STUDY OF THE SEDIMENT TRANSPORT RATES FOR THE NILE DELTA COAST USING MATHEMATICAL MODELS

Abd ElFattah El-Fiky[1], Gamal ElSaeed[2], Ayman Sharaf El-Din[3]

Abstract

The Rosetta Promontory was created by sediment transported along the Nile River and delivered to the coast by the Rosetta branches. Following a long period of accretion, the promontory began to erode in the mid 1900s.

This study deals with coastal processes, documenting the sediment transport rate and shoreline changes and predicting the future shoreline position along the Rosetta promontory. A mathematical model (actually made up of four separate models linked together) was deployed to study such processes where the Nile Delta meets the northern coast. The model is capable of calculating the wave characteristics, current distribution, sediment transport and the corresponding bed level changes. The main objective of this study is to install a station on the north coast of Egypt (at Rosetta) to estimate the amount of erosion and accretion and to have a better understanding of beach stability in view of existing structures.

The present study documented the sediment transport rate and shoreline change and predicted the shoreline position along the Rosetta promontory by applying the numerical model "GENESIS" linked with three other models ("RMA2," "SED2D," and "NMLONG"). On the western side of Rosetta, the results of using the Longuet-Higgins, SPM formula and Gaven-Eagleson equations were in agreement with the measurements.

Keywords: Shoreline change, numerical modeling, coastal engineering, sediment transport, mathematical modeling, wave energy, coastal erosion, Genesis.

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Introduction

Many coastal problems now being encountered worldwide have resulted from the unsustainable use and unrestricted development of coastal areas and resources. These problems include the accumulation of contaminants in coastal areas, erosion, and the rapid decrease of habitats and natural resources.

The loss of coastal land is a serious problem which has both direct and indirect consequences on coastal communities, requiring adjustment of property and, in extreme cases, causing a danger to life.

Since Egypt's Nile Delta is the only delta existing along the southeastern part of the Mediterranean Sea, it is considered one of the most interesting natural laboratories, not only because of its coastal processes and evolution (erosion accretion), but also because of its economic importance related to Egyptian natural resources and land management.

Unlike the other major deltas of the world (e.g. Mississippi and Niger), Egypt's delta was built by the Nile River in relatively recent geological ages. Its area (20,000 km^2) was formed by the sedimentary processes which occurred between the upper Miocene period (some ten million years ago) and the present. In about 460 BCE, the Greek historian Herodotus noted that the delta was built up by the alluvium brought by the old seven or more active branches of the Nile as they crossed the delta (Said 1958, EI-Askary and Frihy 1986, Fanos et al 1995). Those distributaries have been subsequently silted up and replaced by the present branch of Rosetta.

The rate of erosion at the Rosetta promontory represents the highest shoreline regression documented along the Nile Delta coast. This will negatively affect recreational functions of its beach and will threaten agricultural productivity. Moreover, the altered surface will adversely affect the quality of ground water at said location.

Over the course of the twentieth century, the following has happened causing the shoreline to evolve: climate change from Indian monsoons; man-made structures on the River Nile; protective walls along the coast; and the High Dam at Aswan.

The main model utilized to provide a framework for developing solutions to the problems listed above is the "Generalized model for Simulating Shoreline changes" ("GENESIS"). This model collects, organizes, and analyzes data to evaluate and select alternative optimal designs. It is linked to three other models, RMA2, SED2D, and NMLONG, the output results of which are input into the GENESIS model to generate the data sought.

Data collection and processing techniques using the models:

Data enables engineers to know qualitative factors affecting specific areas and ensures more practical solutions. Present data include wave measurements, long-shore currents, water level variations, and wind data for the Rosetta promontory. Specific locations along the Rosetta area where data was collected are shown in Figure (1).

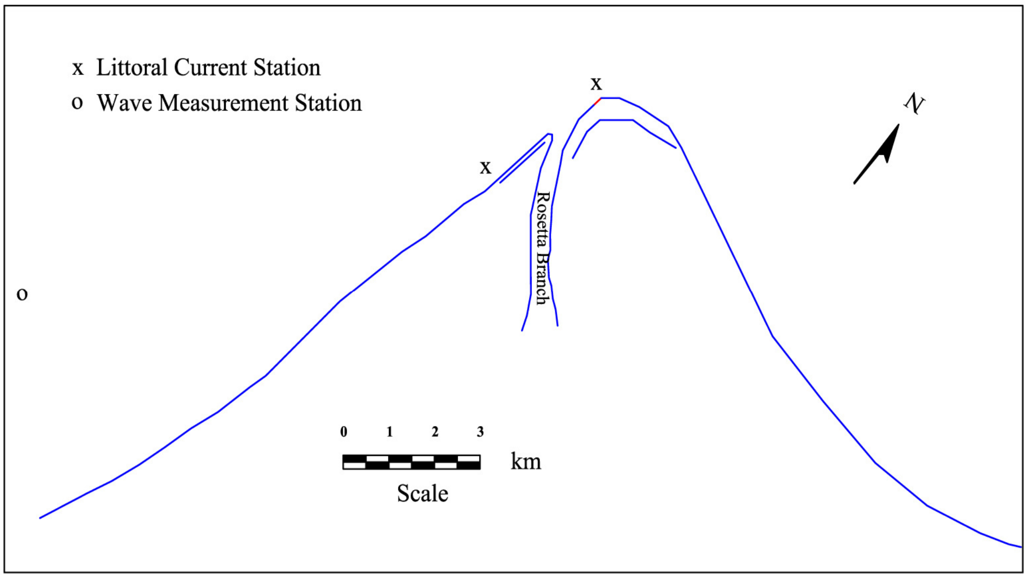

Fig. 1. Diagram showing the collected location for parameters along Rosetta area

At Rosetta, wind speed was determined by analyzing statistical data to obtain occurrence percentages related to both speed and direction. Data was divided into three different wind speed categories (measured in knots) and eight different directions. Mean wave period and heights (including occurrence percentages) were calculated by averaging the value over the appropriate periods of a day, month, or year, respectively. Next, wave direction analysis was derived by evaluating two components of current direction, north and east, for a period of twenty minutes every four hours. Monthly and seasonally maximum and mean wave period and wave height with occurrence percentages for different classes was calculated for sixteen directions. Both graphical and numerical methods were used to analyze wave refraction. For parallel contours neglecting the effect of the current, the refraction co-efficient can be computed using Snell's low (Shore Protection Manual, 1984) which is:

$KR = (\cos \alpha_o / \cos \alpha)^{1/2}$ [Refraction co-efficient] .... (1)

$\alpha = \sin^{-1} (C/C_o \times \sin\alpha_o)$ .... (2)

Where "α" is the angle between the waves. "α_o" is the angle between the deep water wave crest and the shoreline. "C" is wave celerity. "C_o" is wave celerity in deep water.

The other factor affecting the wave height is the shoaling co-efficient which gives the effect of depth itself on the waves and can be computed as follows:

$K_s = [(l/2)(1/n)(C_o/C)]^{1/2}$ [Shoaling co-efficient] ……………………………… (3)

Munk and Sverdrup (1947) derived several relationships between breaker height (H_b), breaking depth (Db), un-refracted deep water wave height (H_o), and deep water wave length (L_o), as seen below:

$H_b/H_o = 1/[3.3 \text{ x } (H_o/L_o)^{1/3}]$ and $D_b/H_b = 1.28$ ………………………………… (4)

The last expression can be computed by the use of the beach slope. The following expression was derived by the Shore Protection Manual (1973):

$D_b/H_b = 1/[b - (aH_b/gT^2)]$ ……………………………………………………… (5)

$$a = 1.36 \text{ g } (1 - e^{-19m})$$
$$b = 1.56/ (1 + e^{-19m})$$

Where "T"= Wave period; "g"= Acceleration of gravity; and $n = 1/2 [1 + (4\pi d/L) \sinh(4\pi d/L)]$.

Long-shore current data was subjected to monthly seasonally statistical analysis to determine long-shore current distribution probability and was tested using the following semi-empirical formulas:

1. The modified Longuet-Higgins (1970) equation:
   $V = 20.7m(gHb) \ l/2 \ \sin2\alpha b$ m/sec [Long-shore current distribution probability]
2. The Galvin-Eagleson (1965) equation:
   $V = KgTm \sin2\alpha_b$ m/sec

Where "V" is the current velocity at the mid surf-zone position, "K" is the dimensionless co-efficient depending solely on the generation of the breaking wave ranging from about 0.6-1.1 with assumed unity. (Galvin-Eagleson, 1965), "g" is the acceleration of gravity, "T" is the wave period, "m" is a beach slope, and "α_b" is the angle between the wave crest and the bottom contour at breaking.

Long-shore sediment transport rate in the surf zone relies mainly on wave action as the principal driving force, and it is calculated as refraction by using a mathematical method according to the pre-dominant wave direction with resulting wave characteristics in the breaking zone (height, celerity, and breaker angle). Accordingly, the long-shore sediment transport rate ("Q") varies from one point to another along the coast due to the shoreline direction ("zero-line"). Inman and Bagnold (1963), and Komar and Inman (1970). provided theories and procedures for estimating the wave-induced long-shore sediment transport rate. Their studies led to the following equation:

$Q = 0.02566 \times C_g \times H_{bs}^2 \sin 2\alpha_b$ m^3/sec [Long-shore sediment transport rate] …….. (6)

Where: "$(C_g)_b$" is the group velocity at breaking (m/sec), "H_{bs}" is the significant wave height at breaking (m) and "α_b" is the angle between the wave crest and the bottom contour at breaking.

Loose sediment constitutes the coast of the Rosetta promontory, subjecting its beaches to tremendous change as a result of wave energy. Significant wave height and period represent the characteristics of the real sea in the form of monochromatic waves which are defined as a train of waves that have the same period as well as those that have different periods. Wave characteristics, such as period, velocity, wave length and wave height, are irregular; therefore, statistical methods must be used to describe wave properties in a study area. Significant wave height is the average height of the highest wave as one third of wave heights which is used to measure the sea's severity.

Wave data recorded at Rosetta in 1986 was used to predict the long-shore current velocity, which is the main cause of long-shore sediment transport. At both the east and west sides of the Rosetta mouth, the predominant direction, maximum velocity, average velocity, and current occurrence percentages were determined on a monthly, seasonally, and annual basis. Results were used to calculate long-shore current velocity and sediment transport rate. The last parameters of waves at their breaking points were used to calculate the long-shore current velocity, comparing the results with the field measurements for the side of the Rosetta mouth.

Wind speed affects wave height after a time shift. It is important to calculate this time or the strong correlation coefficient between the two parameters of wind speed and wave height. To accomplish this, it is possible to look at continuous records from 1986 in which the wave height and corresponding wind speed were recorded together at the same time. Figures (2) and (3) show the monthly, seasonally, and yearly mean and maximum wind speed and the monthly wind rose diagram for the Rosetta area during 1986.

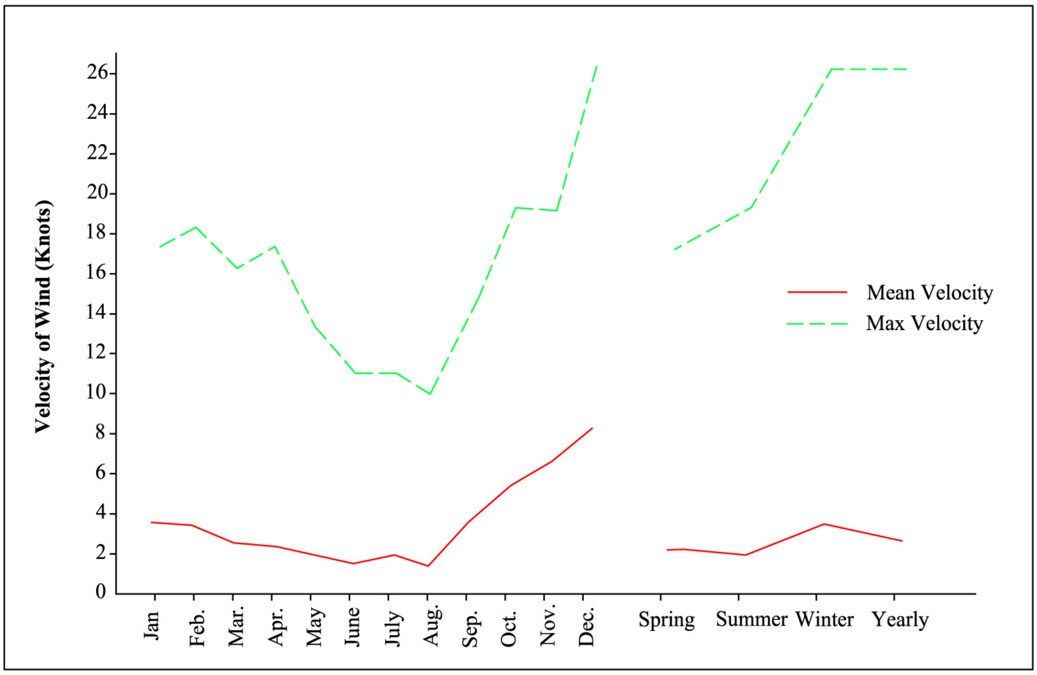

Fig. 2. Monthly, seasonally and yearly mean and maximum wind speed during 1986 for Rosetta area

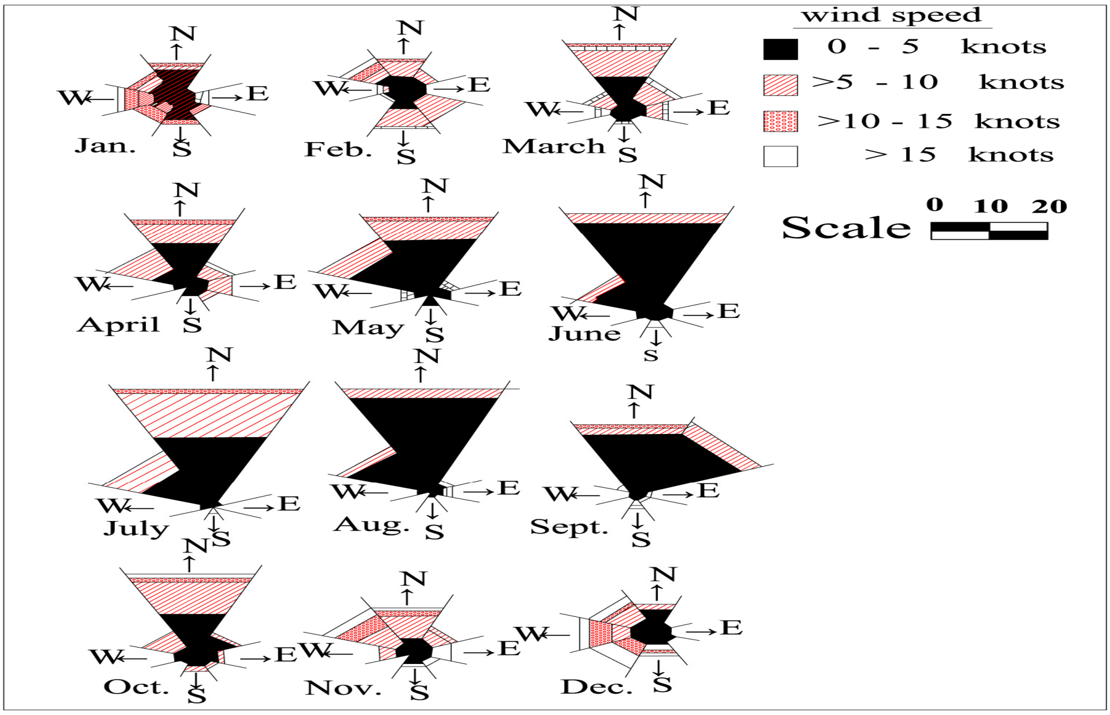

Fig. 3. Monthly wind rose diagram – Rosetta area

In 1986, north and northwest winds prevailed with higher frequencies between the months of March and September. A small percentage came from the northeast direction. During the winter season, the wind direction was variable in all directions, but the wind to the north and northwest was more predominant. In summer, the north wind direction prevailed with high frequency with some winds being northwest. At spring, the predominate wind directions ranged between north and northwest with a small percentage blowing in a northeasterly direction. For the entire annual period, the predominant direction ranged between north (with high frequency) and northwest, with a part of it blowing towards the northeast.

The seasonal sediment transport rate was equal to the sum of the products calculated after multiplying the figures for long-shore sediment transport rates by the occurrence percentages for each record.

Statistical analysis yielded the following measurements:

- Maximum wave height during winter 1986 was 419cm and during spring: 263cm.
- Approximately 87% of all wave height is less than or equal to 1.5m and 13% is greater than 1.5m.
- Average wave height was 100cm, 90cm and 92cm in winter, spring, and summer, respectively and was about 94cm during the year 1986.
- Predominant wave direction for winter ranged between WNW (38%) and NW (20%), and some of it had a N direction.
- Predominant wave direction for spring was between NW (38%), WNW (24%) and NNW (16%).
- Predominant wave direction for summer was NW (54%) with part of it being WNW (19%).
- Predominant wave direction for all of 1986 was NW (42%) with part of being WNW (25%).
- Maximum wave periods were 10.7,9.1, and 10.7 seconds for the three seasons (winter, spring and summer) respectively.
- Average wave period was 6.8, 6.0, and 6.1 seconds for all three seasons respectively.
- Most wave period values were between 5 and 8 seconds (59%) with an average value of 6.5 seconds during the year 1986.
- Wave energy in winter was greater than in the other two seasons (spring, summer) as it depends on wave height.

  NB: All of the points listed above agree with calculations ascertained later by other researchers (Elwany et al 1988, Komar 1990).

Of the three models used, RMA2, SED2D, and NMLONG, specific limitations exist. Nonetheless, each is capable of giving important data by using their respective governing equations and according to the input data given. Additionally, the models were effectively used in combination to yield relevant data subsequently used in the GENESIS model.

Processing

Shores erode, accrete, or remain stable, depending on the rates at which sediment is supplied to and removed from the shore. Determination of long-shore sediment transport rate is a common challenge in coastal engineering.

The movement of sediment on and off shore as well as long-shore is a complicated problem because it results from the interaction of wind, waves, currents, tides, sediment, and bottom topography. After more than one hundred years of research into the sediment transport phenomena, it is still impossible to calculate the exact quantity of sediment moving, whether as bed load and/or suspended load or as a total load in reference to the basic physics of the transport process. Consequently, approximate methods must be used.

Calculations of long-shore sediment transport rates for the Rosetta area were based on the "CERC" formula, or the energetic model equation, which incorporates wave energy flux as part of its computation process for estimating the rate of wave-induced long-shore sediment transport. The results of these studies can are shown in the following equation: $Q=0.02566 \text{ x } C_g \text{ x } H_b / \sin 2\alpha_b \text{ m}^3/\text{sec}$, where (C_g)b is the group velocity at breaking (m) and α_b is the angle between the wave crest and the bottom contour at breaking.

The energetic model's figures are specifically calculated by using wave characteristics recorded throughout the year of 1986 along with the average velocity and the long-shore current occurrence percentages during the same time. In this way, the seasonally average volume of sediment transport rates could be ascertained using the two common model equations (Longuet-Higgins and Galvin-Eagleson) for the two sides of the Rosetta mouth. In addition, the computations were carried out on both a seasonally and a yearly basis (i.e., for spring, summer, and winter seasons as well as for the whole period).

From the data recorded, the following was observed:

- The gross transport is very large during the winter season due to the winter activity which is highly fluctuating and stormy.
- Gross transport during the summer is less than winter due to more swell waves.
- Spring season showed low gross transport, possibly due to the high percentage of reversed direction of long-shore current from April to Mayas well as lower wave energy.
- General direction of sediment transport is toward the east and south for the eastern and western sides of the Rosetta mouth, respectively (i.e., away from the Rosetta mouth).
- Amount of sediment calculated by the CERC formula was greater than that calculated by the energetic model equation (which uses wave characteristics such as average velocity and the percentage of long-shore current occurrence), possibly due to the peculiar features of each formula (CERC depends on wave effect only while the energetic model uses wave effect data [wave energy flux] as well as

long-shore current data).

Computational procedure

From a map that uses a scale of 1:10,000 for the study area, the grid system was applied as the shoreline grid. The shoreline was thus divided into a large number of cells of which thirty-one represented the western side of the Rosetta mouth and 118 represented the eastern side. Each cell unit represents *Sam* in length along the shore.
The operation of the GENESIS model requires the following:

- Directional wave spectrum data recorded by a system (C.A.S.) installed at a depth of 18.0m during the period from 1 Jan 1986 until 31 December 1986.
- Initial shoreline at the beginning of all simulations (survey in S.A. 1996).
- Measured shoreline position corresponding to the end of the simulation (S.A. 1997), used to compute calibration factor.
- Input location and position of structures.

Table 1 shows the seasonally average volume of sediment transport rates using the two common model equations mentioned earlier for the two sides of the Rosetta mouth.

Table 1: Long-shore current characteristics & average of significant wave height and angle at breaking during different season for the two sides of Rosetta mouth

Season	(H_b) Average (m)	Eastern side (α_b = 5°)				Western side (α_b = 6.3°)			
		(V) to east m/sec		(V) to west m/sec		(V) to north		(V) to south	
		Aver.	Percent	Aver.	Percent	Aver.	Percent	Aver.	Percent
Spring	1.26	35.20	48	35.5	47	34.2	35.5	35.7	56.7
Summer	1.28	36.1	57	36.1	37	34.6	22.6	34.2	72.1
Winter	1.37	36.9	60	36.6	33	33.6	39.3	34.3	63.4
Year Aver.	1.30	36.4	57	36.2	36	34.3	28.8	34.8	65

Table 2 shows the seasonally long-shore sediment transport rates on both sides of the Rosetta mouth.

Table 2: Seasonally long-shore sediment transport rates on both Side of Rosetta mouth (x 10^3 m^3/mouth)

Season	Eastern side			Western side		
	Values of Q_s			Values of Q_s		
	CERC formula	Modified Bagnold	Direction	CERC formula	Modified Bagnold	Direction
Spring	50.2	18.1	To East	28.7	13.6	The North
	21.8	17.9	To West	61.6	22.0	The South
	72.0	36.0	Gross	90.3	35.6	Gross
	28.4 (E)	0.2 (E)	Net	32.9 (E)	8.4 (S)	Net
Summer	57.5	23	To East	21.4	8.6	The North
	17.5	15	To West	72.4	29.4	The South
	75.0	38	Gross	94.1	38.0	Gross
	40.0 (E)	8 (E)	Net	51.3 (S)	20.8 (S)	Net
Winter	56.3	28.3	To East	48.4	13.1	The North
	32.4	15.2	To West	62.8	29	The South
	88.7	43.5	Gross	111.2	42.1	Gross
	23.9 (E)	13.1 (E)	Net	14.4 (S)	15.9 (S)	Net

Model result and discussion

According to shoreline changes calculated (by GENESIS) during 1997 along the study area and shown in Figure (4) below.

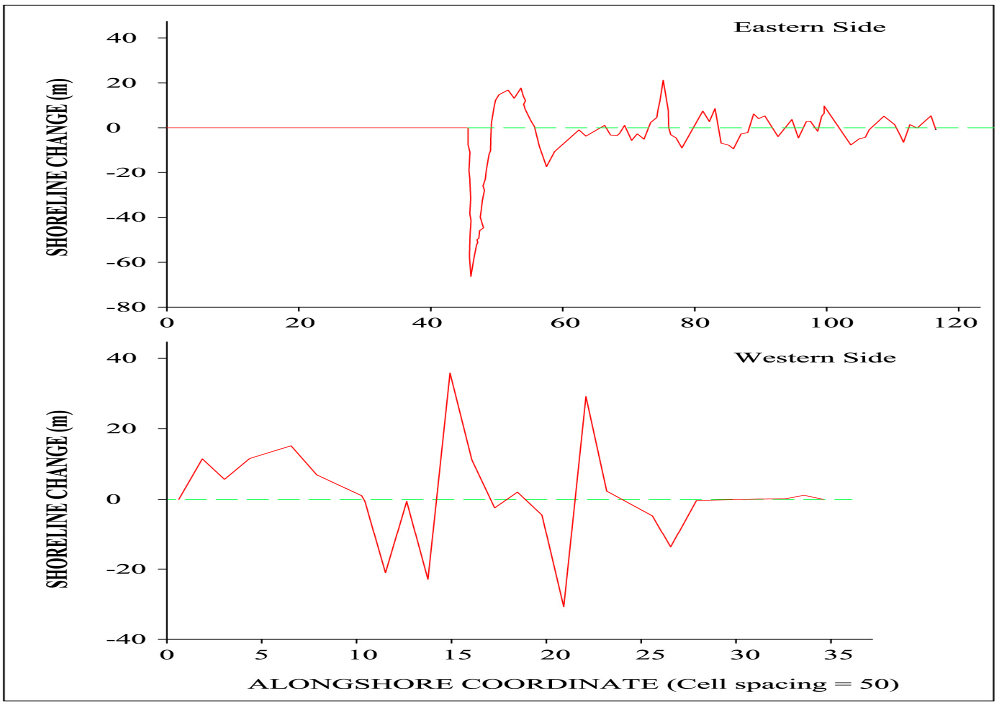

Fig. 4. Shoreline change from initial (1997)

The following deductions were made:

- At the eastern side of the Rosetta mouth, the shoreline oscillated between a backward and forward direction with maximum distances of 60m and 22m respectively. After the end of the eastern wall, the shoreline moved landward with a high distance due to the high wave and littoral current velocity which attacked the area causing erosion at the beginning of it and accretion at the end.
- At the western side of the mouth, the shoreline oscillated between a backward and forward direction with maximum distances of 30m and 36m respectively. The middle part of the study area oscillated between the seaward and landward sides with a high distance due to the effect of a northwesterly strong wave. The end of the western side showed a forward direction of the shoreline which caused sedimentation in the area, possibly due to the predominant southward direction of the littoral current.

With respect to the shoreline position as of 1997, on the eastern side of the Rosetta mouth after the end of the eastern seawall, the shoreline shifted landward, causing erosion; on the western side, the shoreline oscillated but was landward at the middle. The results showed the distribution of sediment transport rate along the study area for the year 1996/1997 as shown in Figure (5). Regarding shoreline prediction for 2010, on the eastern side of the mouth, from the end of the eastern wall, it is predicted the shoreline will shift seaward; for the western side, the shoreline should shift landward and seaward with a minimum of 20m and a maximum of 320m as shown in Figures (6) and (7).

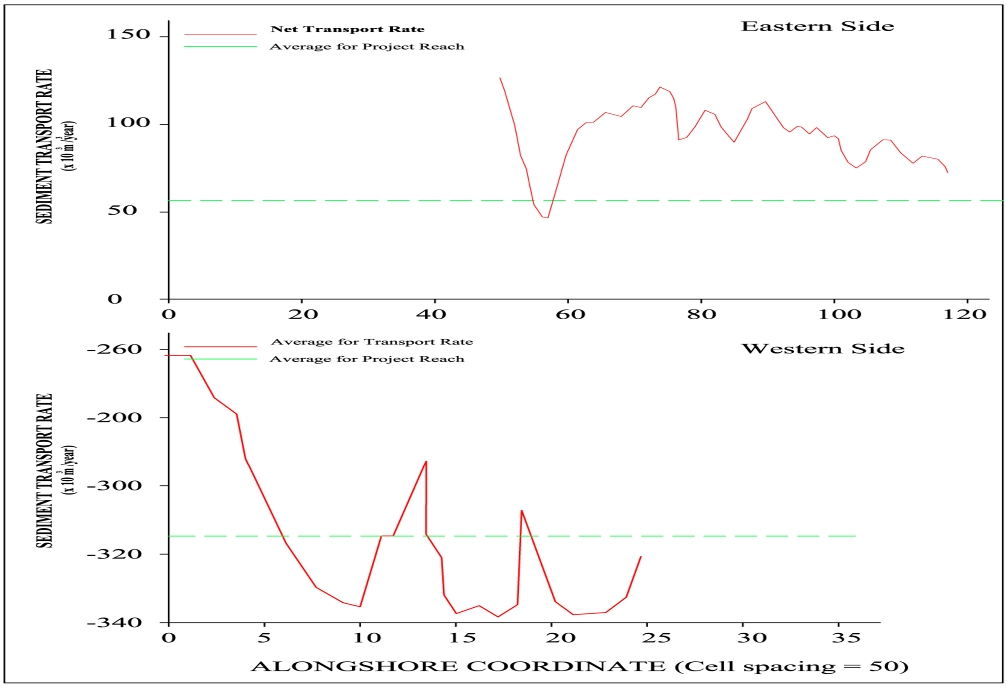

Fig. 5. Rate of sediment transport along Rosetta area 1996/1997 (x 10^3 m^3)

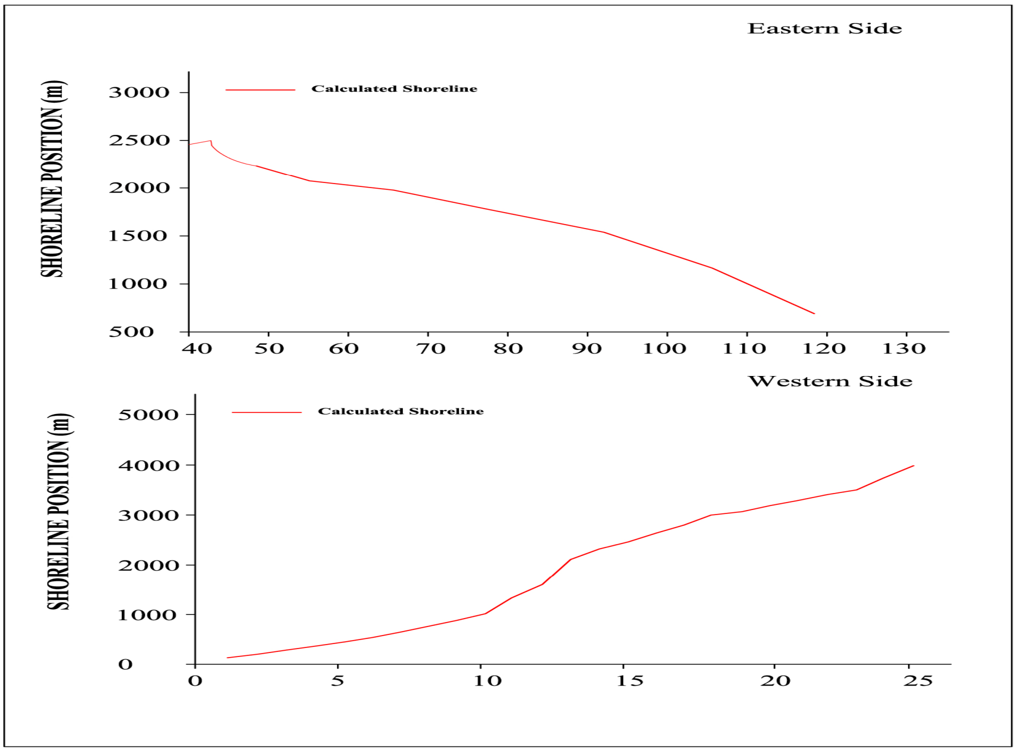

Fig. 6. Shoreline Position after one year (1997)

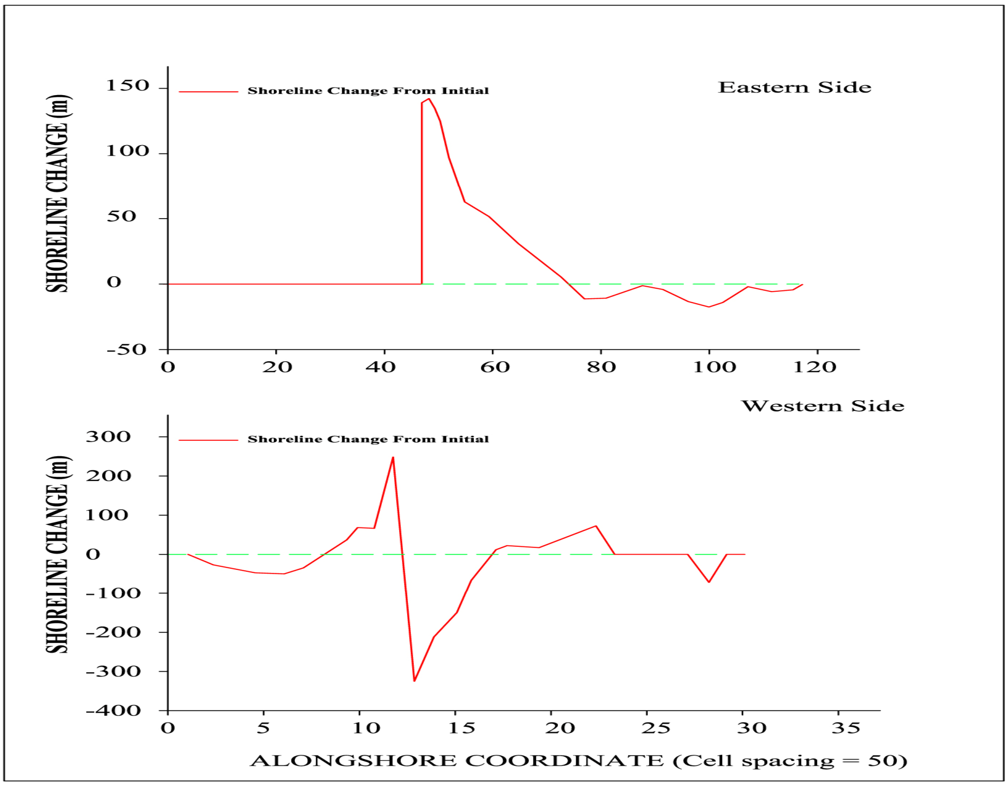

Fig. 7. Shoreline shift at 2010

At Rosetta, the sediment transport was calculated in two places (eastern and western sides of mouth). Using common models on the eastern side, the general direction of sediment transport was towards the east (same direction of long-shore current). The net transport rate was found to be $41x10^4$ and $9.5x10^4 m^3$/year to the east with a gross transport rate of $93.8x10^4 m^3$/year and $46.1x10^4 m^3$/year using the CERC formula and energetic model equation respectively. On the western side, the general direction of sediment transport is from north to south (same direction of long-shore current). The net transport rate was found to be $47.5x10^4$ and $18.5x10^4 m^3$/year to the south suing the CERC formula and the energetic model equation respectively. The gross transport rate was about $117.7x10^4$ and $46.7x10^4 m^3$/year using the same equations respectively.

In using the GENESIS model at the Rosetta mouth, the maximum and minimum sediment transport rates for on the western side were $30.4xl0^4$ and $22.2xl0^4 m^3$/year to the south, respectively. Average rate was recorded as $27.5xl0^4 m^3$/year. On the eastern side, the maximum and minimum rates were $11.8xl0^4$ and $4.2xl0^4 m^3$/year to the east, respectively. Average rate was recorded as $6.0xl0^4 m^3$/year to the east.

Conclusions

As a result of the study, it is deducted that the predominant direction of long-shore current is from north to south for the western side and west to east for the eastern side, and the current reverses its direction to north for the western side and to west for the eastern side due to northeast wind wave action. The last parameters of waves at their breaking point were used to calculate the long-shore current velocity at Rosetta using the aforementioned Longuet-Higgins formula and then comparing the results with the field measurements for the side of the Rosetta mouth. Predicted velocities differ from actual observed values.

From the long-shore sediment transport calculations using the various models discussed in this study, general conclusions may be summarized as follows:

1. Predominant direction of sediment transport is eastward.
2. Sediment transport values are rather large during winter.
3. In the central region of the study area, there is a neural and equilibrium of shoreline where is oscillates between seaward and landward with just a few meters (due to the existence of the detached breakwater).
4. The general predominant directions of sediment transport are eastward and southward for the eastern and western sides of the Rosetta mouth respectively.

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مستخلص البحث:

يعتبر التمثيل الدقيق لانتقال الرواسب خطوة اساسية فى تخطيط وتقييم حواجز الامواج ودراسة اتزان الشواطئ . وفى هذه الدراسة يتم دراسة عمليات النحر والترسيب على طول الساحل الشمالى لجمهورية مصر العربية المطل على البحر الابيض المتوسط وذلك لمنطقة رشيد كحالة دراسة خلال فترتى تمثيل مختلفتين وذلك باستخدام نماذج عددية مختلفة فى ظل وجود منشآت الحماية الحالية كتقييم للاثر البيئى لها .

وقد تم اعداد البيانات المختلفة من امواج ورياح وخلافه وتم حساب كميات الرواسب المنقولة، اولا" باستخدام معادلة (CERC) وكذلك باستخدام (Energetic Equation) فى فصول السنة المختلفة للمنطقتين، كذلك تم تطبيق النموذج العددى (Genesis) وتم عمل معايرة له حتى يتم تطبيق به بالمقارنة مع خط الشاطئ المقاس .

واخيرا" تم استخدام النموذج لتوقع خط الشاطئ بعد ١٠ سنوات، وقد وجد ان افضل حل لاتزان الشاطئ لمنطقة دمياط هو طهير المدخل دوريا" واستخدام ناتج التطهير لتعويض التآكل الحادث فى الشاطئ .

كلمات مفتاحية: تغيرات خط الشاطئ – النماذج العددية – Genesis – هندسة الشواطئ – النحر الساحلى – طاقة الامواج .