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A NATURE-BASED MULTIFUNCTIONAL ISLAND FOR COASTAL PROTECTION AND STRATEGIC DEVELOPMENT IN THE SUEZ CANAL

Akram Soliman Elselmy (1), Wael Aly Kamel (2), Hossam Eldin Moghazi (3) and Radwa Refat (4)

(1) Construction and building department, AASTMT, Alexandria, Egypt, akram_soliman@aast.edu

(2) Construction and building department, AASTMT, Alexandria, Egypt, wael_kamel@aast.edu

(3) Department irrigation engineering and hydraulics, Faculty of Engineering, Alexandria University, Alexandria, Egypt, hossam.moghazi@alexu.edu.eg

(4) Construction and building department, Arab Academy Of Science, Technology And Maritime Transport , Alexandria, Egypt, Radwa.elfatah7@student.aast.edu

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ABSTRACT

This study evaluates the performance of a lotus-shaped artificial island as a nature-based intervention for shoreline stabilization and sediment management in the Bitter Lakes section of the Suez Canal. Building on prior hydrodynamic modeling studies, the current work integrates geotechnical feasibility, long-term shoreline evolution, and cost-benefit analysis to assess the island's multidisciplinary performance. Using the MIKE 21 FM and LITPACK numerical models, simulations showed that the proposed island could reduce wave heights by approximately 30% and vessel-induced current velocities by 30-40%, contributing to shoreline accretion of up to 6.5 meters per year. Sediment deposition increased in flow shadow zones, minimizing scouring and enhancing long-term stability. Geotechnical analysis of Bitter Lakes subsoil revealed weak silty clays, for which a composite ground improvement system incorporating geotextiles and compacted fill was proposed to ensure foundation stability. Economic modeling estimated annual dredging cost savings between $37.8 and $66.15 million, with an expected return on investment (ROI) in 5-7 years. While previous publications addressed the hydrodynamic effects of the island form (El Selmy et al., 2025), this study extends the assessment by integrating geotechnical design and economic performance into a unified feasibility framework. The findings confirm the viability

of the lotus island as a scalable, cost-effective infrastructure intervention for sediment-prone, vessel-dominated waterways.

1. INTRODUCTION

The Suez Canal is a globally strategic maritime corridor, facilitating around 12% of international trade and generating annual revenues exceeding $9 billion (Suez Canal Authority, 2023). With over 20,000 vessels transiting its 190 km length annually, the canal is not only a cornerstone of Egypt's economy but also a linchpin of global logistics (Yuan & Wei, 2021). However, its operational reliability is increasingly threatened by environmental degradation, particularly within semi-enclosed zones such as the Bitter Lakes, where sedimentation, shoreline retreat, and vessel-induced hydrodynamic forces converge (Zhu & Falconer, 2001).

In the Bitter Lakes, vessel-generated wake events produce wave heights ranging from 0.5 to 0.8 m and induce current velocities up to 1.2 m/s, especially along the eastern shore (El Selmy et al., 2025). These dynamics contribute to severe scouring, sediment resuspension, and annual deposition rates of up to 30 million cubic meters (Mahmoodi et al., 2020), driving high dredging costs and reducing navigational efficiency.

Building upon earlier hydrodynamic modeling work (El Selmy et al., 2025), this paper introduces a comprehensive implementation framework that incorporates MIKE 21 and LITPACK simulations, geotechnical foundation assessment, and cost-benefit analysis. By aligning with Egypt's Vision 2030 and SCZone development objectives, the study delivers a replicable, scalable solution that balances environmental resilience with operational efficiency in sediment-sensitive maritime corridors. Figure 1 illustrates the progression of shoreline erosion along the eastern Bitter Lakes from 2010 to 2023, emphasizing the urgency of a nature-aligned intervention.

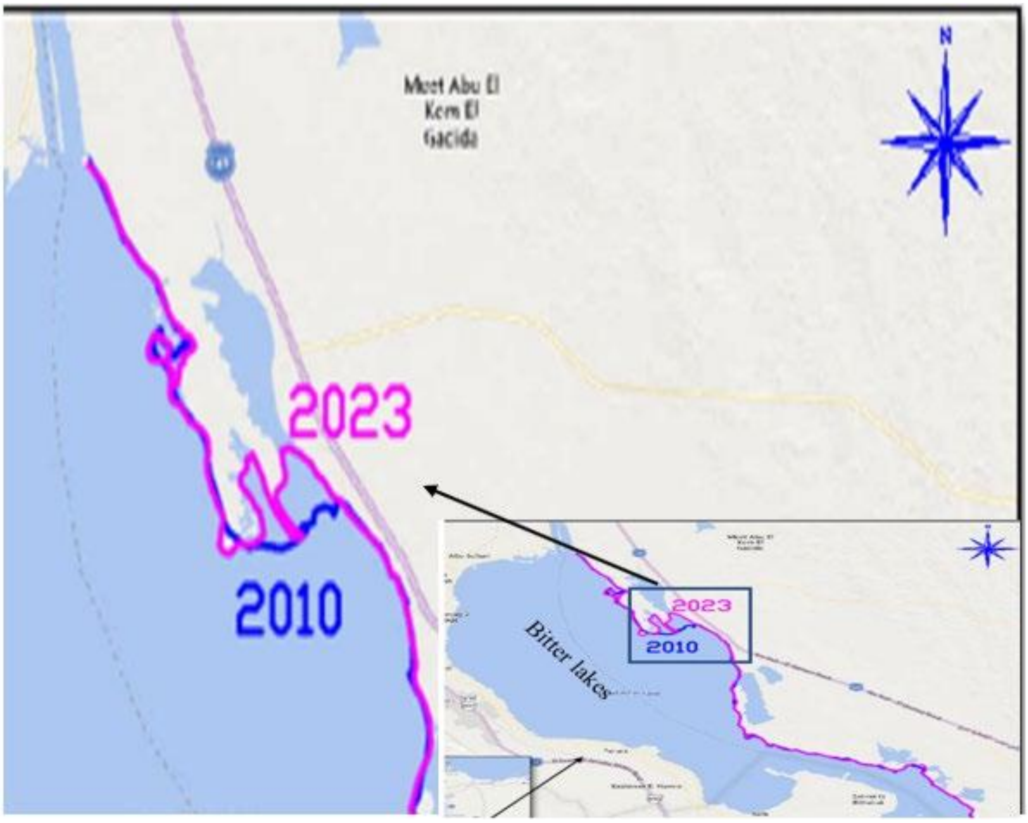

Figure 1: Observed shoreline changes in the Bitter Lakes between 2010 (blue) and 2023 (magenta), indicating areas of erosion and accretion (El Selmy et al., 2025)

To address these challenges, this study proposes a multifunctional coastal protection strategy based on a systems-thinking approach. It evaluates the performance of a lotus-shaped artificial island, a nature-based solution (NbS), designed to attenuate wave energy, capture sediment, and support ecological and logistical functions. While NbS applications are expanding globally, they remain underexplored in high-traffic, vessel-dominated environments due to limited empirical validation (Paxton et al., 2024).

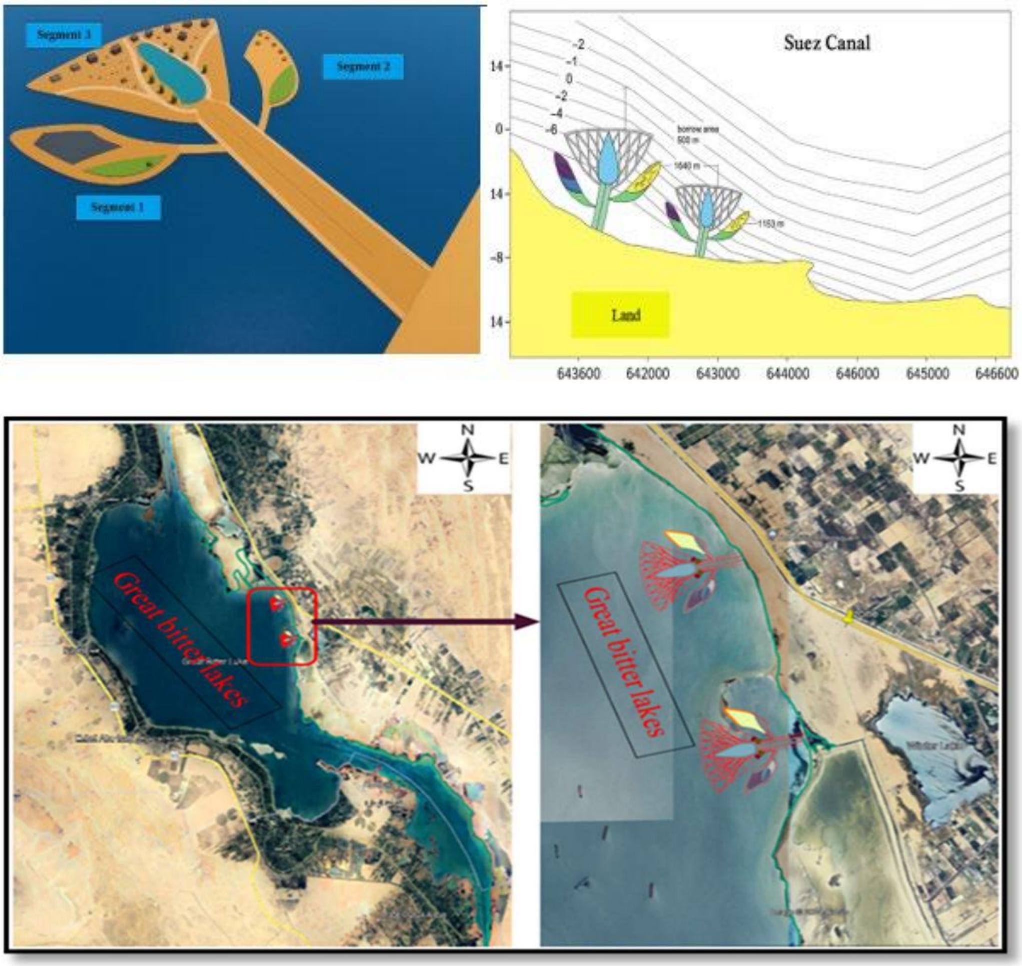

Figure 2: Conceptual design of a lotus-shaped artificial island in the Major Bitter Lakes (El Selmy et al., 2025)

Figure 2 presents the conceptual design and strategic positioning of a lotus-shaped artificial island proposed for the southern Bitter Lakes region of the Suez Canal. Panel (a) illustrates the island's segmented petal-based geometry, biomimetically inspired by the lotus flower. This form was selected for its ability to create multiple hydrodynamic shadow zones behind each petal, thereby dissipating wave energy, redirecting vessel-induced currents, and promoting sediment deposition in sheltered areas. Panel (b) shows the proposed bathymetric alignment, highlighting the island's placement at a moderate depth contour between -8 m and -14 m, where it can most effectively interact with prevailing hydrodynamic forces and sediment transport pathways. The location was chosen based on simulation results from MIKE 21 Flow Model FM, targeting zones of high erosion risk and optimal sediment capture as shown in panel (c).

2. RESEARCH AIMS AND OBJECTIVES

This study aims to evaluate the feasibility and performance of a lotus-shaped artificial island as a multifunctional coastal protection measure for the Bitter Lakes segment of the Suez

Canal, with a specific focus on hydrodynamic behavior, sediment management, and geo-structural viability.

Objectives:

- Simulate the hydrodynamic and morphological impacts of the proposed island using the MIKE 21 and LITPACK models.
- Assess the effectiveness of the design in reducing wave energy, vessel-induced current velocities, and shoreline erosion.
- Analyze the geotechnical suitability of constructing the island over soft marine sediments using ground improvement techniques.

By integrating technical modeling with economic forecasting and policy relevance, this study reframes the Lotus Island not solely as an engineering innovation, but as a scalable, investment-ready solution for adaptive coastal resilience in complex, vessel-influenced waterways.

3. LITERATURE REVIEW

Artificial islands have long contributed to shoreline protection, reclamation, and ecological restoration. Landmark projects like Palm Jumeirah and The World Islands in the UAE demonstrate large-scale land creation in open seas (Yuan and Wei 2021), while the Marker Wadden in the Netherlands showcases sediment reuse for ecological enhancement in semi-enclosed basins (de Vriend et al. 2015). However, such models offer limited transferability to Egypt's Bitter Lakes, where confined geometry, cohesive sediments, and vessel-induced hydrodynamics present distinct challenges. Traditional hard structures along Egypt's coastlines have often worsened erosion and disrupted ecosystems (Hegazy et al., 2019). Similarly, Peberholm Island in Denmark, though successful in integrating infrastructure, lacks relevance due to its low sediment mobility and minimal navigation pressures (Hald and Andersen 2002). Effectiveness under climate stress remains under-explored (Marino et al. 2025). These limitations underscore the need for context-specific interventions such as the Lotus Island, designed to operate effectively under the unique hydrodynamic and geotechnical conditions of the Bitter Lakes. A comparative overview of selected international island projects and their relevance to the Suez Canal context is presented in Table 1.

Table 1: Comparative Table of Global Artificial Island Projects

Project Name	Country	Primary Function	Environment Type	Relevance to Bitter Lakes
Palm Jumeirah	UAE	Tourism	Open Marine	Limited - High wave, deep water
The World Islands	UAE	Luxury Residential	Open Marine	Limited - Non-functional, high sediment loss
Marker Wadden	Netherlands	Ecological Restoration	Enclosed Lake	Moderate - Similar sediment-based restoration
Peberholm	Denmark	Transport Link	Shallow Marine	Moderate - Constructed over soft soils
Lotus Island Concept	Egypt	Coastal Protection	Confined, Vessel-Dominated	High - Custom-fit to Bitter Lakes

3.1 Numerical Modeling Progress

MIKE 21 and LITPACK, developed by DHI, are industry-standard tools for simulating hydrodynamics and sediment transport in coastal environments. While originally optimized for open coasts, their adaptation to confined, vessel-impacted systems like the Bitter Lakes requires careful calibration and scenario-specific configuration (Zhu and Falconer 2001). Recent work by El Selmy, Kamel, and Refat (2025) demonstrated the applicability of these models in such settings by integrating Automatic Identification System (AIS) vessel traffic data with satellite-derived shoreline change analysis. The resulting coupled model effectively reproduced sediment transport pathways and shoreline evolution over time, providing a validated computational base for the present study. Table 2 summarizes the evolution of coastal modeling approaches, from early empirical sediment transport equations to advanced two-dimensional flexible mesh solvers. This progression highlights the growing necessity of integrated modeling platforms, such as MIKE 21-LITPACK, for capturing the morphodynamic complexity of engineered basins like the Suez Canal.

Table 2: Evolution of Numerical Modeling Applications in Coastal Engineering

Era / Period	Modeling Tools	Typical Application	Limitations / Notes
Pre/1990s	Empirical Equations, Hand Calculations	Basic coastal structures	Simplified assumptions, no spatial dynamics
1990s/2000s	1D Numerical Models (e.g., SBEACH)	Beach erosion, cross-shore profiles	Neglects full 2D interaction
2000s/2010s	2D Depth-Averaged Models	Wave-current interaction, tidal flows	Limited vessel wakes modeling
2010s/Present	Flexible Mesh Models, Coupled Modules	Hydrodynamics, sediment transport, shoreline evolution	Requires calibration

3.2 Performance Gaps and Economic Gains

Nature-Based Solutions (NbS) have become central to global coastal adaptation strategies but remain underutilized in vessel-dominated, engineered environments like the Suez Canal. This is largely due to limited empirical validation under high-energy and navigationally complex conditions (Jordan and Frohle 2022; Narayan et al. 2016). El Selmy et al. (2025) demonstrated that a lotus-shaped artificial island could reduce wave heights by 30%, vessel-induced currents by 40%, and shoreline erosion by up to 45% in the Bitter Lakes using calibrated MIKE 21-LITPACK models. Refat (2025) expanded the modeling to evaluate long-term sediment deposition but did not address geotechnical or economic feasibility. This study advances the research by integrating subsurface analysis and quantifying investment returns. As detailed in Table 3, the proposed intervention could generate an estimated $179.3 million annually through reduced dredging costs, enhanced logistics performance, and fewer disruption-related losses, reinforcing its value as a sustainable, multifunctional infrastructure solution for the canal.

Table 3: Projected Economic Benefits of the Lotus-Shaped Artificial Island

Benefit Type	Estimated Annual Value (USD)
Dredging Cost Savings	$108.8 million
Increased Logistical Revenue	$52.5 million (estimated)
Reduced Downtime Costs	$18 million (estimated)
Total Economic Impact	$179.3 million

4. METHODOLOGY

This section presents the integrated methodology used to evaluate the lotus-shaped artificial island's feasibility in the Bitter Lakes, combining conceptual design, numerical modeling, geotechnical analysis, and scenario-based simulations.

4.1 Conceptual Island Design and Functional Zoning

The artificial island was conceptualized using a lotus-inspired geometry that optimally balances wave attenuation, sediment management, and logistical utility. Detailed studies on small-scale island basins reveal complex sediment behavior (Zhou et al. 2023). The design includes three distinct functional zones as shown in Figure 2:

- **Petal Structures:** Radial groins and breakwaters that dissipate energy and trap sediment.
- **Central Core:** Elevated area for logistical and control facilities.
- **Intermediate Ring**: Designed for ecological restoration and wave dampening.

The geometry was modeled and meshed for simulation in MIKE 21's flexible mesh environment. The shape's curvature and placement were optimized based on vessel traffic corridors and prevailing flow patterns in the Bitter Lakes.

4.2 MIKE 21 & LITPACK Hydrodynamic and Morphodynamic Setup

The hydrodynamic and morphological impacts of the lotus-shaped artificial island were analyzed using the MIKE 21 Flow Model FM, a 2D depth-averaged model by DHI, coupled with LITPACK for sediment transport and shoreline evolution. The simulation domain, approximately 150 km^2, used a flexible mesh with 20-200 m resolution, with finer detail around the shoreline and island. Key inputs included tidal and current data from the Suez Canal Authority, sediment grain size ($d50 = 75\text{-}100\ \mu m$), and Manning's n (0.025-0.030), with vessel wakes as the dominant forcing. Minimal wind influence was assumed. The model tracked long-term shoreline changes, sedimentation, and erosion under pre- and post-intervention scenarios, revealing improved stabilization and sediment capture. Figure 3 shows the bathymetry of the southern Bitter Lakes, where the proposed island site, located adjacent to the eastern shore in depths of -8 to -14 m, offers optimal conditions for interacting with vessel-induced currents and sediment transport. The depth gradient supports the island's zoning strategy for coastal protection, wave damping, and ecological enhancement. The MIKE 21 flexible mesh shown in this figure employs variable element sizes ranging approximately from 20 m near the shoreline and island boundaries to about 200 m in deeper offshore areas, ensuring high resolution in zones of complex hydrodynamics and sediment interaction while maintaining computational efficiency.

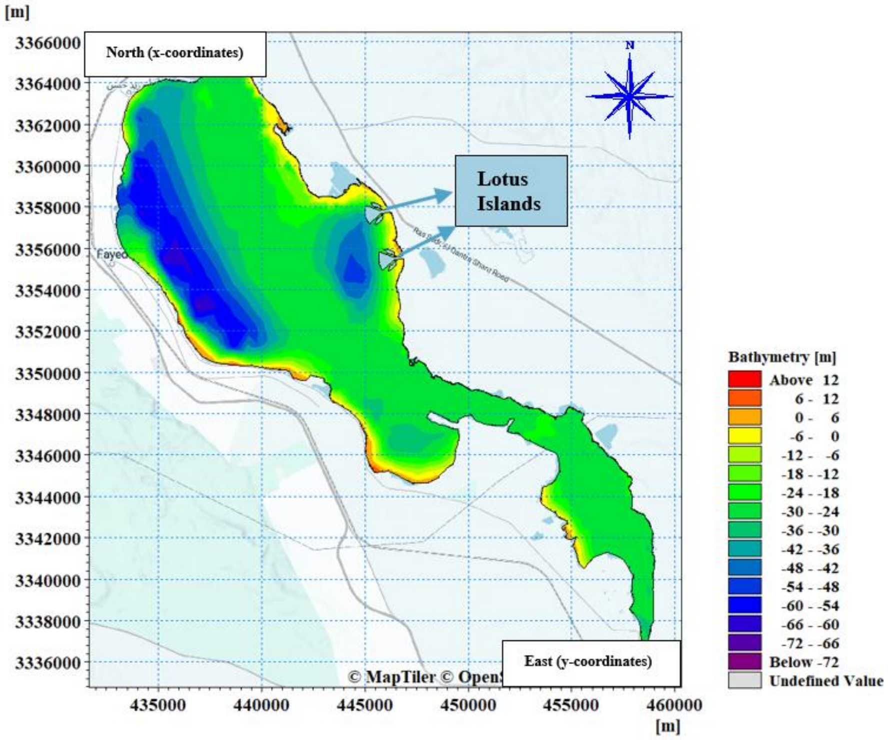

Figure 3: Bathymetry at the artificial island location Generated by using MIKE21 (El Selmy et al., 2025)

4.3 Geotechnical Conditions and Foundation Concepts

Subsurface investigations in the Bitter Lakes revealed a soft, compressible layer of silty clay with undrained shear strengths ranging from 8 to 15 kPa. To ensure structural stability, a composite foundation system is recommended, consisting of geotextile-reinforced bases, pre-compacted sand fill, and deep ground improvement methods such as stone columns or sand compaction piles. As illustrated in Figure 4, the typical soil profile includes loose silty sand overlying soft clay to approximately 15 m depth, underlain by denser sandy strata. These conditions are consistent with previous geotechnical assessments in the Suez Canal region (El-Mahgoub et al. 2018) and align with classical soil stabilization techniques (Terzaghi et al. Mesri 1996).

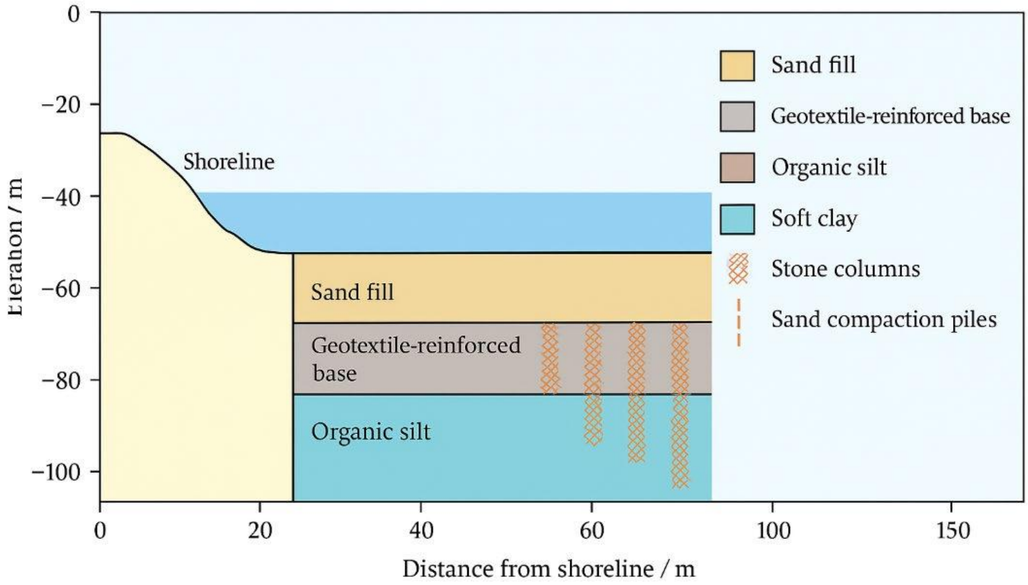

Figure 4: Geotechnical cross-sectional profile of the proposed lotus-shaped island foundation zone

4.4 Model Calibration and Validation

Model calibration and validation confirmed the accuracy of MIKE 21 and LITPACK in representing shoreline evolution and hydrodynamics within the Bitter Lakes. The shoreline analysis was based on Sentinel-2 imagery with a spatial resolution of 10 m and Landsat imagery with a resolution of 30 m, providing sufficient detail for long-term shoreline change detection and model validation. It was compared with model outputs, resulting in a root mean square error (RMSE) of approximately 6.2 m (El Selmy et al. 2025). Simulated wave heights deviated by less than 10% from field sensor observations, while current velocities showed strong correlation with ADCP measurements ($R^2 = 0.88$). These results demonstrate the model's reliability for simulating complex hydrodynamics in vessel-dominated, semi-enclosed basins (Zhu and Falconer 2001). Figure 5 compares observed shoreline positions from 2020 and 2023 with simulated 2023 outputs from the MIKE 21 model, showing strong agreement and validating the model's ability to replicate long-term morphological changes along the Bitter Lakes.

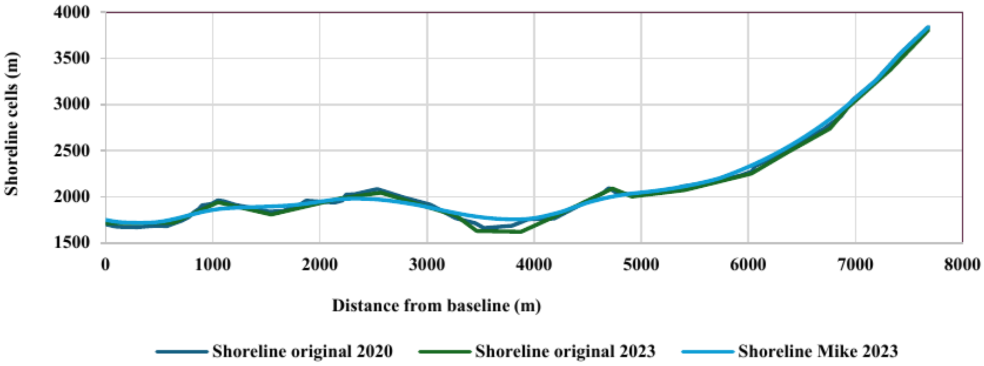

Figure 5: Validation of Modeled vs. Observed Shoreline Movement (2010-2022) (El Selmy et al. 2025)

5. RESULTS AND ANALYSIS

5.1 Hydrodynamic Alterations

A comparative MIKE 21 FM simulation assessed shoreline evolution under baseline and intervention scenarios for the lotus-shaped island in the southern Bitter Lakes. The petal geometry reduced significant wave height (Hs) by approximately 30%, particularly in northeastern and southeastern sectors, where diffraction created hydrodynamic shadow zones (El Selmy et al. 2025). Vessel-induced current velocities dropped by 30-40% along sheltered shores, promoting sediment deposition and minimizing scouring. These calmer zones enhanced shoreline accretion and morphological stability. Recent advances in parameter estimation improve sediment transport model reliability (Zhang et al. 2024). Figure 6 shows post-intervention shoreline response after one year, indicating improved stability relative to the baseline. Simulation results showed that the lotus-shaped island enhanced sediment retention in sheltered zones behind the petal structures, where wave and current energy were significantly reduced. These low-energy areas formed depositional lobes, most notably in the northeastern sector, with simulated shoreline advancement reaching 6.5 m/year. Sediment thickness increased by up to 35 cm over five years, indicating sustained morphological recovery.

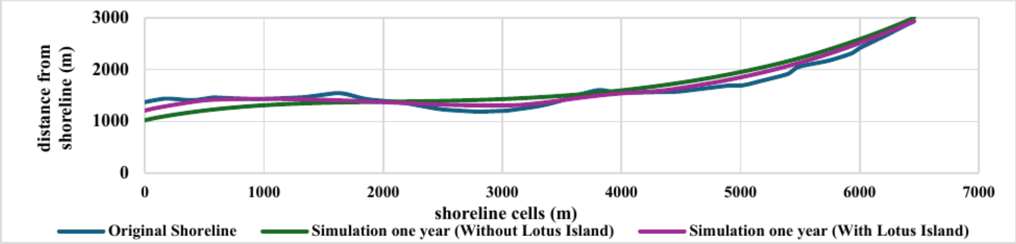

Figure 6: Shoreline Behavior Comparison Before and After Lotus Construction (El Selmy et al. 2025)

This self-reinforcing deposition process aligns with nature-based design principles and contributes to long-term shoreline stability while reducing dredging requirements (Narayan et al. 2016). The hydrodynamic layout of the island was engineered to attenuate vessel-induced wave energy and lower nearshore current velocities. As shown in Figure 7, the structure includes seven curved petals oriented against dominant flow to generate diffraction and flow shadow zones. Each petal incorporates low-crested breakwaters (+1.5 m crest elevation, 3 m width) constructed from rock armor and filter layers. Designed using Goda's wave transmission formula for Hs = 0.65 m, these elements reduced wave heights by 30% and nearshore currents by 30-40%, supporting erosion control and sediment deposition.

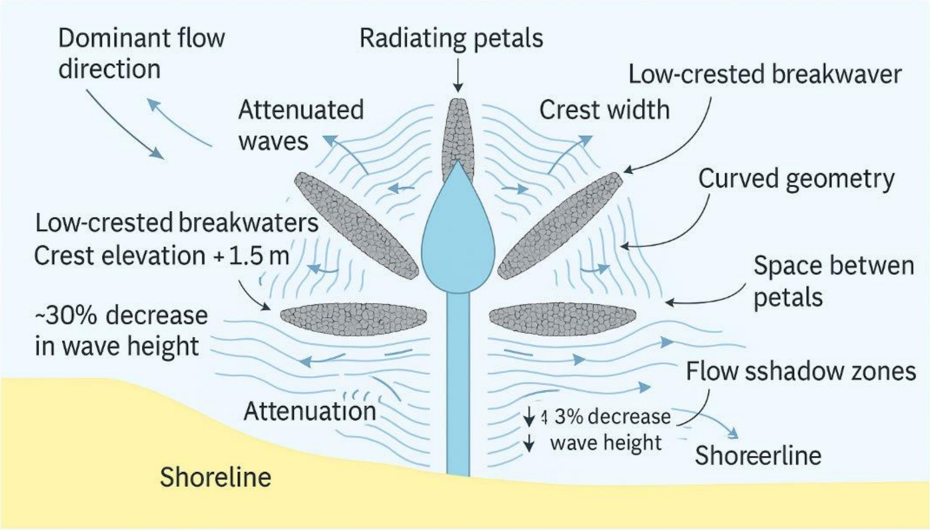

Figure 7: Hydrodynamic design of artificial lotus island

Figure 7 illustrates the hydrodynamic function of the lotus-shaped island in reducing wave energy and redirecting flow. The curved, radiating petals, designed as low-crested breakwaters, achieved a 30-43% reduction in significant wave height (Hs), forming flow shadow zones that promote controlled sediment deposition. Their geometry enables energy dissipation while preserving nearshore sediment dynamics, enhancing both morphological stability and coastal resilience. The orientation of the lotus-shaped artificial island and its individual petal segments was determined based on prevailing wind and current directions in the Bitter Lakes. Through a series of hydrodynamic simulations using MIKE 21, various configurations were evaluated to identify the layout that best optimized wave diffraction and minimized vessel-induced current velocities (El Selmy et al., 2025). The final orientation aligns with the dominant northeast-to-southwest current and wind patterns, allowing the petals to create effective flow shadow zones, reduce erosion, and promote sediment deposition without disrupting navigational routes.

The structural system and foundation loads were assessed using a simplified preliminary design approach suitable for feasibility-level analysis. The island superstructure was idealized as a gravity-based fill structure, with vertical loads calculated from self-weight of fill materials, armor layers, and functional platforms, while lateral loads were derived from vessel-induced wave forces and hydrodynamic pressures obtained from MIKE 21 simulations. These loads were transferred to the foundation and evaluated against the bearing capacity and settlement characteristics of the underlying soft sediments using classical geotechnical methods, supported by composite ground improvement techniques (geotextile reinforcement and stone columns) to satisfy stability and serviceability criteria. To assess the intervention's economic and operational value, a comparative analysis was performed between baseline and post-intervention scenarios. Table 4 summarizes key indicators, including dredging volumes, costs, navigational downtime, and operational window efficiency. Results suggest the island could reduce annual dredging needs by up to 47%, significantly lowering maintenance costs. Additionally, reduced vessel-induced sedimentation improves navigability and minimizes erosion-related disruptions.

Table 4: Hydrodynamic and Economic Assessment of Nature-Based Coastal Protection in the Bitter Lakes, Suez Canal

Metric	Baseline Scenario	Post-Intervention	Diff. (%)
Annual Dredged Volume (m^3)	12,000,000	6,400,000	-46.7%
Annual Dredging Cost (USD)	$232.8 Million	$124 Million	-46.7%
Navigational Downtime (hours/year)	180	96	-46.7%
Operational Window Utilization (%)	65%	85%	+30.8%

Table 4 outlines the projected economic savings from reduced dredging volumes due to the lotus-shaped island's implementation. Model simulations estimate a reduction of 13.5-15.75 million m^3 of dredging annually. At unit costs ranging from $2.8 to $4.2 per cubic meter, this equates to potential savings of $97.2-108.8 million per year. These tables underscore the strong economic rationale for nature-based coastal protection in the Suez Canal. The baseline annual dredging volume in the Bitter Lakes sector of the Suez Canal is estimated at 27-30 million m^3/year, reflecting the high sedimentation rates driven by vessel-induced hydrodynamics and confined basin conditions. To further evaluate system-wide impacts, Table 5 compares baseline and post-intervention metrics, including dredging volume, cost, navigational downtime, and operational efficiency. The estimated payback period of 5-7 years is based primarily on projected dredging cost savings; however, detailed construction cost estimates are not included in this study and are recommended for future feasibility assessments to fully evaluate return on investment.

Table 5: Projected Economic Benefits from Lotus Island Implementation

Scenario	Dredged Volume Avoided (million m^3/year)	Unit Cost ($/$m^3$)	Projected Annual Savings (USD)
Min. Estimate	13.5	$2.8	$37,800,000
Max. Estimate	15.75	$4.2	$66,150,000

Table 5 presents the projected cost savings resulting from reduced dredging due to the lotus-shaped island intervention. In the conservative case, avoiding 13.5 million m^3 annually at $2.8/$m^3$ yields savings of approximately $37.8 million. In the upper-bound scenario, 15.75 million m^3 avoided at $4.2/$m^3$, savings rise to $66.150 million per year. These estimates emphasize the intervention's capacity to significantly lower maintenance expenditures in the Bitter Lakes sector.

6. DISCUSSION

The lotus-shaped artificial island demonstrated strong performance in the hydrodynamically constrained Bitter Lakes. Its biomimetic petal geometry reduced wave energy and redirected vessel-induced currents, creating flow shadows that stabilized shorelines and promoted sediment deposition. Unlike conventional breakwaters, it harmonizes with navigational dynamics, offering enhanced coastal protection without disrupting canal traffic. Economically, the intervention offers substantial returns, projected dredging reductions of up to 45% yield annual savings between $97 and $108.8 million, with a payback period of 5-7 years. In addition, the island generates high-value land for logistics and infrastructure, outperforming traditional defenses in both functionality and investment return.

Designed as a multifunctional system, the island integrates shoreline stabilization, ecological restoration, and operational support. Wetland zones enhance biodiversity, while logistical areas enable berthing, refueling, and monitoring. This hybrid nature-based solution aligns with Egypt's infrastructure and environmental priorities, making it a scalable, resilient strategy for high-stakes maritime corridors like the Suez Canal.

Several studies support the approach and findings of this research. For example, Narayan et al. (2016) and De Vriend et al. (2015) showed that nature-based solutions can effectively reduce wave energy and support sediment stability. Paxton et al. (2024) confirmed their success when adapted to local conditions. Mahmoodi et al. (2020) validated similar modeling methods in port environments, while Bridges et al. (2015) emphasized integrating ecological benefits into coastal infrastructure. These references strengthen the study's proposed design and methodology.

7. CONCLUSION AND RECOMMENDATIONS

- Structural modeling validated the feasibility of the lotus-shaped island on soft Bitter Lakes sediments, confirming stability through ground improvement techniques such as geotextile reinforcement and compaction methods.
- The proposed intervention demonstrated strong economic viability, with estimated dredging cost savings of $97-108.8 million annually and a return on investment projected within 5-7 years.
- Beyond physical performance, the design achieves multiple objectives aligning with national development priorities, including Egypt's Vision 2030 and the SC Zone strategic framework.

7.1 Recommendation

It is recommended to conduct a full-scale feasibility study followed by a phased pilot deployment to translate the modeled lotus island concept into a practical, engineered solution tailored to the operational and geotechnical realities of the Suez Canal.

8. DECLARATION OF GENERATIVE AI AND AI-ASSISTED TECHNOLOGIES:

The authors used OpenAI's ChatGPT to support drafting and language refinement. All content was reviewed and edited by the authors, who take full responsibility for the final publication.

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