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MORPHOLOGICAL DYNAMICS OF AN ENGINEERED COASTLINE: A CASE STUDY FROM CONSTANȚA, BLACK SEA COAST OF ROMANIA

Alexandru-Cristian Cîndescu*, Silică Petrișoaia, Luminița Buga, Alina Spînu

National Institute for Marine Research and Development "Grigore Antipa",
300 Mamaia Blvd., 900581 Constanta, Romania
**Corresponding author: acindescu@alpha.rmri.ro*

ABSTRACT

This study examines cross-shore morphological variability in three beach profiles within the engineered coastal sector of Constanța, Romanian Black Sea, over the period 2022–2024. Annual GPS-based topographic surveys were conducted using high-precision equipment (GIS-grade and geodetic-class RTK receivers with real-time ROMPOS corrections) along fixed transects marked by permanent benchmarks. Morphological changes were evaluated relative to the 2015 post-beach nourishment profile, which served as the baseline for comparative analysis. To explore the influence of hydrodynamic conditions, the evolution of the beach profile was correlated with sea surface height (SSH) data from the Copernicus Marine Environment Monitoring Service (CMEMS), capturing seasonal and interannual sea level variability. Results show that the shoreline response closely follows SSH trends: lower SSH values were generally associated with stable or accreting profiles, while higher values, especially during storm events, triggered crest retreat, scarping, and upper beach erosion. Among the transects studied, CT1 showed the most significant erosion, whereas CT3 exhibited greater resilience due to the development of a berm. These findings highlight the value of integrating SSH variability and high-resolution GPS surveys to enhance coastal monitoring and inform adaptive shoreline management strategies in engineered environments.

Keywords: Beach profiles, coastal morphology, sea level variability, GPS survey, Romanian Black Sea

INTRODUCTION

Coastal systems represent dynamic interfaces between terrestrial and marine environments, shaped by a complex suite of interacting natural processes and human activities (Woodroffe *et al*., 2023). Morphological change along the coast is governed by the interplay of hydrodynamic forces (waves, tides, and currents), sediment availability and transport pathways, geological structure, and climate-driven processes such as sea level rise (Karsli *et al*., 2011; King *et al.,* 2019; Kie *et al*., 2024; Creane *et al*., 2022; Lakku *et al*., 2024).

Superimposed on these natural drivers are anthropogenic interventions, including urban development, port infrastructure, and shoreline stabilization measures that alter sediment budgets and disrupt the natural equilibrium of coastal systems (Ismail & Erüz, 2023; Biondo *et al*., 2020; Todd *et al*., 2019). Understanding how these factors interact to produce spatial and temporal variability in coastal morphology is critical for sustainable shoreline management, hazard mitigation, and climate adaptation strategies (Islam *et al.,* 2025).

Among the techniques available for monitoring coastal dynamics, cross-shore beach profile analysis remains a basis of geomorphological and coastal engineering research (Caldareri *et al.,* 2024; Casarosa *et al*., 2022). Unlike platform-based shoreline indicators that primarily track horizontal displacement, cross-shore profiles capture fine-scale vertical and volumetric changes within the active beach-dune system (Caldareri *et al*., 2024; Suanez *et al*., 2023; Boak & Turner, 2005). These profiles allow for the assessment of morphometric parameters such as berm crest elevation, beach face slope, and subaerial sediment volume, which are essential for understanding sedimentary processes and the functional performance of coastal protection measures. This level of detail is significant in heavily engineered environments, where shoreline behavior is often decoupled from broader-scale littoral drift dynamics (Buscombe, 2008; Diaz *et al*., 2017).

The Constanța coastal sector, located in the central part of the Romanian Black Sea coastline, is a highly modified and socio-economically significant littoral zone. It has been subject to extensive anthropogenic modification over recent decades, including the construction of groins, detached breakwaters, revetments, and artificial beach nourishment projects, most notably the large-scale nourishment initiative completed in 2015 (Cîndescu *et al*., 2024; Bădoiu *et al*., 2022; European Investment Bank, 2022; Juganaru, 2021). This intervention aimed to mitigate frequent erosion, enhance recreational bays, and improve coastal resilience against sea level rise and increased storm activity (Spînu *et al*., 2017). However, post-intervention monitoring has revealed spatial heterogeneity in morphological response, with some areas exhibiting sediment accumulation while others continue to experience profile lowering and erosion (Cîndescu *et al*., 2024). This suggests a complex and site-specific interaction between structural controls and morphodynamic processes that warrants detailed investigation (Cîndescu *et al*., 2024).

This study examines the development and site-specific relationship between structural and morphodynamic processes in an engineered coastal environment, a topic that advances detailed investigation. While cross-shore beach profile analysis is a basis of geomorphological research, this study contributes by quantifying the spatial variability of beach-dune morphology in the Constanța sector over a three-year post-nourishment monitoring period (2022–2024). The distinctive aspect of the Constanța case study lies in its extensive anthropogenic modification, including the large-scale beach nourishment initiative completed in 2015, which serves as a baseline for analyzing subsequent morphological changes. The research is particularly valuable in assessing the performance and resilience of such nourishment interventions under different hydrodynamic conditions by integrating annual GPS-based beach profile measurements with monthly sea surface height (SSH) data. This detailed, post-intervention monitoring approach helps to understand how shoreline behavior is often decoupled from broader-scale littoral drift dynamics in these modified environments.

In this context, the present study aims to quantify the spatial variability of beach-dune morphology in the Constanța sector over a three-year post-nourishment monitoring period (2022–2024). The 2015 beach profiles, corresponding to the immediate post-nourishment state, serve as the morphological baseline for comparative analysis. Annual GPS-based beach profile measurements are integrated with monthly sea surface height (SSH) data from the Copernicus Marine Environment

Monitoring Service (CMEMS) to evaluate the influence of sea level variability on sediment redistribution and shoreline evolution. By correlating SSH trends with observed cross-shore elevation changes, the study assesses the performance and resilience of the nourishment intervention under different hydrodynamic conditions, offering insights for adaptive coastal management in engineered environments.

MATERIALS AND METHODS

The Constanța coastal sector, situated in the central part of the Romanian Black Sea coast, extends from Năvodari to Eforie and features a mix of narrow sandy beaches, eroding loess cliffs, and urbanized shorelines (Badoiu *et al.*, 2022). The area is influenced by a microtidal regime and moderate wave energy, with sediment transport largely driven by northeastern winds. Coastal morphology is shaped by both natural processes and extensive human interventions, including groynes, breakwaters, and beach nourishment projects (King *et al.,* 2019). These factors contribute to high spatial variability in sediment distribution and beach profile characteristics, making the area a relevant case for assessing cross-shore morphodynamics in engineered coastal environments.

Annual morphological surveys were conducted in 2022, 2023, and 2024 at three beach profiles (CT1, CT2, and CT3), aiming to evaluate shoreline dynamics and morphological changes along the along the Constanța coastal sector, in the central part of the Romanian Black Sea coastline (Fig. 1). Changes in the transverse beach profile were monitored along fixed transects, delineated in the field using permanent benchmarks placed at the landward limit of the beach. Sediment erosion and accretion patterns were assessed by analysing shifts in the shoreline or waterline position at annual intervals. Measurements were conducted using high-precision GPS equipment, including GIS-grade (Leica Zeno 20) and geodetic-class (Leica VIVA NET) RTK systems, operating with real-time corrections from the ROMPOS network.

Fig. 1. Map of the Constanța coastal sector showing the location of the three beach profiles (CT1, CT2, CT3) and their permanent benchmarks, along with a regional map of the Black Sea

Given the annual frequency of GPS-based topographic surveys, it is essential to recognize that this approach primarily captures cumulative morphological changes over yearly cycles, rather than short-term, episodic events. While monthly sea surface height (SSH) data allows for the identification of transient hydrodynamic conditions, such as the sharp increase observed during the November–December 2023 Black Sea cyclone, the annual survey interval may not fully resolve the immediate and specific beach profile adjustments triggered by such short-lived, high-energy events. Capturing the rapid erosion or accretion associated with individual storm events would ideally necessitate more frequent, event-driven surveys. Despite this, the integration of annual profile data with monthly SSH trends still provides valuable insights into the broader patterns of sediment redistribution and shoreline evolution under varying sea level conditions over the observed period.

The graphical representation of beach profile data and associated morphometric analysis were carried out using the SANDS Asset Management System (Shoreline and Nearshore Data System), a specialized software suite for coastal asset monitoring and data visualization (Halcrow Group Ltd.). This platform supports the import of GPS-derived transect measurements, computing beach volume and profile metrics, and generating time-series plots to detect trends in sediment deposition and erosion across the 2015 baseline. Its SANDS Viewer and SANDS Free modules were used to examine profile evolution at transects CT1, CT2, and CT3 over the 2022–2024 monitoring period.

To contextualize changes in beach profiles relative to sea level variability, monthly mean sea surface height (SSH) values were retrieved from the Copernicus Marine Environment Monitoring Service (CMEMS) dataset (Jansen et al., 2022). The gridded product provides model-derived SSH estimates for the Black Sea at a spatial resolution of approximately 2.5 km. Dataset was downloaded in NetCDF format and processed using GIS software capable of handling multidimensional raster datasets. The grid cell nearest to the Constanța shoreline (44.114 N; 28.792 E) was extracted for the period from November 2022 to December 2024 (Fig. 2).

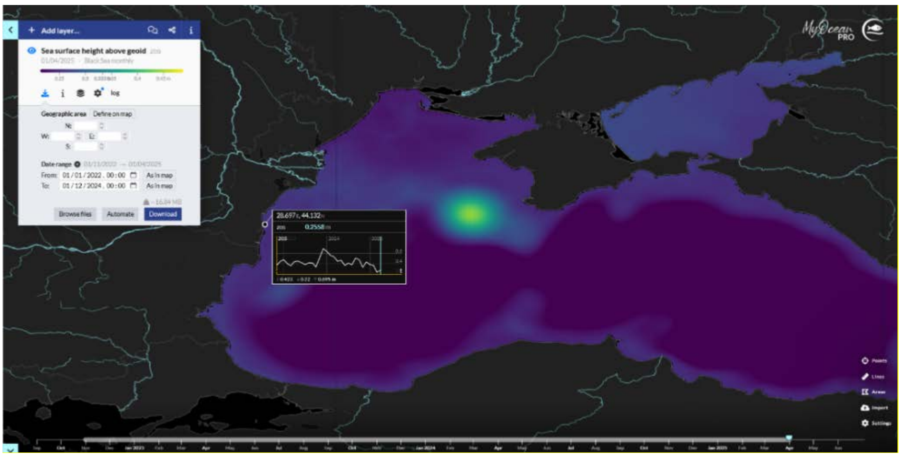

Fig. 2. Example of Sea surface height for the Black Sea from the Copernicus Marine Environment Monitoring Service (CMEMS) dataset. (Jensen *et al.*, 2022, accessed on 11.06.2025)

SSH values were converted from m to cm and used to construct a monthly time series, with annual averages calculated for comparison with GPS-derived beach profile data at three transects (CT1, CT2, CT3).

A classification framework developed through expert judgment and grounded in observed morphological responses for the analysed beach profiles between 2022-2024 was used to interpret SSH variability. Values near 40 cm were considered low to moderate, typically associated with accretion or stable conditions; values around 43 cm indicated moderate to high sea level, often linked to berm formation or minor erosion; and values at or above 46 cm corresponded to high sea levels, generally leading to erosion, scarping, or crest retreat, particularly when coinciding with storm events. This approach enabled consistent interpretation of SSH dynamics in relation to cross-shore morphological adjustments along the Constanța coastline.

To contextualize the short-term morphological variations (2022–2024) within broader hydroclimatic dynamics, we examined long-term sea surface height (SSH) anomalies spanning 1993–2024. Monthly SSH data were obtained from the Copernicus Marine Environment Monitoring Service (CMEMS) Black Sea Physics Reanalysis product, which provides consistent, quality-controlled estimates at ~2.5 km spatial resolution. The grid cell closest to the study area (44.15° N; 28.73° E) was selected to ensure spatial representativeness. Anomalies were computed relative to the 1993–2024 climatological mean to isolate deviations from long-term average sea level conditions. To reduce high-frequency noise and emphasize interannual variability, a 12-month moving average filter was applied. Subsequently, decadal means (1990s, 2000s, 2010s, 2020s) were calculated to identify systematic shifts in SSH anomalies over time. Linear regression analysis was used to quantify long-term trends in the anomaly time series, expressed in m per year, and assess whether these trends indicate progressive sea-level rise or decline.

The long-term SSH anomalies were not directly coupled with the annual beach profile data but served to provide contextual interpretation of the decadal scale forcing influencing sedimentary and morphological responses along the Constanța coastline.

RESULTS AND DISCUSSION

The longitudinal evolution of the CT1 profile from 2015 to 2024 illustrates significant horizontal and vertical variability, driven by both accretionary and erosional processes (Fig. 3).

The 2015 post-nourishment baseline extended to approximately 238 m and featured a relatively stable, gently sloping profile, suggesting successful artificial beach construction. By 2022, the profile had extended to ~271 m, indicating substantial sediment accretion and progradation. This increase was accompanied by slight elevation increases in the upper beach, consistent with dune buildup and berm development (Fig. 3).

In 2023, the profile slightly shortened to ~261 m, with minor crest retreat and mild foreshore adjustment, possibly due to seasonal wave forcing (Fig. 3). By 2024, the profile length decreased further to ~259 m, and the upper and mid-beach segments exhibited signs of vertical lowering, particularly beyond 220 m (Fig. 3). These changes suggest upper beach erosion and scarping likely driven by elevated sea levels or storm events. Overall, CT1 shows a pattern of initial progradation followed by progressive retreat, underscoring its exposure to hydrodynamic forcing and the importance of continuous monitoring to track shoreline stability.

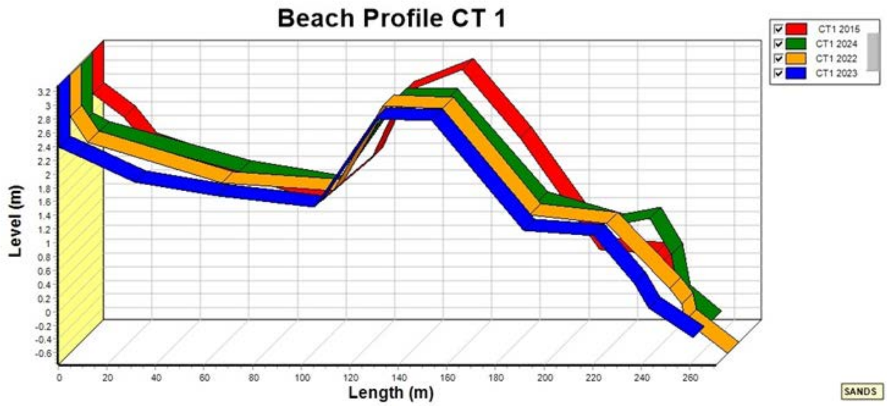

Fig. 3. Temporal evolution of the CT1 beach profile (Constanța sector) from 2015 to 2024

The CT2 profile exhibited notable changes in length and elevation between 2015 and 2024. Following the nourishment works, the 2015 baseline profile extended approximately 192 m, displaying a well-graded artificial beach (Fig.4). By 2022, the profile length had decreased substantially to ~138 m, indicating significant retreat (Fig.4). Despite the shortening, elevation changes were modest, and the overall shape of the profile suggested relative morphological stability in the upper and mid-beach zones.

In 2023, the profile extended slightly to ~147 m, yet signs of minor lowering in the backshore and mid-beach zones were evident, pointing to localized erosion (Fig.4). By 2024, the profile receded again to ~140 m, with backshore and lower foreshore elevations decreasing further (Fig.4). These changes reflect cumulative erosion over the study period, likely driven by hydrodynamic stress, reduced sediment input, and potential storm influences.

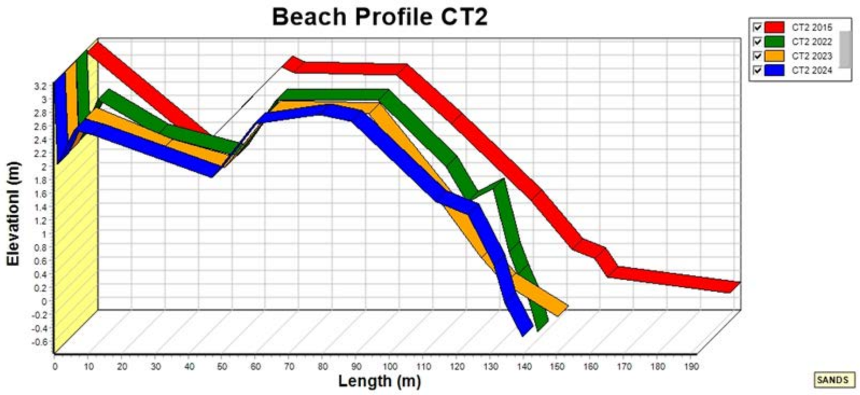

Fig.4. Temporal evolution of the CT2 beach profile (Constanța sector) from 2015 to 2024

The CT3 beach profile reveals a dynamic morphological evolution from 2015 to 2024. In 2015, immediately after nourishment, the profile extended to approximately 143 m and exhibited a smooth, gradually sloping shape, indicative of a well-constructed artificial beach (Fig. 5). By 2022, the profile length increased to ~156 m, accompanied by moderate vertical variability across the lower beach, suggesting low to moderate accretion along the foreshore and upper swash zone.

The 2023 profile showed a reduced extent (~141 m) and more pronounced elevation losses in the mid- and lower-beach zones, particularly beyond 100 m horizontal distance, indicating erosion and possible sediment export seaward (Fig. 5). In 2024, the profile extended slightly to ~142 m, with partial vertical recovery in the mid-beach (100–130 m), suggesting localized reaccumulation of sediment (Fig. 5). However, the terminal segment remained lower than in 2015, implying continued erosional stress. Overall, CT3 exhibited fluctuations in profile length and shape, characterized by alternating phases of accretion and erosion, which were likely modulated by seasonal hydrodynamic forcing and variable sediment availability.

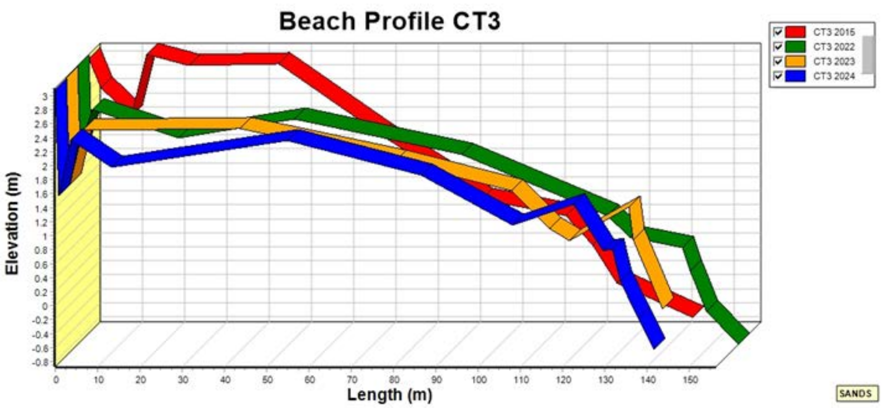

Fig. 5. Temporal evolution of the CT3 beach profile (Constanța sector) from 2015 to 2024

The monthly SSH data for the nearshore area adjacent to Constanța between November 2022 and December 2024 display evident seasonal and interannual variability. Values range from approximately 31.9 cm (November 2024) to 69.6 cm (December 2023), indicating a total fluctuation of nearly 38 cm during the observation period (Fig.6).

SSH tends to be lower during the late spring and early summer months (e.g., June 2023 and June 2024) and higher during autumn and winter, with peaks recorded in December of both 2023 and 2024 (Fig.6). These patterns are consistent with expected seasonal responses to thermal expansion, wind forcing, and hydrological contributions affecting the Black Sea. Notably, a sharp increase is observed during November–December 2023, with values exceeding 65 cm. This anomaly coincides with the occurrence of a major Black Sea cyclone (Dulov *et al.*, 2024), suggesting that extreme atmospheric events can have a significant impact on coastal hydrodynamics. Such disturbances may trigger short-term increases in water level, amplify wave energy, and enhance sediment mobilization. The temporal alignment between the cyclone and the observed SSH peak supports the interpretation that these events can induce rapid vertical changes in beach morphology, particularly in exposed and artificially modified sectors of the shoreline.

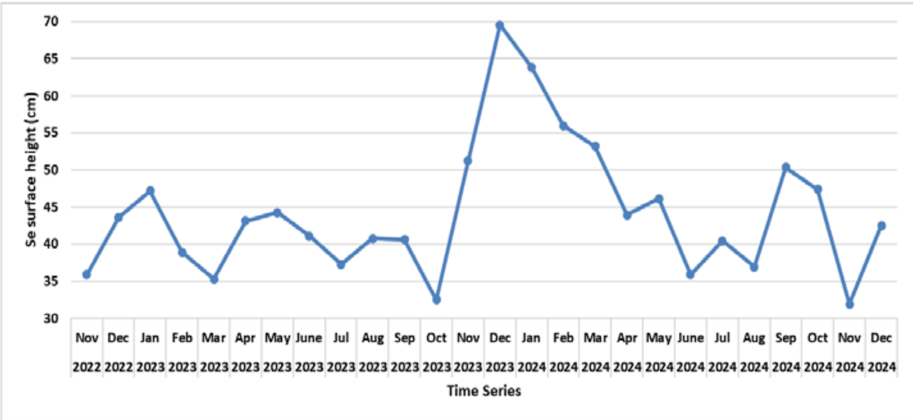

Fig. 6. Monthly sea surface height (SSH) values for the Constanța nearshore area (2022–2024)

Monthly sea surface height (SSH) values for the Constanța nearshore area (2022–2024), based on CMEMS data (Jansen et al., 2022 accessed on 11.06.2025). The blue line shows the monthly fluctuations of sea surface height in centimetres, indicating seasonal and interannual variability from November 2022 to December 2024, with significant peaks corresponding to extreme atmospheric events.

These temporal fluctuations in SSH are crucial for interpreting changes in beach profiles recorded during the same period. Elevated sea levels are typically associated with greater wave run-up and sediment redistribution, while lower SSH may favor beach accretion and structural exposure (Weisse *et al*., 2021; Murphy *et al*., 2023). The integration of SSH variability into coastal morphology assessments allows for a more robust understanding of sediment dynamics and the functioning of engineered shoreline sectors in Constanța.

Comparing with long-term analysis, the daily SSH exhibits considerable short-term fluctuations, ranging from approximately 0.1 m to over 0.8 m, revealing of high-frequency processes such as tides, wind-driven circulation, and atmospheric pressure variations (Fig. 7).

The monthly overlaid means SSH exposes a dominant seasonal cycle, characterized by higher values generally occurring during the summer months and lower values during the winter months. While the long-term trend appears??? relatively stable, the presence of inter-annual variability is evident through the fluctuating amplitude and baseline of the monthly means. Particularly, several extreme high SSH events are observed throughout the record, suggesting episodic influences on sea level.

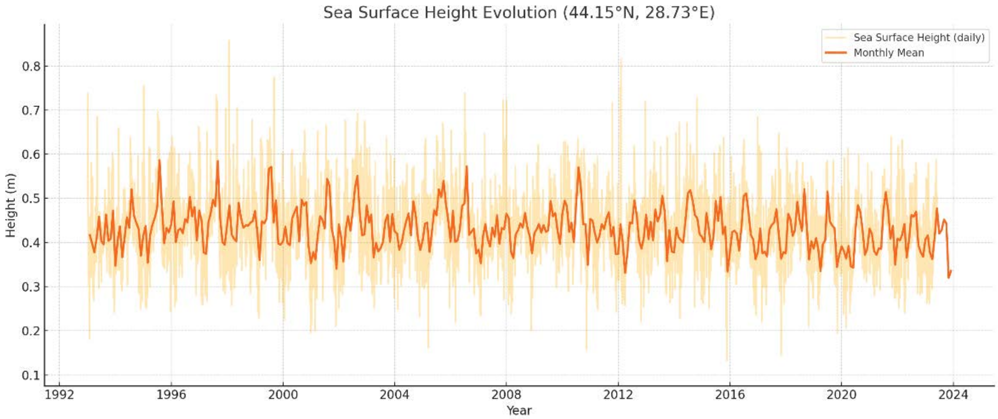

Fig. 7. The temporal variability of sea surface height (SSH) at a specific location, presenting both daily (light orange) and monthly mean (dark orange) data from approximately 1993 to late 2023 (CMEMS data Black Sea Physics Reanalysis)

The comparison between beach profile evolution and sea surface height (SSH) variability over the 2022–2024 period (Fig. 8, Table 1) reveals distinct patterns of sediment dynamics and shoreline response across the Constanța coastal transects (CT1, CT2, and CT3).

In 2022, all three profiles were influenced by relatively low hydrodynamic forcing, with an average SSH of approximately 40 cm. Under these calm conditions, CT1 exhibited clear signs of accretion and dune buildup, indicating favorable conditions for sediment deposition in the upper beach zone. CT2 remained stable, showing neither significant erosion nor accretion. CT3 displayed minor accretion, with modest elevation gains in the berm zone (Table 1).

Table 1. Summary of Beach Profile Morphological Changes and Corresponding Average Annual Sea Surface Height (SSH) Values for the Constanța Coastal Sector (2022-2024)

Year	Profile	Morphological Change	Average SSH (cm/year)	SSH Interpretation (Relative)
2022	CT1	Accretion, dune buildup	40	Low to moderate conditions, generally conducive to accretion or stability
	CT2	Stable		
	CT3	Low accretion		
2023	CT1	Crest retreat	43	Moderate to high, may lead to mild erosion or berm shaping
	CT2	Mild erosion		
	CT3	High berm formation		
2024	CT1	Scraping, loss in upper profile	46	High, likely associated with erosion, scarping, and upper profile retreat, especially when combined with storms
	CT2	Backshore retreat		
	CT3	Stable upper profile		

These patterns reflect a sea state conducive to sediment accumulation, with minimal disturbance from wave action or storm events.

By 2023, the average SSH had risen to approximately 43 cm, coinciding with morphological destabilization. CT1 experienced crest retreat, likely due to elevated wave run-up or occasional overwash events. CT2 showed mild erosion, particularly in the backshore area. CT3, in contrast, developed a prominent berm, indicating increased wave-driven sediment transport and redistribution (Table 1). This variability in profile response suggests spatial differences in wave exposure, sediment supply, or local beach morphology, even over relatively short distances.

In 2024, the average SSH reached ~46 cm, the highest in the three years, and was associated with more pronounced erosional impacts. CT1 underwent scraping, resulting in notable sediment loss in the upper profile, indicative of storm-induced retreat and repeated wave overtopping. CT2 recorded backshore retreat, further evidence of heightened erosion. In contrast, CT3 maintained a relatively stable upper profile, possibly protected by the berm formed in the previous year (Table 1).

The table provides a comparative overview of the morphological changes observed across the three beach profiles (CT1, CT2, and CT3)—including accretion, stability, erosion, berm formation, crest retreat, scraping, backshore retreat, and stable upper profile—in relation to the average annual sea surface height (SSH). The SSH is classified into interpretative ranges (low to moderate, moderate to high, high) for each study year (2022, 2023, 2024). This comparison highlights how fluctuations in sea level shape beach dynamics within the engineered coastal setting of Constanța.

The analysis of beach profile lengths supports the observed link between rising SSH and shoreline retreat. In 2022, when SSH was at its lowest (~40 cm), the profiles reached their maximum extent: CT1 measured 271.02 m, reflecting progradation trends, while CT2 and CT3 extended to 137.88 m and 156.32 m, respectively, indicating stable to mildly accretional conditions (Fig.7).

In 2023, as SSH increased (~43 cm), CT1 and CT3 showed profile contraction, shrinking to 261.42 m and 140.97 m respectively, corresponding with crest retreat and lower beach flattening. CT2, however, recorded a slight increase to 147.21 m, possibly due to local sediment deposition or temporary berm development during calmer periods. By 2024, with SSH reaching ~46 cm, further profile shortening was observed. CT1 decreased slightly to 259.12 m, CT2 contracted to 139.84 m, and CT3 showed a modest recovery to 141.63 m, though still below 2022 levels (Fig.7). These spatial and temporal shifts align with field evidence of scarping, backshore retreat, and profile steepening, particularly following the late 2023 cyclone event.

Beyond the observed annual correlations between beach profile dynamics and short-term SSH variability (Fig. 6, Fig. 7, Fig. 8, Table 1), an in-depth understanding of coastal morphological evolution requires an assessment of longer-term sea level trends and their fundamental drivers. The following analysis extends the temporal scope of our SSH investigation, drawing upon decadal datasets to contextualize the observed persistent changes in beach morphology within the patterns of Black Sea level variability. This provides a more comprehensive hydro-climatological background, showing seasonal cycles, inter-annual oscillations, and long-term trends in sea surface height anomalies that influence coastal processes over extended periods.

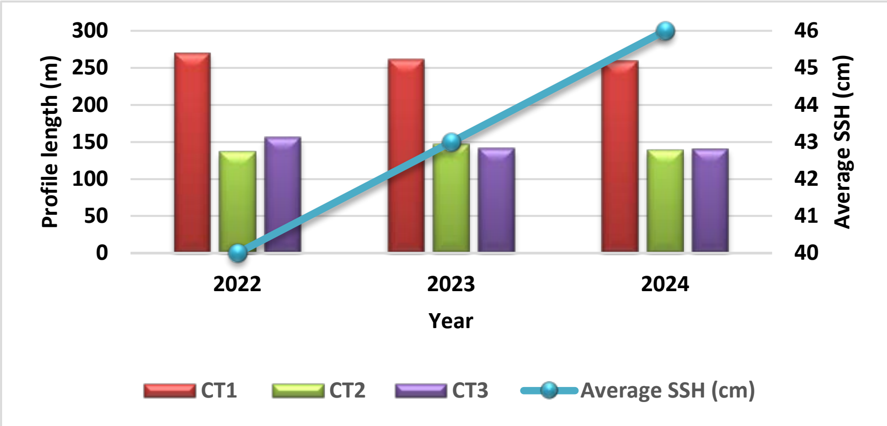

Fig. 8. Temporal evolution of beach profile lengths and average annual sea surface height (SSH) in the Constanța area (2022–2024).

Figure 9 shows a strong annual cycle, with SSH generally increasing from a minimum of approximately 0.398 m in March to a peak of 0.48 m, constant through July and August. Following this summer maximum, SSH exhibits a progressive decline through the autumn months, reaching a secondary minimum around 0.392 m in November, before showing a modest rise towards December. This seasonal pattern suggests the influence of various oceanographic and meteorological factors, such as thermal expansion, freshwater input, and prevailing wind patterns, which contribute to the observed intra-annual variability in sea level.

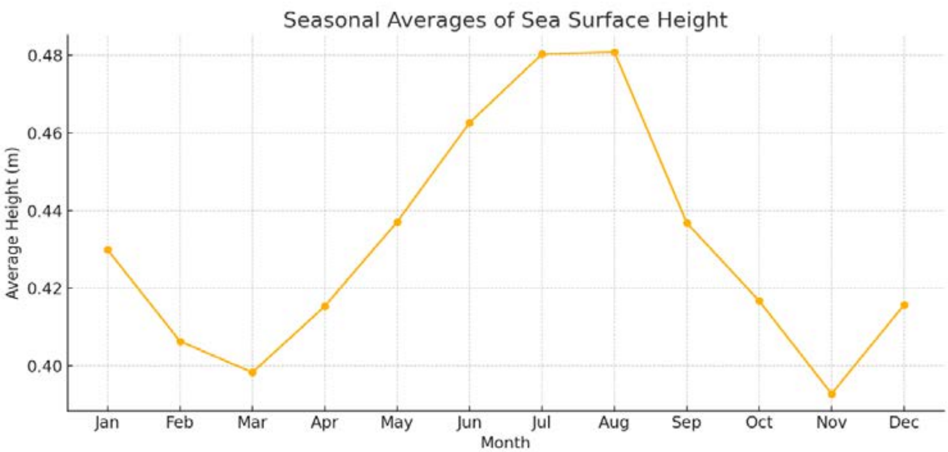

Fig. 9. Seasonal Averages of Sea Surface Height based on CMEMS data (Black Sea Physics Reanalysis, 2025)

Figure 10 highlights the dynamic nature of sea level, emphasizing that while short-term variations and multi-year cycles are present, there is an underlying negative long-term trend in anomalies. This integrated assessment highlights how short-term SSH anomalies, especially when coupled with energetic atmospheric conditions, can drive rapid and spatially variable morphological adjustments, even within engineered or nourished beach systems (Rocha *et al*., 2020).

Figure 10 presents the 12-month smoothed anomalies of sea surface height (SSH) in m over a period spanning from approximately 1994 to late 2023. The orange line illustrates the smoothed SSH anomalies, which display clear inter-annual and decadal variability, characterized by oscillations above and below the zero-anomaly line. Overlaid on these fluctuations, a dashed red line indicates the long-term linear trend, which is calculated to be -0.0010 m/year. This negative trend indicates a slight but persistent decrease in the overall sea surface height anomalies over the observed thirty-year period.

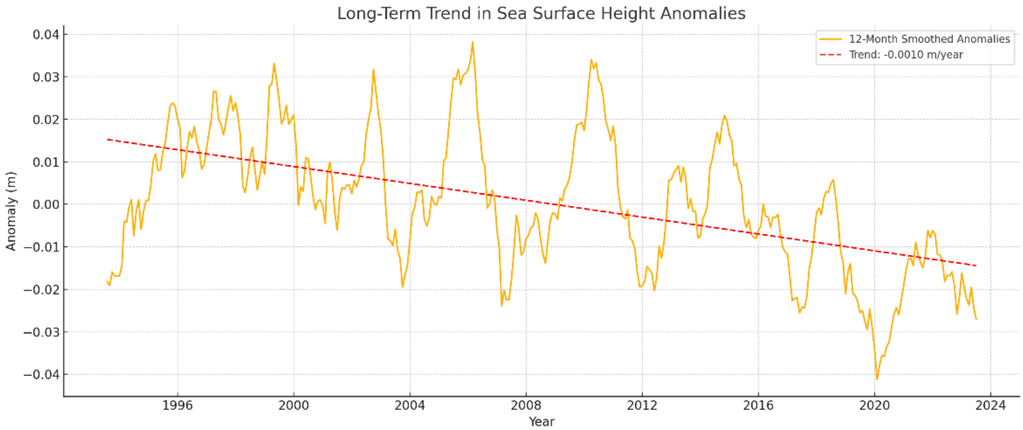

Fig. 10. Long-Term Trend in Sea Surface Height Anomalies

Monthly anomalies show considerable short-term fluctuations with scales ranging from approximately -0.100 m to over 0.100 m (light orange line), indicating significant month-to-month variability (Fig. 11).

Overlaid on this, the red line, describes the 12-month smoothed anomalies, which effectively filter out high-frequency noise and highlight longer-term oscillations and trends. This smoothed curve illustrates evident interannual variability, characterized by periods of positive anomalies (higher than average sea surface height, SSH) and negative anomalies (lower than average SSH). Significant positive peaks are observed around 1999-2000, 2005-2006, and 2009-2010, while significant negative anomalies are evident in the early 1990s, around 2017, and particularly pronounced towards the end of the information, from 2020 to 2023. The Fig. 11 highlights the complex interaction of factors influencing sea level variations at this location over several decades.

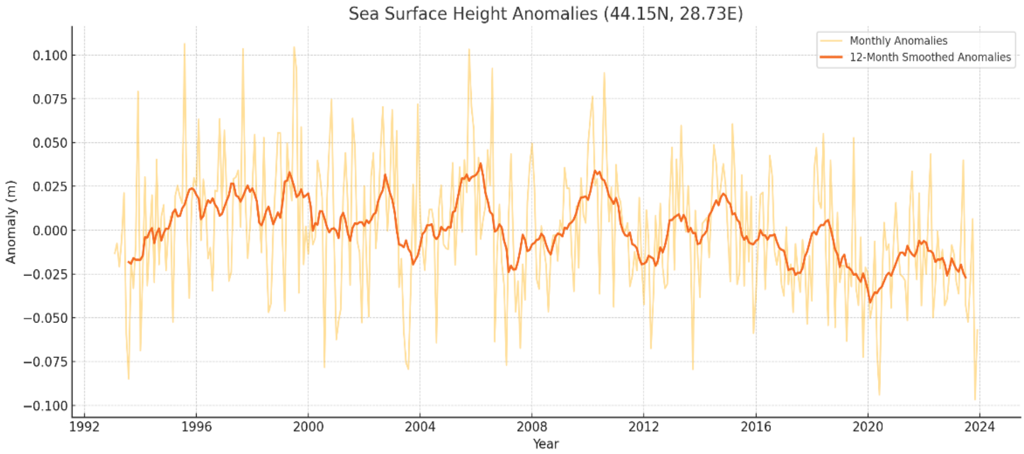

Fig. 11. Sea Surface Height Anomalies (44.15N, 28.73E) - variations in sea surface height relative to a long-term mean at a specific geographical location, based on Black Sea Physics Reanalysis CMEMS data (1993 – 2024)

A clear decreasing trend in decadal SSH anomalies is observed over the approximately three-decade period (Fig. 12). The decade centered around 1990 shows a positive average anomaly of nearly 0.010 m, indicating higher-than-average sea levels for that period. This shifts to a smaller positive anomaly for the 2000s. By the decade centered around 2010, the average anomaly becomes negative, falling to approximately -0.002 m, suggesting a slight drop below the long-term mean. The most recent decade, centered around 2020, exhibits the most significant negative average anomaly, plummeting to -0.022 m. This progressive decline in decadal average SSH anomalies suggests a long-term downward trend in sea level for the observed region, consistent with or contributing to the previously noted negative linear trend in annual anomalies.

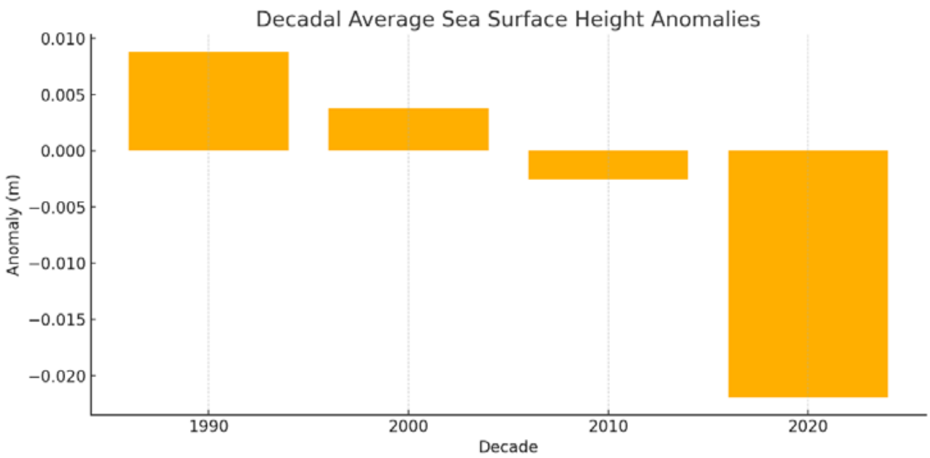

Fig. 12. Decadal Average Sea Surface Height Anomalies – represents the mean sea surface height (SSH) anomalies in m across different decades. The bars represent the average anomaly for each decade, centered around 1990, 2000, 2010, and 2020

From a policy perspective, this study highlights the importance of post-intervention monitoring as an essential component of coastal resilience strategies. Regular assessment of beach profile dynamics and SSH variability should be institutionalized within coastal management frameworks to support evidence-based decision-making. Moreover, the demonstrated utility of satellite-derived SSH data offers a scalable and cost-effective means to enhance early warning capabilities and prioritize intervention zones. Policymakers should therefore consider integrating Earth observation data into national coastal adaptation plans, particularly for regions like the Black Sea that face both natural and anthropogenic pressures (Todorova *et al*., 2019; Bakan& Büyükgüngör, 2000).

Furthermore, the observed effects of episodic events—such as the 2023 Black Sea cyclone—highlight the need for flexible coastal defense policies that accommodate both gradual and abrupt environmental changes. Static design thresholds based solely on historical averages may no longer be adequate in the context of increased climate variability. Adaptive management approaches, including trigger-based re-nourishment and the incorporation of nature-based solutions (e.g., dune stabilization, berm enhancement), should be explored as part of integrated coastal zone management strategies.

CONCLUSION

This study presents an integrated assessment of beach profile dynamics along the Constanța shoreline, linking in situ morphometric data from three beach transects (CT1, CT2, CT3) with satellite-derived sea surface height (SSH) values between 2022 and 2024. Through a combination of precise field surveys and expert-based classification of SSH variability, the research provides a detailed understanding of how nearshore sea level changes relate to sediment redistribution, berm formation, crest retreat, and overall morphological evolution within a highly engineered coastal environment.

Between 2022 and 2024, beach profiles along the Constanța coast exhibited distinct cross-shore morphological changes associated with rising sea surface heights. CT1 experienced progressive erosion, CT2 showed delayed but measurable retreat, while CT3 remained relatively stable due to the formation of a berm. Overall, profile shortening and upper beach loss highlight the influence of elevated water levels and storms, even in engineered environments. These results stress the need for integrated monitoring to inform adaptive coastal management.

The application of an SSH classification framework, developed from expert interpretation of morphodynamical responses, enabled the differentiation of low, moderate, and high sea level conditions and their respective impacts on beach morphology. For instance, lower SSH values (~40 cm) were generally associated with profile stability or accretion, while higher values (≥46 cm), particularly when coinciding with known storm events, corresponded with increased erosion, scarping, and loss of upper beach volume. This typology allowed for a standardized comparison of profile evolution under varying hydrodynamic regimes and provided an explanatory context for observed cross-shore changes.

Importantly, the study illustrates that even modest variations in SSH—when occurring within short timescales or during storm-prone periods—can induce substantial and spatially variable morphological responses, especially in artificially modified sectors. The integration of satellite-based SSH datasets with high-resolution beach monitoring thus offers a cost-effective, scalable, and scientifically grounded method for detecting and interpreting coastal change.

The findings highlight the importance of implementing multidimensional monitoring strategies that combine physical measurements, geomorphological insight, and remote sensing data. Such approaches are essential for developing adaptive coastal management strategies in regions exposed to climate-driven sea level variability and increasing human pressures.

Finally, this research points out the necessity for adaptive coastal management strategies that are dynamic and responsive to both short-term hydrodynamic variability and long-term sea level trends. The integrated approach demonstrated in this paper, combining high-resolution in-situ beach surveys with modelled SSH data, offers a structure for continuous monitoring and evidence-based decision-making in engineered coastal environments. The utility of this methodology can be further enhanced by incorporating detailed wave climate data, developing advanced sediment transport models to quantify volumetric changes and pathways, and implementing rapid, event-driven surveys to capture storm impacts. Such comprehensive, multi-faceted monitoring is essential for predicting future coastal evolution and ensuring the sustainable functionality and resilience of the Romanian Black Sea coastline in the face of escalating climate pressures.

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REFERENCES

Bădoiu, L., Șeuleanu, C., Caloianu, F., & Buzgaru, N. (2022). Monitoring Coastal Evolution in Constanta and Eforie North Areas. *Cercetări Marine-Recherches Marines*, 52: 17-17. https://doi.org/10.55268/CM.2022.52.17

Bakan, G., & Büyükgüngör, H. (2000). The Black Sea. *Marine Pollution Bulletin*, 41(1-6), 24-43. http://dx.doi.org/10.1016/S0025-326X(00)00100-4

Biondo, M., Buosi, C., Trogu, D., Mansfield, H., Vacchi, M., Ibba, A., Porta, M., Ruju, A., & De Muro, S. (2020). Natural vs. Anthropic Influence on the Multidecadal Shoreline Changes of Mediterranean Urban Beaches: Lessons from the Gulf of Cagliari (Sardinia). *Water*, *12*(12), 3578. https://doi.org/10.3390/w12123578

Black Sea Physics Reanalysis. E.U. Copernicus Marine Service Information (CMEMS). Marine Data Store (MDS). https://doi.org/10.48670/mds-00356 (accessed on 21.07.2025).

Boak, E. H., & Turner, I. L. (2005). Shoreline definition and detection: a review. Journal of coastal research, 21(4), https://doi.org/10.2112/03-0071.1

Buscombe, D. D. (2008). Morphodynamics, sedimentation and sediment dynamics of a gravel beach. Student thesis: PhD. https://dx.doi.org/10.24382/4821

Caldareri, F., Sulli, A., Parrino, N., Dardanelli, G., Todaro, S., & Maltese, A. (2024). On the shoreline monitoring via earth observation: An isoradiometric method. Remote Sensing of Environment, 311, 114286. https://doi.org/10.1016/j.rse.2024.114286.

Casarosa, N., Luppichini, M., Bini, M., Berton, A., Merlino, S., & Paterni, M. (2022). A method based on beach profile analysis for shoreline identification. In *Ninth International Symposium" Monitoring of Mediterranean Coastal Areas: Problems and Measurement Techniques".* Firenze University Press. https://doi.org/10.36253/979-12-215-0030-1.05

Cîndescu, A.-C., Petrișoaia, S., Marin, D., Buga, L., Sîrbu, G., & Spînu, A. (2024). The Variability of the Beach Morphology and the Evolution of the Shoreline in the Strongly Anthropized Sector of Eforie North, the Romanian Coast of the Black Sea. *Cercetări Marine - Recherches Marines*, 53: 6-18. https://doi.org/10.55268/CM.2023.53.6

Creane, S., Coughlan, M., O'Shea, M., & Murphy, J. (2022). Development and dynamics of sediment waves in a complex morphological and tidal dominant system: southern Irish Sea. *Geosciences*, 12(12), 431. https://doi.org/10.3390/geosciences12120431

Díez, J., Cánovas, V., Uriarte, A., & Medina, R. (2017). Characterization of the dry beach profile: A morphological approach. Journal of Coastal Research, 33(6), 1292- https://doi.org/10.2112/JCOASTRES-D-16-00179.1

Dulov, V. A., Yurovskaya, M. V., Fomin, V. V., Shokurov, M. V., Yurovsky, Y. Y., Barabanov, V. S., & Garmashov, A. V. (2024). Extreme Black Sea Storm in November 2023. *Physical oceanography*, 31(2), 295-316.

European Investment Bank. Fighting coastal erosion in Romania. https://www.eib.org/en/stories/coastal-erosion-romania (Accessed: 10 June 2025).

Halcrow Group Ltd. SANDS (Shoreline and Nearshore Data System). https://www.sandsuser.com.

Islam, M. K., Jahan, I., & Azad, A. (2025). Spatial Assessment of Coastal Erosion Vulnerability: Natural and Anthropogenic Factors in Chattogram, Bangladesh. Natural Hazards Research. https://doi.org/10.1016/j.nhres.2025.05.001

Ismail N.P., Erüz C. (2023), Coastal habitat changes in the Southeast Black Sea, Turkiye, pp. 124-134. In Gâștescu, P., Bretcan, P. (edit., 2023), Water resources and wetlands, *6th International Hybrid Conference Water resources and wetlands*, 13-17 September 2023, Tulcea (Romania), pp.287.

Jansen, E., Martins, D., Stefanizzi, L., Ciliberti, S. A., Gunduz, M., Ilicak, M., Lecci, R., Cretí, S., Causio, S., Aydoğdu, A., Lima, L., Palermo, F., Peneva, E. L., Coppini, G., Masina, S., Pinardi, N., Palazov, A., and Valchev, N. (2022). Black Sea Physical Analysis and Forecast (Copernicus Marine Service BS-Currents, EAS5 system) (Version 1) [Data set]. Copernicus Monitoring Environment Marine Service (CMEMS).

https://doi.org/10.25423/CMCC/BLKSEA_ANALYSISFORECAST_PHY_007_001_EAS5 (accessed on 11.06.2025).

Juganaru, I. D. (2021). The Beach Extension Project in Mamaia Resort, on the Romanian Black Sea Coast: Certain Benefits, but also Numerous Tourist Complaints. *Ovidius University Annals, Series Economic Sciences*, 21(1).

Karsli, F., Guneroglu, A., & Dihkan, M. (2011). Spatio-temporal shoreline changes along the southern Black Sea coastal zone. *Journal of Applied Remote Sensing*, 5(1), 053545, http://dx.doi.org/10.1117/1.3624520.

King, E. V., Conley, D. C., Masselink, G., Leonardi, N., McCarroll, R. J., & Scott, T. (2019). The impact of waves and tides on residual sand transport on a sediment ‐ poor, energetic, and macrotidal continental shelf. *Journal of Geophysical Research*: Oceans, 124(7), 4974-5002. https://doi.org/10.1029/2018JC014861

Lakku, N. K. G., Chowdhury, P., & Behera, M. R. (2024). An improved hybrid model for shoreline change. *Frontiers in Marine Science*, 11, 1459619. https://doi.org/10.3389/fmars.2024.1459619

Murphy, J., Plater, A., Bird, C., & Arribas-Bel, D. (2023). Spatial-temporal variability: characterization of a beach system using high resolution radar data. *Frontiers in Marine Science*, 10, 1142077. https://doi.org/10.3389/fmars.2023.1142077

Rocha, C., Antunes, C., & Catita, C. (2020). Coastal vulnerability assessment due to sea level rise: The case study of the Atlantic coast of mainland Portugal. *Water*, *12*(2), 360. https://doi.org/10.3390/w12020360

Spînu, A., Diaconeasa, D., Petrișoaia, S., Buga, L., Mihailov, E., Timofte, F., & Sîrbu, G. (2017). Long-and short-term evolution of tourist beaches of the Romanian littoral. Mamaia Bay case study. *J Environ Prot Ecol*, 18(2), 590-596.

Stojanovic, M., Gonçalves, A., Sorí, R., Vázquez, M., Ramos, A. M., Nieto, R., Gimeno, L., & Liberato, M. L. R. (2021). Consecutive Extratropical Cyclones Daniel, Elsa and Fabien, and Their Impact on the Hydrological Cycle of Mainland Portugal. *Water*, *13*(11), 1476. https://doi.org/10.3390/w13111476

Suanez, S., Yates, M. L., Floc'h, F., & Accensi, M. (2023). Using 17 years of beach/dune profile monitoring to characterize morphological dynamics related to significant extreme water level events in North Brittany (France). *Geomorphology*, 433, 108709. https://doi.org/10.1016/j.geomorph.2023.108709

Todd, P. A., Heery, E. C., Loke, L. H., Thurstan, R. H., Kotze, D. J., & Swan, C. (2019). Towards an urban marine ecology: characterizing the drivers, patterns and processes of marine ecosystems in coastal cities. *Oikos*, 128(9), https://doi.org/10.1111/oik.05946

Todorova, N., Alyomov, S. V., Chiotoroiu, B. C., Fach, B., Osadchaya, T. S., Rangelov, M., Vasilev, V. (2019). Black Sea. In World Seas: An environmental evaluation (second edition). *Academic Press,* pp. 209-226. http://dx.doi.org/10.1016/B978-0-12-805068-2.00011-5

Weisse, R., Dailidiene, I., Hünicke, B., Kahma, K., Madsen, K., Omstedt, A., Zorita, E. (2021). Sea level dynamics and coastal erosion in the Baltic Sea region*. Earth System Dynamics Discussions*, 2021, 1-40. https://doi.org/10.5194/esd-12-871-2021

Woodroffe, C. D., Evelpidou, N., Delgado-Fernandez, I., Green, D. R., Karkani, A., & Ciavola, P. (2023). Coastal Systems: The Dynamic Interface Between Land and Sea. In Research Directions, *Challenges and Achievements of Modern Geography*, pp. 207-229. Singapore: Springer Nature Singapore. https://doi.org/10.1007/978-981-99-6604-2_11

Woodworth, P. L., Melet, A., Marcos, M., Ray, R. D., Wöppelmann, G., Sasaki, Y. N., & Merrifield, M. A. (2019). Forcing factors affecting sea level changes at the coast. *Surveys in Geophysics*, 40(6), 1351-1397. https://doi.org/10.1007/s10712-019-09531-1

Xie, D., Hughes, Z., FitzGerald, D., Tas, S., Asik, T. Z., & Fagherazzi, S. (2024). Impacts of climate change on coastal hydrodynamics around a headland and potential headland sediment bypassing. *Geophysical Research Letters*, 51(4), https://doi.org/e2023GL105323.10.1029/2023GL105323