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Mean Sea Level and Tides Variations at Alexandria, Egypt over 1906-2020

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Tides - Tide Gauge - Mean Sea Level - Sea Level Rise - Vertical Datum – Egypt.

Abstract

Sea Level Rise (SLR) is a vital outcome of the environmental global warming phenomenon. This paper aims to investigate the basic properties of tides in Alexandria, Egypt and to analyze SLR in Egypt over a long period to examine the differences in Egypt's vertical geodetic datum. The annual relative SLR at Alexandria between 1906 and 2020 was found to be 2.6 mm/year. Moreover, the relative SLR has been 3.1 mm/y for the last two decades, 2001-2020. It could be considered the most appropriate value to be taken into consideration in Egypt's coastal management activities. Carrying out additional investigations is suggested to investigate possible major variations of MSL in Egypt at other TG sites over both the Mediterranean and Red seas. Based on available data and accomplished results, it is recommended to regard Egypt's MSL datum as a semi-kinematic rather than a fixed one.

1. Introduction

Tides, as a natural phenomenon, are the rise and fall of the ocean and sea surface height caused mainly by the gravity of both the Sun and Moon. The tidal phenomenon differs significantly over space and time. Thus, tidal analysis is one of the main aspects of navigation, harbor activities, and coastal management. A Tide Gauge (TG) station has been traditionally set up to measure and record the tidal variations in a country. Tide patterns have been recently investigated in several TG locations in Egypt such as Mersa Matruh [1] and Alexandria eastern harbor [2,3]. In addition, Ibrahim and El-Gindy [4] have analyzed the tides and storm surges in the eastern Mediterranean Sea from 1923 to 2019. The average of sea heights over a long time series at a TG is conventionally used to define Mean Sea Level (MSL) as a national vertical geodetic datum in a country. Based on such a definition of a specific MSL, the vertical geodetic network is established through many Benches Mark (BM) stations over a spatial region. In Egypt, the first historical TG has been established in Alexandria harbor more than a century ago. The mean value of all observations over 1898-1906 was taken as the MSL datum of Egypt. A central question has been raised in the last few

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decades about the stability of a specific MSL datum over time and its need for continuous updating [5,6].

Sea Level Rise (SLR) is essentially attributed to global warming and climate change factors including ocean thermal expansion, polar ice caps melt and change in terrestrial storage [7]. The Intergovernmental Panel on Climate Change (IPCC) stated that SLR since the mid-19th century has been larger than the mean rate during the previous two millennia [8]. Global SLR will be raised between 0.43 m and 0.84 m by 2100 (ibid). 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 [9]. SLR could be estimated from a variety of techniques and datasets. Relative SLR is primarily measured at TG sites, as well as from satellite altimetry data [10,11]. In another scene, absolute RLR accounts for both relative SLR and vertical movements at the TG sites [12,6]. Dangerous impacts of SLR include, for example, shoreline retreat [13], coastal flooding and inundation [14], coastal erosion [15], and a decrease in water quality in coastal regions [16].

SLR analysis, prediction, and risk assessment have been extensively investigated in Egypt in the last couple of decades. For example, Dawod et al. [17] have estimated both relative and absolute sea level rise in the Nile Delta region using heterogeneous spatial datasets. Their results indicated that absolute sea level rise, over Delta, differed between 5.0 mm/year at Alexandria to 6.9 mm/year at Port Said. Utilizing satellite altimetry data from 1993 to 2013, Shaltout et al. [18] estimated the relative SLR in the Egyptian Mediterranean coast to equal 3.1 mm/year. Additionally, El-Geziry and Said [19] have investigated the sea level pattern and variations in El-Burulls new harbor in the Nile Delta coastal region. Land subsidence and sea level rise across the Nile Delta region have been investigated [20]. That study found that absolute SLR across the Nile Delta varies between 6.7 and 11.4 mm/year. On the other hand, several research studies have been carried out to predict the potential impacts of sea level rise particularly on the Nile Delta region [21]. Additionally, here her [22] developed a vulnerability index to sea level rise for the Egyptian costs. He showed that more than one-third of the 1000-km long coasts are severely vulnerable to SLR. The current study aims to fulfill four objectives. First, to investigate the basic properties of tides at Alexandria in 2020 based on recent 30-minutes tide records. Second, to unify TG datasets come from different sources and construct an integrated dataset at Alexandria, Egypt extends over almost a century. Third, to apply several regression methods and statistical indicators to mathematically define the SLR trend over Egypt. Fourth and finally, to investigate SLR in Egypt over the entire period and on several twenty-year phases to describe the variations of Egypt's MSL vertical datum.

2. Tide and Mean Sea Level

2.1. Title

Tides are the response of the ocean and seas to the gravitational attraction of the Earth, Moon and Sun. That attraction normally produces a semi-diurnal pattern (two cycles per day) as the main component of tides. However, diurnal, and mixed regimes of tides exist in some parts of the world. There are several types of devices utilized to measure and record the variations of sea heights at a specific site or a Tide Gauge (TG). Mainly such instruments (Fig.1) could be divided into floating, pressure, acoustic, and microwave or radar devices [23]. In the float gauge, a pen and chart are used to record graphically the variations of sea height over mostly a day. The pressure gauges constitute instruments that measure subsurface pressure instead of sea level directly. Knowledge of seawater density and gravitational acceleration is required to make the conversion from pressure to sea level. Acoustic tide gauges depend on measuring the travel time of acoustic pulses reflected vertically from the sea surface and then converting it to sea height. Radar or microwave instruments use the same concept of acoustic type but use a microwave instead of acoustic waves. Each type of tide gauge has its own merits regarding the accuracy, accessibility, field requirements, and costs (ibid).

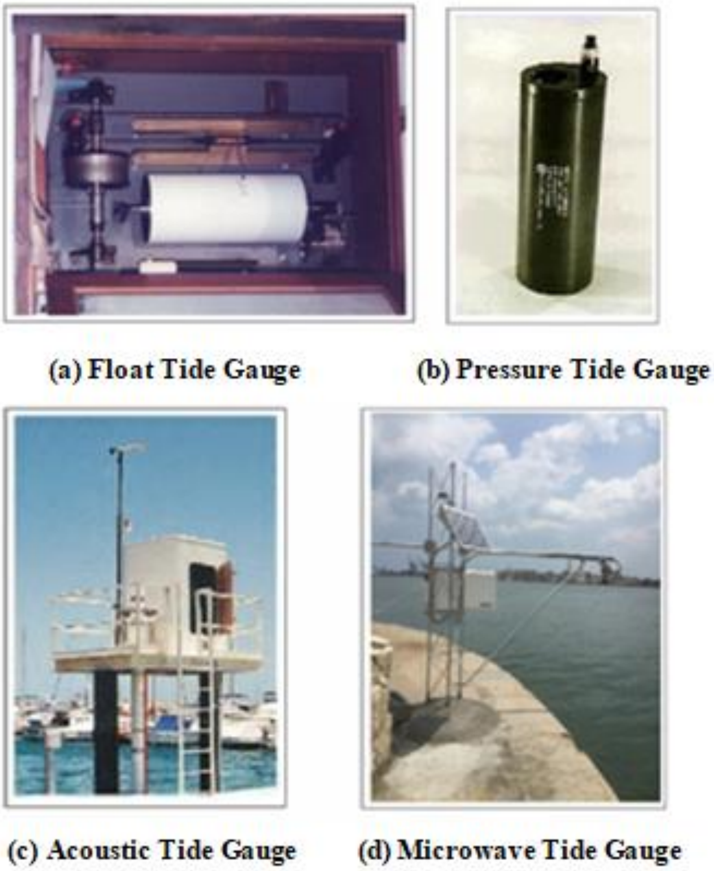

Fig. 1: Examples of the Different Types of Tide Gauges

2-2. Mean Sea Level

Sea level measurements from a TG are usually averaged over a year to estimate its mean annual values. Sea level Rise (SLR) could be investigated by collecting a time-series dataset of such observations at the TG location. Such a series is used to fit the dependent variable (Y), the Mean Sea Level (MSL), as predicted by the independent variable (X) or annual mean sea levels. There is a wide range of regression mathematical formulas applied in such a task to estimate the unknown parameters: a, b, c, and d shown in the following set of equations. A coefficient of determinations, R2, is then computed to represent the goodness of the regression process. Recently, more-complicated models, such as machine learning and neural network, have been utilized in SLR research [24]. The current study, herein, presents a few basic regression models in a general way and the interested readers could refer to any mathematical textbook for more details [25].

(a) Linear regression:

$$Y = aX + b \tag{1}$$

(b) Quadratic polynomial regression:

$$Y = aX^2 + bX + c \tag{2}$$

(c) Cubic polynomial regression:

$$Y = aX^3 + bX^2 + cX + d \tag{3}$$

(d) Logarithmic regression:

$$Y = a + b\ln(X) \tag{4}$$

(e) Hyperbolic regression:

$$Y = a + \frac{b}{X} \tag{5}$$

Additionally, the coefficient of determination, R2, is estimated as:

$$R^2 = 1 - \frac{\sum_i (Y_i - Y_{comp})^2}{\sum_i (Y_i - Y_{mean})^2} \tag{6}$$

where, Y_{comp} is the computed or fitted value of the ith observation, and Y_{mean} is the average of observations.

3. Study Area and Datasets

The city of Alexandria, founded in 331 BC by Alexander the Great, is located on the Mediterranean Sea at longitude 29.87o E and latitude 31.17o N approximately. With a population of more than five million, it is the third-largest city in Egypt and the largest city in the Mediterranean. The first tide gauge, called Port TG herein, has been established in the western harbor of Alexandria (Fig. 2). The device used in that TG was a floating type and the daily high and low water levels were recorded. The mean value of all observations over 1898-1906 was taken as the MSL datum of Egypt. That datum has been defined as 33.8 cm above the zero of the fixed tide staff. It is worth mentioning that the entire precise levelling networks of Egypt have been established based on that MSL datum [6].

In the early 1990s, the Egyptian Navy Hydrographic Department (ENHD) of the Egyptian Naval Force constructed a new tide gauge, Navy TG herein, approximately 800 m west of the historical Port TG (Fig. 2). Also, a floating device has been utilized at that site to record water levels on an hourly basis. It was thought that both TG is on the same ground level, which implicitly meant that the MSL is located also at 33.8 cm above the bottom of the fixed staff. Later, a precise levelling has been carried out to connect both TG sites and the results revealed that the Navy TG is 18 cm higher than the historical Port TG. An agreement has been signed between ENHD and the Survey Research Institute (SRI) of the National Water Research Center (NWRC) in the year 2000 to start scientific cooperation around sea level variations and environmental monitoring. Thus, the device of the Navy TG has been replaced by a modern pressure type and a metrological weather station and a fixed Global Positioning System (GPS) receiver have been installed too [6]. Hence, digital sea level observations of the Navy TG have been recorded since 2001 up till now. Recently, a microwave type TG has been installed in that TG as a precise backup system [26].

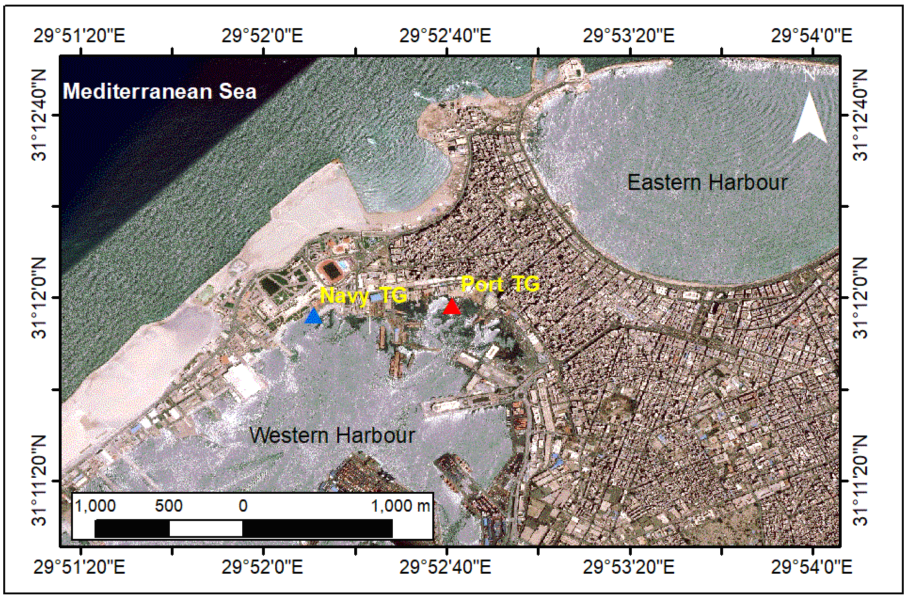

Fig. 2: Tide Gauges at Alexandria City

The datasets utilized in this study consist of four different groups (Table 1). First, the monthly and annual MSL related to the historical Port TG from 1944 to 1992 has been obtained from the Permanent Service of Mean Sea Level (PSMSL) website [27]. It is worth mentioning that this dataset is referenced to the Revised Local Reference (RLR) and a constant of 7.019 m should be subtracted to reference it to the local MSL datum of Egypt [28]. The second group of data contains the hourly sea heights of the Navy TG from 1993 to 2000. As previously stated, a sum of both constants (33.8 and 18 cm) has been subtracted from the original measurements to relate them to the Egyptian MSL datum [6]. The third data source is the Navy TG dataset from 2001 to 2018 as recorded by the pressure-type device every half hour. Lastly, the fourth dataset comes also from the microwave device installed in 2019 at the Navy TG. For both the third and fourth data groups, only 18 cm are subtracted to relate them to the national datum. Consequently, this research has integrated a unique database of sea level heights at Alexandria from 1944 to 2020 referenced to the national MSL vertical datum of Egypt of 1906 for the first time.

Table 1: Utilized Tide Data Sources at Alexandria

Tide Gauge	Data Source	Period	Frequency	Gaps
Port TG	PSMSL	1944-1993	Monthly	1948, 1949
Navy TG	ENHD	1993-2000	Hourly	NA
	SRI	2001-2020	30 minutes	

4. Results and Discussion

4-1. Alexandria's Tide Characteristics

The 30-minutes tide dataset of 2020 has been investigated to illustrate the basic properties of tides at Alexandria city. First, Figure 3 depicts typical hourly tides variations at Alexandria on the 1st of January 2020 (just a typical day in the most-recent available datasets). Tides, on that day, vary between 0.177 m and 0.380 m, with a range equal to 0.203 m and an average value of 0.279 m. It follows the semi-diurnal pattern with two maximum values occurring at midnight and 1.5 PM and two minimum values at almost 7.5 AM and 7.5 PM of local time. Similar results have been reported by El-Geziry and Dabbous [3]. Next, the minimum and maximum values of daily tides over the entire 2020 have been defined. It has been found the maximum tide occurred on August 20 and the minimum tide occurred on February 29 (Fig. 4 and 5). It has been found that a minimum tide equals 0.042 m while the recorded maximum tide equals 0.542. Next, Fig. 6 depicts the monthly annual tide variations of 2020. It reached its highest value from July to August, and the minimum values took place in February and March.

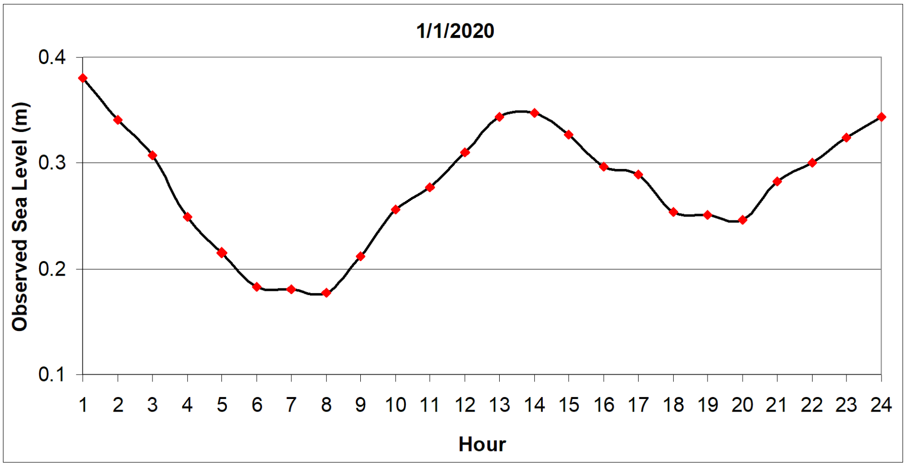

Fig. 3: Typical Hourly Tides of Alexandria on January 1st, 2020

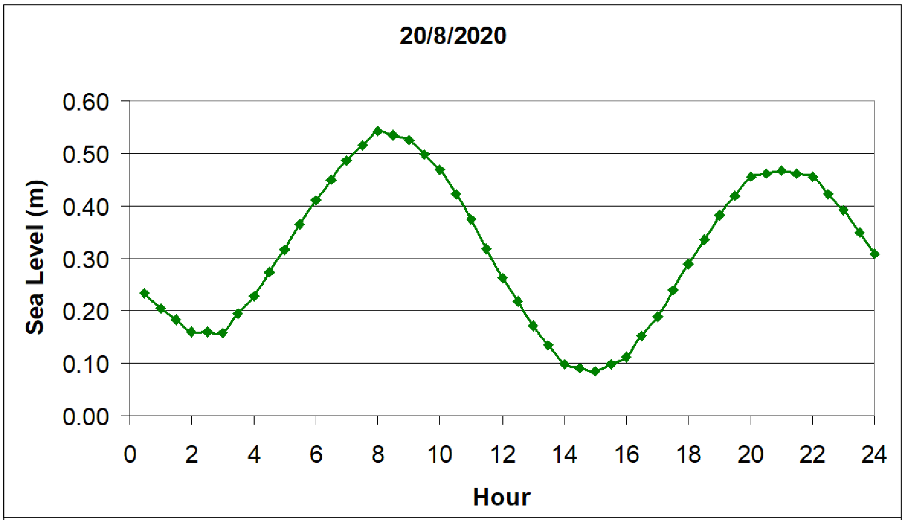

Fig. 4: Maximum Tides of Alexandria in 2020

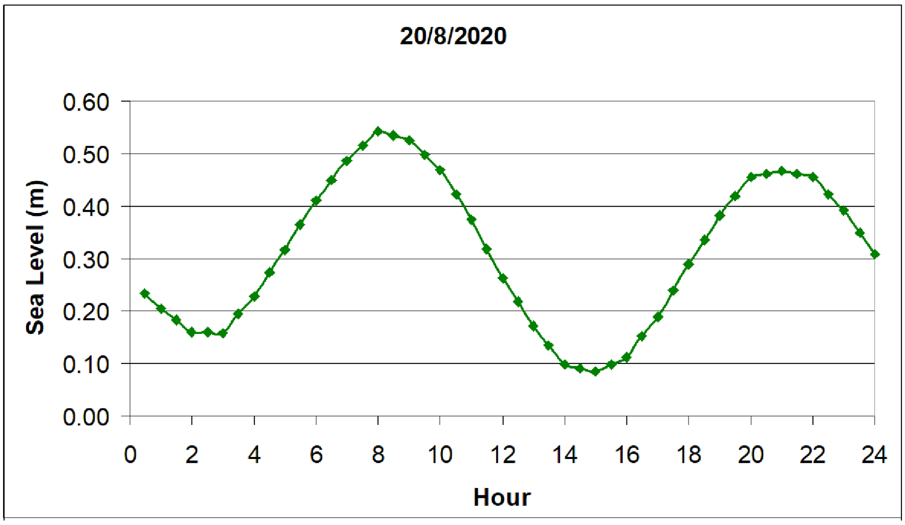

Fig. 5: Minimum Tides of Alexandria in 2020

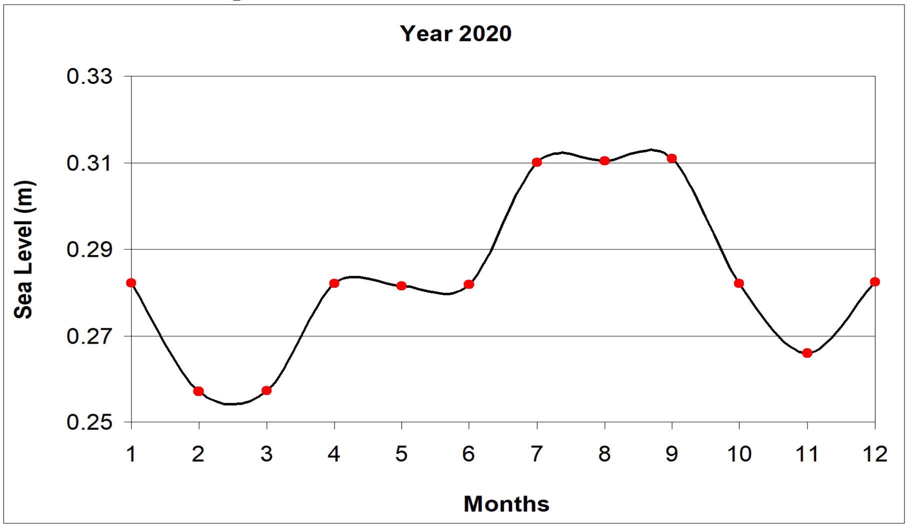

Fig. 6: Monthly Tides of Alexandria in 2020

4.2. Egypt's Mean Sea Level Variations

The unique integrated tide database of Alexandria has been utilized in investigating the relative SLR and MSL variations over 1944-2020 (relative to 1906 MSL datum) for the first time in Egypt. Keeping in mind that few data gaps exist, that database contains annual MSL for 76 years. Fig. 7 portrays the general trend of MSL variations over that specific period, which clearly show a rising MSL. Statistical fitting approaches have been performed to describe that trend mathematically. Linear, quadratic, and cubic polynomial, logarithmic, and hyperbolic formulas (Eq. 1 to 5) have been fitted to the known data and the R2 indicator (Eq. 6) has been computed for each case (Table 2). This table showed that although the quadratic and cubic polynomial model produced a slightly better fit, the linear trend is most utilized in SLR studies for its simplicity in defining and forecasting the SLR [29]. Thus, it can be concluded that the annual linear SLR at Alexandria over 1906-2020 equals 2.6 mm/year. That figure highlights the general trend of relative SLR over more than a decade in Egypt. However, it might not the most appropriate to demonstrate recent SLR magnitude in the country.

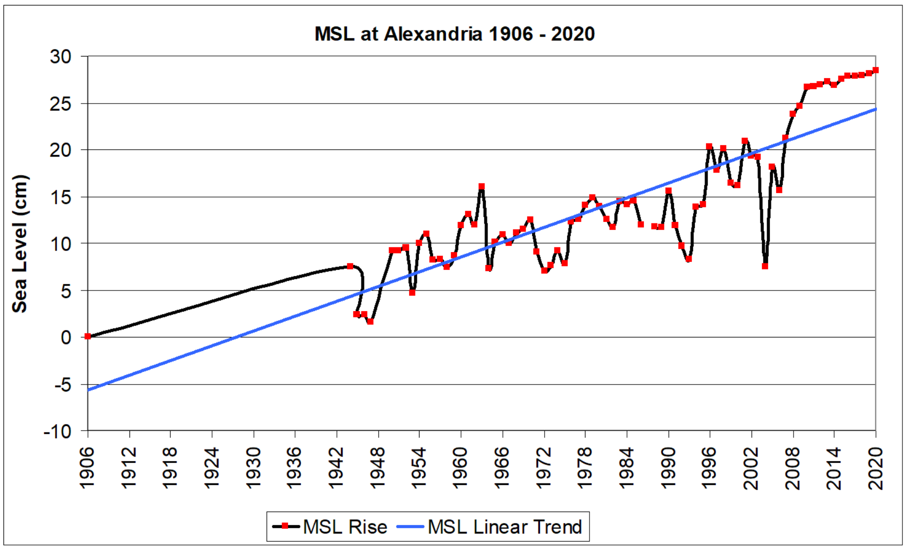

Fig. 7: MSL Variations at Alexandria over 1946-2020 relative to 1906 Datum

Table 2: Statistics of 1906-2020 MSL Fitting Methods

Type	Equation	R2
Linear	MSL = 0.2625 Year - 505.96	0.76
Quadratic Polynomial	MSL = 0.0023 Year2 - 9.0315 Year + 8683	0.82
Cubic Polynomial	MSL = 0.0000 Year3 - 0.0484 Year2 + 96.4235 Year - 41660.3323	0.85
Logarithmic	MSL = 517.88 Ln (Year) - 3917.4	0.76
Hyperbolic	MSL = 529.8565 - (1021780.9758/Year)	0.76

The previous relative SLR figure, 2.6 mm/y, highlights the general trend of SLR over more than a decade in Egypt (referenced to the 1906 Egyptian datum). However, it might not the most appropriate to demonstrate recent SLR magnitude in the country. Hence, the available dataset has been divided into 20-years intervals to consider the 18.6-year lunar-node cycle. That modal cycle is important in investigating SLR precisely [30]. Figures 8-11 and Table 3 demonstrate the attained findings. From these figures and table, several significant remarks could be obtained. First, the linear SLR trend is weak for the first three timespans: 1944-1960, 1961-1980, and 1981-2000 since the R2 values equal just 0.40, 0.01, and 0.20. It might be attributed to the nature and quality of corresponding datasets from PSMSL source (refer to Table 1). Second, the SLR over 1961-1980 is almost steady with no noteworthy rise. Third, the SLR magnitudes of 3.9, 0.04, and 2.0 mm/year corresponding to such periods are not trustable. Fourth, for the last couple of decades, 2001-2020, the attained results prove that the SLR at Alexandria is of high confidence since the R2 reaches 0.77. Fifth and based on that analysis, the relative SLR of 3.1 mm/y over 2001-2020 could be considered the most appropriate value to be taken into consideration in Egypt's coastal management activities. This figure should be regarded as an alarming finding reflecting that the SLR in the last couple of decades is significantly higher than the long-term rise over the entire twentieth century at Alexandria.

Table 3: Statistics of 1906-2020 MSL Fitting Methods

Period	Linear Equation	R2	SLR (mm/y)
1944-1960	MSL = 0.3889 Year - 751.82	0.40	3.9
1961-1980	MSL = 0.0336 Year - 55.03	0.01	0.04
1981-2000	MSL = 0.2024 Year - 389.45	0.20	2.0
2001-2020	MSL = 0.3122 Year – 5.91	0.77	3.1

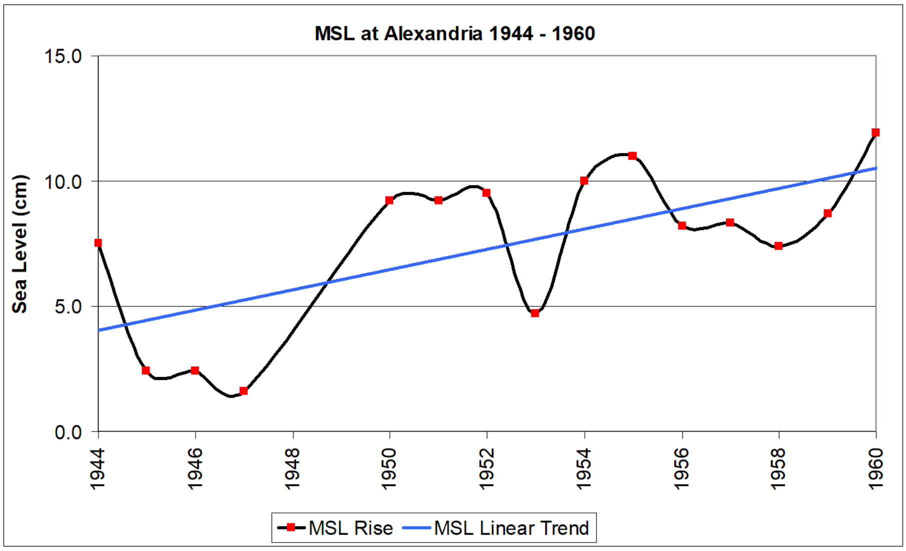

Fig. 8: MSL Variations at Alexandria over 1944-1960

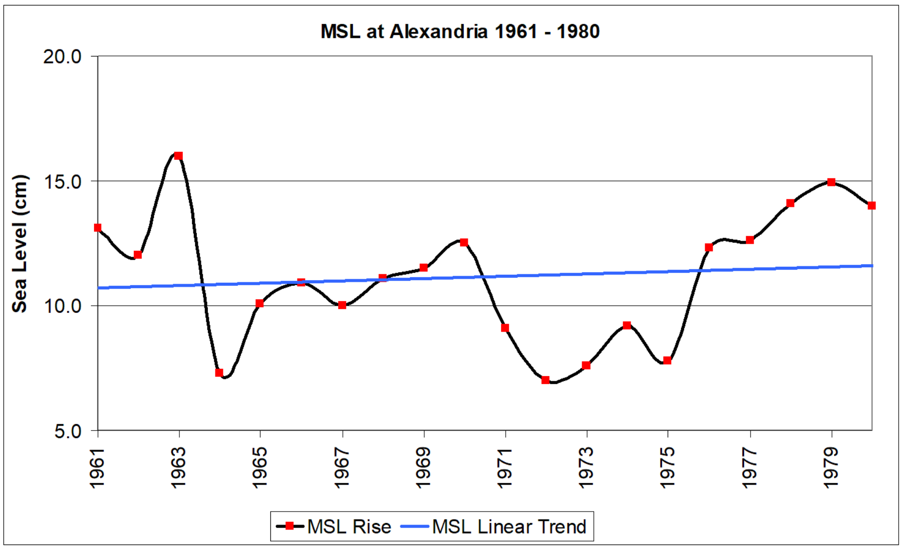

Fig. 9: MSL Variations at Alexandria over 1961-1980

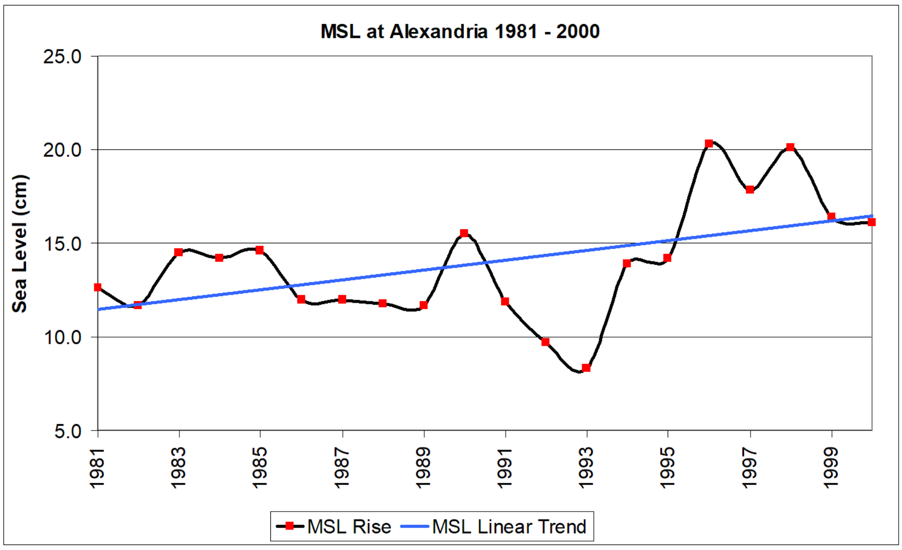

Fig. 10: MSL Variations at Alexandria over 1981-2000

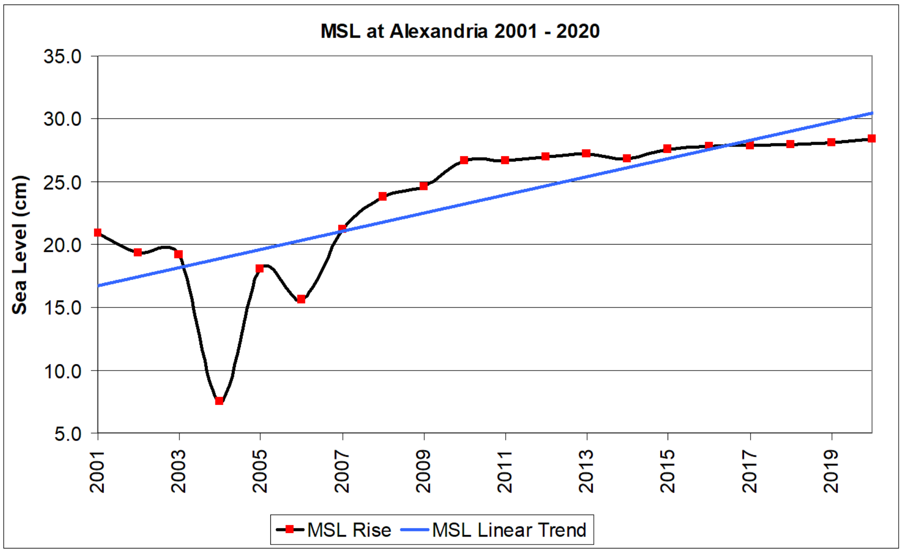

Fig. 11: MSL Variations at Alexandria over 2001-2020

Finally, the values of Egypt's MSL or vertical datum has been investigated over 20-years intervals. Table 4 and Figure 12 present the accomplished findings. Based on the available data, the value of the national vertical datum as defined at Alexandria in 1906 is varying considerably. Its value has been increasing to 7.4, 11.2, 13.4, and 23.8 cm over the 1944-1960, 1961-1980, 1982-2000, and 2001-2020 periods respectively. Additionally, it can be noticed that the MSL has been increased over 1961-1980 by 51% relative to the 1944-1960 mean value. Similarly, it increased by 20% and 78% over the periods 1981-2000 and 2001-2020 relative to each preceding 20-year time span. Thus, it is a matter of fact that the SLR is getting faster in Egypt in the last few decades.
Regarding the accessible datasets and attainable results, the current study implies that Egypt's MSL datum should not be considered as a fixed datum over time. Like the semi-kinematic horizontal geodetic datum of Egypt proposed by Rabah et al. [31], the results of the current research emphasize that the vertical datum should be regarded as semi-kinematic too. Simply, it means that its definition should be updated a suitable span, 20 years for instance. For the time being, it should be considered that the most recent Egypt's national MSL datum is 23.8 cm higher than the traditional 1906-defined one. That fact should be applied in environmental and geomatics activities and studies to get more reliable results. However, it is recommended to perform additional

investigations about other possible major variations of MSL in Egypt at other TG sites over both the Mediterranean and Red Seas. Such a task could be performed utilizing datasets of SRI's tide gauges recently established at Port Said, Suez, and Safaga cities.

Table 4: Average MSL Variations at Alexandria

Period	Average MSL (cm)	Increase Percent
1906 (original)	0.0	NA
1944-1960	7.4	
1961-1980	11.2	51%
1981-2000	13.4	20%
2001-2020	23.8	78%

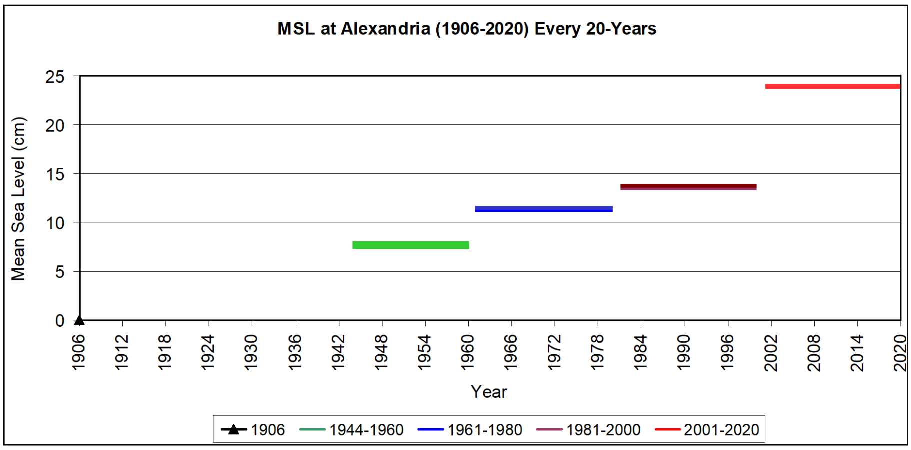

Fig. 12: MSL Variations at Alexandria over 1906-2020 every 20 Years

In addition, the accomplished results showed that elevations of the tide gauges and benchmarks in Egypt need to be corrected as the national vertical datum is changed since its old definition in 1906. The current study suggests that such a task could be performed by establishing and applying 4D databases of tide gauges, particularly over the Nile River, for efficient water resources management. It is a matter of reality that the absolute SLR combines the influences of both relative SLR, from TG, and the vertical land movement. Mohamed and Dawod [32] have utilized geodetic datasets from 2011 to 2019 and have estimated the land subsidence rate at Alexandria as 3.3 mm/year which concluded that the recent estimate of the absolute SLR equals 6.0 mm/year. Such a rate should be considered in environmental investigations and development activities over Alexandria.

5. Discussion/Conclusion

The tidal analysis is a chief feature in navigation and coastal management. On the other hand, it is a matter of reality that the sea level has been significantly raised in the 20th century on a global average. The current research has utilized data from different sources to construct a unique database of sea levels at Alexandria from 1944 to 2020, referenced to the national MSL 1906 vertical datum of Egypt, for the first time in the country. Regarding relative sea level rise, it can be concluded that the annual linear SLR at Alexandria from 1906 to 2020 equals 2.6 mm/year. Furthermore, the available dataset has been divided into 20-years intervals to consider the 18.6-year lunar-node cycle. Attained findings reveal some significant remarks. First, the linear SLR trend is poor for the periods 1944-1960, 1961-1980, and 1981-2000 since the determination coefficients are less than half. Second, the SLR over 1961-1980 is almost steady with no noteworthy rise. Additionally, in the last couple of decades, 2001-2020, the relative SLR equals 3.1 mm/y. Thus, it could be considered the most appropriate value to be taken into consideration in Egypt's coastal management activities. The values of Egypt's MSL or vertical datum have been investigated over 20-years intervals and showed that the value of the national vertical datum as defined at Alexandria in 1906 is varying considerably. Consequently, the SLR is getting faster in Egypt in the last few decades. The current study showed that Egypt's MSL datum should not be considered a fixed datum over time. Based on accessible data and achieved findings, it is recommended that that datum should be regarded as semi-kinematic, which means that its definition should be updated a suitable time, 20 years for instance.

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