

EDDY CURRENTS AND SEDIMENT TRANSPORT OFF THE DAMIETTA NILE

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Abstract

Current meter observations indicate that a trapped eddy with a high-speed outer limb is formed downcurrent of the Damietta Nile promontory. This eddy is instrumental in the formation of the highly mobile sand body that extends seaward from the Damietta mouth, out onto the shelf, and curves back toward the coast just east of the Suez Canal entrance. Orientation of sand waves along the sand belt mirrors the direction of current flow within the eddy and indicates that the zone of reattachment of the separation streamline is located to the east of the Suez Canal. Dissipation of this sand belt will likely result in increased coastal erosion locally.

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Introduction

Between September 1964 and October 1966 the monthly discharge from the Nile River decreased by an order of magnitude, from $1.9 \times 10^{10} \text{ m}^3/\text{month}$ to $4 \times 10^9 \text{ m}^3/\text{month}$, as a result of the closure of the High Dam at Aswan. The corresponding decrease in sediment brought to the coast resulted in the marked acceleration of an already serious coastal erosion problem and the transition of the inner shelf from one dominated by riverine processes to one dominated by marine processes, i.e., waves and currents. The resulting erosion problems along the entire coast fronting the Nile Delta have been the subject of exhaustive studies originally sponsored by the United Nations and continued under the auspices of the Academy of Scientific Research and Technology (ASRT), Cairo. For extensive summaries see UNDP (1976, 1977). These studies emphasized changes in beach morphology as an indication of coastal retreat and relied heavily on large-scale oceanographic cruises (e.g., Summerhayes and Marks, 1976) and reinterpretation of earlier shelf sediment surveys (Misdorp and Sestini, 1976) for knowledge of sedimentation on the adjacent shelf.

Because of wartime conditions, access to the shelf by the U.N. project was greatly restricted, and, according to Nielsen (1977), essentially prohibited east of the Damietta promontory. Accordingly, the start of a joint United States-Egyptian bathymetric resurvey in 1978 of the continental shelf from Damietta eastward past Port Said, at the Suez Canal entrance (Fig. 1), presented an excellent opportunity to further our understanding of the physical processes and sediment transport active in this area. A combined team from the Coastal Studies Institute and the Institute of Oceanography and Fisheries, ASRT, Cairo, was provided space and logistical support on the survey ship U.S.N.S. Harkness to carry out scientific studies of the currents and bottom sediment behavior. The most conspicuous geomorphic features along the coast of the delta are the large promontories or cusped capes at the mouths of both the Rosetta and the Damietta branches. As earlier work (e.g., Murray and Wiseman, 1976) had documented the intermittent presence of a large eddy downstream (west) of the Mississippi delta promontory, it was suspected that the Nile capes might also exert a significant influence on the local current field. A similar suspicion was voiced by Misdorp (1977) to explain the sand distribution east of the Damietta promontory. Thus current observations were concentrated immediately downcurrent or eastward of the Damietta promontory.

In this report we shall emphasize the results of the current studies and the interaction of currents with the bottom. A brief review of physical processes in the local area will be followed by a discussion of the current velocities, temperatures, and salinities obtained during our measurement program. The current velocity field will be shown to have a highly coherent spatial structure intimately related to the geometry of the Damietta promontory. A composite model of the current field constructed from theoretical, experimental, and numerical studies will then be compared to both the observed current field and the observed patterns of sediment movement. The presence of a mesoscale eddy trapped in the lee of the Damietta promontory and its strong control on bottom sediment transport is established, and its implications on the future of the coast between Damietta and Port Said are discussed.

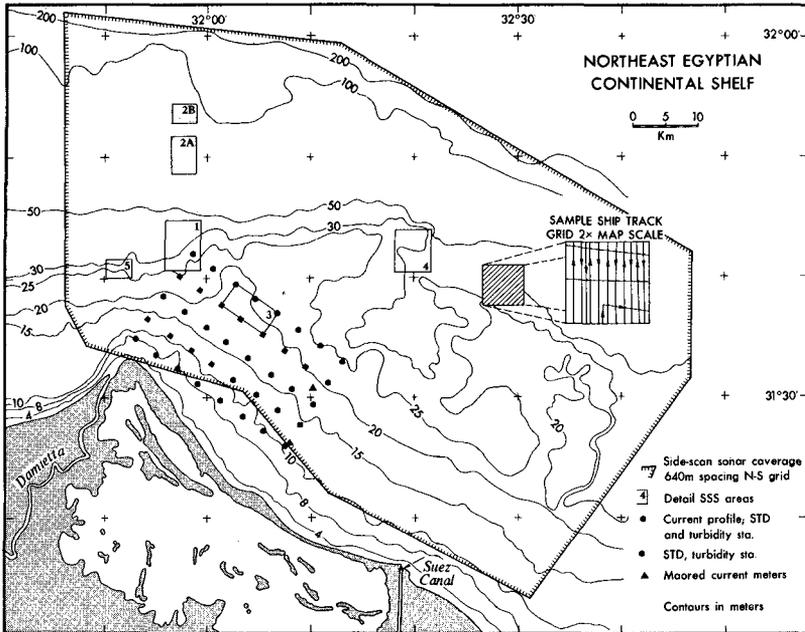


Figure 1. Location map of study area off the Damietta branch of the Nile River. The inset shows a survey grid typical of those carried out over the entire area.

Background Processes

The average properties of winds and currents are obtained from the data archived at the U.S. National Oceanographic Data Center (Fig. 2). A good correlation is clearly seen between the wind direction and the current direction. The modal wind direction is clearly to the southeast from May through October. A strong secondary peak of winds blowing toward the northeast is present from December through March. Both of these winds, with east-going components, can be seen to produce east-flowing currents in the Damietta-Port Said area. Other peaks of wind direction, to the southwest in April-May and October-November, are seen to reverse the dominant current drift to the east and drive the surface currents westerly. Representative background current speeds from this data set are seen to be 15-20 cm/sec.

Direct observations of currents along the Nile Delta coast are discussed in Manohar (1976); Manohar et al. (1977); and Tebelius (1977). Unfortunately, again for security reasons, these measurements were

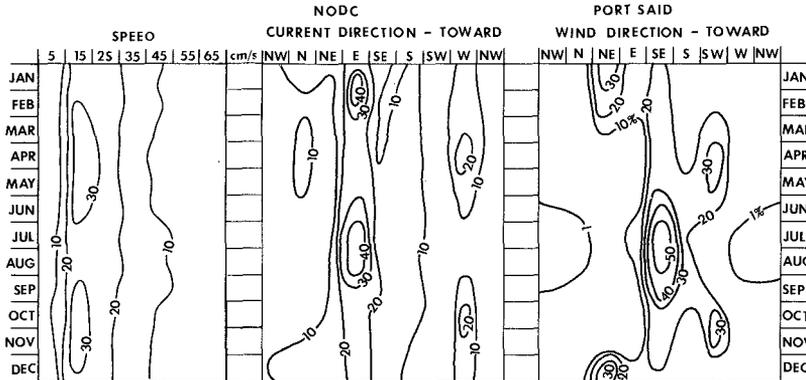


Figure 2. Percentage distribution of current speed and current direction throughout the year for the Port Said 1°-square from NODC data. Percentage distribution of wind direction throughout the year at Port Said from the Sailing Directions.

restricted largely to the surf zone. Manohar (1976) did show current speeds up to 600 m from shoreline in water depths of 2-4 m to reach 30-40 cm/sec, but he noted that these data were as yet unanalyzed. Tebelius (1977) presents a discussion of a current measurement program in Abu Quir Bay, near the mouth of the Rosetta Nile, but, as with Manohar's data, these results do not apply to the inner shelf (10-30 km offshore), which is the focus of this paper.

Perhaps the best source of modern data on the background drift current along the Egyptian Mediterranean coast is Gerges (1978). Analysis of the return data from Woodhead surface drifters released monthly for 18 months in 1976 and 1977 (total of 2,664 drifters) indicated a general easterly drift of 10-15 cm/sec. The May 1977 drifter returns clearly showed the intermittent westerly setting current reversal suggested in Figure 2.

Physical Oceanographic Measurements

Data were collected through the 40-station grid along lines normal to the coast (034° M), moving west to east (Fig. 1). Current meter profiles requiring an anchor station were restricted to the outer, middle, and inner stations on each line; all stations also included a vertical profile of salinity, temperature, and turbidity. Thirty-eight of the forty stations were occupied in the 6-day interval 29 April - 4 May 1978, during which period winds always had onshore components blowing from NNW to NE at 5-10 m/sec.

The current meter profiles at the anchor stations which are of principal interest here were taken from a 12-m-long LCVP, which, while open and rough-riding, proved to be an excellent vehicle for the current studies. Even in light winds the boat swing at anchor was minimal, and good current

data were the rule. The current meter used was a Marine Advisors Q-15 ducted impeller meter with a bidirectional sensing capability designed to mechanically and electronically filter out "noisy" wave motion. A Plessey STD Model 9060 gave in situ measurements of salinity and temperature with a 20-40 ppt salinity range. Wind velocities were measured on the Harkness and LCVF, but the most reliable data were obtained from the Suez Canal Research Center at Port Said.

In addition to the spatial coverage of the current field provided by the anchor stations, two current meter moorings equipped with acoustic releases were installed at the eastern end of the grid, as shown in Figure 1. Each mooring had two Marine Advisors Q series meters in line which had the same response characteristics as the Q-15 profiling meter described above.

Station data. The complete data set on the current field obtained from the anchor stations is presented in Figure 3. Stations on the western most line (1-5) reflect the expected background easterly drift current, but note the unexpectedly strong (~30 cm/sec) surface layer currents at the outer two stations (1 and 3). Also note the sharp deceleration in current speed from station 5 to station 6, which were taken within 1 hour of each other at a time of steady northerly winds. On the following day (30 April) stations 10 and 11, only 4 km apart and taken within 90 minutes of each other, show extreme horizontal current shear. Station 11 is particularly remarkable; speeds of 40 cm/sec throughout the water column from the surface to the bottom were directed seaward essentially against a weak north-northeasterly wind of 2-3 m/sec on that day. It appears likely from the stations that this seaward-directed high-speed zone is only 1-2 grid units (4-8 km) across.

Four stations on the middle and inner lines (13, 15, 16, 18) were next occupied, on 1 May. All four showed a westerly directed current of 10-15 cm/sec against the regional drift, which cannot be accounted for by the weak winds of that day. Clearly a convergence or zone of stagnation exists in the area between stations 6-8 and 13-15. On 2 May the apparently narrow jet of seaward-directed high speeds was again penetrated by stations 21 and 23. It was extraordinary to note the entire water column moving seaward at speeds in excess of 50 cm/sec. The great difference in speed and direction between stations 20 and 21 and between 23 and 25, each taken within 90 minutes of the other, strongly indicate a relatively narrow, highly coherent local circulation system. It appears that the high-speed zone had migrated from the vicinity of station 11 on 30 April, easterly to the vicinity of station 21, 2 days later, on 2 May.

The remaining stations, all located outside the zone of strong seaward flow, must be examined carefully for wind-driven effects in the surface and mid-depth layers. For example, at the shallow nearshore stations (e.g., stations 26, 35) and at deeper stations outside the high-velocity jet, where the speeds are generally lower (e.g., stations 30, 31), the onshore surface layer currents clearly result from local wind driving. In contrast, the remarkably strong seaward motion near the bottom, directed toward the high-speed zone at stations 28 and 33 and again at 26 and 35, indicates that the forces driving the circulation pattern are barotropic, i.e., they extend throughout the water column down to the bottom, where

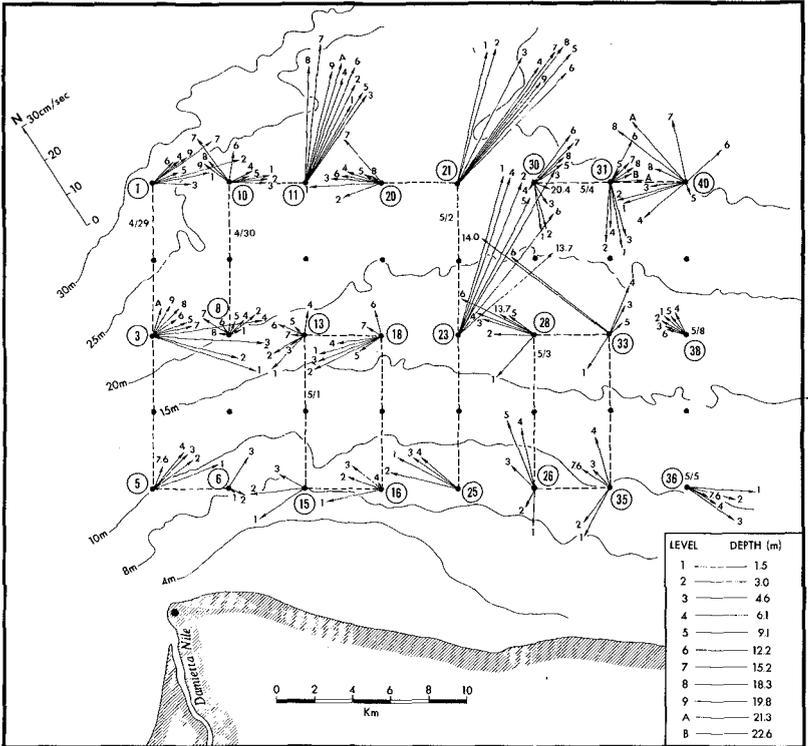


Figure 3. Vertical profiles of current velocity at each grid anchor station. Depth of observation is coded by a level number or letter except where actual depth is stated in metres. Stations occupied on same day are connected by a dashed line.

they overpower the frictional forces associated with wind driving.

Salinity, temperature, and velocity cross sections. Considerable insight into the spatial pattern of the flow field is also obtained by inspecting hydrographic sections. Two offshore lines that were completely covered in 1 day are shown in Figures 4 and 5, the westernmost section off the Damietta promontory and the central section through the core of the offshore jet, respectively. In the Damietta section (Fig. 4A) the along-shore speed component (parallel to the grid) shows a distinct offshore jet with a surface maximum of 25-30 cm/sec located 15 km offshore. Alongshore speeds decrease monotonically with depth. The cross-shore speed component is directed onshore (negative values) only in a shallow near-surface prism in the center of the section. The bulk of the section has offshore components reflecting the shunting of the background flow seaward by the curvature of the Damietta promontory. The salinity values of about 38 ppt are typical of the eastern Mediterranean but are interesting in that they still reflect coastal drainage by slight increases of a few tenths parts

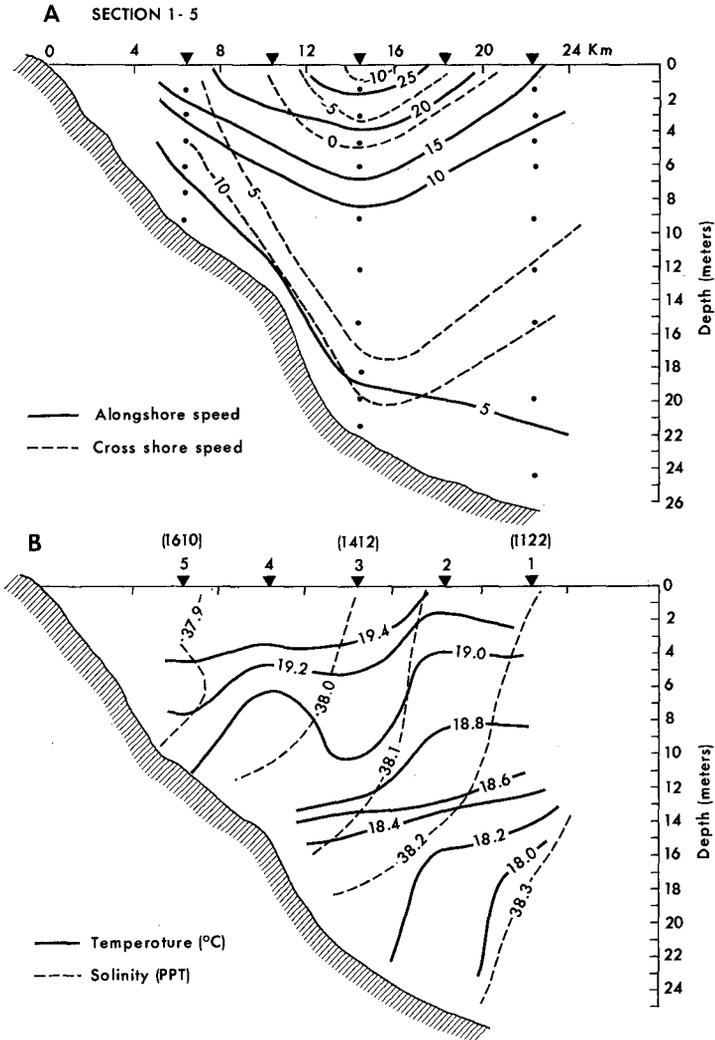


Figure 4. A, alongshore and cross-shore current speed components and, B, salinity and temperature distribution along the cross-shore line through stations 1-5 on 29 April 1978. Cross-shore speeds are positive offshore; alongshore speeds are positive downdrift or to the southeast. Time station was occupied is given above station number.

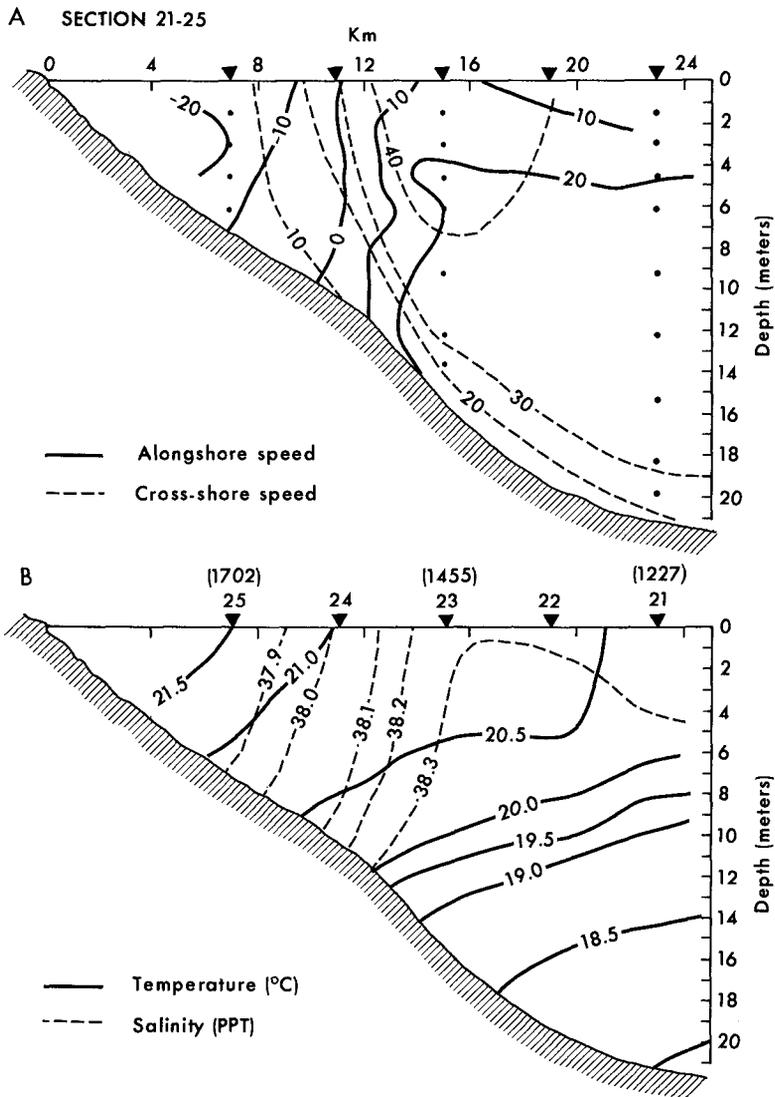


Figure 5. Same as Figure 4 except stations 21-25 on 2 May 1978.

per thousand both with depth and in the offshore direction. The temperature distribution in Figure 4B shows a thermocline at the 12-14-m depth.

Only 3 days later the section through stations 21-25 (Fig. 5), taken 16 km downcurrent (southeast), is in marked contrast to the picture along the Damietta line (Fig. 4). Here the cross-shore speed is the dominant component, showing offshore (positive) values across the entire section, with a maximum of over 40 cm/sec located 16 km offshore. Continuity, of course, demands an inflow somewhere to supply the volume transported offshore in this jet. Equally instructive is the alongshore speed component. Seaward of station 24 (11 km offshore) the flow is entirely downcurrent or southeasterly, while shoreward of this mark the flow is entirely upcurrent or northwesterly. Here, then, is the inshore return flow to resupply the jet. The water temperatures here (Fig. 5B) are consistently higher, by as much as 1-2°C, than in the Damietta section, nicely reflecting the inshore origin of the jet water. The salinities, however, remain a puzzle, requiring further analysis to understand why high salinities (38.2-38.3) characterize the warm offshore jet.

Combining knowledge of the background drift current from the literature with our own current observations (Figs. 3, 4, 5), we can infer a streamline pattern for the flow field around the Damietta promontory, excluding wind effects on the surface layer, as shown in Figure 6. The easterly background longshore flow of 15-20 cm/sec is shunted seaward by

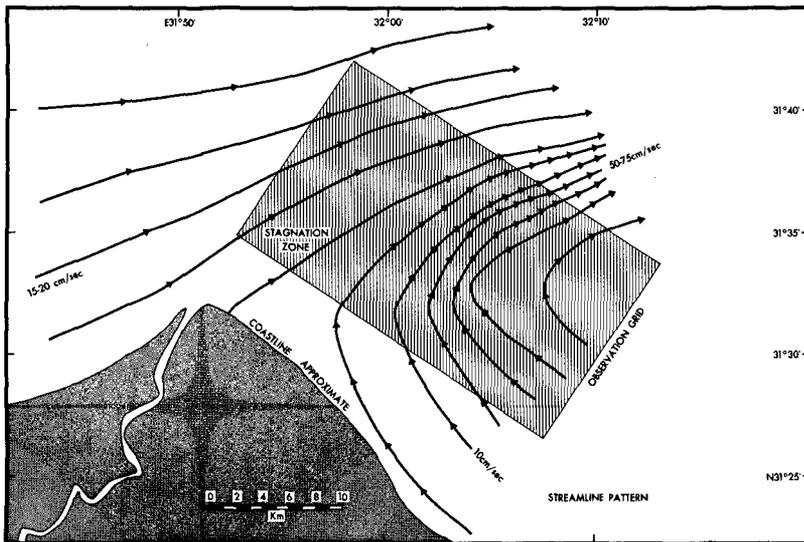


Figure 6. Streamline pattern interpreted from interior layer currents shown on Figure 3. Note narrow zone of high speed exiting seaward edge of grid.

the curvature of the Damietta promontory. Flow separation takes place several kilometres downstream (eastward) of the river mouth and induces a seaward-flowing high-speed jet as the northern limb of a topographically trapped eddy. A broad, slow northwesterly return flow forms as the southern limb of the eddy. The separation streamline must, of course, return to the coast somewhere downstream and form another stagnation zone of divergent currents flowing westward to feed the eddy and eastward to reestablish the background drift current.

A laboratory visualization (Prandtl and Tietjens, 1957) of the type of eddy we believe forms in the lee of the Damietta promontory is shown in Figure 7. The upward (seaward) shunting of the background flow, the high-speed jet, and the inshore return flow are all present, but of course we expect the natural scale eddy to be more elongate alongshore and diffuse due to the gentler angles involved.

Moored current meters. Figure 8 is an example of the current meter data obtained from the outer mooring (Fig. 1). The temporal behavior of the current velocities at these two levels are consistent with the interpretation of the current structure based on the station data. Note that between 27 April and 1 May the upper level currents are generally weaker than the deep currents, except for two short-lived events apparently asso-



Figure 7. Eddy trapped behind tapered edge. (Reproduced from Prandtl and Tietjens, 1957, with permission of Dover Publications.)

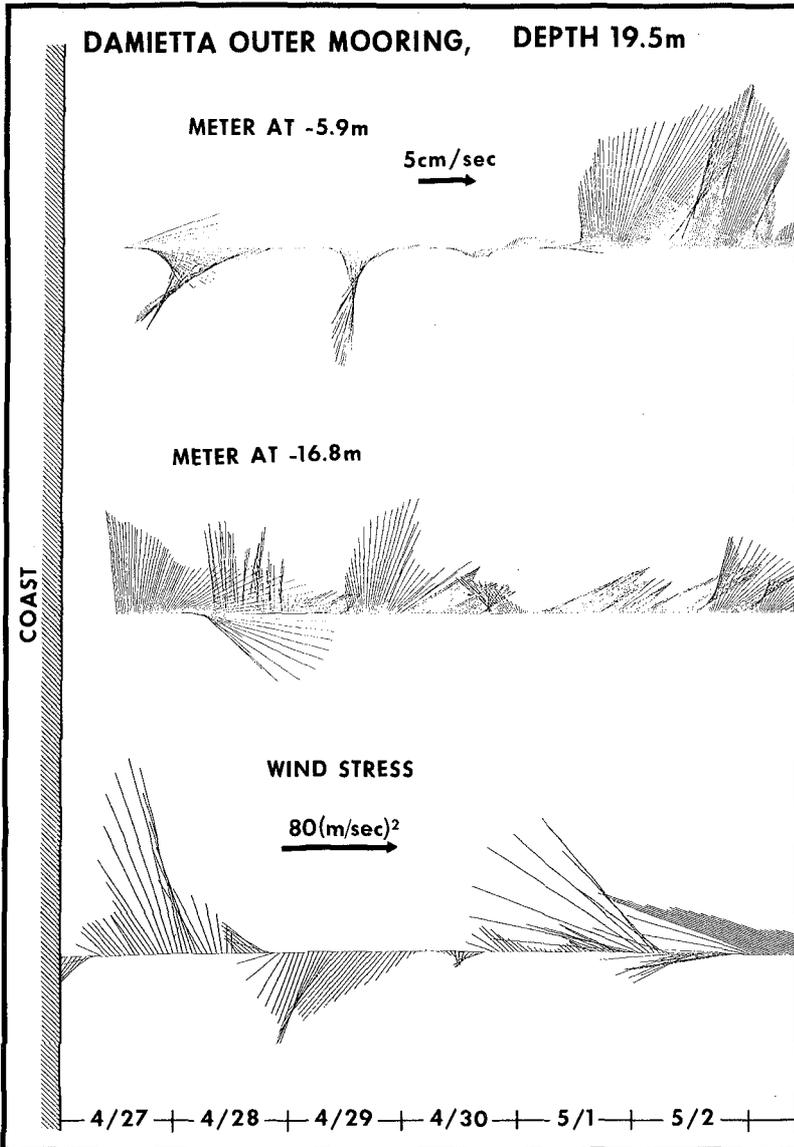


Figure 8. A stick diagram of current vectors at the outer mooring compared to the wind at Port Said (Suez Canal entrance on Fig. 1). The horizontal time lines lie on azimuths to the coast of 215°M.

ciated with wind decelerations at 0400 on 28 April and a wind acceleration at 0600 on 29 April. The deeper currents are persistently more energetic, generally showing an upcurrent or north to northwesterly motion toward the narrow zone of strong seaward flow, thus again indicating the influence of the circulation of the trapped eddy on the currents below the wind-driven surface layer. It is probable that the sudden episode of strong, persistent currents at the upper level on 1 and 2 May reflect the increased influence of the eddy as it migrated southeasterly toward the mooring on 1 and 2 May, as suggested by the station data of Figure 3.

The data from the inner current meter mooring is heavily influenced by accelerations and shifts in the wind. Further analysis will be necessary to establish any relationship between these meters and the eddy circulation system. As anticipated, the current meter records show the tidal current to be on the order of only 5-8 cm/sec, and thus the lack of synopticity of the station data does not seriously disturb the inferred flow field of Figure 6.

Bottom Morphology--Side-Scan Sonar

While performing its primary mission of a detailed bathymetric survey, the Harkness towed side-scan sonar (SSS) over the 4,450 sq km of the Egyptian shelf outlined in Figure 1. The survey grid consisted of north-south track lines spaced at 650 m with a side-scan scale of 400 m (total swath width was 800 m), giving a 150-m overlap on each adjacent line. While these SSS data were taken to assist the bathymetric survey, experienced users can interpret morphologic features, sediment type, and sediment mobility from the same data. Our results from such an interpretation are shown in Figure 9.

After mapping of bottom morphology from the SSS data taken by the Harkness was completed, several areas of special interest in differing types of shelf morphology were chosen for a more closely spaced survey grid with a higher resolution range on the side scan (detail areas 1-5, Fig. 1). In these regions the line spacing was 150 m, with a swath width of 200 m set on the side scan, giving a 50-m overlap on each line. In addition, bottom samples were collected within each area to assess the sediment type composing each morphologic unit. Thus this survey allowed coverage of a large shelf area in greater detail than any other previous survey of the eastern Nile shelf.

Perhaps the most exciting discovery from these data was the presence of a broad sand belt extending from off the mouth of the Damietta eastward and finally curving landward along the eastern boundary of the survey region in the vicinity of the Suez Canal (Fig. 9). This sand belt lies in water depths of 25 to 60 m, and the belt ranges in width from 5 to 20 km. This belt consists typically of large sand ribbons which display small migratory sand waves and fields of large-scale migratory bedforms or sand waves. These features are similar to the sand ribbons described by Kenyon (1970) in European tidal seas, Kenyon and Belderson (1973) in the Mediterranean, and Swift and Ludwick (1976) on the east coast of the U.S. While the major morphologic features forming on the sand belt are the sand ribbons, there are areas where large patches of sand waves are present. Figure 10 shows the detailed mapping of area 1 (see Fig. 1 for location)

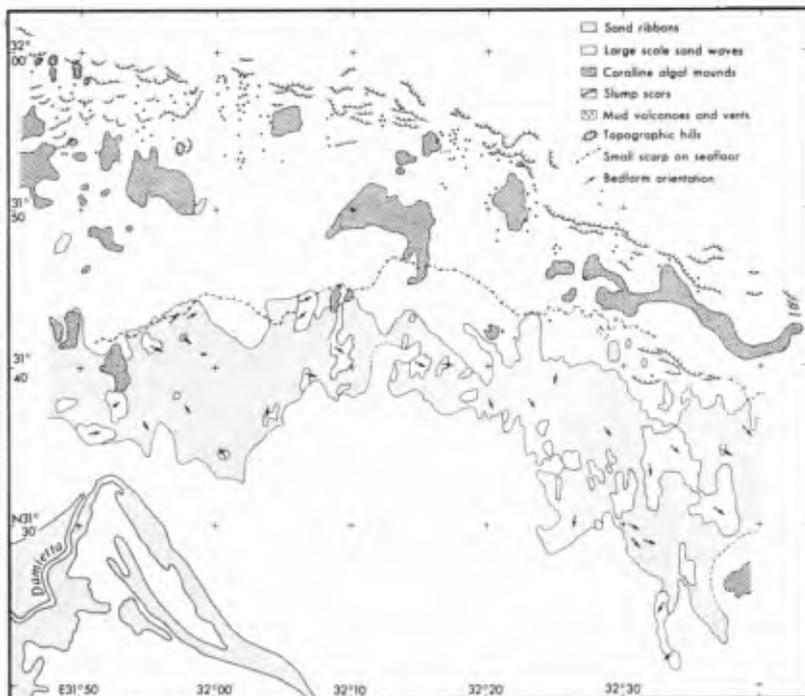


Figure 9. Bottom morphology of the Nile shelf as mapped from side-scan sonar data. Small arrows give direction of movement as determined from bedform orientation.

within the sand belt. Notice that the sand ribbons vary in size considerably, ranging from 150 m wide and 1 km long to much larger, 1-2.5 km wide and 10-18 km long. The sand ribbons display heights above the general sandy silt sea bottom that range from less than 2 m to 10 m. Small-scale sand waves are often found on the ribbons, especially on the larger features, where the ribbons obtain some elevation above the bottom. The sand waves normally display crest lines that are generally perpendicular to the long axis of the ribbons.

Figure 11 is an enlargement of actual side-scan data taken from a sand wave field on one of these ribbons. The sand waves are seen to be about 50 m long and 3-5 m high. Clearly, strong, persistent currents are necessary to mold the bottom to this condition. Utilizing the side-scan sonar data, the orientation of the various bedforms could be mapped, and these are shown on Figure 9. Near the Damietta distributary the bedforms show a general NNW orientation and near the seaward edge swing toward the

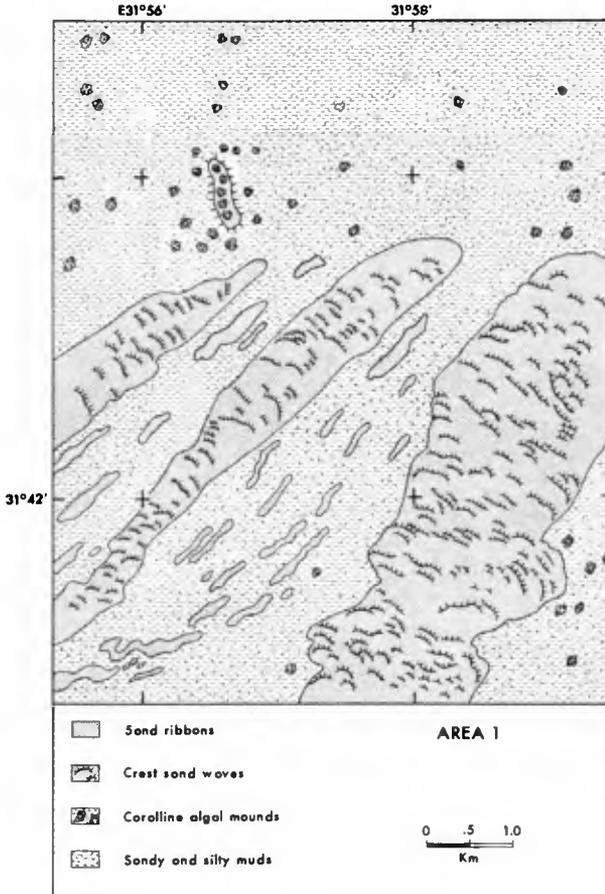


Figure 10. Detailed morphology of sand ribbons and sand waves moving over a mud bottom in area 1 (see location on Fig. 1).

east and ESE. In the central part of the sand belt the bedforms show a general east and southeast direction of sediment migration. Along the easternmost edge of the study region the bedforms display a general southern or toward-shore migration pattern. Note also in this area that there is a large accumulation of sand, and the contour map (Fig. 1) shows the presence of a large shoal just east of the Suez Canal. It is highly probable that this sand migration pattern has been responsible for the sediment accumulation in the Suez Canal region. The pattern of sand wave

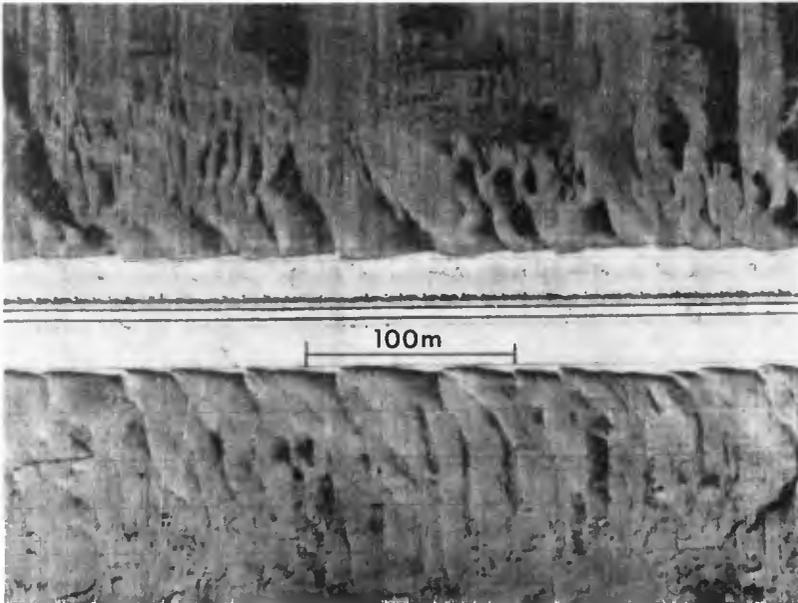


Figure 11. Side-scan sonar image illustrating bedforms on the crest of a sand ribbon. Ship track run parallel to the long axis of the sand ribbon. Lateral scale is in increments of 15 m. Sand waves are 3-5 m high.

movement certainly appears to be with the eddy current structure inferred from Figure 3. This will now be examined in more detail.

Model of Eddy Circulation East of Damietta

Fluid flow around obstacles is a frequent topic for laboratory experimentation in hydro- and aero-dynamics. The experimental results from flow around flat plates and blunt obstacles such as seen in Figure 7 have been used successfully in formulating models of flow separation, cavity (trapped eddy) formation, and return flow for design of nuclear reactor shells (Halitsky, 1968). Only recently have analytical and numerical techniques been successful in describing the air flow over hills. Jackson and Hunt (1975) presented an analytical treatment of the velocity field over gently sloping hills, while Mason and Sykes (1979) recently described a numerical model which treated hills steep enough to produce flow separation.

The essential results of these three approaches, experimental, analytical, and numerical models, have been synthesized in Figure 12 and applied to the Damietta promontory, considered as an obstacle to flow. According to Jackson and Hunt (1975), the background flow U_0 approaching

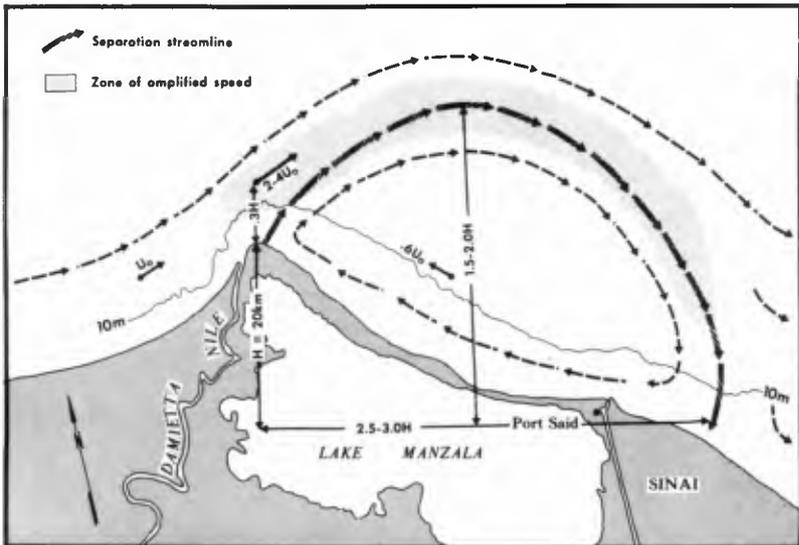


Figure 12. Composite model of flow field around an obstruction, synthesized from experimental, analytical, and numerical studies.

the promontory is amplified into a free jet with a magnitude 2 to 4 times U_0 , located at a position above the obstacle equal to three-tenths of its height (H). Experimental work indicates that the cavity or trapped eddy will resemble an ellipsoid of revolution with a downstream dimension of at least $2.5-3H$ and a cross-stream dimension of $1.5-2.0H$. In the center of the eddy there will be a return flow of $0.6U_0$. The zone of high speed will follow the separation streamline deflected cross-stream by the obstacle. The essential features of these models were reproduced in the elegant numerical solutions of flow over steep topography by Mason and Sykes (1979).

In Figure 13 the basic geometry of the trapped eddy is compared to the current velocity observations and the sand body mapped by side-scan sonar. The zone of high-speed currents first identified in the station data is clearly the right magnitude and location to be on the seaward limb of the trapped eddy. The return flow along the coast at the inner line of stations also fits the model rather well. There can be little question that the high-speed outer limb of the eddy is interacting strongly with the bottom as the curvature of the inner shelf sand body follows the predicted axis of the eddy quite closely except at its eastern end. Far more striking is the agreement among the direction of movement of sand waves shown on the figure, the observed current velocities, and the current speeds and directions expected from the flow separation-trapped eddy model.

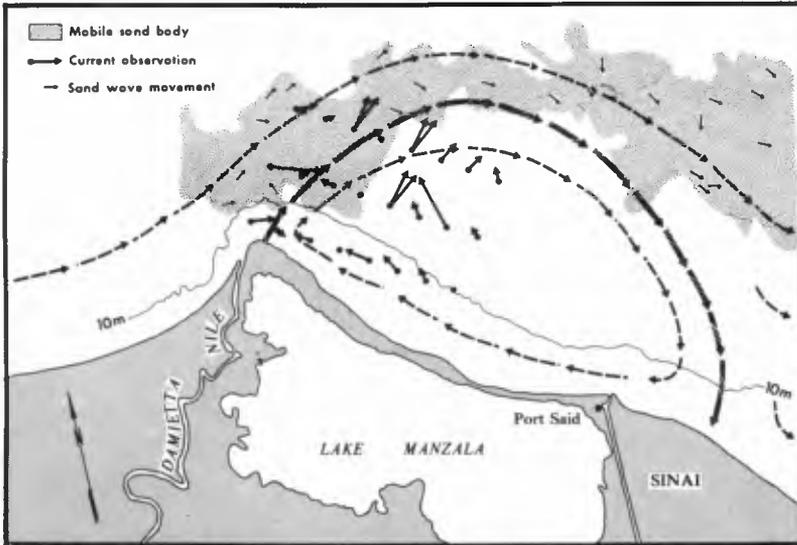


Figure 13. Observations of currents and sand wave movements compared to the composite model of a trapped eddy shown in Figure 12.

Implication to future coastal erosion. The coastline between the Damietta promontory and the Suez Canal is already undergoing severe erosion (Nielsen, 1977). As closure of the Aswan High Dam has cut off the input source of sand for the sediment transport system driven by the Damietta eddy, we expect the arcuate sand ribbon belt to gradually consume itself. The tail or western boundary of the sand belt will migrate eastwardly due to lack of replenishment, and the height of individual sand ribbons will gradually lessen as the arcuate sand belt dissipates, allowing increasingly higher levels of wave energy to impact the coast, accelerating the erosion rate.

Summary and Conclusions

The closure of the High Dam at Aswan on the Nile River markedly accelerated an already severe erosion problem along the Mediterranean coast of Egypt. In 1978 the U.S.N.S. Harkness, while performing a bathymetric resurvey of the shelf between Damietta and a line eastward of the Suez Canal entrance, obtained side-scan sonar coverage of the entire survey area. On the basis of these data a combined program of physical oceanographic and marine geologic measurements was made at a much finer resolution in an area immediately east of the Damietta Nile promontory and leads us to the following conclusions.

1. A seaward-directed jet of high-speed current 4-8 km across forms

off the Damietta promontory and shoots out northeasterly against the prevailing wind. Flow separation occurs a few kilometres east of the vertex of the promontory.

2. A broad, slow return flow to the northwest forms in the shallower waters along the coast. This return flow is highly influenced by the local wind.

3. These two zones are elements of a mesoscale (~50 km) eddy trapped in the lee of the promontory.

4. The spatial and velocity characteristics of the eddy are consistent with a composite model of eddies induced by flow separation based on analytical, numerical, and experimental studies. Further observations of the temporal and spatial behavior of such an important feature are clearly warranted.

5. Detailed side-scan sonar surveys of bottom morphology indicate that the eddy is underlain by a highly coherent, mobile sand belt that extends about 50 km downcurrent (east). Orientation of sand waves reflects the measured currents in the eddy and indicates that reattachment of the separation streamline occurs about 10 km to the east of the Suez Canal entrance.

6. As a principal source or input of sediment to the eddy driven sand belt was shut off by the closure of the Aswan High Dam, we expect the relief on the sand belt (up to 10 m) to diminish gradually, allowing greater wave energy to impact the coast, thus aggravating the local erosion problem.

Acknowledgments

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