AN INTEGRATED APPROACH TO ASSESS LEE SIDE EROSION IN RUBBLE MOUND GROIN SYSTEMS: A CASE STUDY

D. Habib [(1)], Y. Khairy [(2)] and A. Soliman [(3)]

(1) MSC. Student, Construction and Building Engineering Department, Arab Academy for Science, Technology, and Maritime Transport, Alexandria, Egypt, Donnaalaahabib@gmail.com.

(2) Professor, Construction and Building Engineering Department, Arab Academy for Science, Technology, and Maritime Transport, Alexandria, Egypt, Y.khairy@aast.edu.

(3) Dean, College of Engineering and Technology, Arab Academy for Science, Technology, and Maritime Transport, Alexandria, Egypt, akram.soliman@aast.edu.

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ABSTRACT: Coastal erosion along Egypt's Northern Mediterranean coast presents a persistent challenge, particularly near the Kitchener Drainage, where human activities, such as infrastructure development and agriculture, have intensified shoreline retreat. Groynes have been widely used to stabilize the coastline by trapping sediment on the updrift side. However, their application has induced significant downdrift erosion, leading to sediment depletion, beach narrowing, and alterations in the shoreline profile.

This study aims to assess the long term effects of groyne construction in the Baltim region between 2007 and 2020, with a focus on shoreline evolution and downdrift erosion. Numerical modeling was conducted using the one-line model LITPACK, incorporating 31 years of wave data (1993–2023) from the Copernicus Marine Service and bathymetric surveys performed by Archimarine in 2020. Historical shoreline positions were derived from satellite imagery and field measurements to evaluate morphological changes. A brief discussion on mitigation measures and future studies is mentioned.

The LITPACK one line model successfully simulated shoreline evolution, capturing 20m per year erosion rates east of Kitchener Drainage from 2007 to 2013, with model standard deviation of 7m. The model also accounted for the 16 groynes constructed in 2020, where maximum downdrift erosion reached 195 meters, with 100,000 m³/year of sediment loss near the final groyne. The modeling results confirm that continued groyne extensions have not fully mitigated erosion but have shifted the problem further eastward.

1. INTRODUCTION

Coastal zones are active areas where complex interactions between sediment movement, wave action, and human activities shape how shorelines look. (Prasad and Kumar 2014) defined coastal erosion as the landward displacement of the shoreline, primarily caused by waves and currents. As a global issue, mitigation measures and management strategies for coastal erosion involve a combination of approaches, including both soft and hard engineering solutions, as well as strategic planning and monitoring. The selection of these measures depends on factors such as the type of coast, wave climate, surge levels, sediment composition, economic considerations, and recreational value (van Rijn 2011). Hard structures including groynes, detached breakwaters, seawalls and revetments have been used as a defense strategy to protect the coastline (van Rijn 2011).

However, in relation to the case study presented, the focus will be on groyne structures and their implementation to control sediment movement.

(Brown et al. 2016) have shown that the construction of coastal defenses often alters the sediment budget, leading to a "terminal groyne effect," where retreat rates accelerate down drift of the structure. A problem that persists all around the world. In the United States, (Seenath 2022) has chosen a 12.5 km sandy coastal stretch along the Atlantic coast of Long Beach Barrier Island in New York which is managed by 43 groynes to understand the effects of groynes on shoreline evolution and the optimization of modelling approaches with respect to groyne representation. The study used MIKE21 because it links a 2DH coupled wave, flow, and sediment transport model with a one-line model of shoreline change.

Semeoshenkova and Newton (2015) have highlighted five case studies in Europe where groynes have intensified beach erosion. In Costa da Caparica, Portugal, seven groynes and a seawall built between 1959 and 1970 initially stabilized the coast but failed to retain sand and caused downdrift erosion. Similarly, in Huelva, Spain, a 10 km long groyne built in 1981 disrupted littoral currents, leading to severe erosion along 25 km of adjacent coastline. Sitges, Spain, abandoned groyne construction by 1988 due to high costs, inefficiency, and negative aesthetic impacts, as the structures worsened downdrift erosion. In Marina di Massa, Italy, groynes built between 1930 and 1980 interrupted natural sediment transport, accelerating erosion in downdrift areas. Likewise, in Marina di Ravenna-Lido Adriano, Italy, sandbag groynes proved ineffective and further intensified erosion.

Located at the intersection of the Nile River and the Mediterranean Sea, the Nile Delta has historically been a significant source of agricultural productivity and biodiversity. However, exacerbated by climate change, have intensified the rates of shoreline erosion in this region, prompting a deeper investigation into its causes and consequences (Gebreil 2018). Studies have identified that factors such as reduced sediment supply from upstream dams, primarily the Aswan High Dam, along with rising sea levels and coastal development, contribute substantially to the erosion observed along the delta's coastlines(Abd-Elhamid et al. 2023; Elfadaly et al. 2023). The pressing research problem highlights the alarming rate of shoreline retreat, with projections indicating that certain sectors of the coastline may experience losses of up to 10m annually (Deabes 2017).

Shoreline erosion in the Nile Delta has been a significant environmental concern, evolving through various stages of understanding and intervention. Studies focused on basic measurements of coastal erosion, identifying key areas impacted by natural processes and human activities. For instance, (Abd-Elhamid et al. 2023) noted the influence of sediment transport patterns from the Nile River, highlighting the critical balance between sediment supply and erosion.

The aim of this study is to present an assessment to the long term effects of groyne construction specifically East Kitchener Drainage between 2007 and 2020 focusing on shoreline evolution and downdrift erosion. Some mitigation measures are discussed; however, a beach orientation analysis will be conducted later on to fully understand the best mitigation measures to be implemented.

2.METHODOLOGY

Various models and methods are used to measure longshore sediment transport and analyze downdrift erosion, each with specific applications and limitations. Process based numerical models provide more detailed simulations, with LITPACK, a one line model, calculating shoreline evolution and sediment transport rates (DHI 2024), while ShorelineS describes large scale coastal transformations, including spit formation and shoreline undulations (Roelvink et al. 2020). Remote sensing and GIS techniques employ satellite imagery and aerial photography to monitor shoreline changes over time, allowing for large scale assessments of erosion and accretion patterns (Abd-Elhamid et al. 2023). Finally, physical scale models, constructed in laboratory settings, replicate coastal processes under controlled conditions but often face scaling limitations when applied to real world scenarios (Longo 2021).

The methodological approaches to studying shoreline erosion along the Nile Delta have varied significantly, reflecting the complexity of the coastal environment and the environmental challenges it faces. Various research efforts have employed numerical modeling, as seen in the studies analyzing sediment transport and wave dynamics, which provide insights into the interactions between human infrastructure and natural processes. For instance, numerical simulations in the study of wave climate have revealed trends in significant wave height that correlate with coastal erosion, indicating a direct relationship between wave energy and shoreline stability (Abd-Elhamid et al. 2023; Elfadaly et al. 2023). Additionally, fieldwork methodologies involving satellite imagery and shoreline monitoring have documented seasonal and spatial variations in erosion along different coastal zones, revealing that local constructions, such as jetties and causeways, can exacerbate erosion in surrounding areas (El-Gamal et al. 2020; Besset, Anthony, and Sabatier 2017). The use of comprehensive data collection, particularly from tide gauges, allows researchers to estimate the rate of relative sea level rise and its implications for erosion, underscoring the need for adaptive management strategies (El-Gamal et al. 2020).

For this paper, the shoreline erosion due to human interfering and Groyne construction on the western side of the delta (near Kitchener drainage) will be analyzed and studied using the numerical modeling method of LITPACK one line model. LITPACK is one of the modules in MIKE 21 to solve hydraulic and sedimentation problems in coastal areas (Subiyanto and Supian 2021). This method is chosen because it simplifies coastal morphology by focusing on the coastline location (cross-shore direction) and coastal profile at a given longshore position which significantly reduces the computational load and particularly helpful when simulating shoreline changes over long periods (Subiyanto and Supian 2021). The methodology pattern used to setup the model is shown in **Figure 1**.

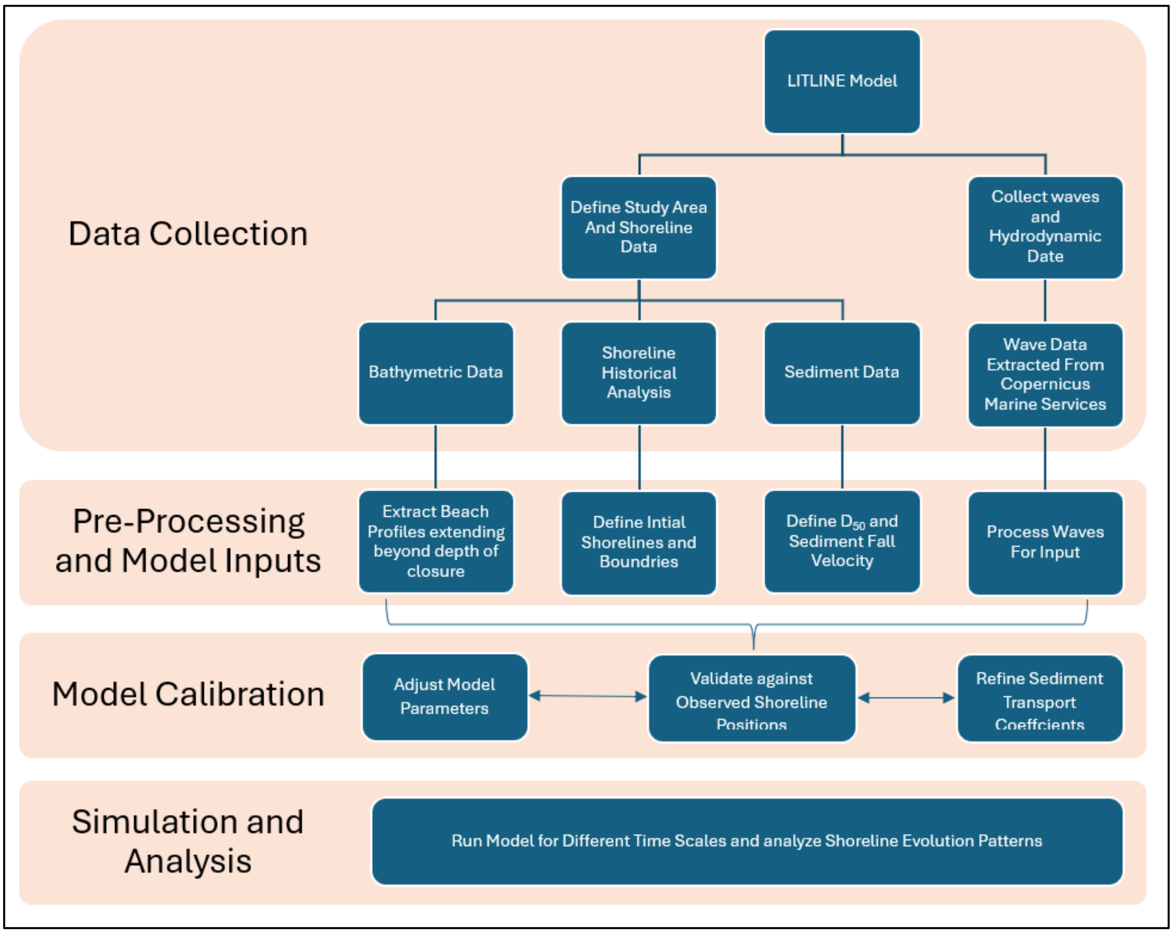

Figure 1. LITLINE Model Methodology

3. NUMERICAL MODEL

The one-line model is a suitable choice when the main concern is the horizontal movement of the coastline due to erosion and accretion. LITPACK one line model was developed to simulate shoreline evolution for the study area to assess the effect of Groyne structures and lee side erosion. The main equation in the one line model is the continuity equation for sediment volumes, Eq.(1) (Subiyanto and Supian 2021).

$$\frac{\partial y_c(x)}{\partial t} = -\frac{1}{h_{act}(x)} * \frac{\partial Q(x)}{\partial x} + \frac{Q_{sou}(x)}{h_{act(x)}\Delta x} \tag{1}$$

Where:

$y_c(x)$: distance from the baseline to the coastline

$h_{act}(x)$: height of the active cross-shore profile

$Q(x)$: longshore transport of sediment

x: longshore position

Δx: longshore discretization step

$Q_{sou}(x)$: source/sink term expressed in volume / Δx

3.1 Study Area

The study area is located along the northern coast of Egypt, adjacent to the mediterranean sea. the geographic coordinates approximately range from 31.3°N latitude to 31.4°N latitude and 30.0°E longitude to 30.1°E longitude (**Figure 2**). The beaches in the area east of the main western drainage (Kitchener) are exposed to critical natural factors, high waves, and continuous erosion processes, which have resulted in the loss of many beaches. This section of the Nile delta entirely is witnessing significant shoreline retreat, posing challenges to its environmental sustainability and economic activities.

Offshore wave data were sourced from the Copernicus Marine Service ("Copernicus Marine Service," n.d.). Global Ocean Waves dataset on a 0.20-degree grid ("Global Ocean Waves Reanalysis," n.d.). Time series of metocean data (spectral significant wave heights, peak wave periods, mean wave directions) were extracted for the offshore point OE at 3-hourly intervals, spanning a period of 31 years (1993-2023). The offshore point OE (Offshore Egypt) and the directional distribution of waves at the offshore point OE is presented in **Figure 2**. The predominant waves are from the North-Western sector.

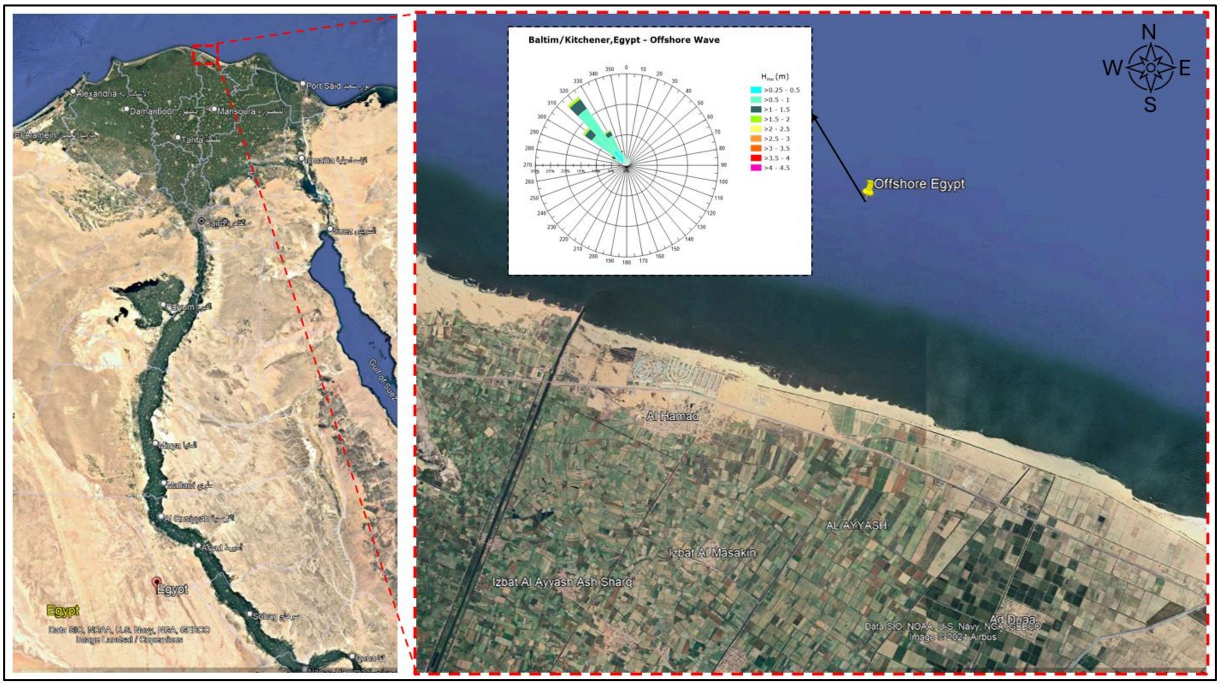

Figure 2: The study area extent and the directional distribution of offshore waves

A bathymetric and topographic survey was conducted by Archimarine for Contracting Company in 2020 participating in one of the Groyne construction projects in the area. Bathymetric extent and data are shown in **Figure 3**.

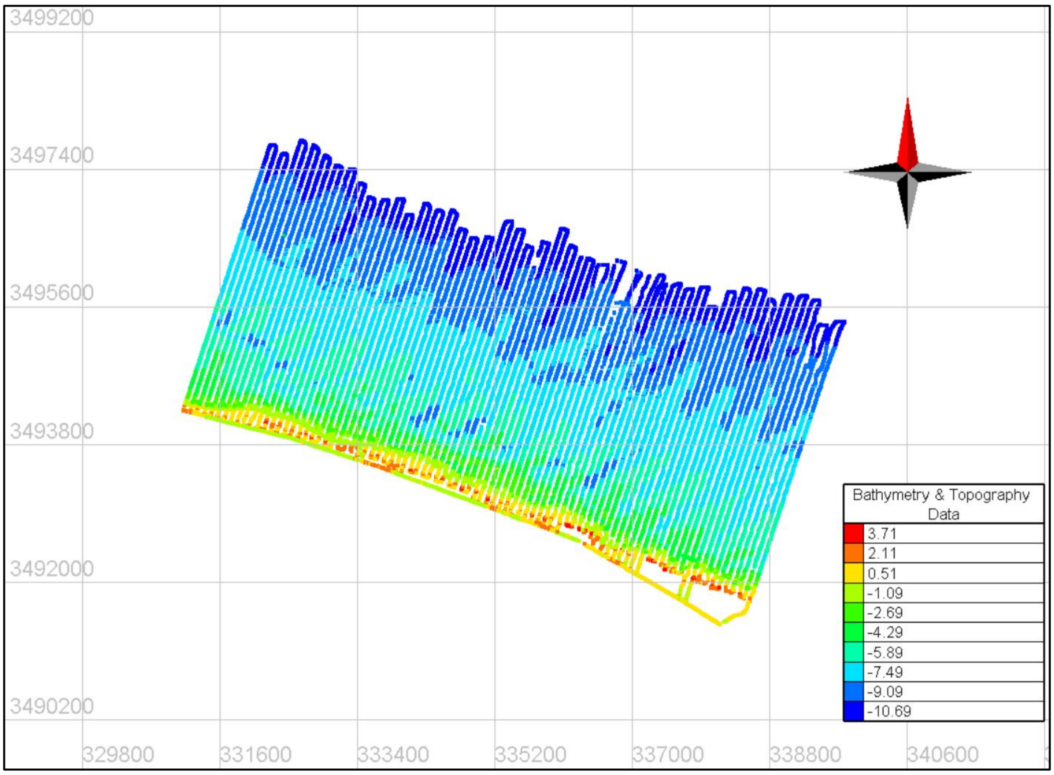

Figure 3: Bathymetric & topographic survey of the study area

3.2 Depth of Closure

The closure depth marks the boundary between the upper and lower shoreface, the part of the coast where most active changes in the profile occur even though sand and bedforms can still move deeper down. This concept was developed based on Hallermeier's 1981 study, which examined how the upper shoreface profile changes over the course of a typical year. Essentially, the closure depth is defined by the impact of the largest storm waves, and (Hallermeier 1980) provided an imperial equation to predict it as follows:

$$h_c = 2.28H_{s,12h} - 68.5\,\frac{H_{s,12h}^2}{gT_s^2} \qquad (2)$$

Where $H_{s,12h}$ is the wave height exceeded 12 hours per year and T_s is the associated wave period, with the closure depth relevant for mean low water conditions. The depth of closure have been calculated for the study area, where the results reflects a closure depth of 6.15m. The beach profile used in the model must cover all the active zone profile, therefore beach profile must be equal or exceeds the depth of closure.

3.3 Beach Profiles

Beach profiles derived from survey data along the coastline are examined, focusing on beach slope characteristics and associated morphological attributes. Forty three (43) transects were extracted at a spacing of approximately 100m perpendicular to the shoreline. The beach profiles are shown (**Figure 4**).

Accretion and erosion on some of the profiles are observed which indicates that a cross shore transport needs to be assessed. However, this will be recommended for further assessment and won't be taken into consideration for this paper. The average beach profile have been adopted for the present study.

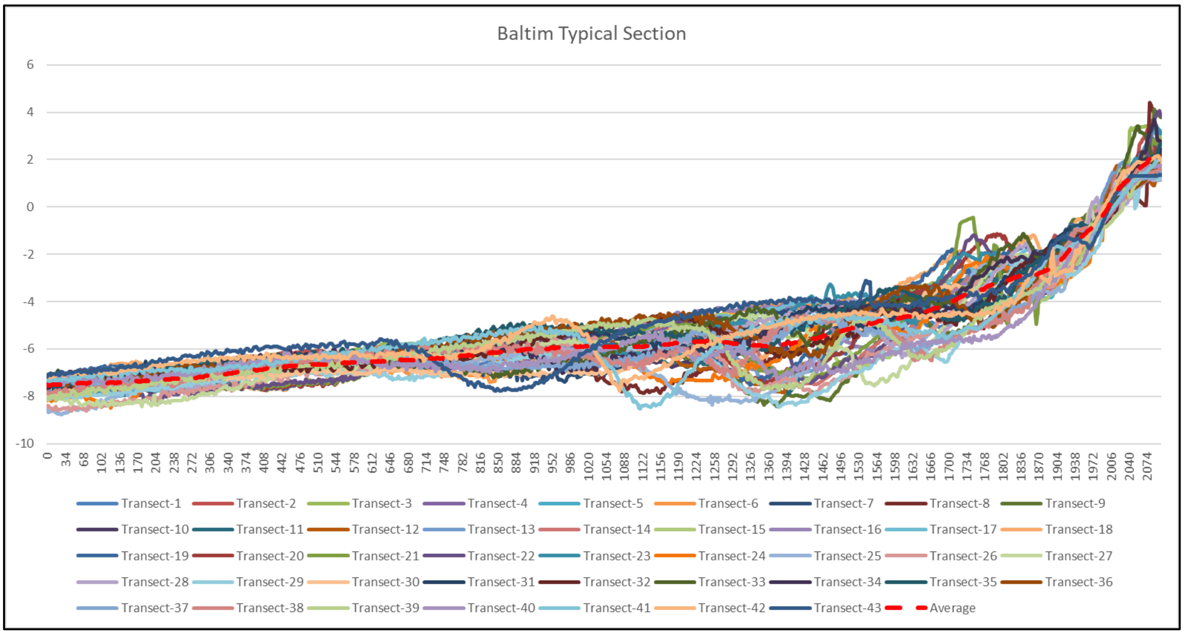

Figure 4: Extracted beach profiles

3.4 Shoreline Historical Analysis

The evaluation of the historical shoreline position was done using satellite imagery. After implementation of beach stabilization efforts on the west part of Kitchener drainage, including the construction of nine groynes. Clear lee-side erosion to the implemented groynes has emerged east of Kitchener drainage between 2007 and 2010 as shown in **Figure 5**. Erosion continued till 2013, when effort to contain this shoreline retreat began. A new groyne system project was initiated at East Kitchener Drainage and concluded in 2018. To secure the drainage from blockage, two jetties project was implemented to be completed in 2020 as depicted in **Figure 6**. The figure also illustrates the widening of erosion on the leeward side as a result of the groyne structures.

Figure 5: Shoreline position between 2007 and 2010

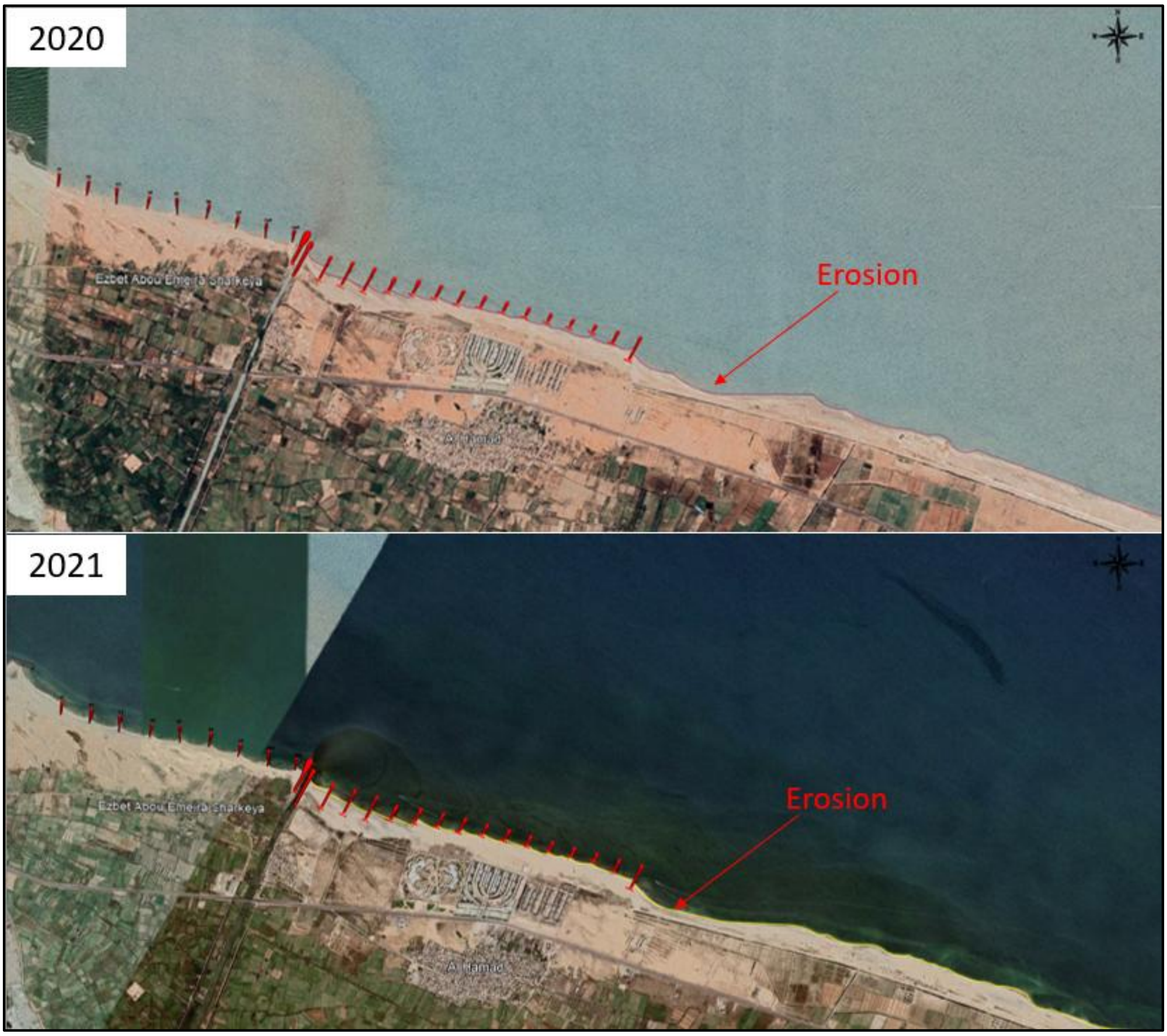

Figure 6: shoreline position between 2020 and 2021

3.5 Model Setup

The shoreline evolution model (LITLINE) is based on the following assumptions:

The description of sediment properties required to model annual sediment drift in DHI's LITDRIFT mode was retrieved from samples taken from North Coast Egypt in 2012 in a project owned by the Egyptian Shore protection Authority as shown in **Table 1** below was cut to show the properties used.

Table 1: Grain size parameters for the collected samples North coast, in 2012.

Profile#	Sample#	Depth(m)	Coordinate	Statistical Parameters	Nomenclature

			North	East	Mean grain size in mm	Sorting(σ)	
40	1	0.0	3494807	330576.4	0.24	0.64	Moderately well sorted fine sand
	2	2.0	3494932	330625.1	0.34	1.03	Poorly sorted medium sand
	3	4.0	3495195	330701.5	0.1	0.52	Moderately well sorted very fine sand
	4	6.0	3495730	330851.1	0.09	0.54	Moderately well sorted very fine sand

The water level is assumed to be constant and equal to MSL.

The shoreline (at MSL) for the beach was projected on a line of reference "the baseline". Groynes present along the beaches have been incorporated in the model.

4. RESULTS AND DISCUSSION

4.1 Model Calibration

The conceptual structure arrangement implemented in the model is shown in **Figure 7**. The model covers around 7km beyond the Groyne structures west Kitchener drainage. Initial shoreline used of year 2007. This was chosen to simulate the effect of these Groyne structure on the adjacent shoreline. Groyne structure at the Western extremity of the beach to reproduce the sediment blockage induced by the Groyne structure present West the Kitchener drainage. The model was executed for the period from 2007 to 2010. Modelled shoreline and measured shoreline are compatible and presented in **Figure 7**. The model significantly could predict the stable alignment of the shoreline with severe erosion behavior Eastern of the jetty. The rate of erosion is around 20 m/year down drift the Groyne and East Kitchener Drainage which is compatible with the rates seen from the shoreline historical analysis. The standard deviation shown by model is 7m which is acceptable for a one line model.

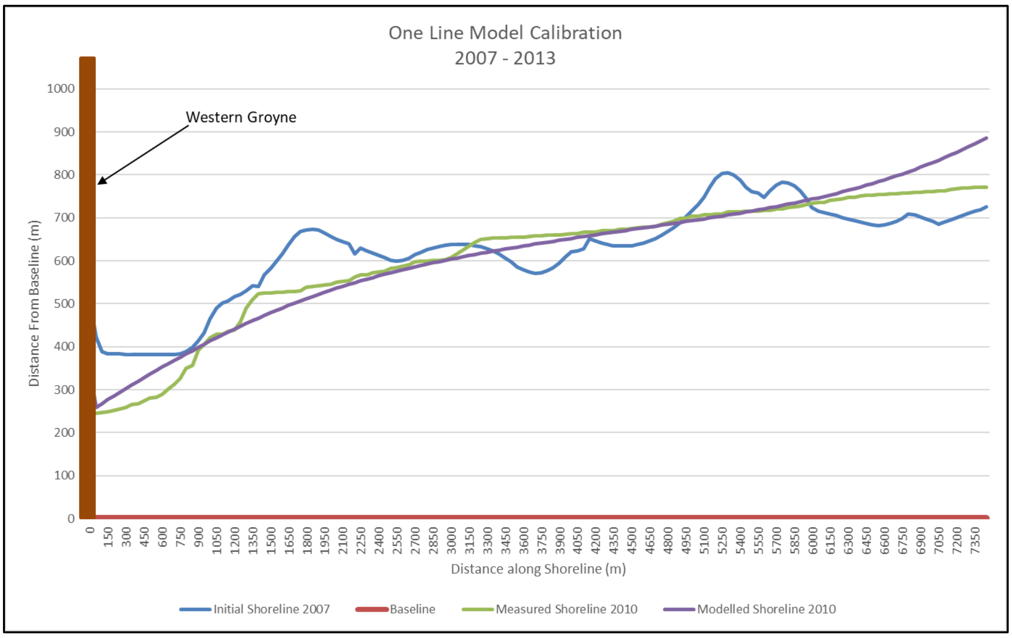

Figure 7: Initial shoreline and model setup for model calibration (shoreline 2007 – 2010)

4.2 Groynes Structures Scenario

The calibrated model was used to simulate the shoreline evolution after the construction of groyne system 2020. The conceptual structure arrangement implemented in the model include initial shoreline of 2013 before the start of the project. Sixten groyne have been adopted in the model simulating zero bypass to represent the actual project structure. The modeled shoreline closely matched observed shoreline changes, demonstrating significant sediment erosion to the down drift of the final groyne. Only small differences might be seen in the shoreline position near the first three groynes due to reported nourishment. The model setup and results are depicted in **Figure 8**. The maximum downdrift erosion rate caused in the vicinity of the last Groyne is around 195m corresponding to an annual sediment rate movement of around 100,000m^3.

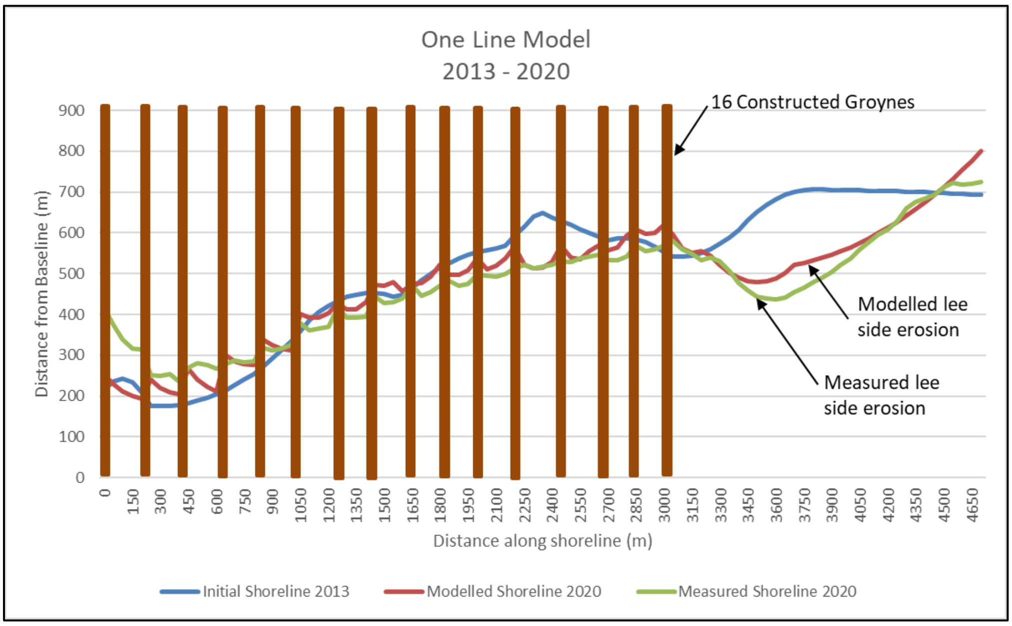

Figure 8. One line model for shoreline and structure 2013-2020

5. CONCLUSIONS AND FUTURE APPLICATIONS

This paper assessed the long term impact of groyne structures on shoreline evolution along Egypt's northern Mediterranean coast, west Kitchener Drainage. Through numerical modeling powered by historical shoreline analysis and measured shorelines through surveys. The findings shows how groynes effectively trap sediment on the updrift side, leading to beach accretion. However, this comes at the cost of severe downdrift erosion, causing shoreline instability. The LITPACK one line model successfully simulated shoreline evolution, showing 20m per year erosion rates east of Kitchener Drainage from 2007 to 2013, with model deviations of ±7m, which is acceptable. The model also captured the effect of 16 constructed groynes in 2020 with maximum observed downdrift erosion reached 195m, with 100,000 m^3/year of sediment loss near the final Groyne.

The modeling results confirm that the continued extension of groynes has not fully mitigated the erosion problem but rather shifted it further eastward.

Annual nourishment scheme can help stabilize the shoreline (Khalifa et al. 2017). This solution is expensive and inefficient. (Wang et al. 2022) emphasizes the need for a sustainable coastal zone management strategy and assesses key parameters for quantitatively pinpointing the impact of hard structures. These parameters include, calculating maximum shoreline recession length in it's exact location and conduct a spatial scope of the downdrift eroding shoreline. Therefore, an analytical model using (Lim et al. 2022) technique to analyze the shape of lee side erosion. Also, a beach orientation analysis will be conducted to discover the best angles for the hard structure to be implemented. Based on above mentioned, different configurations of groynes and other structures will be implemented into the model to assess the most reliable structure type for the area to accommodate the occurring shoreline erosion.

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