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Sedimentation Processes at the Navigation Channel of the Damietta Harbour on the Northeastern Nile Delta Coast of Egypt

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ABSTRACT

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Damietta Harbour is located on the northeastern coast of the Nile delta, Egypt. Two breakwaters were constructed in 1982 to prevent the prevailing NE and SW sediment transport from shoaling the navigation channel, which extends about 20km offshore. However, the harbour channel has experienced continued sedimentation, which has affected navigation. As a result, periodic annual dredging of the channel has being carried out since 1986, averaging of 1.18 × 10^6 m^3/yr. To provide a basis for evaluating this problem and to provide possible mitigation, an intensive 20-month measurement program was carried out including: intensive hydrographic surveying, waves, longshore currents, littoral drift, currents seaward of the breaker zone, offshore currents and water level variation. Results of this study have led to better understanding of the factors controlling the processes of sedimentation of the navigation channel. The sedimentation process is complex and is influenced by the temporal variability in the direction and intensity of the incoming waves, currents, orientation of coastline and seafloor morphology. Sediments are transported to the sink area including the navigation channel from adjacent coastal sources at Burullus and Ras El Bar as well as from the Damietta offshore shoals by several pathways comprising the opposing NE and SW littoral drift, north-northwest and north-northeast offshore currents as well as from onshore sediment movement. Sediments are dispersed primarily away from sediment sources toward the sink area by both contour-flowing bottom and cross-shelf (seaward-trending currents). The general characteristics and interpretation of depth of closure are applied to evaluate the behavior of the harbour breakwaters versus sediment bypassing and to propose measures to mitigate this problem.

ADDITIONAL INDEX WORDS: *Mediterranean Sea, beach erosion, sediment transport, harbour breakwaters, channel sedimentation, Nile delta promontories, closure depth.*

INTRODUCTION

The coastal zone of the Nile delta is presently undergoing extensive changes due to both natural and anthropogenic influences (STANLEY and WARNE, 1993). These changes have induced problems of shoreline erosion associated with sedimentation inside the coastal lagoon inlets and estuaries. These changes have been attributed to cut off sediment supply to the coast due to the construction of dams on the upper Nile River that cut off almost all water discharge from the river, historical changes in climatic conditions, prevailing coastal processes, and adverse effects of protective structures (INMAN and JENKINS, 1984; UNDP/UNESCO, 1978; FANOS *et al.* 1991; 1995). Erosion has affected the agriculture and urban lands along the delta promontories at Rosetta, Burullus and Damietta (Figure 1A). On the other hand, accretion exists within embayments and saddles between these promontories. Part of the accreted sand has induced shoaling and subsequent navigation hazards at the lagoon inlets and navigation channels of the Damietta Harbour. Perhaps, sedimentation of this harbour would have occurred even before damming the Nile River in the 20th century stopped sediments from nourishing delta beaches. In such wave-dominated sandy seabed, driving forces are the primarily factor influencing sedimentation processes in the harbour channel area. The coastline of the Nile delta is typical of microtidal semidiurnal nature. Recorded daily water level variations measured from the mean sea level in the study area reveal high-high and low-low water level of 37cm and −38cm, respectively, with a tidal range of 75cm (this study).

In addition to the Damietta harbour, the two main harbours built on the Nile delta coast are Abu Quir and Port Said (Figure 1A). They were built on high-energy headlands and their entrances were artificially protected by long breakwaters, being 1.5 and 7.7km, respectively. They are successfully operating in terms of stopping sedimentation of their navigation channels. Herein, we focus on the sedimentation processes of the Damietta Harbour located on the northeastern coast of the Nile delta. The harbour was constructed in 1982, and is located about 9.7km west of the Damietta Nile mouth (Figure 1B). The harbour basin was erected inland and its entrance was protected by two breakwaters. The area hosting the navigation channel forms part of the western

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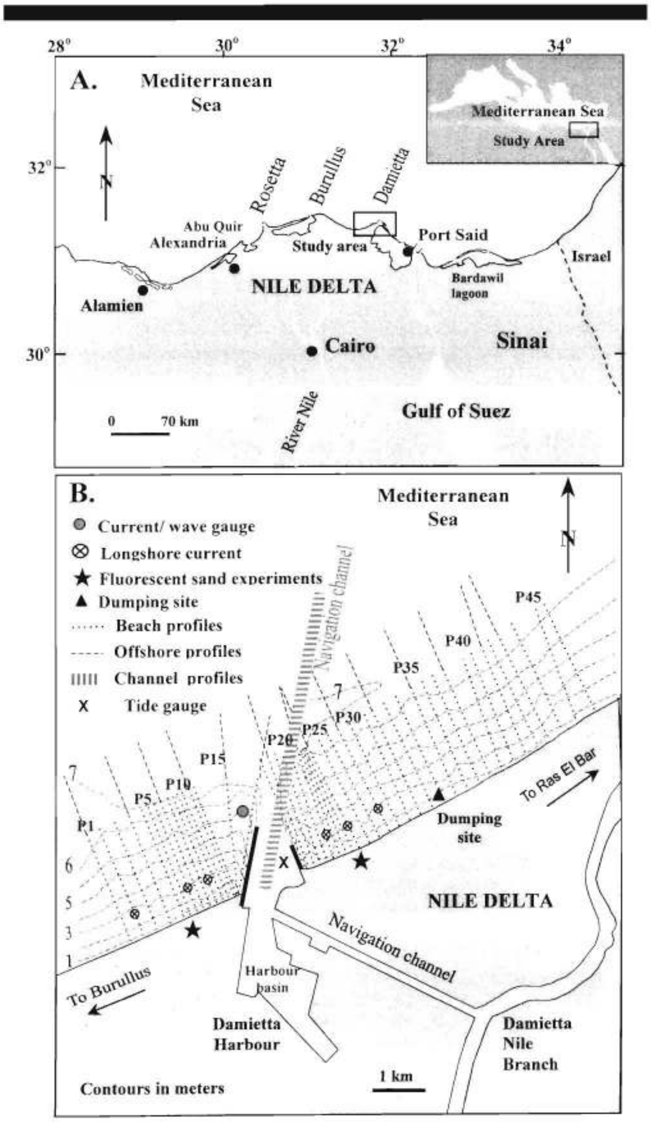

Figure 1. (A) Inset map of the north Mediterranean coast of Egypt showing the general location of the study Damietta Harbour at the northeastern Nile delta. (B) The coastline of the Damietta Harbour showing the positions of 46 hydrographic profile lines examined in this study. Various field activities are denoted by symbols.

shelf of the Nile delta. The western breakwater extends about 1500m parallel to the navigation channel, attaining the 7m-depth contour. The eastern one is about 500m long, perpendicular to the shoreline, and extends to about the 3m-water depth contour. These breakwaters were designed to avoid the NE and SW sediment transport from bypassing the navigation channel (HARRIS, 1979). The navigation channel extends offshore to the middle shelf or about 20km with an average water depth of about 15m. Since January 1984, the channel of the harbour has experienced sedimentation and subsequently threatening the navigation activities (ANONYMOUS, 1998).

To recover the sedimentation problem at the navigation channel, periodic annual or less frequent dredging of the channel has been carried out since 1986 and continued until the present time. The dredged material is recovered by a hopper dredger and has been dumped on the downdrift beaches, 3 km east of the harbour (Figure 1B). Chronic shoaling of this channel has threatening the vessels and cargo ships plus there is the high cost of annual dredging. Based on available data spanning 1986 to 1994, the annual quantity of dredged materials ranged from 0.35×10^6 to 2.0×10^6 m^3, with an annual average of 1.18×10^6 m^3. Of those, 65% were dredged from the first 4km length of the navigation channel of the western breakwater (inner part), while the balance was dredged up to 9km offshore (outer part).

Shoaling of harbour entrances is a worldwide problem. A number of studies called attention to solve or at least to minimize shoaling problems of harbours's basin, entrances and estuaries. Among these studies are the inlet to Corpus Christi Bay, Texas (BEHRENS, 1981), the Bahia Blanca estuary, Argentina (ALIOTTA and PERILLO, 1987; PERILLO and GUADRADO, 1991), the Whangamata harbour, New Zealand (SHEFFIELD *et al.* 1995), and the Baltimore Harbour (JEROME *et al.* 1998). Recommended measures to mitigate such problems include extension of the harbour breakwaters, change orientation and shape of the entrance, construction of additional groin systems at the harbours's updrift side, periodic dredging and sand bypassing.

The present study was undertaken in an effort to better understanding the reasons of sedimentation of the navigation channel of the Damietta Harbour and to provide practical information that could assist in solving this problem. Profile analysis, in conjunction with measurements of hydrodynamic forces, would likely provide information pertaining to dominant sources and dispersal of sediment in alongshore and cross-shore directions involved in the processes of channel sedimentation. Another aspect considered is possible corrective measures proposed to mitigate the problem of channel sedimentation. Therefore, a comprehensive field monitoring program, spanned 20-months, has been initiated in the harbour vicinity. This program includes: beach and offshore profile survey, wave measurements, current measurements, littoral drift experiments, sea level variation and grain size analysis of beach and profile samples.

MONITORING PROGRAM

The purpose of the monitoring program was to evaluate the driving forces controlling the sedimentation pattern in the vicinity of the navigation channel of the Damietta Harbour. The monitoring program spanned the period extending from May 1997 to December 1998. The monitoring area extends 8km along a portion of the shoreline hosted the harbour and approximately 17km offshore. The surveyed profiles are given numbers from 1 at the west to 46 at the east. Locations of various field activities are graphically symbolized in Figure 1B. Table 1 summarizes the overall monitoring program including time span and frequency of various activities.

A total of 46 beach profiles (up to 10m depth) and offshore profiles (up to 20m depth) are included in this study, and numbered consecutively from west to east in Figure 1B. They are connected to each other by a baseline fixed along the

Table 1. *Summary of field monitoring program at Damietta Harbour region spanned 20 months from May 1997 to December 1998.*

Field Activity	Frequency	Time Span
Beach profiles up to 6 m water depth	2	May/June 1997 and April/May 1998
Beach and profile sediment samples	2	May/June 1997 and April/May 1998
Offshore profiles up to 20 m water depth	1	May/June 1998
Waves and offshore currents	Continuous recording	1997 (January, August, October, November, December) and 1998 (May, June, July, August, September, October, December)
Current beyond breakwater zone	2	May/June 1997 to April/May 1998
Shoreline position survey	4	1992, 1997, 1998 and 1975
Longshore currents	Continuous	April 1997 to March 1998
Littoral drift using Fluorescent sand	2	September 1997 to March 1998

study area. The spacing between any two adjacent profiles varies from 50 to 250m depending on the nature of the coastline. Profiles of close intervals are concentrated on both the harbour breakwaters. The direction of the profile lines is more or less perpendicular to the coastline. The beach profiles are surveyed to a 10m water depth or to an offshore distance of 1000m from the fixed baseline. Soundings are taken every 10m from the baseline up to a distance of 250m seaward to precisely trace the details of the surf zone, and then every 50m up to 10m-water depth. The soundings and inland leveling of the profiles are surveyed with the use of an eco-sounder, total station, and graded staff and rubber boat. Soundings are corrected with respect to the mean sea level. These profiles were surveyed two times: May/June 1997 and April/May 1998.

A total of 125 bottom samples were collected using a grab sampler every 100m along selected 14 profile lines during the survey period of May 1998. Beach face samples were also collected at each of these profiles along the entire study area. In the laboratory, grain size analysis was made by standard ro-tap sieving system using whole phi sieve intervals. The mean grain size (Mz) for each sample was calculated using the formula of FOLK and WARD (1957). The resulted values of Mz in phi units are converted to millimeters according the phi transformation: Phi (ϕ) = $-\log_2$ (mm).

Fifteen of these beach profiles have been selected to extend offshore starting from the 4m depth up to 20m (Figure 1B). They are surveyed by the use of a combination of an echo-sounder and the positioning system "FALCON IV MINI-RANGER" utilizing a middle-size boat. Soundings were taken every 10m to a water depth of about 20m, that is equivalent to a distance of approximately 20km offshore. They are surveyed one time May/June 1998. In order to monitor bottom changes of the navigation channel, 69 profiles were also surveyed across the centerline of the navigation channel. They are 600m in length, 300m on each side from the centerline and the spacing between each two profile ranges from 200 to 400m. Soundings were taken every 10m utilizing the same equipment used in the offshore marine profile survey. The surveyed profiles are used to determine temporal and spatial changes in shoreline positions, seabed level and sediment volume. These changes have been interpreted in conjunction with the prevailing coastal processes measured at the study area.

Since surface water waves and associated currents are the primary agent for nearshore changes, a pressure S4DW wave/ current gauge was installed approximately 1200m at the western side of the navigation channel, *i.e.* about 12m water depth (Figure 1B). The wave gauge recorded the directional wave and current spectrum for 20 minute every 4 hours. In the laboratory, data are transferred to the PC computer and analyzed using dedicated software. Results of wave and current parameters are recorded at these periods 1997 (January, August, October, November, and December), and 1998 (May, June, July, August, September, October and December).

Magnitude and direction of the currents beyond the breaker zone were measured along the study hydrographic profiles at 200 meters intervals up to 8 meters water depth. At each station, three measurements were taken: near surface, at mid-depth and near bottom. The measurements have been taken simultaneously during the profile survey using the direct reading current meter (CM-2).

Daily longshore current velocity and direction have been measured at six stations, three at each side of the harbour channel, located at profiles number 2, 7, 10, 22, 26 and 29 (Figure 1B). Longshore current measurements were taken during the period from April 1997 to July 1998. Current measurements are obtained inside the surf zone, in a water depth ranging from 1.2 to 1.5m. Longshore currents are determined by following the movement of a float (buoy), and measuring the time it takes to travel a distance of 20m in the longshore direction. The direction of the current is determined, measurements are taken two times per day, once in the morning and again in the afternoon. Littoral drift was determined using the field and laboratory approach of INGLE (1966). Drift rates in the surface zone measured at 2 sites, at the western and eastern sides of the harbour (Figure 1B).

OBSERVATIONS AND INTERPRETATIONS

Wave Climate

Wave action along the Mediterranean coast of Egypt is seasonal in intensity and direction, and is strongly related to large-scale pressure system over the Mediterranean and the north Atlantic (NAFAA *et al.*, 1991). Monthly wave roses was depicted from the percentage of occurrence of wave height recorded during the recording period, 12 months included in 1997 and 1998. Owing to the space limitation of presenting the 12 monthly wave roses, the total average is depicted in

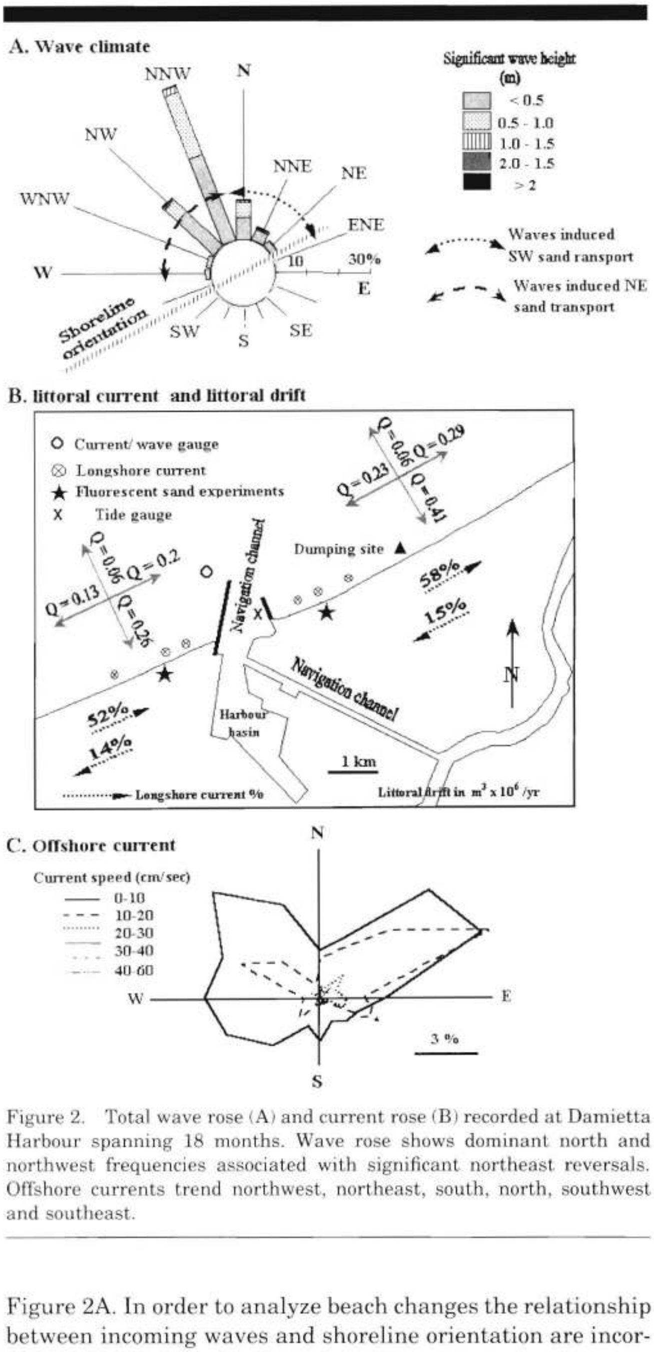

Figure 2. Total wave rose (A) and current rose (B) recorded at Damietta Harbour spanning 18 months. Wave rose shows dominant north and northwest frequencies associated with significant northeast reversals. Offshore currents trend northwest, northeast, south, north, southwest and southeast.

Figure 2A. In order to analyze beach changes the relationship between incoming waves and shoreline orientation are incorporated. Applying the approach of longshore energy flux, reported by KOMAR and INMAN (1970) and MANGOR (2001), the relationship between wave directional components and the present shoreline orientation, 65° to the north, wave exposures are constructed and presented schematically in Figure 2A. Two main wave groups are responsible for generating SE and NW sediment transport (see the two arches in Figure 2A). Accordingly, the predominant wave directions NNW, NW and WNW, totaling 69%, are responsible for the generation of longshore current towards the NE. The second group blown from N, NNE and NE, totaling 29%, generates a reverse longshore current towards the SW particularly during March and April (Figure 2A). The remaining small frequency (2%) represents calm conditions generally for waves approaching from land *i.e.,* from SW, S and SE quadrants. Maximum significant wave height recorded is 4.2 m approaching from the north direction and took place during January 1998. These extreme waves generated a strong bottom current of 140 cm/sec with a maximum peak period of 13 sec. On the whole, the average significant wave height and period are 0.51 m and 6.5 sec, respectively approaching from the northwest.

Longshore Currents

Longshore current data measured on both sides of the harbour breakwaters are subjected to statistical analysis to determine probability distribution of longshore currents. The results are very comparable to each other in their directions and speed. The predominant northeasterly average recorded at the western and eastern sides of the breakwaters is 52 and 58 %, respectively, whereas, currents towards the SW are 14 and 15 %, respectively, at the same sides (Figure 2B). On average the common NE longshore current occurs 55 % of the two measuring stations during the entire period except for January, October, December in which the current reverses to be from NE to SW being 15 %. The rest of the time is related to calm conditions, particularly in April and May and also to perpendicular current components. The reversed southwestward-directed currents are more important along the western flanks of the Rosetta and Damietta promontories, including the study area, due to the local southwest-northeast shoreline orientation, as reported by FANOS *et al.* (1991). This pattern of longshore current directions corresponds to the seasonality of wave action. The predominant wave approach from the NNW, NW and WNW is responsible for generating the north eastward-flowing longshore currents. The remaining portion of waves coming from the N, NNE and NE produces the reversed longshore currents toward the SW. The maximum speed recorded on both sides of the harbour are 57 and 42 cm/sec to the NE and the SW, respectively, with a corresponding average of about 35 and 30 cm/sec toward the NE and the SW, respectively. The opposing NE and SW longshore currents are largely responsible for transporting sediments from the eroded beaches at Burullus and Ras El Bar as well as from sediment dumped at the disposal site east of the harbour towards the harbour breakwaters (Figure 2B).

The study area lies within the eastern part of the Burullus sub-cell. FRIHY *et al.* (1991) and FRIHY and LOTFY (1997) have identified five self-contained sub-cells along the nearshore zone of the Nile delta based on the general erosion/accretion patterns, wave refraction pattern, multiple geomorphologic and petrologic indicators (Figure 3). These sub-cells are part of the regional Nile littoral cells extends from Alexandria to Akko on the northern part of Haifa Bay, Israel (INMAN and JENKINS, 1984). Each delta sub-cell contains a complete cycle of littoral transportation and sedimentation, including sources and sinks. Seasonal variability of wave approach produces converging and diverging current pattern along the delta coast. The principal sources of sediment for each littoral sub-cell are the eroded promontories that supply large quantities of sand. The eroded sand is transported

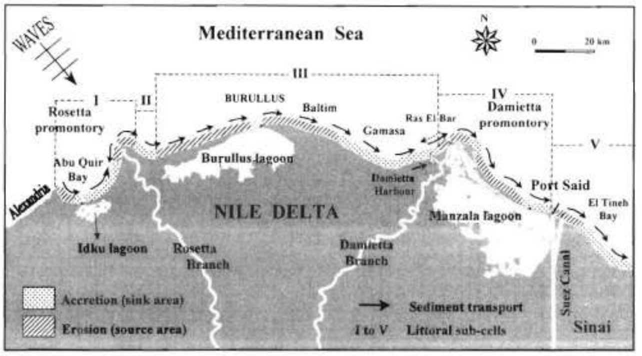

Figure 3. Map of the Nile delta showing the position of the five sub-cells identified by FRIHY *et al.* (1991 and 1997): I = Abu Quir sub-cells; II = Rosetta sub-cells; III = Burullus sub-cell; VI = Damietta sub-cell; and V = Port Said sub-cell.

along the coast by wave and currents until it is intercepted and terminated in the downcoast direction by adjacent sinks including promontory saddles, embayments and long breakwaters. Of particular importance to this study is the Burullus sub-cell, which consists mainly of the arcuate bulge of the central-delta region and part of the western flank of the Damietta promontory including Ras El Bar beach (Figure 3). In this sub-cell, sand eroded from the relict Burullus-Baltim promontory and coastal dunes is transported downcoast to the east and southwest, resulting in accretion along the Gamasa embayment, including the Damietta Harbour channel. For the most part, this sand is wave-driven by eastward littoral currents and currents generated by the east Mediterranean gyre which sweep across the inner shelf (INMAN and JENKINS, 1984). On the other hand, sand eroded from Ras El Bar beach is occasionally directed alongshore toward the west by current reversals.

Offshore Currents

The monthly current data recorded by the S4DW have been subjected to statistical analysis. The probability of a certain current velocity corresponds to a certain direction is determined and depicted as rose diagrams in Figure 2B.The number of occurrence of each velocity group is determined for the main 16 directions (each 22.5° interval). The majority of the current velocity ranges from 0 to 50 cm/sec. Maximum velocities of 140 cm/sec were recorded from a north/ north-east wind direction and corresponds to large waves with a significant height of 4.2 m in January 1998. In general, predominant currents near the bottom range from zero to 20cm/sec during the non-winter seasons.

The examined monthly current roses indicated that the major current components are directed towards east (6%), west (6%), north (4%), south (3%) and in the oblique-shore direction (northwest 24%, northeast 36% and southeast 9% southwest 12%). The remarkable wide fluctuation in offshore current direction and velocities reflect the potential variability of sediment movement back and forth across the navigation channel.

With regard to currents measured beyond breaker zone, the maximum measured current velocity is 12 cm/sec near the bottom. The vectorial distributions of the current data were depicted on maps to interpret their spatial patterns. From this distribution it was found that the spatial distribution of current patterns beyond the breaker zone of the harbour is mainly directed towards the shoreline. Average current components are directed towards the south (41%), southwest (23%), southeast (32%) and north (4%) directions. Locally and very close to the eastern breakwaters the current is reversed towards south east/ east sector forming a gyre and a rip current.

Littoral Drift

The sand movement in the alongshore direction is referred to as the longshore sediment transport, while actual volumes of sand involved in the transport are termed the littoral drift (Q). In this study, the rate of sediment transport was determined using fluorescent tracers and longshore current data. Locations of these activities are shown in Figure 1B. The total littoral drift in the surf zone measured by fluorescent tracers on the western and eastern sides of the harbour was found to be 0.65 and 0.99 × 10^6 m^3/yr, respectively (Figure 2B). The percentage occurrence of sediment transport components from different directions is listed in Table 2.

Littoral drift is also calculated from measurements of waves and longshore currents using KOMAR (1990):

$$Qs = 0.026\,(Hb)^2\,v \qquad (1)$$

Where, Qs is the volumetric sand-transport rate, Hb is the wave breaker height, and v is the longshore-current velocity. Applying this relationship using the available data, the calculated annual net littoral drifts on the western and eastern sides of the harbour breakwaters are 0.71 × 10^6 (0.37 × 10^6 to east and 0.10 × 10^6 to west) and 0.98 × 10^6 (0.57 × 10^6 to east and 0.15 × 10^6 to west), respectively. These values are comparable with the results obtained from the fluorescent approaches applied in this study.

Table 2. *Results of littoral drift rate (Q) using fluorescent sand tracers conducted on both sides of the Damietta harbour.*

	Annual Drift Rate Q × 10^6 m^3								
	W to E		E to W		To onshore		To offshore		
Location	%	Q	%	Q	%	Q	%	Q	Total × 10^6 m^3
1 km west of the Damietta Harbour	30.0	0.20	20.00	0.13	40.00	0.26	10.00	0.06	0.65
1 km east of the Damietta Harbour	29.41	0.29	23.53	0.23	41.18	0.41	5.90	0.06	0.99

Q = littoral drift, W = west, E = east.

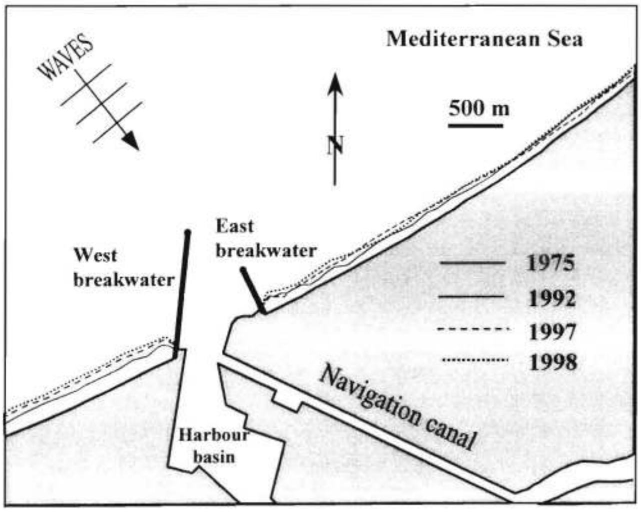

Figure 4. Change in shoreline positions along the Damietta Harbour coast for the years 1992, 1997 and 1998 and 1957.

Profile Analysis

Data obtained from the beach profiles up to 10m depth provide a database to determine; bathymetry, change in shoreline positions, change in seabed level and volumetric analyses. Comparison of these results during the study period from April 1997 to July 1998 has identified the erosion/accretion pattern along and across the monitoring area. Analysis of changes of shoreline positions shows accretion on both sides of the harbour breakwaters except close to the breakwaters where local erosion is taking place due to the vortex and induced rip currents (Figure 4). This shoreline accretion progressively decreases east and west from the harbour. Based on shoreline positions surveyed in June, 1975 and 1998, *i.e.* over 23 years, the estimated maximum rate of shoreline accretion on the western and eastern sides is about 6 and 5 m/yr, respectively. The opposing east and west sand accretion on the updrift beaches of the west and east breakwaters can be visually inferred from configuration of bottom contours lying *between zero (shoreline) and 5m water depth (Figure 5). Based on profile analysis discussed by FRIHY and KOMAR* (1993) the shoreline accretion along the Gamasa embayment including the Damietta Harbour changes to erosion at Burullus and Ras El Bart beaches (Figure 3).

Vertical Change in Seabed Elevation

The vertical changes of seabed relative to mean sea level (MSL) for the beach profile survey of 1997 and 1998 across the study area are shown in Figure 6. The computer-generated spatial interpolation of vertical change reveals areas of erosion and accretion. Generally, areas of erosion (0.0 to -2.5m) exist in front of the harbour site including the navigation channel between the 5-m and 7-m contours. Also, significant erosion (~ -0.5m) is locally observed to include the western flank of the Damietta promontory at Ras El Bar beach and the dumping area for dredged material (see Figure 1B). On the other hand, a broad zone of accretion (0.1 to 2.5m) exists alongshore and across the nearshore area up to 5m depth. The accumulation of these sediments in the proximity of the harbour is a result of sand transport from sediment eroded from areas on both sides of the harbour. The erosion pattern exists in the proximate of the navigation channel could be attributed to the frequent dredging activities in this

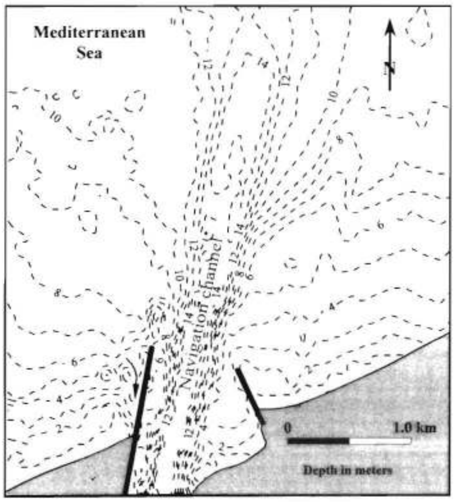

Figure 5. Vertical aerial photograph of Damietta Harbour acquired in June 1991, showing beach sand accumulation on both sides of the harbour breakwaters (arrows) and the local sand shoals accumulated on the updrift side of the west breakwater (asterisk). These sand accumulations indicate sediment transport convergence (Photograph courtesy of Dr. Mahmoud H. Ahmed).

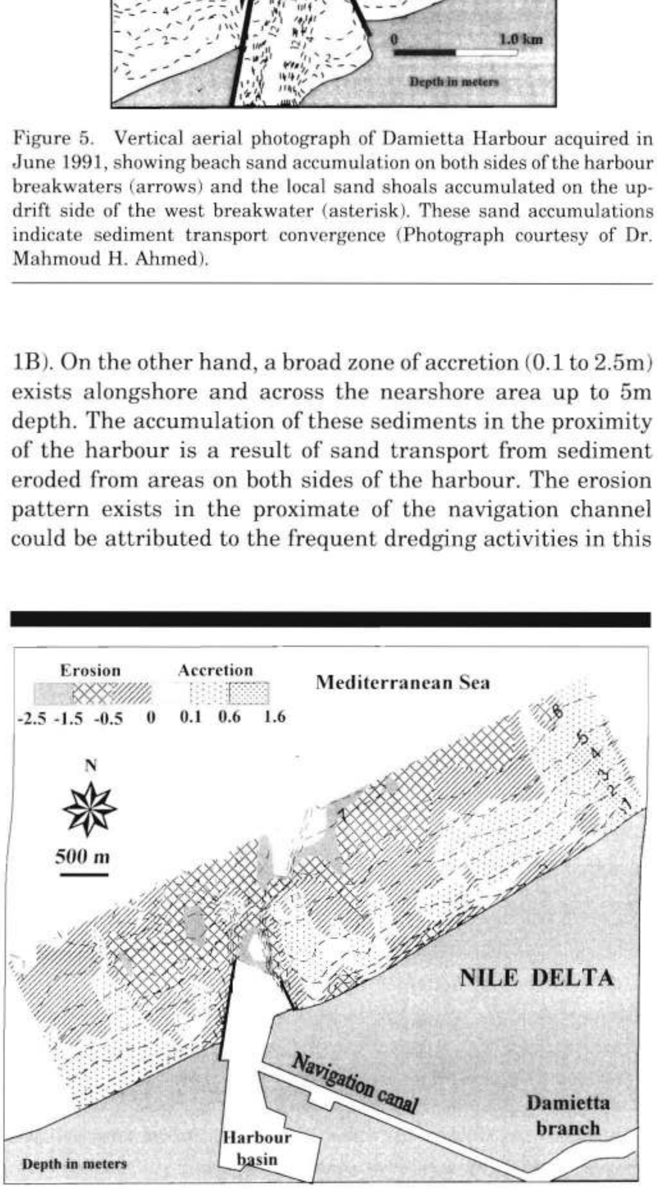

Figure 6. Patterns of erosion and deposition on the littoral zone of Damietta Harbour, as deduced from the vertical changes in the seabed between beach profile survey of 1997 and 1998, superimposed on 1998 bathymetry. Station positions are giver in figure 1B.

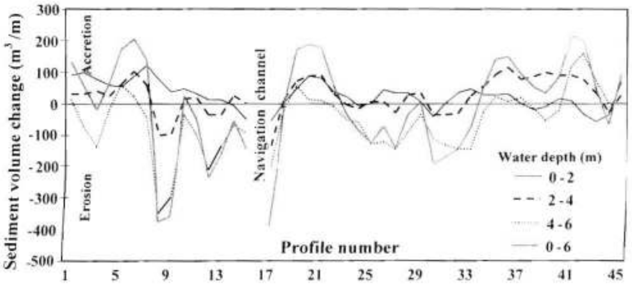

Figure 7. Distribution of volumetric changes of sediments along the coastline of Damietta Harbour for the systematic depth zones: 0–2, 2–4, 4–6 and 0–6 for the period from May/ June 1997 to May 1998.

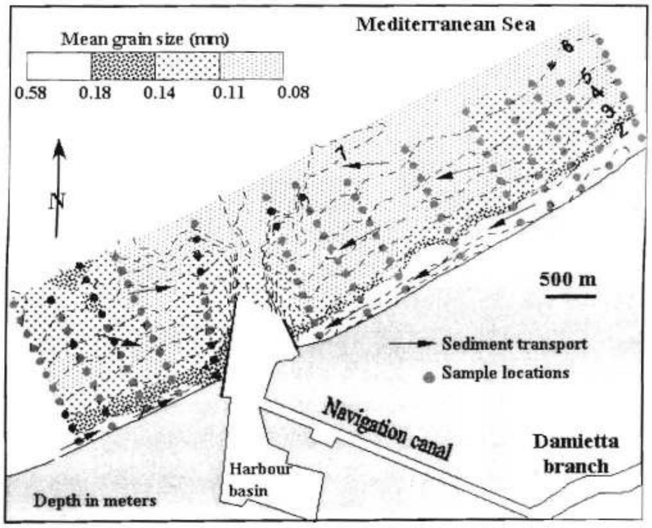

Figure 8. Spatial changes in mean grain size in millimeters for the beach and littoral zone superimposed on 1998 bathymetry. Finning trend displayed by means of arrows indicating downslope and opposing sediment transport.

region. The identified zones of erosion represent areas of sediment source, while zones of accretion act as a sediment sink. The systematic reversal from erosion to accretion may indicate that there has been a zone of opposing currents toward the harbour area.

Longshore Volumetric Change Distribution

Volumetric changes of sediments per linear meter (m^3/m) were determined for the beach profile survey along the entire length of the study area during May 1997 and May 1998. Figure 7 depicts the longshore volumetric changes during the monitoring survey period. The erosion accretion quantities were estimated within water depth zones: 0–2, 2–4, 4–6 and as a total 0–6m depth. Accretion dominates along the western and eastern harbour breakwaters for the depth zones from 0 to 2, 2 to 4 and 0 to 6m. Maximum accretion of these zones is 120, 115 and 220 m^3/m, respectively. On the other hand, volumetric loss of sediments occurs on the lower part of the beach profiles within the 4 to 6m water depths with a maximum of -360 m^3/m. This erosion is attributed to the potential activity of this zone as it lies within the wave breaking area. Significant local erosion, 390 m^3/m, also occurred to the immediate west and east of the breakwaters due to the formation of vortex and rip currents.

Grain Size of Beach and Nearshore Samples

The pattern of accretion on both sides of the harbour breakwaters is reflected on the grain size of beach sand. This accretion is associated with coarser-grained beach sediment (Mz = 0.17 to 0.33mm). The alongshore and cross-shore distribution of mean grain size show distinct variations in grain sizes (Figure 8). Medium and fine sand occur in the beach area (Mz = 0.14 to 0.58mm). Very fine sand and coarse silt cover the nearshore zone including the vicinity of the navigation channel (Mz = 0.08–0.11mm). The spatial distribution of mean grain size shows a general decrease seaward as well as in the longshore direction toward the vicinity of the harbour. Sediments are dispersed parallel to the isobaths due to down-slope movement and alongshore transport. Fine-grained sands (Mz = $<$0.12mm) floor the vicinity of the harbour areas, while relatively coarse-grained sand (Mz $>$ 0.12mm) astride the coastline. These grain size-fining trends provide some indications of sediment transport, with dispersal from the two erosion "source" areas located away on both sides of the harbour, the Burullus headland and Ras El Bar beach. The trends result from processes of selective grain sorting transport during the longshore and cross-shore movements of sand from eroding to accreting areas. Arrows in Figure 8 depict this sediment movement. The processes of grain-size sorting have been established by KOMAR and WANG (1984) and LI and KOMAR (1992) for beach sands on the Oregon and Washington coasts. Locally, FRIHY and KOMAR (1993) have derived a similar relationship for the beach sand of the Nile delta coast. In our case, the fine-grained sediment moves away to be deposited across the nearshore zone and within the navigation channel in particular, which acted as an effective trap for the predominantly NE and SW sand drift. The N-S orientation of the navigation channel interrupts sediment moving from the east or from the west, and acts as an offshore sink.

Depth of Closure

To answer the question of to what depth should the present breakwaters extend, the maximum water depth for significant surface water effects on the sand bottom has to be considered. This depth is an effective factor in planning and designing cross-shore breakwaters and stopping sand bypassing. Considering this depth, the breakwater would provide wave shelter with minimum effect as an obstruction to littoral processes (HALLERMEIER, 1981; STIVE *et al.*, 1991; DAVISON *et al.*, 1992). Earlier studies have indicated that the seaward depth limits of significant wave energy levels interact with a sand bed can be determined by using indirect indicators such as geometric analysis of bathymetric irregularities, distinct changes in petrology of sediments, faunal attributes

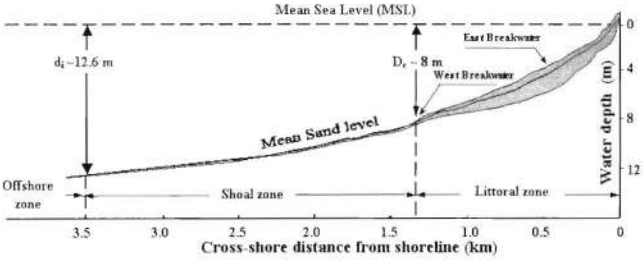

Figure 9. Schematic cross-shore diagram for profile no.18, showing the profile envelope and the estimated depth limits; D_c = closure depth and d_i = seaward limit of the shoal zone. Shown also the positions of the offshore tips of the existing breakwaters of the Damietta Harbour relative to water depth and seaward distance from the coastline.

of bottom sediments and geometry resulted from overlapping of repetitive beach-nearshore profiles (profile envelope) (HALLERMEIER, 1981).

On the other hand, HALLERMEIER (1981) defined two cross-shore zones on wave-dominated sand beaches: (1) the littoral zone which extends to "the seaward limit of intense bed activity caused by extreme near-breaking waves and breaker-related currents"; and (2) the shoal zone, an area where "waves have neither strong nor negligible effect on the sand bed." The boundary between the shoal zone and the littoral zone is d_1, while the seaward limit of the shoal zone is d_l (Figure 9). In practical terms, the observed depth of closure (D_c) which correspond to d_1, beyond which repetitive beach-nearshore profiles show negligible vertical change, can define a significant seaward limit of profile change (NICHOLLS *et al.*, 1998). In this study both the depth limits d_1 and *di* as well as the observed depth of closure (D_c) *are* estimated.

In this study an attempt was made to determine the depth limits and the width of the shoal zone. A profile envelope was constructed based on repeated beach-nearshore profiles surveyed by the Coastal Research Institute approximately on biannual basis since 1972 until now. Only profile no. 18 has been surveyed to 6–7m-water depth in the vicinity of Damietta Harbour. This profile is located 50m east of the east breakwater (Figure 1B). The data of this profile comprise sounding data of water depth (Y) relative to mean sea level (MSL) versus distance from the baseline (X). Unfortunately, the profile envelope resulted from the time series of this profile could not close the envelope at the seaward limit bounded the 6–7m depth (Figure 10). This indicates that the depth of closure D_c—or the seaward limit of significant profile change is deeper. Tentatively, an attempt is made to graphically extrapolate the actual closure depth using the profile envelope (Figure 9). The mean profiles within the littoral zone have a steep foreshore slope (1:50) up to the 10m depth and a gently offshore slope. A reasonable depth of closure of approximately 8m is resulted, corresponds to a distance of about 1.3km offshore. A comparable depth of closure value was obtained at Alexandria by EL RAEY *et al.* (1995).

Moreover, d_1 and d_i, were calculated using the equations of HALLERMEIER (1981).

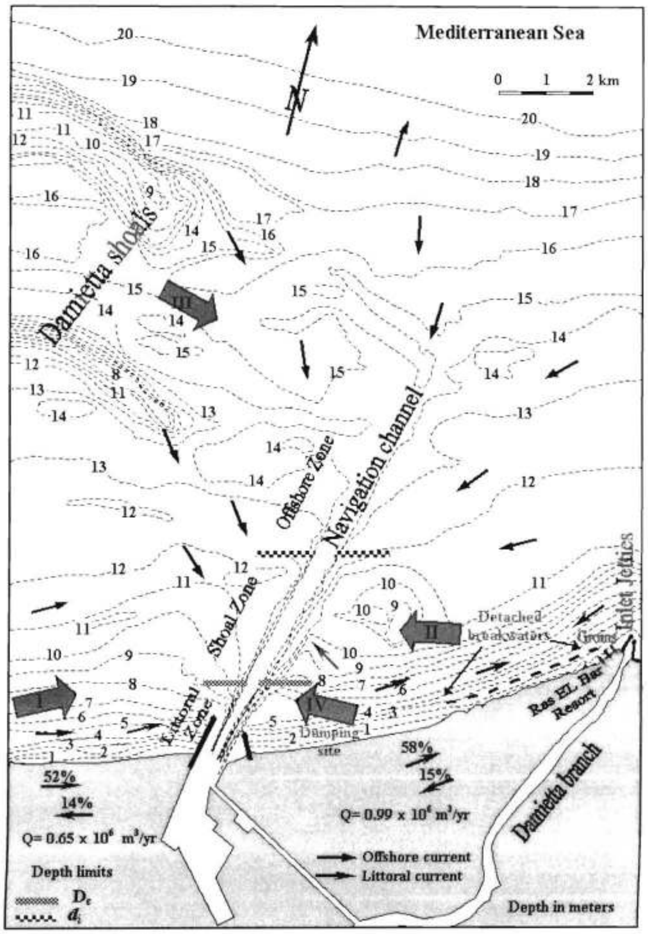

Figure 10. Schematic sediment transport model generalizing the 1998 bathymetric configuration and sand transport paths alongshore and off the Damietta Harbour region. Arrows depict sediment transport paths, within the littoral and inner continental shelf, involved in the sedimentation processes of the harbour channel. The general transport paths indicate that most of the harbour area is interpreted as a sediment sink. Large arrows depict sediment sources; I = Burullus beach; II = Ras El Bar beach III = relict Damietta shoals, and IV = dumped site. Dashed lines marked depth limits (closure depth D_c ~ 8 m and d_i ~12.6m) of which the original breakwaters might be extended.

$$d_1 = 2\bar{H}s + 11\sigma \tag{2}$$

$$d_i \cong (\bar{H}s - 0.3\sigma)\bar{T}s(g/5000D)^{0.5} \tag{3}$$

Where, $\bar{H}s$ is the mean significant wave height in deep water, σ is the standard deviation of the significant wave height, *Ts* is the mean wave period, D is the mean grain size, and g is the acceleration due to gravity. Summary statistics obtained from available wave data recorded by the S4*D*W wave-gauge in this study are used in calculating d_1 and d_i depths. Using Equations 2 and 3 and substituting the calculated average significant wave parameters (H_S = 1.5m, T_S = 6.5 sec, (σ = 0.172m),$\sigma$and a grain size of D = 0.11 mm, the depth of closure d_1 and d_i were calculated yielding 4.9 and 12.6m depth, respectively. These values are utilized to evaluate the capability of breakwaters to protect the harbour entrance from sedimentation. The observed depth of closure value D_c (~8m) is fairly reasonably than the estimated d_l (~4.9m) and d_i (~12.6m).

Using the resulted high-resolution bathymetry map of 1998 scaled 1:20000, it was found that the position of the calculated depth values of d_l (~4.9m) and di (~12.6m) correspond to an offshore distance of 1.3 and 4km, respectively (Figure 10). These positions yielding a shoal zone of about 2.5km wide. According to HALLERMEIER (1981) this zone considered as a buffer region wherein surface wave effects on the seabed are neither strong nor insignificant. Seaward of the shoal zone lies the offshore zone where surface effects on the seabed are usually negligible. According to this consideration, the original length of the east breakwater (500m) was extremely under estimated and consequently did not reach the closure depth (Figures 9 and 10). This situation provides a large window opened to receive sand approaching from the east during littoral current reversals and therefore it failed to stop the littoral sediment bypassing to the harbour channel. To mitigate this undesired sand bypassing the breakwater has to be extended to at least closure depth, safely to the Dc (~8m). Therefore, the east breakwater has to be extended to approximately 1.5km distance from the shore.

On the other hand, the west breakwater, 1500m long and reaching the 7m contour, was relatively short and has to be extended to about 1.7km to reached the estimated depth of closure Dc (~8m) (Figures 9 and 10). However and over time, this length might be not long enough to trap the continuos littoral drift prevailing from the east. As a proper mitigation, limited dredging might also be required to guarantee continued navigational access after extreme yearly wave condition and significant alongshore transport. A more costly alternative is to extend these breakwaters to a length corresponding to d_i (~12.6m) contour that corresponds to ~3.5km distance from the shoreline (Figure10). This will mitigate active sand bed during common median wave conditions and significant on/offshore transport by waves and no dredging should be required.

Sediment Transport Model

The bathymetric map constructed from the deep-water profiles surveyed in July 1998 is shown in Figure 10. Prominent morphologic features in the study area include a wide inner shelf area and the two ancient Damietta shoals. Sediment transport paths are schematically shown by arrows as interpreted from wave and current measurements, littoral drift, profile analysis and pattern of mean grain size of surficial sediments. A number of structures have been constructed along the shore of the Damietta promontory to protect the coast from erosion, and also to mitigate shoaling in navigation channel of the Nile branch. These structures include the three concrete groins built in 1971 and the eight detached breakwaters to protect the coastline of Ras El bar resort beach (Figure 10). The breakwater formation extending approximately 4.5km west of the harbour. They were built in stages from 1991 to 1999, and another series expected to be built to reach the harbour region. They were built in the active surfzone at a water depth between 3 to 4m. Each breakwater is about 200m long with an alongshore spacing of 200m. In addition two long breakwaters also were built to stabilize the mouth of the Damietta Nile branch and to reduce shoaling within the confines of the river mouth.

Our observations indicate that the harbour area lies within the eastern edge of Burullus embayment (Figures 3 and 10), which experience sediment transport convergence. This convergence is related to the interplay of configuration of shoreline, seafloor gradient, the existed north/south navigation channel, prevailing and local reversals of wave-induced littoral and offshore currents. In view of littoral currents, sand transport is directed toward the NE due to the prevailing wave approach from the NNW, NW, and WNW, but there are local reversals. This pattern of longshore transport is also confirmed by field evidence. The tombolos formed behind the newly built detached breakwater system (1991–1998) at Ras El Bar are nearly asymmetrical and show preferential direction of sediment transport to the east (Figure 10). In addition, the slight accumulation of sand on the both sides of the three groins constructed in 1971 east of the detached breakwaters indicate a net NE longshore transport with a slight SW reversal to the west. Sediments interact in the transport processes are mainly derived from the beaches located at west Damietta promontory (Ras El Bar) and Burullus-Baltim headland (Figures 3 and 10). Littoral currents rework and displace sediments of these two eroded zones primarily in directions away from the Damietta promontory and also away from the Burullus-Baltim headland. These protruded coastlines concentrate wave energy and thus are considered as pronounced divergent points as confirmed from the wave refraction patterns (QUELENNEC and MANOHAR, 1977). Along with these regional patterns the fine-grained sediments (~0.11mm) dredged from the channel and placed on the shoreface at 3km east of the harbour site must be considered. The southwesterly reversed longshore currents in part rework and move these sediment toward their original position along the navigation channel.

Acting parallel to longshore currents are the offshore currents. Offshore currents displace reworked shelf sediments flooring the study area including high-relief Damietta shoals toward the navigation channel. These shoals are part of the regional offshore west-east shoal system identified by MISDORP (1976). The two shoals displayed in Figure 10, form part of Gamasa bank system positioned west of the navigation channel. This system consists of three bank groups positioned offshore in front of the Rosetta promontory, Burullus headland and Gamasa. The formation of these shoals are related to the former Nile branches which flowed across the Nile delta and discharged into the Mediterranean at various times during the middle to late Holocene (TOUSSOUN, 1922; STANLEY and WARNE, 1993). During the past millennium, however, flow in most former Nile channels diminished, and only the Damietta and Rosetta branches are active at present (Figures 1 and 3). The Damietta shoals range from 5 to 15km long and 1.5 to 10km width. The top is flat and occurs in a shallow water depth ranging from 4m to 8m, while their edges are steep. These shoals are parallel to the coastline and separated by depressions. They are composed of semi-consolidated sand and mud deposits.

Although these relict shoals have a much greater resistance to erosion than the recent sediments, they show erosional features. Based of comparison of the recent bathymetric survey of 1989 and the old one made by the British Admiralty in 1919, the edges of these shoals display erosive sediment loss particularly at the south and southeast edges. In view of this consideration, the relict bank sediments can be interpreted as a primarily depositional source nourishing the downslope inner shelf area containing the navigation channel. The elevated shoals are acting as a sediment source, explaining why the outer part of the navigation channel is experiencing sedimentation by fine-grained sand and silt. During storms, extreme waves and currents carry some of these sediments into the landward direction. Our observations suggest that seafloor sediments are being deposited toward the area of the Damietta Harbour channel, by alongshore and offshore currents, which herein can thus be interpreted as a sediment trap, and even further to the north on to the adjacent shelf (Figure 10). This transport correlates in part with bathymetry of the seafloor, where both the littoral area, up to 9m depth, and the Damietta bank shoals are systematically sloping toward the broad flat shelf area hosting the navigation channel of the Damietta Harbour. This indicates that the harbour channel area appears to act as a zone of convergence resulting from the opposing littoral and offshore bottom currents, *i.e.*, flow from the southwest and northeast. Subsequently, the opposing current produces bottom sedimentation in the harbour channel and on the updrift beaches of the breakwaters.

SUMMARY AND CONCLUSIONS

An intensive marine monitoring program was carried out to evaluate the sedimentation problem of the navigation channel at Damietta Harbour, which is located on the northeastern sector of the Nile delta. This program spanned 20-months and includes; beach and offshore profiles, measurements of waves, littoral and offshore currents, littoral drift, water level variation and sediment characteristics of beach and surface bottom sediments. Results of the monitoring activities indicate that the processes of sedimentation are mainly controlled by waves, currents, orientation and shape of the shoreline, seabed morphology and grain-size sorting processes. Meanwhile, the existing western and eastern breakwaters failed to prevent sand bypassing into the channel due to their short length. Moreover, and in view of impact mitigation, the rate of long-term dredged sediment for the period from 1986 to 1994 was much higher than expected in the design (1.18×10^6 m^3 /year). In addition, the navigation channel and its adjacent shelf, 20km length and 15m water depth, are acting effectively as a sediment sink for sediments supplied from different directions.

Waves approach the coast from the northwest quadrant, commonly dominated from north-northwest direction induced longshore sediment transport to the northeast, whereas, waves from the northeast sector generates a reverse longshore current towards the southwest. Both the opposing northeasterly and southwesterly paths produce sand accumulation in the littoral zone fronting the Damietta Harbour. Offshore currents vary considerably from month to month. They are flowing towards the east, west, north, northwest, northeast, southeast, with diverse velocities that ranges from 10cm/sec to 50 cm/sec. Wave-driven currents are responsible to accumulate large portion of sediment in the inner shelf off the study area and subsequently negatively affecting the outer part of the harbour channel. The principal sources of sediment contributed to the processes of sedimentation of the harbour are the eroded Burullus and Ras El Bar beaches and the submerged Demitted shoals. These sediment sources supply large quantities of fine-grained sand ($Mz \sim 0.11mm$) to the downcoast sink area of Gamasa embayment, including the navigation channel, directions parallel to contour and also seaward by cross-shelf, down-slope dispersal. These sediment sources concentrate wave energy and thus act as a divergence point. On opposite, the rest of the nearshore and the inner shelf areas, including the navigation channel, behave as a sediment trap.

Unfortunately, the selection of the harbour site did not considered that the harbour is located on the edge of a sediment sink (*i.e.*, convergence area). The lesson learned from this case study is to avoid implementation of new harbours in areas of converging sediment transport particularly in the case of an active surfzone enriched in fine-grained sediment. Although if it is necessary, adequate mitigation should be considered properly including optimum breakwater length to combat any undesirable channel sedimentation with limited dredging. In view of the determined depth limits and the compartmentalized sedimentation system of the coastline hosting Damietta Harbour, the original harbour breakwaters, were not long enough to stop sand bypassing from different directions. Therefore, an additional extension to the existing breakwaters into deeper water that incorporated minimum sediment movement might mitigate the problem of sedimentation of the navigation channel. In view of the estimated closure depth, the west and east breakwaters have to be extended respectively, 1.7 and 1.5km offshore to reach 8m depth of closure, *i.e.* a water depth of little sediment transport. Another lesson is that the selection of the dumping site for dredged material, ~3km east of the harbour site did not consider the southwesterly reversal in the longshore current in this region. These reversed currents in part rework and disperse the dumped sediments for dredging material once again to the navigation channel. This situation has set off a chain reaction that results in a requirement that the dumping site need to be relocated, probably to nourish starving beaches east of the Damietta river mouth. In addition, an optimization analysis is needed considering three variables, the length of the breakwater, the volume of periodic dredging material and the water depth of the navigation channel. Simply, this mathematical analysis should determine the shorter length of breakwaters that would minimize the amount of dredging, which in turn could keep the navigation channel considerably deep for safe navigation with minimum dredging. The case discussed here highlights the necessity for carrying out an EIA study before implementing a harbour project. Understanding of marine processes is necessary to assure a successful project with limited negative impacts on the navigation channel and the surrounding environment.

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LITERATURE CITED

ALIOTTA, S. and PERILLO, G., 1987. A sand wave field in the entrance to Bahia Blanca Estuary, Argentina. *Marine Geology,* 70, 1–14.

ANONYMOUS. 1998. Sedimentation problems of Damietta harbour navigation channel. *Technical Progress Report, Coastal Research Institute,* 35 p.

BEHRENS, E. W., 1981. A large-scale intracoastal circulation pattern affecting estuarine-continental-shelf exchange. *Marine Geology,* 40, 15–25.

DAVISON, A.T.; NICHOLLS, R.J., and LETHERMAN, S.P., 1992. Beach nourishment as a coastal management tool: An annotated bibliography on developments associated with the artificial nourishment of beaches. *Journal of Coastal Research,* 8, 984–10022.

EL RAEY, M.; NASR, S.; FRIHY, O.; DESOUKI, S., and DEWIDAR, KH., 1995. Potential impacts of Accelerated sea-level rise on Alexandria Governorate, Egypt. *Journal of Coastal Research,* USA, Special issue No.14, 190–204.

FANOS, A.M..; FRIHY, O.E.; KHAFAGY, A.A., and KOMAR, P.D., 1991. Processes of shoreline changes along the Nile delta coast of Egypt. *Coastal Sediments'91 Conference,* Washington, 2,1547–1557.

FANOS, A.M.; KHAFAGY A.A., and DEAN, R.G., 1995. Protective works on the Nile delta coast. *Journal of Coastal Research,* 11, 516–528.

FOLK, R.L. and WARD, W.F., 1957. Brazos river bar: a study in the significance of grain size parameters. *Journal of Sedimentary Petrology,* 27, 3–27.

FRIHY, O.E.; FANOS, M.A.; KHAFAGY, A.A., and KOMAR, P.D., 1991. Nearshore sediment transport patterns along the Nile Delta Egypt. *Journal of Coastal Engineering,* 15, 409–429.

FRIHY, O.E. and KOMAR, P.D. 1993. Long-term shoreline changes and the concentration of heavy minerals in beach sands of the Nile delta, Egypt. *Marine Geology,* 115, 253–261.

FRIHY, O.E. and LOTFY, M.F., 1997. Shoreline change and beach-sand sorting along the northern Sinai coast of Egypt. *Geo-marine Letters,* 17, 140–146.

HALLERMEIER, R.J., 1981. A profile zonation for seasonal sand beaches from wave climate, *Coastal Engineering,* 4, 253–277.

HARRIS, F.R.Inc., 1979. Master planning and infrastructures development for the Port of Damietta. Consulting Report to Ministry of Reconstruction and new Communities, Cairo, Egypt, 221p.

INGLE, JR. J.C. 1966. The movement of beach sand. *Developments in Sedimentology,* series 5, New York: Elsevier, 221 p.

INMAN, D.L. and JENKINS, S.A., 1984. *The Nile littoral cell and man's impact on the coastal zone of the southeastern Mediterranean.* Scripps Institution of Oceanography, Reference Series 84-31, University of California, La Jolla, 43p.

JEROME, P. Y.; SANFORD, L., and HALKA J. P., 1998. Sediment resuspension characteristics in Baltimore Harbor, Maryland, *Marine Geology,* 146, 137–145

KOMAR, P.D., 1990. Littoral sediment transport. *Hand Book of Coastal and Ocean Engineering,* HERBICH, J.B. (Editor), 2, 681–715.

KOMAR, P.D. and INMAN, D.L., 1970. Longshore sand transport on beaches. *Journal of Geophysical Research,* 75, 5914–5927.

KOMAR, P.D. and WANG, C., 1984. Processes of selective grain transport and the formation of placers on beaches. *Journal of Geology,* 92, 647–655.

LI, M.Z. and KOMAR, P.D., 1992. Longshore grain sorting and beach placer formation adjacent to the Columbia River. *Journal of Sedimentary Petrology,* 62, 429–441.

MISDORP, R., 1976. The Nile promontories and the Nile continental shelf. *Proceedings of Seminar on Nile Delta Coastal Processes,* Alexandria, Egypt, 456–551.

NAFAA, M.G.; FANOS, A.M., and EL GANAINY, M.A., 1991.Characteristics of waves off the Mediterranean coast of Egypt. *Journal of Coastal Research,* 30:25–34.

NICHOLLS, R.J.; BIRKEMEIER, W.A., and LEE, G., 1998. Evaluation of depth of closure using data from Duck, NC, USA, *Marine Geology* 148, 179–201.

PERILLO, G. and GUADRADO, G., 1991. Geomorphologic evolution of El Toro Channel, Bahia Balanca Estuary (Argentina) prior to dredging. *Marine Geology,* 97, 405–412.

QUELENNEC, R.E. and MANOHAR, M., 1977. Numerical wave refraction and computer estimation of littoral drift; application to the Nile delta coast. *In: UNDP/ UNESCO Proc. Seminar Nile Delta Sedimentology.* Alexandria, Egypt, pp.191–204.

SHEFFIELD, A.T.; HEALY, T.R., and MCGLONE, M.S., 1995. Infilling rates of a Steepland catchment estuary, Whangamata, New Zealand. *Journal of Coastal Research,* 4,1294–1308.

STANLEY, D.J. and WARNE, A.G., 1993. Nile delta: Recent geological evolution and human impact. *Science,* 260, 628–634.

STIVE, M.J.F.; NICHOLLS, R.J., and DEVRIEND, H.J., 1991. Sea-level rise and shore nourishment: a discussion. *Coastal Engineering,* 16, 147–163.

TOUSSOUN, O., 1922. *Mémoires sur les anciennes branches du Nil, Epoque Ancienne.* Mém. Inst. Egypt, 4, 212p.

UNDP/UNESCO, 1978. *Coastal protection studies. Final Technical Report,* Paris, 1, 155p.