



Development of an Inundation Model for the Northern Coastal Zone of the Nile Delta Region, Egypt Using High-Resolution DEM

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Abstract

Egypt is facing several hazardous environmental phenomena, particularly Sea Level Rise (SLR) and land subsidence. It has been considered to be one of the countries most likely to be affected by SLR because of the low elevation of the Nile Delta region's northern coastal zone, like all world Deltas. For that, a GIS inundation model has been generated using an original high accuracy local digital elevation model for the Nile Delta region, Egypt (LDEM) and the SLR data measured by the tide-gauges. This model has been used to determine the vulnerable low laying areas to inundation from future SLR in 2050 and to determine land-use types and percentages that are most likely to be affected in the northern Mediterranean coast of Nile Delta region. Finally, a total Hazard Index Map (HIM) has been produced from combining SLR HIM, and the subsidence HIM for the study area which will present the full danger of the two phenomena on the coastal region. The results have shown that the inundated area calculated from the SLR in 2050 model is about 50 km². From the land-use maps, the areas flooded by the sea represent almost 38.40 km², 3.80 km², 5.20 km², and 2.60 km² for the urban, agricultural lands, fishing farms, and bare areas, respectively. The authorities and decision makers should pay more attention to the hazardous effects due to the impacts of subsidence and SLR in the Nile Delta region, especially the northern coastal zone. More protection construction such as seawalls and breakwaters should be built at the northern coastal zone of the Nile Delta region vulnerable to inundation of SLR, to prevent the occurrence of the predicted inundation scenarios that could be occurred to this region in the future.

Keywords Sea level rise (SLR) · Hazard Index map (HIM) · Geographic information system (GIS) · Nile delta · Egypt

1 Introduction

SLR relative to the land surface changes has happened repeatedly throughout Earth's history for natural reasons. Relative sea level changes develop due to a complex and dynamic interaction between local, regional and global factors. These factors are: global rise or fall of the eustatic sea-level (world sea-level) surface due to the changes in the volume of mid-ocean ridges, and ocean thermal expansion caused from global warming or climatic change due to the increasing concentrations of greenhouse gases in the atmosphere, regional or seasonal oceanographic processes (winds,

storm surges, waves, tsunamis and cyclones), vertical movements of the land (neotectonic effects, Isostatic compaction, oil or groundwater extraction). Ocean thermal expansion has been expected to be the dominating factor behind SLR since it causes sea water to expand when heated, and leads to the melting of glaciers such as Greenland and Antarctica which adds to the rise [1, 2].

The impacts of SLR will not be globally uniform due to the local variations and regional factors in vertical crustal movements (subsidence), topography, wave climatology, long shore currents, and storm frequencies [3]. Low gradient coastal landforms are the most susceptible to inundation including low-lying river Deltas, estuaries, beaches and coastal wetlands, oceanic islands, and coral reefs. Because of the low elevation of the Nile Delta region's northern coastal zone, like all world Deltas, Egypt has been considered to be one of the countries most likely to be affected by SLR [4, 5], and is consequently vulnerable to the direct and indirect impacts of SLR. Possible implications of SLR include:

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- Acceleration of shoreline changes due to erosion and accretion
- Increased flooding due to increased storm surge, high tides, windstorms, and wave damage
- Direct inundation of wetlands and estuaries
- Saltwater intrusion and contamination (salinization) of soil, coastal lagoons, Nile River, and groundwater aquifer
- Damage to urban centers and threats to socioeconomic activities which are considered a major Gross Domestic Product (GDP) contributor of Egypt such as: agriculture lands, fisheries productivity, tourism, industrial activities, commercial centers, trading and transportation centers distributed across a wide range of harbors, human settlements and infrastructure

Researchers are working hard to define the nature of climate change, the rates at which change can take place, and the effects that change may have in the future on SLR to predict its rates. According to the Intergovernmental Panel on Climate Change (IPCC) scenarios, models of global climate have predicted that by the end of the twenty-first century, a global SLR of between 0.18 and 0.59 mm/year will occur [6]. Several tide gauges have been established in Egypt to monitor the variations of sea level [e.g., 7]. In other studies, the vulnerability of the northern coast of Egypt, in general, and the Nile Delta in particular, to inundation by SLR has been repeatedly considered [e.g., 8]. Frihy [1] have integrated the main factors that affect the Egypt's Nile Delta—Alexandria region (erosion and accretion patterns, topography, subsidence rates and relative SLR) to determine the degree of vulnerability to coastal erosion assuming a mean SLR ranging between 1.6 and 2.3 mm/year. They have also conducted a degree of vulnerability analysis to better locate which sectors for their study area need to be evaluated and adapted to possible SLR. Their Results have revealed that not all of The Nile Delta's coastal zone have been vulnerable to accelerated SLR at the same level and that the Nile Delta-Alexandria coast can be categorized into vulnerable (30%), invulnerable (55%) and coastal stretches artificially protected (15%). Frihy and El-Sayed [9] have established, analyzed, and ranked risk areas to suggest adaptation measures to mitigate the SLR's impact along the Egyptian Mediterranean coast based on analysis of vulnerability in society and biophysics. Hassaan and Abdrabo [10] have identified land use areas susceptible to flooding by SLR based on the latest SLR scenarios, using GIS techniques by the year 2100. Their results have indicated that, under various SLR scenarios, approximately 37.96% of the total area of the Nile Delta Coastal Governorates would be vulnerable to flooding. They also found 15.56% of the Nile Delta's total area would be vulnerable to flooding due only to land subsidence, even in the absence of any rise in sea level.

Haggag et al. [11] have developed a GIS inundation model taking in consideration sea or lakes connectivity, with DEM as the main input for understanding the impacts on existing coastal systems, infrastructures and properties and suggest some long-term adaptation measures. The SLR's impact has been assessed by mapping the inundated areas with an SLR 0.5, 1.0, 1.5, 2.0 and 2.5 m, respectively. Hasaan [12] has assessed and analyzed the risks of inundation and its implications of the expected SLR up to the year 2100 in the Governorate of Kafr El Sheik, Egypt, using GIS approaches. Solyman et al. [13] have presented an integrated web map solution methodology for accessing the effect of SLR scenarios on the northern coast of EGYPT. They have included important factors in the designing and implementing of the Egyptian SLR as a web GIS application such as functional module, graphic user interface, downloading time, system performance and the technology related. Hasan et al. [14] have performed a future impact assessment of SLR on Egypt's Nile Delta region by assessing the elevations of the SRTM and the ASTER-GDEM V2 DEMs. Ali and El-Magd [15] have processed Satellite images to identify impact of human interventions and coastal processes along the coast of the Nile Delta, Egypt over the 25 years (from 1990 to 2014) using GIS techniques. Elevation in general is considered to be the most critical factor in evaluating the potential impact of SLR on coastal areas of the Nile Delta region because this area is located in a relatively stable tectonic region [16], with a low land subsidence rates that ranges between approximately 6 mm/year to 8 mm/year [17]. Similarly, this region rarely experiences any catastrophically or disastrous large storm surge waves that are generated by frequent Tsunami earthquake events [18]. During the winter season, the average storm surge height is only 0.6 m [19].

Nevertheless, it can be concluded that the quite diverse estimates of the vulnerable areas to inundation in the Nile Delta coastal area could be due to the wide range of SLR hypothetical scenarios. It can be also concluded that despite their diverse estimates, previous studies agreed that the Nile Delta coastal zone would be highly vulnerable to inundation due to the expected SLR, and that inundation caused by SLR can be identified as a significant natural hazard affecting densely populated and built-up areas. It is also very important to mention that, The DEMs used to assess coastal vulnerability to flooding in previous studies have different horizontal and vertical resolutions. However, the quality of DEM used in environmental assessments can have a significant impact on the detection of topographical features and the magnitude of hydrological processes, since DEM is usually used to derive the information about slope, slope aspects, drainage identification, watershed delineation, flow accumulation, and flow direction. In regards to SLR vulnerability assessment, the estimates discussed in previous studies on Nile Delta inundation due to SLR did not pay much attention to improve the

accuracy of the topographical data which is the determinant factor in the accuracy of the inundation results. Thus, most of the available inundation studies are based on the Global DEM (GDEM) dataset.

Due to the insufficient vertical accuracy of the free GDEM available data sources, incorporating such inadequate elevations in SLR analysis will add more uncertainties to the estimation and assessment of the future impact of SLR on the Nile Delta region. For this reason, a coastal study has been performed on the northern Mediterranean coast of Nile Delta region using the SLR data measured by the tide-gauges installed at Alexandria, and Port Said, and the elevation data provided from the high accuracy LDEM generated by El-Quilish et al. [20] and shown at (Fig. 6).

2 Study Area

The studied area investigated in this study covers most of the Nile Delta region north of Egypt, where its boundaries extend from Alexandria in the west to Port Said in the east at longitudinal lines extend, respectively, from 29.6°E to 32.3°E, and from Cairo in the south to the northern Mediterranean coasts in the north at latitude circles extend, respectively, from 30.0°N to 31.6°N, as shown at (Fig. 1). It is bounded by the two branches of the Nile River of Damietta and Rosetta, and extends from both sides to cover coastal areas, with an overall area of about 23,235 km². The length of the study area is approximately 180 km from north to south, and it covers about 300 km of coastline at the Mediterranean Sea (18% of

the Egyptian Mediterranean coast). Three major coastal lakes “Burullus, Idku, and Mariut” occupy the shoreline. The Suez Canal runs east of the Delta, into its northeast coastal Lake Manzala. The region’s topography smoothly slopes north toward the Mediterranean coast, where the elevation difference between Cairo’s southern peak and the northern coastal fringes is about 18 m (Fig. 2).

3 Data Acquisition

Several types of geospatial data have been acquired, manipulated, and analyzed in the current study. The following sub-sections present characteristics of each data type. The georeferencing of all the used data has been adjusted to World Geodetic System 1984 (WGS84) as horizontal datum and EGM96 as vertical datum.

3.1 Sea Level Rise

The absolute SLR is the product of the general worldwide (eustatic) rise in sea level in addition to any local land-level changes with respect to a geodetic datum and any regional or seasonal oceanographic processes. It is measured mainly by tide-gauges installed at a specific site. The relative continuation of SLR can be noticed in the year to year average measurements of tide gauge records. The SLR rates used in this study have been estimated from tide gauges installed at Alexandria, and Port Said (from 2012 to 2017) [21] (Fig. 3). Those absolute rates combine relative rise from tide gauge

Fig. 1 The study area of the Nile Delta region (WGS84)

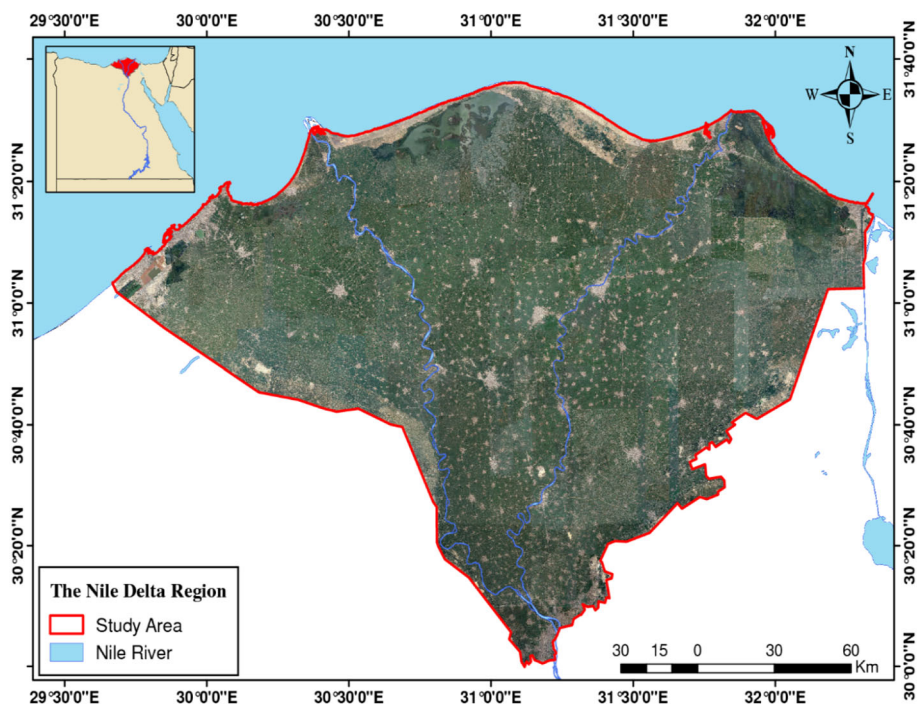


Fig. 2 The Topography of the Nile Delta region (WGS84) [25]

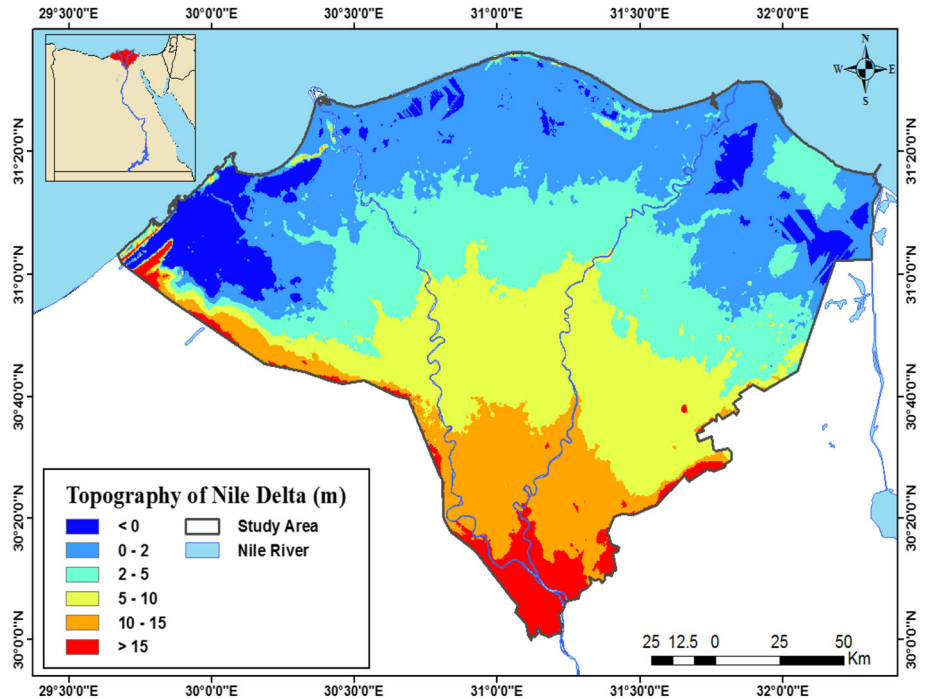
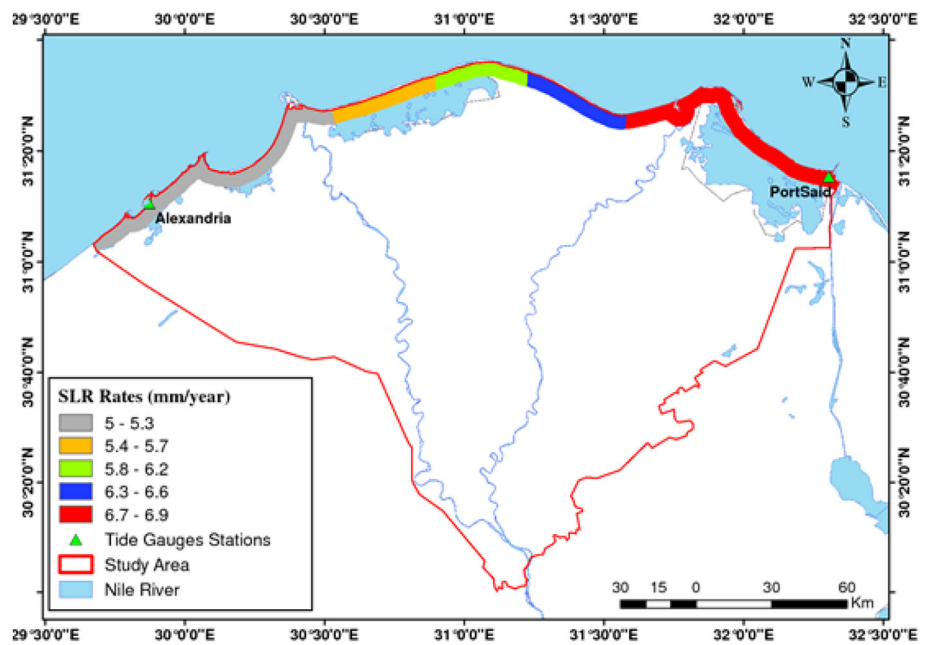


Fig. 3 SLR absolute rates at the coastal zone of the Delta in mm/year (WGS84) (Modified after Dawod [21])



records plus land subsidence rates from GPS data. Measurements indicate that sea level has been continuously rising at a rate of 5.0 and 6.9 mm/year (Table 1), respectively, with an average rate of 6.0 mm/year.

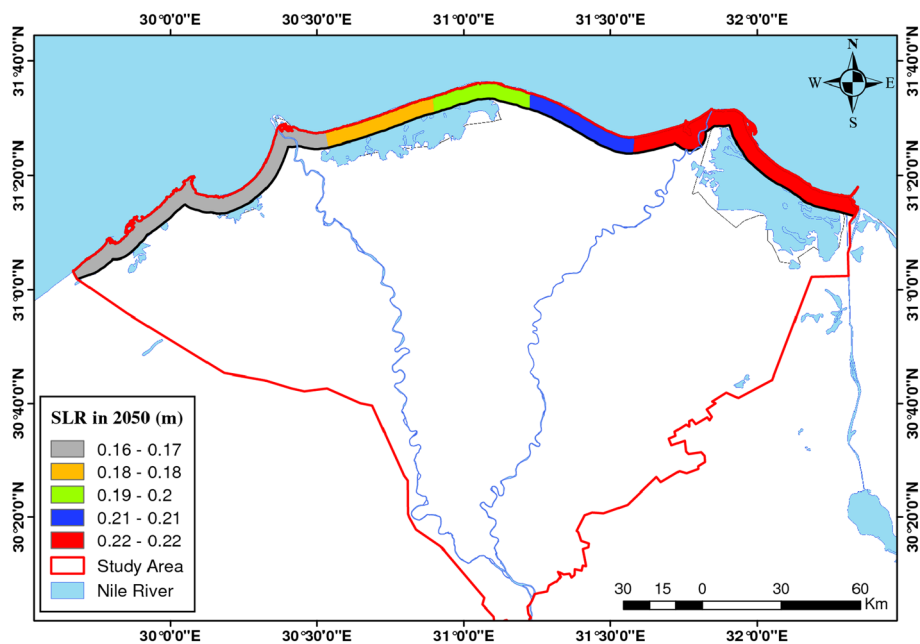
An interpolation process has been performed for the SLR rates points using GIS approaches to produce a SLR raster surface for the coastal zone of the Nile Delta region (Fig. 3). The produced raster of the expected SLR up to 2050 has been calculated by multiplying annual SLR rates by the number of years up to the year 2050. As a result of this step, a new

Table 1 Absolute sea level rise rates 2012–2017

Station	ϕ	λ	Sea level rise rates (mm/year)
Port said	31.26	32.30	6.90
Alexandria	31.18	29.87	5.00

raster surface has been generated representing the SLR for Nile Delta’s northern coastal zone in 2050 in meters (Fig. 4).

Fig. 4 SLR in 2050 at the coastal zone of the Delta in meters (WGS84)



3.2 Subsidence Rates

Although many geodetic monitoring methods and approaches are used to detect land subsidence and deformation such as tide gauge data analysis, radar remote sensing imageries, and repeated levelling data, GPS proves to be the most accurate and precise approach that can attain the millimeter level of accuracy. In the light of that the subsidence rates used in this study has been based on the work of Mohamed et al. [22], since they have developed a high-precision GPS geodetic techniques for seven stations to monitor land subsidence and horizontal deformation in the Nile Delta area covering the period from 2012 to 2015. The vertical land movement rates at these seven locations range from + 4.9 to – 6.5 mm/year as shown at Table 2, with subsidence exist in Port Said and Tanta, while the remaining four stations show uplifting. Furthermore, a spatial model for the vertical movements in the Nile Delta region (Fig. 5) has been developed using the IDW interpolation method within the GIS. From Fig. 5, it can be concluded that the average vertical movement, over the study area, equals – 0.68 mm/year with SD of ± 2.20. Additionally, it can be realized that the middle region of the Delta suffers from land subsidence, particularly at its eastern fringes, while the north-western and the south-eastern regions show an uplift.

3.3 Local Digital Elevation Model

Since there is no published official precise DEM for Egypt, the LDEM for the Nile Delta region, Egypt developed by [20] has been used to investigate the hazardous effects of

SLR phenomena. The LDEM was developed by digitizing over 220 topographic maps and applying nine different spatial interpolation methods (namely; IDW, NNIDW, GPI, SWB, TTR, Kriging, RBF, EBK, and LPI), then comparing their accuracies against eight recent global DEMs (namely; EarthEnv-D90, SRTM1, SRTM 3, ASTER, GMTED2010, GLOBE, GTOPO30, and AW3D30), then using about 200 known GPS/levelling ground control points to evaluate the performance and accuracy of both the global DEMs and the newly developed LDEMs. Their results has shown that that the Kriging-based local DEM is the best and most accurate DEM for this region due to its nearly flat topography and it improved the overall accuracy and reliability of the best available global DEM “EARTHEnv-DEM90” by almost 42%, hence, it is appropriate for geospatial, environmental, and GIS studies in the Nile Delta region, Egypt (Fig. 6).

Table 2 Vertical land movements rates 2012–2015

Station	ϕ	λ	Vertical movement rate (mm/year)
Port said	31.27	32.28	– 4.72
Cairo	30.03	31.22	+ 4.94
Baltim	31.55	31.09	+ 0.71
Abu kebeer	30.73	31.67	+ 3.69
Tanta	30.79	30.99	– 6.51
Abu El_matameer	30.91	30.16	+ 0.55
Matroh	31.20	29.91	– 0.85

Fig. 5 Vertical Ground Movements Annual Rates in mm/year (WGS84) (Modified after Mohamed et al. [22])

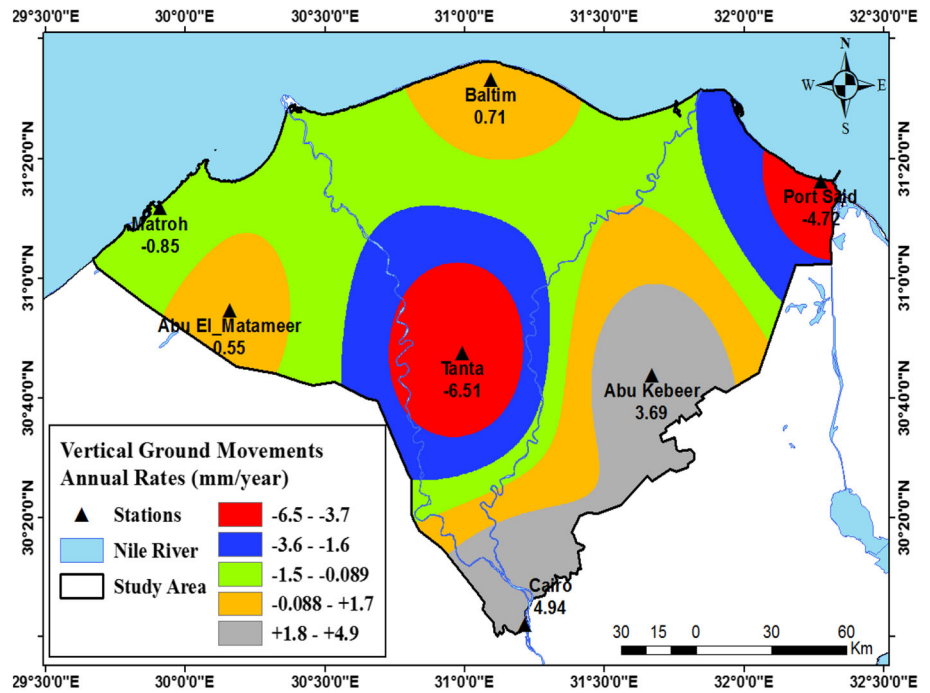
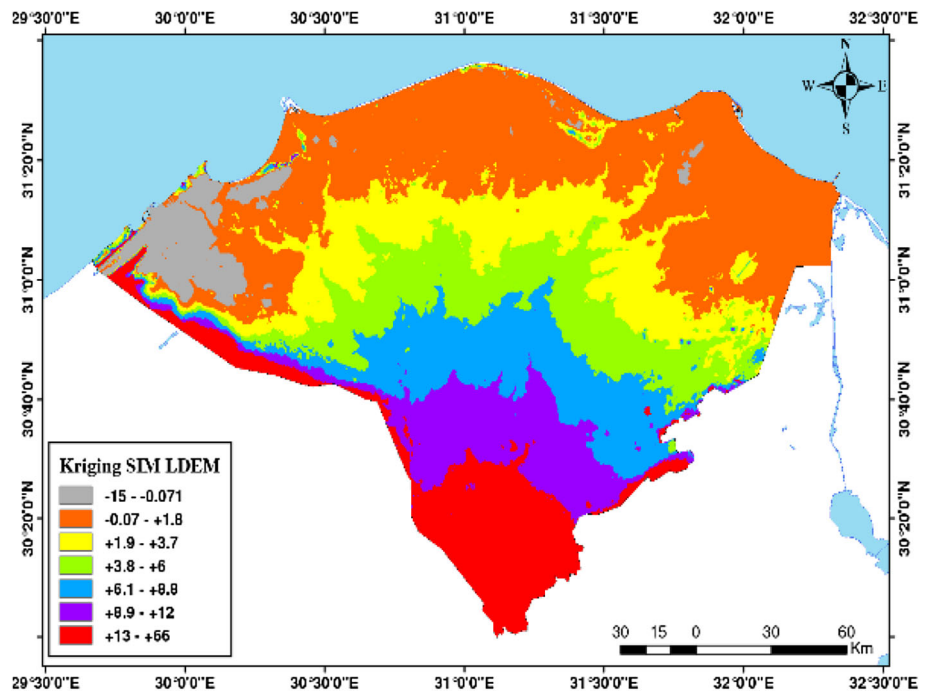


Fig. 6 Best LDEM by Kriging spatial interpolation method (WGS84) El-Quilish et al. [20]



3.4 Urban Land Use Areas

A new 2019 Google satellite map for the Nile Delta region has been used to extract the urban land use and settlement areas using GIS “Image Classification” tool which performs a classification on a series of input raster bands. Figure 7 shows that total urban area amounts 2,759.71 km², which represent 11.88% of the total study area.

3.5 Land Use Map

The Land use map for the Nile Delta region has been extracted from a raster map for the global land cover produced in 2013 by the National Mapping Organizations (GLCNMO) [23, 24]. The map covers the whole globe in grids of 500 m (15 s) intervals, and classifies the land cover status of the entire globe into 20 categories. The classification is based on the

Fig. 7 Urban land use areas (2019)

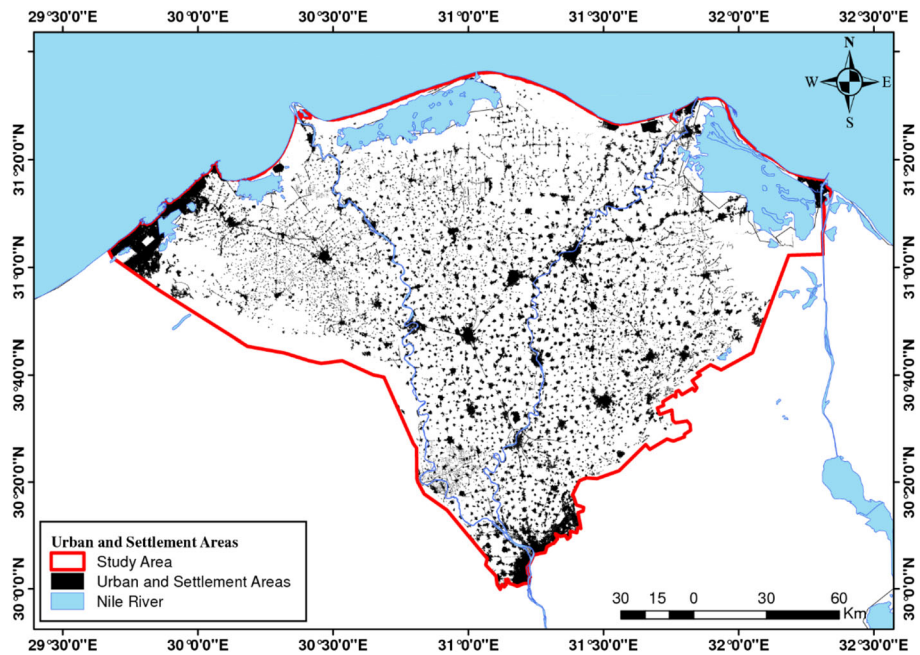
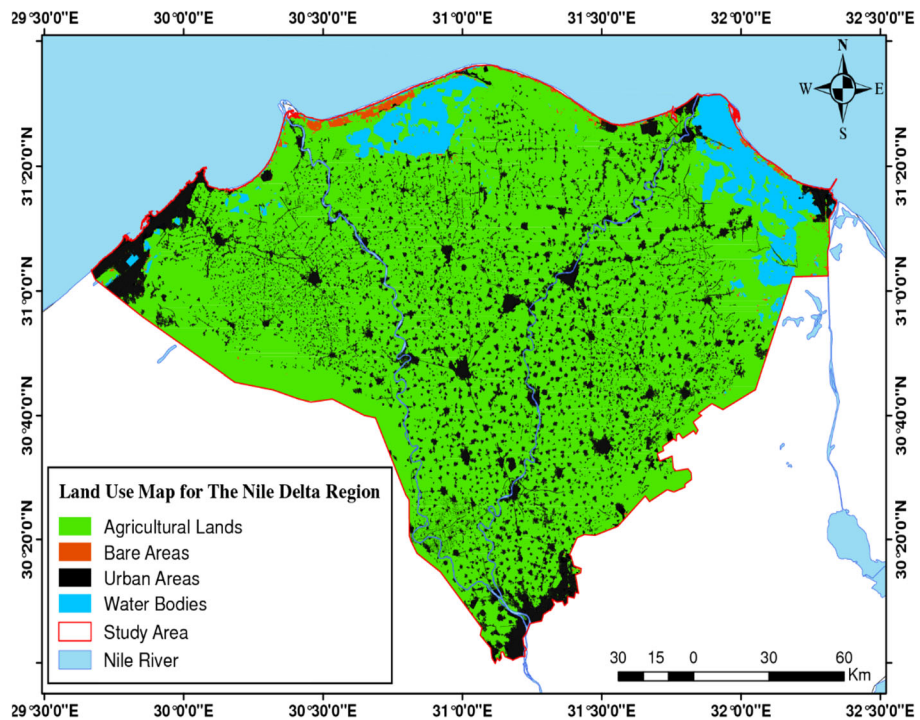


Fig. 8 Land use map for the Nile Delta region (2014)

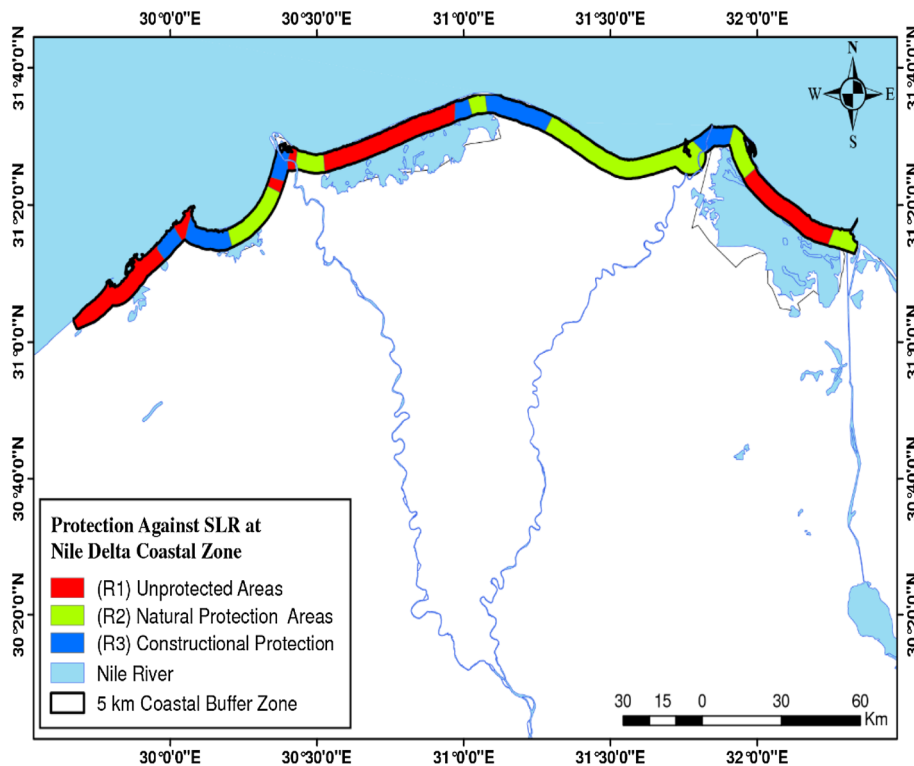


FAO—developed land cover classification system. The map has been reclassified into 4 major categories: agricultural lands, urban areas, water surfaces, and Bare areas consolidated from sand, gravel or/and rock (Fig. 8). The urban land use map shown at (Fig. 7) has been combined with the global land use map to update the urban areas in the map.

3.6 Protection Against SLR

In the last few years, the Egyptian government has constructed few engineering projects to protect the coastal zones of the Delta from the dangerous effects of SLR to protect the beaches of Alexandria, Port Saied and Al-Arish, Damietta, Kafr E-Shikh, and El-Malaha area east of Port Saied. These protection constructions probably have been a major factor

Fig. 9 Protection against SLR (Modified after Frihy et al. [9], and El-Hattab [5])



that assisted in the occurrence of phenomena such as accretion and erosion which had the main responsibility in the general shape of the beach front shoreline of the Delta to take a series of crescent shapes [15].

In this study, the protection areas along the Nile Delta coastal zone has been digitized from the works of Frihy et al. [9], and El-Hattab [5]. These areas have been classified into three main groups: natural protection areas, which are natural high-elevated morphologic features such as sand dunes, constructional protection areas such as seawalls and breakwaters, and finally unprotected areas (Fig. 9).

3.7 Data Management and Manipulation

The process and sequence of data management and manipulation conducted to all the previous set of data is presented in Table 3.

The available utilized geospatial datasets presented and discussed previously will help in developing a GIS model that will increase our understanding particularly for the SLR phenomenon, and eventually assist decision-making process.

4 Hazard Evaluation against SLR and Land Subsidence

This research study aims to generate an inundation model to determine the vulnerable low laying areas to flooding from

Table 3 Data management and manipulation

No	Data	GIS preparation sequence
1	Sea level rise	Define attributes–Interpolation–Clip to study area–Raster calculator
2	Subsidence rates	Define attributes–Interpolation–Clip to study area
3	LDEM	Clip to study area
4	Urban land use Areas	Georeferencing–Image classification–Raster to Polygon–Clip to study area
5	Land use map	Georeferencing–Image classification–Raster to Polygon–Clip to study area
6	Protection against SLR	Georeferencing–Digitizing–Clip to study area–Define attributes

future SLR in 2050, and to determine land use types and percentages that are most likely to be affected by overlying the inundation map upon the land use coverage. Then after identifying the inundated areas, a total HIM for the study area expected in 2050 is generated. The total HIM is combined from the produced coastal inundation hazard map, and the produced subsidence hazard map for all the Nile Delta region. The generated total HIM will present the full danger of the two phenomena on the coastal region along with presenting

the effects of the subsidence only on the rest of the Delta. On the one hand, such an evaluation can help formulate effective adaptation options for specific localized SLR impacts. Furthermore, such an analysis can significantly contribute to the development of an integrated approach to discuss and address the impacts of SLR and subsidence, helping Egyptian authorities and decision makers to face these challenges and to take proactive action to protect future generations from such serious threats.

The whole processing of hazard evaluation against SLR and land subsidence has been summarized at (Fig. 10).

4.1 Development and Processing of the Inundation Model

Despite the uncertainty associated with the proposed climate change scenarios and expected SLR in previous studies, the impacts of SLR need to be assessed and analyzed according to the precautionary approach. For this reason, a coastal study has been performed on the northern Mediterranean coast of Nile Delta region using the local topography represented by

the high accuracy LDEM generated and evaluated by [20] shown a (Fig. 6), and the SLR data measured by the tide-gauges installed at Alexandria, and Port Said shown at (Table 1).

An inundation modeling approach has been used to determine the vulnerability of future SLR based on GIS techniques by using a deterministic line to separate the flooded areas from the dry ones. The areas susceptible to inundation have been identified by first converting the LDEM raster map into a contour map, with a fine contour step of 10 cm. Then, using the 2050 SLR value ranging from 0.16 to 0.22 m, the contour lines produced in the northern coastal zone have been classified, using GIS classification tool, into lines equal to or less than the SLR value and others greater than the SLR values (Fig. 11). Then, a digitizing process has been carried out to detect the contour line that separates the drowning areas from the dry ones. The barrier line that stops the sea advancement to the rest of the Delta regions is always surrounded by low level lines in front of it and some times behind it. The areas surrounded between the front lines that extend to the coast and the barrier line are considered to be the true flooded area.

Fig. 10 The processing of hazard evaluation against SLR and land subsidence

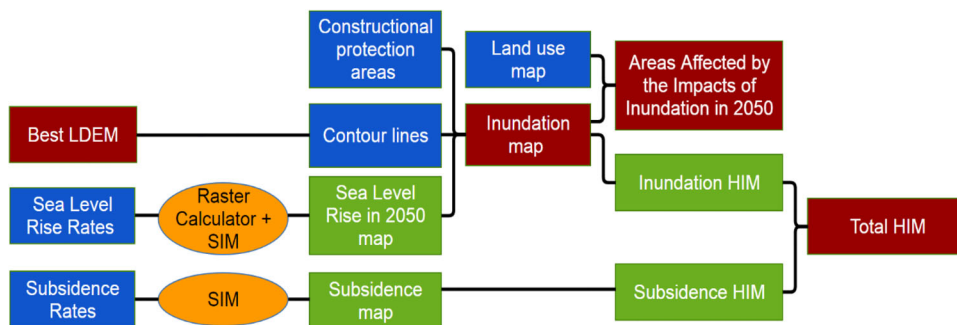


Fig. 11 The produced classified contour lines for the northern coastal zone from the LDEM (WGS84)

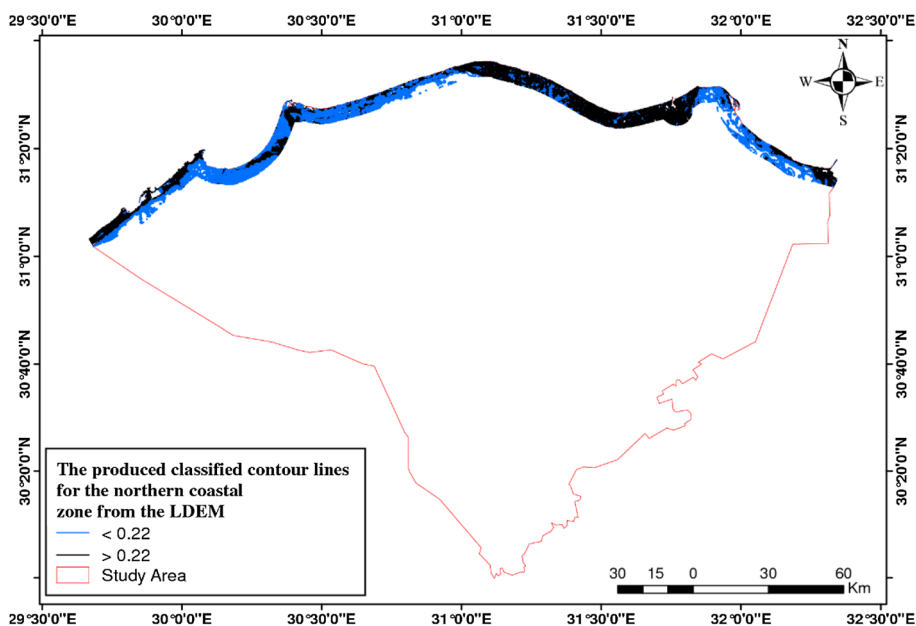




Fig. 12 A sample for the barrier line (red) separating low-lying areas (blue) near the coasts from high ones (black) or far away low-lying areas (WGS84)

As for the other areas behind the barrier line, they confuse the automated GIS techniques and make them incapable to detect the right inundated areas, because the barrier line is lost amid the low-lying lines surrounding it (Fig. 12), for that GIS techniques always approximate them together into one huge inundated area, which can be seen in previous studies as their results always exaggerate the actual occurred inundation. An accurate DEM is required to be used to detect the barrier line amid all the low-lying lines. Furthermore, the areas protected by constructions such as seawalls and breakwaters, shown at (Fig. 9), have been overlaid upon the inundation map to remove them, and to produce an inundation map that represents the areas currently exposed to the impacts of SLR in 2050. The final inundation map due to SLR in 2050 is shown at (Fig. 13). According to the available data the inundated area calculated from the SLR in 2050

Fig. 13 The final inundation map due to SLR in 2050 (WGS84)

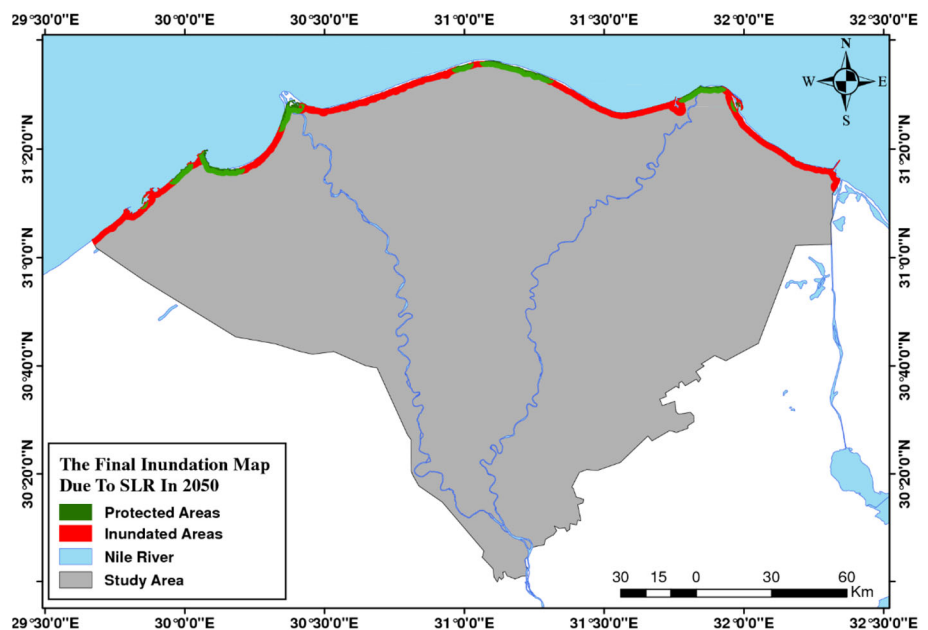


Table 4 Areas affected by the impacts of inundation in 2050

No	Type of land	Area (km ²)
1	Agriculture land	3.8
2	Bare area (gravel, rock)	2.6
3	Fishing farms	5.2
4	Urban area	38.4
Total	50	

model is about 50 km² representing 0.25% of the total study area.

Finally, the inundation map projected for SLR in 2050 is overlaid upon the land use coverage to determine land use types that are most likely to be affected by the impacts of inundation. This has been intended to identify those land uses and other assets that would be vulnerable to inundation. The areas affected by the impacts of inundation in 2050 are shown at (Table 4). The urban areas flooded by the sea represent the major affected type of lands covering almost 38.40 km², as for the other flooded areas including agricultural lands, fishing farms, and bare areas, consolidated with sand, gravel, and/or rock, cover almost 3.80 km², 5.20 km², and 2.60 km², respectively.

The inundated and protected areas due to the SLR in 2050 for each one of the northern Nile Delta governorates are presented in (Fig. 14).

4.2 Total Hazard Index Map

The first part of the total HIM map is produced from the inundation map for the northern coastal zone of the study area in

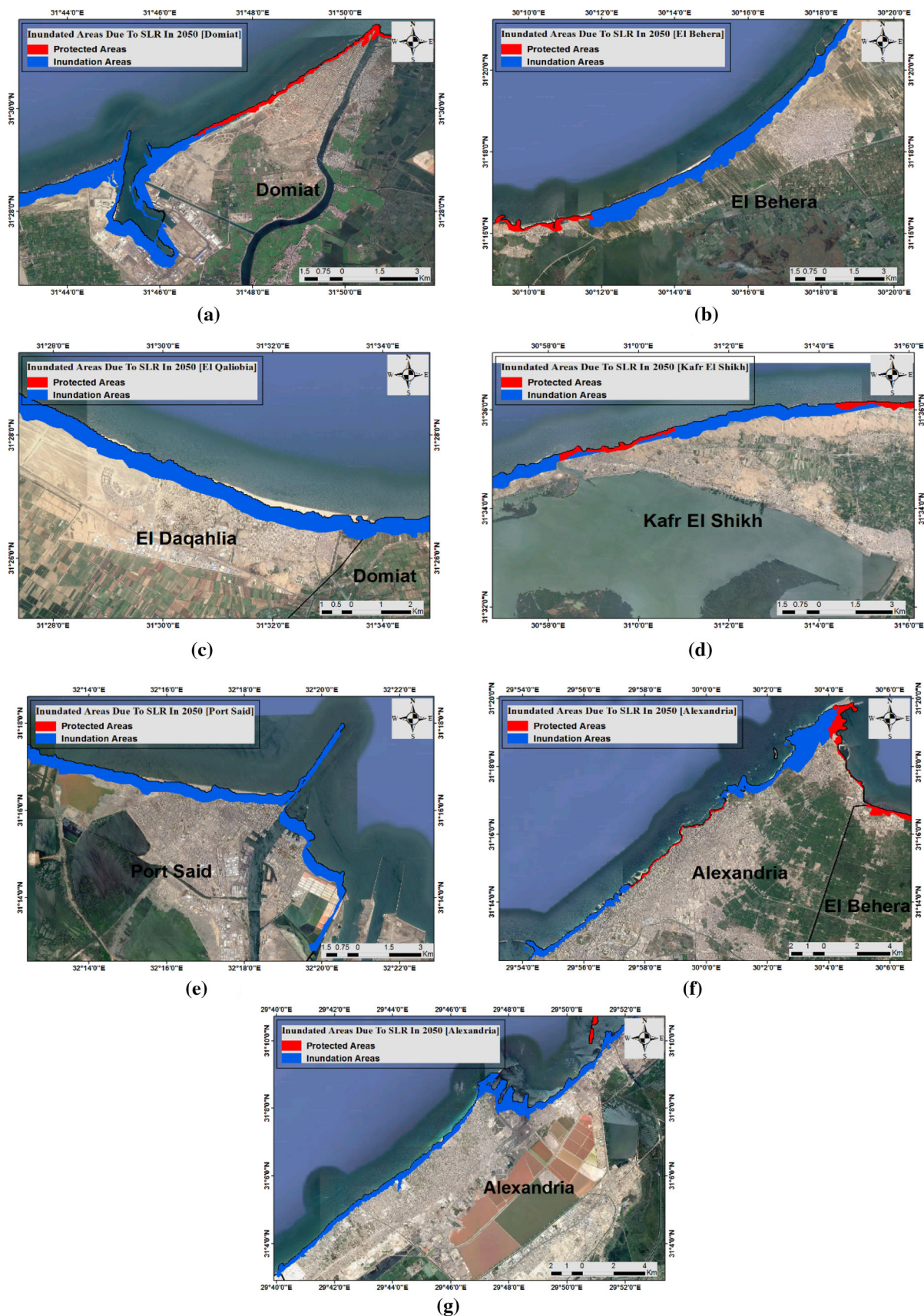


Fig. 14 Inundated Areas Due To SLR In 2050 in **a** Domiat; **b** El Behera; **c** El Qaliobia; **d** Kafr El Shikh; **e** Port Said; **f** Alexandria-North; **g** Alexandria-South

2050, shown at (Fig. 13) by using the using the “Reclassify” tool in ArcGIS to identify risk rank equal to 10 (high risk) for the inundated areas, and risk rank equal to zero (no risk) for the protected areas. The SLR HIM is shown at (Fig. 15).

The second part of the HIM is produced from the subsidence map shown at (Fig. 5) by using the “Reclassify” tool in ArcGIS. In the risk rank for the subsidence rates presented in (Table 5) the subsidence areas are ranked from 1 (low risk) to 10 (high risk) and ranked uplift areas from 1 low risk) to 5 (moderate risk), since the effect of subsidence is considered more dangerous than uplift. The result map is shown at (Fig. 16).

Finally, and due to the considerable risks provided mainly by SLR and the subsidence to the Nile Delta region, a total HIM is produced for the whole Nile Delta region (Fig. 17). The map is a result from combining the SLR HIM map produced for the northern coast of the study area (Fig. 15), and the subsidence HIM (Fig. 16).

5 Conclusions

In this research study a GIS coastal study has been performed on the northern Mediterranean coast of Nile Delta region using the high accuracy LDEM and the SLR data measured by the tide-gauges to generate an inundation model to determine the vulnerable low laying areas to flooding from future SLR in 2050, and to determine land use types and percentages that are most likely to be affected in 2050. A total hazard index map has been developed to depict the hazards of both land subsidence and sea level rise over the Nile delta.

The inundation caused by SLR can be identified as a significant natural hazard affecting densely populated and built-up areas. According to the available data the inundated areas calculated from the SLR in 2050 GIS model are about 50 km² representing 0.25% of the total study area. On the one hand, such an evaluation can help formulate effective adaptation options for specific localized SLR impacts, furthermore, such an analysis can significantly contribute to the development of an integrated approach to address the impacts of SLR helping Egyptian authorities and decision makers to

Table 5 Subsidence risk ranking

Subsidence rates range (mm/year)	Rank
(− 6.47, − 5.85)	10
(− 5.85, − 5.2)	9
(− 5.20, − 4.55)	8
(− 4.55, − 3.9)	7
(− 3.90, − 3.25)	6
(− 3.25, − 2.6)	5
(− 2.60, − 1.95)	4
(− 1.95, − 1.3)	3
(− 1.30, − 0.65)	2
(− 0.65, 0)	1
(0, 1)	1
(1, 2)	2
(2, 3)	3
(3, 4)	4
(4, 5)	5

Fig. 15 SLR in 2050 HIM (WGS84)

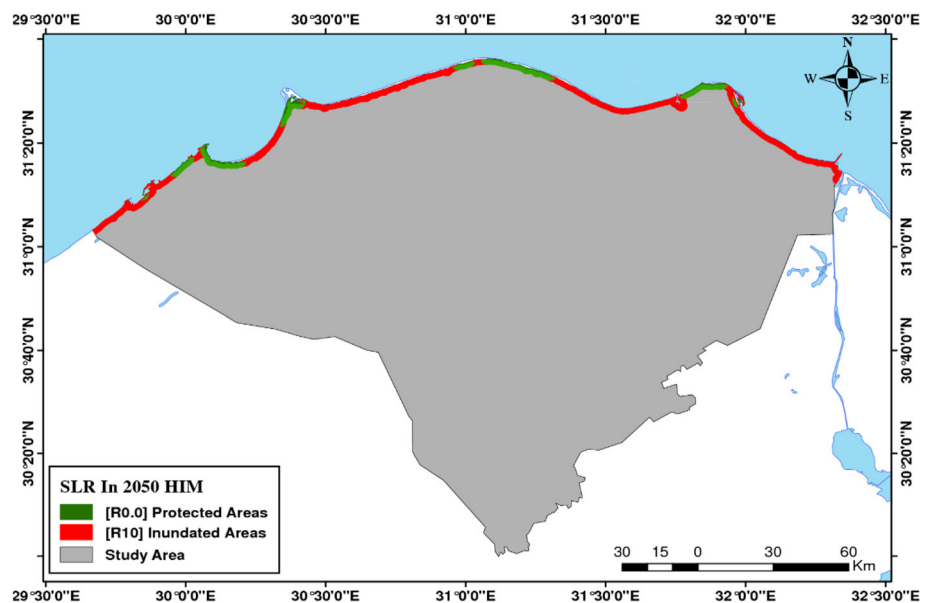


Fig. 16 Subsidence HIM (WGS84)

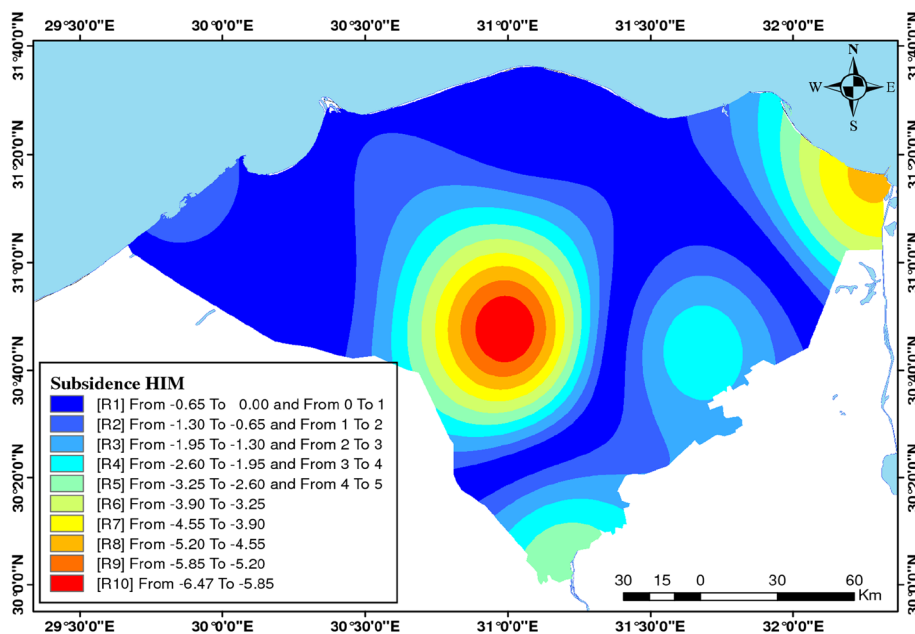
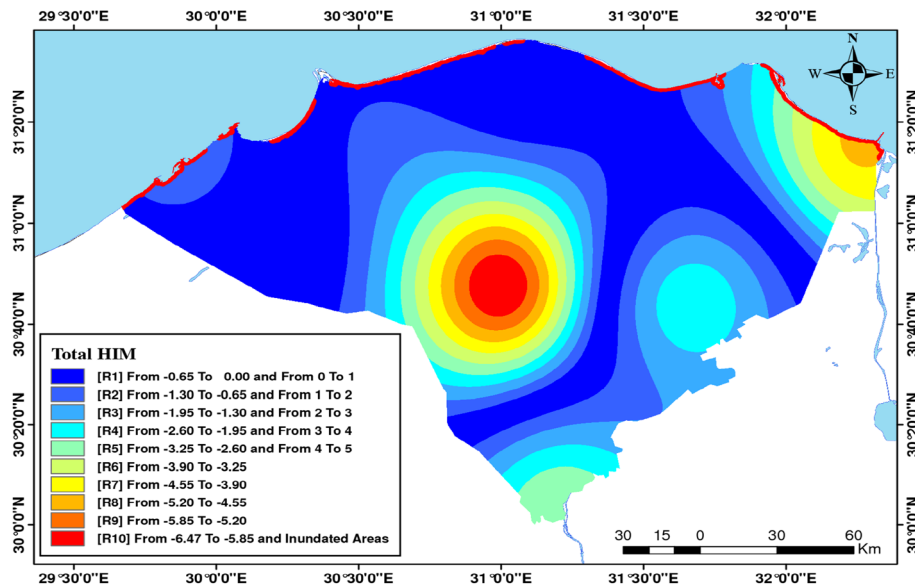


Fig. 17 Total HIM (WGS84)



face these challenges and taking proactive action to protect future generations from such serious threats.

The use of automated GIS techniques should not be used to determine the barrier line that separate the flooded areas from the dry ones, as the barrier line is lost amid the low-lying lines surrounding it, for that GIS techniques always approximate them together into one huge inundated area, which can be seen in previous studies as their results always exaggerate the actual occurred inundation.

Total HIM presents the full danger of the SLR and subsidence phenomenon on the coastal region along with presenting the effects of the subsidence only on the rest of the Delta.

Finally, it is recommended that an integrated GIS database of all tide gauge measurements in Egypt should be developed, and the sea level rise should be spatially analyzed in more details to prevent the occurrence of hazardous scenarios that could be occurred in 2050. Also, the authorities and decision makers should pay more attention to the hazardous effects due to the impacts of subsidence and SLR in the Nile Delta region, especially the northern coastal zone, as it is vulnerable to the effects of both the previously mentioned phenomenon. For that more protection construction such as seawalls and breakwaters should be built at the northern coastal zone of the Nile Delta region vulnerable to inundation of SLR, to

prevent the occurrence of the predicted inundation scenarios that could be occurred to this region in 2050.

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References

- Frihy, O.E.: The Nile delta-Alexandria coast: vulnerability to sea-level rise, consequences and adaptation. *Mitigat Adaptat Strat Global Change* **8**(2), 115–138 (2003). <https://doi.org/10.1023/A:1026015824714>
- Marshak, S.; Jack, R.: "Essentials of geology. WW Norton & Company, New York (2013)
- Gornitz, V.: Global coastal hazards from future sea level rise. *Palaeogeogr. Palaeoclimatol. Palaeoecol.* **89**(4), 379–398 (1991)
- Dawod, G.; Mohamed, H.: Estimation of sea level rise hazardous impacts in Egypt within a GIS environment. Proceedings of the Third National GIS Symposium in Saudi Arabia (on CD), Al-Khobar City, Saudi Arabia April 7 - 9 (2008)
- El-Hattab, M.M.: Improving coastal vulnerability index of the Nile Delta coastal zone, Egypt. *J Earth Sci Climat Change* **6**(8), 293 (2015). <https://doi.org/10.4172/2157-7617.1000293>
- IPCC (2007). "Climate change 2007: the physical science basis: summary for policymakers." Geneva: IPCC, DOI: <https://doi.org/10.1260/095830507781076194>
- Dawod, G.M.: The Establishment of the first modern sea level monitoring system in Egypt. Proceedings of the twelfth international conference on environmental protection, Alexandria university, Alexandria, May 14–16, pp. 12–23 (2002)
- Dawod, G.: The magnitude and significance of long-term sea level rise in Egypt from a geodetic perspective. Proceedings of the twelfth international conference on environmental protection, Alexandria university, Alexandria, May 8–10, pp. 207–215 (2001).
- Frihy, O.E.; El-Sayed, M.K.: Vulnerability risk assessment and adaptation to climate change induced sea level rise along the Mediterranean coast of Egypt. *Mitigat Adaptat Strateg Global Change* **18**(8), 1215–1237 (2013). <https://doi.org/10.1007/s11027-012-9418-y>
- Hassaan, M.A.; Abdrabo, M.A.: Vulnerability of the Nile Delta coastal areas to inundation by sea level rise. *Environ Monitor Assess* **185**(8), 6607–6616 (2013). <https://doi.org/10.1007/s10661-012-3050-x>
- Haggag, M.; El-Shazly, A.; Rakha, K.: Impact of sea level rise on the Nile Delta, Egypt. *Eng. Appl. Sci* **60**(3), 211–230 (2013)
- Hassaan, M.A.: GIS-based risk assessment for the Nile Delta coastal zone under different sea level rise scenarios case study: Kafr EL Sheikh Governorate, Egypt. *J. Coast. Conserv.* **17**(4), 743–754 (2013). <https://doi.org/10.1007/s11852-013-0273-0>
- Solyman, A.A.; El-Hattab, M.M.; Rifai, R.I.; Fakhar, W.M.T.: An integrated web mapping solution to assess the effect of SLR on the Northern Coast of EGYPT: EGSLR thematic cartography for the Society, p. 23–31. Springer, Berlin (2014)
- Hasan, E.; Khan, S.I.; Hong, Y.: Investigation of potential sea level rise impact on the Nile Delta, Egypt using digital elevation models. *Environ Monitor Assess* **187**(10), 649 (2015). <https://doi.org/10.1007/s10661-015-4868-9>
- Ali, E.M.; El-Magd, I.A.: Impact of human interventions and coastal processes along the Nile Delta coast, Egypt during the past twenty-five years. *Egypt. J. Aquat. Res.* **42**(1), 1–10 (2016). <https://doi.org/10.1016/j.ejar.2016.01.002>
- Meshref, W.: Tectonic framework. *The Geology of Egypt* **8**, 113–155 (1990)
- Stanley, J.-D.; Clemente, P.L.: Increased land subsidence and sea-level rise are submerging Egypt's Nile Delta coastal margin. *GSA Today* **27**(5), 4–11 (2017). <https://doi.org/10.1130/GSATG312A.1>
- Yalciner, A.C.; Zaytsev, A.; Aytore, B.; Insel, I.; Heidarzadeh, M.; Kian, R.; Imamura, F.: A possible submarine landslide and associated tsunamis at the northwest Nile delta, Mediterranean sea. *Oceanogr* **27**(2), 68–75 (2014). <https://doi.org/10.5670/oceanogr.2014.41>
- Radwan, A.A.; El-Geziry, T.M.: Some statistical characteristics of surges at alexandria, Egypt. *J King Abdulaziz University: Marine Sci* **179**(1791), 1–17 (2013)
- El-Quilish, M.; El-Ashquer, M.; Dawod, G.; El Fiky, G.: Development and accuracy assessment of high-resolution digital elevation model using GIS approaches for the Nile Delta Region, Egypt. *Am J Geograp Inform Sys* **7**(4), 107–117 (2018). <https://doi.org/10.5923/j.ajgis.20180704.02>
- Dawod, G.; Mohamed, H.; Haggag, G.: "Relative and absolute sea level rise based on recent heterogeneous geospatial data: a case study in the Nile delta Egypt. *J Scient Eng Res* **6**(6July), 55–64 (2019)
- Mohamed, H.F.; Bahaa, A.S.; Magdy, M.H.; Gomaa, M.D.: "High-Precision GPS Monitoring of the Land Subsidence in the Nile Delta: Status and Preliminary Results". Regional conference on surveying & Development. Sharm El-Sheikh, Egypt, 3–6 October (2015)
- Tateishi, R.; Hoan, N.T.; Kobayashi, T.; Alsaaidh, B.; Tana, G.; Phong, D.X.: Production of global land cover data-GLCNMO2008. *J. Geogr.* **6**(3), 99 (2014). <https://doi.org/10.5539/jgg.v6n3p99>
- Tateishi, R.; Uriyangqai, B.; Al-Bilbisi, H.; Ghar, M.A.; Tsend-Ayush, J.; Kobayashi, T.; Kasimu, A.; Hoan, N.T.; Shalaby, A.; Alsaaidh, B.: Production of global land cover data-GLCNMO. *Int J Digital Earth* **4**(1), 22–49 (2011). <https://doi.org/10.1080/17538941003777521>
- Embabi, N.S.: "Sand dunes in Egypt, in sedimentary geology of Egypt: applications and economics, Part 1." The sedimentological society of Egypt: 45–87 (2000)

