Dealing with Future Risks of Sea-Level Rise in the Nile Delta: Impacts and Adaptation Measures

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ABSTRACT

The Nile delta coastal zones have high economic, recreational and ecological importance, with large numbers of new and planned development projects are under consideration. Over 20 million people inhabit the Nile delta coastal areas, and the region accounts for about 40% of the country's agricultural production. The Fourth Assessment Report (AR4) of the Intergovernmental Panel on Climate Change (IPCC, 2007) declared the Nile delta one of three regions on earth that are most vulnerable to sea-level rise in particular the lower delta due to its relatively low elevation. Global sea levels have risen through the past 20th century. The Fifth Assessment Report (AR5) of the Intergovernmental Panel on Climate Change (IPCC, 2014) indicated that global sea-level will continue to rise at a rate very likely to exceed the rate of the past four decades. Although the impacts of sea-level rise are potentially large, the application and success of adaptation measures require more assessment and consideration. This paper presents a review of recent advances in prediction, impact and mitigation of future sea-level rise on the Nile delta of Egypt. Important processes are distinguished; main features of the state-of-the-art are presented, in addition to open essential questions are addressed.

Keywords: Nile-delta, Sea-level rise, Coastal inundation, Mediterranean, Impact assessment, Adaptation measures.

1. INTRODUCTION

Nowadays, low-elevation coastal zones worldwide below 10-m elevation contain approximately 10% of the world population (McGranahan, 2007). Egypt’s coastal-zones constitute a particularly important region from the economic, industrial, social and cultural points of view. In addition to increased tourism activities, a substantial move towards building new industrial complexes is currently under-development. The Nile delta accommodates nearly half of the country’s industrial activity and about 40% of its agriculture production. The wetlands of the Nile delta represent about 25% of the total area of wetlands in the Mediterranean region and produce nearly one-third of the country's fish catch (see Fig. 1).

The Nile delta coastline is located along the south-eastern coast of the Mediterranean Sea. The Mediterranean basin is almost completely enclosed by land with an average water depth of 1500 m and the deepest measured point is 5267 m. The Mediterranean comprises two deep basins: the western and eastern (see Fig. 1). Tides in the Mediterranean are very limited because the Mediterranean is a nearly closed basin with a narrow link to the Atlantic Ocean. For example, the tidal range typically varies from 40 cm to 60 c m at Alexandria.

The Nile delta coastal zone is vulnerable to sea-level rise (SLR) because the region is characterized by relatively low land elevation, which leaves it exposed to rising sea levels. In addition, the Nile delta suffers from local land subsidence that magnifies the effects of rising seas. Maxwell (2008) reported that rates of land subsidence of the Nile delta could reach 5 mm/year and by the end of this 21st century a projected sea incursion could reach 30 km inland in the north-eastern Nile delta.

Similar to other deltaic areas worldwide, the Nile delta is exposed to shoreline changes resulting from erosion and accretion, land subsidence, and SLR resulting from present and future climate change. Potential impacts of SLR on the delta may include increased coastal erosion, overtopping of coastal defenses and increased flooding events, damage to urban centers, retreat of barrier dunes, decreased soil moisture, increased soil and lagoon water salinity, and decreased agriculture and fisheries productivity (MSEA 2001).

Hence, it is important to adapt to SLR in the Nile delta coastal zone not because there is expected threats, but because there are opportunities to avoid adverse impacts by acting now. Such consequences can be avoided by implementing measures in anticipation of SLR. This paper deals with future risks of SLR on Nile delta coastal zone and identifies anticipatory and adaptation options that may be appropriate today in spite of current uncertainties. The paper is arranged as follows. The Nile delta coastal zone is described in section 2. Present and future trends of global SLR are summarized in section 3. Vulnerability of the Nile delta to coastal inundation is discussed section 4. Potential impacts of SLR on the Nile delta coast are presented in section 5. Adaptation measures to SLR are discussed in section 6. Finally, concluding remarks are presented in section 7.

Figure 1: Satellite images of the Mediterranean Sea (top) and the Nile delta (bottom). Source: Google Earth.

2. THE NILE DELTA COASTAL ZONE: RESOURCES AND PROBLEMS

The Nile delta coastal zones have high economic, recreational, ecological, and aesthetic importance. There are huge numbers of new and planned development projects along this zone. Like many other deltas, the coastal zone of the Nile delta has been exposed to extensive changes caused by both natural and anthropogenic influences. Natural factors affecting the Nile delta coast include coastal processes, tectonic activities and climate-induced SLR (e.g., Stanley and Warne 1993). Coastline erosion impacts the national economy by affecting coastal roads, buildings and causes inundation of agriculture land.

2.1 Background Information

The Nile delta, which has generally flat topographic features, occupies an area of 23,284 km^2 that represents about 2.3 % of Egypt’s area. Its apex located, about 165 km upstream, at Cairo at an elevation of +18 m above mean sea level. It is heavily populated with densities up to 1600 inhabitants per square km and hosts about one third of Egypt’s 91 million populations in the 2016 census. The delta coast extends from Alexandria in the west to Port Said in the east, with a total length of about 240 km.

The delta’s coast consists of sandy and silty shores of varying lateral configurations, depending on the outlet location of the Nile' old branches. The delta coastline has two promontories, Rosetta in the west and Damietta in the east with a hump at Burullus and concave between them. There are three brackish lakes connected to the sea: Idku, Burullus, and Manzalla. In addition, there are five harbors located on the coast: Idku fishing harbor, New Burullus fishing harbor, Damietta commercial harbor, El Gamil fishing harbor, and Port Said commercial harbor. Also there are two main drains discharging their water directly to sea, namely: Kitchener and Gamasa. The delta beach and its contiguous coastal flat are backed partially by coastal flat, dunes or by brackish lagoons.

Coastal wetlands in the Nile delta are nearly parallel to the coast and vary in size from small lakes to large lagoons. These wetlands from west to east are: lake Maryut (50.2 km^2); lake Ghalyoun (1.8 km^2); Idku lagoon (63.0 km^2); Burullus lagoon (469.8 km^2);

Manzala lagoon (790.5 km^2); and Port Fouad lake (51.6 km^2)]. The water depth varies from 0.5 to 3.0 m, and they are separated from the sea by long sand barriers that vary in width from 0.5 to 10 km. These lagoons are linked to the Mediterranean by narrow inlets, while most of them are artificially protected by jetties (e.g., Frihy, 2010).

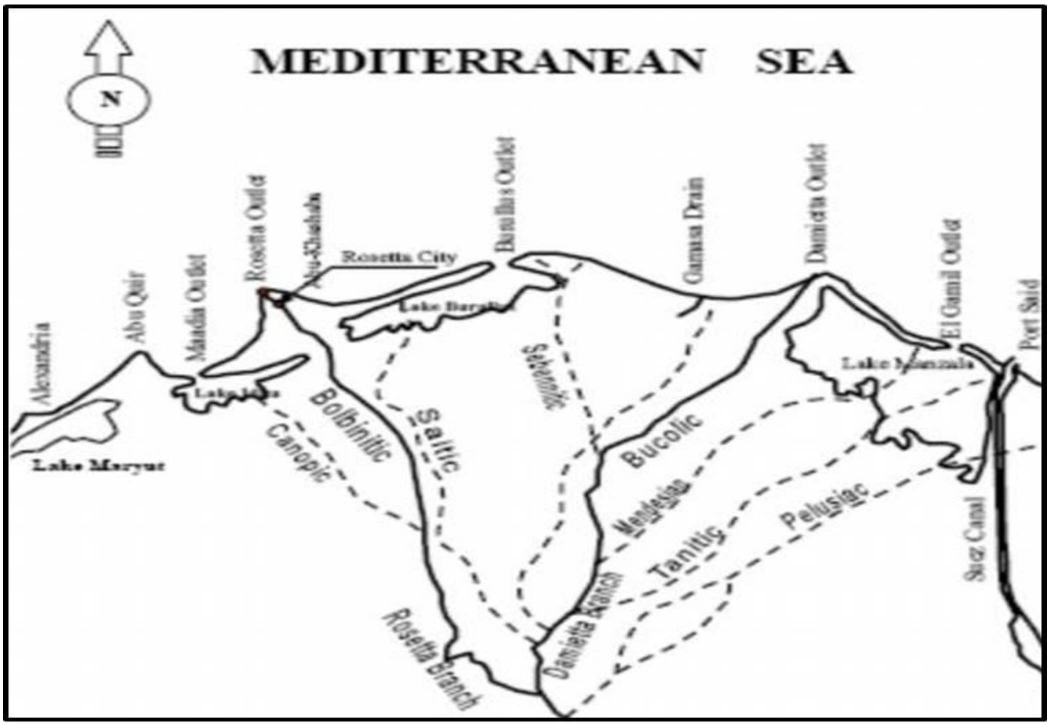

Figure 2: Map for the Nile delta and old Nile branches

The Nile delta formed in relatively recent geological age (Sestini, 1992). It was built up by the alluvium, due to sedimentary processes, carried by the old seven active branches (see Fig. 2) of the Nile as they crossed the delta (Said, 1981; El Askary and Frihy, 1986; Coutellier and Stanley, 1987; Fanos, 1995). Far along, those distributaries had silted up and replaced by the present two main branches: Rosetta and Damietta. The old Sebennetic branch, that crossed the middle of the delta, has formed the central hump of the delta that reaches its maximum east of the Burullus lagoon (Orlova and Zenkovich, 1974). The headland has been exposed to erosion since the termination of this old branch.

The northern Nile delta coastal region comprises six administrative governorates namely (from west to east): Alexandria; Behaira; Kafr El-Sheikh; Dakahlyia; Damietta; and Port Said (see Fig. 3). The main land cover in the northern Nile delta governorates comprises cultivated land, built-up area, wetlands, and undeveloped areas (see Fig. 4). The map shows the area of land uses in the coastal governorates of the Nile delta.

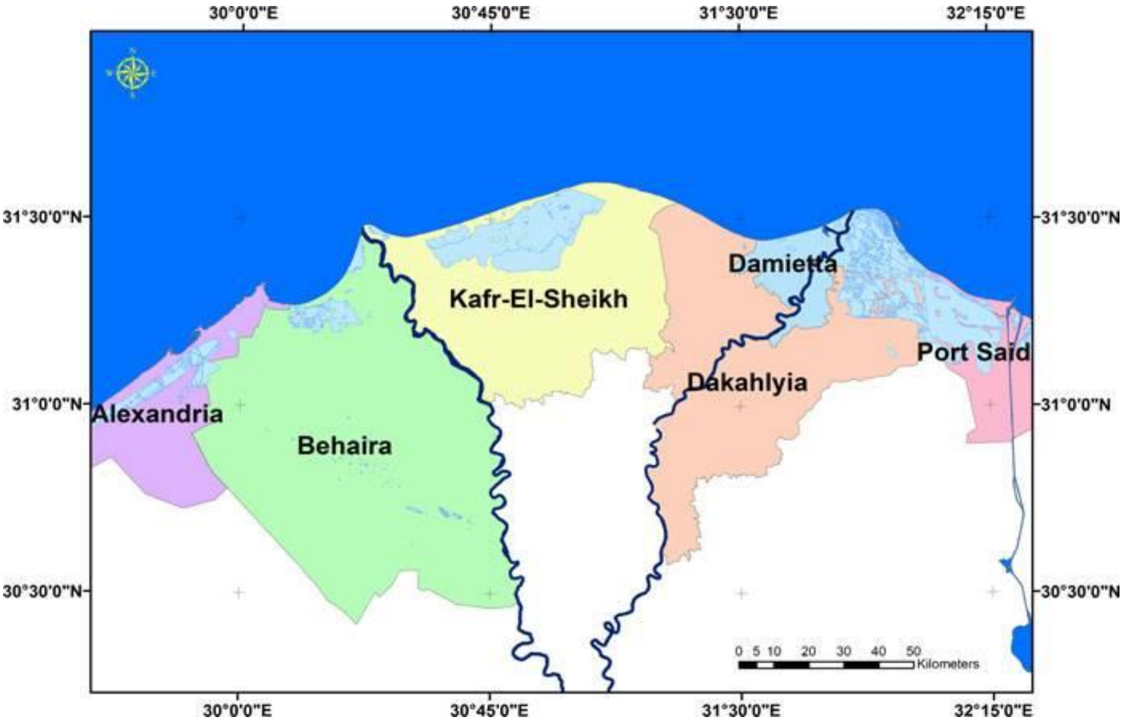

Figure 3: Administrative coastal governorates in Nile delta.

Source: Hassaan and Abdrabo (2013).

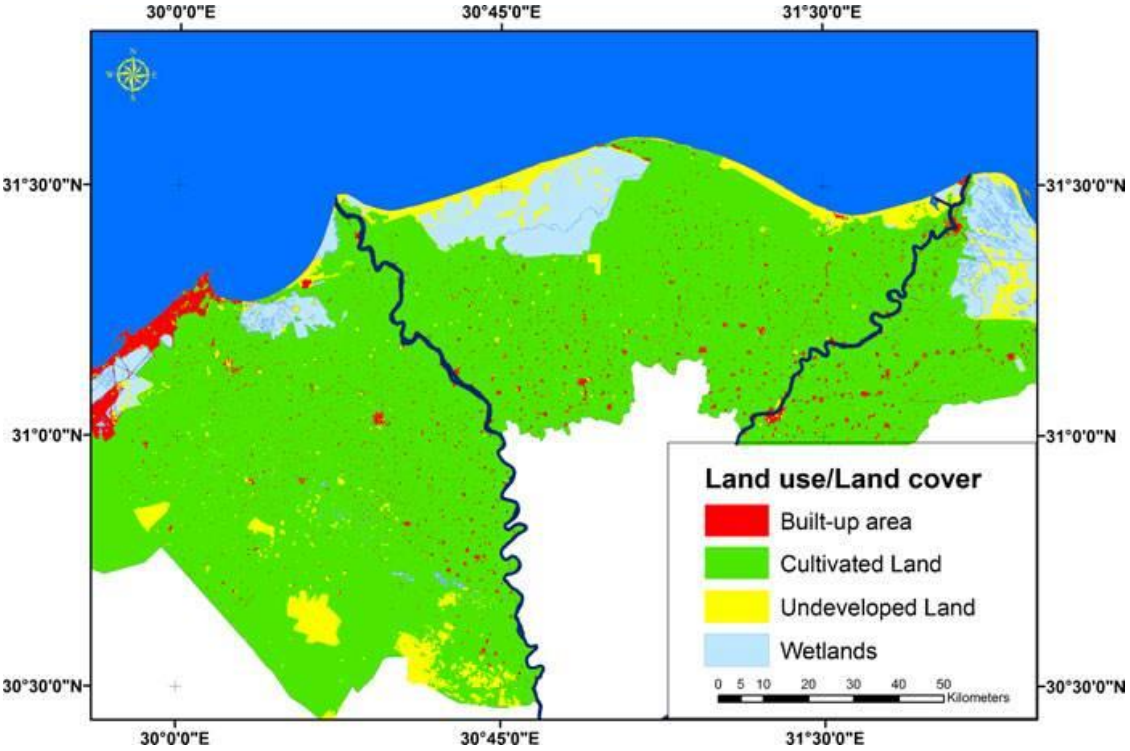

Figure 4: Land use in the Nile delta coastal governorates.

Source: Hassaan and Abdrabo (2013).

2.2 Land Topography

The topography of the coastal plain of the Nile delta varies from high-elevated to low-lying areas. The land topography of the delta and Alexandria region is shown in Fig. 5. The topographic features reveal a degree of vulnerabilities to sea incursion due to SLR. The coastal plain of the Nile delta has a large area between zero and 1 m elevation, with parts below sea-level. The topography of the delta indicates that most of the 50 km wide coastal zone is located below the 2 m contour. The coastline is protected against sea flooding by a sand belt formed by the sediment discharge of the Nile branches. This protective sand belt has been facing rapid erosion since the construction of the High Dam in the 1960's.

Regions below mean sea-level include the delta coastal lagoons, that form a transition zone between land and the sea, in most places separated from the sea by narrow and low-lying sand barriers (Frihy, 2003). Areas above 3 and 4 meters lie within the coastal dunes at the backshore of Abu Quir Bay, Gamasa, and in the southern part of the lower delta coastal plain, corresponding to about 35 km from the shoreline. 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 about 28% of the coastal plain.

The Nile delta coastal plain has a total area of 13610.41 km^2 (Frihy et al, 2010). He categorized topographic features based on their elevations from mean sea-level into the following (see Fig. 6):

1- Low-lying vegetated lands down to -3 m below sea-level (700 km^2; 5.1%)
2- Wetlands, fish farms, lakes and ponds, Zero to -3 m (2261.1 km^2; 16. 61%)
3- Zones between 0 and 1 m (3806.9 km^2; 27.97%)
4- Vegetated lands exist at 1-2 m (2903.8; km^2; 21.37%)
5- Vegetated area between 2-3 m (1955.6 km^2; 14.37%),
6- Desert land between 3-4 m (1558.1 km^2; 11.45%),
7- Coastal dunes (73.75 km^2; 0.54%)
8- Carbonated ridges (237.22 km^2; 1.74%).

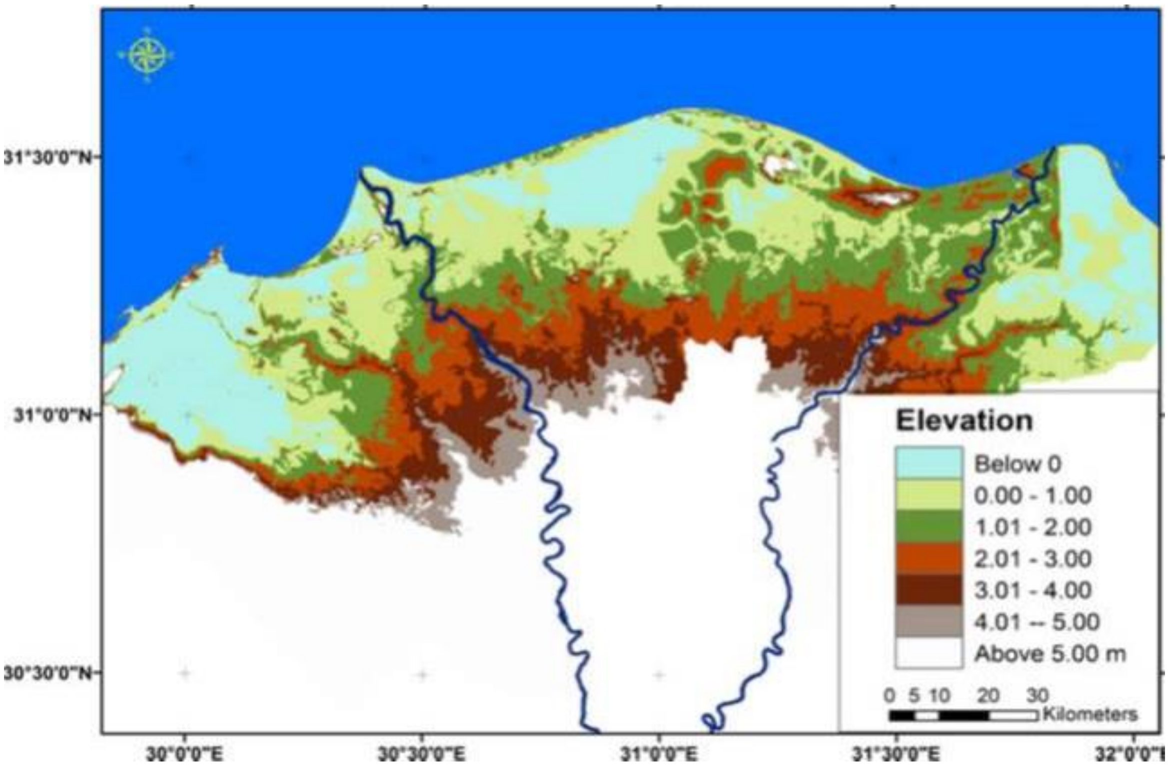

Figure 5: Land topography of the Nile delta coastal governorates.

Source: Hassaan and Abdrabo (2013)

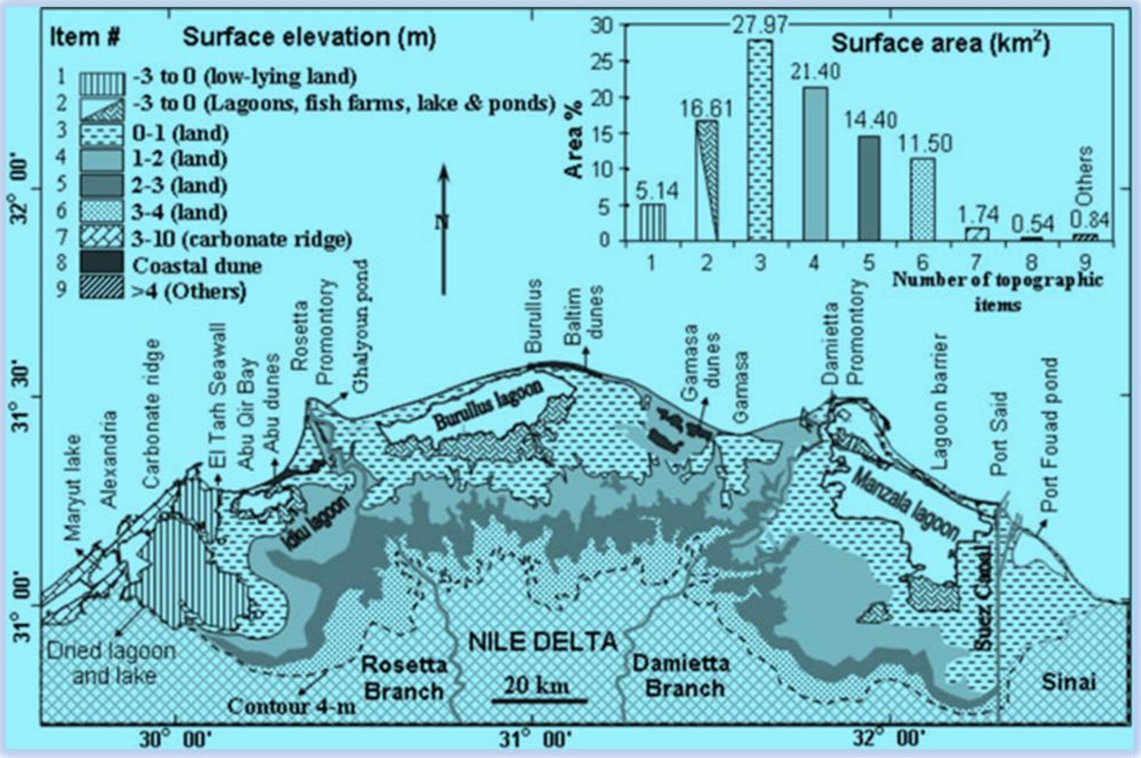

Figure 6: Major topographic features of the Nile delta and Alexandria.

Figure adapted from Frihy et al. (2010).

2.3 Phenomenological Description of the Nile Delta Coastal Processes

The delta's coast between Alexandria and Port Said comprises different coastal sectors. Different zones have been analyzed and compared according to the following aspects; coastal processes**:** to identify the coastal processes, the nature of the shoreline and the wave climate; and shoreline stability: to identify the shoreline stability and expected erosion or deposition of the shoreline, including quantitative estimates of changes per year (Eldeberky et al, 2002).

2.3.1 Shoreline characteristics

The shoreline from Abu Quir to east of Port Said has a gentle slope varying from 1:50 to 1:100 and a smooth wide beach face. The Nile delta shoreline is backed by coastal dunes or by large lagoons (from west to east: Idku, Burullus and Manzala). The western side of the delta is bounded by the rocky headland of Abu Quir, while the eastern limit is formed by Tineh beach. The sediment distribution along the Nile delta coast is shown in Fig. 7. The distribution indicates a decrease of the median grain size from Rosetta mouth (0.34 to 0.40 mm) towards Idku inlet mouth (0.12 to 0.23 mm).

The sediment distribution along the western site of the Dameitta promontory indicates that the median grain size is between 0.25 to 0.35 mm. The sediment distribution along the western site of the Dameitta promontory indicates that the median grain size is between 0.13 to 0.20mm. The shoreline extending east of the Dameitta Promontory is dominated by a spit that grew due to the transport of eroded sediments from the promontory towards the east by longshore currents. The coastline downcoast of the Dameitta spit is composed of sandy coastlines.

The sediments along the eastern side of the promontory are relatively fine with the median grain size between 0.15 to 0.20 mm. The shoreline extending east of Port Said is composed of sandy coastlines. The shoreline profiles in the area are characterized by a steep slope near the shoreline to –2.0 m from where a flatter shore-face extends to a depth of about –5.0 m at approximately 3 km from the coastline. The sediments along the eastern side of the promontory are fine with the median grain size about 0.20 mm.

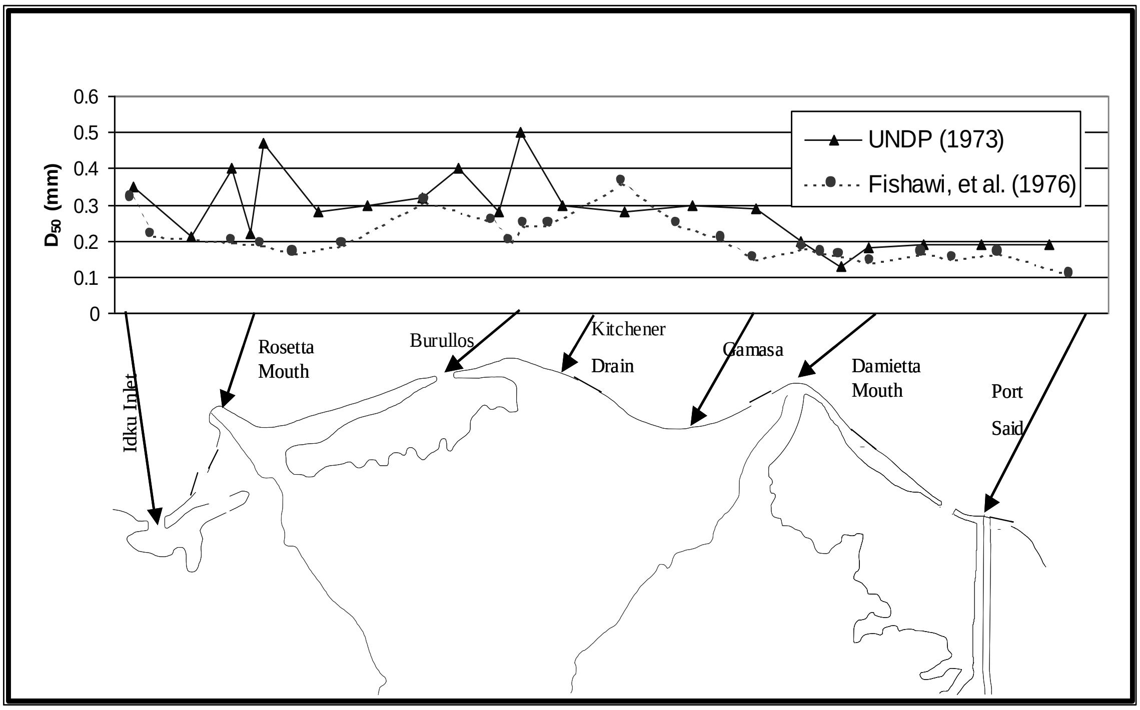

Figure 7: Foreshore grain size from Rosetta mouth to Port Said. Source: Tetra Tech (1984)

2.3.2 Coastal processes

Littoral drift and sediment transport

The Rosetta Promontory has been subject to continuous erosion since the beginning of the twentieth century. Two revetments were constructed by the Shore Protection Authority (SPA) to control the shoreline recession at the Rosetta Promontory. The eastern revetment is 3500 m long and the western revetment is 1500 m long. The shoreline had retreated and had reached the western revetment in 1990 (two years after construction). SPA is planning to extend the shore protection work to the west of the existing western revetment.

The substantial erosion at the Rosetta Promontory is associated with accretion on either side, along the flanks of the promontory. This represents a simple pattern of erosion, extending from the tip of the promontory near the river mouth, with the eroded sand moving along the shore and transported by waves and longshore currents, both eastwards and westwards (El Sayed, 1997). The predominant longshore current southwest of the Rosetta Promontory is directed towards the south. The southward longshore current transports sediments from the area between the west revetment and 3 km south of the Rosetta Promontory resulting in shoreline recession. Sediments transported by southwest longshore currents are deposited southwards inside the Abu Quir Bay. It should be noted that the main factor causing erosion of the Rosetta Promontory is the wave action. This is responsible for the littoral drifts, both eastward and westward.

Tetra Tech (1984) developed a sediment budget for the Nile Delta coastline. Erosion of the Rosetta Promontory was estimated to supply approximately 2.0 million m^3/year to the littoral zone, of which about 0.8 million m^3/year is estimated to be transported into the Abu Quir Bay. Radi (1998) used the LITPACK program developed by DHI to estimate the net longshore sediment transport rates southwest of the Rosetta Promontory. The net westerly transport was estimated to be 1.0 million m^3/year at a profile 3 km southwest of the promontory and 0.6 million m^3/year at a profile 12 km southwest of the promontory. These estimates are expected to be more accurate than Tetra Tech’s estimate because they are based on detailed modelling.

The predominant longshore currents east of Burullus are directed towards southeast. The southeast longshore current transports sediments from Burullus area resulting in shoreline recession. Sediments transported by these currents are deposited along the shoreline southeast Burullus area. Tetra Tech (1984) used empirical relations to estimate the longshore sediment transport. The gross transport rate at the proposed location is estimated to be one million m^3/year. The net transport rate is calculated to be 0.8 million m^3/year in the southeast direction. The results show large gradients in the net longshore sediment transport along the coastline indicating relatively unstable coastlines.

The predominant longshore current west of the Dameitta Promontory is directed towards the western direction. The southwest longshore current transports sediments from the Ras El Bar Peninsula resulting in shoreline recession. Sediments transported by the western longshore currents are deposited northeast of the Dameitta Harbour. The shoreline southwest of the Dameitta Harbour is facing north-northwest nearly perpendicular to the predominant wave direction. The direction of the longshore currents is generally eastward and may reverse (i.e., westward) depending on the incident wave angle. Estimates by Tetra Tech (1984) indicate that the gross longshore transport potential is about 1.0-million m^3/year and the net longshore transport potential is nearly zero. Although the net longshore transport is very small, siltation of the access channel occur because of the large value of the gross longshore transport.

The coastal processes east of the Dameitta spit are complex (Abul-Azm and Rady, 1999). The direction of the littoral drift along the eastern side of the promontory can be inferred from the morphological features and/or the aerial photographs. Tetra Tech (1984) analyzed aerial photos to infer the pattern of the littoral drift along the Nile Delta coast. The pattern shows a divergence of drift from the Dameitta promontory towards the East. A local reversal in the littoral drift direction is seen east of the Dameitta spit with the predominant longshore currents moving westward. This reversal results in transport convergences and associated shoreline accretion in the proximity of Dameitta spit region. A local reversal is also observed farther to the east where the predominant longshore currents are eastward. Estimates of gross and net longshore sediment transport at the proposed site are 1.0 and 0.5 million m^3/year (Tetra Tech, 1984). Data of cross-shore profile up to 2 m indicated slight erosion east of the spit. Data of cross-shore profile up to 6m indicated accretion along the entire coastal stretch between Dameitta and Port Said.

Sogreah (2000) used satellite images to estimate that 0.7 million m^3/year is being transported eastward along the Tineh bay East of Port Said. It should be noted that the access channel of Suez Canal bypass is exposed to substantial siltation. At present, the reported values are 10 million m^3/year (approach channel is 19.5 km long, 250 to 500 m wide, and 21.5 m deep).

Wave climate

The significant wave heights offshore the Nile Delta were estimated by Tetra Tech (1984) using wave hindcast. Hindcast significant wave heights were as follows: Hs = 5m for 10 years return period, Hs = 6 m for 20 years return period, Hs = 7.3 m for 50 years return period. The predominant wave direction is NW with maximum significant wave height in the offshore regions of about 5 to 6 m. Rakha et al. (1999) used the nearshore directional wave model (NSW) of DHI to predict the offshore wave conditions corresponding to the wave data provided at a nearshore location. The model was applied to predict the nearshore wave conditions in the vicinity of the Dameitta promontory of the river Nile. The significant wave height distribution shows that the nearshore wave condition is moderate at Cape Burullus as compared to Burulus headland and the Dameitta area because of the shoreline orientation.

Generally, the high storm waves approach from the NW-NNW during the winter. Local bathymetry and shoreline orientation affect wave transformation in the nearshore areas. The shoreline alignment downcoast the Dameitta spit faces northeast. The local bathymetry indicates a relatively wide surf zone (-5.0 m water depth is about 2km offshore; -10.0 m water depth is about 11 km offshore). Wave refraction and depth-induced wave breaking have strong effects on the nearshore wave transformation and wave energy decay.

Sogreah (2000) analyzed the data obtained by the UKMO model at 22 m water depth (31.5°N, 32.3°E). The records consisted of five years of data, covering the period from May 1995 till April 2000. The deduced wave parameters are the significant wave height, wave period and mean wave direction every 6 hours. The data showed that the highest waves come from 292.5°(NW) with an average significant wave height of 2.8 m and a mean wave period of 10 sec. Sogreah estimated the nearshore wave conditions for the area East of Port Said using a third generation fully spectral wave model SWAN. The model results indicated that waves from all offshore directions decrease in height as they propagate in the nearshore regions of east Port Said. This energy decay is a result of the sheltering effect of Port Said breakwater and the shoreline orientation.

2.3.3 Shoreline stability

Tetra Tech (1984) used maps and photographs to study the shoreline changes along the Abu Quir Bay. They mentioned that the coastline was retreating by a rate of 3m/year to the west of the Idku inlet and advancing by 2 to 3 m/year to the east of the Idku inlet. Tetra Tech (1984) compared the bathymetric surveys between 1971 and 1984. The report concluded that the bed dropped by an average of about 1m at depths between 1.0 to 6.0 m near Idku inlet. El-Sayed (1997) studied the shoreline changes of the Rosetta Promontory. He analyzed sixteen surveys monitored during the period (1988 to 1995). He concluded that erosion is occurring at the Rosetta Promontory and up to a distance 3 km southwest of the promontory. An erosion/accretion variability is occurring west of this sector, i.e., between 3 and 14 km southwest of the promontory. Accretion is the general trend of this fluctuation, which occurs between the shoreline and water depths greater than 4 m.

Changes to the shoreline of the Dameitta Promontory are similar to those of the Rosetta Promontory with a general trend of shoreline recession during the 20th century. The shoreline of the Westside of the promontory, known as Ras El Bar peninsula, retreated at an average rate of 35 m/year between 1900 and 1941. A jetty was constructed on the western side of the branch to protect the shoreline. Although this jetty stabilized the northern part of Ras El Bar, the rest of the coast continued to erode at a lesser rate of 10m/year. This rate was also influenced through the construction of other protective works including two groins and some detached breakwaters.

Fanos (1995) provided the erosion/accretion pattern along the Nile Delta coastline and showed that the coastline of the Nile Delta can be divided into 9 physiographic units (see Fig. 8). The shoreline east of Burullus area is classified as stable coastline with accretion and erosion pockets. Analysis of the coastal process west of the Dameitta Port showed that, although the gross longshore sediment transport is about one million m^3/year, the net longshore sediment transport is found to be negligible. These will result in a dynamically stable coastline although it may be exposed to seasonal erosion or accretion. Fanos (1995) classified the shoreline at this site to be stable with accretion and erosion pockets (see Fig.8). Therefore, the coastline of the proposed site seems to be dynamically stable with accretion and erosion pockets.

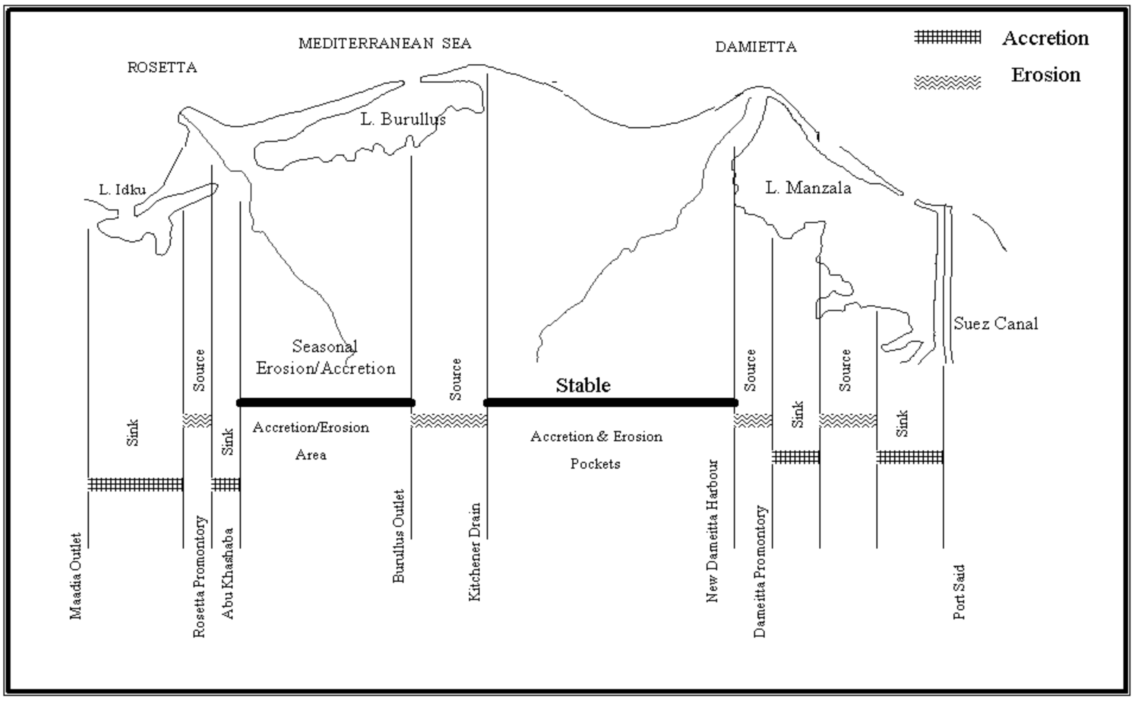

Figure 8: Erosion and accretion pattern along the Nile delta coast. Source: Fanos (1995)

2.4 Coastal Protection Works along the Nile Delta

The Nile delta is considered wave- and current-dominated coastal environment. The degree of exposure to wave action varies with coastline orientation with respect to the incident wave direction. The dominant waves are from the N-W (81%) with 14% from the N-E sector and 5% from the S-W (see Fig. 7, adopted from Frihy, 2003; Frihy et al, 2010). The maximum significant wave height observed west of the Rosetta promontory is 5.4 m from West-North-West direction, whereas the average, wave height and period are 1.2 m and 5.6 sec, respectively.

The coastline of the Nile delta and Alexandria can be divided into a series of sections called littoral cells including sources/ sinks of sediment (Frihy et al. 1991; Frihy and Lotfy, 1997). Previous studies along the nearshore zone of the Nile delta and Sinai coast have identified self-contained sub-cells. These littoral sub-cells are Abu Quir sub-cell, Rosetta Sub-cell, Burullus Sub-cell, Damietta Sub-cell and Port Said sub-cell. The primary sediment sources for each littoral sub-cell are the eroded headlands that supply sand to the coast.

The erosion/accretion pattern along the Nile delta coastline reflects the natural processes of wave induced longshore currents and sediment transport. Seasonal variability of wave approach produces converging and diverging current pattern along the delta coast. Frihy (2003) determined the degree of vulnerability of the Nile delta coastal plain to SLR and erosion processes by analysing the shoreline geomorphology, backshore topography, erosion/deposition events, subsidence, coastal processes, and protection structures along the Nile delta coastline. According to Frihy et al. (2010), “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 shown in Fig. 9. Subsequent to the construction of the High Dam in the Nile River basin in 1964, sand supply to the delta coast from the Nile has terminated and wave-driven longshore currents continued to transport beach sand to the east, resulting in a major adjustment of the Nile Delta coastline. As a result, extensive beach erosion occurs along the outer margins of the Nile delta-promontories. On the other hand, accretion has happened mostly in the saddles or between these promontories (e.g., Frihy et al., 1991; Inman et al., 1992; Frihy and Komar, 1993).

Since 1980, extensive engineering structures were constructed along the Nile delta coastline to reduce the effects of beach erosion, including groins, detached breakwaters, revetments, jetties, and seawalls. For example: Rosetta seawall shore-parallel structures, Burullus-Baltim detached breakwaters, Burullus seawall, Damietta seawall, and El Gamil detached breakwaters (Fanos, 1995; Frihy, 2003; Frihy et al., 2004; Dewidar and Frihy, 2008). Moreover, the quarry stone barrier in Abu Quir bay was reinforced to act as a seawall by elevating its crest to 2.5 above mean sea-level to combat possible SLR and wave overtopping.

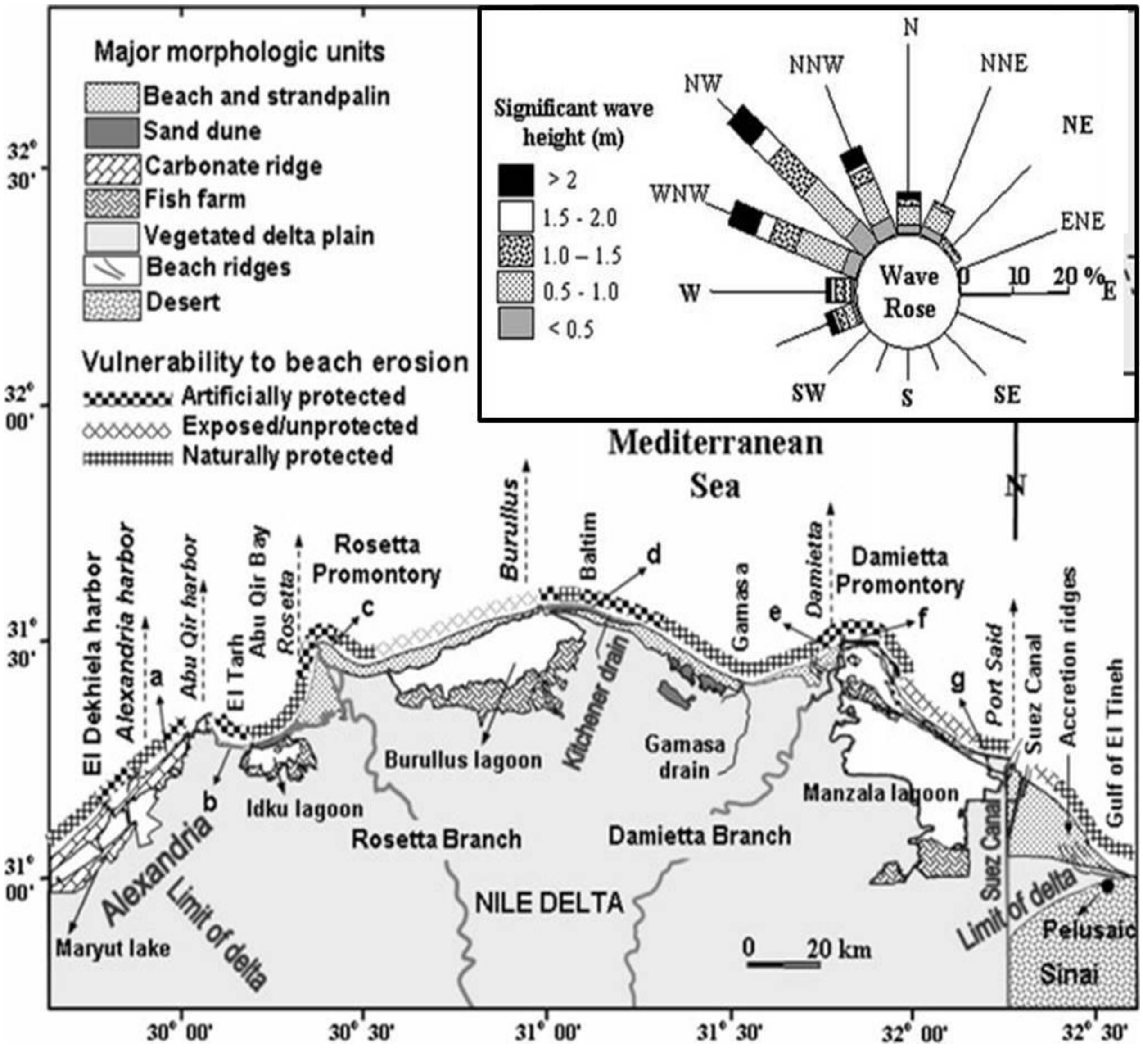

Figure 9: Map of the Nile delta coastline showing main geomorphologic units, coastal sectors, and wave rose at Abu Quir Bay. Figure adapted from Frihy (2003).

Alexandria shoreline is relatively stable since the majority of the coastline is hard rock which constitutes the coastal limestone ridge (Frihy et al., 2004). The Corniche highway built on a vertical wall (20-km long) was constructed to stabilize Alexandria' beaches against erosion. Moreover, breakwaters were constructed to protect four harbors at El Dekhiela, Alexandria (Western and Eastern harbors), and at Abu Quir (Fig. 7). In 2005, two submerged shore-parallel breakwaters were constructed along Mandara-Asafra to mitigate the effects of wave overtopping that impact the low-lying coastal road (2.4 m elevation) during winter storms.

At the Rosetta promontory, because the erosion rates were high at the outer margin, two seawalls extend alongshore to a length of 1.5 km and 3.35 km at the western and eastern shores, respectively, were constructed between 1988 and 1991. They encompass artificial embankments shielded by Dolos concrete units weighing 4–7 tons. The seawalls height is 6.75 m above mean sea level with a width varying from 48 to 70 m. As a result, shoreline retreat is terminated at the tip, which originally was 106 m/year prior to construction of the seawall (Frihy and Komar 1993). However, wave run-up bypassed to frequently flooding the low-lying (0-1 m) area behind the western seawall. Additionally, two series of groins were constructed to control erosion at the eastern and western edges of the seawalls. These include: five groins constructed east of the Rosetta estuary in 2003, their length ranging between 400 and 500 m seaward, spaced 800–900 m apart and another ten short groins (80–150 m long) with spacing between 500 and 600 m were constructed in 2005 at the lee side of the western seawall (Frihy et al., 2008).

Further east, the Burullus-Kitchener drain sector (10 km long) is artificially protected by a series of shore-parallel detached breakwaters and nine short groins that were built between 1993 and 2007. 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 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 (Frihy, 2010).

At Damietta promontory, a seawall of 6-km-length has been constructed, using 4–7 ton Dolos similar to those at Rosetta, to protect the tip east of the Nile mouth. Another series of eight shore-parallel breakwaters were built during 1991–2002 along Ras El Bar resort; to combat beach erosion that was 10 m/year before construction (Frihy et al., 2004).

3. SEA-LEVEL RISE

The Intergovernmental Panel on Climate Change (IPCC, 2014) has confirmed in its Fifth Assessment Report (AR5) that "Warming of the climate system is unequivocal, and since the 1950s, many of the observed changes are unprecedented over decades to millennia. The atmosphere and ocean have warmed, the amounts of snow and ice have diminished, and sea level has risen". Global average sea-level has risen at an average rate of 1.8 mm/year over the period from 1961 to 2003 and at an average rate of about 3.1 mm/year from 1993 to 2003 (UNFCCC, 2004). If the increased rate of SLR reflects an increase in the underlying long-term trend, then the continued growth of greenhouse gas emissions and associated global warming in addition to the rapid breakup of ice-sheets in Greenland and West Antarctic could lead to high values for SLR by the end of this century.

3.1 Global Sea-level Change

Global sea-level are controlled by two main factors that contribute to SLR. Firstly, thermal expansion of sea water due to ocean warming. Secondly, input to water mass from land ice melt and land water reservoirs (IPCC, 2007). The Fourth Assessment Report (AR4) of the Intergovernmental Panel on Climate Change (IPCC) projected that global sea-level will rise by up to 59 cm by the end of the present century (2100) due to ocean warming and glaciers melting.

The evolution of global mean sea-level over the 20th and 21st centuries is shown in Fig. 10. The red curve is calculated based on tide-gauge measurements. The black curve represents the altimetry record zoomed over the 1993–2009 time span. Projections for the 21st century are also shown where the shaded light blue zone represents IPCC-AR4 projections for the greenhouse gas emission scenario. Bars represent semi-empirical projections [red bar: (Rahmstorf, 2007); dark blue bar: (Vermeer and Rahmstorf, 2009); green bar: (Grinsted et al., 2009)]. It should be noted that, as mentioned clearly in the IPCC Report the quantitative AR4 scenarios do not provide an upper limit on sea-level rise during the present century due to uncertainties regarding the large ice sheets in Greenland and Antarctic.

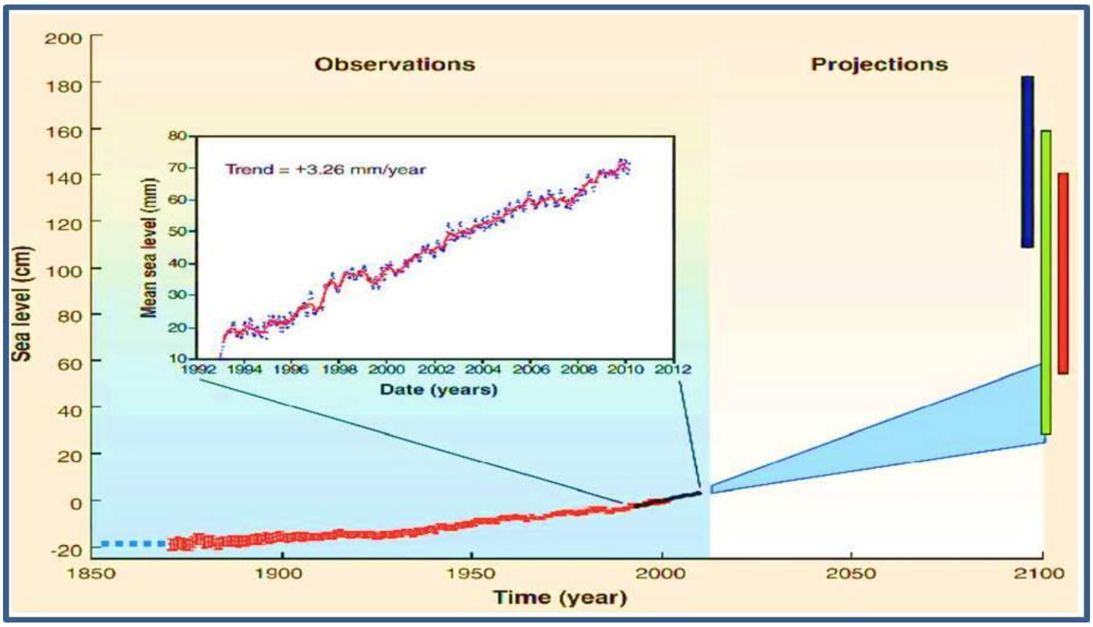

Figure 10: Evolution of global mean sea-level over the 20th and 21st centuries.
Source: Nicholls and Cazenave (2010).

IPCC estimates have been debated in the literature since 2007, and much higher estimates of future SLR have been published. A number of authors have suggested that the reported figures for the possible magnitude of SLR in the IPCC-AR4 underestimate the range of potential SLR during the twenty-first century (Nicholls, 2011). A graphical summary of the range of IPCC-AR4 sea-level-rise scenarios during the present 21st century ranges from a minimum of 0.2 m to a maximum of 2.15 m (Rahmstorf, 2007; Pfeffer et al., 2008; Horton et al., 2008; Grinsted et al., 2009; Vermeer and Rahmstorf, 2009; Jevrejeva et al., 2010), as shown in Fig. 8. It is mentioned that the SLR may well exceed one meter by the end of this century (Cazenave and Lovel, 2010).

The scientific community in Copenhagen Conference (March 2009) on climate change recommended that the projected sea-level rise during the 21st century may be much higher "up to 1-2 m by 2100", which will put the highly populated coastal regions and the fertile deltas, such as Nile, Po, Rhone, at risk of partly disappearing into the Mediterranean Sea (MEDSEC, 2009). Moreover, numerous observations have reported worldwide retreat of glaciers and small ice caps during recent decades, with an appreciable acceleration of this retreat during the 1990. Observations of decrease in mass of polar ice-sheets (Velicogna, 2009; Allison et al, 2009) suggest future (SLR) value of 1 m or more by 2100 (Pfeffer et al, 2008; Lowe et al, 2009).

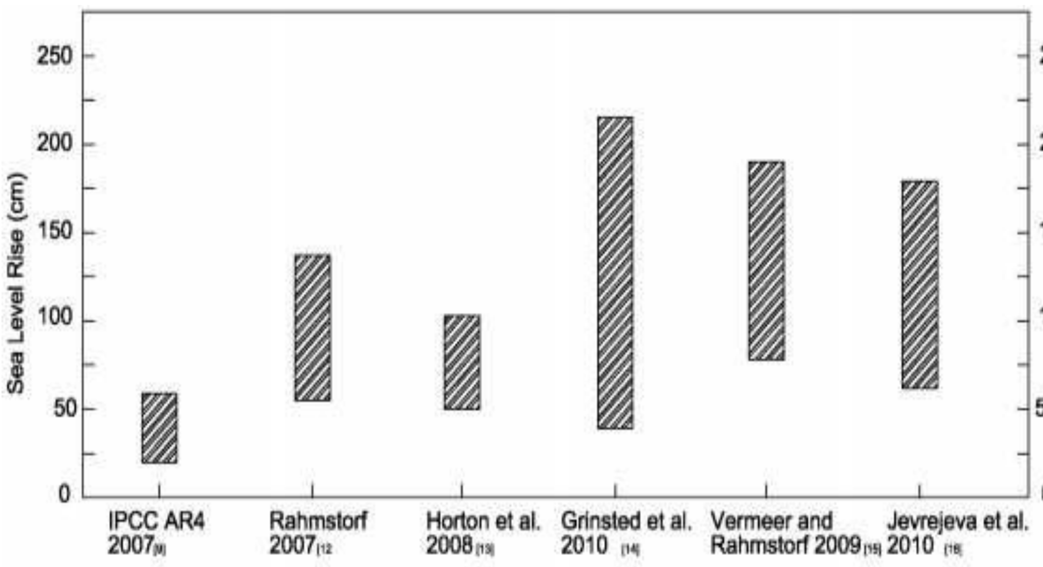

Figure 11: Summary of SLR estimates for the 21st century compared to the IPCC (AR4). Source: Rahmstorf (2010)

These new results have found wide recognition in the scientific community, as recent broad-based assessments show (Rahmstorf, 2010). The rapid changes observed in polar regions suggest that the ice sheets respond to current warming on much shorter time scales than previously anticipated (IPCC, 2007). However, it is unknown whether these processes will continue into the future, resulting in a partial collapse of the ice sheets after a few centuries, or whether a new equilibrium will be reached (Vaughan, 2008). The largest unknown in future SLR during the next decades is the behavior of the ice sheets. Despite large variations in SLR model predictions, depending on the IPCC modeling parameters and scenarios, these studies yield SLR between ~30 and 180 cm by 2100 (Fig. 11). The upper limit of these estimates is well above IPCC-AR4 SLR (Nicholls and Cazenave, 2010).

In this respect, the Mediterranean Sea is a semi-closed basin with the Strait of Gibraltar representing the only significant link between it and the Atlantic Ocean (Gomez, 2003). Recent attempts to estimate future changes in the Mediterranean sea-level during the 21st century proposed a rise in the range of 28.5 and 48.7 cm up to the year 2099 (Chust et al, 2010). Similarly, Tsimplis et al. (2008) suggested that the upper-limit of SLR in the Mediterranean would be 35 cm. While, Bosello et al. (2012) suggested that it would be ranging between 29.2 and 88 cm by the year 2100. Accordingly, these different SLR projections, for the Mediterranean Sea, are in line with the IPCC range of SLR scenarios

Global mean sea-level rise will continue during the 21st century, very likely at a faster rate than observed from 1971 to 2010. Recently, the Fifth Assessment Report (AR5) of the Intergovernmental Panel on Climate Change (IPCC, 2014) indicated that global sea-level will continue to rise at a rate very likely to exceed the rate of the past four decades. This report suggests a higher value of SLR compared to results published in the earlier (AR4) report. In addition, IPCC-AR5 stated that “Changes in many extreme weather and climate events have been observed since about 1950. Some of these changes have been linked to human influences, including a decrease in cold temperature extremes, an increase in warm temperature extremes, an increase in extreme high sea levels and an increase in the number of heavy precipitation events in a number of regions”. Furthermore “Surface temperature is projected to rise over the 21st century under all assessed emission scenarios. It is very likely that heat waves will occur more often and last longer, and that extreme precipitation events will become more intense and frequent in many regions. The ocean will continue to warm and acidify, and global mean sea level to rise”.

3.2 Relative SLR

Anthropogenic processes, such as land subsidence due to oil and groundwater extraction, or reduced sediment supply to river deltas due to construction of dams often magnify local vulnerability associated with climate-related SLR. The magnitude of future SLR, the impacts on low-elevation coastal zones, and the adaptation capabilities remain undefined. Here, we review current knowledge on the magnitude and causes of contemporary SLR, examine future projections and their uncertainties, and discuss SLR impacts. These impacts are sensitive to how societies prepare for and adapt to SLR.

Relative SLR is the rate of sea-level changes at a specific location relative to a local land benchmark. It is composed of two contributions to global-mean change: the eustatic contribution (global changes in sea-level relative to a fixed point) and steric contribution (global changes in sea-level due to thermal expansion and salinity variations). Global-mean change is adjusted to account for regional and local processes, including vertical local land displacement, local sediment transport, isostatic adjustment (changes in the level of the land relative to a fixed point in the earth, possibly due to thermal buoyancy or tectonic effects), and sea-level responses to local and regional meteorological and oceanographic variations (Emery and Aubery, 1991; Church et al, 2001).

SLR impacts are a product of relative “or local” SLR rather than global changes alone (Nicholls, 2011). Relative sea-level change takes into account the sum of global, regional, and local components of sea-level change. The underlying drivers of these components are: i) climate change and changing ocean dynamics, and ii) non-climate uplift/subsidence processes such as tectonics, glacial isostatic adjustment, and natural and anthropogenic induced subsidence.

3.3 Tide-gauge Measurements of Mean Sea-Levels along the Nile Delta

The main data source of sea-level change over timescales of a few decades to century is tide gauge records, some of which date back to the early 18th century (e.g., Wöppelmann et al., 2008). It is well established that long term tide-gauge records can be used to monitor ongoing SLR (Hicks, 1972; Gornitz et al., 1982). An important issue in using this data source to estimate the climate related contributions to sea-level change is the correction of vertical land motion signals in tide gauge records.

Previous studies (e.g., El Fishawi and Fanos 1989; Sharaf El Din et al. 1989; Frihy, 1992) based on tide-gauge analysis indicates that Alexandria sea-level history has a moderate value ranging from 2 to 2.9 mm/yr. Frihy (2003) used tide gauge data recorded at Burullus, Alexandria and Port Said harbors to infer the relative SRL rates including land subsidence. The results, shown in Fig. 12, confirm that the mean sea-level at Burullus, Alexandria and Port Said has risen 1.0, 1.6 and 2.3 mm/year, respectively. Recently, Shaltout et al. (2015) analyzed a long time series of sea-levels at Alexandria Harbor from 1944 to 2006. The results, shown in Fig. 13, indicate two regimes: before the Aswan High Dam was built (1944-1963), sea-levels show a substantial rising trend of 5 mm/year; after the construction of the dam (1964-2006), the trend is milder at a rate of about 2 mm/year. Rate of land subsidence is directly related to thickness of sediment section, with highest values in the eastern part of Manzala lagoon. Stanley and Toscano (2009) noted that subsidence rates range from 0.9 to 4.3 mm/year, varying irregularly from west to east along the northern delta coast. Observations of the subsidence rate at Alexandria using permanent GPS (Wöppelmann and Marcos, 2012) show moderate values of -0.4 ± 0.2 mm/year. On the other hand, larger rates of subsidence were observed at the eastern part of the delta. Tide-gauge data showed that the rate of relative SLR is not evenly distributed along the delta and varies between 1.8 mm/year, in the western side, and 4.9 mm/year in the eastern side (Frihy et al, 2010). Syvitski et al (2009) analysed sinking deltas around the world due to human activities and reported that relative SLR for the Nile delta reaches 4.8 mm/year.

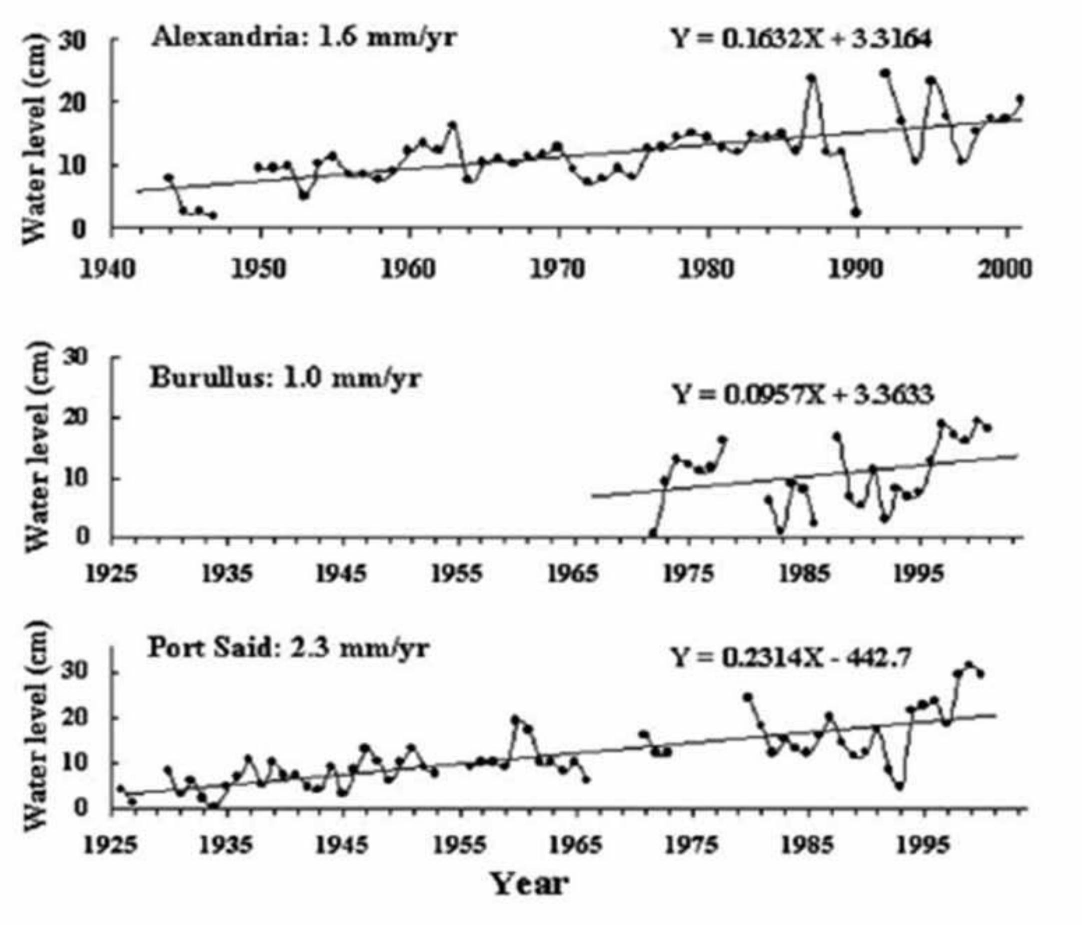

Figure 12: Long-term SLR based on mean annual sea levels measured by tide gauges located at Alexandria, Burullus and Port Said. Source: Frihy (2003).

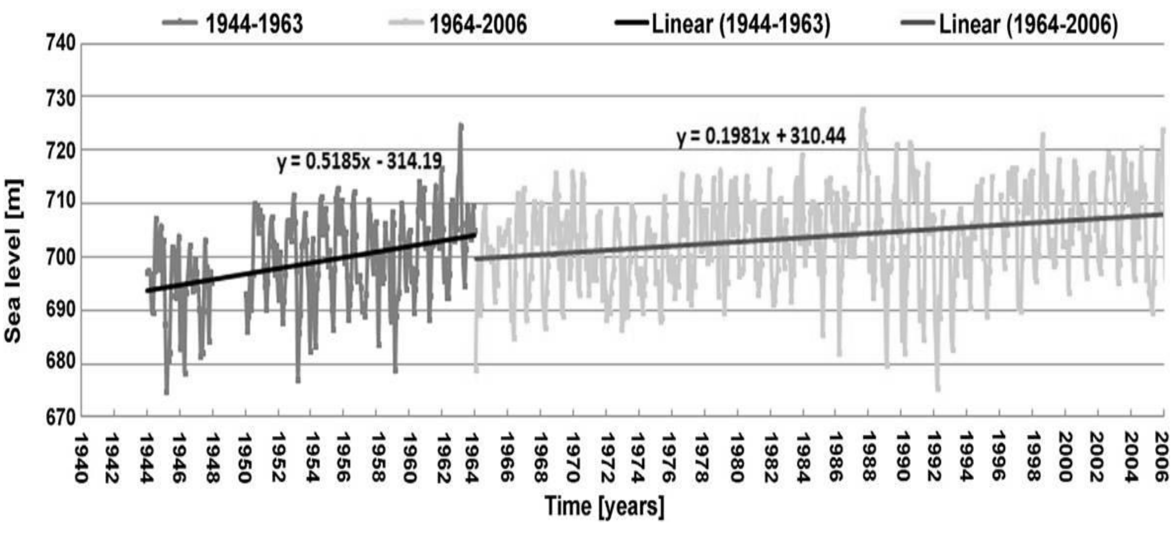

Figure 13: Trend of sea-level at Alexandria. Source: Shaltout et al. (2015).

4. VULNERABILITY OF THE NILE DELTA TO COASTAL INUNDATION

The Fourth Assessment Report (AR4) of the Intergovernmental Panel on Climate Change (IPCC, 2007) declared the Nile delta one of three regions on earth that are most vulnerable to future risks of SLR. These risks are amplified for those regions lacking essential infrastructure and services or living in exposed areas. The section identifies areas, as well as land use/land cover, susceptible to inundation by SLR based upon most recent scenarios of SLR, by the year 2100.

The exposure of the world's largest port cities to coastal flooding, due to SLR and storm-surge was examined by (Hanson et al., 2011). Alexandria, west of the delta, was ranked 11th in terms of population exposed to coastal flooding in 2070s. The impact of SLR and intensified storm surges on specific urban centers of the developing world was examined (Dasgupta et al., 2009) and the top 10 major cities worldwide that are located in storm-surge zones were listed. Port Said city, east of the delta, was found to be the first in the Middle East and North Africa region to be most affected. Therefore, reducing natural risks in coastal lowlands is of utmost importance in coastal management under the current and future climate change.

Despite their diverse assessments, previous studies established that the coastal areas of the Nile delta would be highly vulnerable to inundation due to SLR (e.g., El Raey et.al. 1995, 1997; El Raey 1997; El Raey et al. 2006; Eldeberky, 2011; UNDP-RBAS, 2012; Hassaan and Abdrabo, 2013; Haggag et al, 2013; Refaat and Eldeberky, 2016). Different estimates of areas vulnerable to inundation in the Nile delta are mainly due to the wide range of hypothetical scenarios for SLR employed, which ranged between 0.28 and 3.32 m. For instance, Milliman et al. (1989) assessed the impacts of hypothetical SLR scenarios, ranging between 0 and 2.17 m accompanied with land subsidence ranging between 0.40 and 1.15 m, by the year 2100. They reported that 21.6 to 26 % of the Nile delta livable area would be inundated. Another study covering the whole Nile Delta coastal area, assuming a mean SLR ranging between 1.6 and 2.3 mm/year, suggested that about 30 % of the Nile Delta coast would be vulnerable to SLR (Frihy, 2003). El Nahry and Doluschitz (2010), which studied the impacts of hypothetical SLR of 1.0, 1.5 and 2.0 m, suggested that 28.93, 35.33, and 50.78 %, respectively, of the coastal area of the Nile delta would be flooded. It should be noted that the precision of the topographical data utilized to assess direct inundation by SLR is the determinant factor in the accuracy of the inundation results. Previous studies on the coastal inundation of the Nile delta due to SLR did not pay much attention to enhance the accuracy of the employed topographical data.

4.1 Digital Elevation Data

Modern aerial photography and satellite remote sensing provide continuous surface information by means of optical cameras, radar or laser beams. Digital elevation data have become a widely used in many topographic studies (e.g. Demirkese, 2008; Potts et al, 2008). Digital Elevation Models (DEMs) provide a snap shot of the landscape features and elevation values of a study area such as the Nile delta (Fig. 14). They are generically described as “a spatially geo-referenced data set that is a popular way of encoding the topography for environmental modeling purposes”. DEMs are particularly relevant for many applications such as lake and water volumes estimation, soil erosion volumes calculations, flood estimating, roads, dams and embankment.

DEMs play a fundamental role in mapping. The digital description of the three dimensional surface is important in the study of coastal inundation due to SLR. The accuracy of DEMs depends on resolutions and data sources. The Shuttle Radar Topography Mission (SRTM) during an 11-day mission in February 2000, is considered a breakthrough in digital mapping, provided instantaneous, snapshot of earth's topography (Farr and Kobrick, 2000). SRTM provide DEMs at three different spatial resolutions: 1 arc-second (~30-m resolution); 3 arc-second (~90-m resolution) and 30 arc-second (~1-km resolution). The first resolution (30-m) only covers the United States, whereas DEMs with 90-m and 1-km resolutions cover the entire world (Farr et al., 2007).

Nowadays, DEMs have become a widely used in many impact assessment of SLR on low lying areas. For instance, Hereher (2010) analyzed DEMs and concluded 18.1% of the delta lies below the mean sea-level and that 12.7% has an elevation between 0 and 1 m. The Coastal Research Institute (CoRI) used a varying relative SLR over the Nile delta to improve the predictions obtained from 90-m SAR DEM data (El-Shinnawy, 2011). Recently, Refaat and Eldeberky (2016) utilized three sets of global DEMs: Shuttle Radar Topography Mission (SRTM-30, 2008); (GTOPO-900, 1996); and (GTOPO-900, 2010), to assess inundation of the Nile delta coastal areas by future SLR. Vulnerable locations in the coastal governorates, Beheira; Kafr El Sheikh; Damietta, Dakahlia; Port Said and North Sinai, are labeled alphabetically according to the degree of vulnerability (Fig. 15). The map indicates different levels in different colors in order to identify locations susceptible to inundation. The overall surface area of regions exposed to inundation due to 1-m SLR is 1401.7 km^2 which represents nearly 7% of the Nile delta total area.

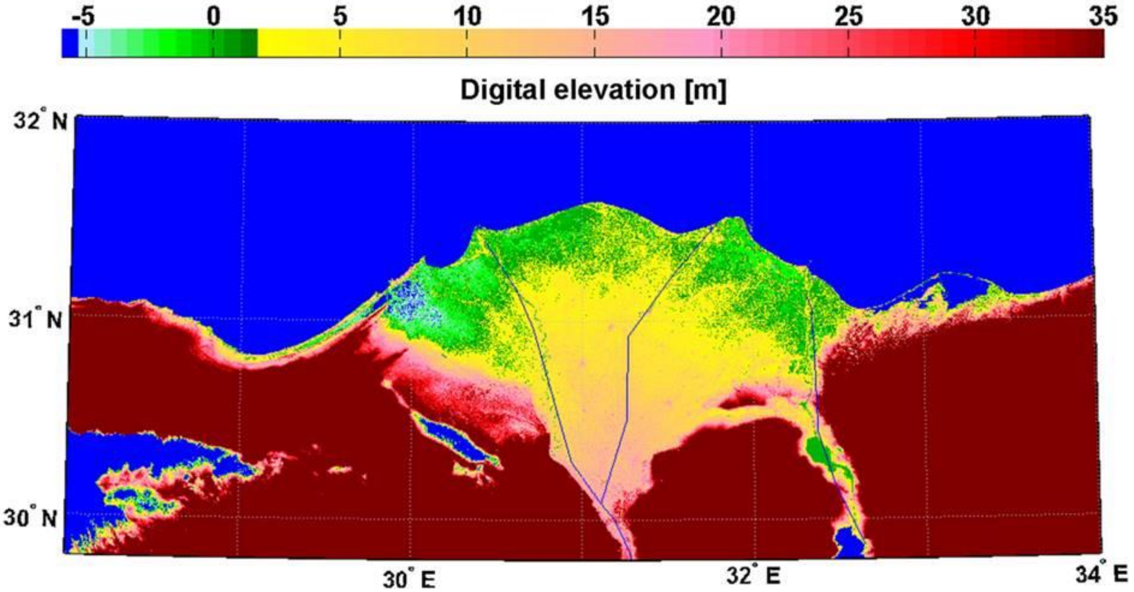

Figure 14: Digital elevation data for the Nile delta. Source: Shaltout et al. (2015).

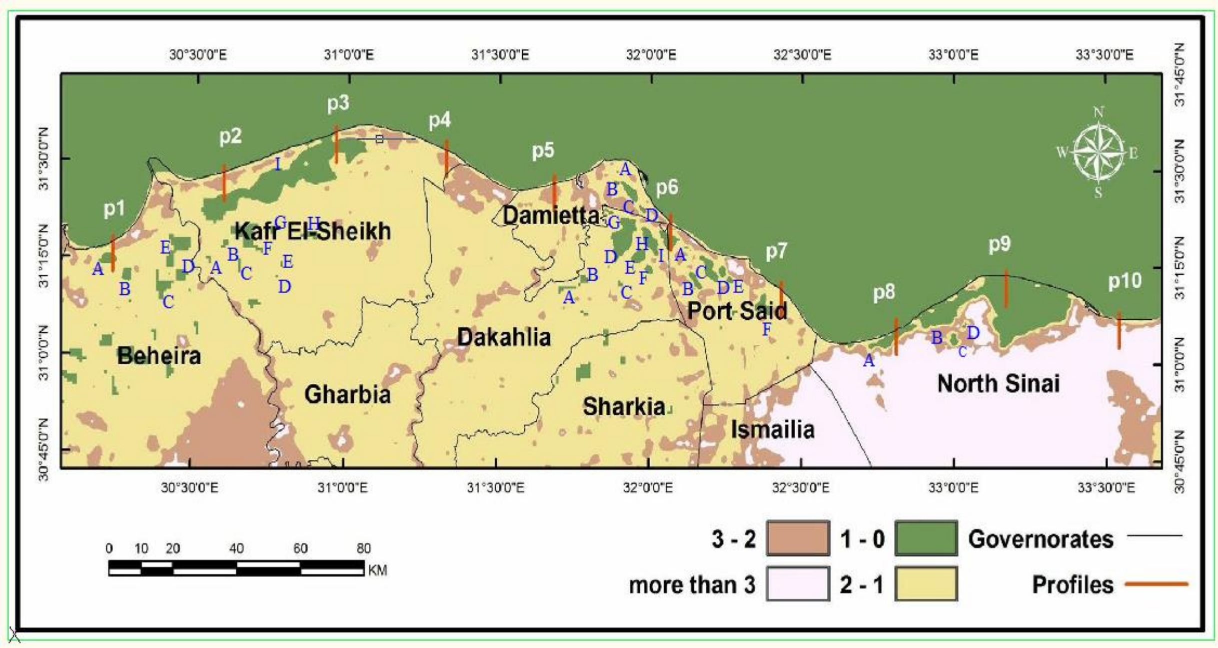

Figure 15: Vulnerability to inundation due to 1-m SLR in the Nile delta.

Source: Refaat and Eldeberky (2016).

4.2 Inundation Analysis and Maps

Inundation analysis for a coastline is a process in which the sea-level along the shoreline is elevated by selecting a land elevation above the current sea-level and then delineating all areas at or below that elevation, thus placing them into the inundation zone (Gallien et al, 2011). The inundation results are often presented in maps visualizing the inundation analysis for different SLR scenarios. In the inundation analysis, a cell in the DEM is classified to be inundated if the location is below the limit of SLR, otherwise the location is considered dry. The outcome of this process shows how the shorelines would change if sea-level were to rise for each increment and consequently several maps of inundation are produced. These vulnerable areas are uniquely identified on the final maps because while they are not directly exposed to SLR impacts, they are at risk of flooding if the topographic feature protecting them fails or breaches. Haggag et al (2013) applied future SLR models with single values i.e. 0.5, 1.0, 1.5, 2.0 and 2.5 m to the DEM of the Nile delta. The extent and depth of inundation is depicted for each SLR projections as shown in Figs. 16, 17 and 18.

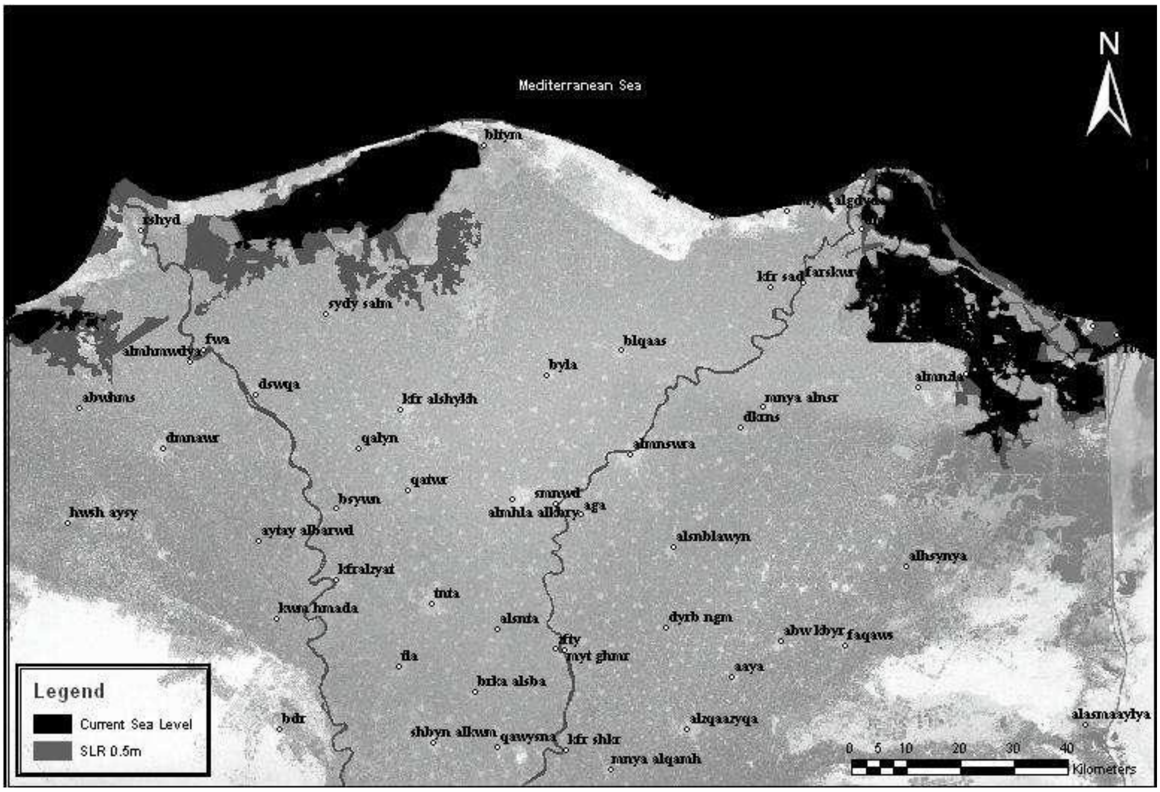

Figure 16: Inundation map for the Nile delta with 0.5-m SLR. Source Haggag et al (2013).

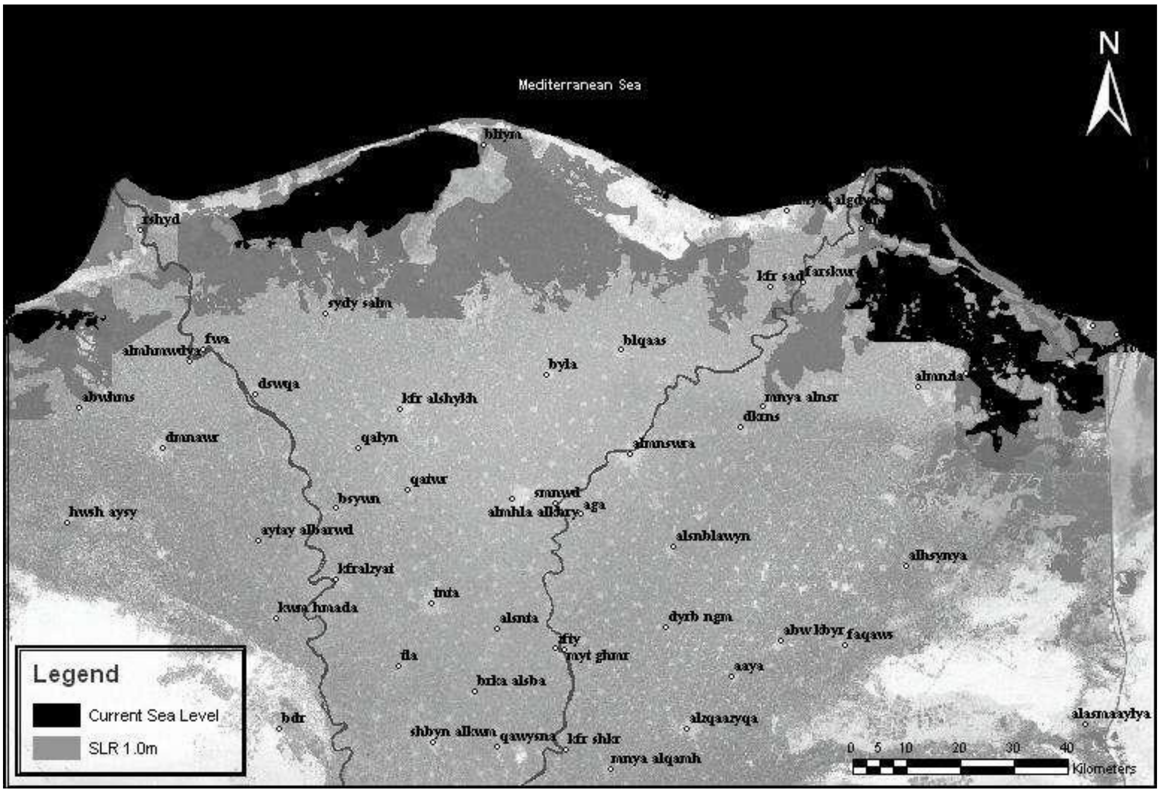

Figure 17: Inundation map for the Nile delta with 1.0-m SLR. Source Haggag et al (2013).

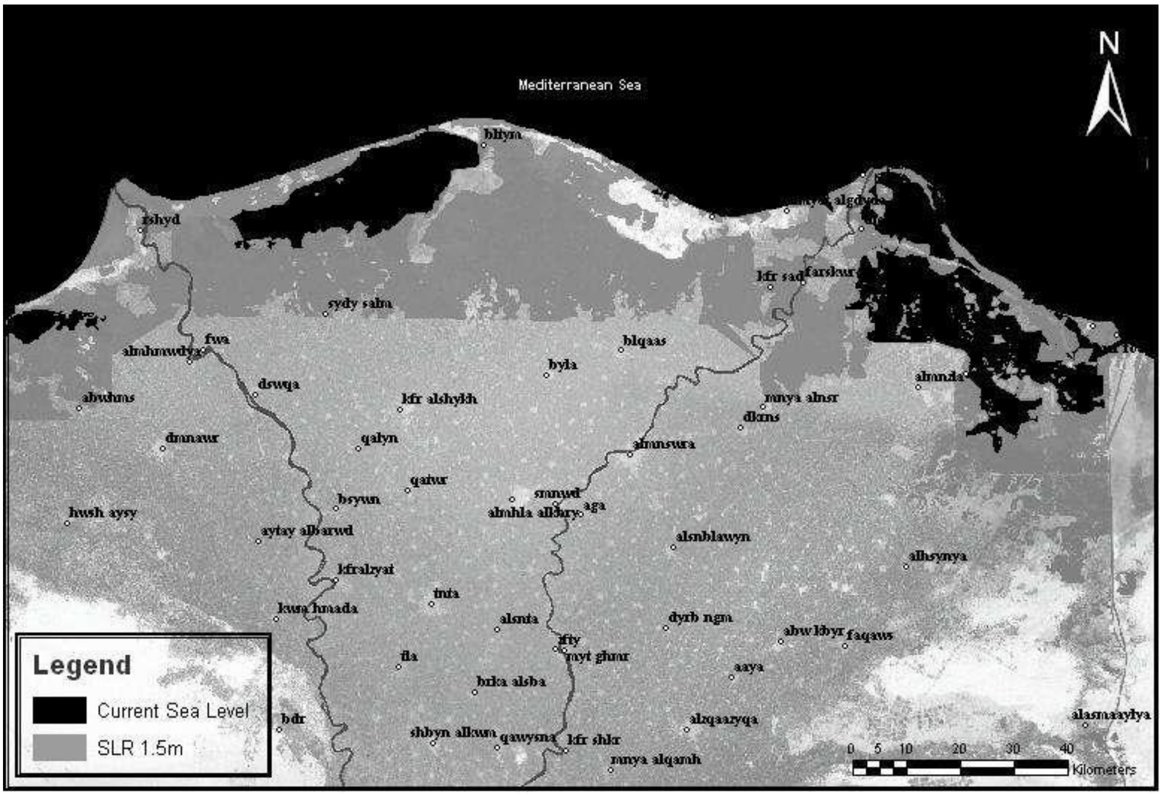

Figure 18: Inundation map for the Nile delta with 1.5-m SLR. Source Haggag et al (2013).

5. IMPACTS OF SLR ON THE NILE DELTA

Generally, climate change will amplify existing risks on the Nile delta and create new risks for natural and human systems. Risks are unequally distributed and are usually larger for disadvantaged people and communities in countries at all levels of development (IPCC, 2007). In urban areas climate change is projected to increase risks for people, assets, economies and ecosystems, including risks of coastal flooding due to SLR and storm surges. These risks are amplified for those regions lacking essential infrastructure and services or population living in exposed coastal areas.

The Fourth Assessment Report (AR4) of the Intergovernmental Panel on Climate Change (IPCC, 2014) declared the Nile delta one of three regions on earth that are most vulnerable to SLR. Impacts of SLR are a product of relative "or local" SLR rather than global changes alone (Nicholls, 2011). Relative sea-level change takes into account the sum of global, regional, and local components of sea-level change. The underlying drivers of these components are: i) climate change and changing ocean dynamics, and ii) non-climate uplift/subsidence processes such as tectonics, glacial isostatic adjustment, and natural and anthropogenic induced subsidence.

SLR can lead to increased risk potential for coastal populations, infrastructure, and investment. The most important goods and services that could be at risk of SLR, and which are readily quantifiable comprise: land; physical structures such as buildings and roads; in addition to agricultural and industrial productivity. Hence, impacts of SLR can be classified into two categories: environmental and socio-economic impacts (El-Raey, 2009).

5.1 Environmental Impacts of SLR in the Nile Delta

Impacts of SLR on environmental aspects in the Nile delta comprise different effects: flooding due to storm surges; erosion; inundation; rising water tables; salt water intrusion; and ecological and biological effects (Nicholls and Klein, 2000). A detailed description for each of these impacts is given in the following sections.

5.1.1 Flooding due to storm surges

One of the first consequences of rising sea-levels on low-lying coastal zones, such as the Nile delta, is an increased flood risk associated with storm surges and extreme precipitation events. Wind storms may cause surges in coastal areas. Storm surges represent a major natural hazard in coastal zones in terms of wave run-up and over-topping. Sea levels are always changing, either rapidly during a storm event, or slowly over years to decades. In fact, low-lying coastal areas that face permanent inundation under a certain scenario of SLR will first experience increased risk of flooding.

Extreme events

A long-term difficulty in the prediction of sea-level change is the effect of climate changes on the frequency, intensity and direction of storms. While mean sea-level is projected to rise during the present 21st century, storms may become more frequent and intense in some regions, whereas less severe in others areas.

The exposure of the world's largest port cities to coastal flooding, due to sea-level rise (SLR) and storm-surge was examined by Hanson et al., (2011). Alexandria was ranked 11th in terms of population exposed to coastal flooding in 2070s. The impact of SLR and intensified storm surges on specific urban centers of the developing world was examined (Dasgupta et al., 2009). Port Said city, east of the delta, was found to be most affected in the Middle East and North Africa region

The effects of climate change are becoming more evident than before. The delta coast was exposed to a severe storm, between the 11th and 13th of December 2010, that presented a major natural risk in coastal areas and lowlands. The area was hit by a strong westerly wind storm that caused storm surges and high waves had not been observed in the previous few decades. The storm was recorded in a sequence of weather observations FUGRO-SEACAST, between the 10th and 13th of December 2010, received from a vessel just offshore Abu Quir (31.5 N, 29.9 E) east of Alexandria. The observations revealed several periods of gale force winds of more than 34 knots (Beaufort scale 8). The bulk of the strong winds, high waves and swell were observed on the night of the 11th with wind speeds in the range of 41-47 knots and observed wave heights between 7-9 m (strong gale, Beaufort scale 9). Although strong winds and high waves in this region are not unusual, this particular storm event was exceptional measured by its total duration. During the storm, the Hydrographic Department of the Egyptian Naval Forces reported a storm-surge of 1.2 m as well as a maximum wave height of 7.5 m offshore Alexandria which forced the closure of the main harbor.

Moreover, the storm affected Alexandria coastal highway and Abu Quir bay as well as the lowlands located between the delta's promontories. The lowlands located behind M. Ali seawall along Abu Quir bay, was subjected to a partial flooding (Ismail, 2011). The storm also caused damage to some coastal structures such as Idku port breakwaters. The damage mechanisms resulted from direct wave and wind forces and wave overtopping.

Storm surge modeling

Modeling storm-surges in the Mediterranean Sea is of direct interest for accurate prediction of associated high sea-levels along the delta coast. The analysis of regional sea-level changes has significantly advanced in recent years; however, large uncertainties still remain. In the recent past, only some studies presented analysis of storm surge simulations in the Mediterranean Sea for the recent past (hindcast) and the future (scenarios).

For example, Soares et al (2002) conducted a 40-years hindcast of wind, water-level and waves in European waters including the Mediterranean. The simulation was done with the Mediterranean Sea model within the HIPOCAS project “Hindcast of Dynamic Processes of the Ocean and Coastal Areas of Europe”. The limited tidal range in the Mediterranean allowed an independent model computation of residuals and tides, and thus, sea-level response was simulated without tide forcing. Ferrarin et al (2010) investigated the interactions between tides, waves and surges in determining the total water level in the Mediterranean Sea using a finite element tide-wave-surge model. The hindcast results showed that the simulation with tides and waves is more accurate than the conventional method (surges plus tides independently) in predicting the total water level along the Italian coast. Marcos et al. (2011) used a two-dimensional (2D) model to investigate changes in storm surges in the Mediterranean Sea due to future climate change. They indicated that the average number of positive surges will decrease, whereas negative surges will increase throughout the 21st century. Tsimplis et al. (2008) investigated future sea-level rise in the Mediterranean Sea using a regional atmosphere-ocean climate model.

The model projected a steric sea-level rise between 13 and 25 cm with lower values in the eastern Mediterranean and higher values at the western Mediterranean.

Eldeberky and Hünicke (2015) simulated water-levels in the Mediterranean Sea using the advanced hydrodynamic model TRIM-NP. The model uses a semi-implicit finite-difference method for solving the 2D shallow-water equations. The TRIM-NP model, which is based on Cartesian coordinates, has been applied to hindcast (i.e., retrospective analysis of the state of a dynamical system using a numerical model) hourly water-levels throughout the region in the Mediterranean Sea for 63 years from 1948 to 2011.

The TRIM model was driven by wind fields and atmospheric pressure generated by the climate model CLM (with spectral nudging) for the Mediterranean region provided by coastDat (a model based regional meteorological reanalysis generated at the Helmholtz-Zentrum Geesthacht in Germany mainly for the assessment of long-term changes in data sparse European regions (Weisse et al., 2009). The meteorological fields were produced at 5 km grid resolution similar to the hydrodynamic model grid used in the simulation. The model results obtained from the hindcast simulation were analyzed in order to extract hourly water-levels at some selected locations. An example of model-data comparisons, given in Fig. 19, shows the hourly model results of sea surface elevation offshore Alexandria and the data obtained from the tide gauge measurements at the same location.

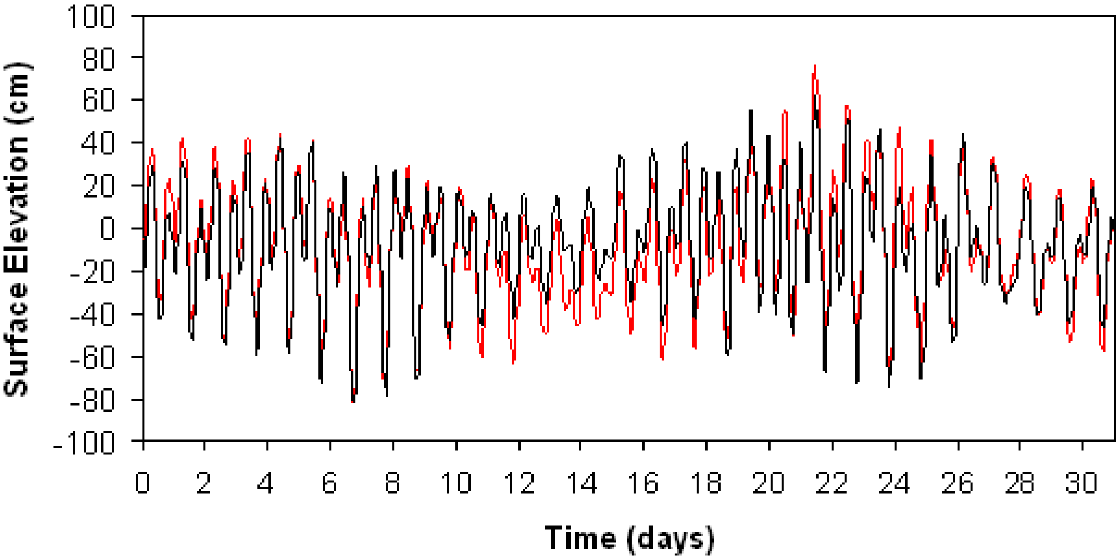

Figure 19: Comparison of TRIM-model results versus tide-gauge measurements offshore Alexandria during December 1991. Source: Eldeberky and Hünicke (2015).

5.1.2 Erosion and Inundation

The coastlines of the Nile delta, Rosetta and Damietta have been experiencing general change due to both natural and anthropogenic pressures. It has been observed that the highest rate of erosion occurs along the outer margins of these projections. This erosion is a result of both effects of termination sediment supply of the Nile River by the High Dam and prevailing coastal processes due to wave action and the currents of the east Mediterranean gyre.

Future SLR is expected to increase rates of erosion of the northern coast and Nile delta (El-Raey et al., 1999) due to increasing wave energy (frequency and strength in extreme events) in the nearshore area. As a consequence, rates of shoreline retreat are expected to increase and eventually lead to dune erosion, breaching of coastal barriers, and destabilization of coastal inlets. Impact of SLR on beach evolution depends largely on geomorphological setting (Stive et al., 1990; Nicholls, 1998). Rising sea-level disturbs equilibrium of beach profile, and hence causes erosion due to profile adjustment (Bruun, 1988).

Many studies determined beach erosion rates along the Nile delta coastline and found to significantly vary from one location to another. Factors acting in processes of shoreline erosion comprise coastal processes, relative SLR, and land subsidence.

Sand barriers of the Nile delta lagoons

The Nile delta lagoons are detached from the open sea by sand barriers that vary in width and subsidence rate. They are susceptible to erosion and future SLR, combined with the effect of prevailing coastal processes. These barriers are undergoing erosion and reformation, except some localized accretion pockets in embayments and at the lee sides of protection structures. Idku-lagoon barrier is relatively wide (0.25-10.0 km), with an elevation between 0-1 m, and is experiencing mild erosion to accretion (Fig. 20a). The width of the Burullus barrier varies from 0.5 to 5.3 km (Fig. 20b) and accretion occurs at a rate of 5 m/year at the west side of the lagoon entrance (Frihy and Komar, 1993). The long-term accretion of this part is effected by blocking the unidirectional easterly longshore sand transport by the jetty constructed at the Burullus inlet. The sand barrier of Manzala lagoon at El Gamil is relatively narrow near its eastern inlet (0.5-2.3 km), and is very exposed to erosion ascribed to both wave-induced longshore current and SLR (Fig. 20b).

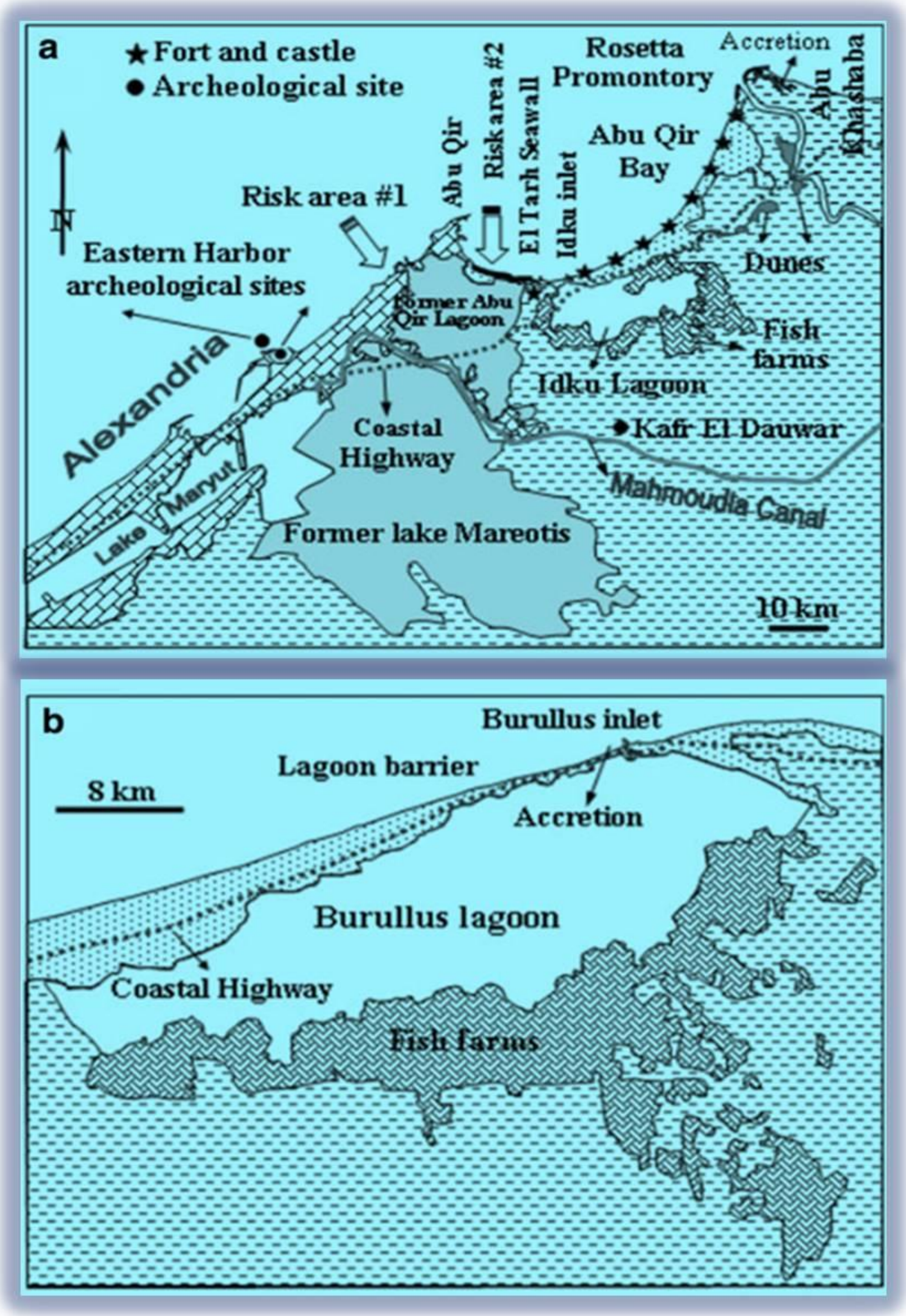

Figure 20: Map showing coastal features (a: top), the northwestern region of the Nile delta and Alexandria showing low-lying areas; (b: bottom), the southern margin of Burullus lagoon at the central part of the Nile delta. Figure adapted from Frihy et al. (2010).

The low-lying land in Abu Quir bay, El Tarh with an area of 700 km^2 (Fig. 20a), is heavily exposed to severe flooding without any global rise in sea-level. This scenario is possible if water bypasses accidentally from the lowest point in the coastal ridge at Mandara beach (risk area #1), that is only 2.4 m above mean sea-level, or from Mohamed Aly or El Tarh seawall (risk area #2).

Northeastern coastline of the Nile delta

Shoreline changes revealed several reversals pattern between erosion and accretion along the delta Northeastern coast. Based on landsat images between 1972 and 2007, Dewidar and Frihy (2009) calculated rates of erosion and accretion, along the northeastern coastline of the Nile delta including Manzala lagoon barrier. They noted a maximum shoreline retreat of 10 m/year at the immediate downcoast of the Damietta spit, and the lowest rate of (-5 m/year) is found east of the El Gamil inlet (Fig. 21). On the other hand, beach advancement at a rate of 20 m/year exists in the downcoast of detached breakwaters built east of the El Gamil inlet and also along the updrift side (8 m/year) of the Suez Canal breakwater at Port Said beach.

Based on their calculated erosion rates caused by coastal processes, SLR and land subsidence, Frihy et al. (2010) identified two risk sites at the exposed Manzala lagoon barrier. The two risk areas are located at the lee-side of the Damietta spit (2.3 km width, risk area #3), and at the narrowest site (500 m width) east of the El Gamil inlet (risk area #4). These locations are shown in Fig. 21. Without coastal protection, the continuous sand barrier at the widest point #3, downcoast of the Damietta spit 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).

On continuous sandy coasts with no inlets, as in risk area #3 (Fig. 21), rising water levels leads to disequilibrium of beach profile, and consequently erosion due to adjustment of beach profile. On the other hand, for sandy coasts with inlets (as in risk point #4), SLR causes further shoreline erosion because the inlet will provide an additional sink for eroded sand, resulting in sedimentation hazard, so-called indirect effect of SLR (Stive et al, 1990).

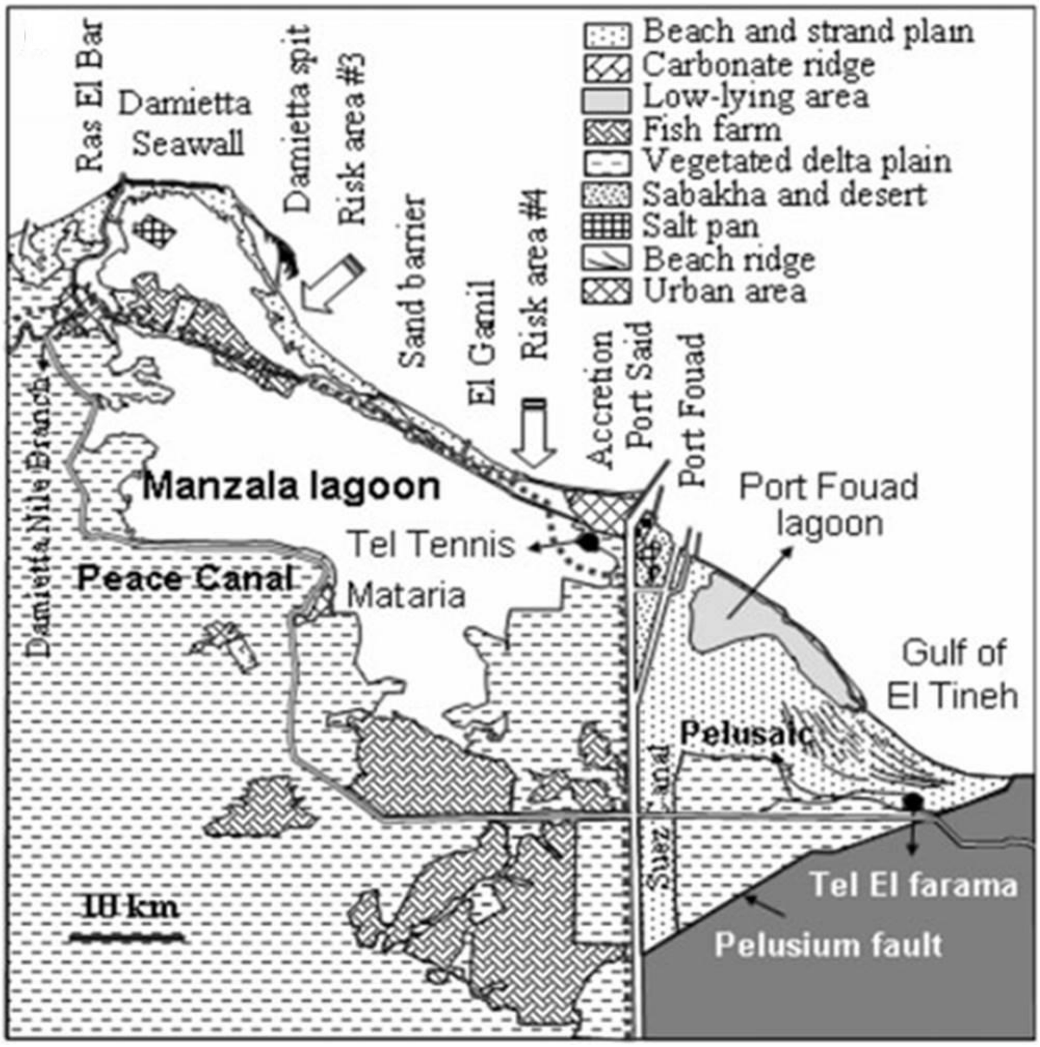

Figure 21: Map of the northeastern region of the Nile delta including Manzala lagoon showing land features. The narrow sand barriers of the lagoon and Port Fouad low-lying sector vulnerable to erosion due to SLR Source: Frihy et al. (2010).

Detailed inundation maps around Burrullus and Manzala lagoons are produced by Haggag et al. (2013) using DEM. The maps, shown in Figs. 22, indicate the inundation risk for different SLR-scenarios (0.5, 1.0, 1.5, 2.0, 2.5 m) if the sand barriers protecting those lagoons fails or breaches. Seawater inundates substantial areas around Burrullus lagoon even for a 0.5-m SLR as shown in Fig. 22a. Water passes the road around the Manzala lagoon once it reaches 1.0 m along a small section as shown in Fig. 22b. Substantial parts of the northern Nile delta will be inundated in case of 1.5-m SLR-scenario.

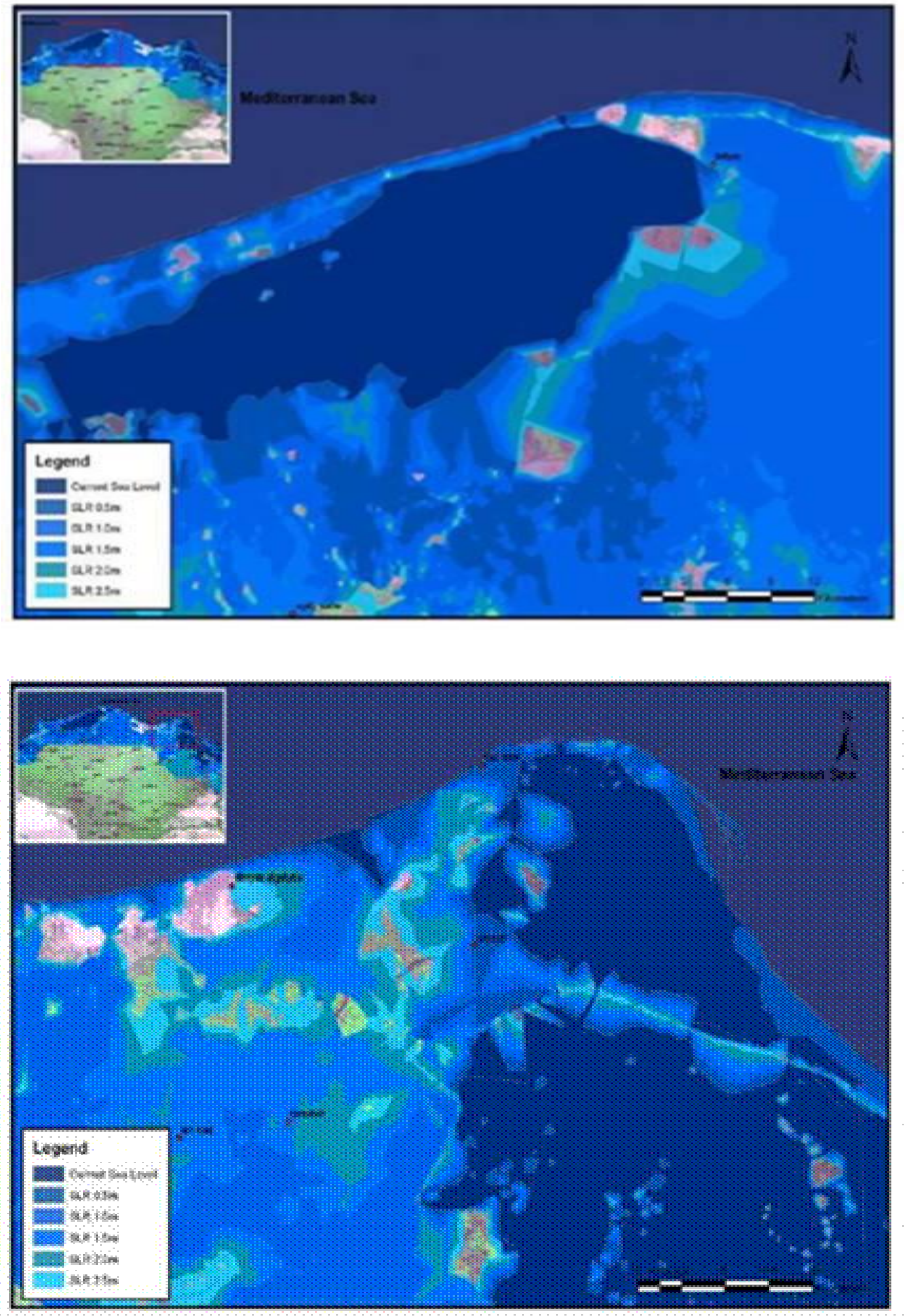

Figure 22: Inundation maps for different SLR-scenarios. (a, top): area around Burullus lagoon, (b, bottom): area around Manzala lagoon. Source: Haggag et al. (2013)

5.1.3 Salt-water intrusion into the Nile-delta aquifer

Seawater intrusion into groundwater aquifers is encountered in almost all coastal aquifers. It is regarded as a natural process that might be accelerated climate-induced SLR. In the Mediterranean coastal plains and lower delta, high rates of groundwater extraction have led to a large reduction in groundwater table. As a result, seawater has intruded into the aquifers. In addition, SLR is expected to exacerbate intrusion of saline water into the fresh groundwater aquifers in the coastal zone.

Rising sea-level will have major impacts on groundwater resources in coastal aquifers (Fig. 23). First, the shoreline will shift to a new landward position and depending on the land topography this shift might be significant and the groundwater in the affected zone will become completely saline. Second, rising sea-level would cause additional pressure head at the seaside and, hence, the seawater water would advance more inland (Sefelnasr and Sherif, 2014). Currently, the total volume of fresh groundwater in the Nile Delta Aquifer is around 883 km^3.

In the northern Nile delta, impacts of SLR comprise sea-water intrusion into coastal freshwater aquifers and rising groundwater tables. As a consequence, contamination of groundwater resources in the upper Nile delta is expected due to increase the occurrence of saline intrusion into coastal aquifers (El-Raey, 2010). Hence, rising sea-level is likely to cause a landward shift of the salt wedge and to increase the rate of saline seepage to the topsoil of the delta.

For instance, the sea incursion into the Manzala lagoon barrier would likely accelerate intrusion of salt water in the groundwater underlying the Nile delta coastal plain and elevate water tables. In addition, the salinity in the Manzala lagoon may increase because of the stronger influence of tidal flows into the lake. Frihy (2003) and Stanley (1997) mentioned "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". Zaid et al. (2014) presented a contour map of groundwater level in the northern Nile delta (Fig. 24). Sefelnasr and Sherif (2014) carried out the first comprehensive assessment for the impacts of the Future SLR in the Mediterranean Sea on the seawater intrusion in the Nile-delta aquifer. They concluded that "about one-third of the groundwater resources will be lost under the condition of 1.0-m SLR, the available volume of the freshwater will be reduced by about 15% assuming that the current pumping rates will be maintained.

Reducing the groundwater pumping by 50% would mostly sustain the freshwater resources under the condition of 0.5-m SLR".

It is anticipated that increasing soil salinity in the lower Nile delta will degrade crop quality and reduce agriculture productivity. As a result, serious implications for food security and public health might lead to significant socioeconomic consequences.

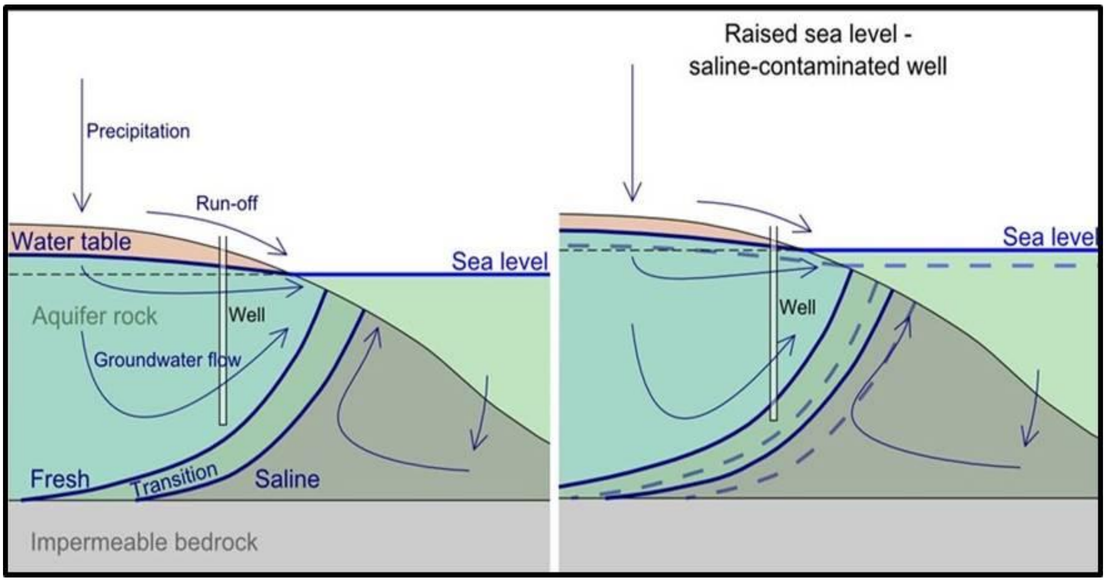

Figure 23: Effect of SLR on a freshwater well to become contaminated with saline water.

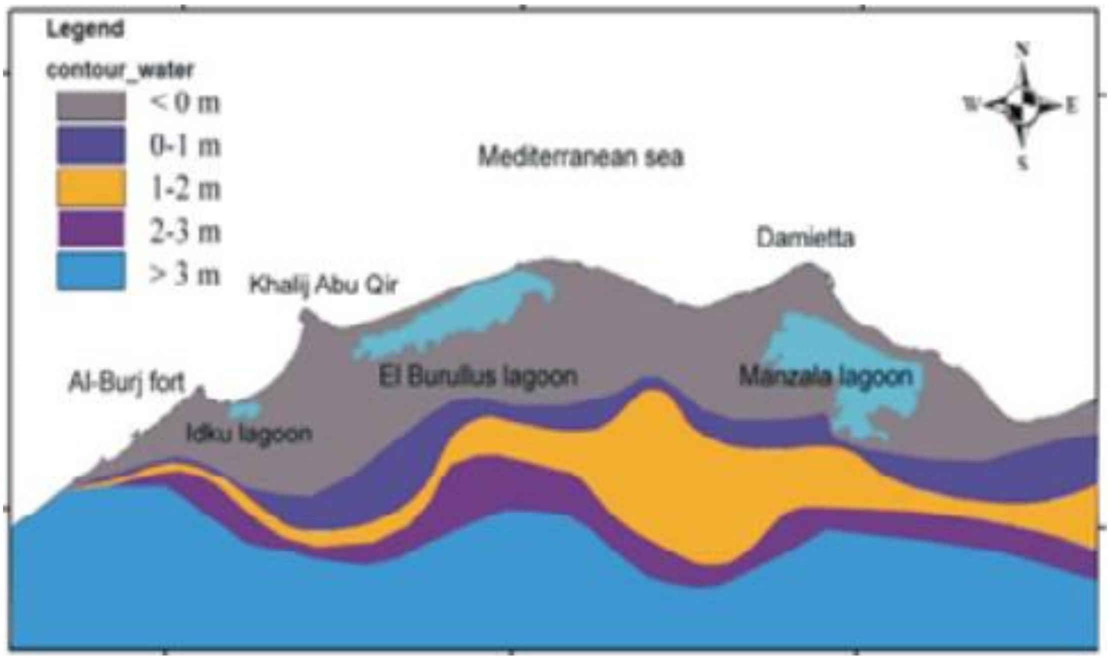

Figure 24: Groundwater level in the northern Nile delta. Source: Zaid et al. (2014)

5.1.4 Ecological and biological effects

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-induced SLR (Nicholls and Hoozemans, 1996).

Coastal wetlands worldwide are ecologically important as they are a potential source for fisheries and act as an allowing passage and breeding of migratory birds. They also are an important spawning area for many fish species. They are naturally inhabited by aquatic vegetation such as reeds and also incorporate small islands; some of them are inhabited by fishermen community. For example, the aquatic vegetation in Idku and Burullus lagoons cover, respectively, an area of 37.7 km^2 and 210 km^2, 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 km^2, corresponding to 4.8 and 2% of the total lagoon areas. To satisfy the country' needs for fish industry, marshes south of the Nile delta lagoons have been rapidly converted to productive fish farms (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 (Figs. 20, 21), 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 km^2 between 2002 and 2007, respectively (Moufaddal et al. 2008). Fish farms at Idku, Burullus, and Manzala lagoons occupy areas of 75.4, 344.4, 414.4 km^2, respectively (Frihy et al, 2010). The total area of these lagoons, including the open-water body, aquatic vegetation, and fish farm areas is 2157.5 km^2 representing about 15.85% of the entire coastal plain of Alexandria and the Nile delta. 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 satellite images.

It should be noted that the resultant siltation at the Manzala 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. In addition, saltwater intrusion would also harm aquatic plants and animals as well as threaten human water supply (IPCC, 1990).

5.2 Socio-economic Impacts of SLR in the Nile Delta

The northern Nile delta and Alexandria are highly populated areas with population distributed in cities and small villages. However, the Nile delta coastal zone suffers from a number of problems such as: fast demographic growth, land subsidence, excessive erosion rates, water logging, soil salination, pollution and degradation of ecosystem. For these reasons, suitable institutional management systems are needed (El-Raey, 1999). Considering socio-economics, the potential impacts of SLR will disturb many sectors of development, including tourism, cultural and natural heritage, crop quality, agricultural productivity, freshwater availability, public health, and socioeconomic benefit (El-Raey, 2010).

5.2.1 Population

The northern Nile delta coastal governorates are highly populated, with population count of 21,735,644 persons representing about 25% of Egypt’s population according to 2015 census. Population of each administrative governorate is: Alexandria (4,812,186), Beheira (5,804,262), Kafr El-Sheikh (3,172,753), Dakahlia (5,949,001), Damietta (1,330,843), Port Said (666,599).

Coastal populations in the Nile delta, particularly those who live in low-lying areas, are exposed to the impacts of SLR, with its associated flooding by storm surge. In a pilot study, El-Raey (1997) analyzed topographic and land-use data in addition to socio-economic information to estimate the numbers of people expected to be affected by SLR Evaluation of the socio-economic impacts due to loss of land and jobs was done. He estimated that a 0.5-m SLR in Alexandria will cause a displacement of nearly 1.5 million people and the loss of about 200,000 jobs by year 2050 (El-Raey, 1999). Dasgupta et al. (2009) concluded that the potential impact due to SLR and intensified storm surges on coastal population will be particularly severe in the Nile delta with inundation risk for about 2.67 million people. He listed the top 10 major cities worldwide that are located in storm-surge zones and Port Said was found to be the first in the Middle East and North Africa region to be most impacted.

The exposure of the world's largest port cities to coastal flooding SLR and storm-surge was examined by Hanson et al., (2011). Alexandria was ranked 11th in terms of population exposed to coastal flooding in 2070s about 4.375 million. It was ranked 20th in terms of assets exposed to coastal flooding in 2070s in value of 563.28 US $billion.

5.2.2 Agriculture

The Nile delta accommodates a substantial area agriculture land and associated economic activities. Agriculture activities are predominant in the region (around 63% of the total agricultural land) due to the nature of the soil (Dawoud, 2004). SLR is expected to have a profound impact on agricultural land in the Nile delta, through either inundation or increasing salinity of groundwater. For three different SLR scenarios (0.5, 1.5, 2.0 m), Abdrabo et al. (2015) indicated that about 7.5%, 36.3%, and 44.0% of the total cultivated area in the coastal governorates (with a market value of 51.7, 196.6 and 232.6 billion Egyptian Pound will be vulnerable to inundation. In addition, they found that the future accumulative crop yield loss due to increasing groundwater level was estimated to be 32.3 billion EGP. Their estimates exclude indirect impacts of higher levels of groundwater table, which may include loss of jobs and/or earnings, impacts on food supply and security in the region. The potential impacts of climate- induced SLR on the Egyptian economy was examined by Smith et al (2013). They assessed the economic impacts of SLR including land subsidence on the Nile delta. It was found that “the high SLR scenario, 109 cm at Port Said, 60 cm at Burrullus lagoon, and 55 cm at Alexandria, inundated 774.3, 523.9, and 625.6 km^2 of agricultural land in the Northeast, North-Middle, and Northwest of the Nile delta, respectively, assuming that no SLR protective measures are implemented”.

Abdrabo et al (2015) concluded that “Although farmers and policy makers have some adaptation options to SLR, if they continue with their given technology, SLR will have a devastating effect on the Nile delta especially the low-lying land”. In addition, their results confirm the importance of groundwater table level for crop revenue/profits and the need to take actions to strengthen existing adaptation options and develop new measures.

Potential implications of SLR on agricultural areas are expected to significant because the cropland in the Nile delta is located in the surge zones and would increase in future SLR. The surge zones will almost double as a result of SLR and intensified storm surges (Dasgupta, 2009). The increase of frequency of extreme events will reduce crop yield as well as causing changes in the agricultural distribution of crops. Anticipated socio-economic impacts comprise loss of jobs and rise of unemployment (Elsharkawy et al, 2009).

5.2.3 Tourism

The coastal cities of Alexandria, Gamasa, Bulteem, Ras El-Bar and Port Said, are popular summers destinations for local Egyptian tourists. The impact of climate-induced SLR is considered serious because it threatens the infrastructure and utilities of coastal tourism sector. For example, the most serious impact of SLR on Port Said Governorate would be the threat to recreational beach communities. El-Raey et al. (1999) estimated losses of land areas and jobs by overlying Bruun’s horizontal retreat distances over land-use areas obtained from satellite images and ground surveys (El-Raey et al., 1998). Their results showed that beach areas, and consequently tourism, are most severely affected, whereas the agriculture sector is the least affected sector. Economic losses are also estimated, for an area of 1-km^2, and found to be \$100 million for beach and agricultural areas and US \$500 million for industrial areas. While the impacted beach areas are large, the percentage losses in industrial areas, transportation network, and urban areas are the most serious. He estimated that the total economic loss is over US \$2.0 billion for a 0.5-m SLR and may exceed US \$4.4 billion for a 1.0-m SLR. Roughly 28,000 to 70,000 people are estimated to be evacuated, and 6700 to 16,700 jobs are expected to be lost for the scenarios adopted. This highlights potential impacts of SLR on coastal cities in the Nile delta

5.2.4 Cultural Heritage

Archaeological sites, particularly those situated in the low-lying areas, might be impacted by sea incursion and flooding. Whereas, others sites located on high-elevated topography or submerged underwater will not be affected. The coastlines of Alexandria and the Nile delta accommodate some archaeological remains and ruins of submerged, buried, and emerged sites. For instance, Tel Tennis and Pelusium sites located in low-lying land and have been exposed to land submergence, and tectonic subsidence (Stanley, 2005). Submerged archaeological sites which were constructed onshore became below water at Abu Quir Bay (Bonaparte’s Fleet, Canopus and Herakleion cities ruins). In addition, Ptolemaic, and Roman ruins are submerged in Alexandria’s Eastern Harbor. Canopus and Herakleion, dated from Greek to Byzantine times, were discovered at depths of 6–7 m in the western part of Abu Quir Bay (Stanley et al, 2001). Few historical military castles are situated along the coastline of Abu Quir bay (Frihy et al, 2010).

6. ADAPTATION MEASURES

Generic responses required to protect people and socio-economic developments against SLR in vulnerable coastal areas can be classified into three alternatives: i) protect; ii) accommodate; iii) retreat, IPCC (1990). Protection of the coastline against the sea involves hard structures (such as sea walls, breakwaters, and rock revetments) or sand dunes commonly used to stabilize the coast so that existing land uses can continue. Accommodation means that people continue to use the coastal area under the threat of SLR, but with adaptation measures such as: emergency flood dealings, converting agriculture to fish farming, and growing salt tolerant crops in vulnerable areas. The retreat option requires no effort to protect the coastal area against the sea, however, in extreme events; an entire coastal area may be abandoned which is not feasible in highly populated areas with extensive socio-economic activities.

United Nations Framework Convention on Climate Change (UNFCCC) defines adaptation as: “Adjustment in natural or human systems in response to actual or expected climatic stimuli or their effects, which moderates harm or exploits beneficial opportunities.” Nicholls (2011) clarified that “Adaptation to SLR using a single generic approach is doubtful. The appropriate combination of protection, accommodation, and retreat is currently being seriously considered worldwide. In practical application, many responses are hybrid, combining elements of more than one approach”. It is worth noting that any adaptation strategy is regularly site-dependent. Therefore, potential adaptation measures require assessment of environmental and socio-economic impacts expenditures and welfares, and accessible technology.

Egypt’s National Strategy for Adaptation to Climate Change and Disaster Risk Reduction (2011) aims at: i) increase the flexibility of the Egyptian community when dealing with the risks caused by climate change and its impact on different sectors and activities; ii) strengthening the capacity to absorb and reduce the risks to be caused by such changes. In essence, the strategy adopts accommodation and protection as the two basic means of defense against SLR, taking into consideration systematic retreat based upon predefined plans, in case the coastal zones are exposed to extreme events.

Several adaptation measures, derived from above generic responses, could be utilized to deal with the impacts of SLR on susceptible coastal areas in the Nile delta. This section presents responses to SLR and state of the art to reduce the anticipated impacts and consequences. It also highlights issues that arise with interventions designed to reduce risks to exposed areas as a consequence of SLR.

Egypt's National Strategy for Adaptation to Climate Change and Disaster Risk Reduction highlights the significance of coastal zones according to their potential exposure to the risks of climate-induced SLR. It assesses the current situation of the coastal zones and all other interconnected sectors, mainly: water resources and irrigation, agriculture, health, urban areas, housing, roads and tourism. Moreover, the national strategy examines the methods and means of adaptation to climate-induced SLR and reduction of disaster risk. It adapts the international consensus, agreed upon in the Copenhagen Accord (2010), that the temperature increase shall not exceed two degrees Celsius as well as two SLR-scenarios of 0.5 and 1 m until the end of the 21st century. Accordingly, the potential exposure of Egyptian coasts to the risks of disasters resulting from SLR has been considered; and direct defense and preventive methods as regards the exposure areas have been suggested.

6.1 Generic Adaptation Options

It is worth noting that an adaptation strategy should comprise alternatives/options that best deal with region-specific risks, the desired protection level, environmental and socio-economic conditions. Optimal adaptation schemes are those that provide protection, accommodate natural coastal processes, and include natural landforms such as barriers and wetlands. The most viable options for adaptation to climate-induced SLR in the susceptible areas in the Nile delta are considered here prior to the evaluation of adaptation measures. Adaptation options and measures are discussed and analyzed based on previous works of experts in the field. These are considered below in details.

6.1.1 Coastline protection

The Breakwaters are hard structures, constructed with natural rocks or concrete units, commonly used to reduce the wave action propagating towards coastline. They can be placed offshore as emerged or submerged breakwaters. Revetments are set as riprap along the shoreline to absorb wave energy. Coastline protection, using breakwaters and revetments, is considered to be the best scheme for protection of low-lying areas, however, is relatively very expensive with adverse environmental impacts. This scheme affects fishing, so the fishermen need new tools and modern motor boats for fishing offshore. Breakwaters and dikes are good tools for protecting cultivated land and infrastructures (e.g. roads) located in the coastal areas.

Groins are also hard structures built perpendicular to the coastline, are used together with beach nourishment to trap sand and stabilize the shoreline. Sand nourishment includes: placing sand onto the open beach, and making artificial dunes as storm barriers. The expense of this scheme is relatively low compared to breakwaters. This option has the advantage of forming new beaches for tourism and creates employment opportunities and does not obstruct finishing activities. This option requires regular nourishment by sand suppletion. The best advantage of this scheme is sustaining the beach for tourism, the protection of hotels, and an increase of jobs in the tourism sector. It has no adverse effects on farmers and workers.

6.1.2 Legal development regulations

Formulating regulations for development comprises legal and regulatory actions to restrict development or ban redevelopment in vulnerable areas such as: accepting erosion-based setback lines, or change of land use. Current institutions and legal systems may be inadequate to implement an adaptation strategy. Authorities may be required both to implement options and to manage them over long periods of time in the face of pressures for development. Coastal management plan and other new regulations are necessary to plan and implement the necessary adaptive schemes.

6.1.3 Integrated coastal zone management

The sustainable coastal development has to be implemented utilizing integrated coastal zone management (ICZM) approach and here is a generic definition and an explanation provided by the European Commission “ICZM is a dynamic, multidisciplinary and iterative process to promote sustainable management of coastal zones. Integrated refers to the integration of objectives and all relevant policy areas, sectors and levels of administration. It overcomes fragmented and sectoral management response and eliminates jurisdictional overlaps. ICZM covers the full cycle of information collection, planning, decision making, management and monitoring of implementation”. Therefore, it signifies the best possible management of resources under multi-criteria analysis (El-Raey et al, 1999).

ICZM provides a major opportunity to assess the impacts of SLR. Since it offers advantages over purely sectoral approaches, ICZM is widely recognized and promoted as the most appropriate process to deal with climate-induced SLR and other current and long-term coastal challenges, Nicholls et al. (2007). The Integrated Coastal Zone Management plan in Egypt was initiated in 1996 with four national strategies: shoreline protection, coastal land use, coastal marine water quality and marine resource preservation (Anon, 1996). Several measures were implemented to address the potential threats on coastal areas. In addition, the National Action Plan on Climate Change include several proposed adaptation measures to deal with future risk of SLR such as beach reinforcement and nourishment, construction of seawalls and breakwaters, tightening of legal regulations and enforcement of laws, adoption of integrated coastal zone management, change in land use and development of comprehensive monitoring. Integrated Coastal Zone Management was enforced by introducing Law 9/2009 to Environmental Law 4/1994. This addition also encourages scientific research and technical coordination among concerned authorities and to help disseminate policies and measures for adaptation to climate change and associated SLR.

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6.2 Adaptation Measures to SLR in the Nile delta

The adaptation measures, presented hereafter, adopt the accommodation and protection schemes as the primary methods of preventing the adverse impacts of climate-induced SLR in the Nile delta coastal zone. According to the international consensus, agreed upon in the Copenhagen Accord (2010), two possible SLR-scenarios of 0.5 and 1 m by 2100 are considered. These two scenarios are also embraced in Egypt’s National Strategy for Adaptation to Climate Change and Disaster Risk Reduction (2011).

The outlines of proposed adaptation measures in the Nile delta coastal zone include (but are not limited to):

- Restoration and strengthening of existing coastal protection structures in risk areas with an emphasis on vulnerable low-lying land.

- Reinstatement and maintenance of sand dunes along the shore and the protective coastal sand belt.
- Preserving and protecting existing coastal wetlands (lagoons and lakes) in the northern Nile delta.
- Setting regulations to restrict development in vulnerable areas such as restrictions on set-back line for new developments at low-lying areas.
- Change of land use in low-lying zones such as converting agriculture to fish farming or salt tolerant crops.
- Relocation of most important infrastructures (major buildings, roads and facilities) in a landward direction.
- Controlling water extraction to minimize saltwater intrusion into ground-water in the upper Nile delta.
- Development of comprehensive monitoring program, early warning systems and decision support systems.
- Promotion of training programs and institutional and technical capacity building to deal with future risks of SLR in the Nile delta coastal zone.
- Improving technical understanding of the coastal inundation problem in the low-lying Nile delta using satellite images and DEM application.
- Encouraging scientific research programs capable of coping with the anticipated changes, demographic studies, socio-economic conditions and population characteristics.

Generally, a natural defense system provides a regular mechanism for protecting the coastal plain of the Nile delta and Alexandria against beach erosion and SLR. This system comprises: i) accreting coastlines, ii) high elevated topographic features such as sand dunes and limestone ridges. An accreting coastline is a natural protection system against the sea when its accreting rate exceeds erosion induced from coastal processes and SLR. Usually, bays and embayments have a higher tendency toward accretion, such as the central part of Abu Quir Bay and Gamasa embayment, than either straight or concave coasts (Lakhan and Pepper, 1997). Fortunately shorelines in these sectors are accreting with an average rate between 5-12 m/year (Frihy, 2003). Another example of natural defense against the sea, the low-lying areas south of Alexandria area (3 m below mean sea level) are not likely to be inundated by SLR because of its natural protection by shore-parallel ridge (5.4-m height).

Coastal protection structures, such as the Rosetta and Damietta seawalls have protected the upland areas from wave attack and SLR. Both natural system and coastal structures act together as a defense line against SLR. However, low-lying areas, without protection, are vulnerable to inundation and sea incursion due to SLR. These risk zones in the Nile delta are described below with adaption measures to minimize the SLR impacts.

- In the southern margins of Idku, Burullus, and Manzala lagoons, low-lying wetlands, below 1-m contour, would be affected by 0.5-m and 1-m SLR-scenarios if coastal protection works are not implemented. On the other hand, high-elevated dune-belts, or accretionary beaches, and artificially protected coastlines are partially protected against rising sea-level.
- The risk area would be in the vicinity the Manzala lagoon, where subsidence rates exceed 5 mm/year. The 0.5-m SLR-scenario would only cause partial inundation of the lagoon area. However, the 1-m SLR-scenario could result in the loss of the entire lagoon area, including surrounding small islands and fish farms, due to inundation.
- The narrow sand barrier of the Manzala lagoon, between El Gamil and Port Said, is vulnerable to sever erosion due to combined effect of coastal processes and SLR. This sector needs protection, and hence, additional considerations in the form of preservation and maintenance must form an important element of adaptation measures to combat the impact of SLR in the area.
- The area located at the lee-side of the Damietta spit on a straight sandy coast with no inlets is vulnerable to SLR. Impacts comprise disequilibrium of beach profile, and consequently erosion due beach adjustment. The continuous sand barrier downcoast of the Damietta spit needs coastal protection to prevent the continuous erosion process at a rate of 10 m/year (Frihy et al, 2010).
- The inundation analysis and maps showed that SLR may first cause sea-water to cross and enter the low-lying areas from the Manzala and Burrullus lagoons (Haggag et al, 2013). The embankment surrounding El-Salam canal (2-m height) could protect the low areas behind it till a level of about 1.0-m SLR. The lower parts of this embankment need to be reinstated by increasing the crest level to 2 m. Construction of a similar embankment should be consider for protection of the Burrullus lagoon, part of adaption measures, to avoid the impact of SLR in this region.

- The risk area west of Abu Quir remains highly vulnerable to storm surges and extreme events due to its relatively low elevation. This zone requires an emergency plan to reduce hazards induced by SLR (Frihy et al, 2010).
- Mohamed Ali seawall/revetment located in Abu Quir Bay protects the agriculture lowland against sea flooding. The seawall was repaired and upgraded in 1981and 2009 before the 2010 storm. Damages from the storm showed urgency for further upgrades (Ismail et al, 2012). It is recommended to increase the height of the seawall cap, and to strengthen the beach top and back-slope. In addition, a drainage facility should be added to the seawall to drain the overtopped storm water in the area behind the wall (Williams and Ismail, 2014).

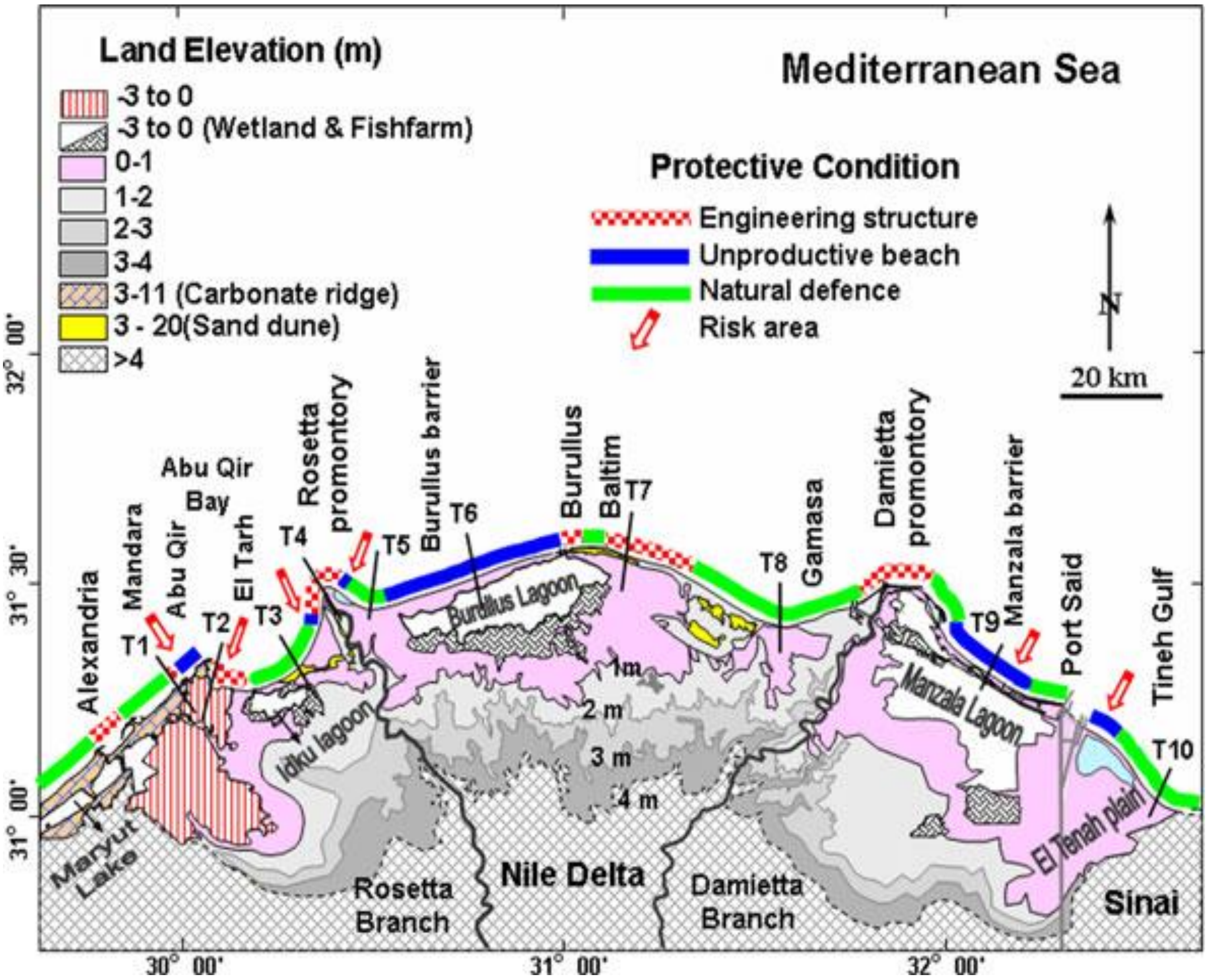

Figure 25: The lower coastal plain of the Nile delta and Alexandria showing land elevation relative to mean sea-level and protective state. Small arrows show risk areas. Source: Frihy and El-Sayed (2013).

7. SUMMARY AND CONCLUDING REMARKS

This paper aims to analyzing the risks and vulnerability, and suggesting adaptation measures to mitigate the impact of the SLR along the coastal zones in the Nile delta of Egypt. Relevant processes are emphasized and essential features of state-of-the-art are described. The Intergovernmental Panel on Climate Change (IPCC) declared in its Fourth Assessment Report (AR4, 2007): the Nile delta is one of three regions on earth that are most vulnerable to SLR in particular its lower coastal plain due to its relatively low elevation.

The Fifth Assessment Report (AR5) (IPCC, 2014) indicated that global sea-level will continue to rise at a rate very likely to exceed the rate of the past four decades. Local land subsidence in the Nile delta would exacerbate the impacts of rising seas. Relative SLR is not evenly distributed along the delta and utmost at the eastern region near Manzala lagoon with a value exceeds 5 mm/year. Based on the international consensus agreed upon in the Copenhagen Accord (2010), two possible SLR-scenarios of 0.5 and 1-m by 2100 are considered. These two scenarios are embraced in Egypt’s National Strategy for Adaptation to Climate Change and Disaster Risk Reduction (2011).

Environmental impacts of SLR on the Nile delta comprise: flooding due to storm surges; increasing beach erosion and inundation of low-lying areas. Moreover, salt-water intrusion would disturb the freshwater in the Nile-delta-aquifer as well as the brackish water wetlands including the coastal wetlands (lagoons and lakes) and fish farms. This may have an adverse impact on agriculture, and potentially on available groundwater resources in the upper Nile delta. The lagoon ecosystem, and hence fish resources, would gradually adapt to increasing salinity. On the other hand, socio-economics impacts of SLR will disturb many sectors of development, including tourism, cultural and natural heritage, crop quality, agricultural productivity, public health, and socio-economic benefits for people.

Although the impacts of SLR are potentially significant, the implementation and success of adaptation measures require further assessment and consideration. The potential impacts of SLR would be serious but manageable if appropriate adaptation measures are taken. Fortunately, many of the adverse consequences can be mitigated by taking timely measures in anticipation of SLR through the implementation of Egypt's National Strategy for Adaptation to Climate Change and Disaster Risk Reduction (IDSC/UNDP, 2011).

Both natural land features and artificial coastal structures act together as a defense line to protect the coastal plain of the Nile delta and Alexandria against beach erosion, SLR and wave action during storm events. The natural system comprises accreting beaches, high elevated topographic features such as sand dunes and limestone ridges. Coastal protection structure, such as the Rosetta and Damietta seawalls have been effective in protecting the upland areas from wave attack and SLR. The most susceptible areas are the Nile delta coastal wetlands and parts of the coastal plain between 0-1 m above mean sea-level. Risk areas in the northern Nile delta comprise: the Manzala lagoon barrier (particularly the narrow sand barrier east of El Gamil), eastern and western sides of the Rosetta city. Whereas, risk areas in the Alexandria region are: Mandara (east of the city) and El Tarh inside Abu Quir bay. Hence, it is recommended to reinstate the existing coastal structures, particularly on the low-lying lands and risk areas, including: the international coastal road, Mohamed Aly seawall, and the embankments of Al-Salam canal that connect the Damietta branch to Sinai.

The current measures for coastal protection against future SLR in the Nile delta are inadequate and need to be upgraded. Proposed adaptation measures in the Nile delta coastal zone include: maintaining coastal protection structures, restoration of sand dunes along the coastline, preserving existing wetlands (lagoons and lakes), setting regulations to control development in vulnerable areas, change of land use, relocation of infrastructures (roads and utilities) in the landward side, development of comprehensive monitoring program, technical capacity building, and finally promotion of research programs capable of coping with the anticipated changes, demographic issues, socio-economic conditions.

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