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Sea level analysis using tide gauge observations at the northern delta coast, Egypt

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ABSTRACT

The current study focuses on the analysis of observed sea level in the northern delta coast, which is considered the most important region in Egypt. The used sea-level data are records of three tide gauge stations located on the north of the delta, on Alexandria, Damietta, and Port Said. Different periods of sea-level records had been used to be analyzed to get the astronomical tide and surge heights. Geotide software had been used to obtain the tidal harmonic constituents. The tidal cycle sort at the three locations of the tide gauges had been calculated and the results were as follows: a mixed semidiurnal tidal type in Alexandria and Damietta, and a semidiurnal tidal type in Port Said. The Mean Sea Level (MSL), referred to the Egyptian Survey Authority datum (ESA-1906), had been calculated, and the tidal datums of each station referred to the International Terrestrial Reference Frame (ITRF-2014) had been calculated else. Ten groups of tidal constituents had been obtained and two of them have the largest amplitudes and they are M2 (Principal lunar), S2 (Principal solar). The amplitudes and percentages of astronomical tide and surge, in the observed sea level data, will be shown in the results section.

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1. Introduction

There is a great interest of sea-level change for many reasons. The most important two reasons are as follows: the change in the Earth’s climate and the social economic outcomes for populations who live near the sea coast (Antonov, J. I., Levitus, S., & Boyer, T. P.,2002; Gornitz 1995)

Variation of the observed sea level at any place in the world depends on numbers of factors such as astronomical components, surge, interannual to secular variability, the seasonal cycle, and variations at interglacial and geological scales (Pugh 1987; Jorda et al., 2012).

Absolute sea level change is difficult to measure. However, relative sea-level changes have been derived mainly from tide-gauge data relative to fixed tide-gauge benchmarks. This relative sea level (RSL) is referred to as sum of changes in sea level and local uplift and subsidence changes in the land.

In the Mediterranean basin, variation of the observed sea level in the northern delta coast results principally from the combination of two heights: astronomical tide which has a minor effect, being about 20 cm, and the surge, which has a major effect, being about 1.00 m under the effect of meteorological factors. These factors are the atmospheric pressure, the air temperature, the wind framework, and the steric impact (Sharaf El-Din 1975; Eid 1990; Saad et al. 2011). Many authors made studies on these meteorological factors, which are affected on the variation of the sea level in the Mediterranean area and throughout the length of the Mediterranean coast of Egypt, e.g. Mosetti and Purga (1990), Tsimplis et al. (2005), Gomis et al. (2008), Hussein et al. (2010), Said et al. (2012)).

The main objective of this research is the analysis of the observed sea level data around the northern delta coast in Egypt to investigate the characteristics of its components, obtain the astronomical tidal constituents, surge heights, and the patterns of sea level.

2. Data and methods of analysis

Different periods of sea-level records, of the northern delta coast in Egypt, have been used in this study. The sea-level data are records of three tide gauge stations located on the north of the delta coast. Figure 1(a) shows the distribution of the three tide gauges. The first set of data belongs to the tide gauge station, which is located on the west of the delta in Alexandria Western Harbour (AWH). This data is divided into two groups, the first group is a continuous half an hour data in the period from 01/01/2009 to 02/11/2010, and the second one is a continuous half an hour

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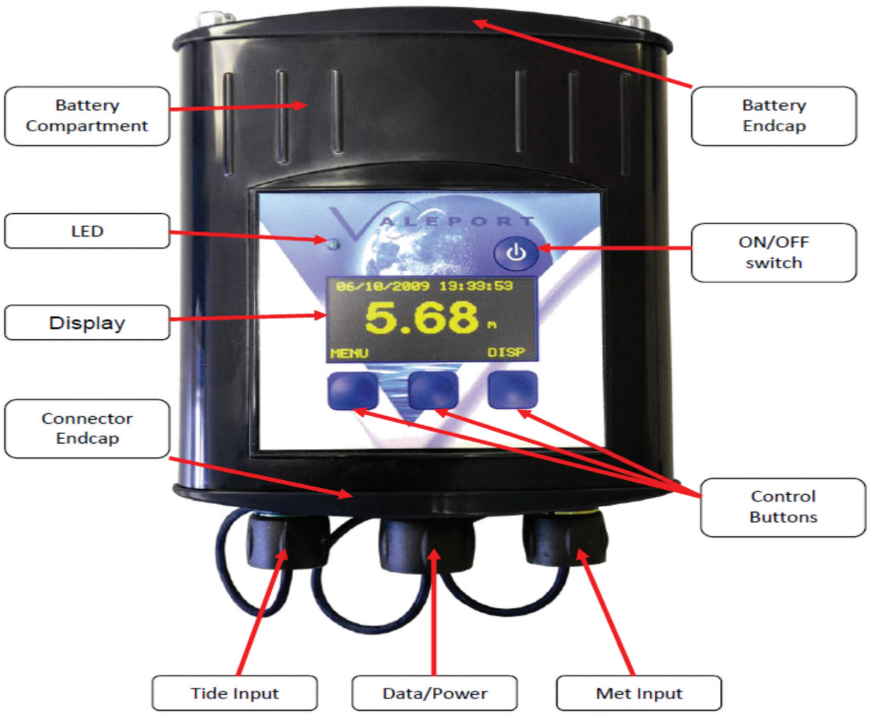


Figure 1 (a) Distribution of the three tide gauge stations in the northern delta coast. (b) Typical tide master tide gauge used on the current study.

data in period from 30/4/2012 to 31/12/2013. The second set of data belongs to the tide gauge station, which is located near the middle of the delta in Damietta harbour in the period from 01/08/2015 to 31/07/2016. The third set of data belongs to the tide gauge station, which is located on the east of the delta in Port Said harbour in the period from 01/01/2015 to 31/12/2015. The sets of data were carried out within the framework of the project entitled "Evaluation of Nile Delta Sinking Hypothesis Using the Global Positioning System (GPS), Tide Gauge and Satellite Altimetry and Gravity Techniques" that has been funded by the Science and Technology Development FUND (STDF), Egypt.

Tide gauge records at the selected locations were made using Valeport tide gauges. Tide Master Express is one of the most updated tide gauges produced by Valeport and had been used at this study. The Tide Master tide gauges had been designed to provide accurate, versatile, and easily deployed tide gauge for use in short or long hydrographic survey operations. Typical tide gauge used on the current study is given in Figure 1(b).

The tidal harmonic theory method is the most important method used in data analysis, which clarifies that the astronomical tidal height can be showed by a large set of tidal frequency components (Pugh 2004). Tidal Analysis calculates the amplitude of each known harmonic frequency component and its phase by an iteration method which is a process of trial and error. The set of amplitudes and phase degrees which are decided by the analysis for a given location are called the Tidal Harmonic Location Constants (Pugh 2004).

By using the results from the analysis, the Mean Sea Level (MSL) for the study period, and the sort of tidal cycle of the study location are determined. The tide cycle type can be determined by using the following constituent factor (Pugh 2004):

$$F = (H_{O1} + H_{K1})/(H_{M2} + H_{S2}) \quad (1)$$

Where:

H_{O1}:The tidal amplitude of the principal lunar diurnal constituent.

H_{K1}:The tidal amplitude of the luni-solar diurnal constituent.

H_{M2}:The tidal amplitude of the principal lunar semidiurnal constituent

H_{S2}:The tidal amplitude of the principal solar semidiurnal constituent.

According to the constituent factor F the sort of a tidal cycle may be considered as follows (Pugh 2004):

RangeTidal cycle type

The constituent factor F0 to 0.25semidiurnal

0.25 to 1.25mixed semidiurnal

1.25 to 3mixed diurnal

larger than 3diurnal

The data was analysed using the Geotide-software to obtain the harmonic tidal constituents. Geotide-software converts the data obtained from tide gauge into tidal harmonic constituents (Bazli and Joanes (2016)), which can then be used to forecast the tide for any date in the future or the past (Pugh 1987; Jorda et al., 2012). The Geotide software is mainly dependent on the concept of expressing the amplitudes of tides at any location as the sum of the whole harmonic constituents (Pugh 1996) as follows:

$$h_{(t)} = H_0 + \sum i = 1tonf_i H_i \cos\left(\alpha_i t + \{V_0 + u\}_i - k_i\right) \quad (2)$$

Where:

$h_{(t)}$:Height of the tide at any time t, above a reference datum.

n:Constituents number which being used in prediction.

H_0: The mean sea level above the datum.

H_i:Tidal constituent amplitude.

α_i:Tidal constituent angular speed (degrees/hour).

t:The time from the initial epoch (hours).

k_i:Tidal constituent epoch relative to the transit of the moon over the location of tide.

f_i:Tidal constituent node factor.

$\{V_0 + u\}_i$: Tidal constituent equilibrium argument at t = 0 (degrees).

$\left(\alpha_i t + \{V_0 + u\}_i - k_i\right)$:The phase at any time t relative to the transit of the moon.

The height, which was obtained from the analysis, consists of two components: the astronomical tide, and the height of the surge. The astronomical tide had been obtained from the analysis, and by using the calculated astronomical tide and subtracting it from the observed sea-level heights, the surge could be obtained (Eid 1990; Svensson and Jones 2004).

3. Results and discussion

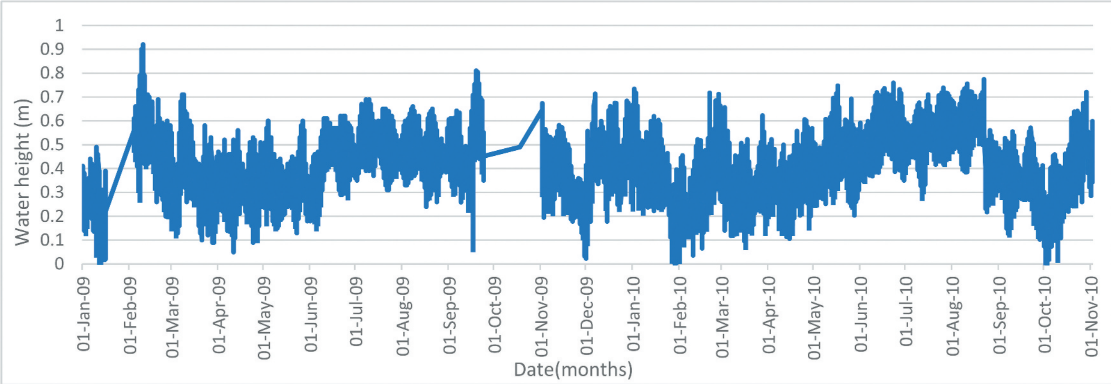
The available data for the three sites located on the north delta coast were analysed using the Geotide software and the results were obtained for each site separately.

3.1. Alexandria station

The two data sets of Alexandria were analysed and common patterns of sea level were obtained where the half-hourly records sea level of the observed data presented in Figure 2. Figure 2(a) shows the data in the period from 01/01/2009 to 02/11/2010, while Figure 2 (b) for the data in the period from 30/04/2012 to 31/12/2013. Within the first group of data, the minimum height of sea-level over the sensor of the tide gauge was 0.00 m on 3 October 2010, the maximum one was 0.92 m on 14 February 2009, and the mean height was 0.404 m, while within the second group, the minimum height was −0.01 m on 20 December 2013, the maximum one was 0.76 m on 20 November 2012, and the mean height was 0.374 m. Figure 3 shows the monthly mean height of the observed data at Alexandria, where Figure 3(a) for the data in the period from 01/01/2009 to 02/11/2010, while Figure 3(b) for the data in the period from 30/04/2012 to 31/12/2013, based on the half-hourly records taken from the tide gauge located within AWH.

Seventeen tidal harmonic components in 10 groups, throughout the study, had been produced. Each tidal constituent has its amplitude and phase as shown in Table 1.

To check the results of the tidal constituents obtained from the analysis, the results were compared with the previous study for the same location, and approximately within the same period (Khedr et al. (2018)) as shown in Table 2. From the comparison, it is clear that the results have approximately the same



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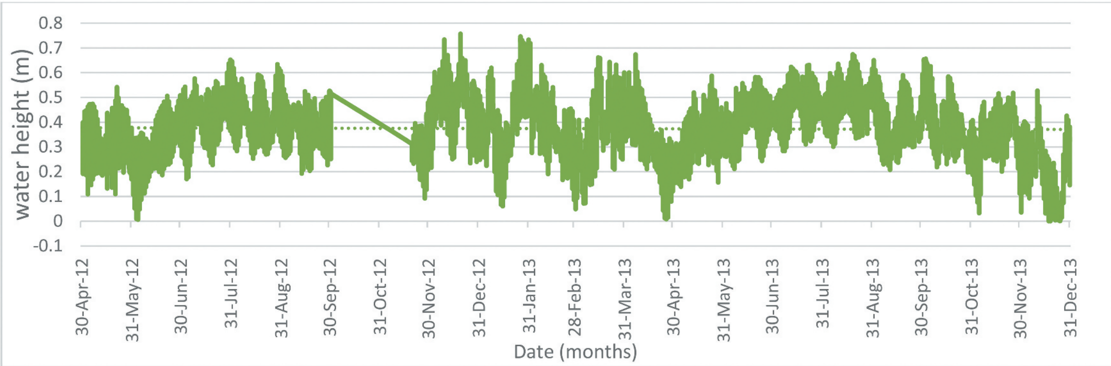
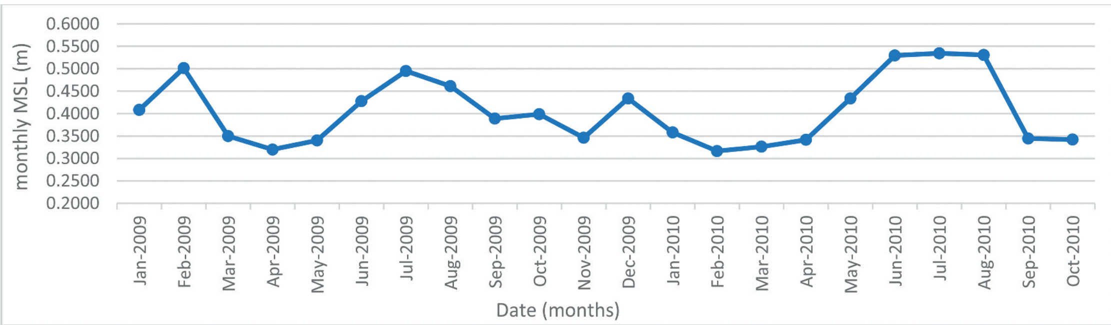


(2-b)

Figure 2. Half an hour recorded sea level of the observed data at Alexandria. (a) for the period from 01/01/2009 to 02/11/2010, and (b) for the period from 30/04/2012 to 31/12/2013. Noting that the straight lines in the Figure are gaps in the observed data.



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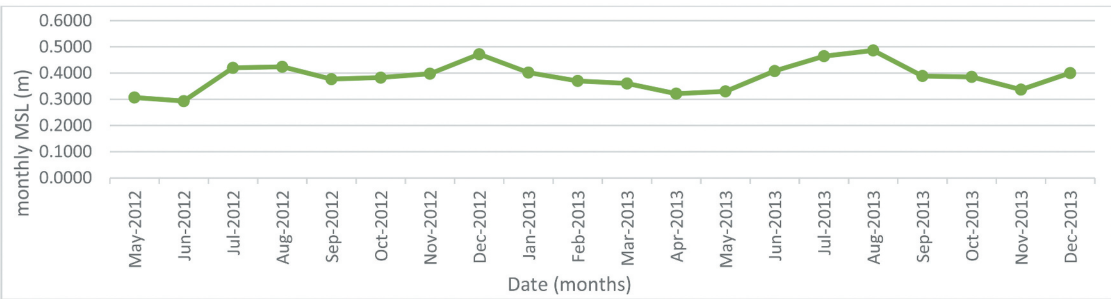


(3-b)

Figure 3. Monthly mean height of the observed data over the sensor of tide gauge at Alexandria. (a) for the period from 01/01/2009 to 02/11/2010, and (b) for the period from 30/04/2012 to 31/12/2013.

Table 1. Amplitudes and phase angels of the tidal constituents from both two groups of data at AWH.

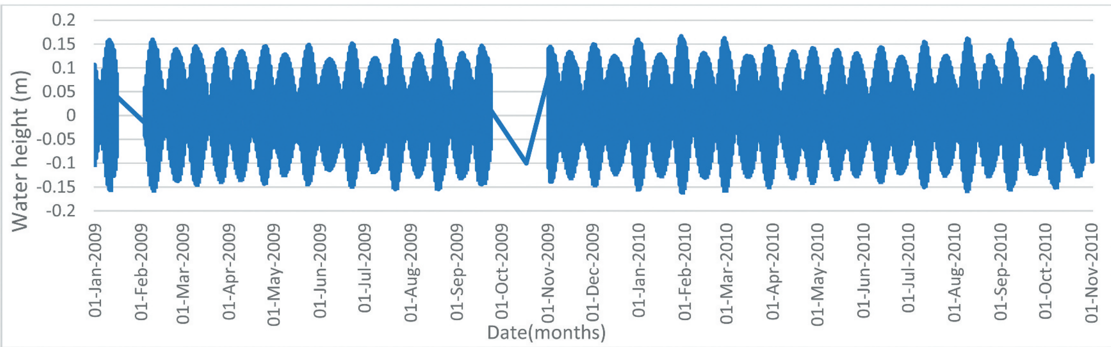
			First group of data (2009–2010)		second group of data (2012–2013)	
Name of Tidal Constituent	Symbol	Period (hours)	Amplitude (m)	Phase (degree)	Amplitude (m)	Phase (degree)
Principal lunar	M2	12.42	0.07372	301.290	0.06714	327.650
Principal solar	S2	12.00	0.04444	316.968	0.04137	342.298
Luni-solar diurnal	K1	23.93	0.01756	305.833	0.01604	317.054
Principal lunar diurnal	O1	25.82	0.01285	272.163	0.01286	289.577
Principal solar diurnal	P1	24.07	0.00627	301.617	0.00585	317.283
Larger lunar elliptic semidiurnal	N2	12.66	0.01206	301.944	0.01163	320.351
Luni-solar semidiurnal	K2	11.97	0.01178	314.286	0.01329	359.934
Larger lunar elliptic diurnal	Q1	26.87	0.00176	247.033	0.00125	232.082
Shallow water of principal lunar	M4	6.21	0.00031	320.865	0.00055	215.844
Shallow water quarter diurnal	MS4	6.10	0.00022	254.469	0.00049	315.563

Table 2. Comparison between the major harmonic constituents in the current study (by Geotide-software), and the previous study (by Delft-3D software) at AWH.

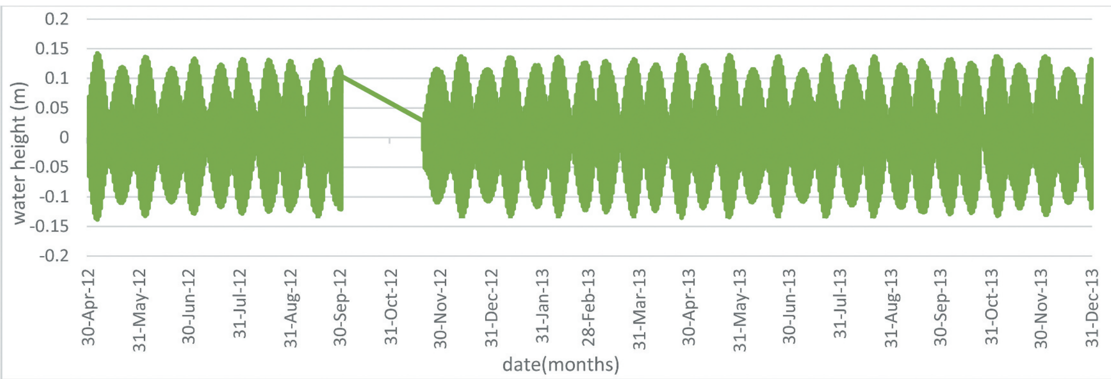
Constituents		M2		S2		K1		O1	
Datasets		Amp. (m)	Phase (deg.)	Amp. (m)	Phase (deg.)	Amp. (m)	Phase (deg.)	Amp. (m)	Phase (deg.)
Previous study	First dataset 11/09/2008 – 2/11/2010	0.074	301	0.045	315	0.017	303	0.013	272
	Second dataset 30/04/2012 – 26/01/2014	0.069	324	0.041	340	0.016	315	0.013	286
Current study	First dataset 01/01/2009 – 31/12/2010	0.074	301	0.044	317	0.018	306	0.013	272
	Second dataset 01/01/2012 – 31/12/2013	0.067	328	0.041	342	0.016	317	0.013	290

accuracy. It is known that the previous study had depended on Delft-3d software which is principally based on the concept of the tidal harmonic theory as on the Geotide software (Roelvink and Van Banning (1995)).

By using Eq. (1) and the amplitude of tidal constituents in Table 1, the constituent factor (F) was calculated to be 0.257 in the first group of data, and 0.266 in the second, which indicates that the tidal cycle of Alexandria is a mixed semidiurnal cycle type in the area of study. Figure 4 shows the astronomical tidal



(4-a)



(4-b)

Figure 4. Astronomical tidal elevations at AWH within the two periods of study. (a) for the period from 01/01/2009 to 02/11/2010, and (b) for the period from 30/04/2012 to 31/12/2013. Noting that the straight lines in the Figure are gaps in the observed data.

elevations at AWH within the two periods of study, where Figure 4(a) for the period from 01/01/2009 to 02/11/2010, and Figure 4(b) for the period from 30/04/2012 to 31/12/2013, which varies between −0.16 and 0.17 m and −0.14 to 0.14 m, respectively. Figure (5) shows the calculated surge elevations at AWH within the two periods of study, where Figure 5(a) for the first period, and Figure 5(b) for the second, which varies between −0. 50 to 0.40 m and −0.39 to 0.39 m, respectively.

Tidal datums can be calculated as shown in the equations below and Table 3 (Doodson 1954) by knowing the values of the main harmonic constituents, and the height of Tide Gauge Zero Level (TGZL) referred to the International Terrestrial Reference Frame (ITRF-2014) or the Egyptian Survey Authority datum (ESA- 1906), where TGZL = −0.2175 m and 14.355 referred to (ESA-1906) and, (ITRF-2014) respectively (Khedr et al. 2018).

(1) Mean Sea Level (MSL) referred to (ESA-1906) = TGZL referred to (ESA-1906) + H_m
(2) Mean Sea Level (MSL) referred to (ITRF-2014) = TGZL referred to (ITRF-2014) + H_m
(3) Highest High-Water Level (HHWL) = MSL (ITRF-2014) + ($M_2 + S_2 + O_1 + K_1$).
(4) Lowest Low-Water Level (LLWL) = MSL (ITRF-2014) − ($M_2 + S_2 + O_1 + K_1$).
(5) Mean High-Water Spring (MHWS) = MSL (ITRF-2014) + ($M_2 + S_2$).
(6) Mean Low-Water Spring (MLWS) = MSL (ITRF-2014) − ($M_2 + S_2$).
(7) Mean High-Water Neap (MHWN) = MSL (ITRF-2014) + (M_2-S_2).
(8) Mean Low-Water Neap (MLWN) = MSL (ITRF-2014) − (M_2-S_2).

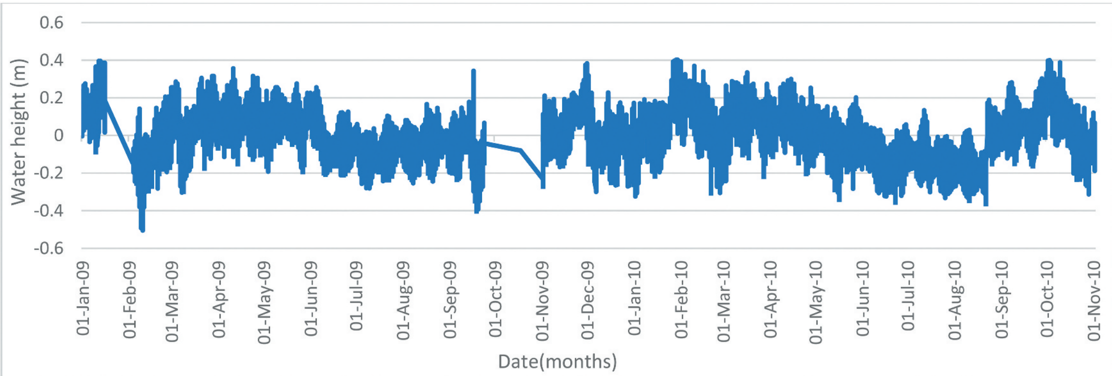
Where H_m is the mean height of sea level over the TGZL obtained from the analysis at AWH which equals 0.404 m and 0.374 m for the two groups of data.

3.2. Damietta station

The observed data of Damietta was analysed using Geotide software, and common patterns of sea level were obtained. The minimum, the maximum, and the mean height of sea-level over the sensor of the tide gauge were obtained and the results were 3.8 m,

Table 3. Major tidal parameters (datums) from both two groups of data at AWH.

Tidal parameters (datums)	First group of data (2009–2010)	Second group of data (2012–2013)	Mean
MSL (ESA-1906)	0.1865	0.1565	0.1715
MSL (ITRF-2014)	14.76	14.73	14.745
HHWL (ITRF-2014)	14.91	14.87	14.89
LLWL (ITRF-2014)	14.61	14.59	14.60
MHWS (ITRF-2014)	14.88	14.87	14.875
MLWS (ITRF-2014)	14.64	14.62	14.63
MHWN (ITRF-2014)	14.79	14.75	14.77
MLWN (ITRF-2014)	14.73	14.70	14.715



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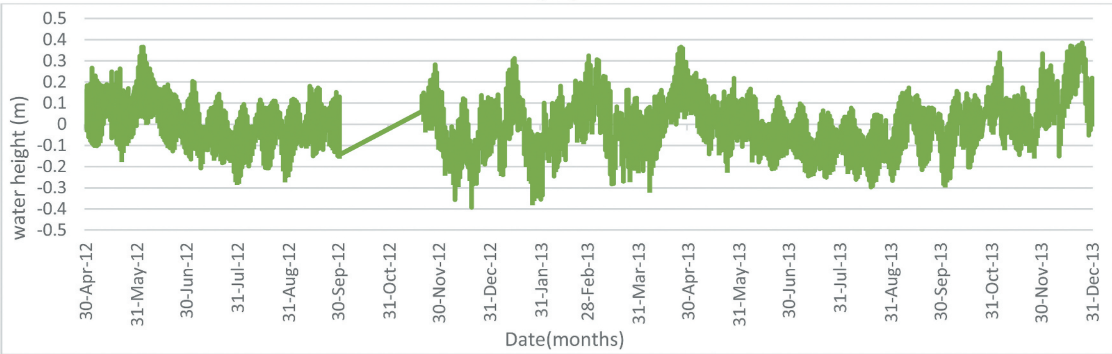

(5-b)

Figure 5. Calculated surge elevations at AWH within the two periods of study. (a) for the period from 01/01/2009 to 02/11/2010, and (b) for the period from 30/04/2012 to 31/12/2013. Noting that the straight lines in the Figure are gaps in the observed data.

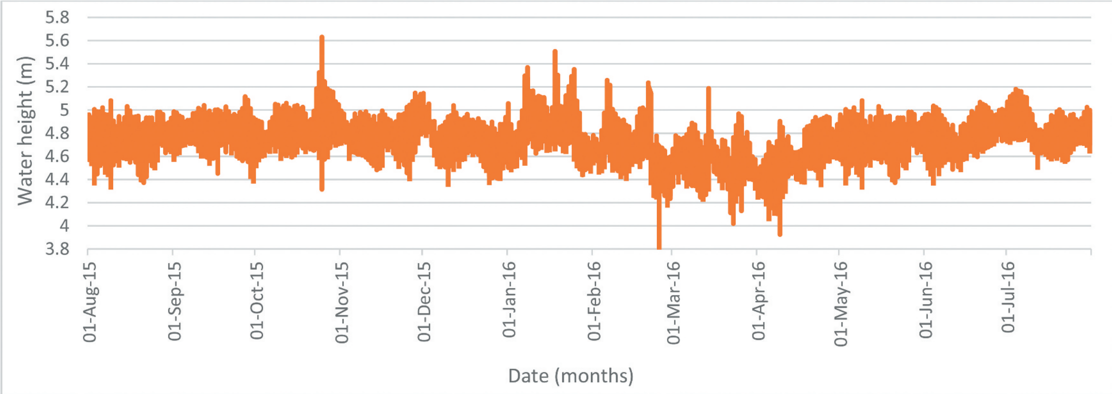

Figure 6. 5-minutes recorded sea level of the observed data at Damietta.

5.62 m, and 4.737 m respectively. Figure 6 shows the 5 min recorded sea level of the observed data at Damietta in the period from 01/08/2015 to 31/07/2016. Figure 7 shows the monthly mean height of the observed sea level at Damietta.

Seventeen tidal harmonic components in 10 groups, over the period of study, had been produced at Damietta harbour. Each tidal constituent has its amplitude and phase as shown in Table 4.

By using Eq. (1) and the amplitude of tidal constituents in Table 4, the constituent factor (F) was calculated to be 0.576, which indicates that the tidal cycle of Damietta is a mixed semidiurnal cycle type in the area

Table 4. Amplitudes and phase angles of the tidal constituents at Damietta harbour.

	The period from 01/08/2015 to 31/07/2016	
Constituents	Amplitude (m)	Phase (degree)
M2	0.10800	335.498
S2	0.06061	308.158
K1	0.01697	297.431
O1	0.01135	319.933
P1	0.00620	304.787
N2	0.01825	074.836
K2	0.01140	292.444
Q1	0.00206	357.750
M4	0.00083	113.211
MS4	0.00059	090.218

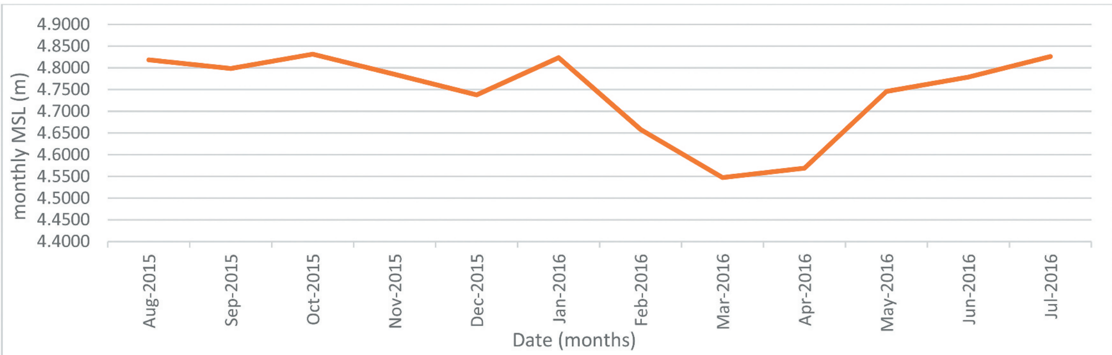

Figure 7. Monthly mean height of the observed sea level over the sensor of tide gauge, within the period of study, at Damietta.

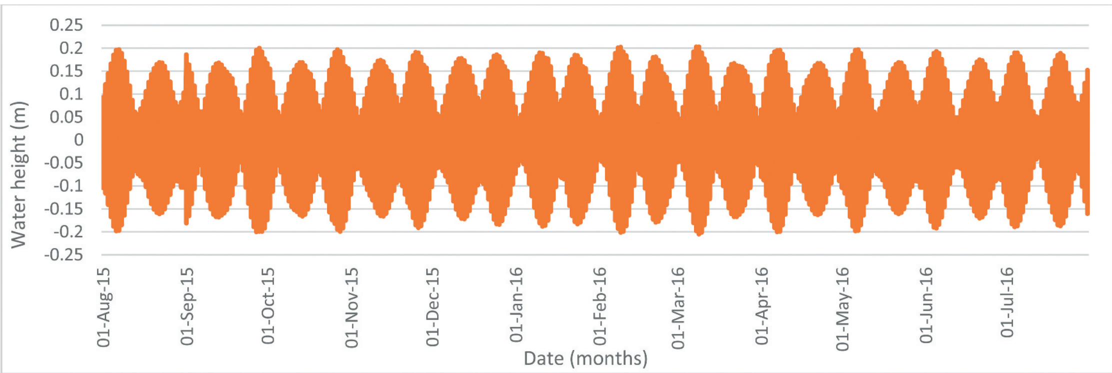

Figure 8. Astronomical tidal elevations, within the period of study, at Damietta.

of study. Figure 8 shows the astronomical tidal elevations at Damietta within the period of study, which varies between −0.21 and 0.2 m. Figure 9 shows the calculated surge elevations at Damietta within the period of study, which varies between −1.05 and 0.92 m.

Tidal datums at Damietta harbour can be obtained by depending on the main values of the harmonic constituents of Damietta, TGZL which equals −4.1305 m and 12.84 m referred to (ESA-1906), and (ITRF-2014), respectively, and Hm at Damietta harbour which equals 4.737 m. The results are as shown in Table 5.

3.3. Port Said station

The observed data of Port Said was analysed using Geotide software, and common patterns of sea level were obtained. The minimum, the maximum, and the mean height of sea-level over the sensor of the tide gauge were obtained and the results were 5.52 m, 7.06 m, and 6.309 m, respectively. Figure 10 shows the 5 min recorded sea level of the observed data at Port Said harbour in the period from 01/01/2015 to 31/12/2015. Figure 11 shows the monthly mean height of the observed sea level at Port Said.

The amplitude and phase degrees of the 10 groups of tidal constituents which were obtained from the analysis will be shown in Table 6.

The results of the tidal constituents obtained from the analysis were compared with the tidal constituents obtained within the period in 1999 (Tonbol and Shaltout (2013)) as shown in Table 7. From the comparison, it becomes clear that the difference between the results in the amplitudes of the tidal constituents in the two studies does not exceed 1 cm, so the results can be considered that they have the same accuracy. Noting that the time interval between the two data sets which are used in the analysis is about 15 years, and within this period there were many factors which affected on the sea level.

The constituent factor (F) was calculated and its value was 0.178 by using eq. (1) and the amplitude of tidal constituents in Table 6, which indicates that the tidal cycle of Port Said is a semidiurnal tidal type in the

Table 5. Major tidal parameters (datums) at Damietta harbour.

Tidal parameters (datums)	Height (m)
MSL(ESA-1906)	0.6065
MSL(ITRF-2014)	17.58
HHWL (ITRF-2014)	17.78
LLWL (ITRF-2014)	17.38
MHWS (ITRF-2014)	17.70
MLWS (ITRF-2014)	17.45
MHWN (ITRF-2014)	17.67
MLWN (ITRF-2014)	17.49

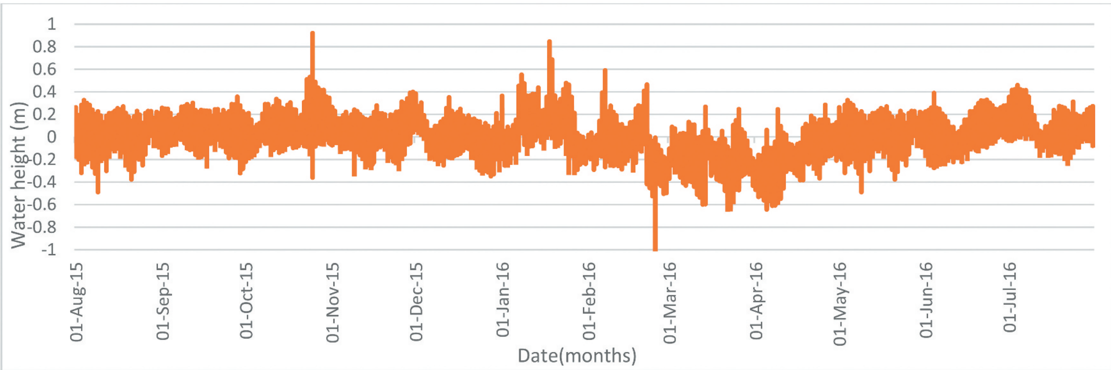

Figure 9. Calculated surge elevations, within the period of study, at Damietta.

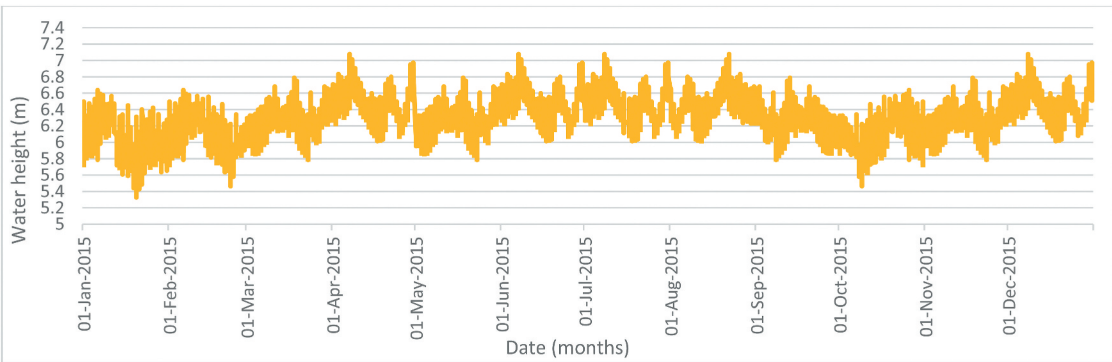

Figure 10. 5-minutes recorded sea level of the observed data at Port Said.

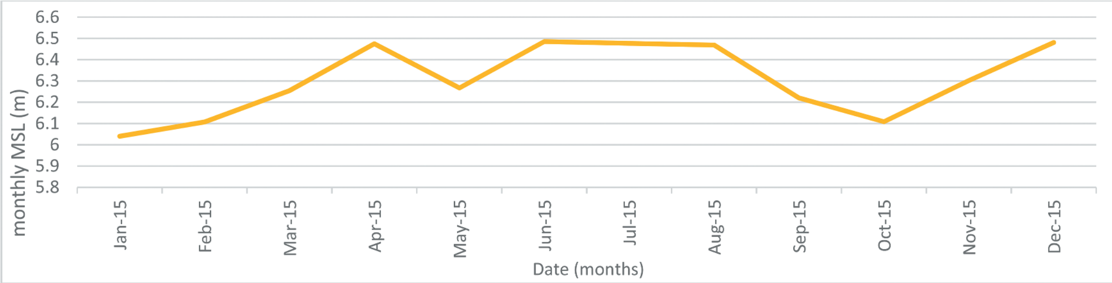

Figure 11. Monthly mean height of the observed sea level over the sensor of tide gauge, within the period of study, at Port Said.

Table 6. Amplitudes, and phase angles of the tidal constituents at Port Said harbour.

	The period from 01/01/2015 to 31/12/2015	
Constituents	Amplitude (m)	Phase (degree)
M2	0.11320	336.483
S2	0.06694	308.189
K1	0.01751	295.205
O1	0.01453	309.215
P1	0.01244	238.207
N2	0.01945	064.742
K2	0.01147	295.553
Q1	0.00367	112.845
M4	0.00170	240.842
MS4	0.00175	089.988

area of study. Figure 12 shows the astronomical tidal elevations at Port Said within the period of study, which varies between −0.2 and 0.2 m. Figure 13 shows the calculated surge elevations at Port Said within the period of study, which varies between −0.96 and 0.85 m.

Tidal datums of Port said harbour will be shown in Table 8, where TGZL at Port said harbour equals −5.7965 m and 10.51 m referred to (ESA-1906) and (ITRF-2014) respectively, and Hm equals 6.309 m.

Noting that the height of MSL, referred to (ESA-1906), in the current study at Port Said, is in a good agreement with the results in the previous study, which equals 0.505 m (Sharaf El-Din (1975)).

4. Conclusion

The variation of the sea level, within the northern delta coast in Egypt, consists of two components: astronomical tide and the surge. This paper shows the patterns of the sea level of three locations on the north of the delta in Egypt: Alexandria over two groups of data, each group within about two years, Damietta over one year, and Port Said over one year. By using sea level data, the astronomical tide and the height of the surge were obtained.

In the present study, both the M2 (Principle lunar) and the S2 (Principle solar) constituents have the largest constituent amplitudes within the three locations on the north of the delta, being 7.4 cm for the former and 4.4 cm for the latter within the first group of data in Alexandria (from 01/01/2009 to 02/11/2010), 6.7 cm for the former and 4.1 cm for the latter within the second one (30/4/2012 to 31/12/2013), results are in very good agreement when compared with the previous, 10.80 cm for the M2 and 6.08 cm for the S2 within Damietta (from 01/08/2015 to 31/07/2016), and finally in port said (from 01/01/

Table 7. Comparison between the major harmonic constituents of Port Said in the current study, and the previous study (Tonbol and Shaltout (2013)).

Constituents		M2		S2		K1		O1	
Datasets		Amp. (m)	Phase (deg.)	Amp. (m)	Phase (deg.)	Amp. (m)	Phase (deg.)	Amp. (m)	Phase (deg.)
Previous study	01/02/1999 – 31/01/2000	0.104	337.2	0.062	337.2	0.022	255.89	0.016	192.28
Current study	01/01/2015 – 31/12/2015	0.113	336.5	0.067	308.2	0.018	295.2	0.015	309.2

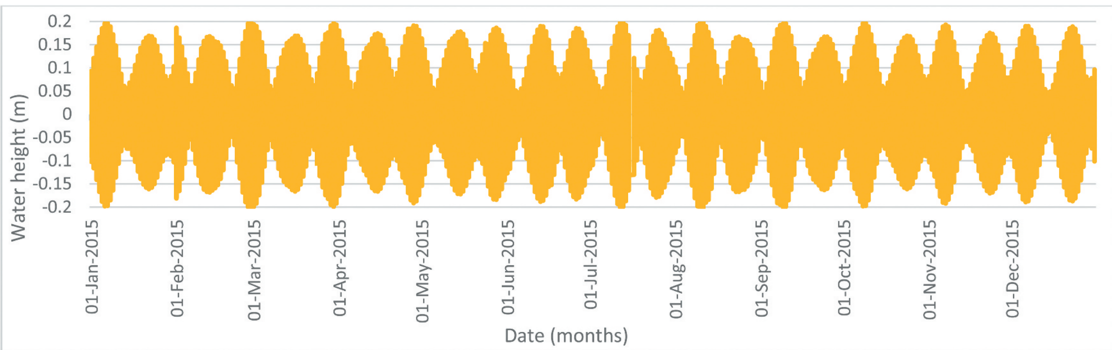

Figure 12. Astronomical tidal elevations, within the period of study, at Port Said.

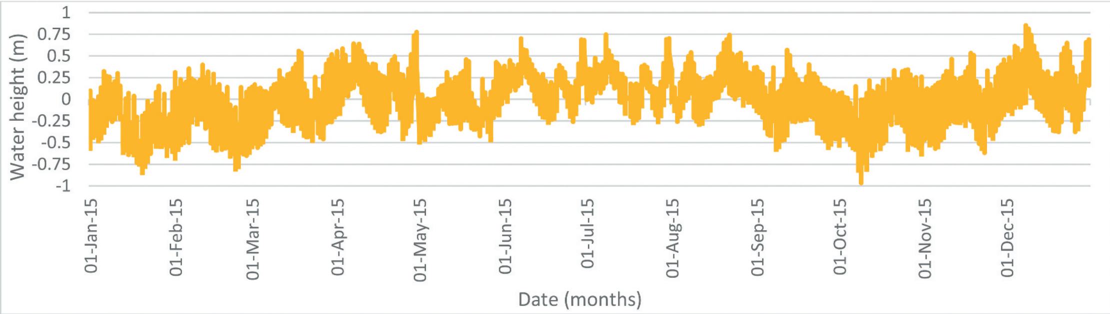

Figure 13. Calculated surge elevations, within the period of study, at Port Said.

Table 8. Major tidal parameters (datums) at Port Said harbour.

Tidal parameters (datums)	Height (m)
MSL (ESA-1906)	0.5125
MSL (ITRF-2014)	16.81
HHWL (ITRF-2014)	17.03
LLWL (ITRF-2014)	16.60
MHWS (ITRF-2014)	16.99
MLWS (ITRF-2014)	16.63
MHWN (ITRF-2014)	16.86
MLWN (ITRF-2014)	16.77

2015 to 31/12/2015) the value of M2 was 11.30 cm, and the value of S2 was 6.70 cm. The tidal cycle at the Alexandria and Damietta is determined to be a mixed semidiurnal tidal type, and at Port Said to be a semidiurnal tidal type.

The Mean Sea Level (MSL) referred to (ESA- 1906) had been calculated and the results are as follows: 0.1715 m in Alexandria, 0.6065 m in Damietta, and 0.5125 m in Port Said within the periods of study, and the tidal datums of each station referred to (ITRF-2014) had been calculated else.

We can notice from the results of this research that astronomical tide varies with 0.01–35.32%, while surge varies with 64.68–99.99% in the first group of observed data at Alexandria, while 0.01–36.32% for the former and 63.68–99.99% for the latter in the second group, and these are 0.01–22.41% for the astronomical tide, and 77.59–99.99% for the surge at Damietta, and finally at Port said we can find that the astronomical tide varies with 0.01–27.28%, while, surge varies with 72.72–99.99%. This might allude to the meteorological and climatic impacts, which are exceptionally created in the northern delta region. In addition, the created neighbourhood seiches may have some effect on the observed surge rise (El-Geziry and Radwan (2012). The more prominent commitment of surge over tidal height assures the nature of low tides at the northern delta region, as within the entire Levantine Bowl. The great effect and strong contribution of the surge in sea-level variation concluded within the display paper is, undoubtedly, in agreement with (Eid 1990), Moursy (1989, 1994) and Saad et al. (2011).

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Disclosure Statement

No potential conflict of interest was reported by the author(s).

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