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Relative and Absolute Sea Level Rise based on Recent Heterogeneous Geospatial Data: A Case Study in the Nile Delta, Egypt

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Abstract Sea level rise and vertical land movements (mainly land subsidence) comprise key elements in coastal engineering and environmental applications, particularly in river delta margins. This study aims to precisely estimate the recent relative sea level changes, vertical land movements, and absolute sea level rise along the coasts of the Nile delta, as a case study, based on modern heterogamous geospatial data. Tide gauge records at five locations along with Global Navigation Satellite Systems (GNSS) observations have been analyzed. The quality of the collected tide datasets is varying from a station to another. It has been found that the confidential relative sea level rise estimates in the Nile delta region, between 1990 and 2016, vary from 2.6 to 4.3 mm/year. In accordance with GNSS-based datasets, the vertical land movements rates at the tide gauge sites range between +0.09 and -4.3mm/year. So, it can be concluded that the absolute sea level rise differ between 5.0 mm/year at Alexandria to 6.9 mm/year at Port Said. Based on the available datasets; it might anticipated that by year 2050 the mean sea level will be raised about 17 and 23 cm, above the 2016-level, at Alexandria and Port Said respectively.

Keywords Sea Level, Land Subsidence, GNSS, Tide Gauges, Egypt

Introduction

Sea level rise is considered strongly related to the global warming phenomena and a major sign of climate changes worldwide. It might be attributed to some primary factors including: ocean thermal expansion; mountain glaciers and polar ice caps melt, and change in terrestrial storage. It is a matter of reality that sea level has been significantly raised in the 20th century on a global average as a measure of climate change. The observed global mean sea rise, from tide gauge records and satellite altimetry data, has been reported as 1.5, 2.0 and 3.2 mm/year for the period 1901-1990, 1971-2010, and 1993-2010 respectively [1]. Sea level changes have a strong regional pattern, with some geographic places show considerable differences of local and regional sea level change from the global rise rate [2]. Causes of such variations include, among other, variability of local surface winds, ocean currents, temperature, and salinity. Based on different scenarios, the anticipated global sea level in 2081-2100, will range from 0.40 to 0.63 m relative to the 1986-2005 level [1]. Few available analyses that go beyond 2100 indicate sea level rise to be less than 1 m above the pre-industrial level by 2300 [3].

Several hazardous impacts of sea level rise have been investigated worldwide, particularly in low-land deltas, which necessitates the development of risk assessment adaptation planning. The impact of sea level rise on urban flood probability has been studied and found significant [e.g. 4]. Additionally, Dessu et al. [5] concluded that sea level rise considerably affect freshwater management and water quality in the Florida coastal everglades. Accessibility of road networks in some regions within Europe could be degraded by sea level rise [e.g. 6]. The quality of groundwater will be altered significantly in coastal regions due to sea water intrusion [7 and 8]. Sea rise will cause shorelines retreat, dune replacement, and residential resilience in coastal areas [e.g.

9]. Geographic Information Systems (GIS) have been applied to create coastal vulnerability index and to develop digital spatial maps for coastal management [e.g. 10]. Regarding Egypt, sea level rise could reduce annual precipitation, increase drought risk, and affect both food security and local economy [e.g. 11].

Tide gauge datasets could not represent global or regional changes in the mass of water. Potential factors affecting the stability of the sea level records include: sea effects from coastal dynamics (such as erosion, sediment transport, air pressure changes, wind direction, storms, etc.), land effects (such as compaction, excavation, Earthquakes, groundwater extraction, etc.) and sea effects from sea level changes (such as temperature and salinity, long-term tectonics, glacial rebound, etc.). Accordingly; absolute sea level rise rate is determined as the sum of relative rise observed from tide gauge stations and the vertical land motion or subsidence rate. Geometrically, land subsidence can be defined as the downward displacement of land surface relative to a specific reference surface, such as the Mean Sea Level (MSL), the geoid, or a reference ellipsoid, or relative to a certain assumed stable point outside the prone subsidence area. Such natural hazard phenomena can be attributed to natural and/or human activities, such as tectonic activities (e.g. earthquake and faulting), volcanic activities, landslide, underground mining activities, excessive groundwater or oil/gas extraction, natural consolidation of alluvium soil, and load of huge constructions. Land subsidence can be monitored by several techniques including levelling, Global Navigation Satellite Systems (GNSS), and the Synthetic Aperture Radar (SAR). Several studies have utilized such techniques for land subsidence all over the world [e.g. 12 and 13]. For the Nile delta region, geological and soil investigations revealed that land subsidence could range from 3.7 to 8.4 mm/year [e.g. 14]. In addition, the subsidence spatial pattern is significantly varied across that region where the rate is higher in the eastern area than in the western part [e.g. 15].

Relative and absolute sea rise estimation have been investigated by several researchers worldwide. For example, Alothman et al. [16] reported that the absolute sea level rate in the Northwest Arabian gulf, between 1979 and 2007, equals 1.5 mm/year. In the East China sea, the relative sea rise rate, in the period 1959-2013, equal 3.4 mm/year [17]. In addition, Parker [18] found that the relative sea levels rose in China during the twentieth century and this part of the twenty-first century from − 1.2 to + 3.2 mm/year, on average + 1.4 mm/year. Moreover; the relative mean sea level rise in the Indian Ocean, between 1950 and 2009, amounts to 1.5 mm/yr [19]. In addition, analysis of several tide gauge records in New Zealand, between 2001 and 2013, revealed that the absolute sea level rise ranges from 1.31 to 2.14 mm/year [20]. The Mediterranean Sea presents an average sea level rise trend of 2.44 mm/year in the period 1993-2012, with considerable spatial variations [21].

Nationally; the sea level rise determination and the assessment of its impacts in Egypt have been investigated extensively in the last couple of decades. Mohamed [22] has analyzed tide gauge records at Alexandria from 1906 to 2003, and has estimated the absolute sea level rise as 2.3 mm/year. Additionally; Firhy et al. [23] found that the analysis of historical records obtained from tide gauges at Alexandria, Rosetta, Burullus, Damietta, and Port Said show a continuous relative rise in mean sea level fluctuating between 1.8 and 4.9 mm/year, where the smaller rate occurs at the Alexandria harbor, while the higher one at the Rosetta promontory. Moreover; Shaltout et al. [24] applied 1993-2013 altimetry dataset to estimate the relative sea level rise rate at the Egyptian Mediterranean coast, and found it to be 3.1 mm/year. Between 1926 and 2000, the absolute sea level rise has been estimated at Port Said as 2.3 mm/year [25]. Land subsidence over the Alexandria coastline, in the west of the Nile delta region, could be up to 2 mm/year and its average equals 0.4 mm/year [26]. Also, subsidence in the central delta ranged from 5 to 9 mm/year in the period 1993-2000 [27].

Impacts of sea level rise on urban areas within the Nile delta region, north of Egypt, has been investigated and found to be vulnerable to inundation under several future sea level rise [e.g. 28 and 29]. For instance, Refaat and Eldeberky [30] have concluded that about 7% of the Nile-delta area is at risk of inundation due to future sea level rise. Moreover; hazards of sea level rise in the Nile delta include decrease in water supply, land supply, food security, and local economy [11]. In addition; other studies have concluded that sea level rise would, also, affect groundwater heads and salinity in the Nile delta region [e.g. 31 and 32].

The current research aims at estimating both relative and absolute sea level rise in the Nile delta coastal region based on recent heterogeneous geospatial datasets. Such measures are extremely valuable for decision makers in coastal management development in the Nile delta region as a case study.

Study Area and Available Data

The overall coasts of Egypt extend approximately over more than 3500 km along both the Eastern Mediterranean and the Red Sea. The current study focuses only on the Nile delta sector, ranging from longitude 29.6^o E to longitude 32.3^o E, and from latitude 29.8^o N to latitude 31.6^o N (Fig. 1). With more than fifty million population, the Nile delta might be considered as one of the most densely populated regions worldwide. The topography of the study area (Fig.1) ranges from elevation -72 meter to 197 meter, with an average of 5.9 meter. As can be seen from that figure that the dominant elevation is less than 10 meter in the northern and middle parts of the delta. Moreover, it can be realized that the northern region of the delta area has an elevation less than almost 5 meter. Within this area, 5 tide gauge stations exist at Alexandria, Damietta, Burullus, Rosetta, and Port Said (Fig.1).

The available tide gauge dataset comprises data from different tide gauges along the Mediterranean coasts with variable time spans.. These tide gauges belong to different local organizations. For the Alexandria station, the historical gauge was established within the Alexandria civilian harbor at the end of the nineteenth century, aiming to define MSL to be adopted as the vertical geodetic datum of Egypt. Observations has been collected between 1898 and 1906, and the average has been set as the national MSL for the Bench Mark (BM) levelling network. Annual sea level data of this station is published by the Permanent Service of Mean Sea Level (PSMSL) international organization [33]. At the mid of 1990s, the Egyptian Navy Hydrographic Department (ENHD) established a new tide gauge at its headquarter in Alexandria, just few hundreds of meters from the historical one. For relating the new and the old gauges, a levelling was carried out and revealed that there was a datum shift of 18 cm between both scales. That implies that for combining datasets from both stations, such a shift should be considered. At the beginning of 2000s, the Survey Research Institute (SRI) of the National Water Research Center (NWRC) has cooperated with ENHD to update the instrument at this location, and start establishing new tide gauges at Port Said on the Mediterranean sea, Suez and Safaga on the Red sea. The other three tide gauges at Rosetta, Burullus, and Damietta belong to the Costal Research Institute (CoRI) of NWRC. Table 1 presents the characteristics of the collected tide gauge datasets at these five stations. It worth mentioning that the sea level measuring devices at these gauges are, recently, updated where pressure-type devices have been replaced by modern precise microwave ones as part of the activities of the undergoing project of adaptation to climate change in the Nile delta through integrated coastal zone management.

Table 1: Available Tide Datasets in the Nile Delta Coasts

Station	Period	Gaps	Data
Alexandria	1944 – 1989		Yearly
	1989 – 2008	2004 – 2007	Monthly
	2008 – 2016		Hourly
Damietta	1999 – 2016	2005 – 2011	Yearly
Burullus	1990 – 2016	2008 – 2012	Yearly
Rosetta	2004 – 2016	2010 – 2012	Yearly
Port Said	2008 – 2016		Hourly

For GNSS monitoring of subsidence in the Nile delta, 24-hours datasets at six stations, covering the period 2012-2015, have been utilized [34]. However; these stations did cover the Alexandria coast. Therefore; subsidence estimate is acquired for another GNSS station located at Alexandria belong to the Système d'Observation du Niveau des Eaux Littorales (SONEL) project, which is an international cooperation aims at providing high-quality continuous measurements of sea- and land levels at the coast from tide gauges (relative sea levels) and from modern geodetic techniques (vertical land motion and absolute sea levels) for studies on long-term sea level trends [35]. That GNSS station is located 3.1 km from the tide gauge. Even tough the number of these GNSS stations is relatively small, they have been utilized in this research since they constitute the only available GNSS data for the time being. The utilized seven GNSS stations are depicted in Fig. 1, and their estimated subsidence rates are shown in Table 2.

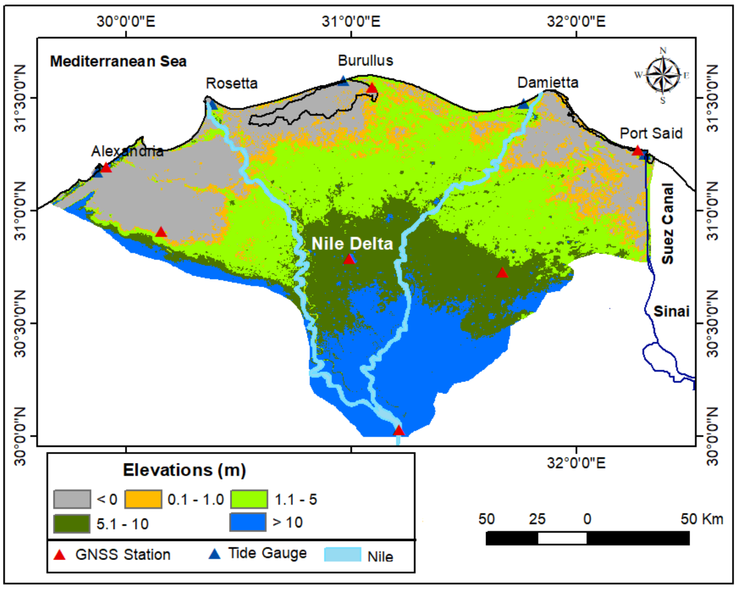


Figure 1: Topography of Study Area, Tide Gauges, and GNSS Stations

Table 2: Vertical Land Movements Rates at GNSS stations in the Nile Delta

Station	Period	Subsidence Rate (mm/year)	Reference
Cairo		+ 4.94	Mohamed et al. 2015
Port Said		- 4.72	
Abu Kebeer	2012-2015	+ 3.69	
Tanta		- 6.51	
Baltim		+ 0.71	
Abu El-Matameer		+ 0.55	
Alexandria	2002-2008	-0.85	SONEL 2019

The linear regression modelling describes the mathematical relationship in both relative and absolute sea level rise [e.g. 36]. Its basic equations could be in the form of:

$$MSL = aY + b \tag{1}$$

where, MSL is the annual mean sea level, a and b are coefficients to be determined, and y is the year.

To judge the attained regression trend, the coefficient of determination, R^2, is evaluated. It is a statistical measure about the quality of the regression model, representing the proportion of the variance in the dependant variable that is predictable from the independent variable. R^2 ranges from zero to one (or from 0 % to 100 %), computed as:

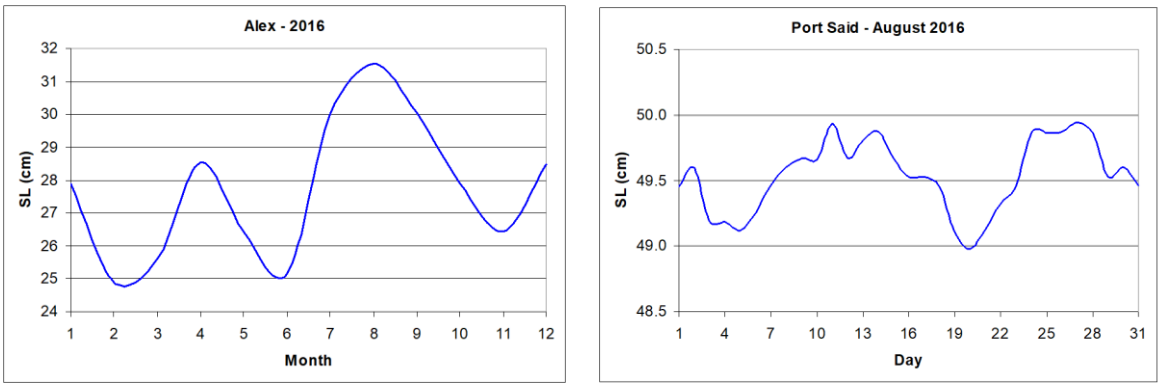
$$R = n(\sum xy) - (\sum x)(\sum y) \Big/ \sqrt{[n\sum x^2 - (\sum x)^2][n\sum y^2 - (\sum y)^2]} \tag{2}$$

where n is the number of known data points, x and y are the two dependant and independent variables to be modeled. Generally, the higher R^2, the better the linear regression model fits the data.

Results and Analysis

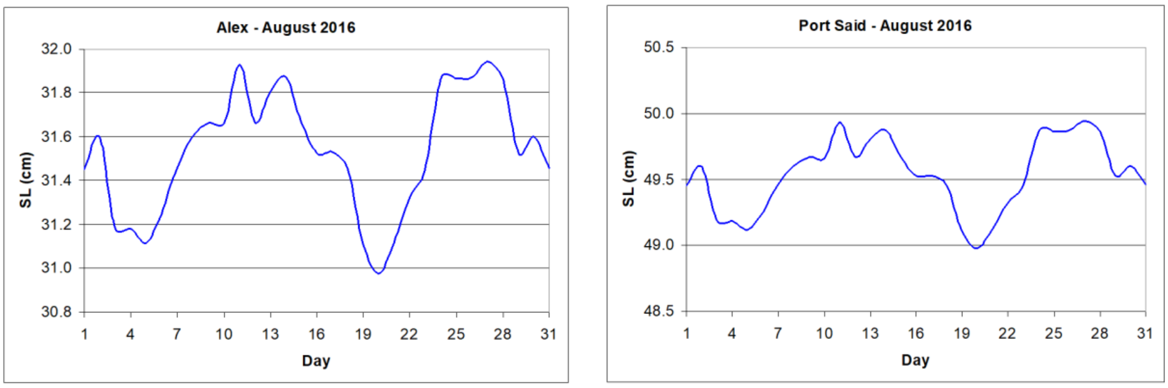
The first step was to analyze the sea level detailed characteristics at both Alexandria and Port Said stations that have available hourly observation records. That step was performed on the most-recent (2016) data. Fig. 2 (a and b) depicts the monthly variations of sea level at these stations. At Alexandria, the sea level varies from a minimum of 24.9 cm in February to a maximum of 31.5 cm in August, with a range of 6.6 cm. Similarly; for Port Said the sea level varies from a minimum of 42.1 cm in February to a maximum of 50.2 cm in August, with a range of 8.1 cm. Over August, the daily sea level variations have a range of almost 1 cm at both stations Fig. 3. Hourly discrepancies of sea level on August 27, that has the maximum daily average, at both Alexandria and

Port Said have been also investigated Fig. 4. It can be seen that both stations have a semi-diurnal tide pattern, with a daily tidal range of approximately 21 cm.



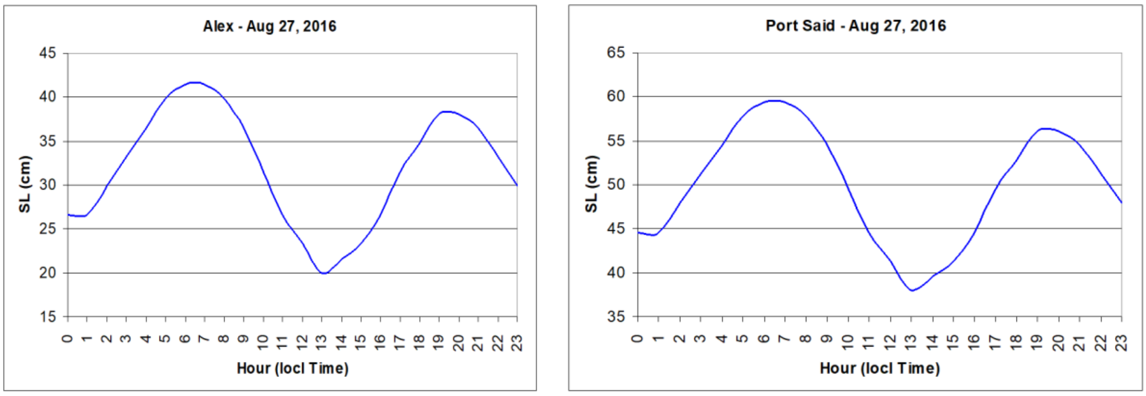
(a) Alexandria (b) Port Said

Figure 2: Monthly Sea Level Variations in 2016



(a) Alexandria (b) Port Said

Figure 3: Daily Sea Level Variations in August, 2016



(a) Alexandria (b) Port Said

Figure 4: Hourly Sea Level Variations in August 27, 2016

Next, the annual averages of mean sea level have been inspected for modelling the relative sea level rise trend at the five locations for the period 1990-2016 Fig. 5. This figure might reveal that there is a datum shift between collected datasets at the five sites so it is recommended to perform a closed loop precise leveling along with GNSS circuit to define a unique vertical geodetic reference for all sea level measurements in the study area to tie each site to the closest BM since exist discrepancies in the national leveling network [e.g. 22].

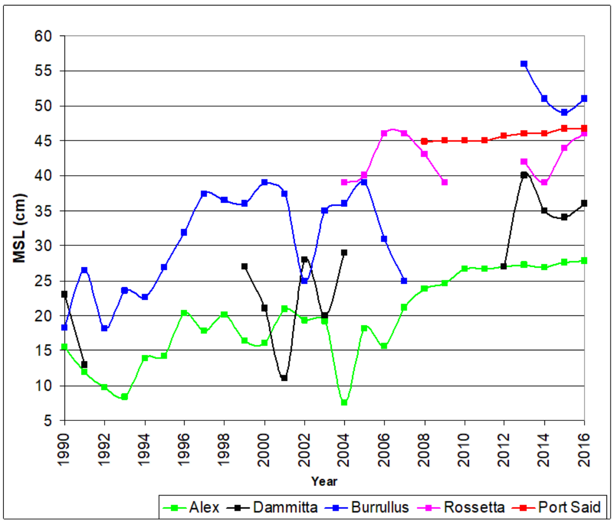


Figure 5: Annual Mean Sea Level Variations

Furthermore; the linear regression modelling has been performed to estimate the relative sea level rise at the five tide gauge sites. Table 3 presents the attained trend formulas along with their corresponding coefficients of determination. The analyses show that all Locations have positive sea rise with a significant quality of fitting, except for the Rosetta tide gauge. That small coefficient of determination suggests that sea level variations at Rosetta do not follow a linear trend. Therefore; the confidential relative sea level rise estimates in the Nile delta region are 4.3, 7.4, 10.3, and 2.6 mm/ year at Alexandria, Damietta, Burullus, and Port Said respectively. Fig. 6 depicts the spatial variations of sea level rise rates along the Nile delta coasts. It worth noting that the coefficient of determination of the regression are moderate for Damietta and Burullus, while its value are relatively higher for Alexandria and Port Said. It implies that the trend of sea rise at Alexandria and Port Said is better following a linear pattern with respect to time. On the other hand, the high sea level rise rates at Damietta and Burullus might be attributed to the specific spatial location of both sites close to the Nile river mouth and the Burullus Lake respectively.

Table 3: Relative Sea Level Rise in the Nile Delta

Station	Sea Rise Trend (cm)	R^2	Period
Alexandria	$MSL_1 = 0.4308\ y - 840.29$	0.76	2008 - 2016
Damietta	$MSL_2 = 0.7439\ y - 1464.3$	0.60	1999 - 2016
Burullus	$MSL_3 = 1.0348\ y - 2037.4$	0.63	1990 - 2016
Rosetta	$MSL_4 = 0.1336\ y - 226.09$	0.04	2004 - 2016
Port Said	$MSL_5 = 0.2569\ y - 471.27$	0.92	2008 - 2016

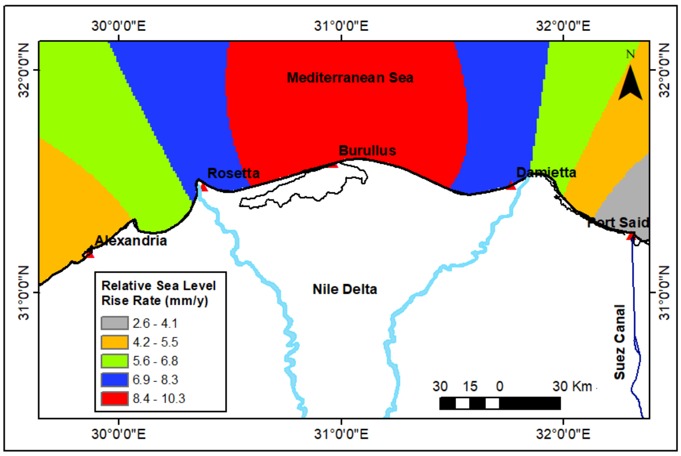


Figure 6: Sea Level Rise at Nile Delta Coasts

Moreover, the absolute sea level rise assessment starts first by estimating land subsidence in the study area. The subsidence rates at the collected GNSS stations have been utilized to develop a spatial subsidence model for the Nile delta (Fig. 7). The Arc GIS software has been applied to model such a phenomenon, and later to interpolate the subsidence rates at the tide gauges. It has been found that the vertical land movements in the Nile delta region vary from subsidence of -6.6 mm/year, at the northeast and central areas, to uplift of +4.9 mm/year, at the southeast part. Vertical land deformations are attributed to several factors such as soil compaction, tectonic movements, and groundwater extraction. Similar results have been reported by previous studies [e.g. 14, 15 and 27]. It has been found that the interpolated values of subsidence rates at the tide gauges equal -0.7, -1.8, -1.0, -4.3, and +0.09 mm/year at Alexandria, Damietta, Rosetta, Port Said, and Burullus respectively. Based on the estimated relative sea level rise and vertical land movements, the absolute sea level rise is determined (Table 4). It is concluded that the absolute sea level rise in the Nile delta region vary between 5.0 at Alexandria to 14.4 mm/year at Rosetta. However; the estimated value at Rosetta might not be trustable enough since its relative sea level rise trend has an insignificant quality measure. Also, the quality indicator of regression (R^2 in table 3) implies that the quality of relative sea level rise modelling at Alexandria and Port Said are better than those of at Damietta and Burullus. These two remarks suggest that estimates of both relative and absolute sea level rise at Alexandria and Port Said are of high confidence to be utilized in coastal management and environmental development policies. So, based on the quality of the collected datasets it can be concluded that the convinced absolute sea level rise, in the Nile delta area, could be considerably varying from 5.0 to 6.9 mm/year. Accordingly; it is anticipated that by year 2050 the mean sea level will be raised by about 17 and 23 cm, above the 2016-level, at Alexandria and Port Said respectively.

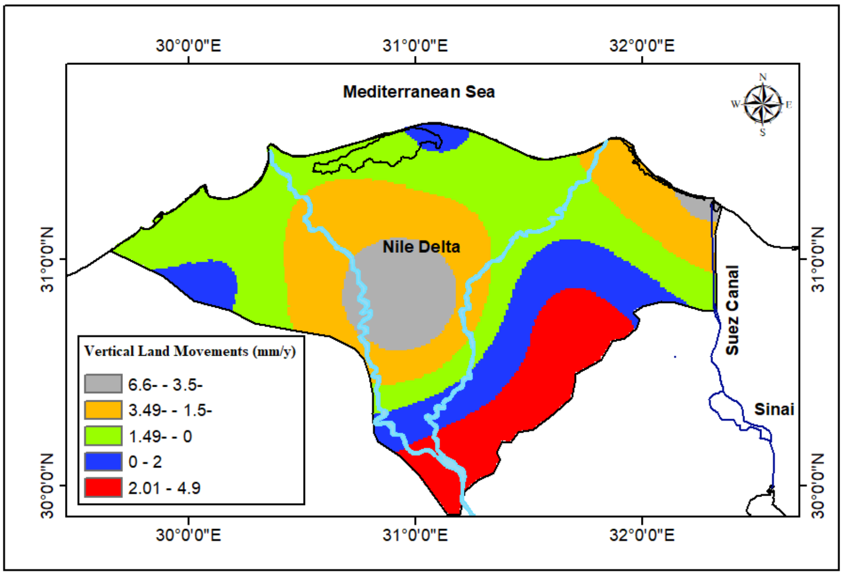


Figure 7: Vertical Land Movements in Nile Delta

Table 4: Relative and Absolute Sea Level Rise Rates in the Nile Delta

Station	Relative Rise (mm/year)	Absolute Rise (mm/year)
Alexandria	+ 4.3	+ 5.0
Damietta	+ 7.4	+ 9.2
Burullus	+ 10.3	+ 10.2
Rosetta	+ 13.4	+ 14.4
Port Said	+ 2.6	+ 6.9

Finally; the long-term analysis of relative sea level rise has been accomplished. Since only the Alexandria tide gauge has a long data series, this investigation has been performed in this location. The collected annual mean sea level, from different sources, cover 72 years from 1944 to 2016. To account for the 18.6-year cycle of lunar nodal tide, the available annual mean sea level dataset has been divided into several 20-year subgroups. The linear regression modelling has been carried out on each sub-group, and on the entire 72-year dataset. Table 5 presents the attained findings, which indicates that there is a considerable increase of the sea rise rate over this time. Although the long-term relative sea rise rate equals 2.6 mm/year, the most recent rate is 4.3 mm/year. Thus; It is recommended that recent estimate of sea rise to be considered in future coastal development, plans rather than depending on the average rate over a long time span

Table 5: Long-Term Relative Sea Level Rise Rate at Alexandria

Relative Sea Rise Trend (cm)	R^2	Period
0.3199 y - 617.2	0.45	1944 - 1968
0.2213 y - 425.92	0.29	1968 - 1988
0.4194 y - 822.12	0.33	1988 - 2008
0.4308 y - 840.29	0.76	2008 - 2016
0.2570 y - 495.41	0.70	1944 - 2016

Conclusions

The Nile delta is one of the most vulnerable regions in the world to sea level rise. Precise estimates of both relative and absolute sea level rise are needed for a wide range of engineering and environmental activities. This study has utilized heterogeneous geospatial datasets with variable quality and time spans at five tide gauge stations along the delta coastlines. Corresponding vertical land movements have been interpolated from a GNSS-based vertical land movement spatial model.

The annual averages of mean sea level have been inspected for modelling the relative sea level rise trend at the five locations for the period 1990-2016. It is noted that there might be a datum shift between collected datasets at the five sites. So, it is recommended that a closed loop precise levelling along with GNSS circuit should be performed to define a unique vertical geodetic reference for all sea level measurements in the study area. Accomplished findings reveal that all investigated locations have positive relative sea rise with a significant quality of fitting, except for the Rosetta tide gauge. Therefore; the confidential relative sea level rise estimates in the Nile delta region are 4.3, 7.4, 10.3, and 2.6 mm/y at Alexandria, Damietta, Burullus, and Port Said respectively. The high values at Damietta and Burullus might be attributed to the specific spatial location of both sites close to the Nile river mouth and the Burullus lake. Even though the number of these GNSS stations is relatively small, they have been utilized in this research since they constitute the only available GNSS data for the time being. Thus; the vertical land movement rates have been estimated as -0.7, -1.8, -1.0, -4.3, and +0.09 mm/year at Alexandria, Damietta, Rosetta, Port Said, and Burullus respectively. Vertical land deformations in the Nile delta caused by several factors including soil compaction, tectonic movements, and groundwater extraction.

Based on the estimated relative sea level rise and vertical land movements, it is found that the absolute sea level rise in the Nile delta region vary between 5.0 at Alexandria to 14.4 mm/year at Rosetta. Accomplished results suggest that estimates of both relative and absolute sea level rise at Alexandria and Port Said are of high confidence to be utilized in coastal management and environmental development policies. So, based on the quality of the collected datasets it can be concluded that the convinced absolute sea level rise, in the Nile delta area, could be considerably varying from 5.0 to 6.9 mm/year. Accordingly; it is anticipated that by year 2050 the mean sea level will be raised by about 17 and 23 cm, above the 2016-level, at Alexandria and Port Said respectively.

For the long-term analysis of relative sea level rise at Alexandria, a dataset of annual mean sea level covering 72 years, from 1944 to 2016, has been inspected. It has been noticed that there is a considerable increase of the sea rise rate over this time period. Although the long-term relative sea rise rate equals 2.6 mm/year, the most recent rate is 4.3 mm/year. Accordingly; It is recommended that recent estimate of sea rise to be considered in future coastal development and environmental plans rather than depending on the average rate over a long time span. It is also recommended that detailed studies to be carried out to monitor and estimate both relative and absolute sea level rise in the Nile delta based on integrating different techniques and observations including tide gauge, satellite altimetry, GNSS, and radar satellite images.

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