CHAPTER ONE HUNDRED NINE

THE NILE LITTORAL CELL AND MAN'S IMPACT ON THE COASTAL ZONE OF THE SOUTHEASTERN MEDITERRANEAN

by

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INTRODUCTION

Man's intervention with coastal processes takes many forms. However, the most serious large scale, long term coastal erosion results from the interception by dams of rivers supplying sediment to the coast. This loss of sediment may have catastrophic effects along coasts where streams discharge directly into coastal waters. The Nile littoral cell is an impressive example of the effect of dams on coastal erosion.

The Nile littoral cell is located in the southeastern Mediterranean Sea and extends 700 km from Alexandria, Egypt in the south to Akko, Israel in the north. The sediment load from the Nile River was deposited along the submerged portion of the delta, where it was sorted and transported to the east by the prevailing waves and by currents of the counterclockwise east Mediterranean gyre that commonly flows at about 50 cm sec^{-1} over the delta. Prior to 1964, the turbid plume of the flood waters of the Nile River could be traced along the Mediterranean coast for over 700 km to the shores of Lebanon. Fine silt and clay sized material were carried easterly and into deeper water, while sand is carried easterly along the shelf and shore as far as Haifa Bay.

Until 1964, the major sediment source of the littoral cell was the Nile River. Construction of the High Aswan Dam, which began filling in 1964, has resulted in a near absence of Nile River flow into the Mediterranean and a corresponding complete loss of the Nile River as a source of nutrients to coastal waters, and as an active sediment source for the delta and the coastline of the Nile littoral cell. As a result, the Nile Delta is now subject to severe erosion in a number of localities.

GEOLOGIC SETTING

The physiography of the Mediterranean basin is best understood in terms of the tectonics of the moving plates of the lithosphere. The complex Mediterranean region results from the collision between the African and the Eurasian plates, a process that is gradually closing the Mediterranean Sea. In the eastern portion of the sea, under-thrusting of Mediterranean seafloor under the Eurasian continental plate has formed a broad zone of plate collision extending from the boot of Italy, eastward and to the south of Greece, Crete and Cyprus. The plate collision has resulted in a mountainous, volcanic belt north of and parallel

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to tbe zone of under-thrusting. The plate collision also has produced a series of transform faults caused by tbe adjustment of interplate continental fragments (e.g. Nur and Ben-Avraham, 1978; Ben-Avraham, 1978; Jongsma and Mascle, 1981). The tectonics is complicated locally by a spreading center in the Red Sea and its transform faults which includes the major Levant rift zone that cuts through the Gulf of Aqaba and the Dead Sea. Local adjustment faults occur in tbe Akko region that probably determine the location of Haifa Bay and Akziv snbmarine canyon.

Sea Level Changes

Fluctuations in the level of the Mediterranean Sea have been important factors in the cutting and filling of the Nile Valley, the formation of the delta, and tbe distribution of Nile River sediments. The Nile valley was cut to its maximum deptb during tbe great Miocene desiccation abont 24 m.y. (million years) ago wben the Mediterranean was isolated from the world oceans, causing the sea to dry and become a salt pan. At that time the river cut a gorge deeper tban the Grand Canyon of the Colorado. The valley began filling over its ancient delta when tbe Mediterranean filled during the Pliocene about 10 m.y. ago. The present Nile Delta bas a sediment thickuess of over 3.5 km along tbe continental shelf, and a sediment volume estimated to be 350 to 387 x 10^3 km^3 (Said, 1981; Ross and Uchupi, 1977; respectively).

There were many sea level fluctuations during the Pleistocene that resulted in Nile valley cut and fill and in different positions in the delta shoreline. Sea level rose from about -140 m, 15,000 years ago and is still rising at a rate of about 15 cm per century. The present sea level rise is a factor in coastal erosion, possibly accounting for a shoreline retreat of 10 to 15 m per century.

Distribution of Recent Sediments

Two major and distinct sediment types are found on the beaches and shelves of the southeastern Mediterranean Sea. A calcareous suite of sediments that consists of shell fragments and other organic detrital material, usually found near its origin, or of carbonate oolites tbought to be brought as windblown sand from the western desert (Hilmy, 1951). Off tbe Nile Delta and elsewhere on the shelf, mounds of living coralline algae contribute coarse debris to tbe surrounding sediments (Coleman, et al., 1981).

The second sediment type consists of sand, silt and clay brought to the sea by the Nile River before tbe Higb Aswan Dam. The clay minerals include montmorillionite, kaolinite and illite. In the past, fine sediments from the Nile River bave provided a major portion of the sediment fill of the eastern portions of tbe Levantine Basin between Cyprus and Lebanon (Venkatarathnam and Ryan, 1971; Nir, 1982a). The sand size fraction of this sediment consists predominantly of quartz with a distinctive admixture of heavy minerals. Amphibole (hornblende) and pyroxine (augite) are dominant and in nearly equal abundance; while the unique yellow-green and brown-violet varieties of augite are diagnostic for Nile sands (Shukri and Philip, 1960).

The Nile River is the only abundant source of sediment in tbe eastern Mediterranean, and wherever these sediments are transported they have overwhelmed the sparse supply of calcareous sediment. Dnring floods through the Rosetta mouth some Nile sediment has gone as far west as Ahu Quir headland. However, the prevailing winds, waves and currents of the east Mediterranean gyre have resulted in an easterly and northeasterly transport of Nile sediment. Nile sediment is dominant from Ahu Quir headland for 700 km to Akko on Haifa Bay.

The heach sands from west of Mersa Matruh for 300 km to Ahu Quir headland are calcareous oolites and shell fragments (Hilmy, 1951; El-Wakeel and El-Sayed, 1978). From Ahu Quir Bay to Haifa Bay the heach and shelf sediments are predominantly from the Nile as shown hy many studies of mineral distrihution (Rim, 1950; Shukri and Philip, 1960; Pomeranchlum, 1966; Nir, 1982a).

A detailed study hy Nir (1980) of the sediments in the vicinity of Haifa Bay shows that the quartz sand from the Nile divides into two distinct paths, separated hy a series of suhmarine kurkar ridges. A shallow (out to 15 m depth) hand of Nile sand follows the coast around Carmel Head and into the hay forming the heaches and wind hlown sand dunes of Haifa hay. Beach accretion and dnne formation at Haifa appear to he the sink for the shallow water Nile sand. A deeper (25 m and over) hand of Nile sand and silt parallels the coast and appears to extend north of Akko. The transport and final sink for this sediment is not clear. At a lower sea level Akziv suhmarine canyon may have heen the sink for sand hypassing Haifa Bay.

SHORELINE CHANGES

Historically the position of the coastline of the Nile Delta has heen determined hy the relative importance of deposition of sediments during the annual floods of the Nile River which huild the delta seaward, versus the action of waves and currents which transport the sediments and erode the delta. Generally, until the heginning of this centnry the discharge of sediment has exceeded the potentital for erosion, and the delta huilt seaward (Figure 1). However, man's intervention, heginning with construction of harriers in the lower reaches of the Rosetta and Damietta hranches and with the construction of the Low Aswan Dam in 1902, changed the pattern to one of erosion. Construction of the High Aswan Dam, which hegan filling in 1964, has resulted in a complete losa of the Nile River as an active sediment source for the delta. As a conaequence, the action of waves and currents, which have remained undiminished, are in the process of eroding and changing the configuration of the coastline of the Nile Delta.

There appears to have heen significant accretion of the Nile Delta from at least 1600 to 1898. During that time Rosetta promontory prohahly extended seaward ahout 8 or 9 km (Sestini, 1976). The promontory extended 3.6 km (37 m/yr) between the surveys of 1800 and 1898, then remained nearly stationary from 1898 to 1909. From the turn of the century to the present the seaward portion of the promontory has eroded at a progressively more rapid rate. The erosion rates for the periods preceeding the surveys of 1926, 1965, 1973 and 1982 heing 18, 20, 125 and 211 m/yr, respectively (Figure 1). The "new" Rosetta Lighthouse which was 1 km inland in 1970, hecame an offshore island in 1976 (Niel-

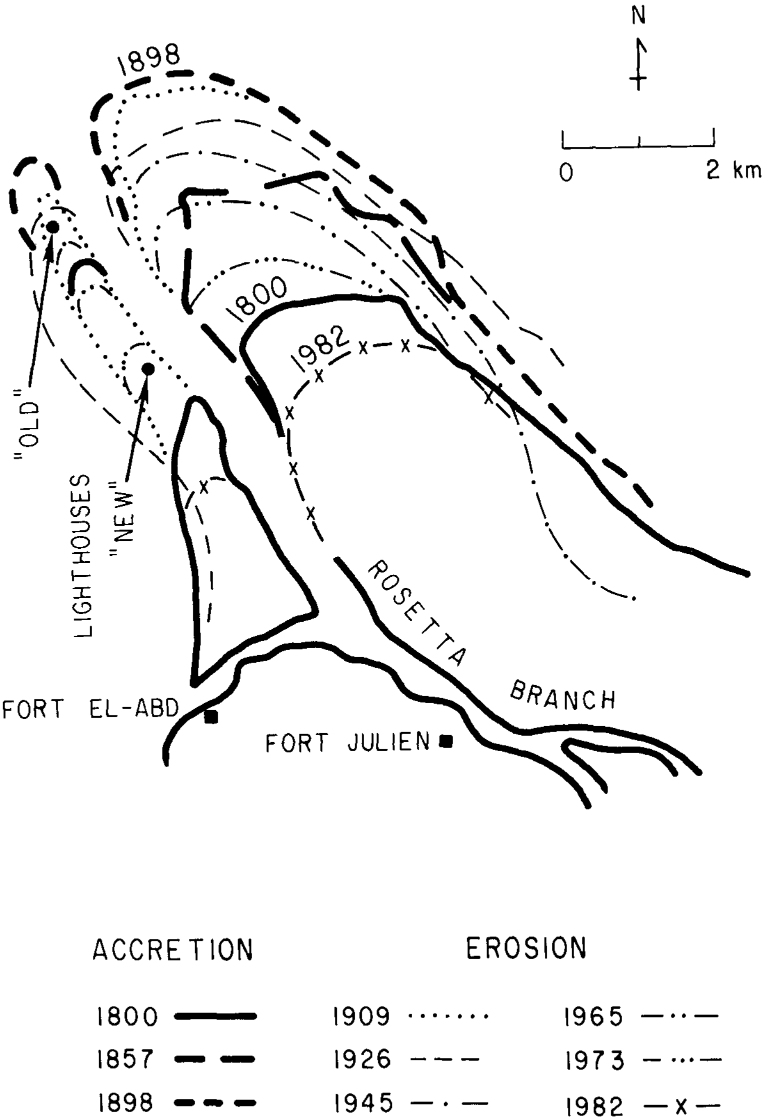

Figure 1. Historical shorelines of Rosetta Promontory (data from Sestini, 1976; Misdorp, 1977; Khafagy, 1981).

sen, 1977; Khafagy et al., 1981).

The establishment in 1971 of a series of beach profiles extending from Abu Quir Bay to east of Ras El Bar was an essential part of the erosion study. Repeated surveys along these profiles has proved to be the most effective means of monitoring the erosion. Comparison of beach profiles show that the coastline has retreated off the delta promontories averaging 160 m between 1971-1972 and 211 m/yr between 1973 and 1982 off the Rosetta branch and 143 m/yr between 1943 and 1973 on the Damietta promontory east of Ras El Bar (ARE/UNESCO, 1973). In contrast there has been a modest shoreline advance (accretion) in the embayments, e.g., 8 m/yr (1947-1965) at the Gamasa outlet (Kadib, 1969; Mobarek, 1972; Orlova and Zenkovich, 1974). Although beach profiles have been conducted since 1971 there are few printed details. Hammad et al (1979) give the average loss of sediment from the shoreline to 6 m depth as 19×10^6 m^3/yr for the period 1972 to 1976. Manohar (1981) graphs results for this same period and others that clearly show the rate of erosion is accelerating.

Inman et al (1976), using only the principal wave component from surface marine observations obtained longshore sand transport rates of about 860,000 m^3/yr to the east near Rosetta and Damietta promontories and somewhat lower values between promontories. Quelennec and Manohar (1977) estimate the net transport rate near the promontories to be more than 3×10^6 m^3/yr with lower rates between promontories. Comparisons of photographs of the entrances to Bardawil Lagoon, about 140 km east of Ras El Bar, show that the volume of sand trapped on the west side of jetties and eroded from the east side gives easterly transport rates of about 500,000 m^3/yr (Inman and Harris, 1970; Inman et al., 1976).

Numerous structures have been built along the coast of Israel. Most were built to widen beaches for recreational use and prevent cliff erosion, and others to provide harbors. Ashdod Harbor diverts sand offshore in amounts that suggest longshore transport rates of 215-560,000 m^3/yr. Other studies indicate longshore sand transport rates of 400,000, 125,000, and 80,000 m^3/yr at Gaza, Hadera and Atlit respectively (Nir, 1982b). from wave measurements Carmel et al (1984b) estimate the transport at Haifa to be about 110,000 m^3/yr. These various estimates of longshore transport are discussed further and plotted in Carmel et al (1984c).

NILE RIVER DISCHARGES

The Nile River derives its waters from the Lake Plateau of Tanzania and Kenya (White Nile) and from the Ethiopian highlands (Blue Nile). It has a drainage basin of about 3×10^6 km^2 and a length of 6800 km. The Nile traverses 35 degrees of latitude in its long northerly flow from its source in Tanzania to the Mediterranean Sea. Before the High Aswan Dam, the river discharged annually 86×10^9 m^3 of water (Hurst, 1952; Said, 1981).

Man's intervention in the flow of the Nile dates back at least to pharaonic times when Senusret had a canal built from the ancient Pelusiac branch of the Nile to the Red Sea (circa 1900 BCE). Modern intervention began with construction of the Delta Barrage below Cairo in

1861. The barrage sluices opened to pass flood waters, of which about 70 percent flowed out the Rosetta mouth and 30 percent through the Damietta. The barrage was the beginning of perennial versus basin irrigation, and the extensive use of Nile silts and clays as nutrients in agriculture. This use continued with the Low Aswan Dam built in 1902, up until the High Dam was completed in 1964, which trapped all of the sediment load.

The Low Aswan Dam was increased in height in 1907 and again about 1929 to a total height of 38 m. The dam is 2 km across and raised the river level for 350 km upstream to the Second Cataract near Wadi Halfa. The Low Aswan Dam was specially provided with sluices to pass the flood waters and their sediment load. However, because of its height and extensive back-up of water, it is not surprising that it trapped some sediment (Hammad et al., 1979). Calculations show that about 60% of the fresh water discharged at the Low Aswan Dam was lost to irrigation and evaporation on its way to the Mediterranean (Sharaf El Din, 1977).

Before 1861, probably <u>much</u> of the fine load and <u>most</u> of the sand was carried during the flood months, and deposited off the Mediterranean delta of the Nile. The erosion of Rosetta promontory which began about the turn of the century was probably in part due to a decreased supply of sediment caused by the Low Aswan Dam (Figure 1).

The flood months of the Nile River are usually taken as July through November, with the maximum monthly discharge of about 17 and $21x10^9m^3$ during August and September respectively. However, measurements show that the rising phase of the flood in August carries the highest percentage of suspended load. A minimum water discharge of $1.5x10^9m^3$ occurs in May. The sand content of the suspended load appears to have been about 30% for the free Nile above the dams, and was about 25% at Gaafra below the Low Aswan Dam. This difference would be expected if the Low Aswan Dam trapped sediment, as sand is more sensitive to changes in river gradient behind dams than is the wash load.

The peak flood water level of the Nile has been monitored for millenia, providing the longest time series of annual floods known (Hurst, 1957; Van Atta and Helland, 1977). The levels were accurately recorded because they provided a reliable method of taxing the people for the irrigation and growth of crops. Unfortunately there has been but little measurement of suspended sediments and no measurement of bedload. According to Quelennec and Kruk (1976) there were two series of suspended load measurements separated by several breaks, including one of 17 years, centered around World War II. Series 1 included the years 1928-1931 and 1938, while series 2 spanned the period from 1955-1969. Suspended load measurements for the free Nile flood above the low dam were made at Halfa only during series 1; while measurements for the Nile at Gaafra below both the low and high dams were made during both series 1 and 2. Series 1 measurements occurred during a period of low river flow (1913-1931) while series 2 included a period of high flow (1953-1963).

There have been a number of studies of suspended sediment discharge of the Nile River. All are based on series 1 and 2 data except for Simaika (1970; see Hammad et al, 1979) who seems to have extended the series 2 data above the Low Aswan Dam from 1955 to some unspecified date by moving measurements from Halfa to Kajnarty. The effect of this move on the quality of data is not discussed. The data of Simaika (1970) and Fahmy (1974) appear to be based on averages of data taken during the relatively short periods of measurement (i.e. 5 and 14 years respectively), and thus do not include a long series of data nor the highest or lowest flow years.

In order to obtain a longer, more representative data base Quelennec and Kruk (1976) correlated the series 1 and 2 suspended sediment data with water discharge for both rising and falling water levels. This gave them a sediment rating curve so that suspended load could be simulated from water discharge, for which there is extensive data. In this way they found that the average annual suspended load of the Nile at Gaafra for the 60 years from 1904 to 1963 to be 160 x 10^6 tons/yr. The lowest sediment load was less than 50 x 10^6 tons/yr in 1913 and the highest was greater than 300 x 10^6 tons/yr in 1954. No sediment has passed the High Aswan Dam since it began filling in 1964. The sediment is deposited and is rapidly filling the headwaters of Lake Nasser behind the dam.

For the sediment budget needed in this study it is necessary to estimate the total load of the free flowing Nile for this century. The data from Simaika has too few years to be representative while that from Quelennec and Kruk (1976) includes the effects of the Low Aswan Dam. Hammad et al (1979) use the data of Simaika and Fahmy to show that the Low Aswan Dam trapped suspended sediment at the rate of 10.5 x 10^6 tons/yr. Thus none of the data is entirely satisfactory for our purposes, and none includes bedload. From standard text such as Schumm (1977) and Richards (1982) it would appear that for rivers with the channel and suspended load characteristics of the Nile, the bedload is between 1% and 10% of the total load.

In lieu of a longer data base, that of Quelennec and Kruk is used here as the best estimate of the long term suspended load of the free Nile. From this the total load is estimated in Table 1 and compared with the measured erosion rate of the Nile delta out to depths of 6m. Since the erosion extends beyond 6m depth, and the erosion rate is increasing with time (Manohar, 1981), the erosion rate of sand must be greater than the measured rate of $19x10^6m^3$/yr along the delta. On the other hand it may not be as great as the $41x10^6m^3$/yr assuming a Nile bedload of 10%. Therefore for purposes of this study it is assumed that the total annual yield of sand of the free Nile was between 20 and $41x10^6m^3$/yr, and was probably about $30x10^6m^3$/yr.

DRIVING FORCES: WINDS, WAVES AND CURRENTS

The circulation in the Mediterranean Sea is both geostropic and thermohaline with salinity, due to an excess of evaporation over precipitation and runoff, increasing to the east where it reaches 39 $^o/oo$ in the Levant Sea off Israel. The surface circulation of the east Mediterranean is dominated by the counterclockwise flow of the east Mediterranean gyre that carries water from the straits of Sicily past the Nile delta, into the Levant Sea, to the north and west of Cyprus, and into the Cretan Sea (Sverdrup et al., 1942, p. 649; Orin, 1971;

Table 1. Estimated sediment yield of the Nile River at Gaafra compared with Nile Delta erosion.

Location and Source of Data	Sediment Rate →	10^6 tons/yr	10^6 $m^3/yr^\dagger$
Nile River Load at Gaafra, 1904-1963			
1. Average suspended load (sand and wash) (Quélennec and Kruk, 1976)		160	
2. Sand in suspended load 0.3 x (1) (Simaika, 1970)		48	30.2
3. Bedload (sand)	(1% of total load)*	1.6	1.0
	(10% of total load)**	17.8	11.2
4. Total sediment load	1% *	161.6	
	10% **	177.8	
Washload (silt and clay (0.7 x (1) (Simaika, 1970)		112	
Sand load (2) + (3)	1% *	49.6	31.2
	10%**	65.8	41.4
Nile Delta Erosion, 1972-1976			
Shore to 6 m depth, 200 km of delta shoreline (Hammad et al., 1979; Manohar, 1981)		30.2	19
Sand yield of Nile before High Aswan Dam			19-41

* Assuming bedload to be 1% of total load. ** Assuming bedload to be 10% of total load. † Assuming "at rest" volume ratio (solid/whole space) of 0.5; ρ_s = 1.59 tons/m^3

Sharaf El Din, 1977; Bethoux, 1980). Surface currents of the gyre impinge upon the shallow Nile delta and sweep across it with velocities of 20 to 100 cm/sec and locally up to 2 m/sec. Prior to the closure of the High Aswan Dam in 1964, the turhid plume from the floodwaters of the Nile River could be traced along the Mediterranean coast for over 700 km from Ahu Quir headland to the shores of Lehanon (Hecht, 1964; Orin, 1969; Sharaf El Din, 1977).

The Damietta promontory of the Nile interacts with the east Mediterranean gyre to form a large eddy that hegins at Damietta, extends offshore for up to 35 km and eastward along the coast for about 70 km. The seaward portion of the eddy is a high speed jet over 5 km wide that forms off the promontory and flows northeasterly and then easterly with measured surface to bottom velocities of over 60 cm/sec (Murray et al., 1981). The eddy drives a field of actively migrating sand ridges easterly over a smooth mud plain. The sand helt hegins in depths of 10 m flows northeasterly, turns easterly and finally arcs southeasterly towards the coast hetween Port Said and Bardawil Lagoon (Coleman et al., 1981). This appears to he a major transport path and sink for Nile sand.

The currents of the east Mediterranean gyre dissipate energy as they flow over the shallow shelf of the Nile delta. There is insufficient current data to make detailed calculations. However the energy loss may he approximated from the drag relation,

$$\text{energy loss/area} = \tau u = c_f \rho u^3$$

where τ is the drag force per unit area (newtons/m^2), u is the mean current velocity (m/sec), $c_f=2x10^{-3}$ is the drag coefficient and ρ is the density of sea water. Assuming that an average current of 50 cm/sec flows over a shallow (<50 m) area of 10^4 km^2, the above relation gives an overall energy dissipation rate of about $2.5x10^6$ kW.

Tidal ranges are ahout 30 cm along the coast of the southeastern Mediterranean. The effect of tides is negligible except near large lagoons, where together with wind and evaporation they control water exchanges through the entrances. Tides will not be further considered here.

Waves

The most common winter storms contain low pressure areas which move from west to east over Southern Europe and the Mediterranean. The track of the storm centers pass progressively over Italy, Greece and southern Turkey, so that the cyclonic winds in the lower quadrants of the storm blow from west to east, progressively covering most of the 2200 km fetch hetween Sicily and Israel. The storms may occur every 6 to 7 days and their centers are often fast moving, with migration velocities of 900 to 1000 km/day. This migration rate is comparable with the speed of the waves, causing the wave height to be enhanced. The waves typically have deep water heights of 3 to 6 m and periods of 8 to 10 sec and sometimes up to 15 sec (Carmel et al., 1984a). The waves arrive off Abu Quir about one-half day hefore reaching the Israel coast.

The details of wave directional climate from measurements along the coasts of Israel and Egypt are given in a series of recent reports (Inman et al., 1982; Lowe and Inman, 1983; Carmel et al., 1984a,h,c; Elwany, et al., 1984). Along the Israel coast near Haifa these measurements reveal a bimodal distrihution of wave height and energy flux with the winter storm waves approaching from south of the beach normal and the lower summer waves from north of the beach normal. The magnitude of the monthly averaged energy flux ranged from 1 to 7 kW/m with an average annual energy flux of 3.3 kW/m. Thus the Mediterranean coast of Israel is a moderately high-energy coast with a bimodal annual cycle (Carmel et al., 1984h,c).

Because of the shorter fetch, the Nile delta coast of Egypt has a slightly lower wave energy, but a more pronounced, unidirectional flux of energy along the coast. The average annual flux of wave energy incident on the Nile delta coast is about 2.5 kW/m (Lowe and Inman, 1983; Elwany et al., 1984). Correcting for refraction, a deepwater energy flux of 2.5 kW/m, results in a total energy dissipation rate due to waves along the 200 km from Abu Quir to Port Said of about 0.5×10^6 kW.

Longshore Sand Transport by Wave Action

Theory and field measurements of waves and the resulting longshore transport of sand show that the sand transport is directly proportional to the longshore power factor of the waves (e.g. Komar and Inman, 1970; Inman et al., 1980).

$$I_1 = K \, [P \sin\alpha \cos\alpha]_b = K \, [C S_{yz}]_b \tag{1}$$

where $K \cong 0.8$ is a dimensionless constant, $P = ECn$ is the energy flux of the waves (watts/m), E is the wave energy per unit area (joules/m^2), Cn is the wave group velocity (m/sec), $S_{yx} = En \sin\alpha \cos\alpha$ is the longshore radiation stress, α is the angle the breaking wave makes with the shoreline, and the subscript b indicates that all properties are measured at the breakpoint of the waves. In the above relation, Q_1 is the immersed weight longshore transport rate (newtons/sec) and may be expressed in terms of the "at rest" volume transport rate Q_1 (m^3/sec)

$$Q_1 = I_1 / \, (\rho_s - \rho) g N_o \tag{2}$$

where ρ_s and ρ are the densities of the solid grains and the water respectively, g is the acceleration of gravity and N_o is the volume concentration of sand, equal to about 0.6 for well sorted sand at rest. For quartz sand in seawater the factor $1/(\rho_s - \rho) g N_o$ has the value of 1×10^{-4} m^3/newton.

The potential for the longshore transport of sand by waves can be calculated from relations (1) and (2) when the wave characteristics at the breakpoint are known. This requires that waves be refracted from deep water to the breakpoint. Application of Snell's law to the refracted waves, and the assumption that the energy flux P=ECn is conserved between wave rays gives the relation between deep water and the breakpoint as

$$P_b = P_\infty \cos\alpha_\infty / \cos\alpha_b \tag{3}$$

where the subscript ∞ refers to waves in deep water. Limited studies of wave refraction along the Nile delta coast were made by Inman et al (1976) and Quelennec and Manohar (1977) using wave data from marine observations. A more comprehensive study is in progress by Elwany et al (1984) based on measurements from wave directional arrays. These measurements show that the prevailing deep water direction for storm waves is from about N60°W, and that the waves commonly have periods of 8 to 10 sec.

A refraction diagram for 8 sec waves from N60°W (Fignre 2) shows pronounced zones of wave convergence and divergence that result in strong gradients of wave height and breaker angle along the coast. This means that the longshore transport rate Q_1 is not constant bnt varies with distance along the coast as shown in the central graph of Figure 2. This variation in Q_1 resnlts in areas of erosion and accretion along the coast. The rates of erosion and accretion are given by the divergence of the drift $\partial Q_1/\partial l$ (eg Inman et al, 1976) as shown in the lower graph of Figure 2. It is to be noted that positive values of $\partial Q_1/\partial l$ indicate erosion while negative values indicate accretion.

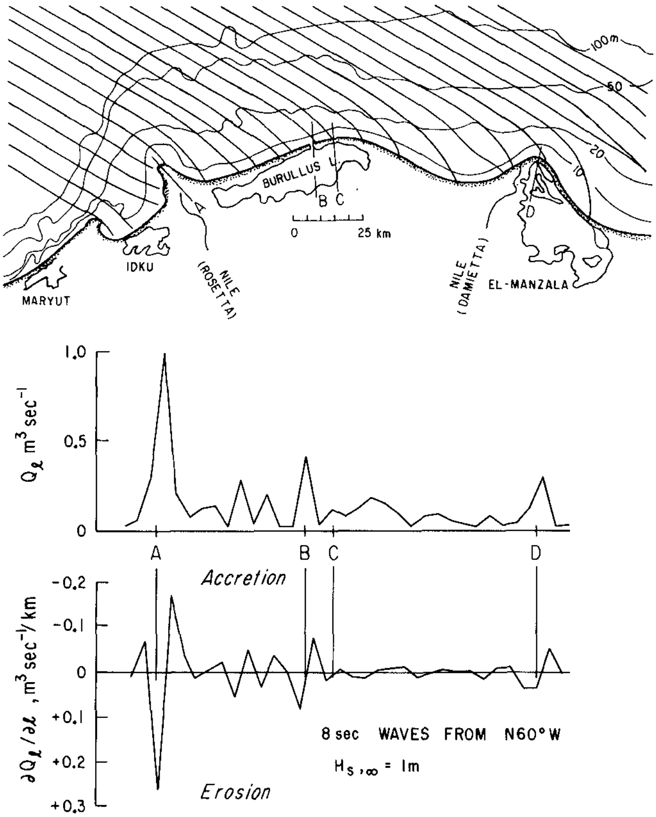

Figure 2. Wave refraction and variation of longshore sand transport (LST) along the Nile delta coast for a 1 m high, 8 sec wave coming from N60°W. Note that the LST (center) is everywhere to the east even though the divergence $\partial Q_\ell/\partial \ell$ shows local zones of erosion (+) and accretion (-) (data from Elwany et al., 1984).

Although Figure 2 is for a single wave condition it illustrates several fundamental aspecta of delta morphology. First, there are three general zones of pronounced erosion, that occur off the promontories of Rosetta, Burullus and Danietta. Zones of accretion occur to the east of each erosion zone. Finally, a net easterly longshore transport of sand occurs in the presence of alternate zones of accretion and erosion as Q_1 is everywhere positive and to the east. Several previous studies have wrongly concluded that the presence of alternate zones of erosion and accretion indicated coastal compartments that were closed to net uni-directional transport of material.

The variations in wave intensity and direction and the resulting complex pattern of wave refraction along the delta coast preclude simple interpretations of the wave potential for a net annual longshore transport of sediment. Therefore, for the present it is useful to take a more aloof view and consider the transport potential that the estimated deep water wave energy flux of $P_\infty = 2.5$kW/m would produce along the coast. Inspection of relations (1), (2) and (3) show that the longshore sand transport is proportional to the product $\cos\alpha_\infty \sin\alpha_b$, which varies along the delta coast. However inspection of the refraction diagrams for prevailing waves (e.g. Figure 2) show that α_∞ commonly varies between 45° and 60° while α_b is most commonly between 20° and 45°. Thus the product $\cos\alpha_\infty \sin\alpha_b$ commonly falls betwwen 0.17 and 0.5, and the longshore transport will commonly fall between 1 and 3×10^6 m^3/yr. Thus a conservative estimate of the net annual longshore transport due to wave action along the delta coast is 1×10^6 m^3/yr to the east.

Wind and Cliff Erosion

Wind storms, and the prevailing winds produce significant sand transport along the Nile littoral cell. Some windblown sand is lost to sea, but most is deposited in coastal sand dnnes as evidenced by the many dune fields along the coast. The most important fields are the Baltim dunes between Burullns and Ras El Bar, the coastal dunes of the Sinai (Tsoar, 1974), and the smaller dune fields along the Israel coast (Nir, 1982a). The rates of sand loss to dunes has not been carefully monitored.

Nir (1982a) points out that the extensive quarrying of beach sand for construction purposes that lasted through the mid 1960's caused a deficit of about one-third of the total beach resources in Israel. Israel beaches still show a deficit of sand that has indirectly accelerated the erosion at Kurkar seacliffs. Sand qnarrying has considerably complicated quantitative sand transport studies along the coast of Israel.

BUDGET OF SEDIMENT FOR THE NILE LITTORAL CELL

The littoral cell is a coastal sedimentation compartment that contains a complete cycle of littoral sedimentation including sources, transport paths and sediment sinks (e.g. Inman and Chamberlain, 1960; Inman and Brush, 1973). When transport rates (fluxes) are assigned to the sources, paths and sinks, the cell can be evaluated in terms of the "budget" of sediment which is subject to the usual constraints associated with the conservation of mass. Evaluation of the transport rates is further constrained by the laws of thermodynamics which govern the partitioning of energy fluxes associated with the forces that drive the sediment. Thus application of the driving forces to the hudget of sediment within the framework of the littoral cell permits critical evaluation of the "goodness of fit" of the processes at work in the cell.

The Nile littoral cell extends from Alexandria, Egypt to Akko on Haifa Bay, Israel. The driving forces are the waves and currents associated with the east Mediterranean gyre. The forces transport Nile River sediment from the delta to Haifa Bay. Althongh many details remain to be clarified, this paper makes clear a numher of aspects important to understanding the hudget of sediment in the Nile littoral cell. These are stated below in the form of tentative conclusions:

1. Mineralogical stndies show that the principal source of sand for the heaches and shelf from Alexandria to Akko was the Nile River. The Nile was also the source of much of the finer sediments on the outer shelf and in the Levant basin (Figure 3).

2. A decline in sediment supply from the Nile to the Mediterranean Sea coast coincided with the constrnction of the Low Aswan Dam in 1902. Completion of the High Aswan Dam in 1964 resnlted in a total loss of Nile River sediment.

3. The net average supply of sand size msterial to the sea by the "free" Nile appears to have been ahout 20 to 40 million m^3/yr. The total supply of all particulate material in the hedload and suspended load wss about 160 million tons/yr.

4. Waves and currents associated with the east Mediterranean gyre are the principal driving forces that transport sediment to the east and northeast along the coast. It is estimated that the energy dissipation due to current action over the sediment hottom of the Nile delta is abont 2.5×10^6 kW, while that associated with wave action nearshore is abont 0.5×10^6 kW. The relative importance of waves and currents in transporting sediment is not clear.

5. Observations near structures show that the longshore sand transport rates by waves is greatest in the vicinity of the Nile delta ($\sim1\times10^6$ m^3/yr), decreases to ahont one-half off Bardawil ($\sim0.5\times10^6$ m^3/yr), and to about one-tenth near Haifa ($\sim0.1\times10^6$ m^3/yr). Longshore sand transport rates hased on models using measured wave energy fluxes are in general agreement with these transport rates.

6. There is over an order of magnitude difference hetween the rates of erosion measured from the shoreline to 6 m depth along the Nile delta ($\sim20\times10^6$ m^3/yr) and the longshore sand transport by waves ($\sim1\times10^6$ m^3/yr). This suggests that currents sweeping across the shallow shelf of the Nile delta are important in transporting sand to the east. The strong eddy off the Damietta promontory appears to be a transport mechanism that moves about 19×10^6 m^3/yr. Accordingly, there must be a numher of "modern", local sediment sinks within the overall cell. One appears to be between Port Said and Bardawil, the other hetween Bardawil and El Arish (Figure 3).

Figure 3. Budget of sediment for the Nile Littoral Cell.

The term "modern" is applicable because as the Damietta promontory erodes back, the intensity of the eddy will decrease, causing the sediment transport capacity to decrease.

7. Windblown sand canses a loss of sand from the beaches of the cell as indicated by the many coastal dune fields. Unfortnnately, the rates of loss have not been carefully monitored. However, loss by windblown sand may help to explain the absence of widening beaches that otherwise would occur under the overall negative gradient in the longshore sand transport with distance to the east.

8. Cliff erosion is not generally important to the budget of sediment except locally in Israel where it may contribute to the beach sediments north of Tel Aviv.

The above tentative conclusions regarding the driving forces, the sediment sources and sinks, and the sediment transport paths have been placed in the framework of the budget of littoral sediment for the Nile littoral cell in Figure 3. It is apparent that much more detailed study is needed to further quantify the budget. However, Figure 3 should serve as a useful framework for the guidance of future studies.

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