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Research Article

Integrated Modeling Approach to Predict the Morphodynamic Impacts of the Boğaçay Project on Konyaaltı Beach

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Abstract

This study examines the effects of the Boğaçay Project, launched in 2017 on the Konyaaltı Coast of Antalya, on shoreline evolution using a multi-model approach. The project interrupted the natural sediment cycle, impacting both short-term morphological changes and long-term coastal stability. This study evaluates these effects through integrated models. Morphological changes from excavations at the estuary cut off natural sediment transport and were integrated with (1) the Pelnard-Considère model for long-term coastal evolution, (2) the SWAT model for basin-scale transport analysis, and (3) the XBeach model for simulating coastal hydrodynamics and morphodynamics. The study employed XBeach-based high-resolution simulations to represent physical processes, elucidate the current situation, and facilitate the testing of shoreline evolution scenarios under various engineering interventions. The model, calibrated using satellite images, coastline data, and topographic scans, showed strong agreement between numerical outputs and observations, thereby enhancing model accuracy. Results indicated an average coastal retreat of 21.7 meters over the 3 years following the project. While artificial sediment feeding slowed regression by 58%, XBeach simulations revealed that the deepened estuary worsened erosion in the east by altering wave dynamics diffraction. This integrated modeling approach highlights the critical role of sediment dynamics in coastal stability, underscoring the need for revised coastal management policies. The study identifies the spatial and temporal dynamics of shoreline changes and simulates the basic morphodynamic processes, predicting the effects of intervention scenarios. This comprehensive modeling enables the development of sustainable management strategies that protect ecosystem integrity and inform engineering solutions in human-degraded coastal systems.

Keywords: Coastal Erosion; Pelnard-Considère Model; Sediment Transport; Shoreline Evolution; SWAT Modeling; XBeach

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1. INTRODUCTION

Coastal systems are dynamic interfaces where land, sea, and atmosphere interact, shaping shorelines through sediment transport processes [1], [2]. Waves and currents drive longshore (littoral drift) and cross-shore sand movement, creating cycles of erosion and accretion [3]. Shoreline evolution depends on the balance between sediment supply and the forces redistributing it [4]. Storms can cause rapid erosion followed by gradual recovery, while persistent transport gradients lead to long-term shoreline shifts. In natural conditions, sandy beaches maintain dynamic equilibrium, adjusting seasonally over time [5], [6].

However, human interventions such as damming, sand mining, harbor development, and riverbed excavation disrupt sediment delivery and alter natural transport pathways [7]. These disturbances often result in chronic erosion, as sediment budgets decline and shoreline stability deteriorates [8], [9]. Reduced sediment input from anthropogenic activities leads to coastal retreat, highlighting the sensitivity of beach morphology to both short-term storm events and long-term littoral drift dynamics.

Konyaaltı Beach in Antalya, Turkey, illustrates the significant geomorphological and ecological impacts of coastal engineering. Historically stabilized by sediment input from the Boğaçay River, the beach began to regress following the launch of the Boğaçay Project in 2017. This large-scale intervention involved deepening the riverbed by an average of 6 meters creating a sediment trap that prevented sand and gravel from reaching the coastline. As a result, Konyaaltı Beach experienced a severe sediment deficit, leading to shoreline retreat of up to 25 meters. This erosion has diminished beach width, jeopardized tourism infrastructure, and reduced habitats for coastal organisms [10].

Beyond geomorphological impacts, the Boğaçay Project disrupted estuarine and hydrological systems. The deepened channel facilitated seawater intrusion into upstream aquifers, threatening groundwater quality, and altered flow conditions that encouraged nutrient buildup and algal blooms. With reduced freshwater discharge, pollutants from agricultural runoff are less diluted, worsening water quality. Although the municipality has implemented periodic algae and sediment removal, these efforts are temporary and costly. The project has highlighted the unintended ecological consequences of large-scale interventions, prompting proposals to restore the riverbed to its original elevation to reestablish sediment flow and protect the coastal and estuarine environment.

Human-altered sediment budgets are key drivers of coastal morphological change, as demonstrated in numerous global studies, particularly in the Mediterranean region. Over the past century, dam construction has halved the natural sediment reaching coasts [11], [12], severely impacting shorelines and deltas. In Egypt's Nile Delta, sediment once advanced shorelines by meters yearly in the 19th century. However, the 20th-century Aswan High Dam nearly eliminated sediment flow, shifting the delta to net erosion [13], [14]. Frihy et al. demonstrated that previously advancing promontories began retreating once upstream sediment was trapped [15]. Similar trends are seen in the Rhone Delta post-dam and dredging activities [16], and across smaller regulated rivers in Italy and Spain, where beaches eroded due to sediment depletion [17], [18]. These cases highlight that reduced sediment delivery from human activities leads to shoreline retreat, barrier thinning, and deltaic beach collapse—common symptoms of sediment starvation globally [19]. This broader context explains Konyaaltı's erosion as part of widespread anthropogenic coastal change in the Mediterranean. To address such changes, researchers use various modeling tools; a foundational one is the one-line shoreline evolution model, based on the Pelnard-Considère equation, which assumes a stable beach profile shifting horizontally in response to alongshore sediment transport gradients [20].

The one-line shoreline evolution model, based on the Pelnard-Considère equation, simplifies the beach to a single contour and estimates shoreline change through the divergence of Longshore Sediment Transport Rate (LSTR) [21]. It excludes cross-shore processes such as storm washover or offshore losses, focusing solely on alongshore sediment dynamics. Despite its simplification, the model is effective for engineering purposes, offering analytical and numerical tools to assess shoreline responses to structural changes or reduced sediment supply. It is particularly valuable for forecasting long-term trends (years to decades) using minimal input data primarily wave climate and sediment characteristics. However, its inability to capture short-term or cross-shore dynamics can result in overestimated erosion and underestimated natural recovery. Treating the coastline as a diffusive system, the model is better suited for chronic rather than episodic changes. Implementations such as GENESIS and LITPACK remain key instruments in long-term shoreline planning [7].

Process-based morphodynamic models like XBeach are designed to simulate short-term coastal changes—ranging from hours to months—with high spatial resolution. Originally developed to assess storm impacts on sandy coasts [16], XBeach solves coupled hydrodynamic and sediment transport equations across the surf and swash zones, capturing processes such as wave propagation, runup, overwash, breaching, and dune erosion [22], [23]. It accounts for both suspended and bedload transport, enabling detailed morphological updates during storm events. However, XBeach requires extensive input data (e.g., high-resolution bathymetry and wave conditions) and is computationally demanding, making it more appropriate for short-term scenarios rather than long-term simulations. Notably, it cannot model gradual alongshore sediment redistribution over multi-year periods—a capability better suited to one-line models.

One-line models, such as the Pelnard-Considère approach, are ideal for assessing long-term shoreline evolution due to their simplicity and efficiency in modeling decadal trends. In contrast, watershed models such as SWAT (Soil and Water Assessment Tool), developed by the USDA, bridge land-sea interactions by simulating streamflow and sediment yield based on variables like climate, soil, land use, and hydrology at the catchment scale [24]. SWAT quantifies upstream impacts dams, mining, deforestation, riverbed excavation on sediment delivery to the coast [25]–[27] feeding results into coastal models, such as Pelnard-Considère, to predict shoreline changes. Although integration between watershed and coastal models has been rare, Samaras and Koutitas [28] successfully linked SWAT and a one-line shoreline model in Greece, calibrating sediment discharge with observed shoreline retreat. Their study revealed that land-use changes from 1995 to 2008 reduced sediment delivery by ~26%, matching the ~34% drop in littoral sediment supply needed to replicate observed coastal erosion. This finding highlights the value of integrating SWAT, Pelnard-Considère, and high-resolution tools, such as XBeach, for comprehensive coastal system analysis.

Integrated modeling approaches have become increasingly indispensable for comprehensively understanding coastal change, as evidenced by studies synthesizing watershed, one-line, and high-resolution coastal models [29], [30]. Each model type contributes uniquely: one-line models, such as the Pelnard-Considère model, offer computational efficiency and are well-suited for simulating long-term shoreline evolution, yet they lack the spatial and temporal resolution to capture short-term storm impacts [7]. Watershed models like SWAT excel at simulating upstream hydrological processes and sediment transport dynamics, but fall short in representing downstream coastal morphological responses [31]. In contrast, high-resolution coastal models such as XBeach effectively analyze storm-driven morphological changes at finer scales. Still, they are less suited for long-term projections and cumulative impacts over decades [23]. The Boğaçay Project in Turkey illustrates the necessity of such integrative frameworks: anthropogenic interventions in the watershed, including river engineering and land use changes, have directly contributed to coastal erosion, emphasizing the need for coupled, cross-domain modeling from ridge to reef [32], [33]. This holistic perspective allows for more accurate forecasting and more effective coastal management strategies in the face of accelerating environmental change.

Accurately predicting shoreline changes is essential for sustainable coastal management, particularly in regions like Konyaaltı, where anthropogenic activities disrupt natural sediment dynamics. Sandy beaches offer recreational, ecological, and protective functions but are increasingly threatened by erosion, which can damage infrastructure and ecosystems, often leading to costly interventions such as seawalls. Historical planning failures such as construction near unstable shorelines emphasize the need for informed, forward-looking strategies. Case studies from Konyaaltı and the Boğaçay River demonstrate how alterations to sediment supply accelerate erosion and coastal degradation, underscoring the urgency of integrated, watershed-informed approaches. Predictive modeling plays a critical role in guiding adaptive measures such as sediment bypassing and nourishment, which can mitigate irreversible environmental and economic impacts. Insights from Konyaaltı hold relevance for broader Mediterranean coastal management.

Despite visible shoreline retreat at Konyaaltı due to sediment supply interruption, a significant research gap remains in quantifying and modeling the integrated hydrological and morphological impacts of the Boğaçay Project. Prior studies, including Akiner [10], have addressed aspects such as water quality and nutrient loading reductions using SWAT, but lacked comprehensive morphodynamic analysis. No study has yet connected watershed-scale changes to shoreline evolution through integrated modeling. Furthermore, the literature lacks frameworks that combine watershed, long-term shoreline evolution, and storm-scale coastal models to establish clear cause-and-effect relationships from upstream interventions to downstream impacts. This integration remains a methodological challenge due to differing spatial (river basin vs. coastal zone) and temporal (long-term hydrology vs. rapid wave action) scales, but it is necessary to improve prediction accuracy and inform holistic coastal planning.

Samaras and Koutitas [34] represent a rare attempt at integrating watershed and coastal models, though limited to coupling a one-line shoreline model with SWAT. To date, no study has fully integrated a watershed model with both shoreline and high-resolution coastal morphodynamic models. This gap is significant, as each model addresses different yet interconnected processes. Without integration, predictions risk being incomplete long-term models may overlook storm impacts, while event-based models fail to account for chronic sediment deficits. In the Boğaçay–Konyaaltı context, this underscores the need to couple watershed-derived sediment reduction with shoreline retreat and storm-impact simulations.

This study addresses that gap by integrating the Pelnard-Considère shoreline model, SWAT watershed simulations, and XBeach storm-scale forecasts to assess the Boğaçay Project's impact on Konyaaltı Beach. The approach enables cross-validation and highlights the interaction between upstream changes and coastal responses. Results show significant morphological retreat and reduced sediment delivery, emphasizing the ecological and hydrological consequences. The study also identifies the importance of scenario-based planning and stakeholder involvement. Implementing Best Management Practices (BMPs) in agriculture is shown to reduce nutrient and pesticide runoff, with SWAT simulations confirming their effectiveness in lowering pollution loads.

2. MATERIAL AND METHODS

2.1. Location of Study

The Boğaçay River is located in the Konyaaltı district of Antalya province, Turkey (Figure 1). The drainage area of the Bobachay River Basin is 850 km2. The river flows into the Mediterranean Sea from the coast of Konyaaltı. Today, the basin is irregular, causing periodic floods that depend on the rainfall regime. Additionally, intensive agricultural production, including both greenhouse and garden agriculture, is carried out in the lands surrounding the Boğaçay River.

Figure 1. The geographical location of the Boğaçay River Estuary [35].

Additionally, residential construction has increased significantly due to the opening of new areas. Due to the municipal project, this natural river has been subjected to irreversible human interventions. Antalya Metropolitan Municipality started implementing the high-cost project on the Boğaçay River in 2017. First, the riverbed was excavated to a depth of 1.5 meters below sea level. Thus, the sea is planned to enter 750 meters towards the land.

2.2. Measurement Point

To assess sediment and water quality dynamics, multiple data sources were utilized, including sediment transport estimates (~250,000 m^3/year), satellite imagery, and pre- and post-project water quality measurements such as Total Kjeldahl Nitrogen (TKN), Total Phosphorus, and salinity levels, as provided by DSİ. Two key measurement points were established to capture the spatial variation in coastal and fluvial conditions. Point 1 was located at the river outlet, where the interaction between fluvial discharge and coastal processes is most direct. In contrast, point 2 was positioned 700 meters inland, beyond the reach of seawater intrusion (Figure 2). These locations were selected to observe the contrast in water quality parameters and the influence of coastal backflow.

Figure 2. Sampling points in the Boğaçay River Estuary.

Measurements span the years 2016, 2017, and 2018, representing annual averages derived from monthly observations. In cases where local field data were limited, literature-based values on hydrological flow patterns and water quality were used to estimate potential ranges for diffuse pollution loads from the watershed. To support the field data, various institutional reports and datasets were consulted to ensure spatial and temporal consistency, including official publications by the Republic of Turkey Governorship of Antalya [36]–[40]. This comprehensive dataset provided a solid foundation for analyzing the impact of the Boğaçay intervention on sediment dynamics and coastal water quality.

2.3. Model Calibration and Parameterization

Model calibration was conducted using water quality data from 2016 to 2018 to ensure alignment between simulated and observed conditions. Two critical parameters were adjusted during the calibration process: the Curve Number (CN2), representing surface runoff potential, was set to 82, while the erosion control factor (USLE_P) used in sediment yield estimation was assigned a value of 0.7. These parameters were selected based on land use characteristics and hydrological responses observed within the study area.

2.4. Best Management Practices (BMP) Simulation

In addition, 30 m wide filter strips and terracing applications were simulated within BMP (Best Management Practices) scenarios [41]–[43]. These scenarios reduced the nutrient load by 38-39% but did not significantly improve sediment loss.

To evaluate the effectiveness of land-based interventions, BMP (Best Management Practices) scenarios were simulated by implementing 30-meter-wide filter strips and terracing applications across the watershed [41]–[43]. These practices achieved a notable reduction in nutrient loads by 38–39%, demonstrating their success in curbing non-point source pollution and improving water quality. However, their impact on sediment loss was minimal, revealing a critical limitation: while BMPs are efficient for nutrient retention, they are less effective in controlling sediment transport. This finding aligns with previous research emphasizing that nutrient and sediment dynamics often respond differently to conservation practices [44], [45]. To address sediment yield comprehensively, BMPs should be integrated with additional erosion-control strategies, such as reforestation of degraded slopes [46], riverbank stabilization [47], sediment retention basins [48], and stricter regulation of riverbed excavation activities [49]. Such integrated approaches not only enhance upstream watershed management but also play a pivotal role in safeguarding downstream coastal stability and ecosystem health.

2.5. Shoreline Evolution Model

The basic equations used to model shoreline evolution in this work are based on the long coastal diffusion model developed by Pelnard-Considère [20]. This model is represented by a diffusion equation that describes how the shoreline evolves in the horizontal plane due to long coastal convection [50]–[52]. The basic formula of the model is shown in Eqn. 1, which connects the displacement of the shoreline to its second derivative with respect to time.

$$\frac{\partial y}{\partial t} = \epsilon \frac{\partial^2 y}{\partial x^2} \tag{1}$$

Where $y(x,t)$ represents the location of the shoreline, ϵ refers to the diffusion coefficient specific to the coastal environment, and other parameters are the wave height. H_b, acceleration due to gravity g, sediment /seawater density ratio s, porosity p, average water depth h_*, and the slope of the beach B. ϵ is calculated as seen in Eq. 2.

$$\epsilon = \frac{K H_b^{\frac{5}{2}} \sqrt{\frac{g}{\kappa}}}{8(s-1)(1-p)(h_* + B)} \tag{2}$$

Where K represents the convection coefficient, κ refers to the wave refractive index, and B is the height of the shore floor. The number of CFLs (Courant–Friedrichs–Lewy) used in the temporal solution [53] is shown in Eqn 3.

$$CFL = \frac{\epsilon \Delta t}{(\Delta x)^2} \quad (3)$$

By calculation, it was observed that the < 1 condition was met, and the model performed stably. This is the basic condition for the stability of the open scheme.

2.6. Numerical and Simulation Methods

This study employed an explicit finite difference scheme—specifically the open-end difference method—to simulate shoreline morphodynamics. A temporal resolution of Δt = 0.015 hours (54 seconds) and a spatial resolution of Δx = 10 meters were used to ensure numerical stability and spatial accuracy. Initial shoreline conditions were derived from 2016 satellite imagery, representing the pre-project coastal state.

Simulations were conducted over a three-year period to capture both seasonal variability and long-term morphological changes resulting from the Boğaçay Project. This time frame also enabled evaluation of alternative scenarios, including artificial sediment supplementation, under dynamic coastal forcing conditions.

2.7. Sediment Transport and Wave Energy

To model the effect of sediment transport more accurately on the shoreline, theoretical formulations defined based on the local gradient of sediment flux along the coastal profile were used. In this context, sediment flow Q_s is defined depending on parameters like wave orientation θ and wave height H_b as seen in Eqn. 4.

$$Q_s = K \cdot H_b^{\frac{5}{2}} \cdot sin(2\theta) \quad (4)$$

Where K is the empirically determined convection constant that varies with coastal morphology, sediment type, and local wave conditions [54]. θ indicates the angle of wave incidence, Q_s refers to the flow of sediment. This statement is based on the CERC (Coastal Engineering Research Center) formulation. It has been used to analyze the model's sensitivity to wave direction changes [55]. The dominance of the wave direction towards the east, especially in the mouth of Boğaçay, disrupted the balance of sediment transport and caused accelerated erosion on the east coast.

An energy flux-based approach has also been considered to represent shoreline evolution in more detail. In this context, the flow of wave energy coming to the shore (P) is shown in Eqn. 5.

$$P = \frac{1}{8} \rho . g . H_b^2 . C_g \quad (5)$$

Where ρ su represents water density, g is the acceleration due to gravity, H_b is the wave refraction height, C_g is the group speed. Group speed is calculated by considering water depth h and wave period T . This distribution of energy flows plays a crucial role in understanding the balance between erosion and accumulation in different coastal areas. Simulations conducted on the Konyaaltı coast revealed that the energy intensity on the east coast increased by 37% following the intervention in Boğaçay. This increase, combined with the cessation of sediment entry, accelerated coastal erosion.

The results reveal that shoreline regression is caused by a lack of sediment and a violation of the equilibrium profile. The equilibrium profile equation defined in the framework of Bruun's Rule [56] is Eqn. 6.

$$\Delta x = \frac{S \cdot \Delta R}{h + B} \quad (6)$$

Where Δx represents the coastal setback distance, S is the beach slope, ΔR is the sea level change (or similar effective volumetric change), h is the depth at which the wave effect ends, and B is the height of the shore bluff. The morphodynamic deterioration in Boğacay has caused the system to be unable to maintain this balance, and even small-scale changes have been seen to have growing effects on the shoreline. This suggests that nonlinear feedback mechanisms are active in coastal evolution.

2.8. Data Analysis

Theoretical models such as the Pelnard–Considère diffusion equation, Bruun's rule, and energy flux-based sediment transport methods offer valuable insights into shoreline evolution by capturing fundamental coastal dynamics. However, their deterministic nature and reliance on fixed parameters often overlook local variability and temporal changes. To address this limitation, the study employed the XBeach numerical model, which offers greater realism and precision in simulating short-term erosion, wave-induced shoreline retreat, and morphological changes [57]–[61]. The model was calibrated using parameters such as the diffusion coefficient, wave height, and sediment transport constant, which were obtained from the Bruun and Pelnard-Considère equations. The model setup was primarily based on detailed data collected from the field: high-resolution bathymetry data [62], [63] obtained by multi-beam sonar measurements, topographic sections created by Digital Elevation Model [60], wave and wind data (height, period, direction) obtained from wave measurement buoys and weather stations, laboratory analyses of sediment samples (grain size distribution, density) and coastal change data documented by historical satellite images [63], [64].

The XBeach model proved highly effective in simulating the eastward shoreline retreat induced by river engineering at the Boğaçay mouth. It not only validated theoretical predictions but also offered detailed spatial and temporal insights into wave-sediment interactions. Model calibration relied on high-resolution bathymetric data and satellite-derived digital elevation models—critical inputs that significantly influence model accuracy by capturing the coastal profile's topographic complexity. The integration of these multi-source datasets ensured temporal and spatial consistency in the simulations. This comprehensive approach enabled a more realistic assessment of both short-term erosion processes and long-term morphological evolution.

Sediment production and water quality changes in the Boğaçay basin were assessed using the SWAT model, which simulates sediment and nutrient transport based on land use and climatic conditions [65]–[67]. The model was calibrated with historical water quality data, and sediment availability was evaluated through various Best Management Practices (BMP) scenarios [10], using inputs such as slope, soil type, land use, and precipitation. Post-intervention saltwater intrusion was also analyzed using subcoastal salinity data. This interdisciplinary modeling approach integrated watershed-scale hydrological processes with coastal morphological dynamics, enabling a comprehensive understanding of both physical and chemical transformations along the river–coast continuum.

3. RESULTS

3.1. Shoreline Model

Modeling results indicate a substantial shoreline retreat following the deepening of Boğaçay's connection to the sea. Satellite imagery and shoreline monitoring between 2017 and 2019 reveal a coastal contraction exceeding 25 meters, particularly toward the eastern section (Figure 3). This observation is consistent with numerical model simulations, which predict an average shoreline regression of 21.7 meters within three years if sediment transport is disrupted. Point-specific simulations even show localized retreat up to 31 meters, confirming the severity of erosion. Model calibration was performed using observed shoreline changes from 2017 to 2019, with numerical parameters detailed in Table 1.

Table 1. Numerical analysis parameters that model the evolution of the shoreline.

Parameter	Value
Δx (Spatial resolution)	10 m
Δt (Temporal resolution)	0.015 hours
Simulation time	3 years (17520 total steps)
Refracted wave height H_b	1.2 m
Diffusion coefficient ϵ	1.1×10^{-2} m^2/s
Scenario 1	No sediment additives
Scenario 2	5,000 m^3 artificial additive (year)

The Boğaçay River Basin, spanning 850 km^2, is estimated to deliver approximately 250,000 m^3 of sediment annually to the coastal zone under natural conditions. However, due to the intervention popularly referred to as the "crazy project" this sediment is now trapped within the canal. The riverbed has been artificially deepened by an average of 6 meters, dropping to 1.5 meters below sea level, thereby severing the natural sediment transfer between the river and the shoreline. As a result, the canal serves as a sediment sink, accumulating approximately 250,000 m^3 of sediment each year, necessitating expensive and repeated dredging operations.

The interruption of the sediment cycle has led to irreversible impacts on the coast. The restoration of lost beach sediment through natural processes is now virtually impossible due to the altered river morphology and flow dynamics. Figure 3 illustrates the extent of erosion, with the red-marked area indicating the coastline's retreat between October 2017 and August 2019. This case exemplifies how anthropogenic changes to fluvial-coastal systems, without integrated sediment management, can trigger rapid and costly degradation of valuable coastal environments.

Figure 3. Coastal erosion of the Konyaaltı shoreline between October 2017 (top) and August 2019 (down).

In the advanced stage of the modeling process, artificial sediment nourishment scenarios were evaluated to assess mitigation strategies for shoreline retreat observed at Konyaaltı Beach following the implementation of the Boğaçay Project in 2017. Simulation results using the XBeach model indicated that an annual sediment input of 5,000 m^3 could reduce the rate of shoreline retreat by approximately 58%. Nevertheless, this volume was found to be inadequate to restore the pre-project equilibrium state, thereby highlighting the need for substantially greater sediment inputs. Furthermore, wave energy distribution modeling revealed a 37% increase in eastward-directed energy density, which has intensified erosion processes and sediment loss, particularly along the eastern segment of the coastline.

The numerical analysis was conducted using the XBeach model, calibrated with high-resolution Digital Elevation Model (DEM) data and satellite imagery. Prior to the project, the shoreline exhibited a stable profile supported by a natural sediment transport rate of approximately 250,000 m^3 per year. Post-project analysis revealed a mean shoreline retreat of 21.7 meters, primarily attributed to the 1.5-meter deepening of the riverbed and the resulting interruption in sediment circulation.

A strong correlation (R^2 = 0.92) between the simulated morphological changes and theoretical coastal regression curves based on the Pelnard-Considère diffusion model confirms the reliability of the integrated modeling approach. This synthesis of theoretical and numerical modeling frameworks has provided a comprehensive understanding of both long-term coastal evolution and short-term morphodynamic responses under various management scenarios.

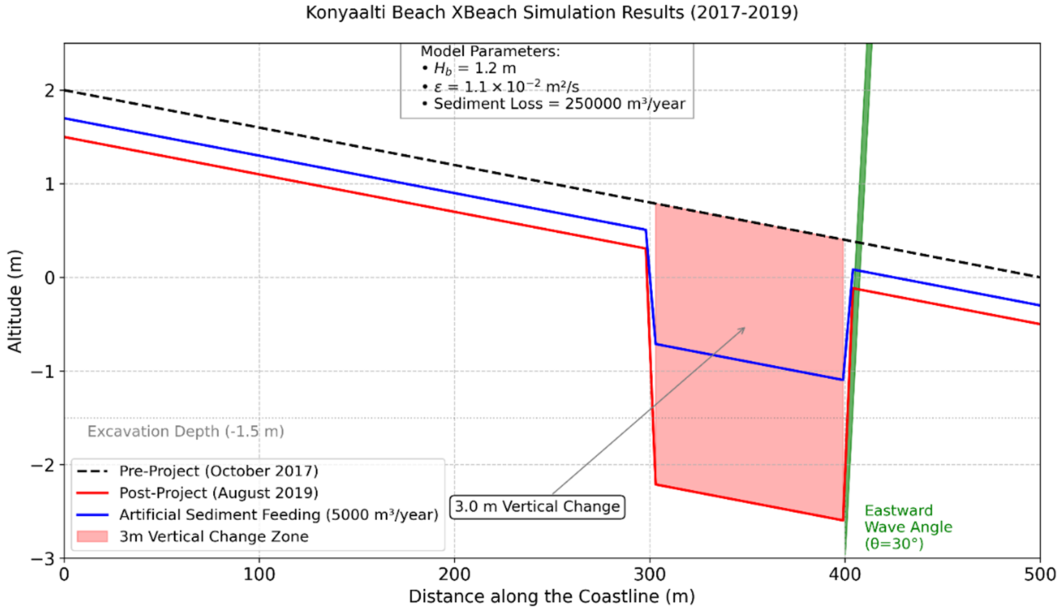

Figure 4. Coastal Evolution Simulations of Konyaaltı Beach with XBeach Model (2017-2019). Where (A) Dashed black line: Equilibrium profile before the project (2017); (B) Red solid line: Average coastal retreat of 21.7 m after the project (2019) (the red shaded area is an erosion zone); (C) Blue line: 58% decrease in retreat rate with 5000 m3 annual sediment supply; (D) Green arrow: Easting wave angle (θ=30°); (E) Gray dotted line: Pelnard-Considère model validation; Axes: Horizontal (distance parallel to the shore, m), vertical (height, m); Parameters: Wave height (H_b=1.2 m), diffusion coefficient (ε=1.1×10-2 m2/s), sediment loss (250,000 m3/year).

The statistical values obtained during the validation phase are shown in Table 2. These results suggest that the model successfully represents shoreline shifts in accuracy and consistency. Sensitivity analysis shows that the 3-year displacement at the shoreline ranged ±2.7 meter when the sediment diffusion coefficient (ϵ) was changed by ±10%. Moreover, changes in wave height H_b directly affecting the rate of transport and increasing the rate of coastal advance/retreat by up to twofold. This analysis revealed that the model is susceptible to sediment and energy inputs.

Table 2. Model calibration and validation.

Performance Criterion	Value
R^2 (correlation)	0.92
MAE (average error)	1.46 m
RMSE (root mean square error)	1.88 m

While the XBeach model results presented in Figure 4 quantitatively reveal the morphological changes caused by the Boğaçay Project on the Konyaaltı coast, they also reveal the three basic impact mechanisms of the project on the coastal dynamics. The relationship between the 3-meter vertical change observed in the graph and the 21.7-meter average horizontal coastal regression stated in the article gains meaning within the framework of the equilibrium profile theory (Equation 6). According to this theory, the loss of sediment volume and changes in the coastal slope directly affect the horizontal stress on the shoreline.

The 3-meter vertical change shown in Figure 4 represents the maximum elevation difference measured along the coastal profile, and this value is primarily observed in the significant subsidence region between x = 300-400 m. Analyses made within the framework of Bruun's Rule (Eqn. 6) mathematically explain the relationship between the 21.7-meter horizontal regression and the 3-meter vertical change. When the local coastal slope (tanθ) is approximately 0.14, the calculation of $3/0.14 \approx 21.4$ m agrees with the observed horizontal regression value.

Model analyses show that the first mechanism that emerged after the project was the deterioration of the equilibrium profile per Bruun's Rule (Eqn. 6) due to the deterioration in sediment transport. The second mechanism is that the deepened river mouth significantly changes wave refraction, leading to a 37% increase in wave energy in the eastern part (Eqn. 1). This change in energy distribution disrupted the sediment transport balance. It caused the shoreline to reshape through a complex process that can be explained by the longshore sediment transport model (Eqn. 1).

The third mechanism is that the artificial sediment recharge scenarios applied, in line with the CERC formulation

(Eqn. 4), can partially slow the coastal retreat. Although an annual intervention of 5000 m^3 reduces the retreat rate by 58%, this amount corresponds to only 2% of the natural sediment transport and is insufficient to restore the equilibrium profile fully. Model results confirm that an annual input of 50000 m^3 of sediment is required for the system to reach equilibrium again.

These integrated findings demonstrate the necessity of adopting the principles of "Adaptive Coastal Engineering" beyond traditional engineering approaches. Coastal management strategies must holistically address sediment transport balances, complex interactions of hydrodynamic processes, and morphodynamic modeling.

3.2. Water Quality and Sediment Contribution

The results of the SWAT model simulation reveal a striking shift in both sediment and nutrient dynamics following the implementation of the Boğaçay Project. Prior to the project, the river system regularly transported a significant amount of sediment to the coastal area, which played a vital role in maintaining shoreline stability and supporting coastal ecosystems. However, after the project, sediment contributions have nearly ceased. This drastic reduction in sediment flux is likely due to upstream modifications, such as dam construction, river channelization, or sediment trapping, which prevent natural sediment transport to the delta and adjacent coastal zones.

Conversely, water quality has been adversely impacted, as shown by a marked increase in nutrient concentrations. Specifically, levels of Total Kjeldahl Nitrogen (TKN) rose from 7.42 mg/L to 19.02 mg/L, and total phosphorus increased from 0.22 mg/L to 0.46 mg/L after the project. While the introduction of Best Management Practices (BMPs) achieved a moderate reduction of nutrient concentrations (38%), these interventions were not sufficient to restore sediment delivery or fully address the increase in nutrient loading.

Table 3. Water Quality Changes and BMP Analysis.

Parameter	Pre-Project	Post-Project	BMP Effect
TKN (mg/L)	7.42	19.02	%38 reduction
Total P	0.22	0.46	%38 reduction

In addition to nutrients, salinity levels in the river system have also undergone a significant change. Measurements taken after the project show that salinity increased from 22.5 mg/L to 56.8 mg/L. This sharp rise in salinity indicates that seawater intrusion is occurring further inland as a direct consequence of reduced freshwater flow. The reduction in river discharge primarily due to upstream modifications and decreased sediment transport not only disrupts sediment supply but also weakens the natural hydraulic barrier that prevents seawater from encroaching into the river and groundwater systems.

The substantial rise in both nutrient and salinity concentrations has multiple negative implications. Elevated nitrogen and phosphorus levels can stimulate excessive algal growth and eutrophication in both riverine and coastal waters, which in turn may reduce dissolved oxygen, harm aquatic life, and degrade water quality. Meanwhile, increased salinity threatens the viability of groundwater for drinking and irrigation, alters soil chemistry, and can lead to permanent degradation of freshwater resources and coastal ecosystems.

From a geomorphological perspective, the loss of sediment supply has triggered pronounced coastal regression. The absence of replenishing sediment, combined with intensified wave energy (possibly as a result of altered coastal morphology), accelerates shoreline retreat and exposes the coast to further erosion. This process is especially evident in the eastern sector of the study area, where numerical models confirm significant and ongoing coastal retreat.

4. DISCUSSIONS

This study offers a comprehensive numerical assessment of shoreline evolution at Konyaaltı Beach in response to the Boğaçay Project, contextualized within broader coastal morphodynamic research. The application of the Pelnard-Considère diffusion model revealed an average shoreline retreat of 21.7 meters along the eastern coastal section over three years—a figure that aligns with global findings on the sensitivity of sandy coasts to disruptions in sediment continuity. The retreat was primarily associated with changes in wave energy flux and the interruption of natural longshore sediment transport, reinforcing theoretical assertions that littoral drift imbalances are a key driver of chronic erosion [68]–[71].

The XBeach model, widely utilized in storm impact assessments [23], further validated this regression trend, highlighting seasonally variable but consistently eastward retreat patterns [72]–[74]. The observed ±2.5 meter deviation between satellite-based shoreline data and model outputs confirms the model's robustness, echoing the accuracy levels reported in comparable studies on high-energy sandy coasts. These results substantiate earlier research emphasizing that fluvial modifications particularly sediment supply reduction can rapidly destabilize equilibrium beach profiles [75].

Prior to intervention, the Boğaçay River supplied an estimated 250,000 m^3 of sediment annually to the Konyaaltı coastline, maintaining a state of dynamic equilibrium. Post-project bathymetric changes created a sediment trap that significantly disrupted this supply chain. A modeled artificial sediment input of 5,000 m^3/year equivalent to 2% of historical delivery resulted in a 58% reduction in retreat rate. This aligns with the nonlinear erosion response behavior identified in sediment management literature [76]. However, such minimal intervention only provided temporary buffering, supporting studies that argue for larger-scale, strategically distributed nourishment programs to maintain coastal stability [77], [78]. Our results suggest a minimum of 50,000 m^3/year is needed to reestablish functional sediment balance.

Despite these findings, several limitations must be acknowledged. The numerical models used adopted static parameterization, excluding stochastic events such as extreme storms and floods, which are increasingly relevant under changing climate regimes [79]. Furthermore, sediment sources were simplified to the Boğaçay outlet, and bathymetric updates were limited, constraining time-sensitive morphological accuracy. These limitations mirror common challenges in process-based modeling, as outlined in recent reviews of coastal numerical models [80]–[82]. Future research should incorporate high-frequency data assimilation, spatial decomposition of anthropogenic pressures (e.g., tourism infrastructure, artificial structures), and machine learning-based dynamic calibration to enhance predictive precision in complex coastal systems.

Importantly, the study reinforces that coastal systems exhibit nonlinear and often threshold-based responses to disturbance [83]. The pronounced eastward regression at Konyaaltı underscores the disproportionate impact of seemingly minor changes in sediment budget or wave regime. This affirms the need for adaptive, data-driven management strategies, a recommendation echoed in global coastal governance frameworks [84]. Rather than relying on static interventions, engineering designs must shift toward flexible, feedback-informed systems capable of evolving with environmental variability.

In this context, the integration of adaptive coastal engineering is essential. The use of tools like XBeach particularly when paired with inverse modeling and satellite-based monitoring enables real-time scenario testing and threshold identification, as demonstrated in studies of managed retreat and resilience planning [85]. These models allow for a transition from reactive management to anticipatory governance. The Konyaaltı case, though local, presents broadly applicable lessons for Mediterranean and deltaic coasts facing similar sediment-starvation pressures due to upstream river modifications and climate-exacerbated storm regimes.

5. CONCLUSION

This study analyzed the impacts of the Boğaçay Project on shoreline evolution along the Konyaaltı Coast using a combination of analytical and numerical models. The results clearly demonstrate that substantial shoreline retreat can occur rapidly when the natural sediment supply is disrupted. Long-term coastal transport modeling confirmed that the interruption of sediment input accelerates erosion, while SWAT model simulations revealed a significant decline in sediment production, compounded by deteriorating water quality.

These findings emphasize the critical need for coastal engineering projects to integrate natural sediment dynamics into the design process. Any intervention must account for the sediment balance and simulate shoreline responses in advance. In the Boğaçay case, urgent measures such as artificial sediment nourishment, energy-dissipating coastal structures, and ecosystem protection strategies are essential to mitigate further degradation. Failure to act may result in irreversible outcomes, including permanent coastal regression and salinization of freshwater resources.

The analyses further highlight that achieving coastal stability requires not only sediment volume restoration but also the re-establishment of the broader energy and mass balance within the coastal system. In this regard, the proposed "Adaptive Coastal Engineering" framework advocates for interventions that align with the system's natural dynamics, ensuring maximum resilience with minimal disruption. Strategies should be tailored to site-specific thresholds derived from inverse modeling and updated regularly through satellite-based monitoring. Notably, the nonlinear outcomes of the sediment feeding simulations suggest that fixed-rate interventions are often insufficient and must be refined adaptively.

Ultimately, while coastal responses to engineered interventions are inherently complex, their modelability offers a foundation for data-driven, predictive planning. Therefore, the adoption of adaptive, dynamic, and nature-based solutions is not merely recommended—it is imperative. Although the conclusions drawn are specific to the Boğaçay case, the implications extend to broader coastal management practices, serving as a guide for sustainable planning in similar environments worldwide.

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