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General Pattern of Alexandria Western Harbor Sea Level Changes

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Abstract. For the safety of navigations at the western harbor of Alexandria, the different variations and seasonal deviations of sea level behavior at the harbor have been obtained by analyzing the monthly changes on water levels through the period (1997-2004). The highest levels are expected about August (60.5 cm) and the lowest are to be at March (40.5 cm). The mean sea level obtained was 50.6 cm. Elevations of sea level extreme are presented and showed maximum observed water level of 76.9 cm and a minimum one of 27.9 cm. The hourly sea level has been analyzed harmonically with the purpose of obtaining the tidal constituents. The most effective constituents are M_2 (6.9 cm), S_2 (4.2 cm), K_1 (1.6 cm) and O_1 (1.2 cm). Estimations of the frequency distribution for both observed and predicted sea level have been made and showed coincidence between the two levels except winter months. Information about the major tidal phenomena and the dominant feature of Alexandria harbor tide are obtained.

Keywords: Alexandria harbor, tide, harmonic constituents, sea level, statistical analysis.

Introduction

The western harbor of Alexandria (Fig. 1) is considered one of the most important trade harbors in Egypt; it has an oblique shape relative to the geographic axis with maximum depth of 16 m and means about 9.5 m. The harbor has a surface area nearly 7.5 km^2; the mean length and width of its basin are 5 km and 1.5 km respectively. It is connected to the Mediterranean Sea by narrow mouth.

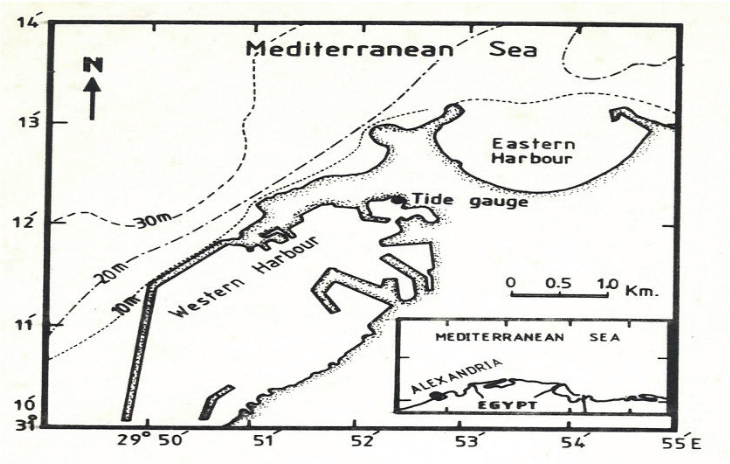


Fig. 1. Position of Tide gauge in Alexandria Harbor.

Although Alexandria coastal waters are almost tideless and the sea level changes are fairly insignificant, the character of these changes is however important for technical purposes especially for oceanographers, engineering and navigators. Earlier studies of sea level variations have shown that the sea level at the south east corner of the Mediterranean has regular seasonal variations, with low levels during spring season and high ones in summer (Striem and Rosenan, 1972; Sharaf El Din, 1975; Hamed, 1983; Eid, 1989; and Moursy, 1994; 1996a, 1998). More detailed description of water changes in this area have been mentioned by Sharaf El Din and Rifaat, 1968; Moursy, 1976; Rady, 1979; El Gindy, 1986; Hamed and El Gindy, 1988; and Moursy, 1992, 1993, 1994).

However, it is necessary to have accurate knowledge of the levels and durations of water oscillations at different periods with their expected levels as well as their extreme heights and their seasonal deviations from normal conditions. For these purposes, the hourly sea levels for the eight years period (1997-2004) have been analyzed to get an estimation of water level variations during this period and illustrate the general picture of sea level at the western harbor of Alexandria basin.

The Dominant Feature of Alexandria Harbor Tide

The western harbor basin of Alexandria is not large enough to generate independent tides. Hence, the tide inside the basin is cooscillating with the Mediterranean tide where the tidal range does not exceed 50-60 cm (Lisitzin, 1974).

1- Harmonic Constituents

The tide gauge records illustrate semi-diurnal oscillations containing two high tides and two low tides each day. In order to get a conception of the tidal phenomena, 60 of tidal harmonic constituents have been determined by a computer program based on the least squares fit for constituent amplitude and phase. The constituents are represented in Table 1. The software package "sea level data processing on IBM-PC version 3", is obtained from National oceanographic data center and University of Hawaii sea level center, 2005.

Table 1. The mean amplitude (cm) and phase (degree) of 60 harmonic constituents during the period (1997-2004) for Alexandria harbor.

Name	Amplitude	Phase	Name	Amplitude	Phase
Zo	50.59	0	M2	6.9	315.756
SSA	3.4	226.92	MKS2	0.43	254.18
MSM	1.44	150.078	LDA2	0.18	219.684
MM	1.37	208.53	L2	0.26	216.174
MSF	0.99	122.876	S2	4.15	329.154
MF	0.91	207.532	K2	1.29	314.722
ALP1	0.09	162.044	MSN2	0.13	127.094
2Q1	0.2	112.328	ETA2	0.22	166.746
SIG1	0.11	211.872	MO3	0.08	152.562
Q1	0.26	264.842	M3	0.16	88.322
RHO1	0.09	204.808	SO3	0.06	165.89
O1	1.26	281.184	MK3	0.06	243.678
TAU1	0.14	209.86	SK3	0.11	120.246
BET1	0.11	167.91	MN4	0.07	208.29
NO1	0.18	276.668	M4	0.11	201.164
CHI1	0.09	96.768	SN4	0.09	170.272
P1	0.59	322.02	MS4	0.1	180.156
K1	1.55	314.374	MK4	0.09	215.994
PHI1	0.15	211.718	S4	0.07	186.68
THE1	0.07	216.278	SK4	0.06	253.698
J1	0.23	329.54	2MK5	0.06	203.684
SO1	0.11	121.2	2SK5	0.04	223.53
OO1	0.1	162.438	2MN6	0.04	87.378
UPS1	0.1	212.266	M6	0.04	216.614
OQ2	0.1	175.03	2MS6	0.06	165.242
EPS2	0.12	222.532	2MK6	0.04	136.07
2N2	0.15	322.166	2SM6	0.06	182.998
MU2	0.26	271.058	MSK6	0.03	266.03
N2	1.2	321.8	3MK7	0.05	158.296
NU2	0.19	277.354	M8	0.04	122.588

Detailed study of these harmonic constituents indicates that a considerable number of these constituents are of no practical significance for the western harbor basin. The dominant feature of tide level variability is the M_2 tide with amplitude of (6.9 cm), followed by the most pronounced tidal constituents S_2 (4.2 cm), k_1 (1.6 cm) and O_1 (1.25 cm).

The ratio $(k_1+O_1) / (M_2+S_2)$ for the amplitudes gave value 0.25 cm which means that the harbor has semi-diurnal tides. The ratio between the amplitudes of the lunar partial tide (M_2) and the solar partial tide (S_2) has a value 1.64 which is fairly close to the theoretical ratio (1:0.5). The astronomical tide z(t) which is expressed mathematically as:

$$z(t) = zo + \sum_{i=1}^{n} f_i A_i \cos(V_i + U_i - g_i + \delta_i t) \quad (1)$$

The above equation is used to predict tidal height.

Where:
A_i, g_i, = the amplitude and phase of the main four tidal harmonic constituents (M_2, S_2, K_1, O_1), (zo = the mean sea level) and the other terms are defined by Godin and Taylor (1973).

Figure 2 shows example of the hourly values of the measured water level with their corresponding predicted tidal level for two days. The coincidences between the two curves are fairly significant.

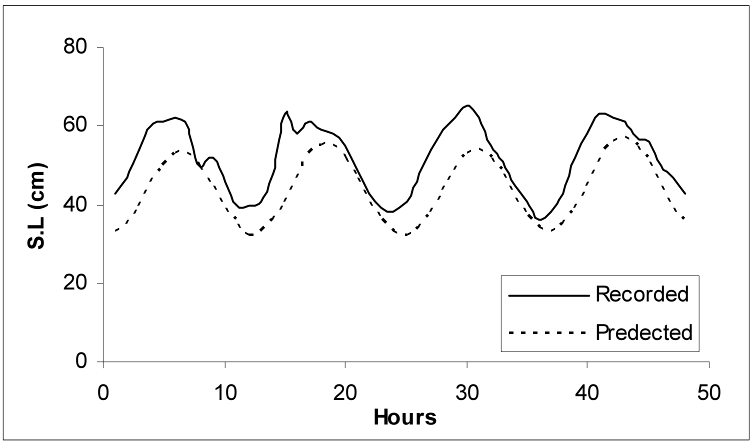


Fig. 2. Recorded and predicted hourly water sea level (S.L) for the two days (20, 21 October, 1998) at Alexandria harbor.

2- Tidal Levels

According to Doodson, 1957 and in a discussion of the precise behavior of tidal level inside the harbor over the eight years, the two theoretical terms were obtained:

Highest high water level (HHWL) = MSL + (M_2+S_2+ k_1+O_1) = 64.6 cm
Lowest low water level (LLWL) = MSL - (M_2+S_2+ k_1+O_1) = 36.6 cm
Highest range of tide = 27.9 cm

Where MSL is the mean sea level, which is 50.6 cm for the eight years period. The other terms represent the amplitudes of the main four tidal harmonic constituents. In determining these two terms over monthly scale it is obvious that the highest high water are expected during August, while the lowest are in February and March as shown in Table 2.

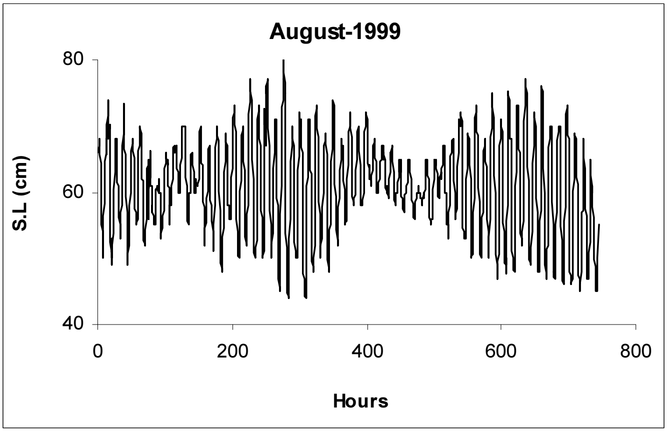
Table 2. Theoretical highest high water level (HHWL) and lowest low water level (LLWL) for Alexandria harbor.

Sea level (cm)	Jan.	Feb.	March	April	May	June	July	Aug	Sept.	Oct.	Nov.	Dec.	Mean
HHWL	63	56.6	54.5	58.2	59.2	64	73	74.5	70.3	69	67	66.1	64.625
LLWL	35	28.6	26.5	30.2	31.2	36	45	46.5	42.3	41	39	38.1	36.625

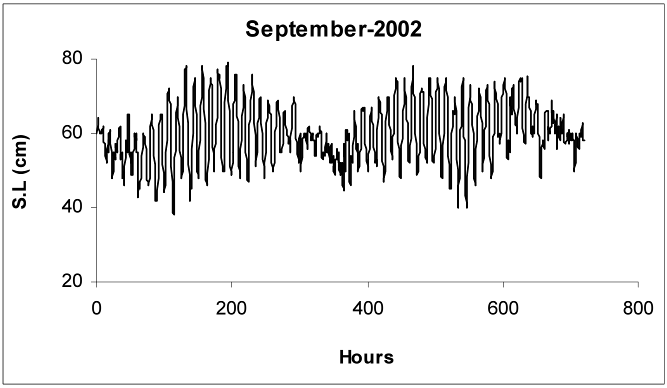
Comparing these theoretical terms with their corresponding recorded one, it can be seen that the maximum observed sea level (76.9 cm) is higher than the theoretical one by 12.4 cm while it is lower by 8.7 cm for the minimum level (27.9 cm). Consequently, the maximum observed sea level range will be greater than the theoretical by 21 cm which is obviously due to the external forces (atmospheric pressure and wind forces) affecting sea level extreme. Where, the response of sea level to atmospheric pressure changes is usually stated as a sea level rise by about 1 cm for each millibar fall. Sharaf El Din, (1975) has noticed that the north winds are the most effective winds on the sea level height at the Egyptian Mediterranean coast. Moursy, (1996b) has shown that the wind from north west, north and north east has an effective role in the sea level variations where the sea level rise by about 0.16 cm for each increase in the wind speed by 1 knot (0.5 m/sec).

3- Spring-Neap Cycle

The semi-monthly tides which are created mainly by the nonlinear interaction of M_2 and S_2 reflect the occurrence of spring and neap tides. From the observed sea level data of the two months August (1999)(a) and September (2002)(b), the rises and falls of spring and neap tides obviously appear in Fig. 3.



(a)



(b)

Fig. 3. Spring and Neap ranges for Alexandria harbor during August 1999 (a) and September 2002 (b).

Concerning the principal characteristics of the tidal levels some of the more important terms connected with the tidal phenomena should be pointed out. These theoretical terms are concerning with the high and low water during spring and neap times, which have been determined by means of the four major tidal harmonic constituents:

$$MHWS = MSL + (M_2+S_2)$$
$$MLWL = MSL - (M_2+S_2)$$
$$MHWN = MSL + (M_2-S_2)$$
$$MLWN = MSL - (M_2-S_2)$$

The results of the calculations indicate that the mean high water spring (MHWS) and the mean low water spring (MLWS) over the eight years give values of 61.7 cm and 39.5 cm and consequently the mean spring range $\{2(M_2+S_2)\}$obtained as 22.2 cm. For neap time, the mean high water neap (MHWN) and the mean low water neap (MLWN) illustrate a value of 53.3 cm and 47.9 cm with mean neap range $\{2(M_2-S_2)\}$of 5.4 cm.

The principal feature of this semi-diurnal tide indicates a ratio of 4:1 between spring and neap ranges, and the theoretical mean range was 14.0 cm.

Changing Sea Level

1- Mean Sea Level

The tide gauge of Alexandria harbor recorded an hourly sea level between 13 cm and 95 cm and daily mean levels between 20.4 cm and 83.4 cm. Example of the hourly recorded sea level for two days is shown in Fig. (2), where it illustrates a semi-diurnal character of common pattern of two tidal peaks in a day. The general phenomena of monthly mean sea level over the eight years are given in Fig. (4), which shows that the water level is highly seasonal in nature, these seasonal cycles apparently reflect high level in summer months where it reached 58.7 cm and 60.5 cm in July and August, while the low levels are shown in February (42.6 cm) and March (40.5 cm). The mean sea level over the eight years obtained as 50.6 cm. It is evidence also that the monthly mean levels are below their average during the first half of the year and above it during the second half.

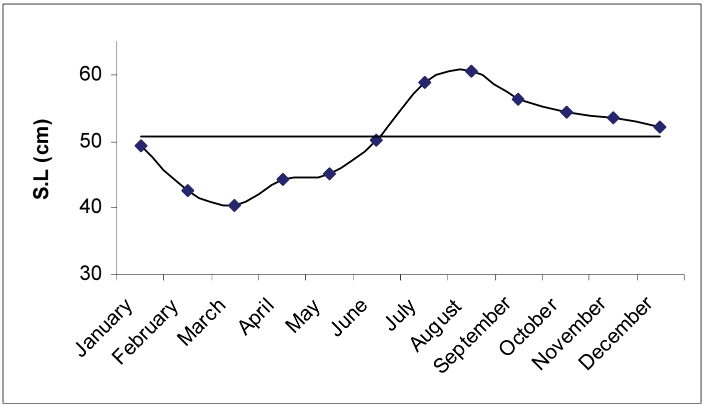


Fig. 4. Monthly variation of sea level for the period (1997-2004) at Alexandria western harbor.

The yearly variations of mean sea level (Fig. 5) are used in order to account the sea level trend and reduce errors in computing sea level trend based on monthly sea level. However, it is obvious from Fig. (5) that the S.L has an increasing trend which is about 4.7 mm/year, so this indicates a sea level rise. The highest annual sea level illustrates an average value of 52.5 cm (2002), while the lowest was 48.6 cm (1997). These fluctuations in the sea level during the eight years are not caused by the astronomical tidal forces but it is strongly affected by meteorology (wind force and atmospheric pressure system).

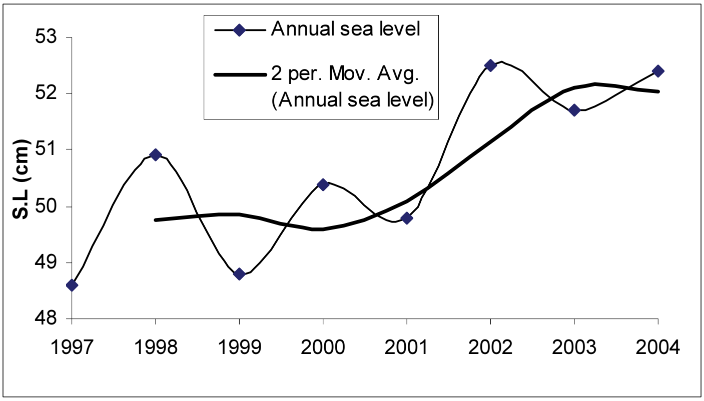


Fig. 5. Annual sea level for the period (1997-2004) at Alexandria western harbor.

2- Elevation of Sea Level Extreme

The monthly mean values over the study period for the maximum and minimum recorded sea level, besides the maximum recorded sea level ranges are given in Fig. 6, which illustrates that the maximum observed sea level appeared during winter months where it reached 80 cm and 83.4 cm in November and December respectively, where it is attributed to the weather conditions during this season (storm surges season). On the other hand, summer months, July and August show high level of 81.4 cm and 79.6 cm. This fact was obtained by Striem and Rosenan, (1972) where monthly barometric pressure has been calculated for Haifa and Port Said representing condition on the eastern Mediterranean coast and for the central Mediterranean by averaging barometric pressure at Rome, Cagliari and Malta. The results indicate that during winter the barometric pressure in the central Mediterranean is lower than it is in the eastern basin, and this would be compatible with a lower sea level in the western Mediterranean. During summer the barometric pressure in the central Mediterranean is higher than that of the eastern basin, and this would be in line with a higher sea level in the eastern Mediterranean.

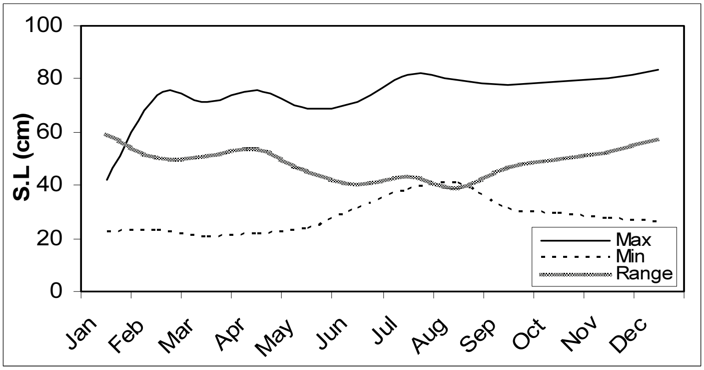


Fig. 6. Maximum, minimum and sea level ranges for the period (1997-2004).

With respect to the minimum observed sea level, it is clear from the graph that these levels occurred during spring months, March (20.2 cm) and April (21.8 cm) while summer months July and August show high levels of 38.4 cm and 40.6 cm. However, the mean values over the 8 years for the maximum recorded sea level obtained as 76.9 cm while it is 27.9 cm for the minimum recorded one. The above discussion for the extreme values of maximum and minimum sea level illustrates that the highest ranges are observed during winter months where the mean values reached 57.6 cm and 59.4 cm in December and January, while the lowest ranges occurred during summer months June (40.4 cm), July (43 cm) and August (39 cm). The annual mean range over the eight years obtained as 49 cm.

*3- Statistical Modeling of Sea Level Distribut*ion

The hourly sea level data has been analyzed statistically with the purpose of obtaining a conception of the characteristics of the sea level variations at the harbor. The properties and the description of these distributions are obtained by the first four moments (mean, variance, skewness and kurtosis), where the mean is the expectation of the random variable x and defined as:

$$E(x) = \int_{-\infty}^{\infty} x f(x) dx \qquad (2)$$

Where:
x = the sea level,

While the variance is the measure of the dispersion or scatter of the values of the random variables about the mean (μ) and is defined by:

$$\mathrm{var}(x) = E[(x-\mu)^2] = \int_{-\infty}^{\infty}(x-\mu)^2 f(x)dx = \sigma^2 = \mu_2 \tag{3}$$

Skewness describes the symmetry of the distribution and defined as:

$$\mu_3 = E[(x-\mu)^3] = \int_{-\infty}^{\infty}(x-\mu)^3 f(x)dx \tag{4}$$

kurtosis measures the degree of peakedness of a distribution about the mean and defined as:

$$\mu_4 = E[(x-\mu)^4] = \int_{-\infty}^{\infty}(x-\mu)^4 f(x)dx \tag{5}$$

These four moments which is concern variations and deviations of sea level about the mean have been calculated for each month separately for the period (1997-2004). The results of the computation for the monthly mean sea level are illustrated in Fig. (4), which shows that the monthly mean sea level are between 40.5 cm in March and 60.5 cm in August. June is the only month which approached to the average (50.6 cm).

Standard deviations for the monthly sea level yield a value between 7.5 cm and 11.9 cm (Table 3). The comparison between months showed that winter months are often deviating from the average, while summer months are somewhat stable.

Table 3. Standard deviations (S.D), Skewness (Sk), and Kurtosis (Ku) of the monthly mean sea level over the period (1997-2004).

Month	Jan	Feb	Mar	Apr	May	Jun	Jul	Aug	Sep	Oct	Nov	Dec	Mean
S.D	11.9	10.3	9.6	10.1	8.3	7.8	7.7	7.5	8.8	9.5	10.8	11.1	9.45
Sk	0.3	0.25	0.29	0.17	0.12	0.07	0.02	-0.04	-0.11	-0.1	-0.06	0.15	0.098
Ku	0.3	-0.3	0.0	0.3	0.3	0.5	0.2	0.6	0.4	0.3	0.3	0.4	0.68

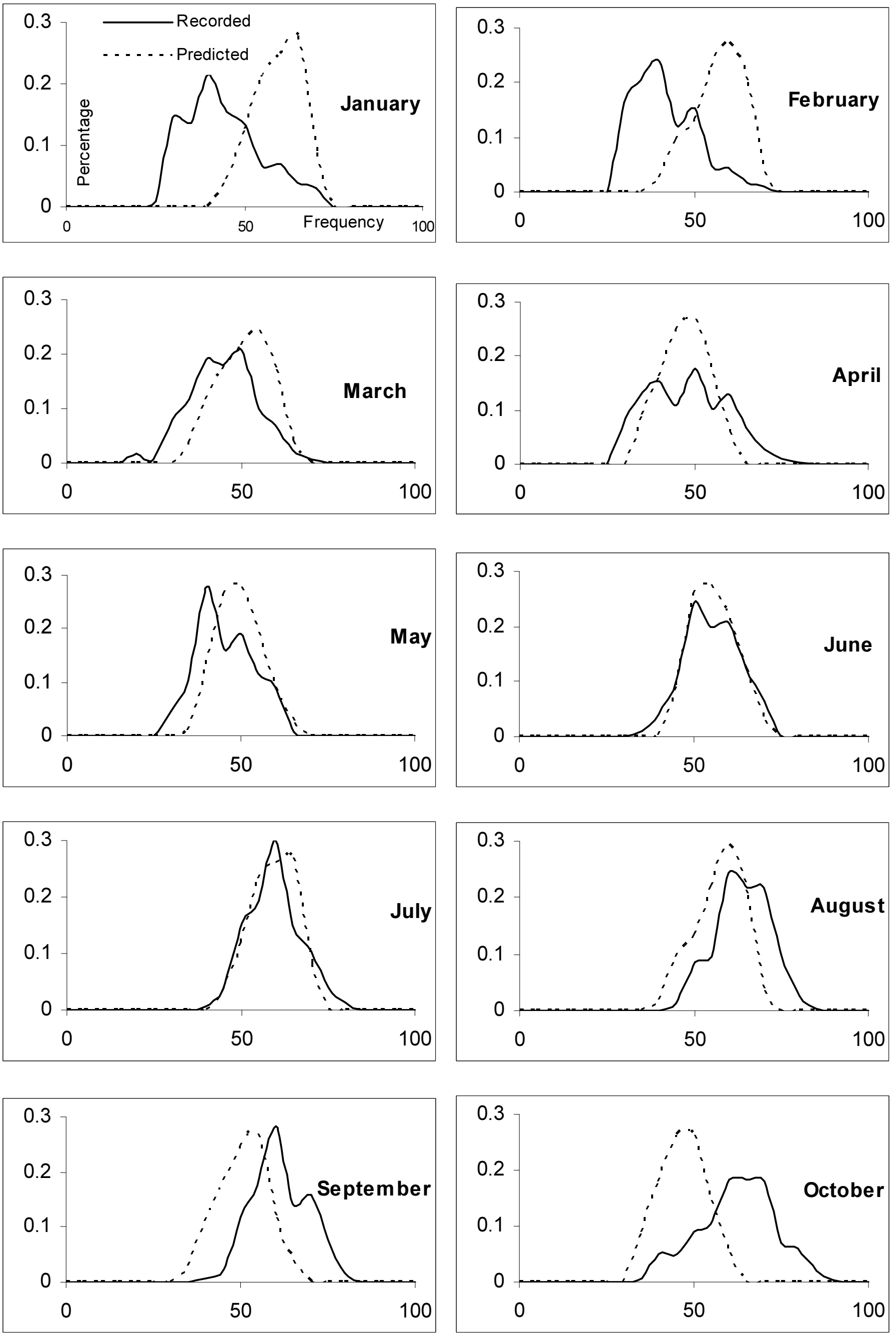
With regard to the symmetrical distribution where skewness is equal to zero, it seems from Table 3 that the monthly average skewness are very near to the normal or asymmetric distribution while it differs in the three months January, February and March, which showed some deviations from the symmetric. It is also noticed that May, September and October approach to the normal with little skewness to the left side. With respect to the fourth moment (kurtosis) it seems from Table 3 that there is no general trend in the peakedness of monthly sea level distribution. However, all months may be considered normally distributed about the mean.

4- Frequency Distribution of Sea Level

The general pattern of monthly frequency distribution of both observed and predicted sea level for the eight years are obtained and presented graphically. Examples of these graphs are shown in Fig. (7) for the year 2002, which refers to the condition of Alexandria sea level and shows the different variations and seasonal deviations of sea level behavior. The graphs illustrate the coincidence between the expected sea level with their corresponding values of the observed one through most of the year except winter months where sea levels deviate from the predicted one. This phenomenon is attributed to the meteorological conditions during this season, where the harbor is exposed to number of storms being most frequent between December and February; the wind speed reaches 12 m/sec or more. These winds with low barometric pressure naturally influence the sea level producing storm surges and consequently a deviation from the normal conditions. The deviation during summer months are relatively small (calm season). These facts appear in Table 4 for the monthly mean of the confidence level (95%) over the eight years, where it seems that winter months show the most pronounced deviations of sea level from the standard form.

Table 4. Confidence level (CF.L) (95%) for the monthly mean sea level over the eight years (1997-2004).

Month	Jan	Feb	Mar	Apr	May	Jun	Jul	Aug	Sep	Oct	Nov	Dec	Mean
CF.L	0.86	0.78	0.69	0.74	0.59	0.57	0.55	0.54	0.64	0.69	0.79	0.8	0.68


Recorded
Predicted
Percentage
Frequency
January
February
March
April
May
June
July
August
September
October
0.3
0.2
0.1
0
0
50
100

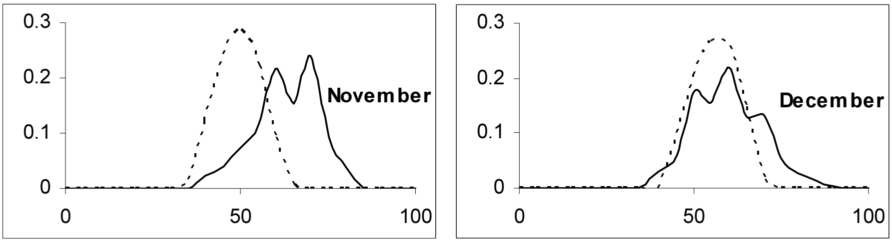


Fig. 7. Frequency distribution of recorded and predicted sea level at Alexandria harbor for the year 2002.

Conclusion

On basis of the analysis on hourly sea level records for the eight years (1997-2004), Astronomical tide has been determined which shows that Alexandria harbor tide is dominated by a twice daily cycle, fundamentally driven by the lunar semi-diurnal constituent M_2 (6.9 cm) and the solar semi-diurnal constituent S_2 (4.2 cm). The tide is more semi-diurnal and less mixed. The most pronounced tidal constituents affecting sea level are M_2, S_2, K_1 and O_1. The spring-neap cycle is very apparent at the water level. Theoretical calculations gave mean high water spring of 61.7 cm and mean low water spring as 39.5 cm Mean high water neap and mean low water neap are 53.3 and 47.9 cm. Consequently spring range is 22.2 cm and the neap range is 5.4 cm. The theoretical mean range of water level obtained was 14.0 cm.

The maximum observed water level was 76.9 cm while the minimum was 27.9 cm and the mean over eight years was 50.6 cm. The water level is highly seasonal in nature which apparently reflect seasonal trend with high water in summer and low in spring. The theoretical highest levels are expected about August (74.5 cm) while the lowest are to be at March (26.5 cm). The level gave an increasing trend of 4.7 mm/year. The analysis showed that winter months are often deviating from normal while summer months are relatively calm. Frequency distribution of monthly sea level illustrates the coincidence between the predicted and observed sea level most of the year with some deviations through winter season (storm season), which can be considered significant for navigations. However, the sea level data at the western harbor of Alexandria are normally distributed.

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النمط العام لتذبذب مستوى سطح البحر فى الميناء الغربى لمدينة الإسكندرية

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جمهورية مصر العربية – الأنفوشي قايتباي

المستخلص. نظرًا لأهمية التغير في مستوى سطح البحر على بناء المنشآت البحرية داخل الميناء فقد تم دراسة الخواص العامة لهذا التغير خلال الفترة من (١٩٩٧–٢٠٠٤م). وجد من الدراسة أن المد والجزر نصف يومي مع وضوح كامل للمد العالي والمد المنخفض خلال الشهر، وأن متوسط سطح البحر خلال فترة الدراسة (٥٠,٦ سم) بينما أعلى قيم للمد العالي هو (٦١,٦ سم) والمد المنخفض يصل إلى (٣٩,٥ سم). واهتمت الدراسة أيضًا بالتغير الموسمي، فقد وجد أن أعلى قيم لمستوى سطح البحر توجد خلال شهري يوليو وأغسطس، بينما أقل القيم لمستوى سطح البحر تحدث خلال شهري مارس وأبريل. بمقارنة التوزيع الترددي (التكراري) لكل من مستوى المد والجزر النظري ومستوى سطح البحر الحقيقي وجد أن هناك تطابق ملحوظ خلال فصول السنة بينما هناك انحراف واضح خلال فصل الشتاء.