

Geomorphological Changes along the Nile Delta Coastline between 1945 and 2015 Detected Using Satellite Remote Sensing and GIS

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ABSTRACT

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This study describes geomorphologic changes along the Nile Delta coastline between 1945 and 2015. The study used topographic maps produced by the Egyptian Geological Survey in 1945 and Landsat satellite imagery taken between 1973 and 2015. The study found that the coastline's geomorphology greatly changed during this time period, especially at Damietta and Rosetta promontories, which were highly eroded after construction of the Aswan High Dam. Other stretches of the coastline also eroded, while some accretion occurred along the coastline down-drift from the promontories. The trend has been erosion of the beaches along the Nile promontories and accretion within the embayments between the promontories, resulting in an overall smoothing of the coastline. A portion of the eroded material has accreted in the form of spits or shoals near the inlets. The principal causal factors of coastline change were the impacts of the Aswan High Dam, sea-level rise, land subsidence, storms, and coastal protection devices. Efforts to stop erosion have had mixed results. Seawalls built along the city of Alexandria have maintained the coastline, while other coastal protection devices have not impeded erosion. Areas of cultivated land are highly susceptible to saltwater intrusion due to sea-level rise and the fact that much of the delta is at or near sea level.

ADDITIONAL INDEX WORDS: *Shoreline changes, coastal morphology, coastal erosion hazard, DSAS, Aswan High Dam.*

INTRODUCTION

The purpose of this study was to document geomorphological changes along the Nile Delta coast between the years 1945 and 2016. It was carried out by comparing satellite imagery and topographic maps of the coast made during the period of study. State-of-the-art techniques were used to carry out the analysis. The significance of this research lies in the fact that nearly the entire population of Egypt live in the Nile Delta, which is at or slightly above sea level. The combined effects of sea-level rise, subsidence, and the Aswan High Dam leave the delta's coastline susceptible to erosion and the Egyptian population at risk.

The Nile Delta coast is one of the world's earliest recognized deltaic systems. The Greek historian Herodotus, in 450 BC, described its triangular shape as a delta since it resembled the inverted Greek letter Δ . It was formed by sedimentary processes between the upper Miocene and the present (Stanley and Warne, 1993) through alluvium brought by the original seven branches of the Nile (El Banna and Frihy, 2009). The delta is located along the Egyptian Mediterranean coast, as shown in Figure 1. It extends approximately 300 km from Alexandria to Port Said. The Nile Delta coast comprises

approximately 22,000 km² and is situated in the NE margin of the African plate at the SE part of the Mediterranean Sea.

Two different types of sandy spits have formed along the outer margins of the Nile promontories at Rosetta and Damietta (Torab and Azab, 2007). Prior to the Aswan High Dam, water from Nile floods occurring between August and October passed to the Mediterranean Sea at Rosetta and Damietta. After the dam was built, water and its suspended alluvial sediments were trapped behind it. The sediment load was reduced from a range of 54,000,000 t (60,000,000 English tons [tn]) to 163,000,000 t (180,000,000 tn) to less than 14,000,000 t (15,000,000 tn) after the dam was built, which was the principal reason for erosion, especially on Rosetta and Damietta promontories.

Land subsidence rates in the Nile Delta coast were measured by Becker and Sultan (2009), Stanley and Goodfriend (1997), and Stanley and Toscano (2009). The results ranged from as low as 2.0 mm/y to as high as 8.0 mm/y. The range of subsidence ranged between 1 and 2.5 mm/y between Alexandria and the central delta. The annual rate was 5.0 mm between Port Said and the Manzala lagoon region (Stanley, 1990). The subsidence rate between El Mansûra and El Mahalla El Kubra ranged between 1.0 and 9.0 mm/y (Aly, Andrew, and Howard, 2012).

The Nile Delta is a wave-dominant delta. Coleman *et al.* (1981), Frihy, Essam, and Waleed (2003), and Said (1993) reported that the main wave direction along the Nile Delta coast is NW. This wave trend creates a NE longshore current

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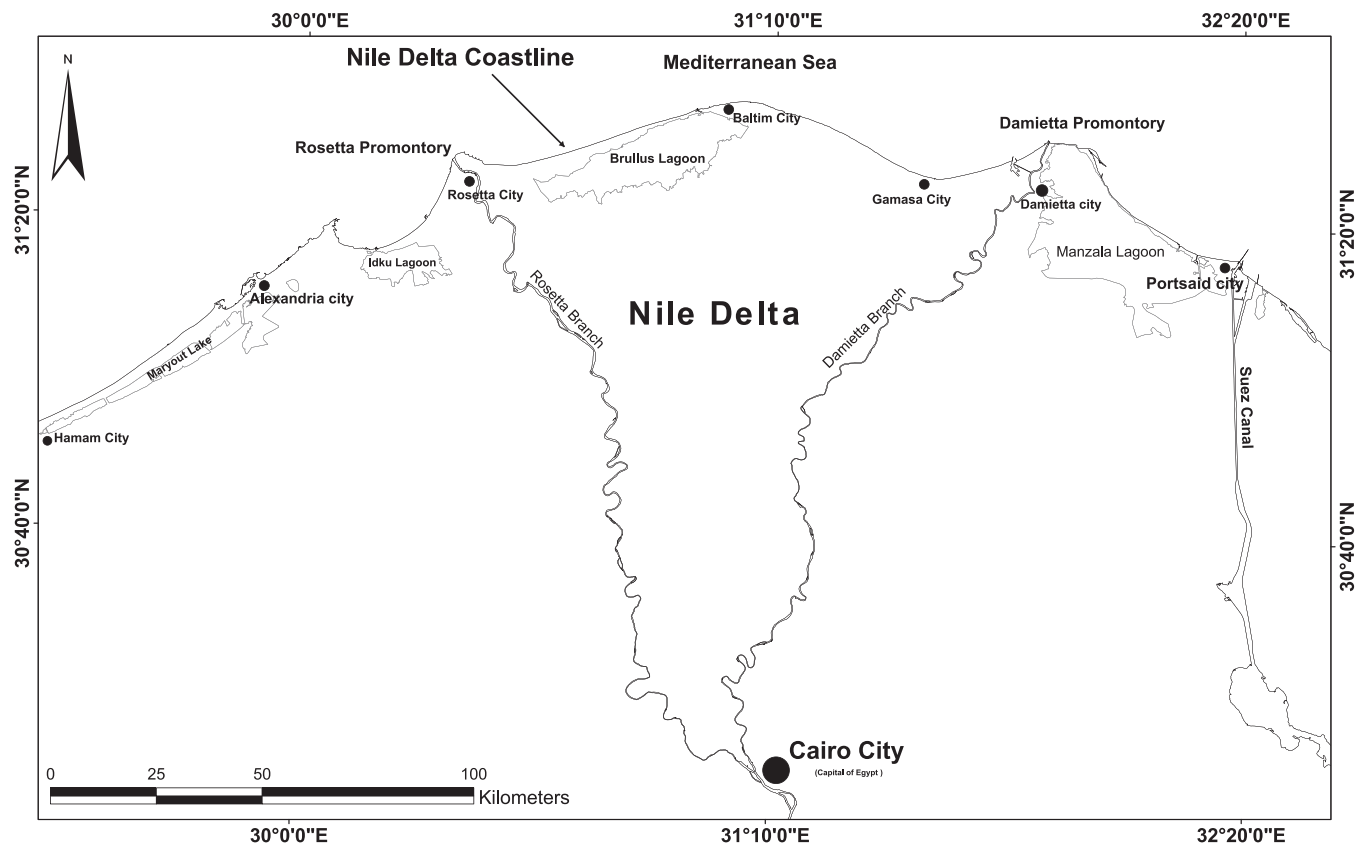


Figure 1. Study area. The study area consisted of approximately 300 km of coastline between Alexandria and Port Said. There are only two outlets to the Mediterranean Sea today (the Rosetta and Damietta). In ancient times, there were seven outlets to the sea.

parallel to the coast. The maximum wave height recorded at Rosetta was 5.4 m, which occurred in 1988 (Frihy, Shereet, and El Banna, 2008).

Studies of the wave refraction and longshore sediment transport rates along the Nile Delta coast were performed by Abdallah, Sharaf El Din, and Shereet (2006), Abo Zed (2007), Elbisy and Bassam (2011), and Isklander (2013). Each reported

zones of wave convergence and divergence resulting in strong longshore gradients of wave heights and breaker angles and, therefore, of sand transport rates.

Isklander (2013) showed that the wave action along the coast is seasonal in nature, with storm waves occurring between October and March. On average, 16 storms occur annually, of which 7 are destructive. Statistical analysis of waves recorded in Abu Quir Bay between 1985 and 1990 showed that waves had an average significant wave height of 1.9 m, an average wave height of 1.1 m, and an average peak wave period of 6.0 seconds. In front of the Damietta harbor between 1997 and 2010, waves had an average significant wave height of 1.0 m, an average wave height of 0.6 m, and an average peak wave period of 6.3 seconds (Isklander, 2013).

The goal of this research was to document where there have been appreciable morphological changes along the Nile Delta coast between 1945 and 2015. The primary objective of this study was to map the coastline over several points in time and measure erosion or accretion. A secondary objective was to forecast changes that might occur in the future.

METHODS

The following section describes how (1) the satellite imagery was preprocessed radiometrically and geometrically, (2) the

Table 1. Specifications of Landsat MSS, TM, ETM, and OLI imagery.

Satellite	Sensor	Footprint (m)	Path/Raw	Acquisition Date
Landsat	MSS	57	P188r39	22 October 1972
			P189r38	03 January 1973
			P190r38, P190r39	31 August 1972
			P191r38, P191r39	19 September 1972
Landsat	TM	30	P176r38, P176r39	20 September 1984
			P177r38, P177r39	11 September 1984
			P178r39	21 November 1984
			P176r38	30 January 2001
Landsat	ETM+	15	P177r38	29 May 2001
			P177r39	11 April 2001
			P178r39	20 May 2001
			P177r38	26 April 2015
Landsat	OLI	15	P176r38	19 April 2015
			P177r39	26 April 2015
			P178r39	28 February 2015

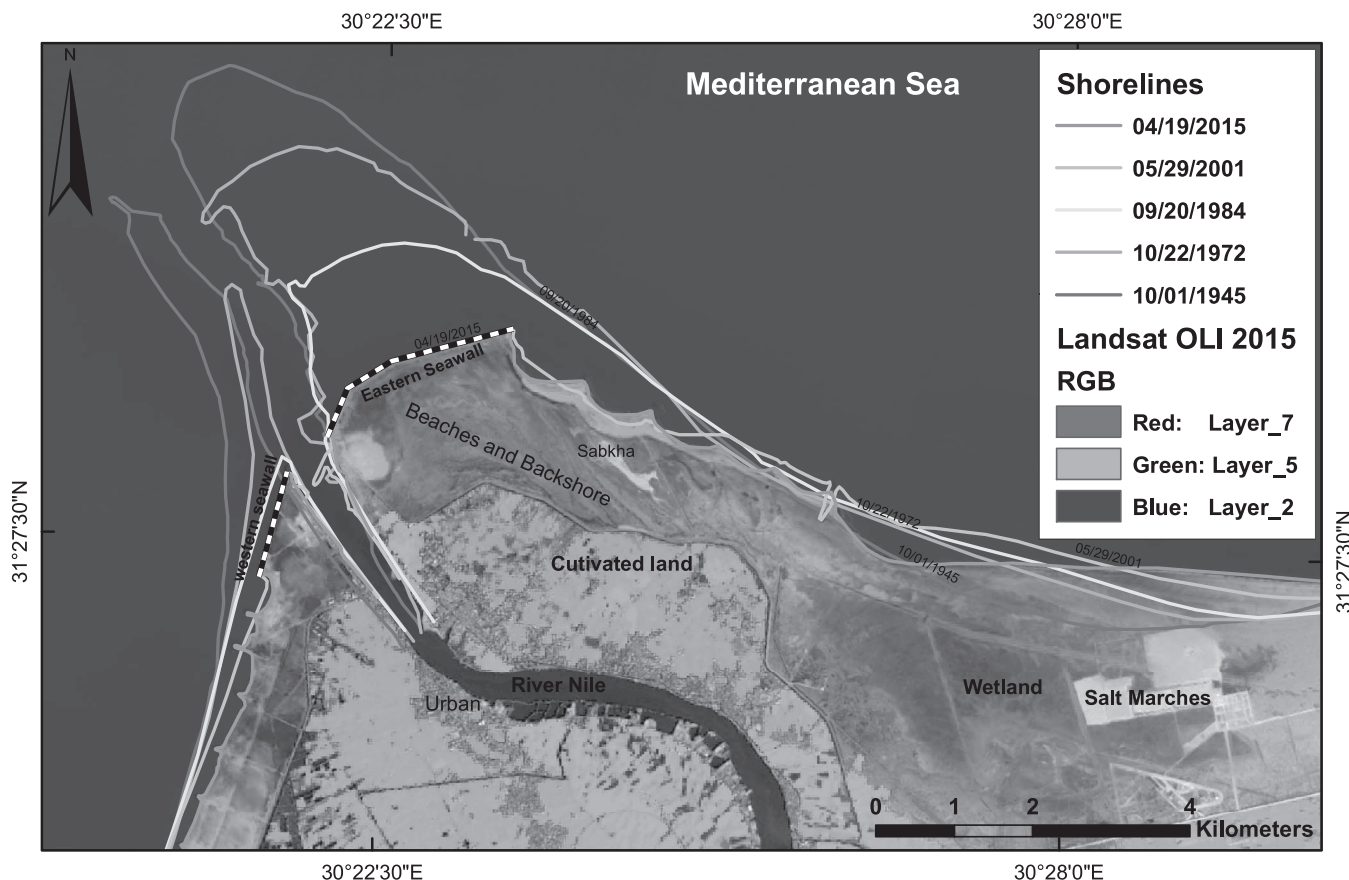


Figure 2. Rosetta Promontory coastline between 1945 and 2015. The map contains an overlay of GIS layers (shorelines from 1945 to 2015) with Landsat 8 images taken in 2015. The coastline along Rosetta Promontory is the most fragile segment of the Nile Delta coast. The highest erosion has occurred in front of the promontory and at the western side, while sedimentation occurred on the eastern side. A reverse of the erosion occurred after construction of the Rosetta seawall, when a new erosion zone formed on the eastern side of the promontory. West of the Rosetta's outlet to the sea there was breaching of seawater into the brackish-water lakes that fringe the Mediterranean Sea.

normalized water indexes were calculated, and (3) the Digital Shoreline Analysis System was incorporated.

Landsat satellite imagery taken in 1972, 1973, 1984, 2000, 2001, 2014, and 2015 was used in this study. Imagery included (1) a multispectral scanner (MSS), (2) a thematic mapper (TM), (3) an enhanced thematic mapper (ETM), and (4) the operational land imager (OLI), as shown in Table 1. Preprocessing of the imagery consisted of (1) geometrically transforming to a Universal Transverse Mercator projection (World Geodetic System 1984, zones 35 and 36); (2) layer stacking four bands of the MSS and seven bands of the TM, ETM+, and OLI; (3) application of radiometric, spatial, and spectral enhancements and principle components analysis (on band 4) to reduce signal noise, haze, and clouds, as well as histogram equalization, color matching and resolution merge; and (4) mosaicking the scenes into one image.

The approach of this study was to compare the Nile Delta coast as shown on topographic maps produced in 1945, using aerial photography and ground surveying techniques, with modern satellite imagery taken between 1973 and 2015. The

topographic maps were part of a 1:25,000-scale map series made by the Egyptian Geological Survey and the British Ordnance Survey. Aerial photographs were taken of the Nile Delta coast, and topographic maps were produced using standard photogrammetric techniques. The area of study was covered by 40 map sheets that were referenced to the Egyptian National Grid Georeference System. The topographic maps were digitized, and the projection system was transformed from the Egyptian National Grid to match the projection and coordinate system of the satellite images.

Radiometric and spatial enhancements were applied to the satellite imagery to ensure accuracy. The spatial resolution across the different sensors was handled using spatial enhancement indexes and the edge detection convolution filter to extract shorelines. The radiometric resolution of the Landsat OLI imagery was rescaled from unassigned 16-bit, 0- to 255-pixel values to a floating single image ranging between 0 and 1 pixel values. The Normalized Difference Water Index (NDWI) and the Modified Normalized Difference Water Index (MNDWI) were applied using ERDAS IMAGINE's Model

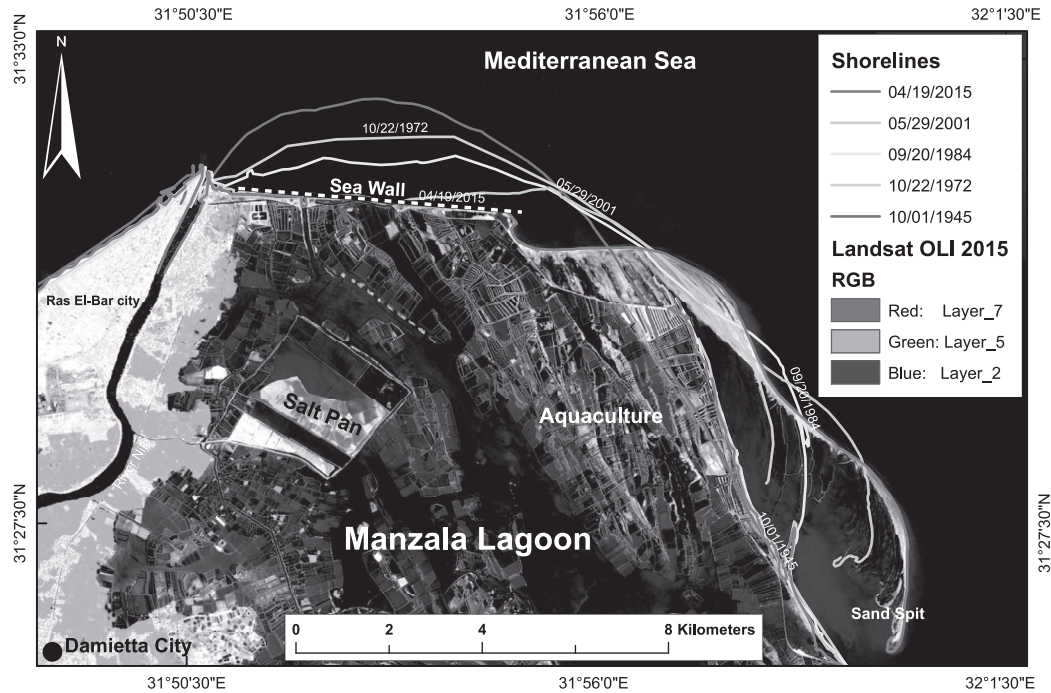


Figure 3. Damietta Promontory coastline between 1945 and 2015. The second-highest coastal erosion rates are at the eastern part of the Damietta outlet. East of the coastal erosion zone a sedimentation zone has formed a sand spit.

Builder to spatially enhance the water/land features. The objective of these enhancements was to classify the outputs to a range of 0 to 1. A binary threshold was used to classify water vs. land, and then the coastline was delineated. Because the MSS image lacks a middle infrared band (MIR), only the NDWI was applied using the Modeler Function in ERDAS Imagine. The resultant NDWI images highlight water bodies present in the study area. This index ranges from -1 to +1 with water bodies of high values (close to +1). As TM and ETM+ images have spectral bands within the visible, near, and middle infrared spectral bands, the MNDWI was applied using the Modeler Function in ERDAS Imagine in order to eliminate any noisy pixels.

The NDWI was represented by the following equation:

$$NDWI = \frac{Green - NIR}{Green + NIR}, \quad (1)$$

where Green = reflected radiation between 600 and 700 nm and near-infrared (NIR) = reflected radiation between 700 and 900 nm. The NDWI was applied to all of the Landsat MSS images.

For the Landsat TM, ETM, and OLI images, coastline extraction used the Modified Normalized Difference Water Index (MNDWI). The MNDWI is expressed as follows:

$$MNDWI = \frac{Green - MIR}{Green + MIR}, \quad (2)$$

where Green = reflected radiation between 600 and 700 nm, and mid-infrared (MIR) = emissive radiation between 1500 and

Table 2. Average and highest coastal erosion and accretion rates along the Nile Delta coast between 1945 and 2015.

Coastal Segment	1945 to 1972 (Before AHD)				1972 to 1984 (After AHD)				1984 to 2001 (Before Seawall)				2001 to 2015 (After Seawall)			
	Erosion		Accretion		Erosion		Accretion		Erosion		Accretion		Erosion		Accretion	
	A	H	A	H	A	H	A	H	A	H	A	H	A	H	A	H
Hammam to Dekheila coast	2.80	9.60	0	0	1.20	2.8	1.80	4.40	0.93	2.40	0.82	4.90	0.97	3.94	1.40	7.80
Dekheila Headland	1.70	1.70	4.60	5.30	0	0	23.10	63.80	2.60	4.70	70.80	131.75	0.60	0.63	4.60	6.93
Alexandria City beaches	2.60	5.20	2.30	6.50	3.70	10.20	2.96	7.06	1.90	7.50	2.50	7.40	1.49	4.40	3.30	29.30
Abu Quir Headland	0	0	9.70	24.50	2.50	3.50	23.40	88.70	2.10	2.40	34.40	55.09	44.90	68.40	3.30	13.20
Abu Quir Bay	3.20	11.20	2.97	5.30	4.40	13.80	2.60	5.90	4.70	17.60	5.00	18.02	5.30	16.90	3.13	13.80
Rosetta Promontory	28.70	72.20	10.00	18.00	71.70	140.60	10.10	13.30	52.20	158.98	9.97	18.70	11.50	35.20	10.30	13.20
Burullus Headland	3.60	7.70	4.90	17.30	4.50	16.80	3.70	11.98	3.10	20.70	3.80	15.700	3.60	30.40	4.99	32.80
Damietta Promontory	7.60	13.20	20.00	60.90	13.13	45.20	19.60	78.03	20.60	50.20	15.40	129.48	12.00	93.90	27.60	177.60
Port Said beaches	6.90	18.80	9.50	23.40	7.90	24.20	8.30	43.80	8.20	19.17	6.40	33.70	8.00	24.97	5.50	17.54
Overall	5.00	72.20	7.20	60.90	8.30	140.60	7.50	88.80	8.23	158.98	6.90	131.75	7.00	93.90	5.97	177.60

AHD = Aswan High Dam, A = average rate (m/y), H = highest rate (m/y).

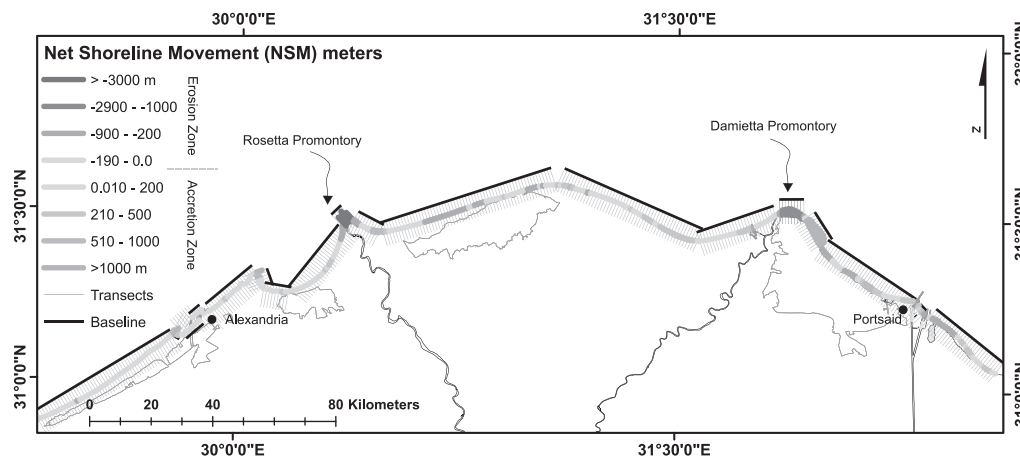


Figure 4. Net change in coastline between 1945 and 2015. The map shows 19 segments along the Nile Delta coast according to direction angles of the coastline. Transects came from segments crossing the shorelines at specific stations. Automatic calculations using the DSAS of the net shoreline movement represents the total distance between the oldest and newest shoreline. The highest coastal erosion zones (dark gray) are distributed spatially along the Nile Delta promontories (-5328.7 m), while the highest coastal sedimentation zones (light gray) are located at the eastern side of Rosetta Promontory (+3000 m).

1700 nm. The algorithm was used to calculate MNDWI in ERDAS Imagine.

The Digital Shoreline Analysis System (DSAS) v.4.3 is an ArcGIS tool that computes rate-of-change statistics from multiple coastline positions (Thieler *et al.*, 2009). The output of the DSAS data set was analyzed for (1) the net shoreline movement (NSM) representing the total distance between the oldest and most recent coastlines; (2) the end-point rate (EPR), which was calculated by dividing the distance of coastline movement by the time elapsed between the oldest and the most recent coastline; and (3) the shoreline change envelope (SCE), the distance between the coastline farthest from and closest to the baseline at each transect. The SCE computes distance *vis-à-vis* rate. The SCE represents the total change in coastline movement for all available coastline positions and is not related

to their date. Figure 2 shows Rosetta Promontory’s EPR, Linear Regression Rate (LRR), NSM, and SCE between 1945 and 2015. Figure 3 shows Damietta Promontory’s EPR, LRR, NSM, and SCE between 1945 and 2015.

RESULTS

The Nile Delta coast exhibited geomorphological change between 1945 and 2015 in some areas and was stable in others. The analysis assessed changes in coastline accretion and erosion rates before construction of the Aswan High Dam in 1964 and after its completion in 1970. The study also analyzed coastline accretion and erosion before and after construction of seawalls built along Rosetta and Damietta promontories between 1984 and 2001.

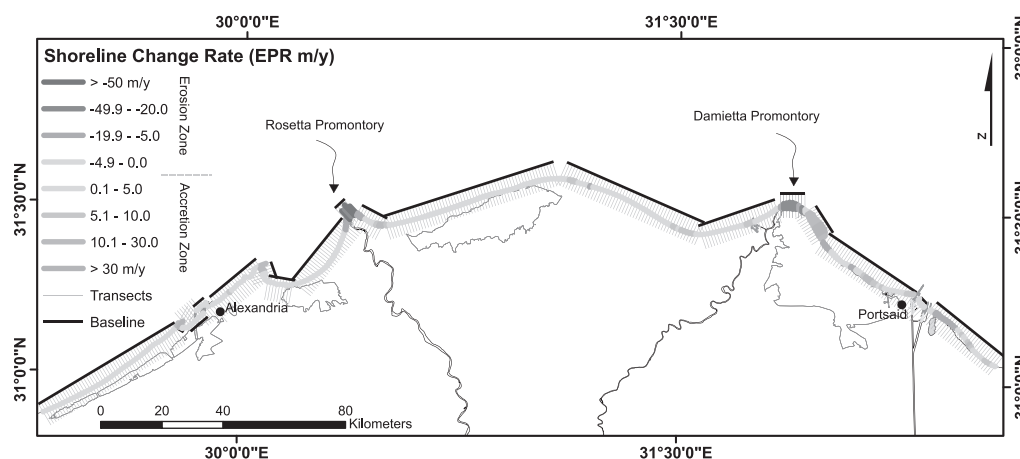


Figure 5. Autocalculation of the end-point rate from 1945 to 2015 using DSAS and ArcGIS. It represents the shoreline change rate either in erosion or deposition from 1945 to 2015. The highest coastal erosion zones (dark gray) are distributed spatially along the Nile Delta promontories (≥ 50 m/y), while the highest coastal sedimentation zones (light gray) are located at the eastern sides of Rosetta Promontory (≥ 30 m/y).

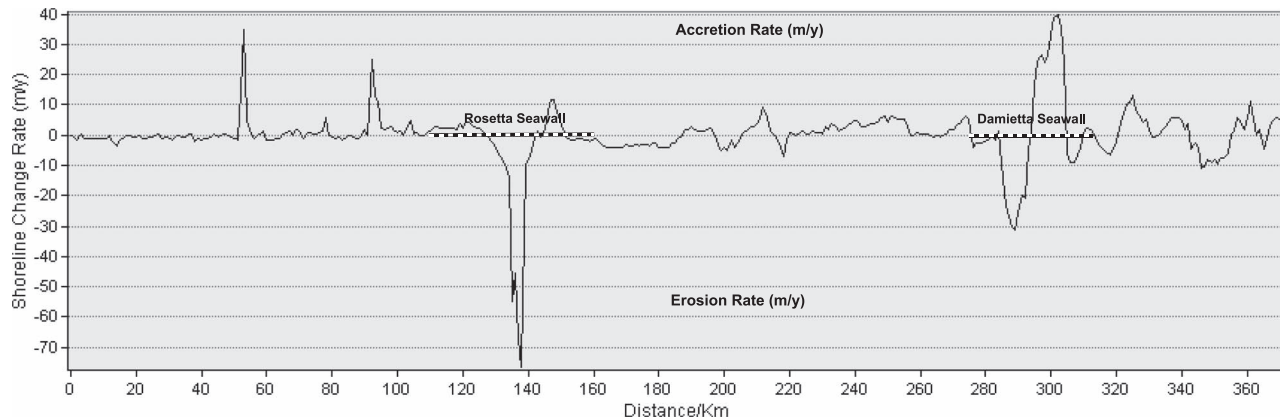


Figure 6. End-point rate of erosion and depositional zones along the Nile Delta coast between 1945 and 2015. It appears that the highest rates were along the Nile Delta promontories and in the artificial ports.

A comparative spatial analysis was done along the coast to analyze and map areas of accretion and erosion along the coastline. The Nile Delta coast was divided into five zones with relatively homogeneous geomorphological change patterns: (1) Alexandria to Al Hammam, (2) Abu Quir to Rosetta Promontory, (3) the Burullus Headland, (4) Damietta Promontory, and (5) the Al Manzala coastal barrier to Port Said. The results are summarized in Table 2.

Using the DSAS, 373 transects, each separated by 1 km, were superimposed on the Nile Delta coast. The baseline was divided into 19 segments. These segments were divided and designated according to the direction angle of the coastline. The total distance of changed coastline either by erosion (–) or accretion (+) ranged between +5329 m and –2771 m, as shown in Figure 4. The EPR is shown in Figures 5 and 6.

Following is a description of coastal morphology changes in the Nile Delta coast during the study period. The coastal sections were selected with respect to their relative homogeneity in regard to change.

Al Hammam to Alexandria

This section of the coastline begins at Al Hammam at the western part of the Nile Delta and ends at the Abu Quir Headland east of Alexandria. The total length of this section is 92 km, and it was divided into 92 one-kilometer transects.

The segment from Al Hammam to the Dekheila Headland included 52 one-kilometer transects. Of these transects, 88% indicated erosion between 1945 and 2015; the highest level of erosion was –236.6 m, and the average rate was –1.0 m/y. Six transects indicated accretion. The greatest distance was 140.0 m, with an average of +0.2 m/y. The average erosion was –2.8 m/y between 1945 and 1972, –1.2 m/y between 1972 and 1984, –0.93 m/y from 1984 to 2001, and –0.97 m/y between 2001 and 2015. Between 1945 and 1972, the coastline accreted an average of +1.8 m/y, between 1972 and 1984 it accreted +0.8 m/y, between 1984 and 2001 it accreted +1.4 m/y, and between 2001 and 2015 it accreted 1.2 m/yr.

The Port of Dekheila was built on the Dekheila Headland as an extension of the Port of Alexandria in 1986. The coastline accreted +2431 m between 1945 and 2015 with an average of +13.7 m/y. The coastline accreted at an average rate of +4.6 m/y between 1945 and 1972, +23.1 m/y between 1972 and 1984, and +70.8 m/y between 1984 and 2001 during construction of the port. Between 2001 and 2015 the coast accreted 4.6 m/y. The average erosion rate was –1.7 m/y between 1945 and 1972, –2.6 m/y between 1984 and 2001, and –0.6 m/y between 2001 and 2015.

The Alexandria coastline extends from east of the Port of Dekheila to the Abu Quir Headland. It consists of 36 transects. Recreational beaches have been artificially renourished since 1934, and the road from Montaza to the Ras El Tin Palace is protected by a seawall. In addition, concrete blocks were placed along the coast in 1984. Breakwaters were constructed to protect the El Dekheila Harbor, Western Harbor, Eastern Harbor, and Abu Quir Harbor at the same time. Groins were constructed at El Shatby, Stanley, El Asafra, El Mandara and Abu Quir recently. Between 1945 and 2015, –124.2 m eroded at an average rate of –0.9 m/y. The highest accretion was +389.5 m, which averaged +1.2 m/y. Analysis of 36 transects along the city of Alexandria indicated erosion along 18 transects and accretion along 15 transects.

The coastline erosion rate was –2.6 m/y. between 1945 and 1972. The average was –3.7 m/y between 1972 and 1984 and –1.9 m/y between 1984 and 2001. Erosion was –1.49 m/y between 2001 and 2015. The average accretion rate was +2.3 m/y between 1945 and 1972. It increased to +3.0 m/y between 1972 and 1984 and +3.3 m/y between 2001 and 2015 due to beach renourishment projects.

Abu Qur Bay to Rosetta Promontory

Between Abu Quir Bay and Rosetta Promontory, the coastline is highly dynamic. The Abu Quir Headland is a port built in 1983. Six transects were used to measure changes between 1945 and 2015. As a result of building the port, the coastline accreted into the sea +1741.0 m, with the highest rate at +25.0 m/y and an average rate +9.2 m/y. The average coastline accretion rate was +9.7 m/y between 1945 and 1972

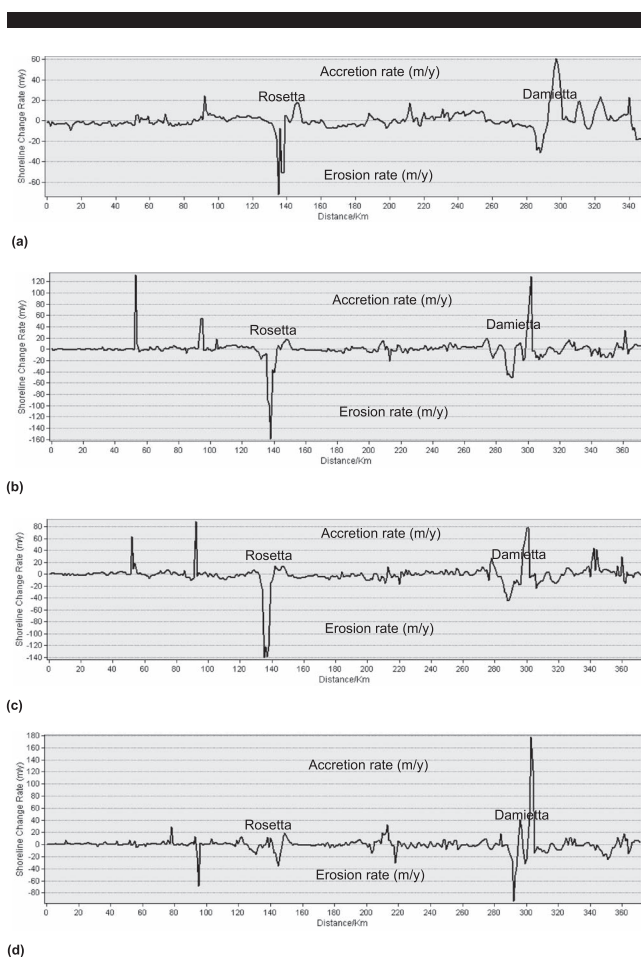


Figure 7. Coastline change rate between 1945 and 2015. This graph shows the EPR of erosion and depositional zones (in m/y) along the Nile Delta coast from 1945 to 1972 (before construction of the Aswan High Dam) and from 1984 to 2015 (after construction of the dam). The rates clearly increased after the Aswan High Dam was constructed due to trapping sediments behind the dam. A statistical graph shows the EPR of erosion and depositional zones (in m/y) along the Nile Delta coast from 1984 to 2001 (before construction of Nile Delta coastal protection seawalls) and from 2001 to 2015 (after construction of the seawalls). It is clearly seen that the rates have decreased suddenly at the areas in which the seawalls were constructed, while new coastal erosion and depositional zones have been formed in different locations along the Nile Delta coast.

and +23.4 m/y between 1972 and 1984. From 1984 to 2001, the average accretion rate was +34.4 m/y, while between 2001 and 2015 the rate was +3.3 m/y. The erosion rate was -2.4 m/y between 1972 and 1984 and -2.1 m/y between 1984 and 2001. Between 2001 and 2015, the coastline eroded an average of -44.9 m/y.

In Abu Quir, 36 transects were used. It eroded -674 m with an average of -4.5 m/y between 1945 and 2015. The greatest distance the coastline accreted was +332 m, with an average of 2 m/y. The average erosion rate was -3.2 m/y between 1945 and 1972. It was -4.4 m/y between 1972 and 1984, -4.7 m/y from 1984 to 2001, and -5.3 m/y between 2001 and 2015. The coastline accretion rate was +3.0 m/y between 1945 and 1972. It was +2.6 m/y between 1972 and 1984, +5 m/y between 1984 and 2001, and +3.1 m/y between 2001 and 2015.

The outlet of Rosetta Promontory and its eastern and western sides were measured using 15 transects. Eight transects indicated erosion, with the greatest distance being 5329.0 m. All of the transects indicating erosion were in front of the outlet of Rosetta or on its western side. Seven transects were measured on the eastern side of Rosetta Promontory. They indicated accretion between 1945 and 2015, with the greatest distance being 828.2 m.

At Rosetta Promontory, the average erosion rate was -28.7 m/y before the Aswan High Dam and -71.7 m/y after. The erosion rate between 1984 and 2001 was -52.2 m/y, while between 2001 and 2015 the rate was only -11.5 m/y as a result of construction of a seawall. While the seawall slowed erosion in front of the Rosetta's mouth, the eastern side of the seawall deteriorated, and this area eroded -35.2 m/y between 2001 and 2015.

Burullus Headland

The Burullus Headland coastline extends from the east of Rosetta to Gamasa, west of Damietta Promontory. A total of 109 transects were used to measure the coastline accretion and erosion along this zone; 51 indicated erosion in three locations: (1) on the western side of the Burullus Headland, (2) on the eastern side of the outlet of Burullus Lagoon, and (3) at the outlet of the Kitchener drain. The greatest erosion distance was -500 m between 1945 and 2015. Accretion was indicated at 58 transects in four locations: (1) the eastern Rosetta Promontory, (2) the western side of the outlet of Burullus Lagoon, (3) the Baltim coast, and (4) the eastern part of the Burullus Headland. The coastline accreted +639.4 m.

The average erosion rate was -3.6 m/y between 1945 and 1972. Erosion was -4.5 m/y between 1972 and 1984, -3.1 m/y between 1984 and 2001, and -3.6 m/y between 2001 and 2015. The average coastline accretion rate was +4.9 m/y between 1945 and 1972, +3.7 m/y between 1972 and 1984, +3.8 m/y between 1984 and 2001, and +4.99 m/y between 2001 and 2015.

Damietta Promontory

Damietta Promontory and its eastern and western sides were measured using 47 transects. In 22 transects, the coastline eroded in three different locations: (1) the eastern side of Damietta Harbor, (2) in front of Damietta Promontory, and (3) along the Lake Manzala barrier. The greatest eroded distance was -2170.2 m, with an average rate of -9.5 m/y. Coastline accretion of +2771 m, with an average of +12.8 m/y, was indicated at 25 transects. The coastline accreted in two locations: (1) on the western side of Damietta Harbor, because the sediments accumulated behind the protection barrier, and (2) at the eastern side of Damietta Promontory, because depletion of sediment after construction of the Aswan High Dam allowed sand spits to form in front of the promontory.

Along Damietta Promontory, the average erosion rate was -7.6 m/y between 1945 and 1972. It was -13.1 m/y from 1972 to 1984 and -20.6 m/y between 1984 and 2001. A seawall was built in 1998, but areas of severe erosion occurred anyway, with the highest rate being -93.9 m/y between 2001 and 2015. Accretion averaged +27.6 m/y at the eastern sector of Damietta Promontory, as shown in Figure 7.

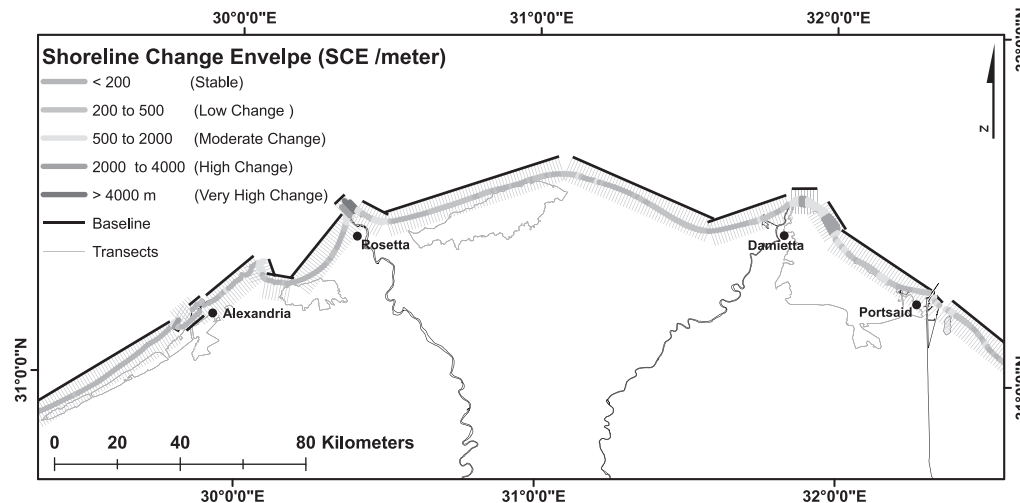


Figure 8. Net change in the Nile Delta coast between 1945 and 2015. Five relatively homogeneous coastal change zones were identified along the Nile Delta coast. Alexandria is the most stable zone; the Burullus and Manzala lagoon barriers are a low- to medium-change zones, and the artificial ports are also medium-change zones. The Nile Delta promontories had the highest change.

Manzala Lagoon Barrier to Port Said

From Manzala Lagoon to Port Said, 68 transects were drawn. They indicate erosion averaging -5.5 m/y. Of 68 transects, 38 indicated an accreting coastline with an average of $+4.5$ m/y. The average erosion rate was -6.9 m/y between 1945 and 1972, -7.9 m/y between 1972 and 1984, -8.2 m/y between 1984 and 2001, and -8.0 m/y between 2001 and 2015. The average coastline accretion rate was $+9.5$ m/y between 1945 and 1972, $+8.3$ m/y between 1972 and 1984, $+6.4$ m/y between 1984 and 2001, and $+5.5$ m/y between 2001 and 2015.

DISCUSSION

Geomorphological changes along the Nile Delta coast were classified into five relatively homogeneous types: (1) stable (51% of the coast), (2) change of 200 to 500 m (33% of the coast), (3) change of 500 to 2000 m (12% of the coast), (4) change of 2000 to 4000 m (3% of the coast), and (5) change greater than 4000 m, which happened only on Rosetta Promontory. The net changes on the coast are shown in Figure 8 and Table 3.

Between 1945 and 2015, 50% of the coastline eroded and 50% accreted. The greatest distance of erosion was -5329 m, and the greatest accretion was $+2771$ m. While several factors are responsible for the coastal change, the Aswan High Dam had the most profound effect in accelerating coastal erosion rates. This was true especially in front of and around the Rosetta and Damietta promontories. Measurements indicate that, at Rosetta

Promontory, the highest coastline erosion rate increased from -72 m/y between 1945 and 1972 (before the AHD) to -141 m/y between 1972 and 1984 (after the dam) and then to -159 m/y between 1984 and 2001. On Damietta Promontory, the highest coastline erosion rate was -13 m/y before the dam (between 1945 and 1972) and -45 m/y after the dam (between 1972 and 1984). It was -50 m/y between 1984 and 2001.

Beginning in 1991, the Coastal Research Institute built seawalls in severely eroded areas. These included seawalls around Alexandria, the Mohamed Ali Seawall in Abu Quir Bay, the Rosetta Seawall, the Alborg Baltim Seawall, and the Damietta Seawall. Although the seawalls have slowed erosion, they have caused erosion elsewhere. For example, the eastern side of Rosetta Promontory has a new coastal erosion zone as a result of construction of the Rosetta Seawall, with an erosion rate of -35 m/y between 2001 and 2015. Also, at Damietta Promontory, a new coastal erosion zone appeared as a result of construction of the Damietta Seawall.

CONCLUSIONS

The coastline of the Nile Delta will continue to change as a result of sea-level rise, continued loss of sediment from the Nile, and loss of mangrove plantations. Some parts of the delta are likely to accrete, but the majority will probably erode. Sea-level rise is probably the most significant long-term threat to the Egyptian Mediterranean coastline.

Table 3. Shoreline change detection between 1945 and 2015.

Class	Shoreline Change	Range of Change (m)	Number of Transects (Out of 373)	Distance along the Coast/km	% of the Nile Delta Coastline
1	No change (stable)	<200	190	190	50.94
2	Low change	200 to 500	125	125	33.51
3	Moderate change	500 to 2000	45	45	12.06
4	High change	2000 to 4000	11	11	2.95
5	Very high change	>4000	2	2	0.54

Regardless of the prediction (conservative or worst-case), coast will be lost at an accelerating rate. The coastal fringing brackish-water lakes will almost certainly be breached by salt water and become saltier. This will ruin a now-thriving fishery. Coastal cities such as Port Said, Suez, Damietta, and Rosetta could be underwater within 50 years regardless of actions to protect them. Alexandria will continue to be protected, but it will likely become an island accessible only *via* bridge. Egypt will almost certainly have to raise roadways and install drains in coastal cities to pump out seawater percolating up through the sand.

The greatest cost, however, will be loss of arable land that now lies at or below sea level. This land has been subsiding for centuries, and it is only protected by dunes now being undercut by sea-level rise. Saltwater intrusion will probably occur and exacerbate already waterlogged and saline soils. Since the water from the Nile is increasing in salinity due to higher evaporation in Lake Nasser, it cannot be relied upon to flush the salts from the soil.

The combined effects of the sea-level rise, subsidence, and construction of the Aswan High Dam will certainly lead to an accelerated loss of the Nile Delta coast in the future. Existing barriers to the sea will be breached and result in large land losses due to the fact that most of the Nile Delta is remarkably flat topographically. It is imperative that effective barriers be built as soon as possible in the most vulnerable parts of the coastline, such as Rosetta and Damietta promontories and the city of Port Said. The city of Alexandria is likely to become, essentially, an island in the not-too-distant future since it is well protected seaward but surrounded by lowlands. Other cities on the coast are not as well fortified against the sea.

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