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FORECASTING OF THE STORM SURGE IN WINTER AT ALEXANDRIA (EGYPT)

By

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التنبؤ بإرتفاع مستوى سطح البحر الناشىء عن العواصف في موسم الشتاء عند الأسكندرية

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نتيجة لتعرض المنطقة الساحلية بالأسكندرية للعواصف الجوية لاسيما خلال فصل الشتاء ، فإن مستوى سطح الماء يتأثر سواءاً بارتفاع أو الإنخفاض مما يؤثر على المنشأت الساحلية والتخطيط العمراني بالقرب من السواحل . ويمثل هذا البحث محاولة للتنبؤ بإرتفاعات المياه الناشئة عن العواصف الجوية القوية والمتوسطة القوة عند الساحل وذلك باستخدام نماذج إحصائية مبنية على تحليل العلاقات متعددة المتغيرات . وقد استنتجت معادلات يمكن إستخدامها في هذا التنبؤ . وقد وجد أن أهم المتغيرات في حالة العواصف الجوية القوية هي متوسط الإرتفاعات الناشئة عن العوامل الجوية خلال ١٢ ساعة قبل العاصفة ، وكذلك سرعة الرياح عمودياً على الساحل والضغط الجوي عند الأسكندرية قبل العاصفة بثلاث ساعات . كما وجدت عدة معدلات للتنبؤ بالعواصف المتوسطة . ويمكن معرفة نوع العواصف من حيث قوتها مسبقاً باستخدام الخرائط المتتابعة لتوزيع الضغوط الجوية .

Key Words: Storm surge, Alexandria harbor.

ABSTRACT

Since storms frequently occur in the winter season, at Alexandria, SE of the Mediterranean Sea, storm surges often affect this area. In this paper, we attempt to forecast the storm surge heights in the commercial Western Harbor of Alexandria, during both strong and moderate storms, using statistical multiple regression analysis. On applying different statistical models and after validation, the present results showed that a strong surge (Y) can be forecast using a three hour prognosis model expressed by: $(Y=0.85^{*}\ HT12\ +0.84^{*}\ n3\ +2.27^{*}\ p3)$, where HT12 is the mean surge height over 12 hours preceeding the forecast time, n3 and p3 are the wind velocity component normal to the shore in (knots) and the atmospheric pressure (mb) respectively three hours before the forecast time. On the other hand, three equations were found to be convenient to forecast the moderate surge at Alexandria. The occurrence of strong or moderate surges cases could be forecast using the meteorological synoptic conditions over the Eastern Mediterranean.

INTRODUCTION

During the winter season, surges that are generated at Alexandria by frequently occurring storms, could cause damage to the harbor installations, especially, when unexpectedly severe storms occur. Therefore, it is of practical importance to predict these surges, as early as possible and as accurately as possible, so that one can distinguish between dangerous surges and those that cause little harm. Hence, the sea level records inside the Western Harbor of Alexandria, where the mean depth is about 10 meters, will be used to investigate this problem. The shape of the harbor and the position of the tide gauge are shown by (Fig. 1).

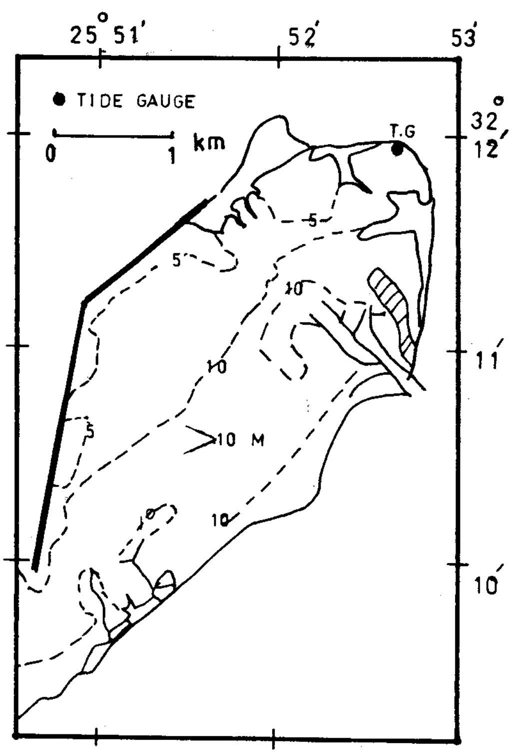

Fig. 1: The shape and the contour lines of Western Harbor of Alexandria and the position of the tide gauge.

Previous studies:

Moursy (1976) calculated the storm surge heights during the stormy days, with wind speeds more than 20 knots, of Winter season over the period 1965-1969 by subtracting the astronomical tide from the observed sea level. Hamed (1983), determined the number of stormy days at Alexandria over a 20 years period and concluded that the maximum number of the stormy days were during winter and early spring, with a much lower number in autumn while the summer season was free of storms. He also studied the effect of the movement of the atmospheric depressions on the variations of the sea level at Alexandria. An empirical relation, relating the surge height to wind speed and atomospheric pressure, was found in the form:

$$R = 3.04 * W - 0.05 * W^2 + 0.31 * P - 328.51$$

where R = residual height (cm)
W = wind speed in knots
P = atmospheric pressure (mb).

This equation estimated the surge. Forecasting could not be done with this relationship.

Later, Hamed and El-Gindy (1988) classified the storm surge at Alexandria, according to their height and the associated synoptic pattern during winter season (December, January and February) over the period 1971-1984. Five types of storm surges were identified. Type (A) represents the weak surge case with a maximum residual height of the order of 12-18 cm, a maximum wind speed of 24 knots and minimum pressure of 1008 mb. The type B has a maximum surge between 20 and 24 cm and a wind speed that does not exceed 29 knots, with minimum pressure of 1012 mb. Type C is a moderate surge associated with the movement of depressions over the Eastern Mediterranean eastward near Crete. The maximum residual height occurs when the depression center is located near Crete. The average maximum residual in this case is 26-30 cm with a maximum wind speed in excess of 29 knots, and pressure reaching 1005 mb. Type D has a strong surge between 35 and 38 cm, wind speed reaching 30 knots and pressure as low as 1004 mb. Finally, type E has the strongest surge, reaching 43 cm. The occurrence of this type is associated with wind speeds up to 35 knots and pressures as low as 1002 mb. This strong surge occurs when the center of the depression passes near the Northern Egyptian coast towards Cyprus. The frequencies of occurrence of the different storm surge types are shown by (Table 1).

Table 1

Numbers of occurrence of different storm surge types at Alexandria Western Harbor in the period 1971-1984. (After Hamed and El-Gindy, 1988)

Surge type Month	A	B	C	D	E	Total
December	12	18	32	9	2	73
January	15	14	36	15	8	88
February	8	7	6	2	0	23
Total	35	39	74	26	10	184

Objective of the study:

In this paper, an attempt is made to formulate short-term forecasting equations of the storm surge height at the Western Harbor of Alexandria, using multiple regression analysis. The forecasting equations will be validated using sets of data not included in the fitting procedure. The analysis will be applied in two separate cases: the moderate surge and the strong surge. However, it should be mentioned that some uncertainties in forecasting are caused by the inaccurate predictions of the motion and strength of the storm, 24 hours in advance, in addition to potential errors in the observed data (Welander, 1961).

Data used:

The data used are the hourly surge height in the harbor, atmospheric pressure and wind velocity. The surge data were obtained by subtracting the hourly predicted heights from the observed water levels. The constants of the four harmonics used in the hourly predictions are those published by (Rady, 1979), as shown by (Table 2). Mean sea level was 45.1 cm. The hourly values of wind velocity were decomposed in two directions; parallel and normal to the shore. Two storm events were chosen

Table 2

Constants of four tidal constituents used in prediction of tidal height at Alexandria, (Rady, 1979)

Harmonic Ref.	M2	S2	K1	O1
Amplitude H(cm)	7.09	5.20	1.66	1.23
Phase angle pH°	256.1	255.8	280.5	249.8

to fit the surge models. The first one caused an extremely strong surge (peak greater than 40 cm), which occurred on December 3, 1977, and the second one caused a moderate surge (peak less than 30 cm) which occurred on December 12, 1977. For validation, two other storm events were analyzed; the storm of December 10, 1978, which represents a strong surge case and the storm of February 8, 1979, which represents a moderate surge.

METHODS OF ANALYSIS

For the purpose of this study, five multiple regression models are used for the above mentioned storm periods. The first four models were suggested by (Jensen *et al*, 1968) for the Esbjerg Harbor in the North sea, while the last model is proposed by the authors. All these models are based on the assumption that the storm surges at Alexandria respond in an approximately linear fashion to meteorological forcing and sea level height before the storm arrival.

The computational procedure is based on the equation:

$$Y = b_o + \sum_{j=1}^{q} b_j \; {*X_j}$$

where b_0 = constant values

b_j = coefficient of X_j variable

q = number of the variables in the model.

The values of b_o and b_j's can be determined by the least square method.

The variables in the different models are as follows:

1. *Model I:*

In this model the variables included are atmospheric pressure in mb (Pi), the surge height (HTi), wind velocity component parallel to the shore (Vi) and the observed water level (Hi), where i is the number of hours before prediction time. The values of i are equal to 3 in the case of atmospheric pressure and wind velocity component, 3, 6 and 15 in the case of surge height and 9 for the observed water level, i.e. 6 variables; P3, HT3, HT6, HT15, H9 and V3, are used for prediction of surge three hours before its occurrence.

2. *Model II:*

In this model, six independent variables are used as in model I, with the replacement of HT6 by HT12.

3. *Model III:*

This model forecasts the surge six hours in advance. The independent variables are P6, H6, HT6, H9, HT12, HT18, V6 and n6, where n6 is the wind velocity component normal to the shore, 6 hours before forecasting time.

4. *Model IV:*

It is a 3 hour prognosis model in which six independent variables are considered; P3, V3, H3, HT3, HT12 and HT15.

5. *Model V:*

This is the most general model, for three hour prognosis, where the above mentioned 16 variables are included.

The most relevant variables in the above five models are chosen by the stepwise regression method.

RESULTS OF ANALYSIS

The coefficients of the different variables as well as the total correlation coefficients and the standard error of estimates were calculated for each of the above models, using all regression analysis, in which all the independent variables are included, and the stepwise regression, in which only selected variables are chosen according to their contribution to total variance. The software MICROSTAT (version 1984) was used in these calculations. Some of the results of this analysis are shown for the case of strong surges (Table 3) and moderate surge (Table 4). The best models for prediction of Alexandria surge heights were chosen according to the total correlation coefficient and the statistical error of estimate.

Table 3

Results of multiple regression analysis on hourly surge heights at Alexandria Western Harbor in winter using different models for strong surge (peak > 40 cm).

3 December 1977	All regression			Stepwise regression			
No. of the model	TCC*	SEE**	I.V.***	TCC	SEE	I.V.	NDP****
1	0.784	3.61	P3- HT3- H9- HT6 HT15- V3	0.762	3.48	HT3- HT15	31
2	0.770	3.66	P3- V3- HT3- H9 HT12- HT15	0.762	3.48	HT3- HT15	31
3	0.884	3.84	P6- V6- N6- H6- HT6 H9- HT12- HT18	0.822	3.12	V6- N6- H9	31
4	0.889	2.71	V3- N3- H3- HT6- HT12 HT15- P3	0.855	2.79	N3- P3	31
5	---	---	---	0.855	2.79	N3- P3	31

* TCC = Total correlation coefficient.

** SEE = Standard error of estimate (cm).

*** I.V. = Independent variables.

**** NDP = Number of data points.

Table 4

Results of multiple regression analysis on hourly surge heights at Alexandria Western Harbor in winter using different models for moderate surge (peak is 20-30 cm).

12 December 1977	All regression			Stepwise regression			
No. of the model	TCC*	SEE**	I.V.***	TCC	SEE	I.V.	NDP****
1	0.709	2.85	P3- HT3- H9- HT6 HT15- V3	0.636	2.89	H9- V3	31
2	0.759	2.63	P3- V3- HT3- H9 HT12- HT15	0.729	2.61	P3- H9- HT12	31
3	0.810	2.48	P6- V6- N6- H6- HT6 H9- HT12- HT18	0.746	2.54	P6- H9- HT12	31
4	0.778	2.59	V3- N3- H3- HT6- HT12 HT15- P3	0.745	2.59	H3- HT3- HT12- HT15	31
5	---	---	---	0.746	2.54	H9- HT12- P631	

* TCC = Total correlation coefficient.
** SEE = Standard error of estimate (cm).
*** I.V. = Independent variables.
**** NDP = Number of data points.

In the case of the strong surge on December 3, 1977, it can be concluded that:

1. All total correlation coefficients are significant at the 95% confidence limit, where for 31 data pairs, the critical value is 0.296.
2. The highest total correlation coefficient and the least standard error of estimate were associated with model IV for all regression and stepwise regression analyses. However, in the stepwise model the number of the independent variables has been reduced from 6 to 2. Therefore, mode IV given by stepwise method is the most suitable model for forecasting, where the atmospheric pressure and the wind velocity component normal to shore, three hours before forecasting time, are the only independent variables included. Using model V, results are coincident with that of model IV. The best fit equations of the different models, using the stepwise method, are as follows:

Models I & II

$$Y = 25.67 + 0.63 * HT3 - 0.33 * HT15 \tag{1}$$

Model III

$$Y = 70.51 + 0.50 * V6 + 0.88 * n6 - 0.53 * H9 \tag{2}$$

Models IV & V

$$Y = 25.29 + 0.84 * n3 + 2.27 * P3 \tag{3}$$

The constant term in (Equation 3) expresses the influence of the established surge height before the storm. This value is expected to be different from one storm to another. Assuming that this constant is proportional to the mean surge height in the 12 hours before the storm arrival $(\overline{HT12})$, from HT15 to HT3, it can be expressed by $(0.85 * \overline{HT12})$, where the factor 0.85 is the ratio (constant of the (Equation 3) $(\overline{HT12})$, as determined from the data of the storm in December 3, 1977. Therefore, (Equation 3) can be modified as follows:

$$Y = 0.85 * \overline{HT12} + 0.84 * n3 + 2.27 * P3 \tag{4}$$

In the case of the moderate surge, on December 12, 1977, (Tabele 4), it can be again concluded that all total correlation coefficients are significant at the 95% confidence limit. The highest correlation coefficient and the lowest standard error of estimates were associated with model III, with the all regression method. However, applying the stepwise regression method, models III & IV have nearly the same efficiency in forecasting the surge at Alexandria. Model III and V identical. For forecasting purposes, model V was chosen, where three independent variables are considered; P6, H9 and HT12. The stepwise regression equations of the moderate surge can be expressed as follows:

Model I:

$$Y = 39.58 - 0.26 * H9 - 0.28 * V3 \tag{5}$$

Model II:

$$Y = 64.40 - 1.47 * P3 - 0.40 * H9 - 0.53 * HT12 \tag{6}$$

Model III:

$$Y = 62.24 - 1.94 * P6 - 0.38 * H9 - 0.45 * HT12 \tag{7}$$

Model IV:

$$Y = 7.72 + 0.45 * H3 - 0.48 * HT3 - 0.68 * HT\,12 + 0.43 * HT\,15 \tag{8}$$

Model V:

$$Y = 62.24 - 0.38 * H9 - 0.45 * HT12 - 1.94 * P6 \tag{9}$$

For the validation of the forecasting models, in the strong surge case, the surge of December 10, 1978, was simulated using equations 2, 3 and 4, as well as the all regression equations. The results are shown by (Fig. 2), which shows that:

1. The times of the peak surges are well forecast from the different models.
2. Models III and IV (Equations 2 and 3) give nearly the same estimates from the regression and stepwise analyses, which

are higher than the observed ones, while (Equation 4) given the best estimates for the surge.

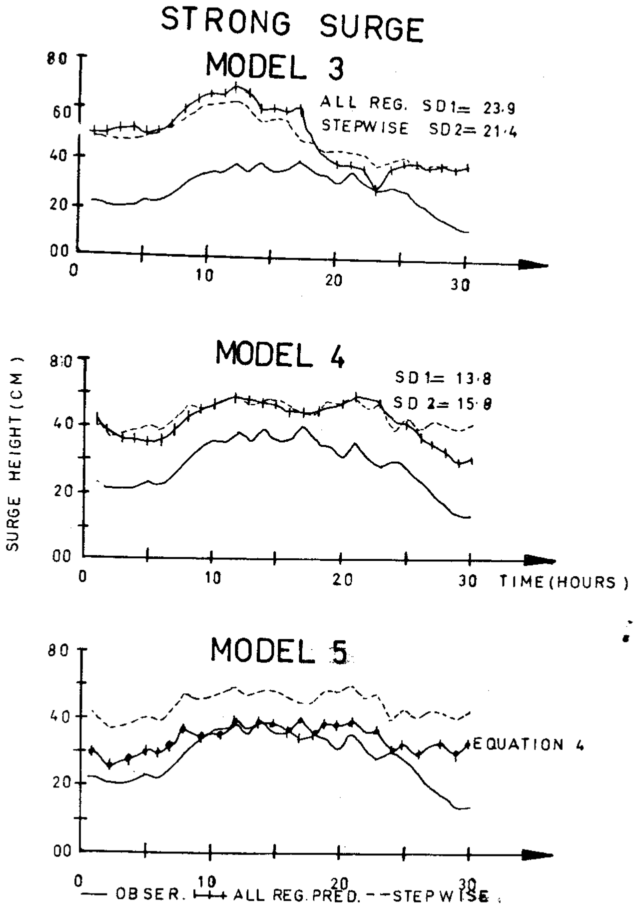

Fig. 2: The strong storm surge time series, observed and predicted by some suggested models.
SD1 is the standard deviation between observations and predictions by all regression method.
SD2 is the standard deviation between observations and predictions by stepwise regression method.

On the other hand, the predictions of the moderate surge heights, on February 8, 1979, using (Equations 7, 8, and 9) as well as all regression equations are shown by (Fig. 3). All regression models given much higher values than observed ones, while the stepwise regression equations give estimates closer to observations with a standard deviation of about (5.1-5.7) cm.

SUMMARY AND CONCLUSIONS

In the present work, five models were fitted for short term prediction of storm surges at Alexandria, using all regression and stepwise regression methods, in the cases of strong and weak surge events. The constants, total correlation coefficients and the standard errors of estimates were calculated and the most significant models were validated using other storm periods.

The (Equation 4), including the wind velocity component normal to the shore and the atmospheric pressure three hours before forecasting times, and the mean surge over 12 hours (HT15 to HT3) before storm arrival, was found to be the most convenient model to forecast the strong surge at Alexandria.

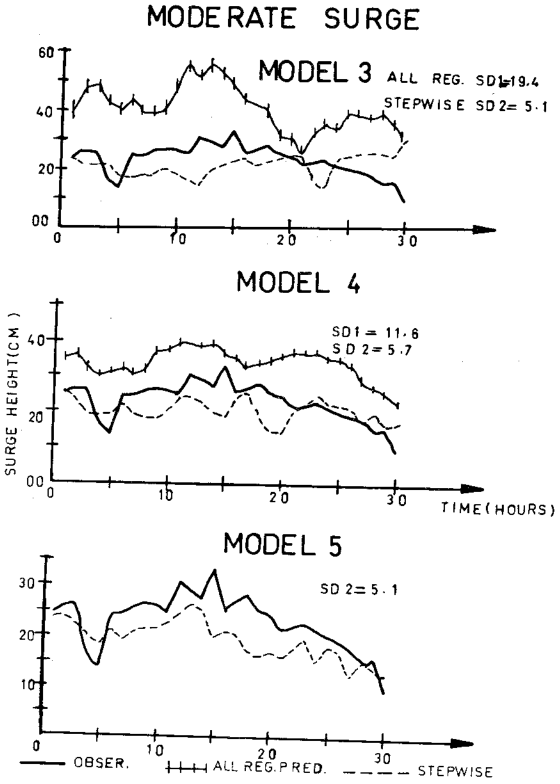

Fig. 3: The moderate storm surge time series, observed and predicted by some suggested models.
SD1 is the standard deviation between observations and predictions by all regression method.
SD2 is the standard deviation between observations and predictions by stepwise regression method.

In the case of moderate surge type, it was found that the best equations in forecasting surge heights are given by the stepwise method, (Equations 7, 8 and 9) with a standard error (5.1-5.7) cm. The type of surge expected to arrive at Alexandria can be forecast from the meteorological synoptic situation, (Hamed and El-Gindy, 1988.).

The relatively high standard deviation between observed and predicted surges could probably result from the variable relative importance of wind velocity and the atmospheric pressure due to the different speeds of the atmospheric depressions over the region. The wind velocity is expected to be more effective when depressions move faster, while the pressure barometric influence becomes more important for slow depression movement. However, the fitted equations are valid for forecasting within the limits of the estimated error.

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