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Impacts of Sea Level Rise on Coastal flooding of Nile Delta, Egypt

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ABSTRACT

Many studies have investigated impacts of Sea Level Rise (SLR) on Nile Delta coastal zones in Egypt. Previous studies depended on areal surveying maps to develop digital elevation model (DEM) for Nile Delta coastal zones. Lacking field measurements and data to develop DEM that presents the actual situation of Nile Delta coastal zones, previous studies concluded that 20-30% of Nile Delta area will be inundated and lost if sea level rises by one meter. Accordingly, the current study aims to assess impacts of SLR on coastal inundation by utilizing field measurements of tide gages and land surveying data of 200 hydrographic profile across the coast line of Nile Delta.

To achieve study objective, DEM maps through GIS process were developed by Coastal Research Institute (CoRI). After developing the DEM maps, two modules with three scenarios (CoRI, B1, and A1F1) were introduced in each module to assess SLR expected and its impacts on Nile Delta coastal zones. The two modules initiated are business as usual module (module 1) and actual situation module (module 2).

Results indicate that for the first module (business as usual module), vulnerable areas to coastal flooding represent about 3.33%, 4.25%, and 11.75% of the total area of the Nile Delta for CoRI, B1, A1F1 scenarios respectively. On the other hand, considering the natural and man-made protection systems (module 2), vulnerable areas have percentages of 0.74, 0.97, and 3.01 of Nile Delta area for CoRI, B1, and A1F1 scenarios respectively. This means that less than 1.0% of the Nile Delta area will suffer from coastal flooding resulted from SLR expected by the end of the current century by CoRI and B1 scenarios and about 3% by A1F1 scenario by.

The study recommends further detailed studies to quantify impacts of SLR on coastal physical systems, infrastructure, saltwater intrusion, water resources, wave climate and water current patterns, erosion/accretion patterns and socio-economic sectors.

Keywords: Impacts, Sea Level Rise, Nile Delta, Costal Zones, Coastal Flooding

I. INTRODUCTION

Like other deltaic regions worldwide, the Nile Delta is subject to shoreline changes resulting from erosion and accretion, land subsidence, and sea level rise resulting from climate change. IPCC (2014) (1) in their fifth assessment report, stated that both relative see level rise (RSLR) and impacts are also influenced by a variety of local processes unrelated to climate (e.g., subsidence, glacial isostatic adjustment, sediment transport, coastal development),

Lacking field measurements and data to develop DEM that presents the actual situation of Nile Delta coastal zones, previous studies concluded that 20-30% of Nile Delta area will be inundated and lost if sea level rises by one meter.

As cited in ElGanzori (2012) (2), recent studies by CoRI used flow models in estimating the vulnerable areas due to SLR on the Nile Delta Mediterranean coast. These estimates were compared with previous results based on GIS techniques only, and they found that flow modeling techniques are more accurate in estimating the flooding extent due to considering mass conservation and the momentum in the governing equations of the flow model.

Utilizing tide gages measurements collected over the last three decades as well as tide gages measurements in Alexandria harbor and Port Said harbor, the current study has estimated sea level rise expected till the end of the current century. In addition, digital elevation model (DEM) for the coastal zone of Nile Delta has been developed. Furthermore, two modules with three scenarios in each (CoRI, B1, and A1F1) have been developed to assess SLR expected and its impacts on Nile Delta coastal zones, Elshinnawy (2008) (3). The two modules initiated are business as usual module (module 1) and actual situation module (module 2). Accordingly, current study aims to elaborate results of sea level rise impacts on coastal inundation of Nile Delta, Egypt.

II. METHODS AND MATERIAL

A. Study Area

The study area includes the entire coastline of the Nile Delta in Egypt which extends from Alexandria in the west to Port Said in the east with a total length of about 240 km, figure (1). It lies between longitudes 30° 12' and 32° E and latitudes 31° 12' – 31° 36' N.The coastline has two promontories, Rosetta and Damietta, a hump at Al-Burullus and concave between them.

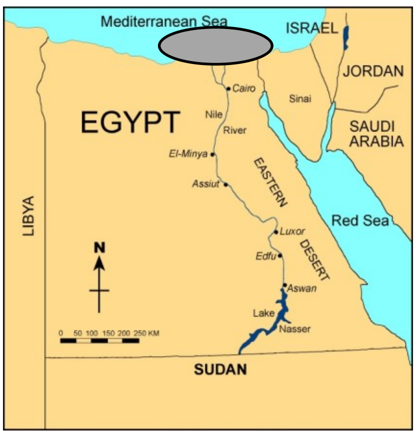


Figure (1): The study area includes the entire coastline of the Nile Delta in Egypt

There are three brackish lakes connected to the sea: Idku, Al-Burullus, and Al-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. The inland boundary of the study area extends from shoreline to contour line (+3 m) above mean sea level.

B. Data Statistical Analysis

Tide gauges measurements at Alexandria (west zone), Al-Burullus (middle zone), and Port Said (east zone) have been collected and statistically analyzed to estimate sea level rise (SLR) trend over the last three decades at each of these regions. Results indicate that SLR varies from region to another because of the land subsidence effect.

Estimated trends for SLR at Alexandria, Al-Burullus, and Port Said are 1.6, 2.3, 5.3 mm/year respectively. These values associate the effect of both SLR and land subsidence. In order to study the impact of climate warming on SLR, land subsidence at the three locations has been investigated.

C. Land Subsidence of the Nile Delta

According to Stanley (1990) (4), the long-term subsidence rates at or near the Nile Delta coast, averaged for the mid-to upper Holocene, range from about 0.1 to 0.25 cm/y between Alexandria and the north-central delta margin. Rates increase markedly eastward to a maximum of about 0.5 cm/y in the Port Said-Al-Manzala lake region, and this rapid lowering explains the presence of thick marine delta lobe sequences of Holocene age in cores in the north-eastern delta. Warne and Stanley (1993) (5) reassessed these estimates and suggested that they were minimum rates because sediment reworking can cause radiocarbon dated cores to be older than the burial age. Stanley (1997) (6) concluded that higher values (lowering to 5 mm/year) are recorded along the north east corner of the delta. Aly (2005) (7), used radar interferometry for measuring urban subsidence and coastal change in the Nile Delta. He highlighted the urgent need of regular monitoring of subsidence and coastline retreat in the Nile Delta. Recently, Becker and Sultan (2009) (8) reported moderate subsidence rates (4–6 mm/yr.) around Al-Manzala Lagoon.

Based on previous brief, the average of long-term subsidence rates at or near the coast for the mid- to upper Holocene ranges from about 0.1 to 0.25 cm/yr between Alexandria and the north-central delta margin. Rates increase markedly eastward to a maximum of about 0.5 cm/yr in the Port Said-Manzala lagoon region [4]. Accordingly, land subsidence value at Port Said considered in the current study is 4.0 mm/y as an average value of subsidence during the past 7000 years (2.6 to 4.1 mm/y). Knowing that the global average sea level rise is 1.2 mm/y, the difference between this value and tide gauge trends at Alexandria and Al-Burullus was considered as the land subsidence value for the middle Delta Region, Table (1)

Table (1) Sea Level Rise and Subsidence Rates at Nile Delta Zones

Region	Alexandria (West Zone)	Al-Burullus (Middle Zone)	Port Said (East Zone)
Tidal Trend (mm/y)	1.6	2.3	5.3
Subsidence (mm/y)	0.4	1.1	4
SLR (mm/y)	1.2	1.2	1.3

D. Expected Sea Level Rise till 2100

The projected values of the mean surface air temperature, 2000-2100, for the low scenario (B1) and for the high scenario A1F1 of SRES are given in table (2).

Table (2) Projected Values of Mean Air Temperature

Temperature Change for Years 2025, 2050, 2075 and 2100 (ºC)					
2000	Scenario	2025	2050	2075	2100
0.6	B1	0.9	1.3	1.8	1.8
0.6	A1F1	1.2	2.2	3.2	4.0

The average increase in global warming at the end of the twenty century was about 0.6 ºC (IPCC, 2007) [9]. Assuming linear variation of global warming with time during the last two decades, the value of 0.006 C0 could be accepted as the average annual temperature change during the last twenty years.

Assuming that the land subsidence will occur with the same rates, the projected average sea level rise at the end of the years 2025, 2050, 2075, and 2100 has been estimated applying the projected average surface warming given in table(2). Results are shown in table (3).

Table (3): Projected (low and high) Average Annual Sea Level Rise (cm) Relative to Year 2000 Sea Level.

City	Scenario	2025	2050	2075	2100
Port S3aid	B1	18.12	39.5	64.3	72.5
	A1F1	27.9	68.8	109.6	144.0
Al-Burullus	B1	8.75	19.5	32.25	35.0
	A1F1	14.75	37.5	60.3	79.0
Alexandria	B1	7.0	16.0	27.0	28.0
	A1F1	13.0	34.0	55.0	72.0

E. Vulnerability Assessment (Expected Coastal Flooding)

1) VA Methodology: After creating DEM for the Nile Delta, two modules were initiated with three scenarios introduced in each module to assess the vulnerability for the three Nile Delta regions. The two modules initiated are business as usual module (module 1) and actual situation module (module 2). Each module has the following three scenarios:

- Expected impact of SLR on the coastal zone according to tide gauges measurements carried out by CoRI over the last three decades, (CoRI scenario assuming same increase rate of air temperature till 2100)
- Expected impact of SLR according to B1 scenario, and
- Expected impact of SLR according to A1F1 scenario.

In these three scenarios, Alexandria represents the western region of the Nile Delta, Al-Burullus represents the middle Delta region, and Port Said represents the eastern Nile Delta region. River Nile branches are considered the natural divide between the three regions. For accuracy reasons, land subsidence was subtracted from the projected sea level rise values estimated due to air temperature increase till the end of the current century. In module (1), all protection systems as well as lakes borders levels have been ignored while module (2) has considered the natural sand dunes system in the middle delta region, Mohammed Aly Sea wall at Abu-Qir Bay and Al-Salam canal banks at the western and southern borders of Al-Manzala Lake as well as Al-Burullus lake borders levels.

II. RESULTS AND DISCUSSION

A. Preliminary Results (Business as usual) : Module1

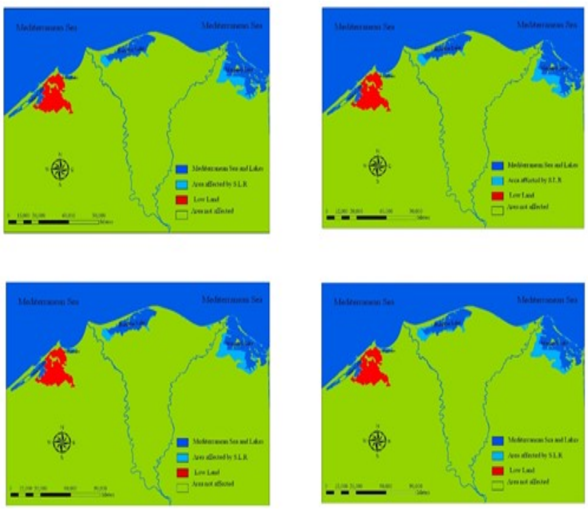
1) CoRI Scenario: According to field measurements, table (4) summarizes average annual trends and expected sea level rise till 2100. Results of the first scenario (same increase rate of air temperature till 2100) indicate that areas located to the west of Al-Burullus Lake as well as those located to the west and to the south of Al-Manzalla Lake are the most vulnerable areas to SLR, figure (2).

Table (4): Trend and expected sea level rise (SLR) Till 2100 according to field measurements (CoRI-2008) [10]

Station	Average SLR/year (cm)	SLR 2025 (cm)	SLR 2050 (cm)	SLR 2075 (cm)	SLR 2100 (cm)
Alexandria	0.16	4.0	8.0	12.0	16.0
Al-Burullus	0.23	5.75	11.5	16.25	23.0
Port Said	0.53	13.25	26.5	39.75	53.0

Results presented in table (5) show that about 633 km^2, 692 km^2, 748.4 km^2, and 832.6 km^2 will be affected till years 2025, 2050, 2075, and 2100. These values represent about 2.53%, 2.75%, 3.0%, and 3.33% of the Nile Delta area. Most of these areas are located in the eastern region according to subsidence effect. On the other side, western region will suffer from SLR less than other areas as the subsidence effect is minimal. Red color in Figure (2) indicates low laying area (-1.5 to -2.5 m) protected by Mohammed Aly sea wall.

CoRI 2025 CoRI 2050



CoRI 2075 CoRI 2100

Figure (2): Vulnerable areas due to tide gauges measurements by CoRI, 2008[10]

Table (5): Total affected area and its percentage to the Nile Delta area According to CoRI measurements till 2100 (Considering Mohammed Ali wall and zero level for lakes borders)

Year	2025	2050	2075	2100
Total Area Affected (km^2)	633.8	691.8	748.4	832.7
Total % of the Nile Delta Area	2.53	2.57	3.0	3.33

2) B1 Scenario: According to temperature increase and its projection till the end of the current century, Table (6) presents the expected SLR till 2100 according to the low scenario (B1 scenario) of the special report on emission scenarios (SRES), IPCC-2007[9]. Expected vulnerable areas due to SLR are shown in Figure (3).

Table (6): Expected sea level rise (SLR) Till 2100 by projected increase in air temperature (B1 Scenario)

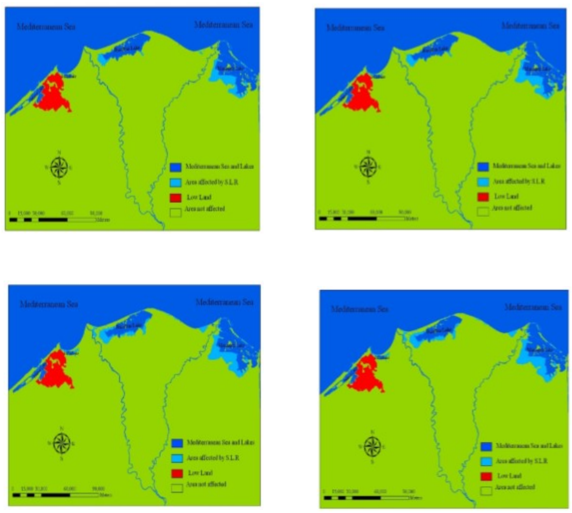
Station	SLR 2025	SLR 2050	SLR 2075	SLR 2100
Alexandria	7.0	16.0	27.0	28.0
Al-Burullus	8.75	19.5	32.5	35.0
Port Said	18.125	39.5	64.3	72.5

Analysis of results presented in table (7) specify that about 658 km^2, 752 km^2, 1022 km^2, and 1059 km^2 will be affected till years 2025, 2050, 2075, and 2100 respectively of the coastal region of the Nile Delta. These values present about 2.63%, 3.0%, 4.1%, and 4.23% of the Nile Delta area.

Table (7) Total affected area and its percentage to the Nile Delta area According to B1 scenario till 2100

Year	2025	2050	2075	2100
Total Area Affected (km^2)	657.7	752	1021.9	1058.8
Total % of the Nile Delta Area	2.63	3.0	4.1	4.23

B1 2025 B1 2050



B1 2075 B1 2100

Figure (3): Vulnerable areas due to B1 Scenario

3) A1F1 Scenario: Results of the this scenario represent the worst case that the Nile Delta could face if the concentrations of CO2 reached the expected optimum value of 1550 ppm considered in A1F1 scenario modeling instead of 375 ppm concentration of the year 2004.

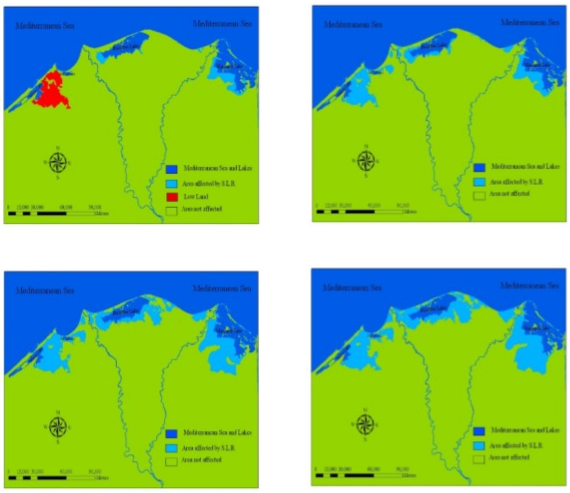
Results of this case, Table (8) and Figure (4) represent the maximum vulnerability condition of coastal flooding at Nile Delta coastal zone according to module(1).

Analysis of results presented in table (8) indicate that about 701 km^2, 766.5 km^2, 2348 km^2, and 2938 km^2 will be flooded till years 2025, 2050, 2075, and 2100 respectively of the coastal region of the Nile Delta. These values present about 2.8%, 3.1%, 9.4%, and 11.75% of the Nile Delta area.

Table (8): Total affected area and its percentage to the Nile Delta area (A1F1 scenario)
(Considering Mohammed Ali wall and zero level for lake's borders)

Year	2025	2050	2075	2100
Total Area Affected (km^2)	701	766.5	2348	2938
Total % of the Nile Delta Area	2.8	3.1	9.4	11.75

A1F1 2025 A1F1 2050



A1F1 2075 A1F1 2100

Figure (4): Vulnerable areas due to A1F1 Scenario

B. Lakes Boundaries

Elshinnawy , (2008) (3) stated that levels of Al-Manzalla Lake borders were considered 2.5 m above mean sea level in module (2).

In his hydrological study about Al-Burullus lake, Elshinnawy , (2003) (11) indicated that water levels in the lake vary between 26 cm to 62 cm. Leveling study indicated that levels of lake borders vary between 50 cm in the north to 2.0 m in the south.

C. Final Results (Actual Situation): Module (2)

In this module, natural and man-made supporting systems have been considered in initiating module (2). These systems are:

- Natural sand dunes exist mainly in the middle region
- Mohammed Ali sea wall with crest levels varies from 2.25m to 3.0 ms.
- Al-Manzalla Lake is bounded in the west and in the south by Al-Salam canal that have banks elevations vary from 0.5 m in the north to more than 2.5 m in the west and in the south.
- Boundaries of Al-Burullus Lake vary from 0.5 m in the north to more than 2.0 m in the west and in the south.

According to these findings and for accuracy purposes to get the actual situation that the coastal zone of the Nile Delta might face regarding climate change impact on sea level rise, the above data were utilized in the modeling process to define the vulnerable areas by implementing the same three scenarios in module (2).

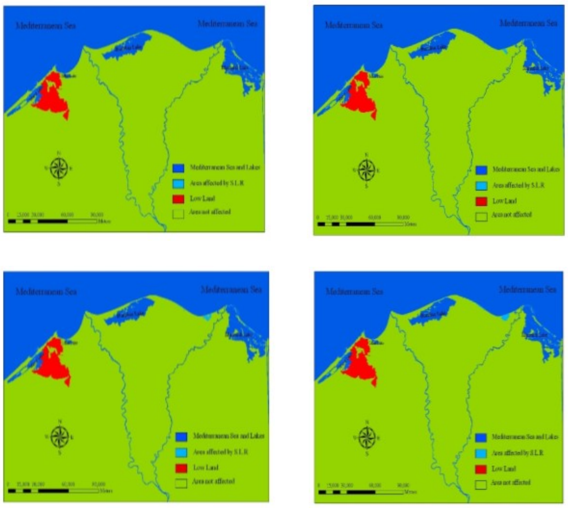
1) CoRI scenario: Results of CoRI scenario indicate that the sandbar located between Al-Manzalla Lake and the Mediterranean in the east region is vulnerable to SLR. Regarding the middle region of the Delta, the area located between Gamasa City and New Damietta is also vulnerable as well as Al-Burullus sandbar. Estimated areas expected to be flooded by sea level rise till the end of the current century in the Nile Delta coasts and their percentage are presented in table (9)and illustrated in Figure (5).

Table (9): Total affected area and its percentage to the Nile Delta area According to CoRI measurements till 2100
(With Mohammed Ali wall and lakes borders)

Year	2025	2050	2075	2100
Total Area Affected (km^2)	93.68	134.0	139.2	183.8
Total % of the Nile Delta Area	0.37	0.54	0.56	0.74

Results presented in table (9) reveal that about 94 km^2, 134 km^2, 139 km^2, and 184 km^2 will be affected till years 2025, 2050, 2075, and 2100 respectively of the coastal zone of the Nile Delta. These values present about 0.37%, 0.54%, 0.56%, and 0.74% of the Nile Delta area. Most of these areas are located in the middle region of the Delta. On the other side, western region will suffer from SLR less than other areas as the subsidence effect is minimal.

CoRI 2025 CoRI 2050



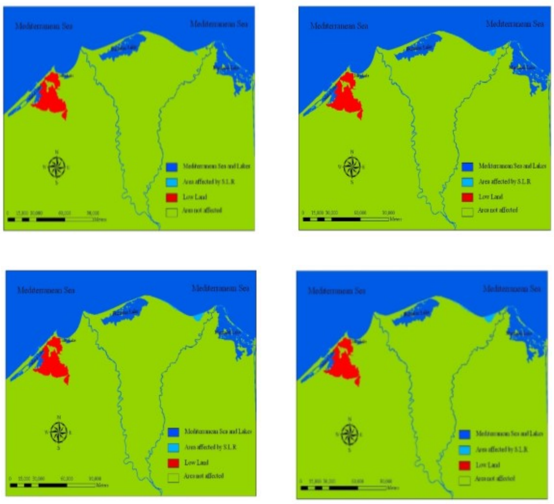
CoRI 2075 CoRI 2100

Figure (5): Vulnerable areas due to tide gauges measurements by CoRI, 2008[10]

2) B1 Scenario: Results of B1 scenario indicate the same trend of vulnerability in the coastal zone of the Nile Delta as mentioned in CoRI scenario with some increase in the vulnerable areas in the middle region. Figure (6) illustrates the vulnerable areas in the Nile Delta regions.

Analysis of results presented in table (10) specify that about 119 km^2, 170 km^2, 222 km^2, and 243 km^2 are vulnerable till years 2025, 2050, 2075, and 2100 respectively of the coastal region of the Nile Delta. These areas present about 0.45%, 0.68%, 0.89%, and 0.97% of the Nile Delta area.

B1 2025 B1 2050



B1 2075 B1 2100

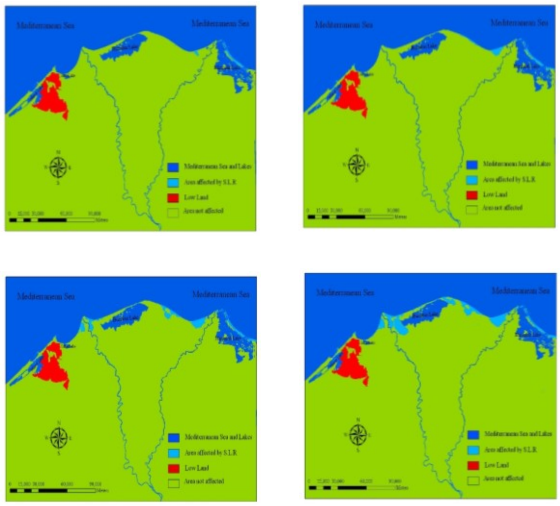
Figure (6): Vulnerable areas due to B1 Scenario

Table (10): Total affected area and its percentage to the Nile Delta area (B1 scenario)
(With Mohammed Ali wall and lake's borders)

Year	2025	2050	2075	2100
Total Area Affected (km^2)	118.5	169.45	221.83	243.1
Total % of the Nile Delta Area	0.45	0.68	0.89	0.97

3) A1F1 Scenario: Results of the this scenario represent the actual situation that the Nile Delta could face considering the fact that the borders of the lakes are above zero level (from 0.5m to 2.5 m on average) and the low lands at Abu-Quir Bay is protected by Mohammed Ali sea wall constructed in 1830. Accordingly, expected vulnerable areas are shown in Figure (7).

A1F1 2025 A1F1 2050



A1F1 2075 A1F1 2100

Figure (7): Vulnerable areas due to A1F1 Scenario

Analysis of results presented in table (11) specify that about 153 km^2, 256 km^2, 450 km^2, and 761 km^2 will be affected till years 2025, 2050, 2075, and 2100 respectively of the coastal zone of the Nile Delta. These values present about 0.61%, 1.03%, 1.8%, and 3.01% respectively of the Nile Delta area.

Table (11): Total affected area and its percentage to the Nile Delta area (A1F1 scenario)
(With Mohammed Ali wall and lake's borders)

Year	2025	2050	2075	2100
Total Area Affected (km^2)	152.86	256.27	450	761.4
Total % of the Nile Delta Area	0.61	1.03	1.8	3.01

III. CONCLUSION

The current study provides an assessment to vulnerability of the Nile Delta coats to sea level rise (SLR) expected from the climate change. The study was carried out by using actual measurements of tide gages for the last three decades to estimate the trend of average mean sea level in three locations represent Nile Delta coastal regions. Statistical analysis of data indicated that the average mean sea level rise changes from region to another due to land subsidence. Statistical analysis indicated that the rate of average mean SLR is 5.3mm, 2.3mm, and 1.6 mm in Port Said, Al-Burullus, and Alexandria respectively. The three scenarios named; CoRI scenario, B1 scenario, and A1F1 scenario were developed according to temperature projection in 2025, 2050, 2075, and 2100. The study was carried out in two different modules. Results indicate that for the first module the vulnerable areas represent about 3.33%, 4.25%, and 11.75% of the total area of the Nile Delta for CoRI, B1, A1F1 scenarios respectively. On the other hand, considering the natural and man-made protection systems, vulnerable areas have percentages of 0.74, 0.97, and 3.01 of the area of the Nile Delta area for CoRI, B1, and A1F1 scenarios respectively. This means that less than 1.0% of the Nile Delta area will suffer from sea level rise in CoRI and B1 scenarios and about 3% with A1F1 scenario.

IV. RECOMMENDATIONS

As the study emphasized on coastal flooding due expected SLR, the following aspects are recommended to be covered in further studies for the coastal zones of the Nile Delta as well as other deltas worldwide:

Potential impacts on land and groundwater salinity, patterns of waves and currents, erosion and accretion systems due to current and wind actions, lakes ecosystems, coastal water resources and drainage systems, fisheries due to changes expected in current patterns, infrastructures and natural resources of the coastal zone, evaporation from oceans and seas open waters and their role in reducing SLR, and plankton role in absorbing CO2 and generating O2.

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