alexandria, including:
a Isopach map showing sediment thickness of mid-Holocene to present age lying above basal transgressive sands (after Stanley 1990).
b Holocene subsidence rates calculated from radiocarbon-dated core sediments (Stanley and Warne 1993). **c** Earthquake epicenters in the lower Nile Delta between 1900 and 1997 together with major active “fault” trends, modified after Zaghoul et al. (1999) and Garziglia et al. (2008)



in the NW Nile Delta and the Alexandria region (Stanley and Warne 1993a, b). The lowest estimates are for the Alexandria coastal plain, where subsidence rates are estimated to be 0.0–0.5 mm/year.

Together with the stratigraphic factors, tectonic activities also contribute to processes of subsidence and RSL changes. As a result of the complex tectonic setting of the Eastern Mediterranean, earthquakes occurred in the vicinity of the Egyptian continental margin both in recent and historical times (El Araby and Sultan 2000; El Sayed et al. 2004). Offshore Egypt, the magnitudes are moderate to high ($M_s = 6.7$), and some earthquakes have effected northern Egypt (Ambraseys et al. 1994). Earthquakes

recorded in the Nile Delta region are generally of moderate-magnitude between 1.0 and 5.4 (Richter scale), with a geographic tendency along the eastern Nile Delta margin and offshore to the north. Figure 4c depicts the geodynamic setting of the lower Nile Delta and continental margin including earthquake epicenters and major active fault trends described by Zaghoul et al. (1999) and Garziglia et al. (2008). As noted in this Figure, the structural pattern of the Egyptian margin results from a complex interplay of fault trends. These include N–S faults (Sebnennitic), NW–SE faults (Tamsah, Manzala, Baltim, Suez-Cairo-Alexandria line), and NE–SW (Rosetta, Qattara-Eratosthenes line, Idfina, Gamlasa, Pelusium line)

and W-E faults (Mit Ghamr Sheer). These structural trends indicate that the main cause of subsidence in this northern Nile Delta region is ongoing faulting, as well as down-warping, of the underlying 3,000 m of Late Miocene to Quaternary sequences. The whole northern Nile Delta plain has been lowered north of a flexure roughly 30 km inland from the coast (Stanley and Warne 1993a, b).

Methods

Absolute sea level change is difficult to measure. However, relative sea-level changes have been derived mainly from tide-gauge data relative to fixed tide-gauge benchmarks. This relative sea level (RSL) is referred to as sum of global changes “eustatic” (~1 mm/year) and local uplift or subsidence. Annually and to some extent monthly averaged values of sea-level data gathered from six localities from Alexandria to Port Said, were statistically analyzed using the least square regression technique. Tide-gauge station data (coordinates, start and end years, datum, duration, gabs, and slope) of the Nile Delta and Alexandria are listed in Table 1. Their locations are shown as vertical dashed arrows in Fig. 1. All data were checked prior to use. All time series were examined visually to eliminate any stations having sudden large deviations that may resulted from datum shifts. Some of these data have been reported on previous studies, others are updated by providing a few additional data points for analysis, and few have been analyzed for the first time. Data comprise the annually averaged tide-gauge records calculated from the hourly heights of sea level taken (with discontinuance) at

Alexandria (1944 through 2006; 60 years), Abu Qir (1992 through 2005; 14 years), Rosetta (1969 through 2008; 17 years), the Burullus (1976 through 2006; 24 years), the Damietta (1990 through 2007; 13 years), and Port Said harbor (1926 through 2000; 47 years). Annual records of Alexandria are also analyzed to assure acceleration of sea-level rise during the twentieth century up to the present time (for 1944–1979 and 1980–2006 time periods). Although the data records at Abu Qir (14 years), Rosetta (17 years), and Damietta (13 years) are short, they have been analyzed for the first time to provide additional spatial coverage.

The interaction of Holocene sediment thickness, subsidence rate, tectonism, and land topography of the study area provide a unique opportunity to directly discuss the degree of contribution of these factors to RSLR. Therefore, the statistical relationships between rate of sea-level changes estimated in the present study versus Holocene sediment thickness and land subsidence are also correlated. Values of Holocene thickness and land subsidence were derived from Stanley (1990) and Stanley and Warne (1993), Table 1. In addition, an attempt has been made to project the average rate of the estimated sea-level rise on the current land surface topography of Alexandria and Nile Delta coastal plain. High-resolution satellite images combined with field observations are used to map and measure prominent land surface features and shoreline positions. Two image sources spanning the study area are used: rectified enhanced thematic mapper (ETM+) scene acquired in 2006 (path/row 177/38), and 2007 (path/row 176/38), with a resolution of 14.25 m. Ikonos satellite image dated 2006 (resolution of 1 m) covering the central

Table 1 Information on tide-gauge stations used in the present study and their corresponding underlying Holocene thickness and rates of land subsidence at the coastal plain of the Nile Delta and Alexandria

| Tide-gauge station | Gauge coordinates | Start and end year | Gauge datum | Duration (years) | Record gap (years) | Slope (mm/year) | Holocene thickness (m) | Subsidence rate (mm/year) |
|--------------------|--|--------------------|-------------|------------------|--------------------|-----------------|------------------------|---------------------------|
| Alexandria | (Lat. 31° 52.3293' N; Long. 28° 20.663'E) | 1944–2006 | Harbor | 60 | 3 | 1.8 | 0.0 | 0.0 |
| Abu Qir | (Lat. 31° 52.3293' N; Long. 28° 20.663'E) | 1992–2005 | MSL | 14 | 0 | 3.4 | 17.5 | 0.25 |
| Rosetta | (Lat. 31° 52.3293' N; Long. 28° 20.663'E) | 1969–2008 | MSL | 17 | 23 | 4.9 | 35.0 | 4.0 |
| Burullus | (Lat. 31° 52.3293' N; Long. 28° 20.663'E) | 1975–2006 | MSL | 24 | 7 | 3.0 | 12.5 | 1.5 |
| Damietta | (Lat. 31° 52.3293' N; Long. 28° 20.663'E) | 1990–2007 | MSL | 13 | 5 | 2.9 | 35.0 | 1.5 |
| Port Said | (Lat. 31° 52.3293' N; Long. 28° 20.663'E) | 1926–2000 | Suez Canal | 47 | 2 | 2.8 | 46.5 | 3.98 |

Holocene thickness and rate of subsidence are given in Stanley (1990) and Stanley and Warne (1993a, b), respectively

MSL (Mean Sea Level) or “Survey Datum” estimated from averaging of 10 years’ records between 1896 and 1906

Harbor Datum lies 33.8 cm below the MSL

Suez Canal Datum lies 17.633 m below the Survey Datum (Mean Sea Level)

sector of the Nile Delta was also used. Manual digitization is used to trace protective structures and mapping major topographic features with average relief up to 4-m contour in conjunction with field in situ observations. Areas of mapped topographic features, including coastal dunes, carbonate ridge, low-lying areas, and coastal wetlands (ponds, lagoons, lakes and fish farms) were measured using AutoCAD version 2008. Relative proportions of areas of topographic features were calculated relative to the study coastal plain spanning between the coastline and up to the 4-m contour above mean sea level, within about 50 km of the coast. This information together with other factors discussed in the text was used to identify risk areas vulnerable to effective of accelerated sea-level rise.

Discussion

In this study, we attempt to link the updated rates of sea-level changes determined at the coastal plain of Alexandria and the Nile Delta with the geological processes acting in the study area (thickness of Holocene sediment that is susceptible to compaction and dewatering, subsidence rates, and tectonic activity). As a first step, RSLR is established to assess a relative contribution of these factors and also to predict possible impacts on the study area. Water level data recorded by tide gauge stations are analyzed to estimate RSLR at Alexandria western harbor, Abu Qir, Rosetta promontory, Burullus headland, Damietta promontory, and Port Said Harbor. These records demonstrate the sea level due to astronomic tide as well as other oceanographic parameters (temperature, atmospheric pressure, wind surge, wave induced set-up, etc.). In addition, they incorporate vertical land movements due to natural compaction and dewatering of subsurface sediments, and tectonic activity (regional down or up-warping and movement along growth faults). However, the relative contribution of global warming effect is not yet well established.

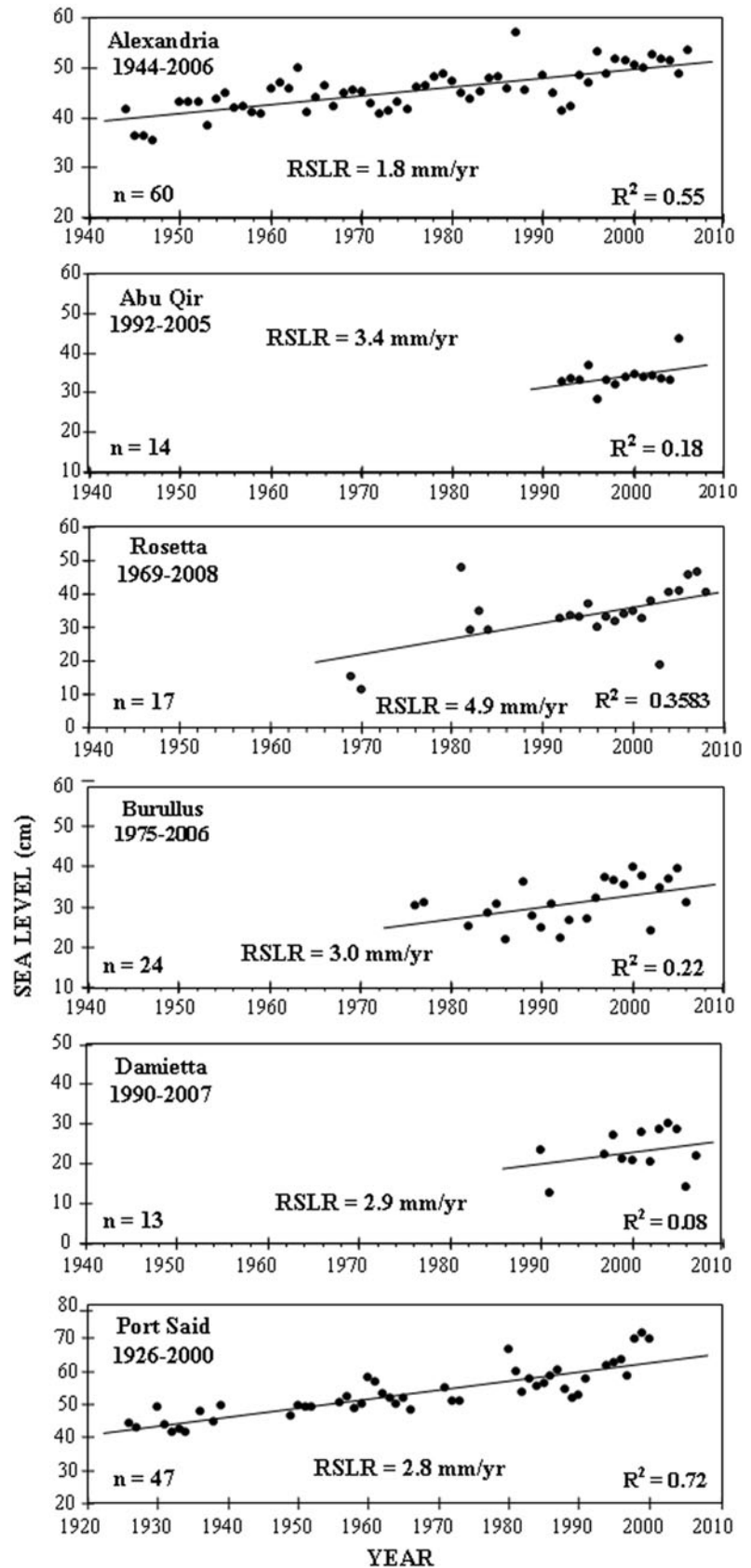
Linear regression lines of the data have been plotted in order to distinguish the broad temporal trend (Fig. 5). They all show an upward trend, but with a different magnitude. The slope of the trend lines indicates that mean sea level at Alexandria, Abu Qir, Rosetta, Burullus, Damietta, and Port Said has risen 1.8, 3.4, 4.9, 3.0, 2.9, and 2.8 mm/year, respectively (Table 1). The rates of estimated sea-level are in the range of most estimates of regional sea-level recorded by Emery et al. (1988), El Fishawi and Fanos (1989), Sharaf El Din et al. (1989) and Frihy (1992b).

This upward trend in sea-level rise is higher than the one given by the Intergovernmental Panel on Climate Change (1–2.5 mm/year) (Warrick et al. 1995), and demonstrates that other geologic factors also contribute to the sea-level

rise, such as land subsidence and tectonic activities. On the other hand, they are lower than the rates (3–10 mm/year) estimated at other Mediterranean deltas like Rhone and Po (Stanley 1997), and Ebro (Sanchez-Arcilla et al. 2008). Besides, uplift or subsidence appears to be dominant in other Mediterranean areas also due to the active tectonism, even without any global sea-level rise (GSLR). In contrast to the Egyptian coast and due to tectonic motion, a decreasing downward trend between -0.5 to -2.8 mm/year has been documented at the coastline of Israel (Emery et al. 1988).

Of the six examined gauges, two are located in Alexandria on the western delta limit and four along the Nile Delta coastline. The two tide gauges of Alexandria, at the western harbor and Abu Qir, are positioned on a land surface of that underlain by carbonate rocks of the coastal ridge II. In contrast to the delta gauges, the two sites of Alexandria represent the coastal plain uncontrolled by Holocene mud subsidence. Alexandria western harbor gauge show sea-level rising at a rate of 1.8 mm/year, while the Abu Qir records show a much higher average rate of about 3.4 mm/year, despite being positioned on the same ridge II. We attribute the lower rate of sea-level rise at Alexandria western harbor (1.8 mm/year) to the tectonic activity of the NE Rosetta structural lines (structural up-warping and movement along growth faults), and not to the effect of natural compaction and dewatering of Holocene deltaic sediments (Fig. 4c). Similarly, the higher value of SLR at Abu Qir peninsula (3.4 mm/year) is likely supported by active faults in the region, despite the absence of Holocene sediment underneath. Interaction of the Abu Qir fault (S–N) together with the Suez Cairo-Alexandria (NW–SE) (Fig. 4c) and Qattara-Eratosthenes structural lines (NW–SE) may be responsible for down-warping of this ridge area, leading to land submergence and sea-level rise. This suggests that RSLR estimated in this area has resulted from the effect of vertical land motion “tectonic subsidence” and not principally from compaction and dewatering of thick Holocene sediment underneath. As seen in Fig. 4c, Alexandria is a tectonic area with a complex fault system. The shore-parallel carbonate ridge (usually called Ridge II or El Max-Abusir ridge) beneath Alexandria was stretched, down-bowed, and offset in a NE direction to shallow depths in Abu Qir Bay (Stanley 2005a). In contrast to Alexandria and Abu Qir gauges, rates of RSLR estimated at Rosetta (4.9 mm/year), Burullus (3.0 mm/year), and Damietta (2.9 mm/year) have likely resulted from the effect of subsidence due to compaction of the underneath Holocene sediments rather than tectonic events. The estimated rates at these three localities are generally proportional to the measured Holocene mud thickness, being 35, 12.5, and 35 m, respectively (Table 1; Fig. 4a).

Fig. 5 Comparison of relative sea-level trends estimated from annual tide-gauge records at Alexandria, Abu Qir, Rosetta, Burullus, Damietta and Port Said. Solid line is the regression relationship. The regression lines together with the slopes (RSLR) are indicated. They all show an overall upward trend of relative sea-level (RSLR) fluctuates between 1.8 and 4.9 mm/year. Tide gauge locations are shown in Fig. 1



Sediment core analyses indicate that the thickness of the Holocene sequence at Port Said gauge ranges to 46.5 m that corresponds to a subsidence rate of 5 mm/year (Stanley and Goodfriend 1997). Despite this higher subsidence rate, a relatively lower estimate RSLR is recorded at Port Said gauge (2.8 mm/year). The exceptional lower rate of RSLR estimated in this particular area appears not to be comparable with the subsidence rate. This could be attributed to the effect of tectonic uplift resulting from the movements of the earth's crust which in turn may counter or delay process of land lowering and SLR. In fact, this area has been affected by a vertical land motion resulting from the active normal Pelusium strike-slip fault system that trends NE to SW and clearly defines the eastern margin of the Nile Delta, as discussed by Neev et al. (1987) (Fig. 4c).

Predictions of greenhouse-related sea-level rise vary considerably, but all concur that acceleration is likely. Until now such predictions remain controversial and have not been accepted by many scientists. For example, the analyses of tide-gauge data by Woodworth (1990) and Douglas (1991, 1992, 2001) did not find a statistically significant acceleration of GSL (Global Sea Level). In order to examine whether there has been any acceleration, the 60 years annually time series of Alexandria is included in this study to investigate the possibility of accelerating sea level rise during late twentieth century up to 2006 (Fig. 6). Yearly data are statistically analyzed for the periods of 1944–1979 and 1980–2006. Results show minor statistically significant acceleration of RSLR as compared to trends estimated between 1944–1979 (34 years) and 1980–2006 (26 years) (Fig. 6). In general, the curve of 1980–2006 appears to be slightly higher than that of 1944–1979 trends. This indicates that sea level at this particular site has been—accelerating during the last 26 years. This could be attributed to the active episodic effects of land-level changes, emergence or subsidence, or/and as a result of the effect of global warming. Evidently, Alexandria coastal plain has been affected by a diverse vertical land motion, emergence, and subsidence, which resulted from the effect of Abu Qir and Rosetta fault zones (Fig. 4c). As a result of this active tectonism, Emery et al. (1988) have reported a land uplift of 0.7 mm/year at the Alexandria Harbor using short records (1958–1976; 19 years). Based on carbon-dated sediment cores, this complex pattern is supported by the study of Warne and Stanley (1993), who reported uneven vertical land motion across the coastal plain of Alexandria that varies from subsidence (–5 mm/year) to emergence (7 mm/year).

The general rising of RSL at Abu Qir, Rosetta, Burullus, Damietta and Port Said, with an alongshore fluctuation that varies from site to site, may have been related to geological factors. As discussed earlier, Stanley (1988 and 1990) has reported an eastward higher subsidence rate as a response

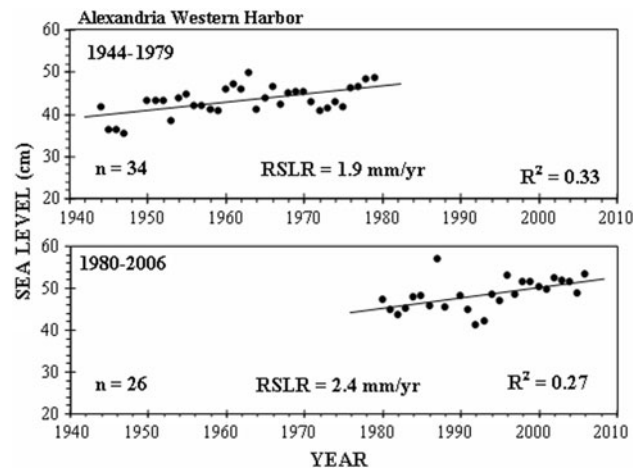


Fig. 6 Comparison of relative sea-level trends estimated from monthly tide-gauge records at Alexandria for the years 1944–1979 and 1980–2006 time periods. Despite the upward trends noticed at the two periods, relative sea-level (RSLR) is slightly accelerated during the more recent period (2.4 mm/year) relative to the older one (1.9 mm/year), possibly due to the effect of climate change

of land motion due to tectonic activity and to tilting of the Nile Delta plain to the northeast. This tilt motion may be related to the dominant SW-NE trending faults, recently active along the NE Nile Delta margin (Fig. 4c). The Pelusium Line extends from the Levant directly to the Gulf of Tineh and probably into the Nile Delta and has been responsible for the continuing sea-level rise and more rapid land subsidence (Stanley 1990). This indicates that coastal and offshore sectors are subjected not only to subsidence due to compression/dewatering of late Quaternary deposits, but also to structural fault displacement of thick underlying older strata. Associated with these faults, the coastal plain has been affected by a series of small earthquake epicenters in historical and recent time (Kebeasy 1990).

In order to assess the relative contribution of geological factors in the estimated relative sea-level changes, a statistical correlation analysis was conducted between these changes and both Holocene sediment thickness, and their corresponding subsidence rate. These data are summarized in Table 1. Correlation analysis yielded a weak positive correlation coefficient between the estimated rate of sea-level changes and both Holocene thickness ($R^2 = 0.13$) and Subsidence rate ($R^2 = 0.32$). These relatively weak correlations indicate that geodynamic elements contribute more to processes of lateral changes of RSL than of natural compaction and dewatering of the Holocene mud underneath the coastal plain of the Nile Delta and Alexandria.

Vulnerability and topographic variability

As far as vulnerability is concerned, both low-lying and high elevated topographic areas are discussed to define their

susceptibility to possible incursion by accelerated sea-level rise. The surface topography of the coastal plain of Alexandria and the Nile Delta varies from high-elevated features to low-lying areas, each reflecting a certain degree of susceptibilities to erosion and thereby sea incursion. Major topographic features with their various levels are spatially distributed in Fig. 7. The relative proportions of these units, relative to the coastal plain of the study area, up to the 4-m contour, are depicted as a bar chart in Fig. 7 (upper right diagram), while the real values are shown in Table 2. The coastal plain has a total area of ~13610.41 km². The identified topographic features are categorized in Table 2 according to their elevations from mean sea-level into the following: 1- low-lying vegetated lands down to -3 m below sea-level (700 km²; 5.1% of the coastal plain), 2- Zero to -3 wetlands of lagoons, fish farms, lakes and ponds (2261.1 km²; 16. 61%), 3- vegetated areas between 0 and 1 m (3806.9 km²; 27.97%), 4- vegetated lands exist at 1–2 m (2903.8; km²; 21.37%), 5- vegetated area between 2–3 m (1955.6 km²; 14.37%), 6- vegetated and desert between 3–4 m (1558.1 km²; 11.45%), coastal dunes (73.75 km²; 0.54%), and 7- carbonated ridges (237.22 km²; 1.74%).

Low-lying areas (below sea-level of zero up to 1 m elevation) are dominated across much of the coastal plain of the Nile Delta and cover 27.97% of the coastal plain (~13610.41 km²), and they may be susceptible to serious land loss due to sea incursion unless protection control measures are implemented such as the barrier at Manzala lagoon. Rising sea level increases vulnerability of these low-lying areas, especially to wind-induced waves driven onto the coast during winter storms. Starting from the west, the 15-km long coastal road named “Corniche” fronting the northeast-southwest metropolitan strip of Alexandria elevates from 2.4 m to 12.3 with an average of 5.4 m above mean sea level (Frihy et al. 2004a, b). The highest

elevation exists at Stanley (12.3 m) and Miami beaches (9.4 m), while the lowest point positioned at El Mandara (2.4 m) (Figs. 3c, g, 8). The marked undulation of the Corniche land surface reflects the original topography of the carbonate ridges running parallel to the coastline which spatially form the coastal strip of Alexandria Metropolitan area (Figs. 8a, 9a). With the exception of the lowest point at El Mandara, this elevated coastal carbonate sand ridge II underlying Alexandria and Abu Qir cities acts as a natural barrier between the sea and the low-lying El Tarh area. This ridge is one of eight coast-parallel carbonate rocks (termed kurkar ridges or aeolianite in Israel) in this region (Butzer 1960; Hassouba 1980). These high-relief ridges blanket the backshore and the upland areas from Alexandria to Sallum on the Abu Qir lagoon and Mareotis lake south of Alexandria. It was an active wetland area until at least the early nineteenth century (Chen et al. 1992; Arrowsmith 1802). Although it is now completely drained and cultivated, its existence can still be distinguished on satellite images. Fortunately, this low-lying area is now protected to the northeast by El Tarh or Mohamed Aly barrier built in 1820–1830 (Figs. 2b, 3b). This east-west directed barrier had been built by Mohamed Ali (was appointed Ottoman Governor of Egypt in 1805) to mitigate incursion of salt in the banks of Mahmoudia Canal, which was the only source of fresh water to Alexandria diverted from the Rosetta Nile branch (El Rafeay 1948). Diverse socio-economic frameworks, including cultivated land, power plant, and petroleum/gas factories lie directly in the lee side of this seawall (10-km-long by 2.5-m-tall).

El Tarh low-lying area (700 km²) could have a catastrophic flooding without any global rise in sea-level if water bypasses accidentally from the lowest point in the limestone coastal ridge at Mandara beach (risk area #1), that is now 2.4 m above mean sea-level, or from Mohamed Aly or El

Fig. 7 Major topographic features lying below and above mean sea-level up to 4 m contour backing the coastlines of the Nile Delta and Alexandria, each reflecting different susceptibilities to sea incursion (updated from Frihy 2003). Bar chart in the upper right diagram shows proportions of areas of major topographic features depicted from data in Table 2. Item #9 “others” combine areas of river channels, small islands, drains and urban areas

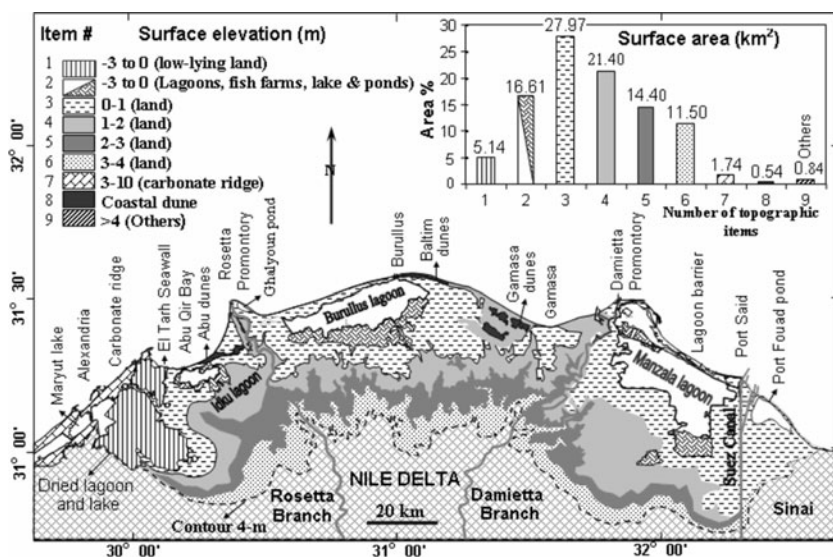


Table 2 Relative proportions of areas of major topographic features of the lower coastal plain of Alexandria-Nile Delta region. Proportions are calculated relative to the coastal plain area between the coastline and up to contour 4-m above mean sea level, within about 50 km of the coast (coastal plain area = ~13610.41 km²). Areas of lagoons include small islands and aquatic vegetation. For comparison, relative proportions of areas of major topographic features are diagrammatically depicted as a bar chart in Fig. 7b

| Topographic features | Elevation from sea-level (m) | Surface area (km ²) | % relative to areas of 0 to 4-m land contour |
|---|------------------------------|---------------------------------|--|
| Dune and ridges | | | |
| Abu Qir dune | 5–15 | 11.610 | 0.085 |
| Baltim dune | 10–20 | 11.283 | 0.083 |
| Gamasa dune | 10–25 | 50.859 | 0.374 |
| Total dunes | | 73.752 | 0.542 |
| Carbonate ridge | 2.4–11.0 | 237.221 | 1.743 |
| Wetlands | | | |
| Maryut lake | 0–1 | 50.2 | 0.369 |
| Idku lagoon | 0–1 | 63.0 | 0.463 |
| Idku lagoon fish farm | –3 to 0 | 75.4 | 0.554 |
| Burullus lagoon | 0–1 | 469.8 | 3.452 |
| Burullus lagoon fish farm | –3 to 0 | 344.4 | 2.530 |
| Manzala lagoon | 0–1 | 790.5 | 5.808 |
| Manzala lagoon fish farm | –3 to 0 | 414.4 | 3.045 |
| Ghalyoun pond | 0 to –2 | 1.8 | 0.013 |
| Port Fouad lagoon | 0 to –3 | 51.6 | 0.379 |
| Total | | 2261.1 | 16.613 |
| Low/high elevated lands | | | |
| El Tarh low-lying area | –3 to 0 | 700 | 5.143 |
| Vegetated area | 0–1 | 3806.926 | 27.971 |
| Vegetated area | 1–2 | 2903.815 | 21.369 |
| Vegetated area | 2–3 | 1955.617 | 14.369 |
| Vegetated area | 3–4 | 1558.080 | 11.448 |
| Others (river channels, islands & drains) | | 113.91 | 0.837 |

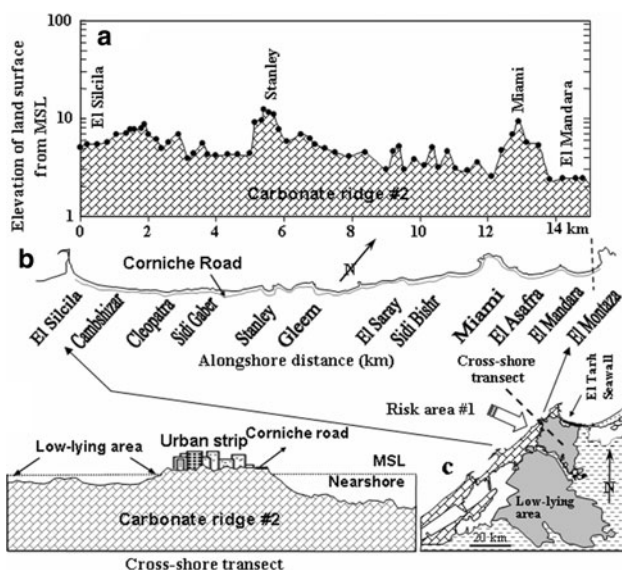


Fig. 8 a Alongshore-altitude of the coastal road “Corniche” backing Alexandria coastline from El Silcila to El Mandara, where the lowest point at El Mandara is highly vulnerable to storm-surge wave overtopping and possible flooding due to sea-level rise [data from Frihy et al. (2004a, b)]. The general topography of this region is schematically diagrammed in the cross-shore transect (b and c). Large low-lying area is dominated south of Alexandria Metropolitan strip that built on the high elevated-coastal ridge II

Tarh seawall (risk area #2) (Fig. 9a). As evidenced from the land survey of Frihy et al. (2004a, b), it is evident that Alexandria, including Abu Qir city to the east, is not a below-sea level sector, but is built on the subaerially exposed shore-parallel carbonate ridges. These ridges blanket the backshore and the upland areas from Alexandria to Sallum on the Egyptian/Libyan border (see inset of Fig. 1). They elevate progressively from ~10 m along the coast to ~100 m some 40 km inland. In the seaward direction, they also extend underwater down to ~20-m depth across the continental shelf of the Arabs Gulf between Alamein and Alexandria as interpreted from analysis of remote sensing (Lindell et al. 1991) and nearshore profiles (Frihy et al. 2004b). The origin of these ridges varies from marine, such as offshore bars and beach deposits, to eolian (Fourtau 1893; Shukri et al. 1956; Said et al. 1956; Butzer 1960).

With the exception of the Maryut lake and coastal lagoons (Idku, Burullus and Manzala), a large low-lying dry area of 700 km² occupies the western sector between Alexandria and the Nile Delta at El Tarh and the elevated carbonate ridge on which Alexandria was built (Fig. 9a). This cultivated low-lying area that backs the Alexandria region is now 1.5–3.0 m below mean sea level. They are protected to the west by shore-parallel coastal ridge on

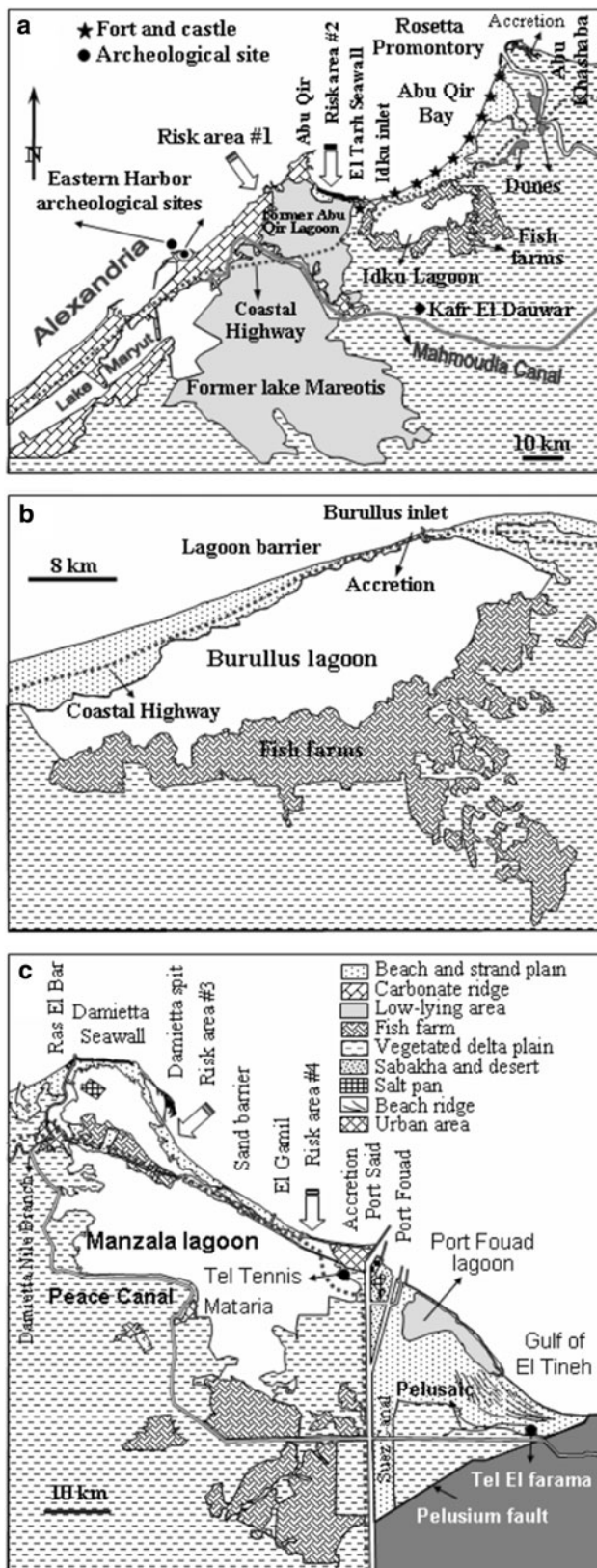


Fig. 9 Detailed land surface features along the coastal plains of Alexandria and Nile Delta: **a** The northwestern region of the Nile Delta and Alexandria showing large-scale low-lying area (700 km²). It was an active wetland and eventually drained and converted to agriculture land by the end of the nineteenth century (Arrowsmith 1802; El Rafeay 1948; Chen et al. 1992; Goodfriend and Stanley 1996). Fish farms and archeological sites are denoted. **b** Fish farms border the southern margin of Burullus lagoon at the central “bulge” of the Nile Delta (from ETM Satellite image 2007). **c** The northeastern region of the Nile Delta including Manzala lagoon region showing fish farms distributed inside and on the southern border of Manzala lagoon. The narrow sand barriers of the lagoon and Port Fouad low-lying areas are much vulnerable to beach erosion due to climate change (from ETM Satellite image 2006). Risk areas, #1 to #4, vulnerable to RSLR are positioned in **a** and **c**

which the city of Alexandria was built in the fourth century BC and from the north by El Tarh seawall (Fig. 9a). This shore-parallel carbonate ridge II attains an average altitude of 5.4 m above mean sea-level. The cross-shore topographic variability of this region is simply plotted in Fig. 8a–c, depicting the nearshore zone, Corniche road, Alexandria metropolitan strip, and El Tarh low-lying area. This information is completely different from what is stated by other researchers claiming that Alexandria is a low-lying coastal city (e.g. El Raey et al. 1995, 1997). However, the low-lying cultivated area (700 km²) SE of Alexandria at El Tarh and Abu Qir city is safe unless damage to El Tarh seawall (risk area #2) happens, for example, by an earthquake or a tsunami which may cause a catastrophic flooding of this low-lying area. These extreme events can also affect the lowest point east of Alexandria (risk point #1). Accidentally in December 2003, a large storm surge generated a high wave that flooded the low-lying Cornish road at El Mandara which lies on the lowest point of the coastal ridge. In order to face the frequent effect of storm wave-run up, a submerged shore-parallel breakwater (2 km long by 15 m width) was built recently off the lowest point #1 at Mandara-Asafra beach (Fig. 2a).

Coastal lagoons are defined as water bodies separated from the sea by a land barrier, which through one or many inlets is connected with the sea. Coastal wetlands on the Mediterranean deltas are most likely to be affected by loss or significant change due to projected climate change that particularly accelerates sea-level rise (Nicholls and Hoozemans 1996). Coastal wetlands in the study area lie approximately parallel to the coast and vary in size from small to large scale water bodies (Figs. 1, 2c–g, 9a–c). These wetlands are from west to east (a) lakes [Maryut (50.2 km²) and Ghalyoun (1.8 km²)], and (b) lagoons [Idku (63.0 km²), Burullus (469.8 km²), Manzala (790.5 km²) and Port Fouad (51.6 km²)]. Lagoons vary in depth from

0.5 to 3.0 m., and are separated from the sea by a long sand barrier that varies in width from 0.5 to 10 km. They are connected to the Mediterranean by narrow inlets, while most of them are artificially protected by jetties. Similar to other worldwide coastal wetlands, they are socio-economically and ecologically important as they are a potential source for fisheries, tourism, and act as an allowing passage and breeding of migratory birds (Moufaddal et al. 2008). They also are an important spawning area for many fish species. They are naturally inhabited by aquatic vegetation such as reeds and also incorporate tens of small islands; some of them are inhabited by fishermen community. For example, the aquatic vegetation in Idku and Burullus lagoon cover, respectively, an area of 37.7 km² and 210 km², i.e., 60% and 46% of the total surface area of these lagoons. (Moufaddal et al. 2008). There are also 10 and 30 islands in Idku and Burullus, respectively, in which they cover an area of 3.0 and 9.2 km², corresponding to 4.8 and 2% of the total lagoon areas.

To satisfy the nations' needs for fish industry, marshes south of the Nile Delta lagoons have been rapidly converted to productive fish farms (Moufaddal et al. 2008; El Banna and Frihy 2009). These low-lying fish farms (~2–3 m water depth) cover large areas along the southern margins of Idku, Burullus, and Manzala lagoons (Fig. 9a–c), and markedly extends further inland to at least 7, 24, and 12 km, respectively, from the present southern lagoon margins. As a result of fish farm and landfill activities, the size of open-water areas of Idku and Burullus lagoons is now reduced by 1.6 and 4 km² between 2002 and 2007, respectively (Moufaddal et al. 2008). To quantify real open-water lagoon surface and contiguous fish farms, their areas are measured from recent satellite ETM + images (Table 2), and mapped in Fig. 9a–c. Our estimation from these images reveals that fish farms at Idku, Burullus, and Manzala occupy areas of ~75.4, ~344.4, ~414.4 km²%, respectively. The total areas of these lagoons, including the open-water body, aquatic vegetation, and fish farm areas (2157.5 km²) account for about 15.85% of the entire coastal plain of Alexandria and the Nile Delta (Table 2). The measured areas of Idku and Burullus lagoons and their associated fish farms are nearly comparable to those measured by Moufaddal et al. (2008) using 2007 ETM + satellite images.

The sand barriers that separate the Nile Delta lagoons from the open sea vary in width, degree of erosion, and subsidence rate. Some of them are vulnerable to erosion that is being accelerated by the sea-level rise, combined with the effect of prevailing coastal processes. These sand barriers are experiencing erosion and reshaping, but with localized accretion in embayments and at updrift or lee sides of protection structures. The sand barrier of Idku lagoon, 0–1 m elevation, is relatively wide (0.25–10.0 km) and experiences smooth erosion to accretion processes (Fig. 9a). The width

of the Burullus lagoon barrier ranges from 0.5 to 5.3 km and is narrower to the west of the lagoon entrance where accretion prevails at a long-term rate of 5 m/year (Frihy and Komar 1993). The long-term accretion of this narrow extension (3.8 km long) is effected by blocking the unidirectional easterly longshore sand transport by the jetty constructed at the Burullus inlet (Fig. 9b). In contrast, the sand barrier of Manzala lagoon at El Gamil is relatively narrow near its eastern inlet (0.5–2.3 km wide), and is highly exposed to erosion processes due to both wave-induced longshore current and sea-level rise Fig. 9c.

In contrast to the aforementioned low-lying areas, a high-elevated land surface in the form of coastal dunes exists in the backshore of Abu Qir Bay, Baltim, and Gamasa (Figs. 1, 2d, 3f, h). These dunes cover a total area of 73.75 km², relative to the entire coastal plain (~13610.41 km²). Baltim dunes cover an area of 11.28 km² (maximum of 20 m height), and extend laterally by 18 km in length and ranges in width from 500 to 800 m (Figs. 2d, 3f). We believe that this dune system, although experiencing sea cutoff erosion, together with the shore-parallel protective structures built along eroded sectors shown in Fig. 3f, would act to limit possible sea-level rise resulting from climate change in some coastal sectors. Dramatically, the remnant active longitudinal or “seif” dunes (10–25 m height, 50.86 km²) that cover the coastal plain of Gamasa, as well as the barchan dune belts along Abu Qir Bay (5–15 m height, 11.61 km²) has been subjected to intensive anthropogenic degradation, including land reclamation, urbanization, and road construction (Banna and Frihy 2009). Accordingly, 60% of the original active dunes of Gamasa has disappeared compared to the period from 1955 (aerial photograph) to 2002 (ETM satellite image 2002), for agricultural and urban expansion (Fig. 3h). As a consequence, the continuing degradation of these coastal dunes which have been acting as natural protective areas against sea-level rise would be a problem for the coastal building and the international highway in front of these dunes (Banna and Frihy 2009). In addition, accretionary beaches along promontory saddles, bays, and embayments could also reduce the effects of erosion induced by accelerated sea-level rise (Figs. 1, 3d, 9a, c). In other words, this shoreline progradation would help to counter the likely erosion due to sea-level rise. The shorelines of these sectors have experienced sand accretion of between 5 and 10 m/year (Frihy 2003), and exist at the central part of Abu Qir Bay (14.0 km long), Abu Khashaba east of the Rosetta estuary (10.0 km long), Gamasa embayment (8 km long), and the Gulf of El Tineh east of the Suez Canal (12 km long) (Figs. 1, 3d, 9a, c).

Significant accretion also occurs along interrupted coasts by engineering structures at updrift sides of long Jetties and also in the lee sides of shore-parallel breakwaters. Coastal

extensions of jetty updrift act as sediment sink for sand coming from the erosion of adjacent shores by the NW wave-induced longshore current to the east, and thereby protect the backshore behind. Significant updrift sand accumulation produced by the blockage of the eastward longshore sediment transport by jetties occur along coastal stretches at the west Burullus inlet (3.8 km long), west of the Suez Canal entrance at Port Said beach (7.0 km long), and along the Gulf of Tineh in the Sinai Peninsula (12.0 km long) (Figs. 1, 2g, 9b, c). Updrift accretion of 8 m/year has been calculated by Dewidar and Frihy (2009) along the Port Said beach to the west of the Suez Canal breakwater, in which this stretch essentially acts as a sediment sink for sand coming from the erosion of adjacent western shores including the Damietta promontory. In the present study analysis of shoreline changes was carried out using aerialphotos and satellite images between the years of 1955 and 2008 (i.e., spanning up to 53years), indicating a shoreline advance of 2.5 m/year at Port Said beach (Fig. 2g). Moreover, along the Burullus-Baltim coastline, substantial accretion (tombolo) has accumulated rapidly at a maximum rate of 37 m/year, and has filled the shadow area between the coastline and the detached breakwaters of Baltim (Figs. 2d, 3f; Dewidar and Frihy 2008). Similarly, these authors have detected a beach accretion of 20 m/year east of El Gamil inlet that is caused by the interruption of the prevailing eastward sediment transport by the tombolos, formed in the leeside of the constructed five detached breakwaters (Fig. 2g).

Projection of RSL trend

Future RSL cannot be projected for the entire coastline of the study area because it is not topographically uniform in terms of land features and protective structures. In addition, some areas of the coastal plain have been subsided; other sectors may have been uplifted in response to tectonic activities of thick underlying older strata. In this study projection of future RSL trend is assessed only for the aforementioned vulnerable risk areas that are characterized by highly exposed narrow/low-lying subsiding barriers of the Manzala lagoon. On the other side, areas protected by both natural defense systems (prograding coastal areas, high-elevated dunes or carbonate ridges) and shore-parallel protective structures are not included in such assessment. Two approaches are applied here for projecting sea-level rise: (a) the IPCC's scenario of 1-m rise of sea-level, and (b) the possible erosion of the Manzala lagoon barrier based on long-term rate of shoreline changes.

Scenario of 1-m

As most of the strand plain of the Nile Delta elevates between zero and 1 m, the common scenario of 1-m rise of

sea-level could be applied, particularly for the exposed Manzala lagoon barrier which has no natural or man-made protection. The averaged rate of sea-level rise obtained at the study sites is approximately 3 mm/year. This rate, if remained constant, can produce a vertical rise of ~ 30 cm across the study area within the next 100 year. Therefore, in exposed coastlines with no protection, a 1-m sea-level rise requires ~ 333 year to inundate the topographic zones of up to 1-m inland contour (Fig. 7). This estimate is also under the assumption that there is no natural readjustment of the seabed gradient against sea-level rise, as was stated by Bruun (1962).

Eroding the whole lagoon barrier

The IPCC reported that a 1-cm rise of the sea-level erodes beaches about 1 m horizontally. This assumption mainly depends on the characteristics of the coastlines which are controlled by many different variables, including interactions between shore lithology, geomorphology, wave climate, seabed gradient, currents, and storm frequencies. As beach erosion rates along the study area significantly vary from one site to another, we prefer not to apply the IPCC's estimates to assess future projection of the sea-level rise. Beach erosion rates have been determined by many researchers along the study area. These estimated rates consider all factors acting in processes of shoreline erosion, including coastal processes, accelerated RSLR, land subsidence, and tectonic events. Along the northeastern coastline of the Nile Delta including Manzala lagoon barrier, Dewidar and Frihy (2009) have calculated rates of erosion and accretion from analysis of ten scenes of landsat sensors (MSS, TM and ETM+) at unequal intervals spanning a 35-year period between 1972 and 2007. In their analysis, the rates of shoreline changes have been calculated at 852 alongshore locations using a Digital Shoreline Analysis System (DSAS) program. Alongshore rate of changes along the northeastern coast of the Nile Delta shows several reversals between erosion and accretion with a maximum erosion of -10 m/year at the immediate downcoast of the Damietta spit, where the lagoon barrier is relatively wide (2.3 km) (Fig. 9c). The lowest rate of erosion (-5 m/year) is positioned east of the El Gamil inlet where the lagoon barrier has a minimum width of 500 m. In contrast, beach accretion of 20 m/year exists in the lee side of the five detached breakwaters constructed east of the El Gamil inlet and also along the updrift side (8 m/year) of the Suez Canal breakwater at Port Said beach (Fig. 9c).

Based on estimated beach erosion caused by coastal processes and geological factors (sea-level rise and land subsidence) two risk points are identified at the exposed Manzala lagoon barrier. The two risk areas of Manzala

lagoon barrier are positioned at the lee-side of the Damietta spit (2.3 km width, risk area #3), and at the narrowest point (500 m width) east of the El Gamil inlet (risk area #4) (Fig. 9c). As mentioned earlier, the sandy barrier of the Manzala lagoon is influenced by mean subsiding rates, from 4 to 5 mm/year due to the compaction of thick Holocene sediment underneath and the effect of the SW-NE trending faults (Stanley 1988, 1990). In the absence of any coastal protection, the uninterrupted sand barrier at the widest point #3, downcoast of the Damietta spit, where a sediment deficient prevails, will be eroded by 230 year from now (2.3 km width eroded by -10 m/year = 230 years). Further east, along the same barrier, the narrowest risk area #4 will be totally eroded by the next 100 years (500 m eroded by -5 m/year = 100 years).

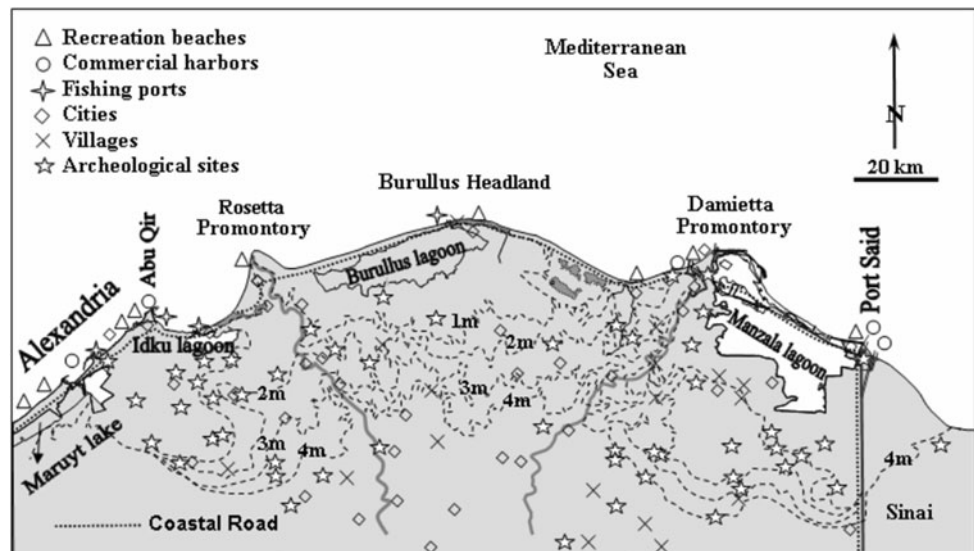
It has been established that there are two distinct effects of sea-level rise on beach evolution, depending on geomorphologic setting (Stive et al. 1990; Nicholls 1998). On uninterrupted sandy coasts with no inlets, as in risk area #3, rising water levels induces profile disequilibrium, and hence erosion due to profile adjustment. This direct effect of sea-level rise is often known as “the Bruun rule” (Bruun 1962, 1988). In contrast, on interrupted sandy coasts with inlets, as in point #4, sea-level rise causes additional erosion of the shoreline as the inlet/lagoon system will provide an additional sink for eroded sand, resulting in sedimentation hazard; this was termed the indirect effect of sea-level rise by Stive et al. (1990). The resultant siltation at the inlet leads to reduced water exchange between the lagoon and the sea, resulting in poorer circulation in the lagoon, degradation of the water quality, and subsequently affects the fishing industry of the lagoon.

When the expected impacts of the increased greenhouse effect are taken into account, sea incursion by the aforementioned approaches would inundate all lands below the 1-m contour. Accordingly, as the barrier width at the risk areas # 3 and #4 at the Manzala lagoon barrier progressively decreases to the extent of being removed, upland areas (strand plain) behind the beach will be increasingly exposed to wave action, and significant losses could occur during coastal storms occurring after accelerated sea-level rise. It would be expected that erosion, caused by the sea-level rise and coastal processes, of the loose sandy barrier of the Manzala lagoon might expose this barrier to the open sea and thereby negatively affect both the backshore environments and associated socio-economic activities. These include the lagoon ecosystems, fish farms, cultivated lands, and the coastal highway which extends parallel to the shore and in upland areas from Sallum on the Egyptian/Libyan border to Raffh at Gaza strip. Some sectors of this highway run through the coastal lagoons, and thereby are susceptible to sea-level incursion (Figs. 2g, 9a–c). With

the continuous sea-level rise, the Peace Canal or “Al-Salam Canal” south of the Manzala lagoon will be seriously affected. This canal brings water from the Damietta Branch of the Nile, under the Suez Canal to the Sinai Peninsula to irrigate a total of 600,000 acres (Bleier 1997) (Fig. 9c). Now, this project provides irrigation waters to the area east of the Suez Canal at Tina Plain (50,000 acres). The cost of the project is estimated to exceed 5 billion Egyptian pounds (about \$1.5 billion). The marine incursion into the Manzala lagoon barrier would likely accelerate intrusion of salt water in the groundwater underlying the Nile Delta plain and higher water tables. Saltwater intrusion would also harm aquatic plants and animals as well as threaten human water supply (IPCC 1990). Frihy (2003) and Stanley (1997) reported a close correspondence of the subsiding terrain with the 1.0 m contour, where marked landward salt incursion is greatest under the NE sector of the Nile Delta.

Taking into account socio-economics, the lower Nile Delta and Alexandria is a high-density populated area with a population scattered out in cities and small villages. They also contain numerous archeological sites (Fig. 10). Most of these sites occur on ‘Tell’ or ‘Kom’, respectively, corresponding to Arabic words for ‘mound’, describing the usual appearance of archaeological sites in the region. As a consequence of sea incursion and flooding, major archeological remains, particularly those located in the lowland areas of the region, might be affected, while others on high elevated land or underwater will not. A number of archeological remains of submerged, buried, and emerged coastal sites originally bounded the coastline of Alexandria and the Nile Delta (Figs. 9a, c, 10). Some of them, like Tel Tennis and Pelusium sites, lie in low-lying areas and have experienced land submergence, compaction, and tectonic subsidence (Stanley 2005b). Submerged archeological sites which were built onshore went underwater at Abu Qir Bay (Bonaparte’s Fleet, Canopus and Herakleion cities ruins); Ptolemaic, and Roman ruins submerged in the eastern sector of Alexandria’s Eastern Harbor below 8 m from MSL. Canopus and Herakleion, dated from Greek to Byzantine times, were discovered at depths of 6–7 m in the western part of Abu Qir bay (Toussoun 1934; Stanley et al. 2001). Five Historical military castles, older than 200 years, are located along the coastline of Abu Qir Bay (location in Fig. 9a). In addition to the fish farms and archeological sites, sea-level rise may negatively affect other socio-economic components, including agriculture, industry, cities, harbors, villages, and recreation beaches. Geographic positions of recreation beaches, commercial harbors, fishing ports, cities, villages, archeological sites, and the coastal highway are shown in Fig. 10.

Fig. 10 Geographic locations of major archeological sites and socio-economic components, including recreation beaches, commercial harbors, fishing ports, cities, and villages. Archeological sites and the coastal highway in the lower coastal plain of Alexandria and the Nile Delta, in which most of them will be excessively inundated and eventually lost, if sea-level will rise by a 1 m. Archeological sites are positioned from the web-pages of Egypt Exploration Society Delta Survey (<http://www.ees.ac.uk/deltasurvey/dsintro.html>)



Conclusions

The Nile Delta coast is an area which warrants measurements of RSLR because all geological factors contributing to land subsidence or uplift are present.

Values of sea-level rise updated and/or recalculated in the present study yield a modest rise in sea level. Rates of estimated sea-level rise differ significantly from site to site due to a number of factors that have induced land motion, either up or down (relative to sea level), including structural faulting, earthquakes, and sediment compression/dewatering. Analysis of the tide gauge data show that the rates of RSLR are unevenly distributed across the study area. Analysis of annual tide-gauge records obtained from tide gauges at Alexandria, Abu Qir, Rosetta, Burullus, Damietta, and Port Said show a continuous rise in mean sea level fluctuating between 1.8 and 4.9 mm/year. Rates of RSL do not systematically increase as expected from west to east, i.e., from Abu Qir to Port Said. Although examined gauges have operated over different time periods, the magnitude of sea-level rise is not consistent with variability of Holocene sediment thickness and calculated subsidence rate laterally along the Nile Delta coastline. This is confirmed from the correlation coefficient calculation between the estimated rates and the Holocene thickness ($R^2 = 0.13$), and subsidence rate ($R^2 = 0.32$). This weak correlation implies that subsidence due to land motion and tectonism is a major control of RSL changes affecting the coastal plain and contiguous Nile Delta shelf. This, in turn, confirms that coastal and offshore sectors are subjected not only to subsidence due to Holocene mud compression/dewatering, but also to structurally faulting and seismic activity. In other words, the general trend in RSLR is much dominated by tectonism, rather than compaction of Holocene sediments.

As Alexandria-Abu Qir region is dominated by complex tectonism, land subsidence at Abu Qir is significantly higher (3.4 mm/year) as compared with the Nile Delta, in spite of the absence of the soft fluviomarine deltaic mud underlying this area, which in turn has resulted from its tectonic setting that appeared from the associated fault system. This region has also undergone periodic cycles of emergence and submergence and is seismically active.

Since there is considerable variability in subsidence or uplift, and different geomorphologic and morphodynamic factors for each coastal sector, the study area should be treated individually and not as one unit when dealing with sea-level rise projection and other related scenarios. This means that not all the coastal plain of the Nile Delta and Alexandria is vulnerable to accelerated sea-level rise at the same level due to the high variability of the land topography. This information is completely different from claiming that a 90-cm-rise in sea levels from global warming by the end of this century would inundate much of the Nile Delta (Stanley 1988; El Raey et al. 1997; World Bank 2007). The topography includes high-elevation features: sand dunes carbonate ridges, protection works, and low-lying wetlands (lagoons, fish farms, and ponds). Accretionary or prograding beaches (5–10 m/year) along embayments and the Nile Delta promontory saddles also can compensate for erosion induced from the effect of accelerated sea-level rise.

A sea-level increase of 3.0 mm/year results from average rates estimated at Alexandria, Abu Qir, Rosetta, Burullus, Damietta, and Port Said. This average rate fits within the lower estimated prediction made by the Intergovernmental Panel on Climate Change (IPCC). The IPCC's Third Assessment Report projected that the global

average sea level would rise by between 9 and 88 cm between 1990 and 2100. If the average trend is linearly projected across the coastal plain of the study area, the sea-level rise will not likely inundate low-lying areas south of Alexandria area (3 m below mean sea level) because of its natural protection by the 5.4-m elevated carbonate shore-parallel ridge beneath Alexandria and also by Mohamed Aly or El Tarh seawall to the northeast (2.5 m height).

Other local low-lying wetlands and fish farms (<1 m depth) which border the southern margins of Idku, Burulus, and Manzala lagoons would be affected if coastal protection measures are not taken. In marked contrast, less vulnerable areas, including those fronted by high elevated dune belts, prograding or accretionary beaches, and artificially protected coastlines may be partially protected from future rise of the sea level. In the same manner, the coastal plain extending from Abu Qir peninsula (Alexandria) eastwards to Sallum westwards, ~600-km-long, is expected to be invulnerable to sea-level rise due to the existence of the high-elevated shore-parallel carbonate ridges.

The continued and increasing rate of sea-level rise will impact primarily the vulnerable areas on the lower coastal plain of the Nile Delta, but not the entire plain. It is thus fortunate that not all the coastal plain of the Nile Delta is a uniformly lowland. Nevertheless, subsidence and accelerated world sea-level rise will contribute to coastal erosion and incursion of salt in the groundwater underlying the northern delta plain. These processes must be taken into account as protection measures are implemented in this vital area of Egypt.

The most vulnerable areas are coastal wetlands (lagoons, lakes and ponds) and most of the 0–1 m elevated strand plain. The most hazardous region would be the Manzala lagoon area, where subsidence rates exceed 5 mm/year. Two risk points (#3 and #4) are positioned along the narrow barrier of this lagoon. However, the high projection of a 1-m rise could result in the loss of the entire lagoon area including surrounding small islands and fish farms. Consequently, sea incursion will gradually lead to significant change in the ecologic system including fisheries and wildlife as well as water penetration in the surrounding ground water table. Recreation beaches, commercial harbors, fishing ports, cities, villages, fish farms, archeological sites, and the coastal highway adjacent to these lagoons appear to be threatened socio-economically as a result of possible change in climate. Since wetlands act as buffers to the inland penetration of coastal flooding, the loss of cultivated Nile Delta land to south of wetlands will be under threat.

The identified risk areas (#1 to #4) at Alexandria and Manzala lagoon barrier remain highly vulnerable to geohazards that may likely be induced from sever erosion,

storm surges, earthquake, and tsunami events. This might require a contingency plan to reduce catastrophic hazards for these vulnerable risk areas.

Impacts of sea-level rise can be countered by other natural and anthropogenic factors. Topographic components such as sand dunes, progradation beaches, beach nourishment, and protective measures would counter beach erosion induced from sea-level rise. Therefore, additional considerations of these counter components in the form of preservation and maintenance must form an important element of coastal management of the study region. As low-lying lands are most vulnerable to be impacted, early protection of the Nile Delta was undertaken during Mohamed Aly era in the nineteenth century, confirming that humans always respond promptly to defend coastal lands from continued encroachment of the sea.

Benefits gained from understanding interactions between rate of sea-level rise, subsidence, topographic variability, structural faulting, and seismic activity can help in reducing uncertainties associated with local sea-level rise projections, thus contributing to more effective coastal management of the study area including adaptation strategies that would help to minimize negative consequences on socioeconomics and ecological impacts. Proposed adaptation measures may include maintaining shore protection structures and beach nourishment with a high priority to lowlands, restrictions on set backline at low-lying areas, dune restoration/conservation, controlling water extraction/pumping to minimize intrusion of salt water into ground water at the Nile Delta plain margin, relocation of buildings, and other infrastructure in a landward direction. Institutional and technical capacity building is needed to integrate both climate change and coastal management.

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References

- Ambraseys MM, Melville CF, Adam RD (1994) *The Seismicity of Egypt, Arabia and the Red Sea: a historical review*. Cambridge University Press, Cambridge, p 216
- Arrowsmith A (1802) *Plan of the Operations of the British and Ottoman Forces in Egypt*. London (map, 1sheet)
- Bleier R (1997) Will Nile water go to Israel?: North Sinai pipelines and the politics of scarcity. *Middle East Policy* 5:113–124
- Blodget HW, Taylor PT, Roark JH (1991) Shoreline changes along the Rosetta-Nile Promontory: Monitoring with satellite observations. *Mar Geol* 99:67–77
- Broadus JJ, Milliman S, Edwards D, Aubrey, Gable (1986) Rising sea level and damming of rivers: possible effects in Egypt and

- Bangladesh. In: Titus J (ed) Effect of changes in Stratospheric Ozone and Global Climate, vol 4, pp 165–189
- Bruun P (1962) Sea level rise as a cause of shore erosion. *Proc Am Soc Civ Eng J Water Harbors Div* 88:117–130
- Bruun P (1988) The Bruun rule of erosion by sea-level rise: a discussion on large-scale two- and three-dimensional usages. *J Coastal Res* 4:627–648
- Butzer KW (1960) On the Pleistocene shorelines of Arabs' Gulf, Egypt. *J Geol* 68:626–637
- IPCC (Intergovernmental Panel on Climate Change (1990) Scientific Assessment of Climate Change. WMO/UNEP Intergovernmental Panel on Climate Change, Geneva, 365 pp
- Chen Z, Warne AG, Stanley DJ (1992) Late Quaternary evolution of the northwest Nile Delta between Rosetta and Alexandria, Egypt. *J Coastal Res* 8:527–561
- Church JA, Gregory JM, Huybrechts P, Kuhn M, Lambeck K, Nhuan MT, Qin D, Woodworth PL (2001) Changes in sea level. In: Houghton JT, Ding Y, Griggs DJ, Noguer M, van der Linden PJ, Dai X, Maskell K, Johnson CA (eds) IPCC third assessment report—climate change 2001: the scientific basis. Cambridge University Press, New York
- Coleman JM (1982) Deltas: processes of depositional and models for exploration. *Int. Human Resources Development Corp*, Boston, p 124
- Delft Hydraulics/CRI (1991) Implication of relative sea-level rise on the development of the lower Nile Delta, Egypt. Pilot study for a quantitative approach. Final Report, p 300
- Dewidar Kh, Frihy OE (2008) Pre- and post-beach response to engineering hard structures using Landsat time-series at the northwestern part of the Nile delta, Egypt. *J Coast Conserv Plan Manage Springer*, 11:133–142
- Dewidar Kh, Frihy OE (2009) Automated techniques for beach erosion assessment using Landsat series along the Northeastern Nile Delta, Egypt, under publication
- Douglas BC (1991) Global sea level rise. *J Geophys Res* 96:6981–6992
- Douglas BC (1992) Global sea level acceleration. *J Geophys Res* 97:12699–12706
- Douglas BC (2001) Sea level change in the era of the recording tide gauge. In: Douglas BC, Kearney MS, Leatherman SP (eds) Sea level rise: history, consequences. Academic Press, San Diego, pp 65–93
- El Araby H, Sultan M (2000) Integrated seismic risk map of Egypt. *Seismol Res Lett* 71:53
- El Banna M, Frihy OE (2009) Human-induced changes in the geomorphology of the northeastern coast of the Nile delta, Egypt. *Geomorphology* 107:72–78
- El Fishawi NM, Fanos AM (1989) Prediction of sea level rise by 2100, Nile delta coast. *INQUA, Commission on Quaternary Shorelines, Newsletter* 11:43–47
- El Raey M (1997) Vulnerability assessment of the coastal zone of the Nile Delta in Egypt to the impacts of sea-level rise. *Ocean Coast Manag* 37:29–40
- El Raey M, Nasr S, Frihy O, Desouk S, Dowidar Kh (1995) Potential impacts of accelerated sea-level rise on Alexandria Governorate, Egypt. *J Coastal Res* 51:190–204
- El Raey M, Fouda, Nasr S (1997) GIS assessment of the vulnerability of Rosetta area, Egypt to impacts of sea rise. *J Environ Monit Assess* 47:59–77
- El Raey M, Dewidar Kh, El Hattab M (1999) Adaptation to the impact of sea level rise in Egypt. *J Climate Res* 12:117–128
- El Rafeay A (1948) History of the national movement and evolution of the governing regime in Egypt (Second Part). 353 pp (in Arabic)
- El Sayed MKh (1988) Sea level rise in Alexandria during the late Holocene: archaeological evidences. In: *Rapp. Comm. Int. Mer. Medit.*, p 31
- El Sayed MKh (1991) Implications of climatic changes for coastal areas along the Nile Delta. *Environ Prof USA* 13:59–65
- El Sayed A, Korrat I, Hussein HM (2004) Seismicity and Seismic hazard in Alexandria (Egypt) and its surroundings. *Pur Appl Geophys* 161:1003–1019
- Emery KO, Aubrey DG, Goldsmith V (1988) Coastal neo-tectonics of the Mediterranean from tide-gauge records. *Mar Geol* 81:41–52
- Fanos AM, Khafagy AA, Dean RG (1995) Protective works on the Nile Delta Coast. *J Coastal Res* 11:516–528
- Fourtau R (1893) La region de Maryut; 'etude Geologique. *Bulletin de l'Institut d'Egypt*; ser. 3, 141 pp
- Frihy OE (1992a) Beach response to sea level rise along the Nile delta coast of Egypt. In Woodworth PL (ed) Sea level changes: determination and effects geophysical monograph 69. American Geophysical Union, IUGG, vol 2, pp 81–85
- Frihy OE (1992b) Sea-level rise and shoreline retreat of the Nile delta promontories, Egypt. *Nat Hazards* 5:65–81
- Frihy OE (2003) The Nile delta-Alexandria coast: vulnerability to sea-level rise, consequences and adaptation. *J Mitigation Adapt Strateg Glob Change* 8:115–138
- Frihy OE, Dean R (1992) Artificial beach nourishment projects on the Egyptian coast. In: *International Coastal Congress (ICC) Kiel, Germany, 7–12 September 1992*, pp 84–95
- Frihy OE, Komar PD (1993) Long-term shoreline changes and the concentration of heavy minerals in beach sands of the Nile delta, Egypt. *Mar Geol* 115:253–261
- Frihy OE, Fanos MA, Khafagy AA, Komar PD (1991) Nearshore sediment transport patterns along the Nile Delta Egypt. *J Coastal Eng Neth* 15:409–429
- Frihy OE, El Banna MM, El Kolfat AI (2004a) Environmental impacts of Baltim and Ras El Bar shore-parallel breakwater systems on the Nile delta littoral zone, Egypt. *Environ Geol* 45:381–390
- Frihy OE, Iskander MM, Badr AE (2004b) Effect of shoreline and bedrock irregularity on the morphodynamics of Alexandria coast littoral cell, Egypt. *Geo-Mar Lett* 24:195–211
- Frihy OE, Shereet S, El Banna M (2008) Pattern of beach erosion and scour depth along the Rosetta Promontory and their effect on the existing protection works, Nile Delta, Egypt. *J Coast Res* 24:857–866
- Garziglia S, Migeon S, Ducassou E, Loncke L, Mascle J (2008) Mass-transport deposits on the Rosetta province (NW Nile deep-sea turbidite system, Egyptian margin): characteristics, distribution, and potential causal processes. *Mar Geol* 250:180–198
- Goodfriend GA, Stanley DG (1996) Reworking and discontinuities in Holocene sedimentation in the Nile Delta: documentation from amino acid racemization and stable isotopes in mollusk shells. *Mar Geol* 129:271–283
- Goodfriend GA, Stanley DG (1999) Rapid strand-plain accretion in the northeastern Nile Delta in the 9th century A.D. and the demise of the port of Pelusium. *J Geol* 27:147–150
- Gornitz V (1991) Global coastal hazards from future sea level rise, palaeogeography, palaeoclimatology, palaeoecology. *Glob Planet Change Sect* 89:379–398
- Hassouba AM (1980) Quaternary sediments from the coastal plain of northwestern Egypt from Alexandria to El Omyid, PhD thesis, Imperial Collage, London, 320 pp
- Houghton JT, Meira Filho LG, Callander BA, Harris N, Kattenberg A, Maskell K (1996) Cambridge University Press, Cambridge, pp 359–405
- Ibrahim MM (1963) The last subsidence movement of land on the Mediterranean coast, unpublished report, Mineral Wealth and Ground Water. Ministry of Scientific Research, Egypt, p 12
- Inman DL, Elwany HS, Khafagy AA, Golik A (1992) Nile Delta profiles and migration sand blankets. In: *Proceeding at the 23rd*

- international conference on coastal engineering. American Society of Civil Engineering, vol 2, pp 3273–3284
- Kebeasy RM (1990) Seismicity. In: Said R (ed) *Geology of Egypt*. Balkema, Rotterdam, pp 51–59
- Kuenen PH (1950) *Marine geology*. Wiley, New York, p 568
- Lakhan VC, Pepper DA (1997) Relationship between concavity and convexity of a coast and erosion and accretion patterns. *J Coastal Res* 13:226–232
- Lindell LT, Alexandersson ET, Norman JO (1991) Satellite mapping of oolitic ridges in Arabs Gulf, Egypt. *J Geocarto Int Sweden* 1:49–60
- Milliman JD, Broadus JM, Gable F (1989) Environmental and economic implications of rising sea level and subsidence deltas: The Nile and Bengal examples. *Ambio* 18:340–345
- Morton RA, Buster NA, Krohn MD (2002) Subsurface controls on historical subsidence rates and associated wetland loss in south-central Louisiana. *Trans Gulf Coast Assoc Geol Soc* 52:767–778
- Moufaddal W, El Sayed E, El Deghady E (2008) Updating morphometric and edaphic information of lakes Edku and Burullus, northern Egypt, with the aid of satellite remote sensing. *Egypt J Aquat Res* 34:291–310
- Neev D, Bakler N, Emery KO (1987) *Mediterranean coasts of Israel and Sinai*. Taylor & Francis, New York, p 130
- Nicholls RJ (1998) Assessing erosion of sandy beaches due to sea level rise. In: Maund JG, Eddleston M (eds) *Geohazards in engineering geology, geological society, London*. Engineering Geology Special Publications, vol 15, pp 71–76
- Nicholls RJ, Hoozemans FM (1996) The Mediterranean: vulnerability to coastal implications of climate change. *Ocean Coast Manag* 31:105–132
- Pirazzoli PA (1991) *World Atlas of Holocene sea-level changes*. Elsevier Oceanography Series 58, Amsterdam, p 300
- Ross AD, Uchupi E (1977) The structure and sedimentary history of the southeastern Mediterranean Sea-Nile Cone sea. *Am Assoc Petrol Geol Bul* 61:872–902
- Said R (1981) *The geological evolution of the River Nile*. Springer, New York, p 151
- Said R, Philip G, Shukri NM (1956) Post tyrrhenian climatic fluctuations in Northern Egypt. *Quaternaria* 3:167–172
- Sanchez-Arcilla A, Jimenez JA, Valdemoro HI, Gracia V (2008) Implications of climatic change on Spanish Mediterranean low-lying coasts: The Ebro Delta case. *J Coast Res* 24:306–316
- Sestini G (1989) Nile Delta: a review of depositional environments and geological history. In: Whateley KG, Pikerling KT (eds) *Deltas. Sites and traps for fossil fuels*. Blackwell Scientific Publications, Geological Society Special Publication, London, vol 41, pp 99–127
- Sestini G (1990) Impacts of global climate change in the Mediterranean region: responses and policy options. In Titus JG (Ed) *Changing climate and the coast, vol 2: Western Africa, the Americas, the Mediterranean basin, and the rest of Europe*, pp 115–125
- Sestini G (1992) Implications of climate change for the Nile delta. In: Jeftic L, Milliman JD, Sestini G (eds) *Climate Change and the Mediterranean*. Environmental and Societal Impacts of Climate and Sea-level Rise in the Mediterranean Sea. Edward Arnold, London, pp 533–601
- Sharaf El Din SH, Khafagy AM, Fanos AM, Ibrahim AM (1989) Extreme sea level values on the Egyptian Mediterranean coast for the next 50 years. *International Seminar on Climatic Fluctuations and Water Management*, Cairo, p 15
- Shukri NM, Philip G, Said R (1956) *The Geology of the Mediterranean Coast between Rosetta and Bardia, Part II, Pleistocene sediments: Geomorphology and microfacies*. *Bulletin de l'Institut d'Egypt* 37:395–427
- Sneh A, Weissbrod T (1973) Nile delta: the defunct Pelusiac branch Identified. *Science* 180:59–61
- Stanley DJ (1988) Subsidence in the northeastern Nile delta: rapid rates, possible causes, and consequences. *Science* 240:497–500
- Stanley DJ (1990) Recent subsidence and northeast tilting of the Nile delta, Egypt. *Mar Geol* 94:147–154
- Stanley DJ (1997) Mediterranean deltas: subsidence as a major control of relative sea-level rise. *Bulletin Institut Oceanographique Monaco* 18:35–62
- Stanley DJ (2005a) Growth faults, a distinct carbonate-siliciclastic interface and recent coastal evolution, NW Nile Delta, Egypt. *J Coast Res* SI:309–318
- Stanley DJ (2005b) Submergence and burial of ancient coastal sites on the subsiding Nile delta margin, Egypt. *Méditerranée* 104:65–73
- Stanley DJ, Goodfriend GA (1997) Recent subsidence of the northern Suez canal. *Sci Corresp* 388:335–336
- Stanley DJ, Warne AG (1993a) Nile delta: recent geological evolution and human impacts. *Science* 260:628–634
- Stanley DJ, Warne AG (1993b) Nile delta: recent geological evolution and human impacts. *Science* 260:628–634
- Stanley DJ, Warne AG (1994) Worldwide initiation of Holocene marine deltas by deceleration of sea-level. *Science* 265:228–231
- Stanley DJ, Goddio F, Schnepf G (2001) Nile flooding sank two ancient cities. *Nature* 412:293–294
- Stive MJ, Roelvink JA, DeVriend HJ (1990) Large scale coastal evolution concept. In: *Proceedings 22nd coastal engineering conference ASCE*, New York, pp 1962–1974
- Toussoun O (1934) Les ruines sous-marines de la Baie d'Abuquir. *Bull Soc R Arch Alexandria* 29:342–352
- Warne AG, Stanley DG (1993) Late Quaternary evolution of the northwest Nile delta and adjacent coast in the Alexandria region, Egypt. *J Coast Res* 1:26–64
- Warne AG, Stanley DG (1995) Sea-level change as critical factor in development of basin margin sequence: new evidence from late Quaternary record. *J Coast Res Spec Issue* 17:240–321
- Warrick RA, Oerlemans J, Woodworth PL, Meier MF, le Provost C (1995) Changes in sea level. In: *Climate change 1995: the science of climate change*
- Woodworth PL (1990) A search for accelerations in records of European mean sea level. *Int J Climatol* 10:129–143
- World Bank (2007) *World Bank weighs sea level risks in poor areas*. <http://www.msnbc.msn.com/id/17150339>
- Zaghloul ZA, Elgamal MM, El Araby H, Abdel Wahab W (1999) Evidences of neotectonics and ground motions in the northern Nile Delta. In: Zaghloul ZM, Elgamal MM (eds) *Deltas-Modern and Ancient*. *Proceedings of Mansoura University, first international symposium on the deltas*, Egypt, pp 209–217