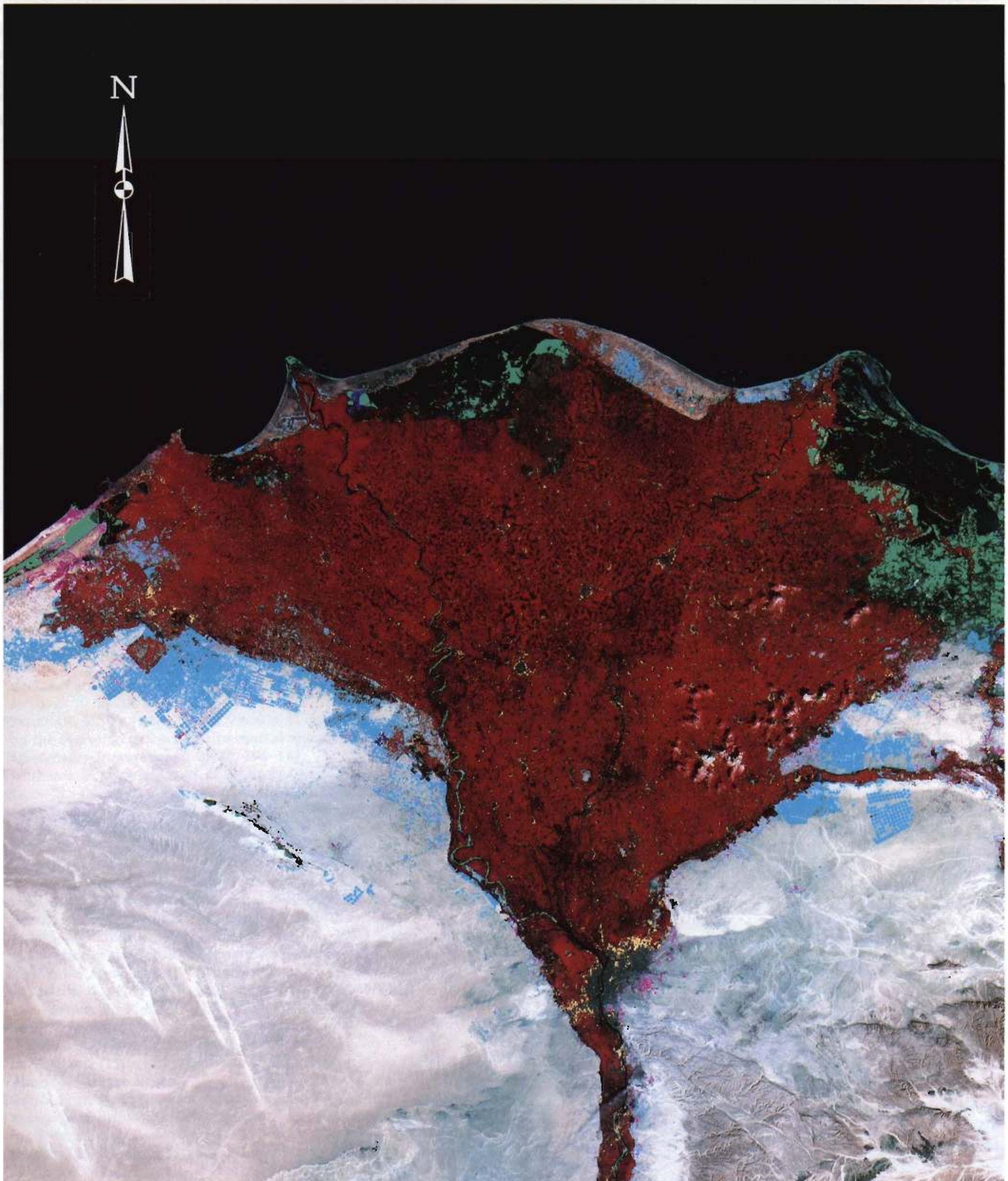

Plate 1. Satellite mosaic of the River Nile delta in Egypt, compiled by Earth Satellite Corporation, using Landsat images from 1972 to 1990. The image records Cairo at the delta apex, vegetation (red), urban expansion (yellow), development of large sand dunes (pink), coastal erosion (especially of the two promontories), and formation of salt pans (white, far right). Reclamation projects are draining what is left of lagoons and marshes (green). The Sweet Water Canal (red) extends from the eastern delta margin to the Suez Canal. Conversion of desert to agriculture along the delta margins is shown in light blue. Further explanations are presented in the accompanying article. Photo provided by D.J. Stanley, Smithsonian Institution, Washington, D.C.

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Nile Delta in its Destruction Phase

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ABSTRACT

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All deltas undergo alternating construction to destruction phases due to fundamental changes in the relative influence of sediment input from rivers and redistribution by marine coastal processes. During the past 7000 years world deltas, including the Nile, have been in an overall construction phase. However, the Nile delta has converted to a destruction phase during the past 150 years, triggered by water regulation which has disrupted the balance among sediment influx, erosive effects of coastal processes, and subsidence. This former depocenter has been altered to the extent that it is no longer a functioning delta but, rather, a subsiding and eroding coastal plain.

Symptoms of the destruction phase of the Nile delta include accelerated coastal erosion and straightening of the shoreline, reduction in wetland size, increased landward incursion of saline groundwater, and buildup of salt and pollutants to toxic levels in wetlands and delta plain. Without seasonal flushing by floods, the former delta plain surface is now incapable of recycling and/or removing agricultural, municipal and industrial wastes generated by Egypt's rapidly expanding population. Moreover, the remaining capacity of the system to regenerate itself will further diminish as water is diverted away from the delta for new irrigation and municipal projects in the Egyptian desert, and water allocations to Egypt are decreased by upstream countries.

Reestablishing some level of natural hydrology is the only credible solution for attaining equilibrium among sediment accretion on the delta plain to offset subsidence, progradation along the coast to offset erosion, and sufficient water influx to flush and remove the high levels of salt and pollutants throughout the system. However, increased Nile water and sediment discharge could begin to restore a functioning delta system only if there is a substantial reduction in human impacts.

ADDITIONAL INDEX WORDS: *Aswan dams, barrages, canals, coastal erosion, delta construction, delta destruction, diseases, drill cores, Egypt, industrial waste, lagoons, Lake Nasser, land conversion, Mediterranean Sea, Nile Cone, Nile delta, pollution, population pressure, River Nile, salinization, waterways, wetlands.*

"in the part called the Delta, it seems to me that if the Nile no longer floods it, then . . . the Egyptians will suffer."

Herodotus, *The History*

INTRODUCTION

Marine deltas evolve from interaction of global-to-regional scale natural processes, plus the additional influence of more area-specific conditions (SHIRLEY, 1966; MORGAN, 1970; BROUSSARD, 1975; COLEMAN, 1982; OTI and POSTMA, 1995; MILLIMAN and HAQ, 1996). Delta progradation typically prevails during construction phases when fluvial processes dominate at the mouth of a river, while destruction phases occur when marine coastal processes dominate. Largely from analysis of drilling and seismic survey data, geologists have interpreted the evolution of the Nile delta and contiguous Nile Cone along the northeastern African platform during the past ~5 1/2 million years (Figures 1 and 2). These studies (*e.g.* SESTINI, 1989) indicate that interaction of natural factors (tectonic framework, climatic and sea-level fluctuations, fluvial and marine processes) produced a partially superposed sequence of Neogene to Quaternary Nile deltas. Evolution of these stacked depocenters involved alternating construction and destruction phases, typical of deltas in general. Waxing and waning of depocenters were primarily a function of changes in interaction between fluvial input and sea-level change.

Most geological studies of the Nile have focused on the construction phase of the most recent (Holocene) depocenter (SESTINI, 1989, 1992; SAID, 1993; STANLEY *et al.*, 1993; STANLEY and WARNE, 1993a; WARNE and STANLEY, 1995; EL-SAYED, 1996). When described by Herodotus almost 2450 years ago, the Nile delta was actively prograding. However, human modification of the lower Nile system during the past 150 years has almost completely terminated Nile delta progradation and aggradation. The Nile River's classic fan-shaped depocenter appears to have been altered to a greater degree by intensified anthropogenic activity than most of the other populated world deltas. These changes are primarily a function of rapid population increase during the 20th century (JEFTIC *et al.*, 1992), and have serious ramifications for

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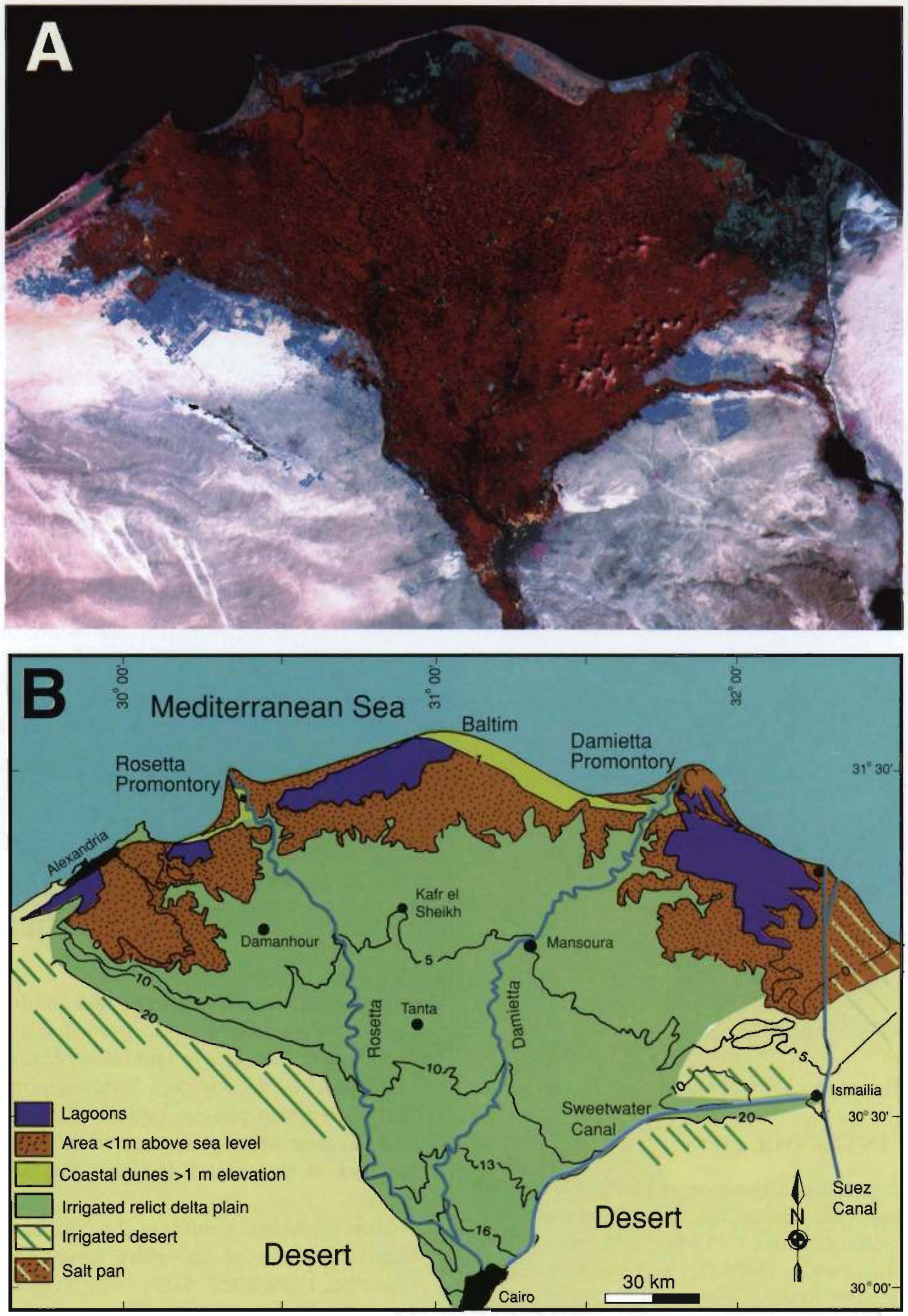

Figure 1. (A) Landsat mosaic (1972–1990) of the Nile river delta, bounded by desert, showing urban expansion (yellow), development of large sand dunes (pink), coastal erosion, and formation of salt pans (white, far right). Reclamation projects are reducing the remaining lagoons and marshes (green), and new agriculture projects developing along the delta margins (blue). The satellite image was provided courtesy of Earth Satellite Corporation. (B) Main topographic and geographic features of the Nile delta (contours in m) and major cities (modified from Sestini, 1992).

Egypt. Not only is the Nile delta subject to intense human pressures, it also remains vulnerable to natural factors such as coastal erosion that continue unabated. Anthropogenic pressures have degraded the Nile delta to such an extent that the depocenter is no longer an actively functioning delta. Principal consequences affecting the human-induced delta destruction phase include: incursion of the sea and saline ground water into low-lying northern sectors, coastal erosion, and decreased capacity to regenerate itself.

No other country is as dependent on a single fluvial system

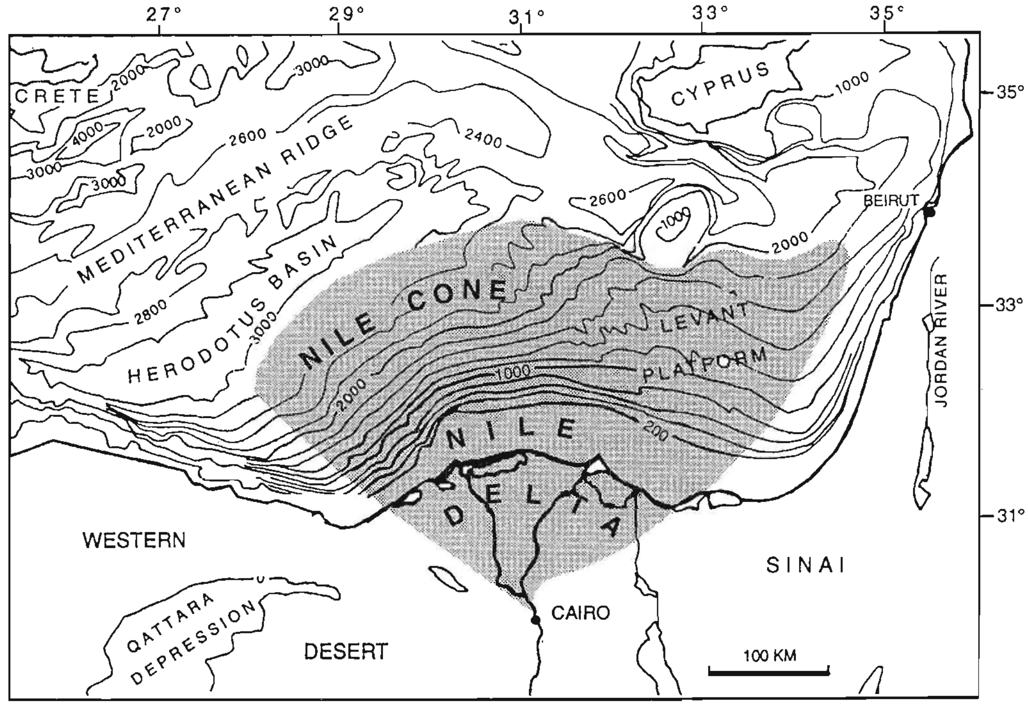

Figure 2. Southeastern Mediterranean (contours in m) with shading showing Nile delta and its subaqueous extensions, the Nile shelf and Nile Cone (modified from Sestini, 1989).

as Egypt, which is situated in the eastern Sahara (Western Desert, NW Sinai), one of the world's most extensive and severe deserts (BISWAS, 1992, 1993; SAID, 1993; Figure 1). The population of Egypt has increased from 10 to nearly 65 million in the past 100 years, with a growth rate that approximates 1 million per year (WORLD BANK, 1990). This results in a per-capita arable land area of only 0.06 hectare, the lowest of any African country. More than 90% of the population lives adjacent to and relies directly on the Nile and its delta, terrains that constitute less than 5% of the country's total area. About 40 million people (locally to >1000 persons/km^2; Figure 3) are now concentrated between the Nile delta apex at Cairo and the delta coast, an area the size of Delaware, one of the smallest states in the U.S. Recent hydrographic studies show that 98% of the available freshwater in Egypt is presently utilized (SAID, 1993), and water is the country's major constraint for sustaining its growing population (U.S. DEPARTMENT OF AGRICULTURE, 1976).

Herein, we focus on the modern Nile delta of Egypt (Figure 1) to develop the postulate that intensified human pressure can modify the evolution of some deltas to a greater extent than natural factors, and induce the transition from construction to destruction phase. The intent of the study is: (1) to review the natural factors that led to the construction phase of the Holocene delta; and (2) to evaluate the type and extent of human alterations and their impact on the Nile delta. We hope that this information will provide some practical insight for future planning of this and other densely populated marine deltas.

EARLY NILE DELTA EVOLUTION

A review of the long-term history of the Nile delta provides a gauge to compare the earlier natural ecosystems with the present relict delta that is undergoing a human-induced destruction phase. During the Cenozoic, the northeast African platform was not drained by a single master stream, as it is today, but by a succession of at least three different major systems that evolved and migrated through time in response to large-scale lateral structural displacement, major uplift (especially in the Red Sea-Eastern Desert-Sinai region), and sea-level changes. Recent investigation shows that, prior to Miocene time, some important ancestral rivers actually flowed from east to west, rather than from south to north (ISSAWI and MCCAULEY, 1993). The north-flowing Nile system that extends across East Africa to the general area of the modern Nile delta is a geologically recent phenomenon that dates back to the late Miocene (SAID, 1981).

The marked drawdown of sea level at that time, primarily caused by restriction of passages between the Atlantic and Mediterranean and evaporation of sea, has long been a source of geological interest. Regional studies identified a much-altered oceanic communication between the two water bodies (through southern Spain and northern Morocco), and consequent major paleogeographic responses, especially in late Miocene time (review in GIGNOUX, 1955, his Chapter 10). More recently, some workers have generalized that the Mediterranean during the Messinian was a dry desert formed in a deep depression that locally exceeded 3000 m (HSU *et al.*,

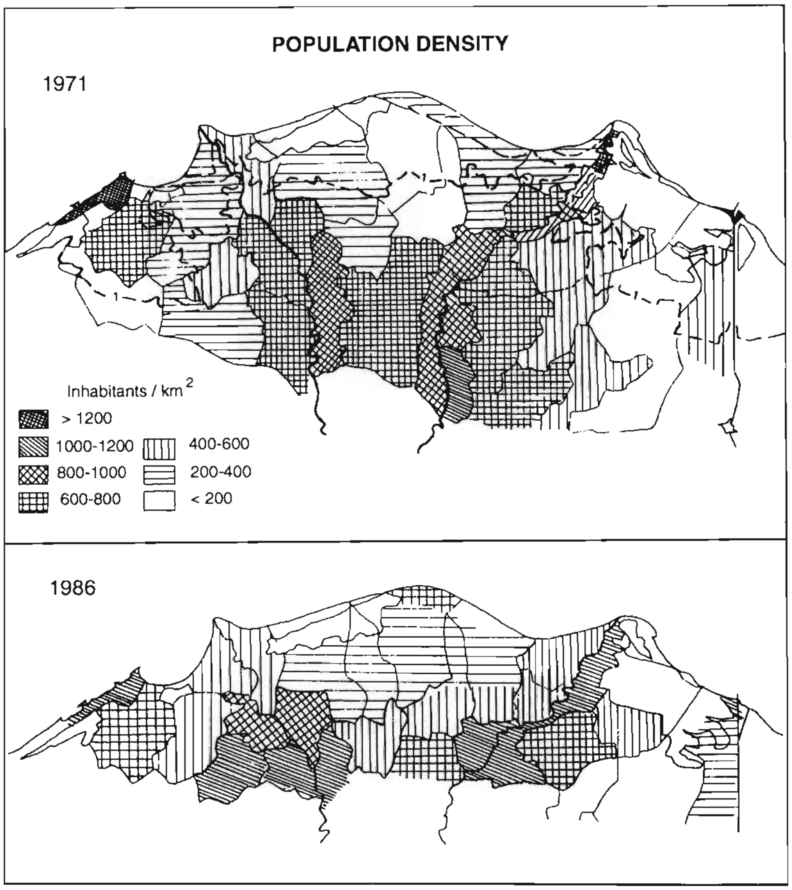

Figure 3. Population in the central and northern Nile delta, highlighting increased density from 1971 to 1986 (after Sestini, 1992).

1973). In fact, studies of the Miocene to Pleistocene stratigraphy of eastern Mediterranean margins record a substantial, but less extreme, lowering of sea level to about 1500 m (STANLEY, 1977). This event induced incision of the Egyptian margin by the ancestral Nile to form a deep valley (SAID, 1981).

The Nile delta began to develop in Messinian time, as the Nile extended northward from the African lakes plateau, and crossed the Sudd, Central Sudan, Ethiopian highlands, and Cataracts region of Sudan to Upper and Lower Egypt (SESTINI, 1989). During the Messinian lowering of sea level, the Nile (Eonile, Table 1) discharged its load on a broad, subaerially-exposed continental margin (Figure 4A). The early Pliocene marine transgression that followed, caused the sea to invade and fill the incised and down-faulted valley of the Nile to as far south as Middle Egypt (Figure 4B). Structural displacements of eastern Egypt continued to affect the Nile system during the Pliocene and Pleistocene (Figure 4C).

Ancestral Nile flow fluctuated markedly during its history (BUTZER and HANSEN, 1968; WENDORF and SCHILD, 1978; and SAID, 1981, 1993; Table 1). Field mapping, seismic surveys and drilling, primarily for hydrocarbon exploration, have revealed a thick (to >3000 m; Figures 4, 5) accumulation of superposed and partially overlapping terrigenous depocenters in the vicinity and underlying the Holocene delta plain (ZAGHLOUL *et al.*, 1977, 1979a,b; RIZZINI *et al.*, 1978; SHAWKY ABDINE, 1981; SCHLUMBERGER, 1984). Alternating construction and destruction phases were a function of interaction among sediment supply, tectonic displacement and major rises and fall of sea level that induced development of this stacked delta sequence.

Surveys at sea indicate that early Pliocene to modern delta facies underlying the subaerial Nile delta plain extend and interfinger with widely dispersed submarine sections of comparable age in the Nile Cone (ROSS and UCHUPI, 1977; STANLEY, 1977). The Cone, comprising thick terrigenous units of Nile derivation, forms the slope off Egypt (Figure 5), and is many times larger than the subaerially exposed fan-shaped Nile delta. The Cone is roughly 500 km wide and 800 km in length (Figure 2), comprises largely silt with interfingering sand strata, and locally exceeds 3000 m in thickness (Figure 5). This arcuate sediment prism extends from the North African coast northward to the Mediterranean Ridge (FINETTI, 1976), and from eastern Libya to the Israeli-Lebanese margin (ROSS and UCHUPI, 1977).

The Neogene to Pleistocene Nile Cone is derived from ter-

Table 1. *Synthesis of major events that shaped the Nile River and delta since the late Miocene (modified from* SAID, *1993).*

Dates (in thousand years)	Nile Phase	Summary of Processes and Responses
6000–5400	Eonile	Incision of Nile canyon in response to desiccation and lowered Mediterranean (late Miocene, Messinian)
5400–3300	Gulf	Rising waters of the regenerated Mediterranean fill the incised canyon, converting it into a long N–S trending estuary (early Pliocene)
3300–1800	Paleonile	Local river occupies the long estuary and fills the valley with sediments (Pliocene)
1800–800	Desert	Egypt converted into desert, and river stops flowing (early Pleistocene)
800–400	Prenile	Egyptian river with an African connection fully established; the river carries many more times the volume of sediment than historic Nile (Pleistocene)
400–present	Neonile	A generally less competent river with oscillations in flow volumes between 100 and 300 m^3/annum. The first Neonile phase interrupts a wet phase (400,000–200,000 years); this is followed by one that is seasonally erratic (200,000–70,000 years), then by a seasonally flowing river (70,000–12,000 years), and finally by the modern perennial Nile (12,000–present)

rigenous sediment carried by traction and downslope gravitative mechanisms from the coast to beyond the shelfbreak. Sediment accumulation rates on the Cone increased substantially during late Miocene to late Quaternary sea-level low stands, when the Nile discharged its load directly onto the upper slope (BARTOLINI *et al.*,1975). This sea-level effect is demonstrated by incision of the Alexandria canyon on the outer shelf and by study of late Pleistocene Cone deposits formed about 20,000 years ago, during the most recent lowering of sea level. At that time, the proportion of sand markedly increased relative to silt and clay near the shelf break, on the Cone surface and in basin plains at the base of the Cone (MALDONADO and STANLEY, 1976, 1978; STANLEY and MALDONADO, 1977).

Largely a depositional feature resulting from >5 million years of Nile discharge, the Cone forms a highly irregular topographic surface influenced by isostatic subsidence, faults and underlying salt tectonics (ROSS and UCHUPI, 1977; ALMAGOR, 1979; GARFUNKEL, 1984; SCHLUMBERGER, 1984; STANLEY, 1985; BELLAICHE and MART, 1995). Some tectonic structures, especially large-scale faults that extend from the Levant-North Sinai sector to the Nile delta region, are an integral part of active Eastern Mediterranean formative processes (Figure 6). The NE-SW trending Pelusium shear system, Nile delta block faults, and offshore rotational and graben fault systems are among the more important regional structures that have affected the Egyptian shelf, coast and slope topography and depositional patterns (NEEV, 1975; NEEV *et al.*,1976, 1980; MART, 1984). Other structures are produced by isostatic loading and gravitative phenomena, and still others by compaction and underlying halokinesis.

HOLOCENE PALEOGEOGRAPHY AND DELTA DEVELOPMENT

Stratigraphic analysis of late Pleistocene alluvial to Holocene deltaic deposits in drill cores (Figure 7A) serves to detail the history of the modern Nile depocenter (FOURTEAU, 1915; ATTIA, 1954; SNEH *et al.,* 1986; SESTINI, 1989; STANLEY *et al.,* 1996). Core analysis provides a basis to determine long-term trends in delta evolution, record the relative influence of natural factors in formation prior to human modification, and to differentiate the effects of natural versus anthropogenic processes in the modern Nile.

Data and interpretations, from the northern delta, are presented in COUTELLIER and STANLEY (1987), STANLEY *et al.* (1992b), ARBOUILLE and STANLEY (1991), CHEN *et al.* (1992), WARNE and STANLEY (1993b), and STANLEY and HAMZA (1992). The thickness of Holocene strata beneath the modern delta plain ranges from 10 to 50 m, and tends to increase northward toward the coast. Thickening is a direct function of subsidence of the delta substrate north of a coast-parallel hingeline (WARNE and STANLEY, 1993a; Figure 7B).

The following abbreviated summary of late Quaternary paleogeographic history is extracted, from STANLEY and WARNE (1993a, p.631–632):

> From ~35 to 18 ka, most of the region was an alluvial plain across which seasonally active braided channels flowed (Figure 8A). During sea-level lowstand, when the coast migrated by as much as 50 km to the north, floodplain mud accumulated in ephemeral, seasonally dry depressions. Carbonate-rich desert sand and sabkha mud were deposited in the west, in a generally arid climate. These desert deposits accumulated between and near older, elevated carbonate ridges (BUTZER, 1960; STANLEY and HAMZA, 1992; HASSOUBA, 1995). Intermittent marine incursions during this period are recorded by localized, shelly shoreline sand (COUTELLIER and STANLEY, 1987).
>
> As sea level rapidly rose ~15 to 8 ka, the high-energy shoreline migrated landward (southward), and former alluvial plain deposits were reworked. The landward limit of the nearshore sand approximates the extent of the ma-

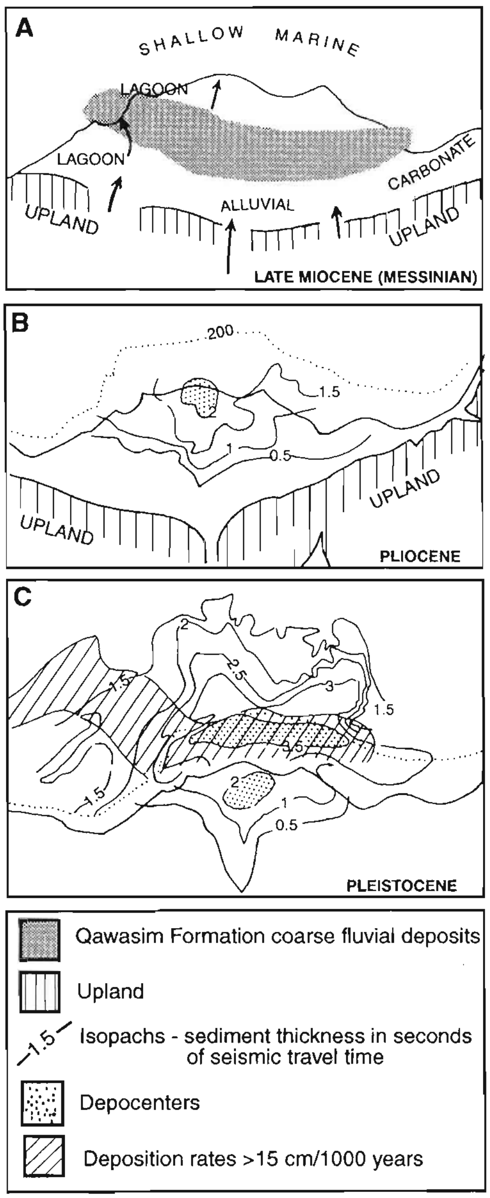

Figure 4. Geologic reconstructions of the Egyptian platform and Nile delta region during the late Miocene, Pliocene and Pleistocene; isopachs highlight the extensive accumulation of clastic sediments, including stacked delta sequences since the Pliocene (modified from Sestini, 1989).

rine transgression onto the former alluvial plain; absence of this transgressive sand in the south and west (Figure 8B) indicates that the northern delta region was tilting to the northeast as early as the late Pleistocene. The position of Nile channels during this period is currently unknown.

By 7.5 ka, the modern Nile delta had begun to form. Progradation of this delta occurred during deceleration in the rate of sea-level rise and rapid influx of sediment; as a result, reworking of these deposits by waves and currents was limited. At ~6.5 ka (Figure 8C), sea level was at 9 to 10 m below its present stand (PIRAZZOLI, 1991; TOSCANO and LUNDBERG, 1998), the river gradient was steeper, and climate was somewhat more humid. Both delta morphology and facies distribution were primarily controlled by the Sebennitic channel, which transported large volumes of medium to coarse sand to the coast. This sand formed an extensive accreted beach ridge system at the headland of a cuspate-shaped, river-dominated delta. Sand ridges developed a nearly continuous barrier along seaward margins of widespread lagoons and marshes. Coalescing delta lobes developed seaward of major distributary mouths (such as the Mendesian and Pelusian) in the Manzala lagoon region (COUTELLIER and STANLEY, 1987; PUGLIESE and STANLEY, 1991). This preservation is in large part a result of the northeast tectonic tilt of the delta and rapid burial of these deposits. Lobe deposits off distributaries to the west (including Sebennitic and Canopic) have not been recovered.

By ~4 ka, sea level continued to rise, but more slowly, and the gradient of the delta plain diminished. Climate had become arid, flood levels subsided, and more distributary channels carried a less coarse bedload. This period records the transition from a river-dominated, cuspate delta to a wave-dominated, arcuate delta (Figure 8D). The northeastern sector continued to prograde, whereas the north-central coast began to retrograde. The continuous belt of coastal sand along the delta margin continued to serve as a barrier for extensive lagoon-marsh environments. Humans, who had settled in the delta as early as predynastic time [~7 to 5 ka (SNEH and WEISSBROD, 1973; HOFFMAN, 1979; HASSAN, 1984; WENKE, 1991)], established important population centers such as Buto and Menshat Abu Omar (KROEPER and WILDUNG, 1989; ANDRÉS and WUNDERLICH, 1991). Nonetheless, wetlands remained the primary ecosystem in the northern delta during early to mid-Pharaonic time (BALL, 1942; BUTZER, 1976; STANLEY *et al.*, 1992a).

By ~2 ka (Figure 8E), sea level had risen to about 2 m below the present level, and marine waves and currents molded the coastline so that the delta margin configuration began to resemble the modern shoreline. By this time, the delta had become more wave dominated and had a gentle, arcuate form. However, there remained at least five distributaries, most with small promontories, that continued to transport significant volumes of sediment to the coast during annual floods (TOUSSOUN, 1922; EL BUSEILI and FRIHY, 1984). Extensive coastal dune fields developed in the north-central delta from eroded Sebennitic promontory sediments. By this period, humans were significantly influencing delta evolution: population increased in the delta during Hellenistic time, particularly in the Alexandria-Naukratis sector (DE COSSON, 1935); the Damietta (Bucolic) and Rosetta (Bolbitine) channels were maintained by artificial excavation (SAID, 1981); and intensified irrigation and wetland drainage projects were substantially modifying the delta surface (BUTZER, 1976).

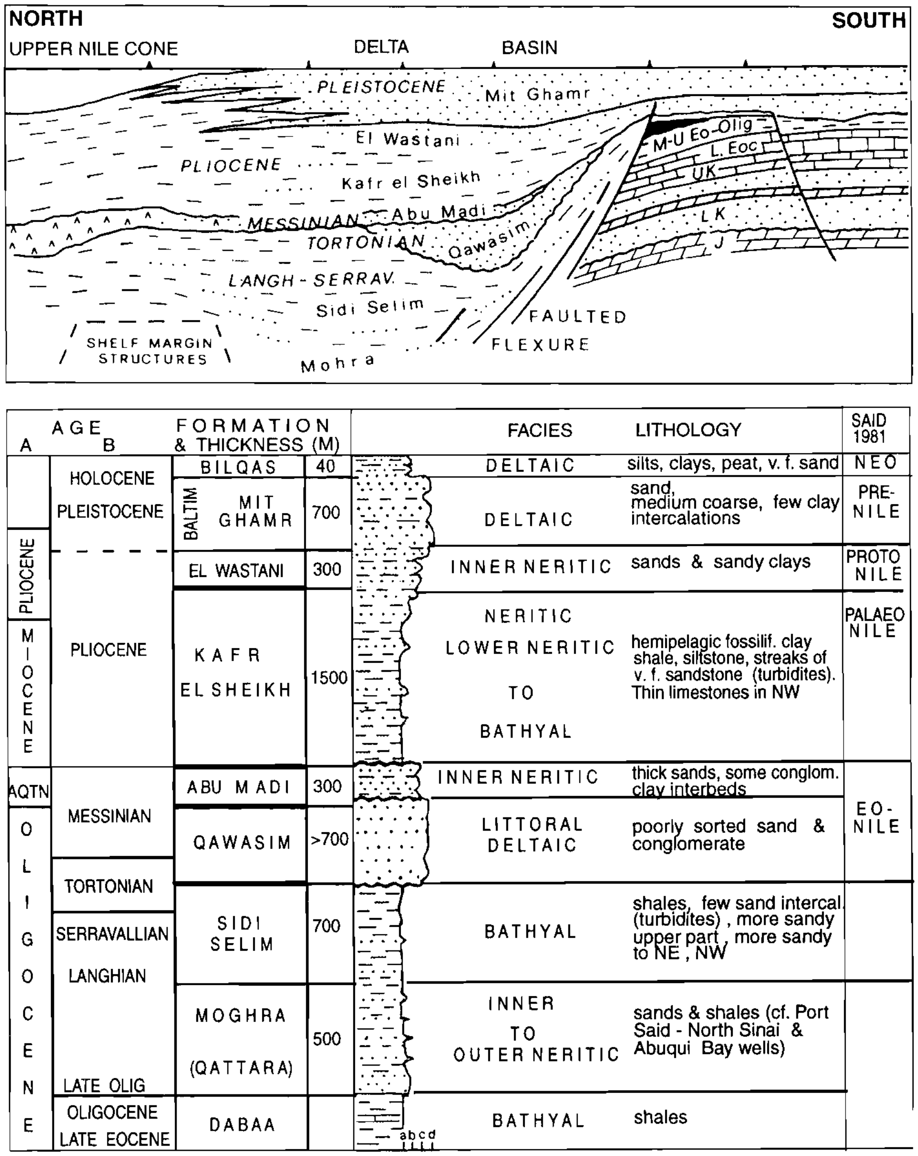

Figure 5. Upper, schematic stratigraphic and tectonic configuration from the Nile delta to the Upper Nile Cone. Lower, stratigraphic log showing late Eocene to Holocene formations, their thicknesses and lithologies (modified from Sestini, 1989). Ages A and B are different time interpretations for the formations shown. The Miocene to Holocene Nile river phase terminology is after Said (1981), and further explained in Table 1.

During the first millennium A.D., major Nile distributary channels were reduced to two, the artificially maintained Damietta and Rosetta branches. Distinct promontories accreted at their mouths because they were the only two channels transporting sediments to the coast (Figure 2). As other distributary channels were converted into canals and drains that no longer extended to the coast, their waters were diverted for irrigation, and flow was reduced. Wetlands of the middle and southern delta were extensively drained and cultivated (Hoffman, 1979; Wenke, 1991). Coastal dune fields continued to expand, particularly in the vicinity of Baltim and west of the Rosetta promontory.

The Nile delta began its most recent construction phase during the period of worldwide deceleration in rise of Holocene sea level, from about 8000 to 6500 years BP. This was the time when most of the world's marine deltas evolved, as the rates of fluvial input at river mouths became greater than rates of sea-level rise and marine incursion (Stanley and Warne, 1994).

NATURAL NILE DELTA PROCESSES

The modern Nile delta has formed at the mouth of one of the world's longest (6690 km) rivers, which drains a basin area of ~2,880,000 km^2 (Figure 9). Annual average discharge

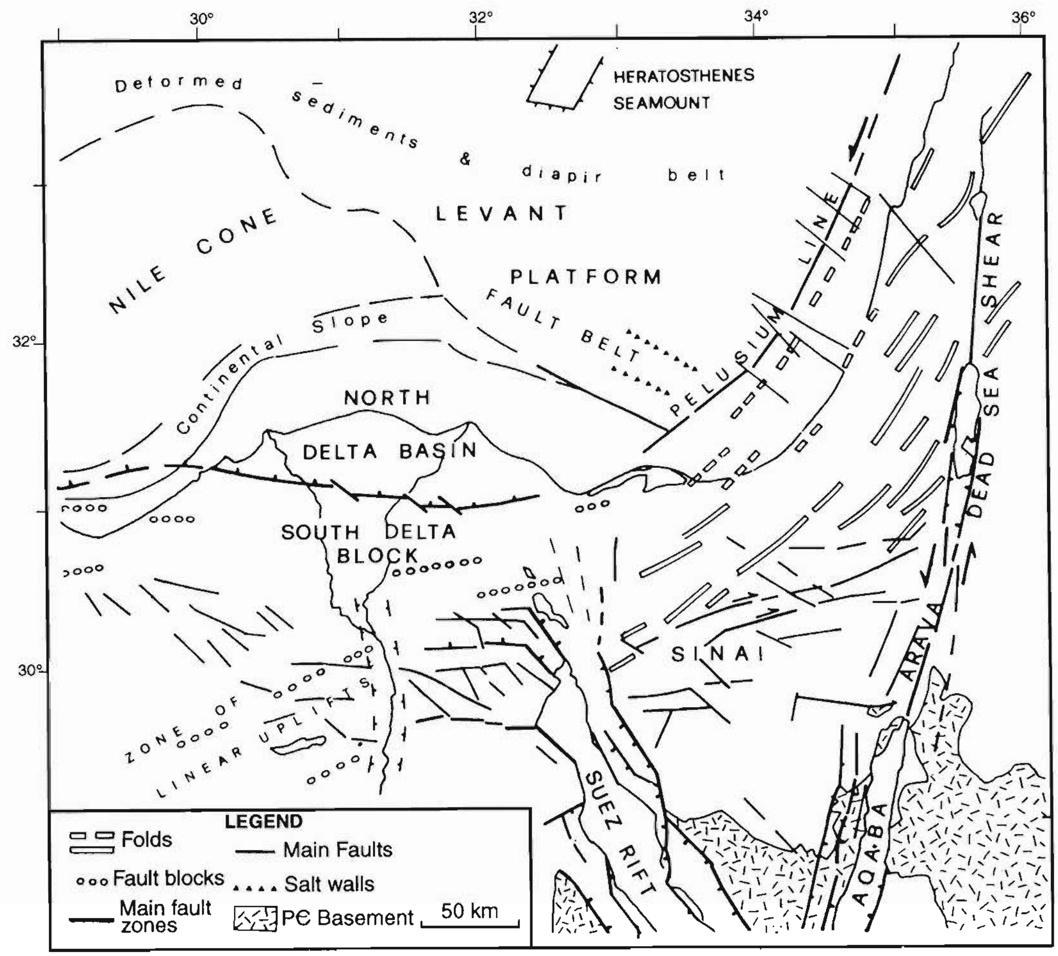

Figure 6. Major structural features in the southeastern Mediterranean, including those affecting the Nile River, Nile delta and Nile Cone (after Sestini, 1989).

exceeded 100 billion m^3 in the 19th Century, and has averaged 84 billion m^3 during the 20th Century (Sestini, 1992; Said, 1993). The Nile during the Holocene is characterized by a generally low discharge rate when compared to many shorter rivers with smaller drainage basins (Coleman, 1982). More than 80% of the Nile river's total discharge occurs from August to October, while ~20% (~15 billion m^3) is distributed during the remaining 9 months (Figure 10).

The delta is sited in a hyperarid region, with temperatures ranging to over 30° C in July, and mean annual precipitation ranging from ~200 mm at the coast to <100 mm on the delta. Mean potential evapotranspiration rates range from ~600 to 1100 mm/year (Beaumont *et al.*, 1976); potential evapotranspiration is the maximum amount of evaporation and transpiration that would occur from a vegetated surface if an abundant and continuous supply of moisture is available in the upper soil layers.

The delta plain encompasses ~22,000 km^2 and is delineated to the north by a wave-cut arcuate coast that is ~225 km long. The delta radius, from its apex at Cairo to the coast, is 160 km, and elevation decreases from 18 m at Cairo to 1 m or less along much of the coast (Figure 1B). The plain is constrained along its NW margin (Figure 8G) by Pliocene delta and Pleistocene coastal carbonate terrains (Said, 1981; Hassouba, 1995), and to the northeast by a major NE-SW trending fault system (Neev *et al.*, 1976; Figure 6).

Delta development is largely a balance between rates of fluvial sediment input and accumulation at and near a river mouth and adjacent shelf, versus rate of sediment removal by coastal processes at these sites (Figure 10). Since the late Pleistocene, most Nile River sediment carried to Egypt has been transported by the Blue Nile and Atbara river which drain the Ethiopian Plateau and whose flow is induced primarily by summer monsoon rains in this region (Hurst, 1931–1966; Butzer and Hansen, 1968). In marked contrast, a large portion of sediment carried by the longer and more continuously flowing White Nile, draining the larger Central African (Kenyan) Plateau, is deposited in the Sudd swamps of southern Sudan well to the south of Egypt (Figure 9). Recent core analysis has identified the presence of some thin

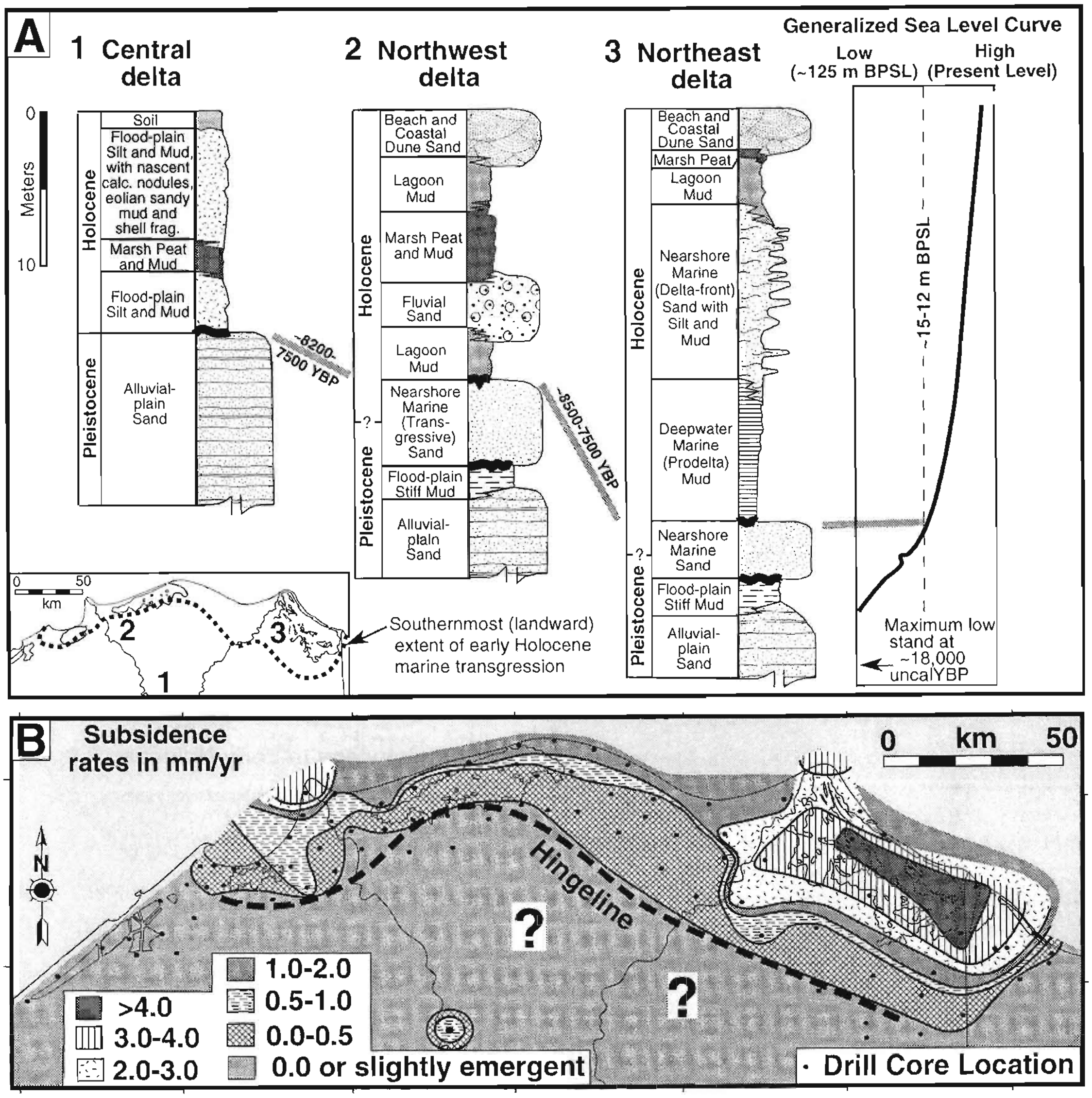

Figure 7. (A) stratigraphic logs, simplified from numerous core sections, depicting late Pleistocene alluvial sequences overlain by Nile delta Holocene deposits. Transition from late Pleistocene to nearshore transgressive to Holocene deltaic units is related to deceleration in rate of sea-level rise (modified from Stanley and Warne, 1993b). (B) schematic showing land subsidence rates in the northern delta, with values ranging to >4 mm per year. Hingeline delimits marked change in rates of subsidence north of which thickened Holocene sections occur (modified from Stanley and Warne, 1993a).

Holocene-age strata sections derived from episodic, yet powerful, White Nile floods (FOUCAULT and STANLEY, 1989; HAMROUSH and STANLEY, 1990).

Late Pleistocene deposits along the Nile valley record significant discharge fluctuations, such as the remarkably low flow from ~19,000 to 13,000 years BP during an arid period, and major White Nile floods from ~12,000 to 10,800 years BP (ADAMSON *et al.*, 1980); this latter phase records a wet period with high discharge and large volumes of coarser bedload (SAID, 1981). Analyses of Holocene records (POPPER, 1951; BELL, 1975; QUELENNEC and KRUC, 1976; HASSAN, 1981), including river terrace formation, Nilometer and other historic documentation, serve to estimate annual flow volumes (SAID, 1993; Figure 11) and suspended load variability over the past 10,000 years. Analyses indicate that flows during the early Holocene were as much as 3 times historic annual flow volumes. Short-term flood peak cycles (8–12, 18–20 and 60–90 years) which prevailed during the past two millennia have also been identified (HURST, 1931–1966; HAMID, 1984; SESTINI, 1989).

Prior to emplacement of barrages on the Nile and in the delta during the last century, the average annual sediment load, primarily silt carried in suspension, ranged from 50 to 300 × 10^6 tons (QUELENNEC and KRUC, 1976). During peak flood months of August and September (Figure 10), much of this load was transported to and beyond the delta coast.

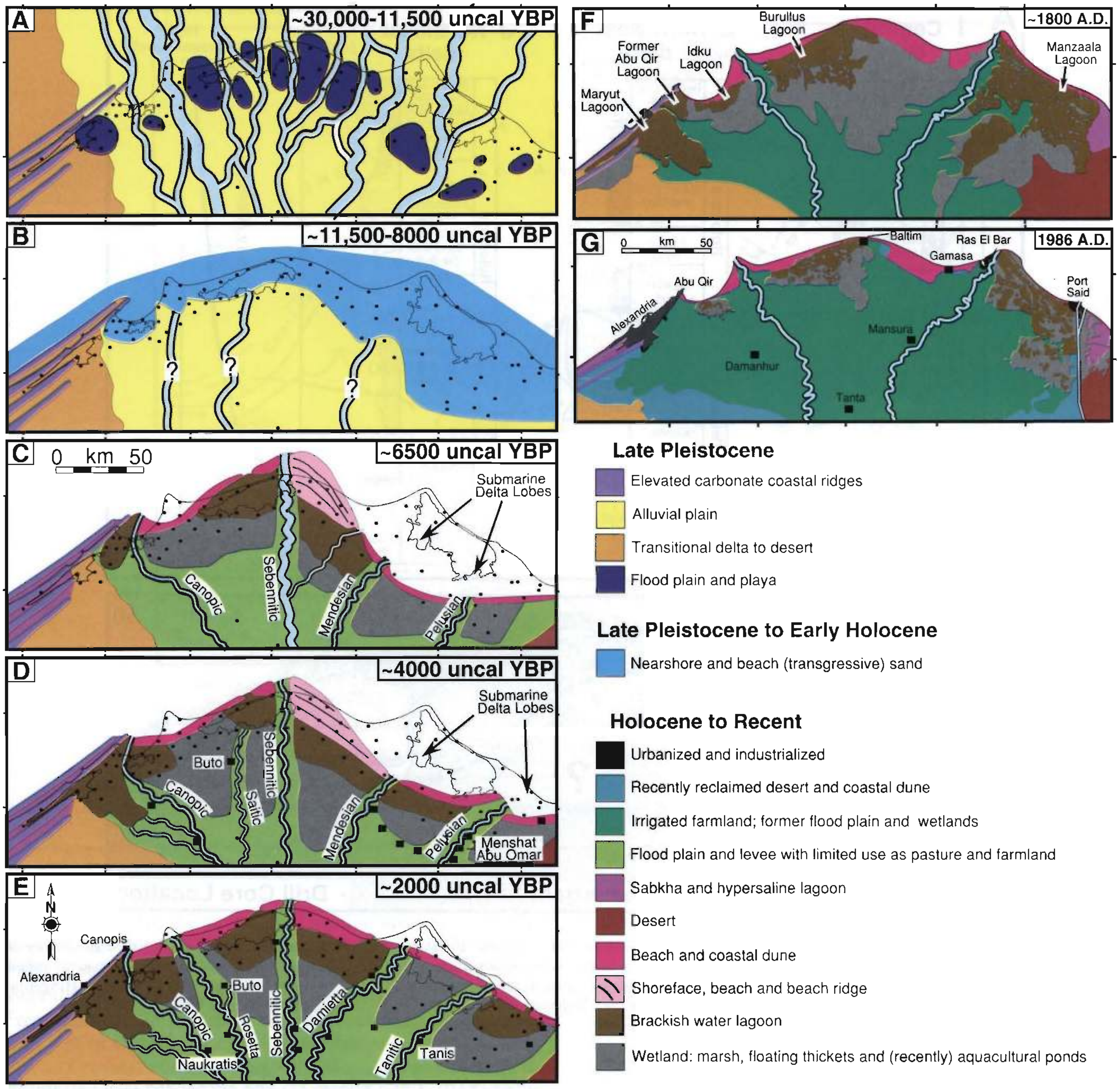

Figure 8. Time-slice paleogeographic maps depicting the evolution of the northern Nile delta from ~30,000 years BP to present (modified from Stanley and Warne, 1993a).

Nearly a third of the sediment load bypassing Aswan accumulated in the Nile valley and on the delta plain, accounting for as much as 5 to 10 $\times$ 10^6 tons of deposits per year in the delta proper. By the beginning of this century, however, up to 60% of water discharge was already lost in Egypt through seepage and evaporation associated with irrigation practices between Aswan and the Mediterranean coast (Sharaf El Din, 1977).

Nile sediment reaching the coast in summer and early fall was reworked by marine processing in a general eastward direction along the coast and on the shelf, especially in winter and spring (Figure 10). Patterns of fluvial sediment distribution that bypassed the coast and accumulated on the continental shelf off the Nile and southeastern Mediterranean margin have been reviewed in UNDP/UNESCO (1976, 1977, 1978) and Summerhayes *et al.* (1978). A model, known as

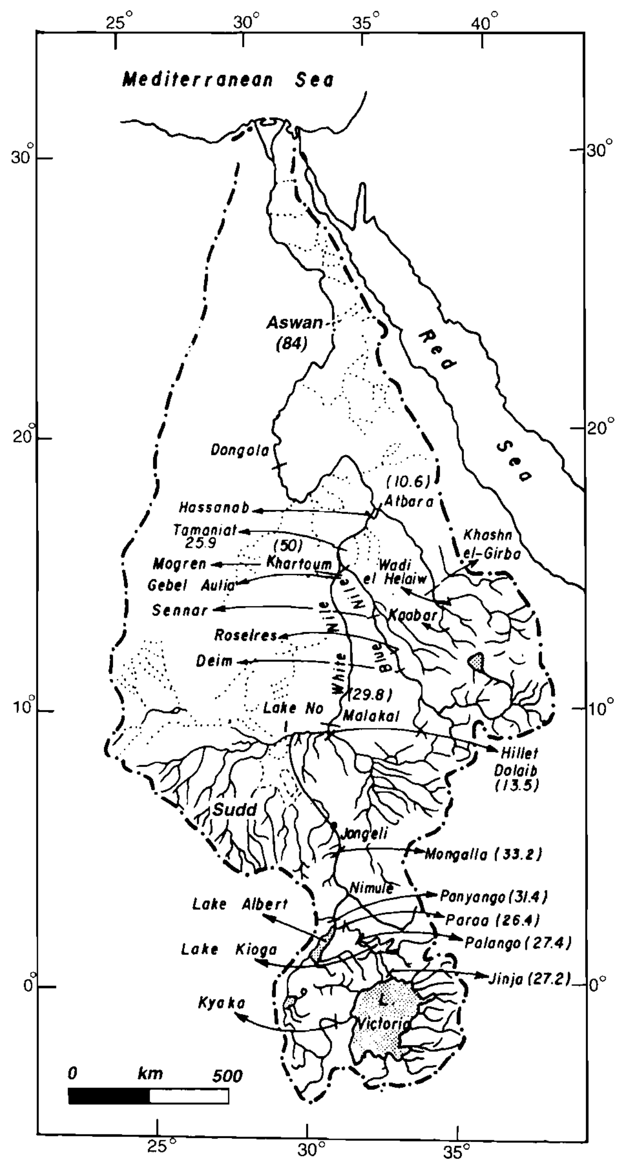

Figure 9. Map of east-central and NE Africa showing Nile River drainage basin and 1912–1982 average discharge in billion cubic meters (in brackets) of river water. Mean annual flow to Egypt during the 20th Century is 84 million m^3 (after Said, 1993).

the Nile Cell (INMAN and JENKINS, 1984), depicts the cyclic pattern of sediment discharge, transport by strong coastal shelf currents and deposition in the southeast Mediterranean (Figure 10). Archaeological evidence from the coast indicates that this regime has been in effect since the past 7000 years (STANLEY and GALILI, 1996). The southeastern Mediterranean, including the Nile delta margin, is characterized by a very low tidal range (spring tides average 30–40 cm), N-NW offshore winds that are active during most of the year, and the large-scale counter-clockwise circulation pattern that drives water masses eastward (Figure 10). Offshore surface geostrophic eddy velocities range to >0.25 cm/sec (SHARAF EL DIN, 1973; POEM GROUP, 1992).

As a response to an oblique wave approach, active longshore currents are generated with velocities measuring from 20 to 50 cm/sec, and occasionally to >100 cm/sec (UNDP/UNESCO, 1977). Storm waves with heights of 1.5 to 3 m approach the coast from the northern quandrant (commonly from the northwest), actively eroding and displacing sediment as coarse as sand eastward from the Nile delta coast to northern Israel (POR and BEN TUVIA, 1981; INMAN and JENKINS, 1984; FANOS, 1986: STANLEY, 1989; STANLEY *et al.*, 1998). Seasonal variability of wave approach produces converging and diverging current patterns along the coast, and—since the late Holocene—there has been a 2.5 to 7 km-wide zone of active sediment transport along the coast from the Nile delta to the Levant. Sand and coarse silt in this nearshore zone are eroded, stirred and displaced primarily toward the northeast and east (MANOHAR, 1976, 1981), some to depths of from 25 m to as much as 60 m (COLEMAN *et al.*, 1980; MURRAY *et al.*, 1981).

During much of Holocene time, the above active coastal processes, interacting with Nile sediment discharged at the coast, produced the arcuate-shape coastline and formation of coastal barriers and dune fields along much of the delta coast (STANLEY *et al.*, 1992b). These littoral processes also formed distinct, offshore coast-parallel sediment (SUMMERHAYES *et al.*, 1978) and faunal (BERNASCONI and STANLEY, 1997; STANLEY and BERNASCONI, 1998) patterns (Figure 12). Extensive wetlands, comprising marsh and shallow lagoons (JACOTIN, 1826; HALIM and GERGES, 1981; KERAMBRUN, 1986), formed landward of these sand barriers and dune fields (Figure 8). As demonstrated by coring in the northern delta, these wetland deposits constitute the most widespread and thickest Holocene lithofacies (STANLEY and WARNE, 1993a; STANLEY *et al.*, 1996), and their positions have continuously shifted through the Holocene construction phase of the delta.

From ~7500 years BP to the latter part of the last century, the coastline shifted as a function of the relative rate of sediment input and coastal erosion, and the form and elevation of the delta plain was a balance between sea level and sediment accretion (WARNE and STANLEY, 1995). Initiation of the delta followed a deceleration in rate of sea-level rise (Figures 7A, 13) from approximately 1 cm to 1 mm per year (STANLEY and GOODFRIEND, 1997). Tide gauges and other evidence indicate that world sea level is continuing to rise at or slightly more than 1 mm per year (MILLIMAN *et al.*, 1989; DELFT HYDRAULICS, 1991; MILLIMAN and HAQ, 1996; ZERBINI *et al.*, 1996; TOSCANO and LUNDBERG, 1998). Land subsidence in the northern delta continues at a rate between 1 mm (ZAGHLOUL *et al.*, 1990) and 5 mm (EMERY *et al.*, 1988; STANLEY, 1988b, 1990; STANLEY and GOODFRIEND, 1997) per year, with highest rates measured in the Port Said area (Figures 7B, 13). The rise of sea level, coupled with lowering of land, has resulted in an asymmetric rise of relative sea level across the low-lying northern margin of the delta. During the construction phase, however, sediment accumulation associated with annual flooding offset the effects of relative sea-level rise in the northern delta producing a mosaic resource-rich ecosystem.

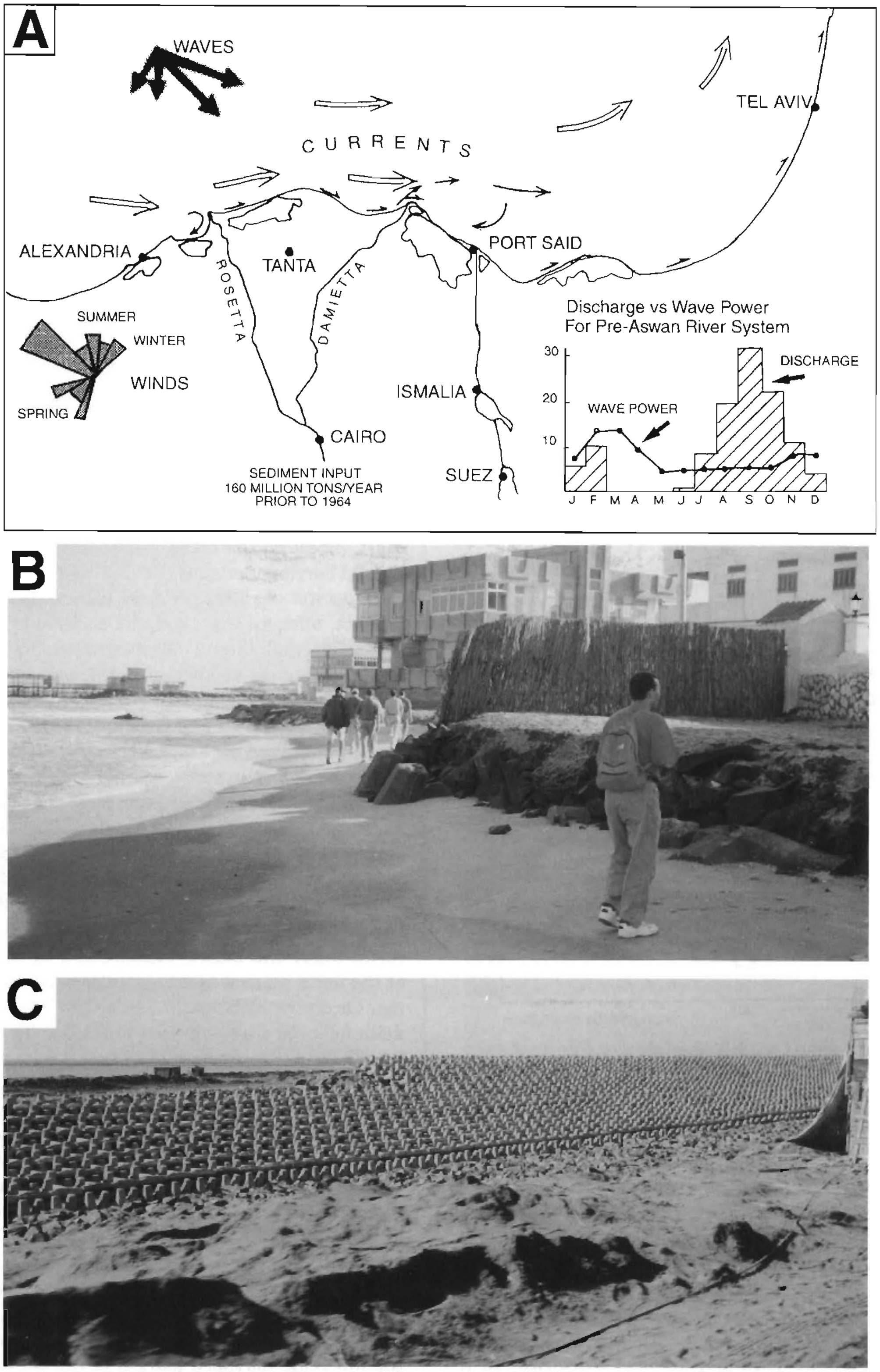

Figure 10. (A) Nile Littoral Cell, showing sediment discharge from the Nile delta before closure of the Aswan High Dam (pre-1964), and eastward dispersal of this material by wind, wave, longshore currents and offshore counterclockwise eddy. Also shown is a graph summarizing the relative influence of wave power and sediment discharge, on a monthly basis (after Sestini, 1989). (B) Coastal erosion at mouth of the Damietta branch, Ras El-Bar (view taken toward east); (C) extensive protection measures east of Ras El-Bar (view toward southwest). Photographs B and C were taken in November 1997.

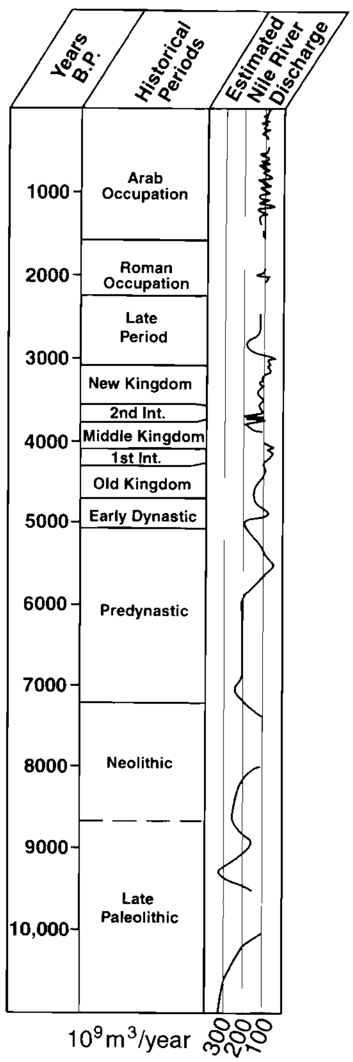

Figure 11. Nile River fluctuations, showing large-scale waxing and waning of flow during the Holocene (modified from data in Said, 1993).

HUMAN INFLUENCES UNTIL THE MID-1800's

Hunting-gathering cultures evolved to early agriculture and domestication in southern Egypt (WENDORF and SCHILD, 1978) and, subsequently, in the lower Nile and delta region (STANLEY and WARNE, 1993b). Humans began to settle the Holocene Nile delta plain shortly after its formation, between 8000 and 7000 years ago (HOFFMAN, 1979; HASSAN, 1984; WENKE, 1991; WARNE and STANLEY, 1993a; STANLEY and WARNE, 1997). The oldest known Neolithic site (~7000 years BP) north of Cairo is Merimda, positioned on the southwest margin of the delta (Figure 14). To date, however, there is only limited evidence of early settlement patterns and habitat substrates in the delta proper because subsidence and sedimentation accretion have buried sites with thick sequences of Nile silt (STANLEY *et al.,* 1992a). From about ~7500 years BP to the present, the delta plain accreted silt ranging from 10 to 50 m in thickness (Figure 7A) at rates of roughly 1 to 7 mm per year.

The delta is positioned in a highly arid region that was subject to unpredictable annual fluctuations in Nile flow and, therefore a principal challenge for even earliest settlers was water management to avert famine. A thorough review of the role of water in the early history of the Nile valley and delta is provided by BUTZER (1976) who refers to early human-land relationships as a floodplain civilization.

Large portions of the delta plain were inundated and uninhabitable for several months of the year. During early cultural phases, humans utilized natural flood basins on the delta plain to entrap flood waters and nutrient-rich soils during Nile flood stages in late summer and early fall. By November, however, most of these basins had drained as water level lowered as a response to evaporation, soil infiltration and dropping groundwater level. The Dynastic period, starting at ~5050 years B.P., began at a time when the climate in Egypt had become hyperarid and stream discharge significantly reduced (Figure 11).

At about this time, natural basin irrigation was being modified by artificially raising levees around depressions to help to retain water to grow crops during winter to summer when Nile flow was low (Figure 10). This activity served to increase areas that could be cultivated and equalize year-to-year productivity of naturally irrigated floodplains (BUTZER, 1976). One of the first firm evidences of canal construction and artificially regulated irrigation is a depiction on the mace-head of the Scorpion King near the end of the Predynastic era (~5100 years BP). During the First Dynasty (from ~4900 years BP), methodologies involving deliberate flooding and draining by sluice gates had evolved. By Old Kingdom time (from ~4575 years BP), only the northernmost third of the delta, with its extensive marshes and wetlands (Figure 8), remained relatively unaffected by irrigation works. Aridification increased to its present level by about 4500 years BP, and records reveal that Dynastic irrigation technology progressively advanced. This led to increased Nile water regulation, with building of artificial levees and enlarging and dredging of natural overflow channels (BUTZER, 1976). Mechanical lift irrigation, made possible by the introduction of features such as the shaduf during the 18th Dynasty (from ~3550 years BP), allowed planting of several crops a year, even during the dry summer season. Increasing irrigation and navigational activity along delta distributaries modified their meandering and avulsion patterns.

During early irrigation phases, when a conscious effort was made to collect fertile silt and nutrients, farmers had to face problems of increased salt concentrated by evaporation and transpiration from slow moving and standing water. As delta settlement proceeded from south to north and along the delta margins, salinization became acute especially during periods of decreased Nile discharge. At such times, clays accumulated with increased concentrations of sodium-rich solubles, and agricultural productivity decreased. This phenomenon became progressively more acute as agriculture intensified, and especially during the Ptolemaic period (~2300–2030 years BP) when demographics and political centers shifted to Lower Egypt and the delta. Balancing the need of Nile water for

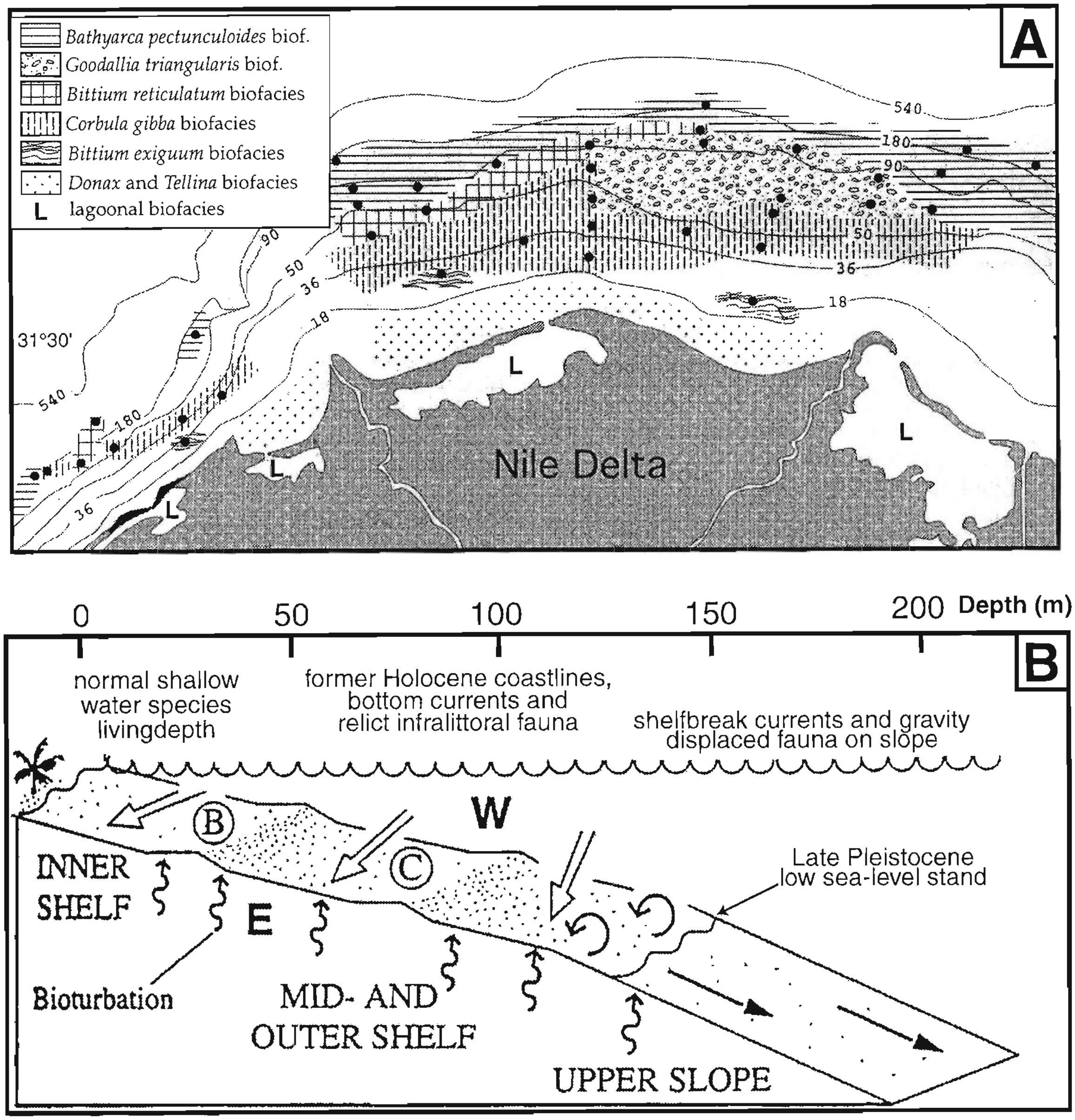

Figure 12. (A) Distribution of molluscan biofacies on the Nile shelf showing contour and coast parallel patterns related to predominant east-flowing bottom currents (after Bernasconi and Stanley, 1997). (B) Molluscan distributions are related to Late Pleistocene-Holocene lower sea level stands that account for relict biofacies, and strong bottom currents that flow primarily parallel to contours and the coast and distribute modern biofacies laterally (Stanley and Bernasconi, 1998).

irrigation and navigation, the major distributaries in the delta were artificially reduced to two nearly 1000 years ago, the Damietta flowing to the NE, and the Rosetta to the NW (Toussoun, 1922).

Salinization over broad areas became a more serious problem in the delta after introduction of perennial irrigation associated with development of successful high water head canal systems that became widespread after 1800 AD. Consequently, water tables remained high for extended periods which promoted salt to build up in the root zone. By the mid-19th Century, a dense irrigation waterway system was in place throughout much of the delta (Sestini, 1989). The annual flood cycle, however, continued to inundate the delta, deposit a thin blanket of silt, flush out salts, and transport water and sediment across the delta to the sea.

INCREASING HUMAN CONTROL OF NILE FLOW

Mid-19th Through 20th Century

Annual variability of Nile flow, resulting in too much or too little water required for cultivation and other human activi-

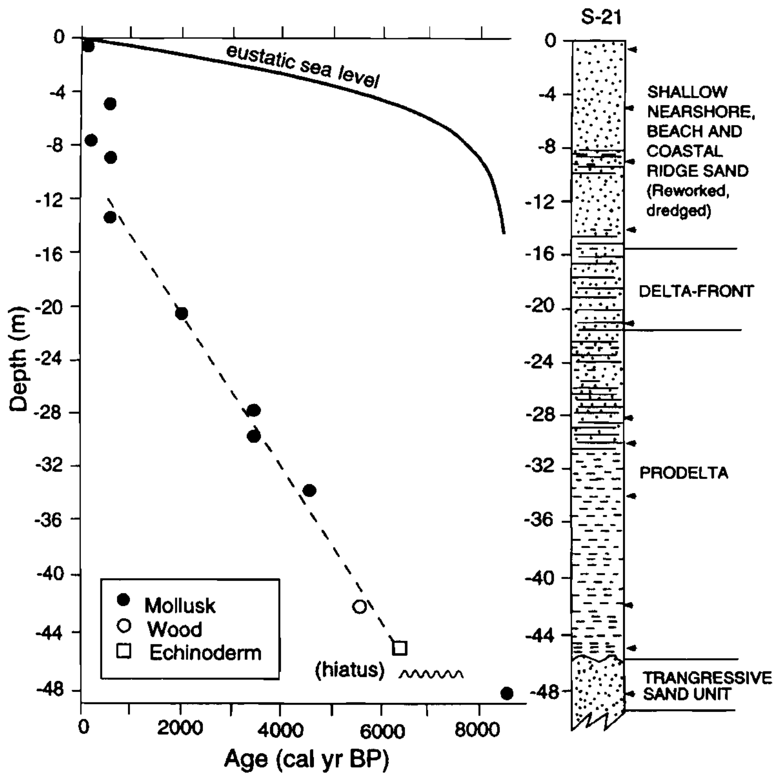

Figure 13. Radiocarbon (AMS) dating of Smithsonian core S-21 near Port Said shows marked subsidence of land (long-term average to at least 4 mm/year) and eustatic rise in sea level, resulting in a minimal relative rise in late Holocene sea level of 5 mm/year (from data in Stanley and Goodfriend, 1997).

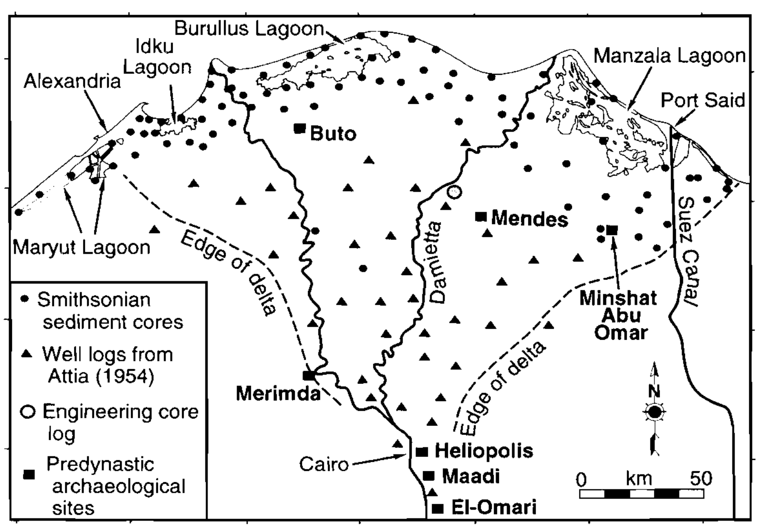

Figure 14. Location of Predynastic archaeological sites and available core information in the Nile delta (after Stanley and Warne, 1993b).

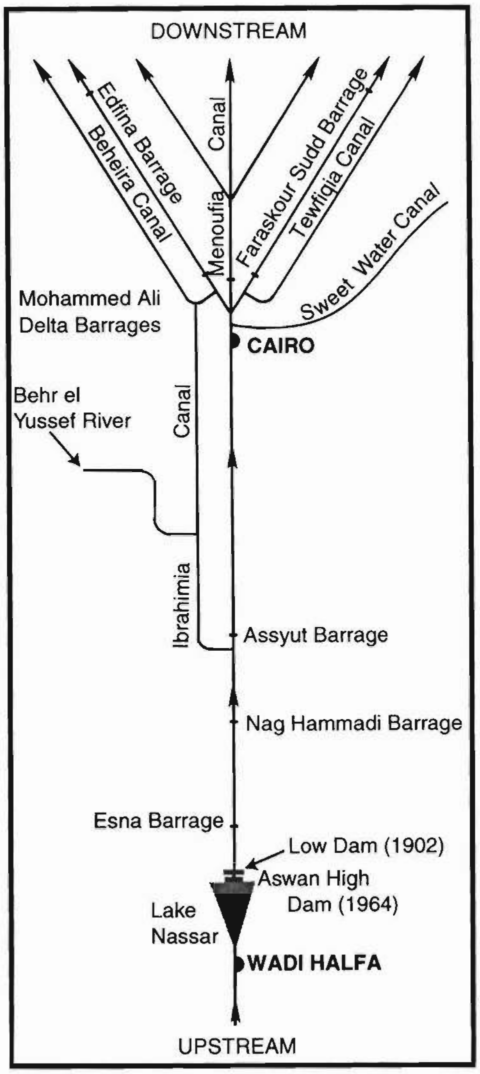

Figure 15. Structures emplaced on the Nile River and in the delta after the mid-19th Century that regulate flow and have fundamentally altered the depositional regime of the delta (modified from Waterbury, 1979).

ties, was the most critical problem affecting populations in the lower Nile valley and delta during the many millennia of agriculturally-based society. To avoid famine, annual river flood stage had to exceed the channel bank level; however, river stages greater than 1.5 m above bank level caused widespread damage to irrigation structures and habitats.

Human needs had become such that, by the 19th Century, large-scale measures were implemented to control river flow and establish a means of water retention. As a first major step, the Mohammed Ali Delta barrages were constructed between 1843 and 1861 north of Cairo, at the point where the Nile divides into the Damietta and Rosetta branches (Figure 15). To divert increments of flood waters for use in their vicinities additional barrages were constructed during the latter part of the 19th century (WATERBURY, 1979), and were subsequently modified and improved at Assyut (1902), Zifta (1903), Esna (1909), Nag Hammadi (1930), and the northern delta canals (after World War II) at Edfina and Faraskour Sudd (Figure 16A, D).

Retention of sufficient Nile waters within Egypt to allow perennial irrigation in the delta was made possible by construction of the first (Low) dam at Aswan in 1902, which was subsequently heightened in 1912 and 1933. The Low Dam entrapped the receding phases of the annual flood, but allowed the bulk of flood discharge to pass through dam sluice gates and flow northward to the Mediterranean. Thus, the Nile barrages and Low Dam provided partial flood control and a much improved water supply during the dry season by the turn of the 20th Century. Negative aspects of these water control structures included overwatering of some sectors and inadequate drainage of the delta plain which, in turn, elevated salinity in soils.

Egypt's continuously growing population and consequent increased municipal, agricultural and industrial needs for water in the first half of the 20th Century heightened the necessity for multi-year water storage capability. Existing structures could retain less than 20% of the annual Nile discharge, and so were only partially effective in minimizing hardships following years of low floods. These conditions, coupled with advances in civil engineering technology, led to construction of the High Dam at Aswan after World War II. This structure, enclosed in 1964 (Figure 17), increased Egypt's cultivated area for perennial irrigation, eliminated dangers of high floods, lowered the river level to improve drainage, and generated hydroelectric power needed for increased industrialization (WATERBURY, 1979; SAID, 1993). The Egyptian government prior to and during construction weighed these advantages against such problems as possible reservoir-induced seismic activity in the vicinity of the dam and Lake Nasser reservoir (KIJKO *et al.*, 1985; KEBEASY *et al.*, 1987), water loss by evaporation (estimated at ~14 billion m^3/year; PEARCE, 1994) and seepage in the reservoir, silt and nutrient deprivation for the lower Nile valley and delta, and accelerated coastal erosion (KASSAS, 1972).

Since construction of the High Dam, less than 2% of sediment bypasses the High Dam turbines and most of the ~100 to 110 million tons of sand, silt and clay per year, accumulate along a 220 km stretch in the southern part of Lake Nasser reservoir near the Egypt-Sudan border. The New Nile delta forming in this sector (Figure 18) is now locally >40 m thick (MANCY and HAFEZ, 1983). The toe of this new delta is migrating northeastward and is now about 280 km southwest of the High Dam. The life of the reservoir, however, is expected to be ~500 years (ELDARDIR, 1994).

A new source of sediment for the delta is provided by water flow released below the dam that scours the former Nile channel and banks along the valley. Down cutting is limited by sediment armoring associated with underlying Pleistocene gravels (SCHUMM and GALAY, 1994). Reworked sediment, with an altered mineralogical composition, is now transported to and north of Cairo (STANLEY and WINGERATH, 1996). The lower Nile carries a significantly reduced sediment load than before the High Dam, but its silt concentrations are as much as 890 g/m^3 in the Cairo area (WATERBURY, 1979).

Historically 80% of the annual silt load was flushed out to

Figure 16. Photographs, taken in November 1997, showing human modification of the Rosetta and Damietta distributaries of the Nile in northern delta. (A) Edfina barrage, view towards NE (Figure 15); (B) vegetated islands forming in the Nile channel below Edfina, view towards ENE; (C) sea water entering the mouth of the Rosetta branch as shown by landward-driven waves, view towards NE; (D) Faraskur Sudd barrage, view towards NW; (E) vegetated islands and fishing huts in river channel just below Faraskur Sudd barrage, view towards W; and (F) artificial structures emplaced to protect rapidly eroding coast at the Damietta promontory, east of Ras El-Bar (in distance), view towards W.

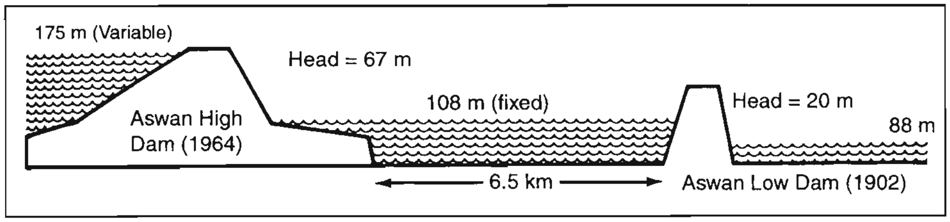

Figure 17. Schematic of the Low (1902) and High (1964) dams at Aswan depicrting water heads and reservoirs for water retention, hydroelectric power generation, and downstream flow regulation (after Waterbury, 1979).

sea, but now what little reworked sediment transported to the Nile delta north of Cairo is distributed into more than 10,000 km of waterways that form a dense network across the depocenter (STANLEY, 1996; Figure 19). Less than 10% of the former Nile river sediment load is now delivered to the Mediterranean coast. Most of the sediment reaching the coast is transported by pumping from Maryut lake in the Alexandria area, and via Idku, Burullus and Manzala outlets (Figure 19). With the two large barrages in place near the mouths of the Nile's Rosetta and Damietta distributaries (Figure 16), little water and sediment are discharged across the promontories to the sea.

Channelization and absence of overbank flooding associated with the complex network of canals within the relict delta plain distribute negligible quantities of sediment to farm fields. This irrigation system (Figure 19) traps sediment in a sieve-like fashion to such a degree that it has altered sediment accumulation rates within the delta more directly and significantly than the Aswan dams and Nile barrages. Moreover, this high-density waterway network, coupled with inadequate drainage has exacerbated water logging and salinity in the low-lying delta plain. Reduction in total amount of silt distributed on the delta plain surface proper and government restrictions on the exploitation of Nile sediment have seriously impacted the brick industry which, until a quarter of a century ago, was a major delta activity.

Routing of nearly all surface water north of Cairo, via delta canals and drains to the marshes and lagoons, has substantially increased sedimentation rates in northern wetlands (STANLEY, 1996). Delta lagoons now act as sumps that trap considerable volumes of sediment and numerous by-products. This is recorded by increased accumulation rates in southern portions of lagoons, such as in central Manzala lagoon where rates have nearly doubled (from 0.7 to 1.2 cm per year) since 1964 (BENNINGER *et al.*, 1998).

Current and Future Measures

With redistribution of existing water resources, it is hoped that future populations can occupy 25% of their country's

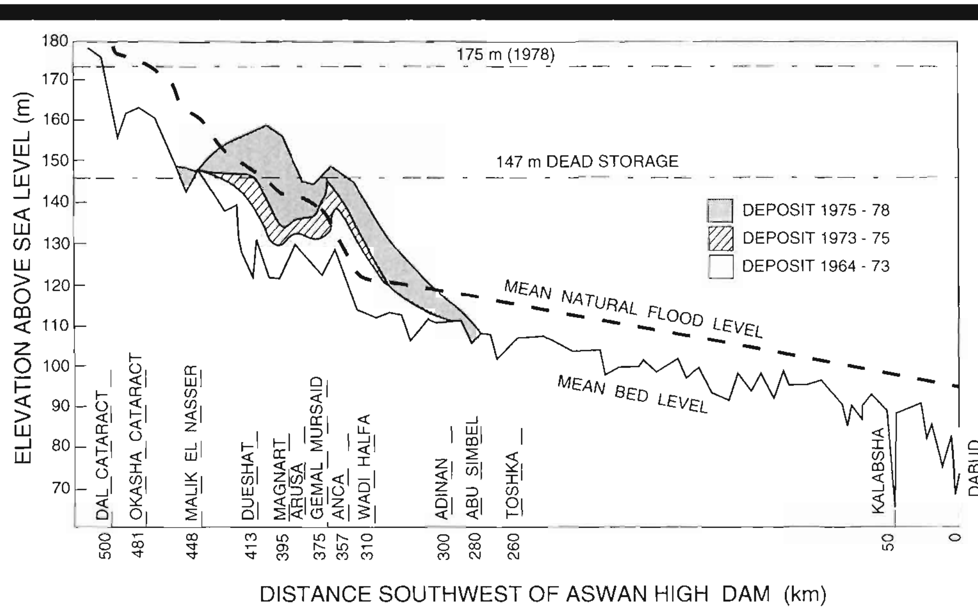

Figure 18. Cross section of Lake Nasser showing the New Nile delta that has accreted along a 220-km stretch, about 280 km southwest of the Aswan High Dam (Mancy and Hafez, 1983).

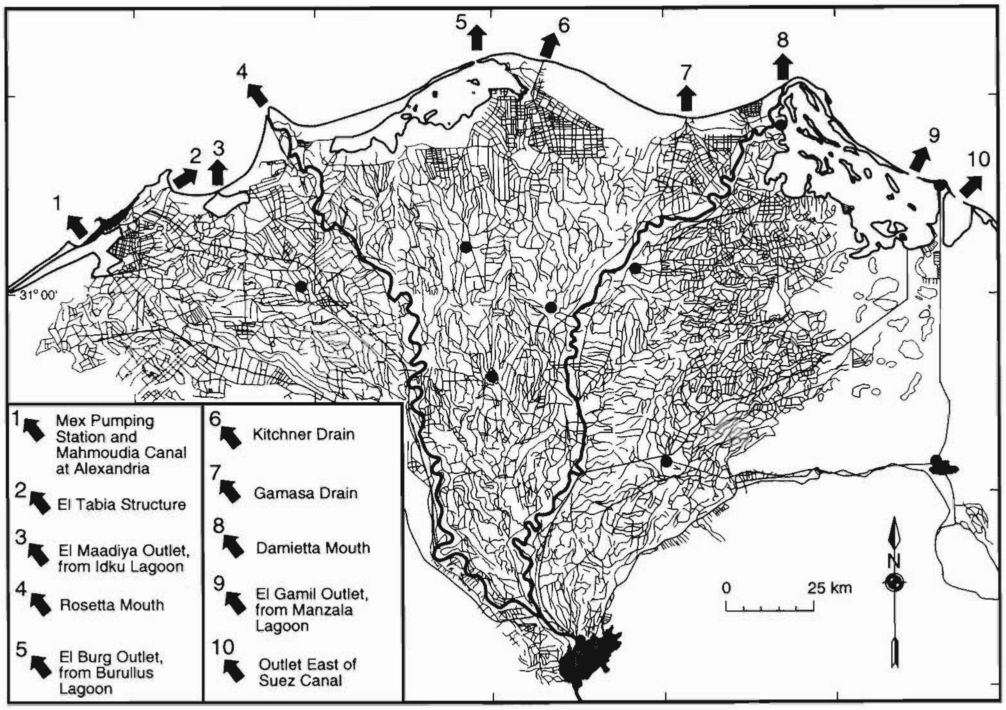

Figure 19. Map depicting Nile delta waterways network; only the large and intermediate size channels are shown. Relatively minor amounts of sediment bypass the coast at 10 localities (after Stanley, 1996).

area, rather than the 5% surface as at present (ANONYMOUS, 1997; GREENBERG, 1997). Several large-scale activities recently initiated for irrigation and water distribution in the desert, however, will substantially decrease the amount of water available to the Nile delta. One such project, now well under construction, will enhance agricultural development of the desert and expand areas such as El-Arish on the NE Sinai coast. Two billion m^3 of Nile water, plus an additional 2 billion m^3 of reused drainage and other wastewater, will be distributed annually from the northeast delta across the northern Sinai via the Al-Salam Canal (Figure 20). Currently, this large open waterway extends under and east of the Suez Canal.

An even larger-scale project, in active planning and initial construction stage, is referred to as the New Delta Canal project (Figure 20). Its aim is to convert large areas of Western Desert into farmland to attract large proportions of future Egyptian populations. The New Delta Canal project will carry 5 billion m^3 of Nile water annually from the southern part of Lake Nasser, for a distance of 500 km, to a series of desert oases in Egypt's western desert along a path subparallel to the Nile valley.

Arguments favoring implementation of these two major diversions of Nile water include estimates that an equivalent volume of water (9 billion m^3 annually) can be saved by improving present primitive irrigation methods, reusing more agricultural drain water, and reducing more water-dependent crops such as rice and sugar cane. In addition to these large undertakings, there are other water control projects underway and planned that will redistribute large volumes of Nile water toward regions that are undergoing increased development, such as the northwestern Egyptian coast that extends from west of Alexandria toward the Libyan border. In spite of some opposition, pressure to embrace these water distribution projects is based on Egypt's need to produce sufficient food to feed its population, and "greening" of the desert is viewed as essential. Thus, the Nile delta will receive less water in the new century than at present, as more than 98% of Nile water in Egypt is already in use in this desert region and population continues to expand. A greater potential threat to the welfare of the delta than the above water diversion projects are hydro- and geopolitical considerations pertaining to the reduced amount of Nile water that will be allocated to Egypt. Increased proportions to countries upstream from Egypt are now proposed (*cf.* WATERBURY, 1979; POSTEL, 1992; SAID, 1993). Egypt lies at the end of the Nile River 'pipeline' (Figure 9) with nine other developing countries positioned along the river above it: Sudan, Central African Republic, Zaire, Uganda, Rwanda, Burundi, Tanzania, Kenya, and Ethiopia. Hence, Egypt is increasingly vulnerable to the amount of water it receives. The Sudan and Ethiopia, in particular, with rapidly growing populations and consequent increased water needs, are seriously vying for larger proportions of Nile water (PEARCE, 1994; MARCUS, 1997). Although presently hampered by internal conflicts, these and other countries are pursuing international hydropolitical discussions and taking steps to obtain considerably larger allocations.

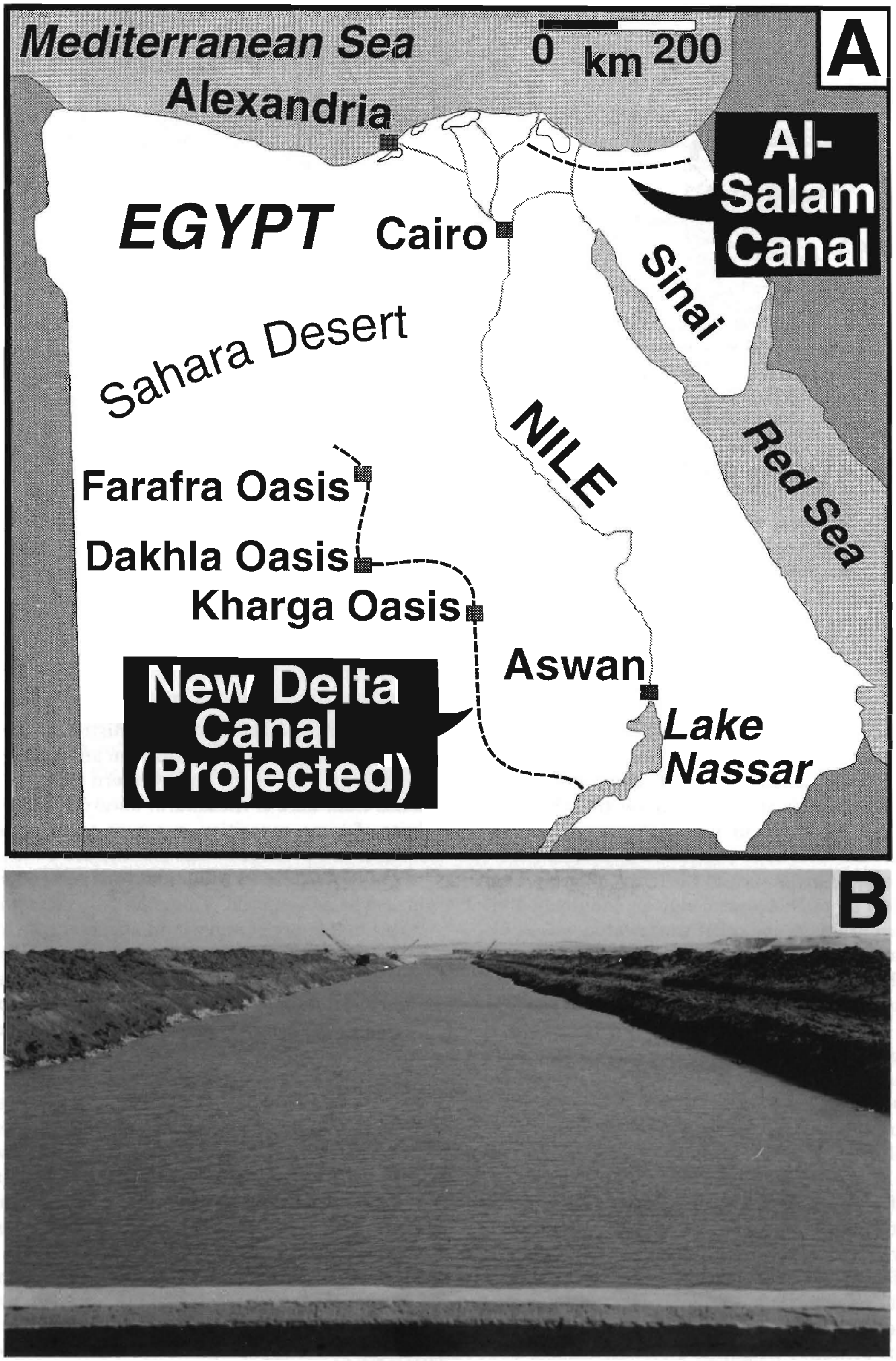

Figure 20. (A) Al-Salam Canal and New Delta Canal projects that will divert Nile water away from the lower Nile valley and Nile delta (after Anonymous, *The Economist,* 1997). (B) View toward east in the NW Sinai (near Pelusium) showing construction of Al-Salam Canal east of the Suez Canal (photograph taken in November 1997).

If (or more likely, when) larger proportions of Nile water are utilized by upstream countries, the Nile delta destruction phase will accelerate as less water and sediment are discharged northward to the Mediterranean.

ATTRIBUTES OF THE DEGRADING NILE DELTA

Drilling through Neogene, Pliocene and Pleistocene series near the mouth of the Nile has shown a sequence of partially superposed deltas that waxed and waned during the past 5 ½ million years. These alternating phases of delta build-up and cut-back are the result of an interplay of two sets of competing processes. In the case of the Nile delta which is located in a desert environment, factors conducive to delta construction phase are perennial flow of water and sediment punctuated by annual floods, sediment accumulation across the delta and along the coast, small tides, gentle rise in sea level, and minor offset of strata by faults in a region of relatively infrequent high-intensity earthquake activity (STANLEY, 1997). Factors promoting delta destruction phase are strong wave-driven coastal currents and subsidence.

During the past 7500 years, the Nile and other major world delta systems have experienced an overall constructive phase (STANLEY and WARNE, 1994). Within this overall construction phase, a series of lesser and more localized construction and destruction cycles have characterized delta systems (COLEMAN and WRIGHT, 1975; COLEMAN, 1988; PENLAND *et al.*, 1988), including the Nile (Figures 8, 11). During the past two centuries, water control measures have seriously curtailed (a) Nile flow below Aswan and in the delta, (b) flushing of the delta plain during annual floods, (c) influx and deposition of sediment across the delta plain, and (d) bypassing of sediment to and beyond the coast. At the same time, natural delta destruction processes, particularly coastal currents and subsidence, continue unabated. As a consequence, the natural Holocene delta construction phase has been terminated, and the Nile's depocenter has entered an artificial destruction phase. The fluvial-deltaic prism at the Nile mouth is now a relict delta or, in other words, an eroding coastal plain. Attributions of the human-induced destruction phase Nile delta are described below.

Accelerated Coastal Erosion

During most of its 7500 year history, the delta coast has been prograding, with some areas such as the northeast delta building out at an average rate to 10 m per year. Like all deltas, progradation was uneven along the coast, in response to changing location of mouths of distributary channels and altered discharge volume from the Nile through time (Figure 8). By the end of the last century, the strong marine current and wave regime along the shoreline and on the shelf had produced a gently arcuate coastline with only a few protuberances, including the Damietta and Rosetta promontories (Figure 1).

An obvious consequence of naturally reduced Nile flow and sediment discharge in the 20th Century and closure of the Low Dam in 1902 has been accelerated erosion of the promontories at the two Nile mouths (Figure 21, EL-ASKARY and FRIHY, 1986; SESTINI, 1992). Since 1964, coastal erosion has cut back the north-central delta stretch near the town of Baltim. Coastal areas east of eroded sectors have experienced sand accretion (FRIHY *et al.*,1988; SMITH and ABDEL-KADER, 1988), which has resulted in an overall straightening of the shoreline (MANOHAR, 1981; FRIHY, 1988; SMITH and ABDEL-KADER, 1988). Moreover, southeastward-directed winds have expanded coastal dunes with some large dune fields (Figure 1) migrating onto wetlands and over the cultivated delta plain (STANLEY *et al.*, 1992b).

Among the regional consequences of coastal erosion are accelerated sand accumulation along the groin constructed at the mouth of the Suez Canal at Port Said, and coastal accretion along the Gulf of Tineh east of the Canal. Farther to the east, depletion of Nile-derived sand has been identified on sectors of the Sinai, Gaza and Israeli margins (NIR, 1982). Evidence includes exposure of submerged archaeological sites that had been buried by Nile sand (GALILI *et al.*, 1993), accelerated erosion of coastline stretches, and changes in petrological composition of coastal margin deposits (POMERANCBLUM, 1966; STANLEY, 1989; STANLEY *et al.*, 1998).

The Egyptian shelf and Nile Cone, integral parts of the Nile Cell (INMAN and JENKINS, 1984; Figure 10), are also experiencing the destruction phase of the delta. Accumulation rates in these offshore sectors have been low following the rise of sea level during the past 18,000 years, because most sediment discharged at the delta coast to the sea was diverted to the E and NE by strong bottom currents. Moreover, the supply of sediment derived from west of the Alexandria region has been relatively minor.

Without replenishment of sediment by annual Nile floods, overall erosion of the shelf is accelerating (STANLEY, 1988a). Carbonate sediment from the Alexandria margin to the west is insufficient to replace the former Nile sediment flood onto the shelf. Currently, these bottom shelf currents are transporting relict sediments eastward (Figures 10, 12), and continuing to smooth existing bathymetric irregularities such as relict terraces and strandlines (SUMMERHAYES *et al.*, 1978). Some near shelfedge deposits are transported onto the upper Nile Cone surface by traction and gravitative processes, but this slope continues to be characterized by low sediment accumulation rates (MALDONADO and STANLEY, 1976, 1978).

Increased Effects of Salt

Salt buildup was long associated with natural delta plain evolution in a hyperarid climate, but accumulation of salt increased markedly after 1800, following implementation of irrigation systems that fostered perennial agriculture but reduced the influence of annual flushing by floods. As a result of subsidence, the surface area with elevation of less than 1 m accounts for roughly 15% of the delta area (Figure 22), and the area with an elevation that is presently below sea level accounts for 4% of the delta. Prior to emplacement of the Aswan dams and other water control structures, sediment accretion on the delta plain offset the effects of relative sea-level rise. Since the mid-1800's, there has been a considerable change in low-lying areas that have a natural hydraulic connection with the sea. Although land subsidence and concurrent rise of sea level have continued during the destruction

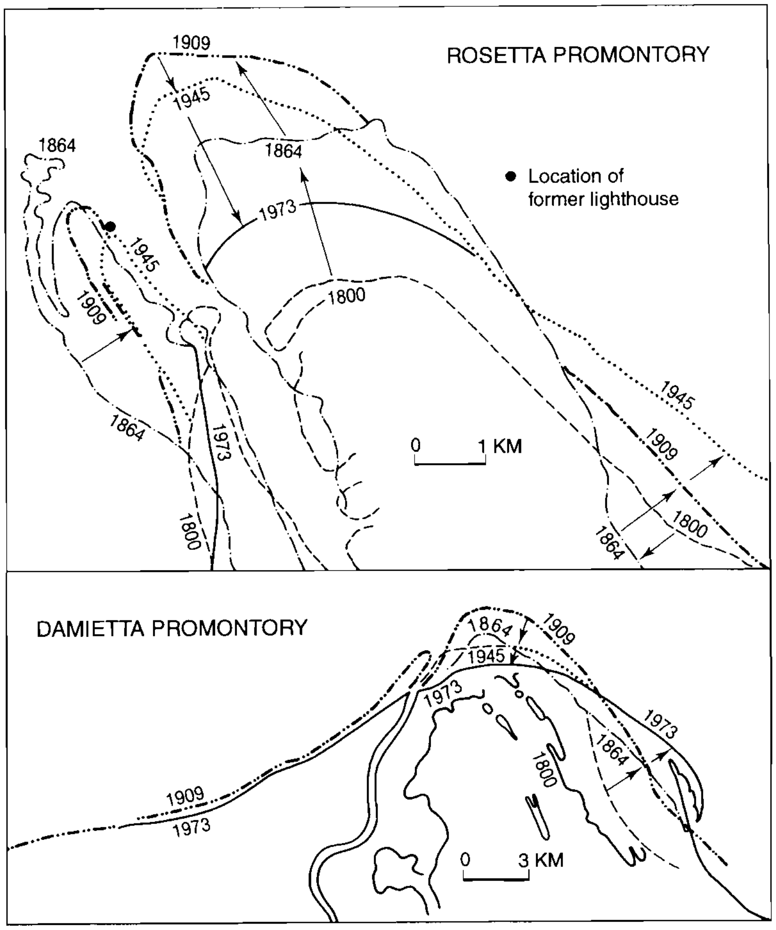

Figure 21. Maps showing coastal changes at the Rosetta and Damietta promontories during the 19th and 20th Centuries. Note transition from progradation to cut-back shortly after the turn of the century, particularly rapid erosion (to >50 m/year) at Rosetta, and eastward deflection of sand and formation of spits at Damietta (after Sestini, 1992).

phase, there has not been an increase in brackish-water wetland areas because of artificial conversion of wetlands to agriculture. In this century, changes in fauna and flora indicate that salinities in the northern portions of lagoons adjacent to the coast have increased, a probable response to relative rise in sea level (RANDAZZO *et al.,* 1998). In contrast, southern landward sectors of some lagoons have become less saline due to increased amounts of canal and drain waters diverted into these wetlands (REINHARDT *et al.,* in press).

Less obvious than changes on the delta plain surface, but significantly more important, are changes of salinities in delta groundwater. Hydrogeologic studies have recorded distinct distributions of fresh, brackish and saline waters that underlie the delta plain (Figure 22). While these distributions generally parallel the coastline (SHATA and EL FAYOUMI, 1970; KASEF, 1983), saline groundwater area is larger in the northeast delta. Land subsidence rates are highest in this sector (Figures 7B, 13), providing evidence that marine water intrusion toward the S and SW is a function of subsidence. Monitoring of groundwater chemistry shows that saline distributions continue to increase, implying that marine intrusion of groundwater has accelerated during the recent destruction phase. Salinization of the soil profile has increased as a result of lack of annual inundation and flushing of the delta plain by Nile floods. Salt is concentrated in surface waters by evaporation as they pass slowly through the extensive network of irrigation canals within the delta (Figure 19). Recent restrictions limiting the quantity of irrigation water applied to agricultural areas further increase the amount of salt left in the soil.

Wetland Loss and Ramifications

Wetlands, among the world's most diverse terrestrial ecosystems, are an integral part of natural delta systems. Subsurface studies have shown that they were widespread in the northern part of the Nile delta since the early Holocene (STANLEY and WARNE, 1993a). Marsh and lagoon areas migrated laterally during Nile delta construction (Figures 8), and these subsurface facies locally account for as much as

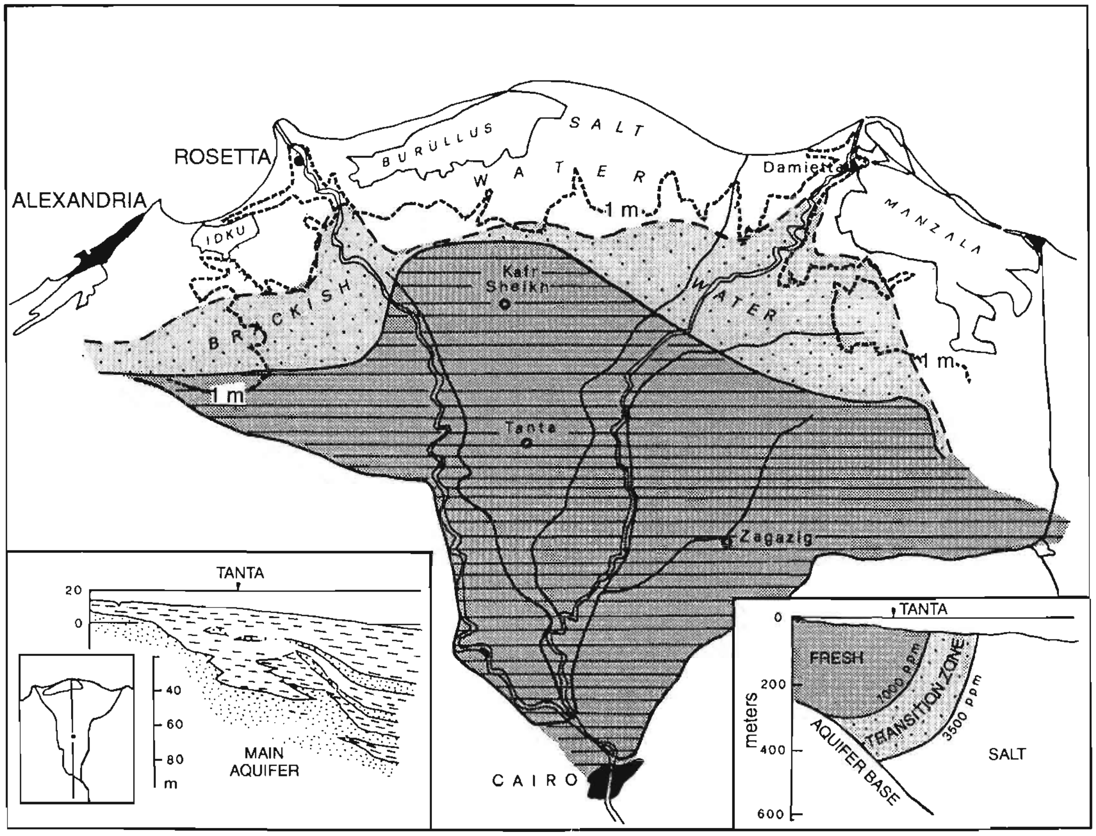

Figure 22. Groundwater salinity distribution in the Nile delta, showing incursion of saline groundwater into the northern delta, and asymmetric distribution of brackish and salt water (modified from Kashef, 1983 and Sestini, 1992).

half of recovered core sections in the northern part of the depocenter (Stanley *et al.,* 1996). Availability of renewable resources in these ecosystems in an otherwise arid environment was a primary factor in attracting humans to the Nile delta shortly after its formation (Warne and Stanley, 1993a; Stanley and Warne, 1993b, 1997). As the construction phase of the depocenter evolved, the delta surface became progressively more populated and irrigation practices of levee and drain construction diminished and fragmented natural wetland areas. Mapping in the early 19th Century (Jacotin, 1826), however, shows that wetlands remained widespread in the northern delta (Figures 8F).

Large-scale anthropogenic alterations of wetlands began during the early 19th Century Napoleonic-British campaigns in Egypt. Modifications included successive flooding and draining of Lake Maryut near Alexandria (Jacotin, 1826; De Cosson, 1935), subsequent reduction of this water body by pumping, and drainage and eventual disappearance of Abu Qir lagoon by the end of the 1800's (Chen *et al.,* 1992). Since that time, remaining lagoons have been artificially fragmented and reduced in size (Figure 8G; Shaheen and Yosef, 1978; Loizeau and Stanley, 1993, 1994).

Isolation of the eastern quarter of Manzala lagoon by construction of the Suez Canal in 1869 is a striking example of artificial loss. Situated in a hyperarid climate, most of the once freshwater marsh and brackish lagoon system in this eastern portion has degraded to lifeless salt pans (Figures 1, 8G). As a result of increasing human pressures, including advances in ditching and pumping technologies, ever-increasing areas of all wetlands are being converted for agricultural and aquacultural use (Figure 23). Present open-water environments account for less than 30% of wetland areas mapped 200 years ago (Figure 8F, G), and water control structures have essentially eliminated inundation of flood waters from the Nile to the delta. Nevertheless, coastal lagoons currently receive more surface drainage water by increased diversion of waste water via canals and drains.

Reduction and fragmentation of wetland areas (Figure 24A) have converted these diverse ecosystems to degraded, largely monospecific floral (such as *phragmites*) and faunal marsh and lagoon systems. Human modifications have precipitated destruction of valuable wildlife habitats, including migratory bird flyways and nesting areas, and habitats for much-needed fish and shellfish. Reduction in fish catches in delta lagoons is particularly serious for Egypt, because much of its fish industry off the mouth of the Nile was lost after closure of the High Dam (Halim *et al.,*1967; Halim and Gerges, 1981; Wahby and Bishara, 1981; Dowidar, 1988).

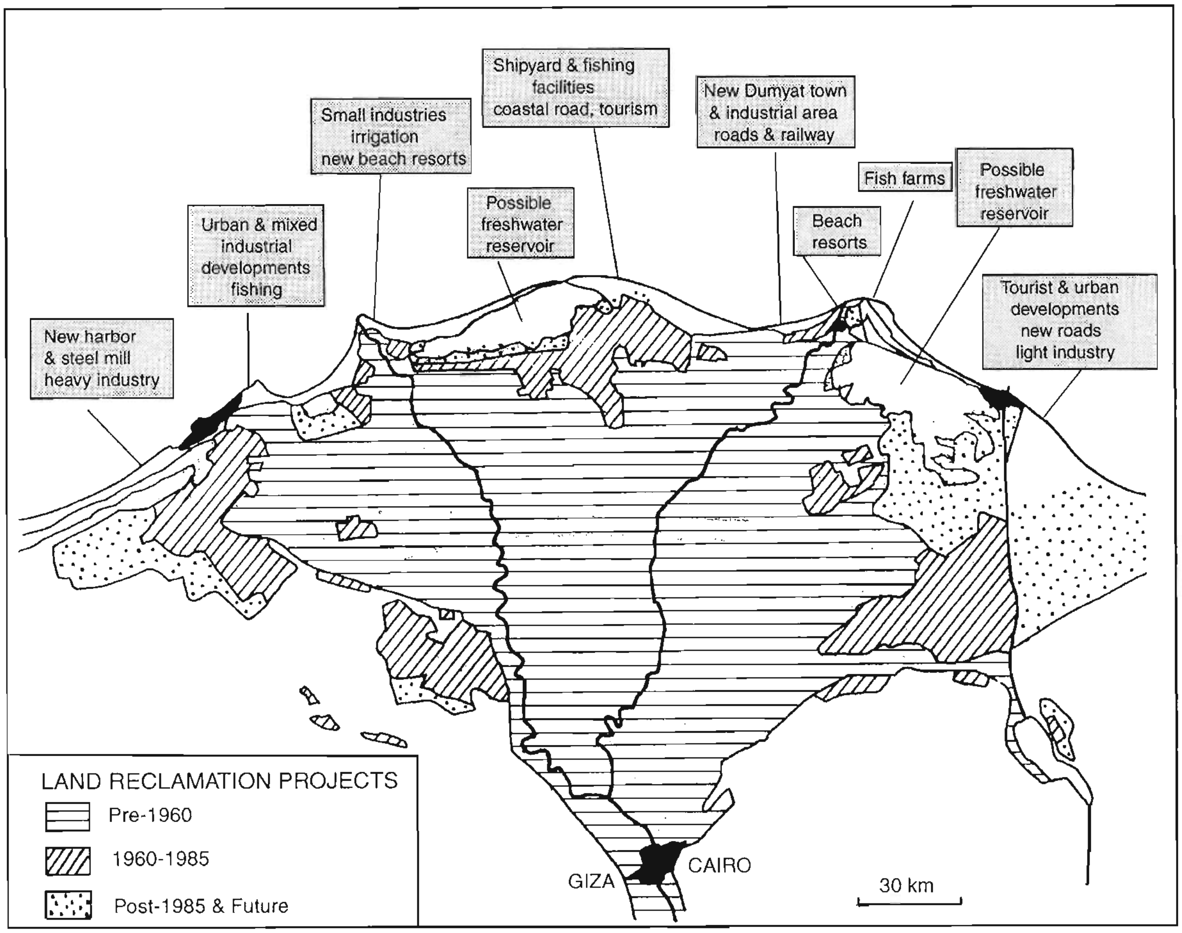

Figure 23. Reclamation projects in the Nile delta from pre-1960 to 1985 and other recent anthropogenic modifications (modified from Sestini, 1992).

Consequently, there has been increasing dependence on catches in delta lagoons during the last three decades (GEORGE, 1972). Of the four remaining water bodies, Manzala lagoon has been the principal source of fish (Figure 24B, C) but, in recent years, catches have declined as a function of reduction of its surface area (RANDAZZO *et al.*, 1998; Figure 24A), and concomitant influx of polluted agricultural, municipal and industrial wastewater (WAHBY and BISHARA, 1977).

Other Human Impacts on the Delta Plain

During most of its construction history, natural environments of the Nile delta were capable of sustaining human needs, with minimal impacts to the ecosystem. By the end of the last century populations increased and technology advanced to such levels that natural limits were exceeded and Nile delta ecosystems no longer functioned as sustainable resources. Located in a hyperarid environment and surrounded by lifeless desert, expanding populations in the delta have had no viable alternative but to continue to exploit the declining ecosystem, entraining further environmental decline. In addition to entrapment of sediment behind the dams at Aswan, accelerated coastal erosion, and increased salinity and wetland loss (particularly in the northern delta), other factors need to be considered. Increased regulation of water flow, for example, has induced a series of environmental impacts across the entire delta plain, such as increased pollution and infectious diseases.

Wastewater and sediment discharged along the margins of delta wetlands have increased concentrations of heavy metal, nutrient and other chemical concentrations. These pollutants have been introduced by expanded use of chemical fertilizers needed to replace nutrients that were supplied by flood-borne silts that annually blanketed the delta plain surface prior to closure of the Aswan dams. These chemical fertilizers and pesticides enter the delta's irrigation drainage systems that eventually discharge into wetlands. To this polluted drainage system are added untreated wastes from industries that have increased since the 1950's. Untreated domestic wastes from essentially all villages and cities across the delta are also released into discharge drains. This highly concentrated wastewater slowly flows through open drains northward and debouches into marshlands and lagoons where solids and pollutants are released and accumulate. Increasing concentra-

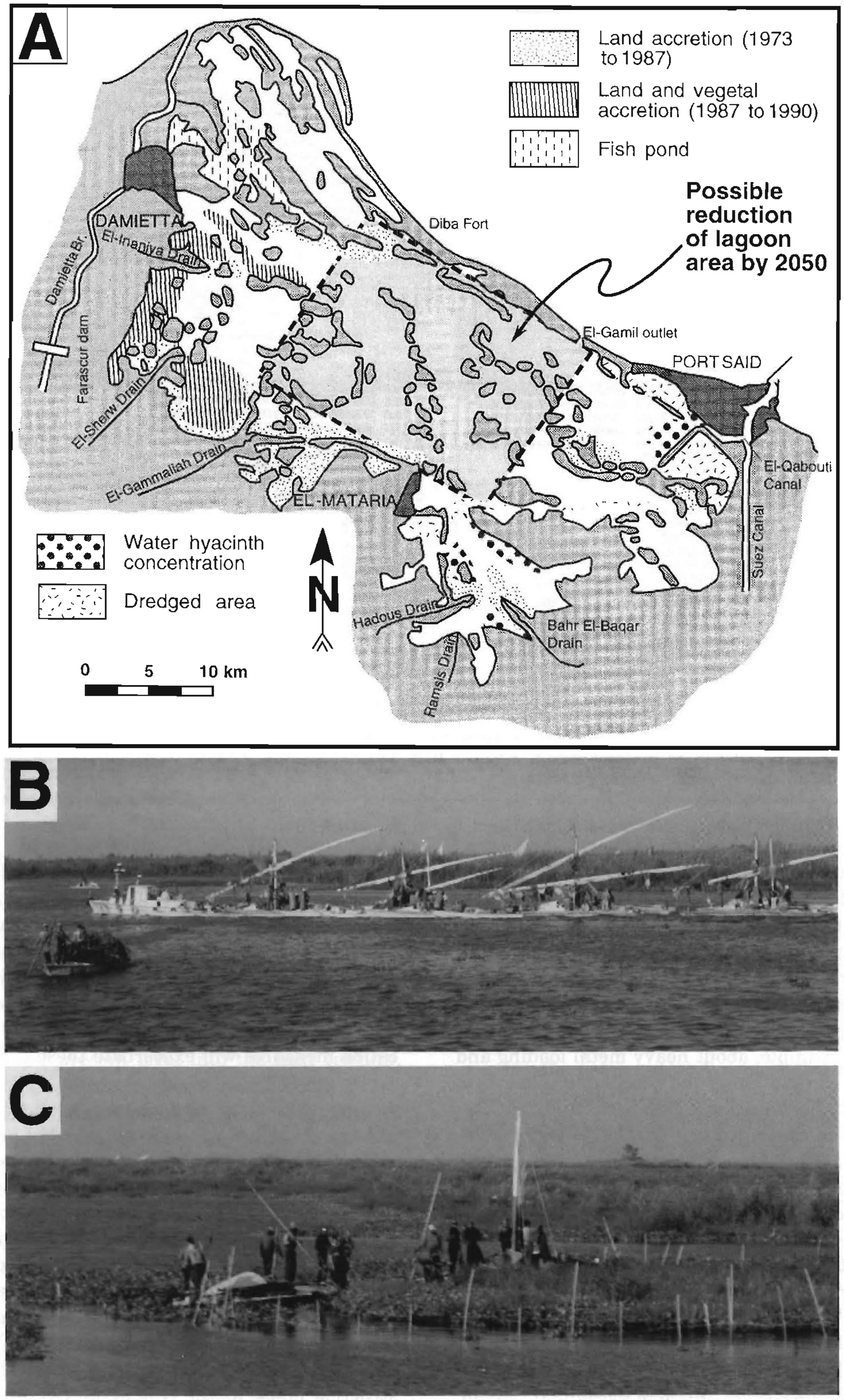

Figure 24. (A) Manzala lagoon in northeast Nile delta showing human-induced changes and possible reduction of lagoon area by mid-21st Century (after Randazzo *et al.*,1998). (B, C) Photographs (taken in November 1997) showing fishing activity in the eastern lagoon, near El-Mataria (in B, view towards N; in C, view towards NW).

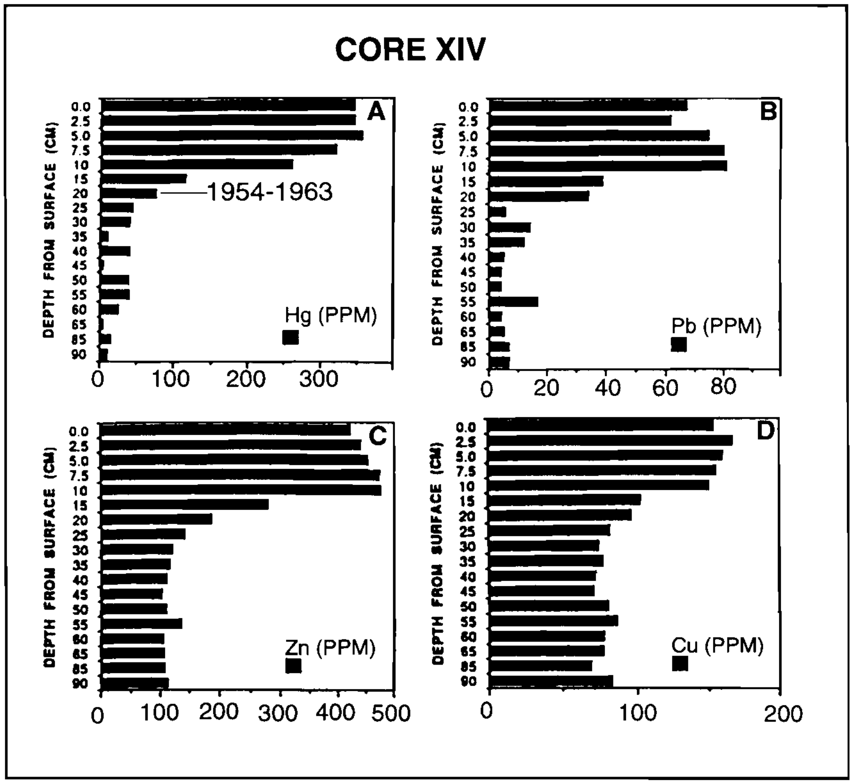

Figure 25. Analyses of mercury, lead, zinc and copper in core XV recovered near the outfall of Bahr El-Baqer drain (Figure 24), a waterway that releases large volumes of untreated wastewater in SE Manzala lagoon (modified from Siegel *et al.*,1994). Graphs show a marked increase in concentrations of potential toxic elements during the latter half of the 20[th] Century.

tions of human, agricultural and industrial wastes are accumulating in wetlands that are decreasing in area, amplifying toxic effects of pollutants (Figure 25).

Deposition of untreated wastes have entrained eutrophication and toxin levels in wetlands to the point of inducing widespread health hazards (EL-DIK *et al.,* 1990; IDRIS and NOUR, 1990; ELSOKKARY, 1992; SIEGEL *et al.,* 1994). There is valid concern, for example, about heavy metal loading and the problem of bioaccumulation in the population sector that consumes fish and shellfish during a long period of time (SIEGEL, 1995). Because of continued degradation of water quality on the delta plain, high proportions (locally >50%) of the inhabitants have contracted schistosomiasis, a blood fluke that lives a portion of its life cycle in snails that act as intermediate host. These snails proliferate on Nile hyacinth (*Eichhornia crassipes*) that choke slow moving and stagnant water of the extensive delta irrigation canal system, marshes and shallow lagoon sectors (Figure 24C). Humans contract the parasite by contact with larvae-infested waters. Untreated human wastes released into almost all water bodies across the delta exacerbate this chronic problem.

Other diseases, such as lymphatic filariasis (elephantiasis of the limbs and genitals), are reappearing due to environmental degradation of the delta surface. A major cause of this resurgence is the pervasive shallow ponds of untreated human waste located near the closely-spaced villages across the southern and central delta (HARB *et al.,* 1993).

It is clear that regulated flow of Nile waters and absence of annual flooding have eliminated the positive aspects of delta surface flushing that once removed salts as well as some of these toxic and infectious wastes. Further reduction in Nile flow to the delta, and intra- and international water reallocation measures will exacerbate these problems.

RELICT NILE DELTA: WHAT LIES AHEAD . . . .

The Nile delta has been transformed within the past 150 years from a constructive wave-dominated delta that took more than 7000 years to develop, to an eroding coastal plain that is now well into its destruction phase. All deltas go through transitions from construction to destruction phases, triggered by fundamental changes in interactions among natural factors, such as rapid rise or lowering of sea level. However, no active system among the world's populated deltas has been so inextricably converted to a human-induced destruction phase as the Nile delta. Symptoms of the dysfunctional Nile delta include absence of sediment influx that does not offset the erosive effects of coastal processes and subsidence. Moreover, without seasonal flushing by floods, the former delta plain surface is now incapable of recycling and/or

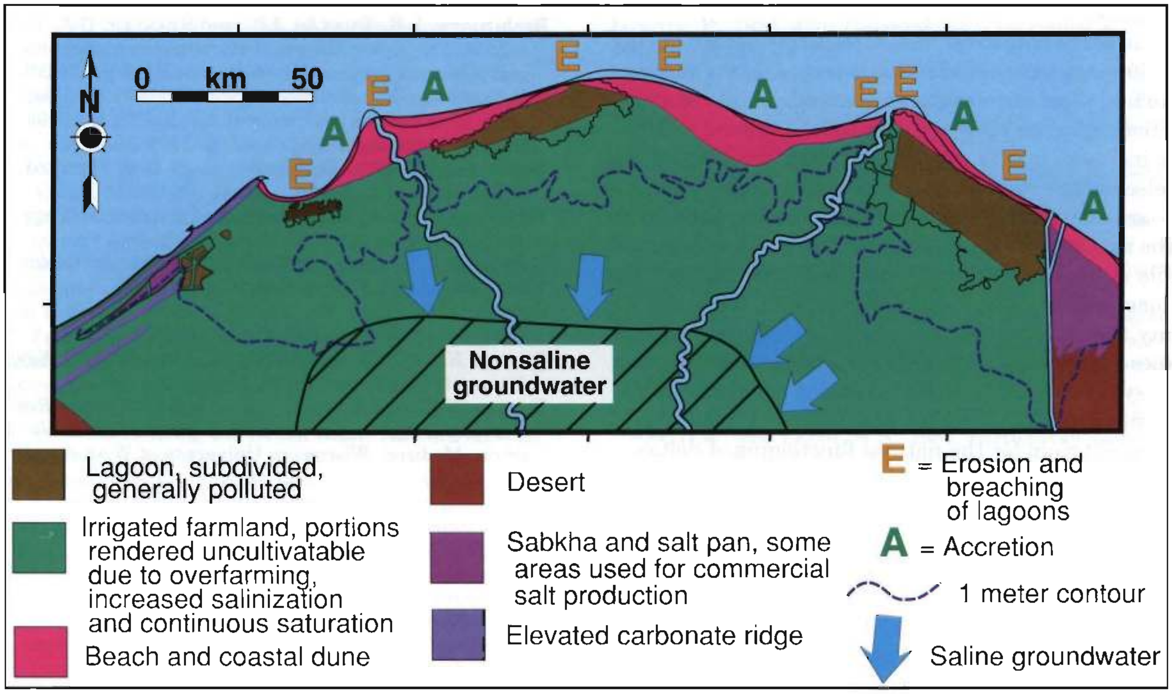

Figure 26. Scheme showing the Nile delta in its destruction phase, as a dysfunctional depocenter on the Egyptian coast. Altered balance among factors such as depletion of fluvial water and sediment, accretion of pollutants, coastal processes, and subsidence are depicted (modified from Stanley and Warne, 1993a).

removing agricultural, municipal and industrial wastes generated by Egypt's rapidly expanding population.

Populations in this region are expected to increase to 85 million by the year 2010, with consequent accelerated degradation of the relict delta. What remains of the capacity of the system to regenerate itself will be even further diminished by anticipated diversions of water (probably in excess of 10 billion m^3) away from the delta by new desert reclamation projects within Egypt, and anticipated decreased total water allocations to Egypt from upstream countries.

Being conservative and assuming that the human pressures continue at their present level into the next century, we infer that conditions within the delta have become unsustainable, it is not likely that some human-induced changes can be reversed, and the delta plain will undergo marked environmental decline. Among the most significant changes are (Figure 26): continued erosion and straightening of the coast east of Alexandria; further reduction in total wetland size, with consequent reduced fish yields; accelerated landward incursion of salt in groundwater; and continued buildup of salt and pollutants to toxic levels in both the wetlands and delta plain. In essence, the capacity of the now-relict Nile delta to provide sufficient food and potable water will markedly decline, even if populations were to remain at their present level.

For this coastal depocenter to become a functioning delta once again, it would be necessary to reestablish the influx of water and sediment at magnitudes and frequencies that characterized this system prior to construction of major water control and irrigation structures. Measures such as wastewater treatment and construction of coastal protection structures (SESTINI, 1992) are insufficient to offset the impacts of municipal, agricultural and industrial by-products incurred by current population levels. Reestablishment of some level of natural hydrology would be the only possible way for the delta system to reestablish equilibrium between sediment accretion on the delta plain to mitigate subsidence, progradation along the coast to offset erosion, and sufficient water influx to flush and remove the high levels of salt and pollutants throughout the system. Major flushing of the delta by opening the gates at the Aswan High Dam is not likely to be instigated because of human and property safety considerations below Aswan, and loss of vital fresh water to the Mediterranean. Increased Nile water and sediment discharge could begin to reestablish some equilibrium between natural and anthropogenic processes only if there is a substantial reduction in anthropogenic impacts in the delta.

Although the problems associated with the demise of the relict Nile delta are now particularly acute, the fundamental problems underlying this dysfunctional system are not unique. Many deltas in world regions face the need to share water with upstream partners through international agreements, regulation of water and sediment upstream that alters natural deltaic functions, and increased populations that impact delta plains. It is apparent that increasing water needs for populations and consequent upstream regulation of water and sediment flow are triggering fundamental changes from long-term Holocene construction of deltas to their destruction phase.

In the case of the Nile River, measures implemented during the past 150 years have satisfied short-term needs of the rapidly expanding population at the expense of viability of a natural functioning delta. As world populations expand and water needs increase, it is inevitable that more river and delta systems elsewhere—even those positioned in more temperate settings—are being subject to conditions similar to those of Egypt. The anthropogenically-induced consequences recorded in the Nile system can at least serve as a type-example for coastal zone managers and those members of the scientific community that advise governments on watershed management issues for populated world deltas. Rational decisions in each river system should balance increasing population needs with continued influx of water and sediment required to maintain equilibrium for the natural functioning of deltas.

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LITERATURE CITED

ADAMSON, D.; GASSE, F.; STREET, F., and WILLIAMS, M., 1980. Late Quaternary history of the Nile. *Nature*, 288, 50–55.

ALMAGOR, G., 1979. Relict sandstone of Pleistocene age on the continental shelf of northern Sinai and Israel. *Israel Journal of Earth Sciences*, 28, 70–76.

ANDRÉS, W. and WUNDERLICH, J., 1991. Late Pleistocene and Holocene evolution of the eastern Nile delta and comparisons with the western delta. *In*: BRÜCKNER, H. and RADTKE, U., (eds.), *From the North Sea to the Indian Ocean*. Germany: Franz Steiner Verlag, 121–130.

ANONYMOUS, 1997. Egypt, back from the desert. *The Economist*, 12 April 1997 issue, 36, 41.

ARBOUILLE, D. and STANLEY, D.J., 1991. Late Quaternary evolution of the Burullus lagoon region, north-central Nile Delta, Egypt. *Marine Geology*, 99, 45–66.

ATTIA, M., 1954. *Deposits of the Nile Valley and Delta*. Cairo: Geological Survey, Publication 65, 356p.

BALL, J., 1942. *Egypt in the Classical Geographers*. Cairo: Survey of Egypt, Government Press, 203p.

BARTOLINI, C.; MALESANI, P.G.; MANETTI, P., and WEZEL, F.C., 1975. Sedimentation and petrology of Quaternary sediments from the Hellenic Trench, Mediterranean Ridge and Nile Cone, DSDP Leg 13 cores. *Sedimentology*, 22, 205–236.

BEAUMONT, P.; BLAKE, G.H., and WAGSTAFF, J.M., 1976. *The Middle East: a Geographical Study*. London: Wiley, 572p.

BELL, B., 1975. The oldest records of Nile floods. *Geographical Journal*, 136, 569–573.

BELLAICHE, G. and MART, Y., 1995. Morphostructure, growth patterns and tectonic control of the Rhône and Nile deep-sea fans. *American Association of Petroleum Geologists Bulletin*, 79(2), 259–284.

BENNINGER, L.K.; SUAYAH, I.B., and STANLEY, D.J., 1998. Manzala lagoon, Nile delta, Egypt: Modern sediment accumulation based on radioactive tracers. *Environmental Geology*, 34(2/3), 183–193.

BERNASCONI, M.P. and STANLEY, D.J., 1997. Molluscan biofacies, their distributions and current erosion on the Nile delta shelf. *Journal of Coastal Research*, 13(4), 1201–1212.

BISWAS, A.K., 1992. The Aswan High Dam revisited. *ECODECISION*, September, 67–69.

BISWAS, A.K., 1993. Land resources for sustainable agricultural development in Egypt. *AMBIO*, 22(8), 556–560.

BROUSSARD, M.L., (ed.), 1975. *Deltas, Models for Exploration*. Houston: Houston Geological Society, 555p.

BUTZER, K.W., 1960. On the Pleistocene shorelines of the Arab's Gulf, Egypt. *Journal of Geology*, 68, 626–637.

BUTZER, K.W., 1976. *Early Hydraulic Civilization in Egypt*. Chicago: University of Chicago Press, 134p.

BUTZER, K.W. and HANSEN, C.L., 1968. *Desert and River in Nubia: Geomorphology and Prehistoric Environments at the Aswan Reservoir*. Madison, Wisconsin: University of Wisconsin Press, 562p.

CHEN, Z.; WARNE, A.G., and STANLEY, D.J., 1992. Late Quaternary evolution of the northwestern Nile delta between the Rosetta promontory and Alexandria, Egypt. *Journal of Coastal Research*, 8, 527–561.

COLEMAN, J.M., 1982. *Deltas, Processes of Deposition and Models for Exploration*. Boston: International Human Resources Development Corporation, 124p.

COLEMAN, J.M., 1988. Dynamic changes and processes in the Mississippi river delta. *Geological Society of America Bulletin*, 100, 999–1015.

COLEMAN, J.M. and WRIGHT, L.D., 1975. Modern river deltas: variability of processes and sand bodies. *In*: BROUSSARD, M.L., (ed.), *Deltas Models for Exploration*. Houston: Houston Geological Society, pp. 99–149.

COLEMAN, J.M.; ROBERTS, H.H.; MURRAY, S.P., and SALAMA, M., 1980. Morphology and dynamic sedimentology of the eastern Nile delta shelf. *Marine Geology*, 41, 325–339.

COUTELLIER, V. and STANLEY, D.J., 1987. Late Quaternary stratigraphy and paleogeography of the eastern Nile delta, Egypt. *Marine Geology*, 77, 257–275.

DE COSSON, A., 1935. *Mareotis: Being a Short Account of the History and Ancient Monuments of the Northwestern Desert of Egypt and of Lake Mareotis*. London: Morrison and Gibb Ltd., 219p.

DELFT HYDRAULICS, 1991. Implications of relative sea-level rise on the development of the lower Nile delta, Egypt. *Delft Hydraulics, Report H 927*.

DOWIDAR, N.M., 1988. Effect of Aswan High Dam on the biological productivity of southeastern Mediterranean. *In*: EL-SABH, M.I. and MURTY, T.S., (eds.), *Natural and Man-made Hazards*. Dordrecht: D. Reidel, 477–498.

EL-ASKARY, M.A. and FRIHY, O.E., 1986. Depositional phases of Rosetta and Damietta promontories on the Nile delta coast. *Journal of African Earth Sciences*, 5, 627–633.

EL BUSEILI, A. and FRIHY, O.E., 1984. Textural and mineralogical evidence denoting the position of the mouth of the old Canopic Nile branch on the Mediterranean coast of Egypt. *Journal of African Earth Sciences*, 2, 103–107.

ELDARDIR, M., 1994. Sedimentation in Nile High Dam reservoir, 1987–1992, and sedimentary futurologic aspects. *Sedimentology of Egypt*, 2, 23–39.

EL-DIK, M.S.; MAHMUD, S.H.; GURSKIY, Y.N., and LOTFI, M.F., 1990. Effect of anthropogenic pollution on water composition in the eastern harbor of Alexandria. *Oceanology*, 30, 301–302.

EL-SAYED, M.K., 1996. Rising sea-level and subsidence of the northern Nile delta: A case study. *In*: MILLIMAN, J.D. and HAQ, B.U., (eds.), *Sea-Level Rise and Coastal Subsidence*. The Netherlands: Kluwer Academic Publishers, 215–233.

ELSOKKARY, I.H., 1992. Trace metals in sediments and waters: Case study from Egypt. *In*: VERNET, J.-P., (ed.), *Impact of Heavy Metals in the Environment*, Amsterdam: Elsevier Publishers, 355–379.

EMERY, K.O.; AUBREY, D.G., and GOLDSMITH, V., 1988. Coastal neo-

tectonics of the Mediterranean from tide-gauge records. *Marine Geology,* 81, 41–52.
FANOS, A.M., 1986. Statistical analysis of longshore current data along the Nile delta coast. *Water Science Journal,* 1, 45–55.
FINETTI, I., 1976. Mediterranean Ridge: a young submerged chain associated with the Hellenic Arc. *Bollettino di Geofisica Teorica ed Applicata,* 18(69), 31–65.
FOUCAULT, A. and STANLEY, D.J., 1989. Late Quaternary palaeoclimatic oscillations in East Africa recorded by heavy minerals in the Nile delta. *Nature,* 339(6219), 44–46.
FOURTAU, R., 1915. Contribution à l'étude des dépôts nilotiques. *Mémoires de l'Institut Egyptien,* 8, 57–94.
FRIHY, O.E., 1988. Nile delta shoreline changes: aerial photographic study of a 28-year period. *Journal of Coastal Research,* 4(4), 597–606.
FRIHY, O.E.; EL FISHAWI, N.M., and EL ASKARY, M.A., 1988. Geomorphological features of the Nile delta coastal plain: a review. *Acta Adriatica,* 29(1/2), 51–65.
GALILI, E.; DAHARI, U., and SHARVIT, J., 1993. Underwater surveys and rescue excavations along the Israeli coast. *The International Journal of Nautical Archaeology,* 22, 61–77.
GARFUNKEL, Z., 1984. Large scale submarine rotational slumps and growth faults in the Eastern Mediterranean. *Marine Geology,* 55, 305–324.
GEORGE, C.J., 1972. The role of the Aswan High Dam in changing the fisheries of the southeastern Mediterranean. *In:* TAGI FARVAZ, M. and MILTON, P.J., (eds.), *The Careless Technology.* New York: The Natural History Press, 159–178.
GIGNOUX, M., 1955. The Neogene. *In:* WOODFORD, G.G., (ed.), *Stratigraphic Geology.* San Francisco: W.H. Freeman and Co., 554–603.
GREENBERG, S.H., 1997. The White, the Blue . . . and the 'New Nile.' How much can a river give? *Newsweek,* 12 May 1997 issue, 23.
HALIM, Y. and GERGES, S.K., 1981. Coastal lakes of the Nile delta. Lake Manzala. *Symposium on Coastal Lagoons, UNESCO, Technical Papers in Marine Science,* 33, 135–172.
HALIM, Y.; GERGES, S.K., and SALEH, H.H., 1967. Hydrographic conditions and plankton in the SE Mediterranean during the last normal Nile flood. *Internationale Revue der gesamten Hydrobiologie,* 52, 401–425.
HAMID, S., 1984. Fourier analysis of Nile flood levels. *Geophysical Research Letters,* 11, 843–858.
HAMROUSH, H.A. and STANLEY, D.J., 1990. Paleoclimatic oscillations in East Africa interpreted by analysis of trace elements in Nile delta sediments. *Episodes,* 13(4), 264–269.
HARB, M.; FARIS, R.; GAD, A.M., and HAFEZ, O.N., 1993. The resurgence of lymphatic filariasis in the Nile Delta. *Bulletin of the World Health Organization,* 71, 29–54.
HASSAN, F.A., 1981. Historical Nile floods and their implications for climatic change. *Science,* 212, 1142–1145.
HASSAN, F.A., 1984. Environment and subsistence in predynastic Egypt. *In:* CLARK, J.D. and BRANDT, S.A. (eds.), *From Hunters to Farmers.* Berkeley: University of California Press, 57–64.
HASSOUBA, A.M.B.H., 1995. Quaternary sediments from the coastal plain of northwestern Egypt (from Alexandria to El Omayid). *Carbonates and Evaporites,* 10(1), 8–44.
HERODOTUS, 1987. *The History* (GREEN, D., translator). Chicago: The University of Chicago Press, 699p.
HOFFMAN, M.A., 1979. *Egypt Before the Pharaohs.* New York: Knopf, 391p.
HSU, K.J.; RYAN, W.B.F., and CITA, M.B., 1973. Late Miocene desiccation of the Mediterranean. *Nature,* 242, 239–243.
HURST, E.H., 1931–1966. *The Nile Basin.* Cairo: Physical and Nile control Department, Ministry of Public Works, Vols. 1–9.
IDRIS, H. and NOUR, S., 1990. Present groundwater status in Egypt and the environmental impacts. *Environmental Geology and Water Science,* 16(3), 171–177.
INMAN, D.L. and JENKINS, S.A., 1984. The Nile littoral cell and man's impact on the coastal littoral zone in the SE Mediterranean. *In: Proceedings, 17th International Coastal Engineering Conference.* Sydney: ASCE, 1600–1617.
ISSAWI, B. and MCCAULEY, J.F., 1993. The Cenozoic landscape of Egypt and its river systems. *Annals of the Geological Society of Egypt,* 19, 357–384.
JACOTIN, E., 1826. *Atlas Géographique: Description de l'Egypte.* Paris: Panokouke, 48 plates.
JEFTIC, L.; MILLIMAN, J.D., and SESTINI, G., (eds.), 1992. *Climate change and the Mediterranean. Environmental and Societal Impacts of Climate Change and Sea-Level Rise in the Mediterranean Sea.* London: Edward Arnold, 673p.
KASEF, A.I., 1983. Salt water intrusion in the Nile delta. *Ground Water,* 21(2), 160–167.
KASSAS, M., 1972. Impact of river control schemes on the shoreline of the Nile delta. *In:* FARNAR, M.T. and HILTON, J.P., (eds.), *The Careless Technology: Ecology and International Development.* New York: Natural History Press, 179–188.
KERAMBRUN, P., (ed.), 1986. *Coastal Lagoons of the Southern Mediterranean coast (Algeria, Egypt, Libya, Morocco, Tunisia): Description and Bibliography.* UNESCO Reports in Marine Science, 34, 182p
KEBEASY, R.M.; MAAMOUN, M.; IBRAHIM, E.M.; MEGAHED, A.; SIMPSON, D.W., and LEITH, W.S., 1987. Earthquake studies at Aswan reservoir. *Journal of Geodynamics,* 7(3/4), 173–193.
KIJKO, A.; DESSOKY, M.M.; KEBEASY, R.M., and HASEAB, G.H., 1985. Preliminary estimation of seismic hazard in the Aswan lake area in Egypt. *Acta Geophysica Polonica,* 33(3), 269–277.
KROEPER, K. and WILDUNG, D., 1985. Minshat Abu Omar. Vor- und Frühgeschiechte im Niledelta. *Archäologie in Deutschland,* 4, 10–17.
LOIZEAU, J.-L. and STANLEY, D.J., 1993. Petrological-statistical approach to interpret recent and sub-recent lagoon subfacies, Idku, Nile delta of Egypt. *Marine Geology,* 111, 55–81.
LOIZEAU, J.-L. and STANLEY, D.J., 1994. Bottom sediment patterns evolving in polluted Mariut lake, Nile delta, Egypt. *Journal of Coastal Research,* 10, 416–439.
MALDONADO, A. and STANLEY, D.J., 1976. The Nile Cone submarine fan development by cyclic sedimentation. *Marine Geology,* 20, 27–40.
MALDONADO, A. and STANLEY, D.J., 1978. Nile Cone depositional processes and patterns in the Late Quaternary. *In:* STANLEY, D.J. and KELLING, G., (eds.), *Canyons, Fans, and Trenches.* Stroudsburg, PA: Dowden, Hutchinson & Ross, 239–257.
MANCY, K.H. and HAFEZ, M., 1983. Water quality and ecosystem considerations in integrated Nile resources management. *In:* ELASSIOUTI, I.M. and MARKS, D.H., (eds.), Water resources planning in Egypt. *Proceedings of the International Conference, Cairo, Egypt,* 469–485.
MANOHAR, M., 1976. Dynamic factors affecting the Nile delta coast. *In: Proceedings of the Seminar on Nile Delta Sedimentology.* Alexandria: UNESCO/ASRT/UNDP, 104–129.
MANOHAR, M., 1981. Coastal processes at the Nile delta coast. *Shore and Beaches,* 49, 8–15.
MARCUS, A.D., 1997. Water fight-Egypt faces problem it has long dreaded: less control of the Nile. *Wall Street Journal,* 22 August 1997, A1 and A9.
MART, Y., 1984. The tectonic regime of the southeastern Mediterranean. *Marine Geology,* 55, 365–386.
MILLIMAN, J.D.; BROADUS, J.M., and GABLE, F., 1989. Environmental and economic implication of rising sea level and subsiding deltas-the Nile and Bengal examples. *Ambio,* 18, 340–345.
MILLIMAN, J.D. and HAQ, B.U., (eds.), 1996. *Sea-level Rise and Coastal Subsidence: Causes, Consequences, and Strategies.* Coastal Systems and Continental Margins, v. 2. Dordrecht: Kluwer Academic Publishers, 369p.
MORGAN, J.P., (ed.), 1970. *Deltaic Sedimentation, Modern and Ancient.* Tulsa: Society of Economic Paleontologists and Mineralogists, Special Publication No. 15, 312p.
MURRAY, S.P.; COLEMAN, J.M., and ROBERTS, H.H., 1981. Accelerated currents and sediment transport off the Damietta Nile promontory. *Nature,* 293(5827), 51–54.
NEEV, D., 1975. Tectonic evolution of the Middle East and the Levantine basin (easternmost Mediterranean). *Geology,* 3, 683–686.
NEEV, D.; ALMAGOR, G.; ARAD, A.; GINZBURG, A., and HALL, S.K.,

1976. The geology of the southeastern Mediterranean. *Geological Survey of Israel Bulletin,* 68, 55p.

NEEV, D.; GREENFIELD, L., and HALL, J., 1980. Slice tectonics in the Eastern Mediterranean Sea. *In:* STANLEY, D.J. and WEZEL, C.F., (eds.), *Geological Evolution of the Mediterranean Basin.* Berlin: Springer, 249–272.

NIR, Y., 1982. Offshore artificial structures and their influence on the Israel and Sinai Mediterranean beaches. *In: Proceedings of the 18th Coastal Engineering Conference ASCE, Capetown, South Africa,* 1837–1856.

OTI, M.N. and POSTMA, G., (eds.), 1995. *Geology of Deltas.* Rotterdam, The Netherlands: A.A. Balkema, 315p.

PEARCE, F., 1994. High and dry in Aswan. *New Scientist,* 7, 28–32.

PENLAND, S.; BOYD, R., and SUTER, J.R., 1988. Transgressive depositional systems of the Mississippi delta plain: a model for barrier shoreline and shelf sand development. *Journal of Sedimentary Petrology,* 58, 6, 932–949.

PIRAZZOLI, P.A., 1991. *World Atlas of Sea-Level Changes.* New York: Elsevier, 300p.

POEM GROUP, 1992. General circulation of the Eastern Mediterranean. *Earth-Science Reviews,* 32, 285–309.

POMERANCBLUM, M., 1966. The distribution of heavy minerals and their hydraulic equivalents in sediments of the Mediterranean continental shelf of Israel. *Journal of Sedimentary Petrology,* 36(1), 162–174.

POPPER, W., 1951. *The Cairo Nilometer.* Los Angeles: University of California Press, 269p.

POR, F.D. and BEN TUVIA, A., 1981. The Bardawil lagoon (Sirbonian lagoon) of North Sinai. A summing up. *Rapport, Commission Internationale pour l'Exploration Scientifique de la Mer Méditerranée,* 27(4), 101–107.

POSTEL, S., 1992. *Last Oasis: Facing Water Scarcity.* New York: Norton, 239p.

PUGLIESE, N. and STANLEY, D.J., 1991. Ostracoda, depositional environments and late Quaternary evolution of the Eastern Nile delta, Egypt. *Il Quaternario,* 4, 275–302.

QUELENNEC, R.E. and KRUC, C.B., 1976. Nile suspended load and its importance for Nile delta morphology. *In: UNDP/UNESCO Proceedings of the Seminar on Nile Delta Sedimentology.* Alexandria: Academy of Scientific Research and Technology, Egypt, 257p.

RANDAZZO, G.; STANLEY, D.J.; DI GERONIMO, S.I., and AMORE, C., 1998. Human induced sedimentological changes in Manzala lagoon, Nile delta, Egypt. *Environmental Geology,* 31, (in press).

REINHARDT, E.G.; STANLEY, D.J., and PATTERSON, R.T., 1998. Strontium isotopic-paleontological method as a high-resolution paleosalinity tool for lagoonal environments. *Geology* (in press).

RIZZINI, A.; VEZZANI, F.; COCOCCETTA, V., and MILAD, G., 1978. Stratigraphy and sedimentation of the Neogene-Quaternary section in the Nile delta area. *Marine Geology,* 27, 327–348.

ROSS, D.A. and UCHUPI, E., 1977. Structure and sedimentary history of southeastern Mediterranean Sea-Nile Cone area. *American Association of Petroleum Geologists Bulletin,* 61, 872–902.

SAID, R., 1981. *The River Nile.* Berlin: Springer-Verlag, 151p.

SAID, R., 1993. *The River Nile, Geology, Hydrology and Utilization.* Oxford: Pergamon Press, 320p.

SCHLUMBERGER, 1984. *Well Evaluation Conference Egypt.* Paris: Schlumberger Middle East, Editions Galilée, 248 p.

SCHUMM, S.A. and GALAY, V.J., 1994. The River Nile in Egypt. *In:* SCHUMM, S.A. and WINKLEY, B.R., (eds.), *The Variability of Large Alluvial Rivers.* New York: American Society of Civil Engineers Press, 75–100.

SESTINI, G., 1989. Nile delta: a review of depositional environments and geological history. *In:* WHATELEY, M.K.G. and PICKERING, K.T., (eds.), *Deltas: Sites and Traps for Fossil Fuels.* London: Geological Society Special Publication, 41, 99–127.

SESTINI, G., 1992. Implications of climatic changes for the Nile delta. *In:* JEFTIC, L.; MILLIMAN, J.D., and SESTINI, G., (eds.), *Climatic Change and the Mediterranean,* London: Edward Arnold, 535–601.

SHAHEEN, A.H. and YOSEF, S.F., 1978. The effect of the cessation of Nile flood on the hydrographic features of lake Manzala, Egypt. *Hydrobiology,* 84, 339–367.

SHARAF EL DIN, S.H., 1973. Geostrophic currents in the southeastern sector of the Mediterranean Sea. *Acta Adriatica (Symposium on eastern Mediterranean Sea),* 18, 221–235.

SHARAF EL DIN, S.H., 1977. Effect of the Aswan High Dam on the Nile flood and on the estuarine and coastal circulation pattern along the Mediterranean Egyptian coast. *Limnology and Oceanography,* 22 (2), 194–207.

SHATA, A. and EL FAYOUMI, I., 1970. Remarks on the hydrogeology of the Nile delta. *In: Hydrology of Deltas, IASH/UNESCO, Bucharest Symposium,* Paris: UNESCO, Vol. 1, 189–197.

SHAWKY ABDINE, A., 1981. Egypt's petroleum geology: good grounds for optimism. *World Oil,* December, 99–112.

SHIRLEY, M.L., (ed.), 1966. *Deltas in Their Geologic Framework.* Houston: Houston Geological Society, 251p.

SIEGEL, F.R., 1995. Environmental geochemistry in development planning: an example from the Nile delta, Egypt. *Journal of Geochemical Exploration,* 55, 265–273.

SIEGEL, F.R.; SLABODA, M.L., and STANLEY, D.J., 1994. Metal pollution loading, Manzalah lagoon, Nile delta, Egypt: Implications for aquaculture. *Environmental Geology,* 23, 89–98.

SMITH, S.E. and ABDEL KADER, A., 1988. Coastal erosion along the Nile delta. *Journal of Coastal Research,* 4, 245–255.

SNEH, A. and WEISSBROD, T., 1973. Nile delta: the defunct Pelusian branch identified. *Science,* 180, 59–61.

SNEH, A.; WEISSBROD, T.; EHRLICH, A.; HOROWITZ, A.; MOSHKOVITZ, S., and ROSENFELD, A., 1986. Holocene evolution of the northeastern corner of the Nile delta. *Quaternary Research,* 26, 194–206.

STANLEY, D.J., 1977. Post-Miocene depositional patterns and structural displacement in the Mediterranean. *In:* NAIRN, A.E.M.; KANES, W.H., and STEHLI, F.G., (eds.), *The Ocean Basins and Margins, Volume 4A, The Eastern Mediterranean.* New York: Plenum Press, 77–150.

STANLEY, D.J., 1985. Mud redeposition processes as a major influence on margin-based sedimentation. *In:* STANLEY, D.J. and WETZEL, F.C., (eds.), *Geological Evolution of the Mediterranean Basin.* New York: Springer Verlag, p. 377–410.

STANLEY, D.J., 1988a. Low sediment accumulation rates and erosion on the middle and outer Nile delta shelf off Egypt. *Marine Geology,* 84, 111–117.

STANLEY, D.J., 1988b. Subsidence in the northeastern Nile delta: Rapid rates, possible causes and consequences. *Science,* 240, 497–500.

STANLEY, D.J., 1989. Sediment transport on the coast and shelf between the Nile delta and Israeli margin as determined by heavy minerals. *Journal of Coastal Research,* 5, 813–828.

STANLEY, D.J., 1990. Recent subsidence and northeast tilting of the Nile delta, Egypt. *Marine Geology,* 94, 147–154.

STANLEY, D.J., 1996. Nile delta: extreme case of sediment entrapment on a delta plain and consequent coastal land loss. *Marine Geology,* 129, 189–195.

STANLEY, D.J., 1997. Mediterranean deltas: subsidence as a major control of relative sea-level rise. *Bulletin de l'Institut Océanographique, Monaco,* Número spécial 18, 35–62.

STANLEY, D.J.; ARAD, V.; BARTOV, Y., and EL BEDEWY, F.M., 1993. *The Nile Delta, Bibliography of Geological Research.* Egypt: Geological Survey and Israel Geological Survey, Report GSI/22/93, 169p.

STANLEY, D.J.; ARNOLD, D., and WARNE, A.G., 1992a. Oldest Pharaonic site. *National Geographic Research and Exploration,* 8(3), 264–275.

STANLEY, D.J. and BERNASCONI, M.P., 1998. Relict and palimpsest depositional patterns on the Nile shelf recorded by molluscan faunas. *Palaios,* 13, 79–86.

STANLEY, D.J. and GALILI, E., 1996. Sediment dispersal along northern Israel coast during the early Holocene: geological and archaeological evidence. *Marine Geology,* 130:11–17.

STANLEY, D.J. and GOODFRIEND, G.A., 1997. Recent subsidence of the northern Suez Canal. *Nature,* 388, 335–336.

STANLEY, D.J. and HAMZA, F.H., 1992. Terrigenous-carbonate sediment interface (late Quaternary) along the northwestern margin of the Nile delta, Egypt. *Journal of Coastal Research,* 8, 153–171.

STANLEY, D.J.; MCREA, J.E. JR., and WALDRON, J.C., 1996. *Nile*

Delta Drill Core and Sample Databases for 1985–1994: Mediterranean Basin (MEDIBA) Program. Smithsonian Contributions to the Marine Sciences, 37. Washington D.C.: Smithsonian Institution Press, 428 p.

STANLEY, D.J. and MALDONADO, A., 1977. Nile Cone: Late Quaternary stratigraphy and sediment dispersal. *Nature,* 266, 129–135.

STANLEY, D.J.; NIR, Y., and GALILI, E., 1998. Clay mineral distributions to interpret Nile cell provenance and dispersal: III. Offshore margin between Nile delta and northern Israel. *Journal of Coastal Research,* 14(1), 196–217.

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

STANLEY, D.J. and WARNE, A.G., 1993b. Sea level and initiation of Predynastic culture in the Nile delta. *Nature,* 363, 435–438.

STANLEY, D.J. and WARNE, A.G., 1994. Worldwide initiation of Holocene marine deltas: deceleration of sea-level rise as principal factor. *Science,* 265, 228–231.

STANLEY, D.J. and WARNE, A.G., 1997. Holocene sea-level change and early human utilization of deltas. *GSA Today,* 7(12), 1–7.

STANLEY, D.J.; WARNE, A.G.; DAVIS, H.R.; BERNASCONI, M.P., and CHEN, Z., 1992b. Nile delta: the late Quaternary north-central Nile delta from Manzala to Burullus lagoons, Egypt. *National Geographic Research and Exploration,* 8, 22–51.

STANLEY, D.J. and WINGERATH, J.G., 1996. Clay mineral distributions to interpret Nile cell provenance and dispersal: I. Lower River Nile to delta sector. *Journal of Coastal Research,* 12(4), 911–929.

SUMMERHAYES, C.; SESTINI, G.; MISDORP, R., and MARKS, N., 1978. Nile delta: Nature and evolution of continental shelf sediment system. *Marine Geology,* 24, 37–47.

TOSCANO, M.A. and LUNDBERG, J., 1998. Early Holocene sea-level record from submerged fossil reefs on the southeast Florida margin. *Geology,* 26, 255–258.

TOUSSOUN, O., 1922. Mémoire sur les anciennes branches du Nil. *Mémoires de la Société Géographique d'Egypte,* Cairo, 4, 144.

UNDP/UNESCO, 1976. *Proceedings of the Seminar of Nile Delta Sedimentology, Alexandria, Oct. 1975.* Cairo: Academy of Scientific Research and Technology, 257p.

UNDP/UNESCO, 1977. *Proceedings of Seminar on Nile Delta Coastal Processes with Special Emphasis on Hydrodynamical Aspects.* Alexandria: UNDP/UNESCO, Egyptian Academy of Scientific Research and Technology, 624p.

UNDP/UNESCO, 1978. *Arab Republic of Egypt: Coastal Protection Studies, Project Findings and Recommendations.* UNDP/EGY/73/063 Final Report. Paris, FNR/SC/OSP/78/230, 483p.

U.S. DEPARTMENT OF AGRICULTURE, 1976. *Major Constraint to Increasing Agricultural Productivity.* Foreign Agricultural Economic Report 120. USDA/AID/Ministry of Agriculture, Egypt.

WAHBY, S.D. and BISHARA, N.F., 1977. Physical and chemical factors affecting fish distribution in Lake Manzala. *Acta Ichthyologica et Piscatoria,* 7(1), 16–29.

WAHBY, S.D. and BISHARA, N.F., 1981. The effect of the River Nile on Mediterranean water, before and after the construction of the High Dam at Aswan. *In: River Input to the Ocean Systems.* Paris: UNESCO Publ., 311–318.

WARNE, A.G. and STANLEY, D.J., 1993a. Archaeology to refine Holocene subsidence rates along the Nile delta margin, Egypt. *Geology,* 21, 715–718.

WARNE, A.G. and STANLEY, D.J., 1993b. Late Quaternary evolution of the northwest Nile delta and adjacent coast in the Alexandria region, Egypt. *Journal of Coastal Research,* 9, 26–64.

WARNE, A.G. and STANLEY, D.J., 1995. Sea-level change as critical factor in development of basin margin sequences: New evidence from late Quaternary record. *Journal of Coastal Research,* Special Issue 17, 231–240.

WATERBURY, J., 1979. *Hydropolitics of the Nile Valley.* New York: Syracuse University Press, 301p.

WENDORF, F. and SCHILD, R., 1978. *Prehistory of the Nile Valley,* New York: Academic Press, 414p.

WENKE, R.J., 1991. The evolution of early Egyptian civilization: issues and evidence. *Journal of World Prehistory,* 5(3), 279–329.

WORLD BANK, 1990. Arab Republic of Egypt: country economic memorandum, economic readjustment with growth. *In: World Bank Report, No. 7447-EGT, vol. 2 (main report),* 72p.

ZAGHLOUL, Z.M.; ABDEL-DAIEM, A.A., and TAHA, A.A., 1990. Geomorphology, geologic evolution and subsidence of the Nile delta during the Quaternary. *Bulletin of the Faculty of Science,* 17(1), 471–495.

ZAGHLOUL, Z.M.; ANDRAWIS, S.F., and AYAD, S.N., 1979a. New contribution to the stratigraphy of Tertiary sediments of Kafr El Dawar well no. 1, NW Nile delta, Egypt. *Annals of the Geological Survey of Egypt,* 9, 292–307.

ZAGHLOUL, Z.M.; TAHA, A.A.; HEGAB, O.A., and EL-FAWAL, F.M., 1977. The Neogene-Quaternary sedimentary basins of the Nile delta. *Egyptian Journal of Geology,* 21, 143–161.

ZAGHLOUL, Z.M.; TAHA, A.A.; HEGAB, O.A., and EL-FAWAL, F.M., 1979b. The Plio-Pleistocene Nile delta: sub-environments, stratigraphic section and genetic classification. *Annals of the Geological Survey of Egypt,* 9, 283–291.

ZERBINI, S.; PLAG, H.-P.; BAKER, T., and 13 others, 1996. Sea level in the Mediterranean: a first step towards separating crustal movements and absolute sea-level variations. *Global and Planetary Change,* 14, 1–48.