DOI: 10.55268/CM.2025.55.116

REVISED BRUUN RULE: A CRITICAL ANALYSIS OF THE IMPACT OF SEA LEVEL RISE ON SANDY BEACHES

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ABSTRACT

The Bruun Rule (1962) offers a simplified model for predicting shoreline retreat due to sea-level rise, assuming cross-shore sediment redistribution within an equilibrium beach profile. Despite its widespread use in sandy coastal systems, it overlooks key processes such as longshore transport, dune dynamics, and sediment supply variability. This paper reviews the theoretical foundation, mathematical formulation, and practical applications of the rule, featuring comparative case studies from different geographic regions, with a specific focus on its application to the Romanian Black Sea coast. Results highlight significant discrepancies between model predictions and observed shoreline behavior, especially in morphodynamically complex. Alternative models, including the Dean Rule, Davidson-Arnott's conceptual framework, and advanced numerical simulations, demonstrate improved predictive capabilities by incorporating multi-dimensional sediment transport and local conditions. The case of Musura Island in the Danube Delta further illustrates the limitations of the Bruun Rule in dynamic, sediment-rich contexts. Although the Bruun Rule remains relevant as a fundamental estimation tool, effective coastal management, in the context of climate variations, increasingly relies on hybrid, data-driven approaches that integrate empirical observations with process-based modeling

Keywords: Bruun Rule, shoreline retreat, sea-level, coastal erosion, sediment transport

INTRODUCTION

The study of coastal erosion processes and shoreline dynamics is a key area of the geological sciences and physical geography, with direct applications in the planning and management of coastal zones. The Bruun Rule, formulated in 1962, is one of the fundamental theoretical rules developed to explain the behaviour of beaches in relation to sea level variations, and it stands out for its simplicity and wide applicability. It describes how the shoreline retreats and sediments are redistributed to create an equilibrium profile that maintains a constant water depth in the nearshore zone.

The Bruun Rule has been a widely used tool for analysing the evolution of sandy beaches and for coastal engineering projects. However, as more empirical data have been gathered and observations of the coastal environment have grown in complexity, numerous criticisms and improvements to the original rule have been proposed. Today, this approach is complemented by conceptual and numerical rules that take into account a greater number of variables and can be adapted to various regional contexts.

This article aims to review the foundations of the Bruun Rule, analyze its applications in case studies from different geographic regions, and present theoretical and instrumental alternatives that have been developed to address its limitations.

The objective of this analysis is to provide a critical evaluation of the Bruun Rule, encompassing its fundamental concepts, practical applications, and the limitations that have prompted the emergence of contemporary alternatives. Finally, current research directions will be discussed, including emerging numerical rules and their implications for the sustainable management of coastal areas.

A qualitative synthesis approach was used to better understand how the Bruun Rule—an influential coastal erosion model—has been developed, debated and applied in different parts of the world. This approach followed a structured process that unfolded in three main stages.

MATERIALS AND METHODS

The first step was to select and analyse a broad range of scientific literature in order to trace the conceptual evolution of the Bruun Rule. The focus was on identifying key theoretical ideas, as well as refinements to the rule's mathematical formulation and the various criticisms it has faced. Alongside this, case studies from different coastal settings were examined to determine how the rule is used in practice, and whether it remains effective in diverse environmental conditions. Materials were carefully selected for academic relevance and geographic diversity using platforms such as Google Scholar, ResearchGate, and Academia.edu.

To complement the theoretical research, a remote sensing campaign using LIDAR technology was carried out in 2010 across the Danube Delta. The aim was to evaluate flood vulnerability and monitor vertical changes along the shoreline. In the case of Musura barrier island, a cross-profile was derived from the Digital Terrain Model (DTM) — with data kindly provided by Danube Delta National Institute for Research and Development (DDNI) — offering valuable insights into elevation and slope, essential for analysing shoreline dynamics and refining model estimates.

In the second phase, the collected literature was organised into five key themes: (1) the theoretical and mathematical foundations of the rule, (2) comparisons with other coastal models, (3) real-world applications and field-based evaluations.

The third and final stage of the study narrowed the focus to Musura Island in the Danube Delta, with an in-depth case study. A mixed-methods approach was adopted here, drawing on field data gathered between 2008 and 2018. Variables such as shoreline width, sea-level rise and sediment characteristics were processed using GRADISTAT software. The Bruun Rule was then applied using theoretical assumptions and measured parameters to estimate shoreline retreat. These estimates were compared with the actual morphological changes observed in the field. ArcMap was also used to map the four key reference points (M1 to M4) identified on Musura Island, complementing the analysis and improving spatial understanding.

Developed by Per Bruun in 1962, the Bruun Rule is a key theory with significant applications in shoreline management and the assessment of the impact of climate change (Everts, 1985). The rule describes how rising sea levels cause changes to the shoreline, particularly the retreat and erosion of beaches. According to the rule, the shoreline moves inland by a proportional distance for every centimetre of sea level rise, which can be calculated based on the beach slope and sediment characteristics (Bruun, 1962). Therefore, the Bruun Rule is essential for understanding coastal erosion processes and predicting shoreline changes. Examples from the scientific literature are included, as well as a case study applied to Island Musura, in order to compare theoretical predictions with the observed shoreline evolution. The aim of the discussions is to highlight the accuracy of the model, the conditions under which it can be validated, and its implications for coastal management strategies.

Basic assumptions and mathematical background of the Bruun Rule:

Bruun's rule provides a simplified but significant conceptual approach about how beaches respond to sea level rise through a mechanism of sediment transport and equilibrium between the emergent and submerged zones, based on five principals:

(1) **Beach equilibrium profile**. Beaches are considered systems in a stable morphological equilibrium, determined by wave action and sedimentary characteristics. This profile can be translated to land in the event of sea level rise, through erosion and sediment redistribution in the upper zone of the beach.(Bruun, 1962).

(2) **Erosion and Sediment Redistribution**. As **sea levels rise**, material from the upper part of the beach is **eroded** and transported to the submerged area (nearshore). This redistribution compensates for sediment losses, maintaining an overall morphological balance (Schwartz, 1967)

(3) **Sediment deposition on the seabed**. Eroded sediments are deposited near the shore, in an area bounded by the **depth of the equilibrium profile**. This process is essential for maintaining a constant depth in the coastal zone, despite variations in sea level. (Schwartz, 1967).

(4) **Shoreline translation**. Sea level rise causes a **retreat of the shoreline** towards land, as the entire beach profile is displaced. The phenomenon is caused by erosion and redeposition and plays an essential role in coastal dynamics in the context of climate change (Bruun, 1962).

(5) **Periodic profile adjustment.** Balanced beaches can undergo periodic adjustments due to external factors, such as wave patterns or seasonal variations in sea level. These adjustments are vital for ensuring long-term stability (Dean & Dalrymple, 2004).

According to the principle of mass (sediment) conservation, what is eroded from the upper part of the beach (including dunes/berms) is redistributed to the submerged area to maintain the equilibrium profile:

$$R = \frac{L * S}{(B + h)} \quad (1)$$

Where *R* represents shoreline retreat (horizontal movement towards land), *S* is sea level rise, *h* is the maximum depth to which waves can transport and redistribute sediments, *L* is the horizontal distance from the shoreline to the maximum depth of wave action *h*, *B* represents height of berms or dunes that can be eroded (Fig.1). Even a small increase in the sea level can result in significant shoreline retreat.

Although the rule is easy to use and understand, its long-term applicability is becoming increasingly important in the context of rise in sea levels. (Ranasinghe & Stive, 2009).

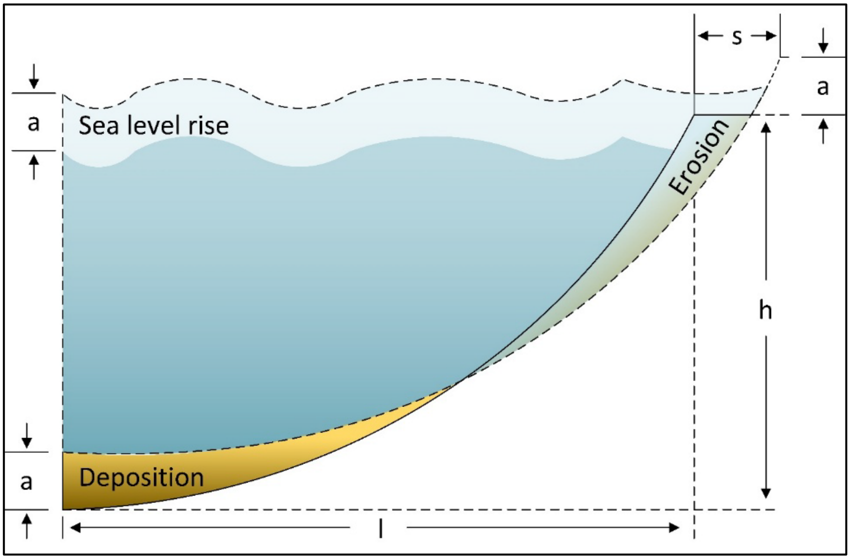

Fig.1. Graphical representation of sediment mass conservation according to Bruun's rule (1962), illustrating shoreline equilibrium in response to sea level rise.
(adapted from Healy,1996).

Weggel (1979) modified Bruun's rule by proposing a conceptual model designed to improve the accuracy of predictions regarding shoreline retreat in the context of sea level rise. The Weggel modification incorporates more topographical complexity by taking into account nearshore bars, which are commonly found in real-life beach profiles. It incorporates specific angles (α, β) that accurately describe the geometry of the shoreline and model sediment redistribution in both directions. This provides a more realistic estimate of morphological equilibrium recovery following a sea level rise event. The formula developed by Weggel takes the height of the shoreline dunes into account, making it a more realistic model than Bruun's rule.

$$S = a * l/(h + D) \quad (2)$$

Where *l* is the length of the seabed area up to a certain depth and D is the dune height.

Although the rules can produce significantly different results, Weggel's rule is based on stronger logic than Bruun's rule (Fig. 2).

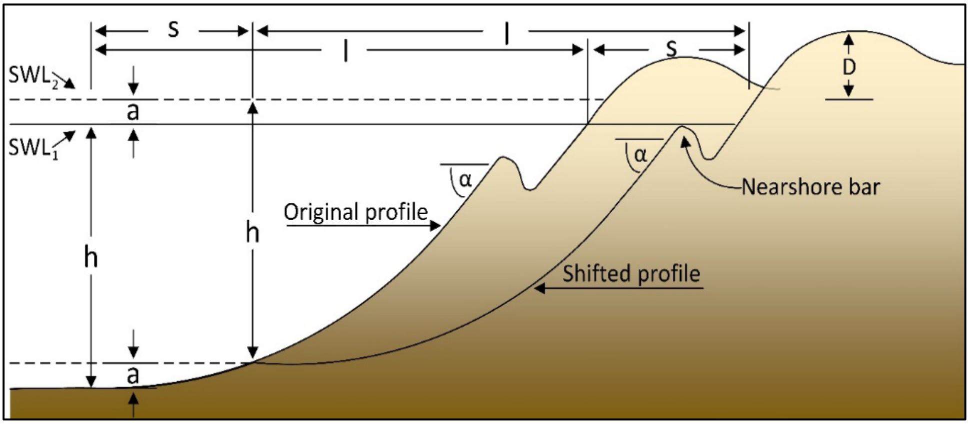

Fig. 2. Modified Bruun rule (after Weggel, adapted from Healy, 1996), illustrating key parameters: SWL_1/SWL_2 – sea levels before/after rise; *a* – sea level rise; *h* – active depth; *D* – depth of closure; *s* – shoreline retreat; *l* – transport length; *α* – slope of bar zone; nearshore bar and profile shifts are also shown.

Several alternative models to Bruun's rule have been proposed in studies dedicated to coastal erosion and shoreline evolution, with the aim of providing a more detailed and realistic understanding of the processes involved.

Dean's rule for beach equilibrium profile

Robert G. Dean introduces the concept of the beach equilibrium profile, which reflects the balance between wave energy and sediment distribution along the coast.

Unlike the classic Bruun model, which only analyses sediment transport perpendicular to the shore, Dean's rule also considers longshore transport (Dean, 1977; Dean, 2004). This extension enables a more accurate evaluation of shoreline changes, particularly in coastal regions where longshore currents play a dominant role. (Dean, 1977; Cooper & Pilkey, 2004). Mathematical formulation of the beach equilibrium profile according to Dean's rule describes how the depth gradually increases from shore towards the open sea in a typical equilibrium beach profile. The exponent 2/3 is derived from the equilibrium between the forces exerted by the waves and the resistance offered by the sediments.

$$h(y) = A * y^{2/3} \tag{3}$$

Where - h(y) is the water depth at a distance y from the shoreline (m), y is the horizontal distance from the shore to the open sea (m), A is an empirical scaling parameter that depends on the sediments size and wave energy ($m^{1/3}$).

This formula can be used to recreate beach profiles in numerical models, which can then be applied to coastal evolution models and simulations of the response to rising sea levels.

Davidson-Arnott and modern numerical rules

In recent decades, numerical models have been developed that enable the detailed simulation of erosion and sedimentation processes in coastal areas. Integrating topographical data, hydrodynamic conditions (e.g. waves and currents) and sediment characteristics, these models can provide short- and long-term predictions of shoreline changes.

Robin Davidson-Arnott developed a conceptual model describing the behaviour of sandy shores in the context of rising sea levels. According to the model, shoreline erosion and dune migration occur simultaneously: the beach retreats inland and the dunes move upwards and forwards. This maintains a balance between erosion and accumulation. The model emphasises the significance of the interaction between the beach and dune systems, and the impact of climatic factors and local conditions on the geomorphological evolution of the coast (Davidson-Arnott, 2005).

One such model is NEWTS1.0 (Numerical Erosion of Waves and Transgressive Scarps), which can simulate both uniform and wave-induced erosion, as well as the evolution of rocky shores in closed basins. This allows the impact of multiple erosion processes on coastal morphology to be assessed (Palermo, 2024).

RESULTS AND DISCUSSION

Evaluation of the Bruun Rule's Impact through a series of Case Studies

A relevant example is the study conducted by the National Institute for Marine Research and Development 'Grigore Antipa' in the Eforie Nord area of the Romanian Black Sea coast. The study investigated the morphological variability of the beach and the evolution of the shoreline in an area characterised by high cliffs and narrow beaches where human impact is significant. Several stages of coastal protection measures were implemented in this region, including the construction of transverse and longitudinal dikes, as well as beach nourishment. Periodic shoreline monitoring revealed both seasonal changes (rapid erosion in the cold season and beach reconstruction in the warm season) and progressive long-term changes. The in-situ data were integrated into a GIS management system, enabling comparative analyses at different time intervals. The study highlights the importance of continuous monitoring and applying protection measures adapted to local conditions for the effective management of coastal erosion (Cîndescu, 2024).

Bruun's rule was applied to estimate the retreat of the shorelines in response to projected sea-level rises in the Damietta and Rosetta areas of the Nile Delta. An annual shoreline retreat of 2.5 m per year for Damietta and 2.7 m per year for Rosetta was calculated, corresponding to sea-level rises of 37.93 cm and 44.17 cm, respectively, by the year 2100. However, these values account for only 9.6% (Damietta) and 4.3% (Rosetta) of the total previously observed shoreline retreat in the field (28 m/year in Damietta and 58 m/year in Rosetta). Therefore, the main causes of shoreline retreat are sediment supply deficiency and prevailing coastal processes, rather than sea-level rise alone. The study was based on data collected twice a year between 2006 and 2010, during which numerous coastal protection structures were implemented in the area (Elshinnawy & Almaliki, 2021).

Danube Delta – Testing the Bruun Model on Musura Island

This case study evaluates the applicability of the Bruun Rule in the highly dynamic environment of the Danube Delta, with a focus on Musura Island. While the Bruun Rule assumes a stable, equilibrium-based sediment profile, Musura Island is part of a deltaic system that is characterised by ongoing evolution and variability. Between 2005 and 2008, the island experienced rapid erosion and landward migration, resulting in the loss of some monitoring benchmarks. From 2008 to 2018, Musura Island experienced significant growth, with its surface area expanding and sediment masses shifting predominantly northward and eastward. This indicates sediment deposition and morphological changes.

Active profile widths were determined via surveys conducted in 2008 and 2018 during expeditions carried out by the Department of Physical Oceanography and Coastal Engineering of the National Institute for Marine Research and Development 'Grigore Antipa' along four cross-sections (M1–M4) spanning Musura Island.

Samples collected were taken from multiple points around the island, from the lagoon edge to depths of 10 metres underwater, at locations including: Hg-0.5m (lagoon edge at -0.5 m), F.A./L. (water's edge facing the lagoon), C ½ (midsection of the coastal barrier), V.L. (vegetation line/base of dune facing the sea), M.B. (mid-beach), F.A./M. (water's edge facing the sea), and depths: H-1, H-3, H-5, H-7, and H-10 m (Tabel 1).

The mean particle diameter (Dm) ranged from 0.13 to 0.14 mm for the surface samples (lagoon and coastal barrier at a depth of 1 m), indicating fine sand with very good sorting (So = FB), symmetric skewness (Sk = S) and mesokurtic kurtosis (Kg = M). These sediments are predominantly (>95%) composed of fine (NF) and very fine sand (NFF), with fine sand accounting for around 62% of the total. The only notable exception is the water's edge facing the sea, where fine and very fine sand are almost equally balanced (49% each).

In order to evaluate how well the Bruun Rule applies to a real-world setting such as Musura Island, it is essential to understand how sediments are composed and how they move. This model is based on the premise that the coastal sediment profile remains relatively stable over time. In Musura's deltaic environment, sediments are constantly brought in, shifted around and deposited by the Danube River and the sea.

These ongoing changes shape the island's coastline in unpredictable ways, through erosion or accretion, and often stray far from the simplified conditions on which the Bruun Rule is based. Therefore, examining sediment features such as grain size, sorting and variation across the area is crucial to determining whether the model can be applied to such a complex and ever-changing landscape.

Table 1. The granulometric parameters of the sediments

Sample	Dm	So	Sk	Kg	NFG	NG	NM	NF	NFF
Hg-0.5m	0.14	FB	S	M	0	0.1	1.2	67.4	31.2
F.A./L.	0.13	FB	S	M	0	1.1	0.6	55.8	42.8
C 1/2	0.14	FB	S	M	0	0.1	0.9	70.9	27.9
V.L.	0.14	FB	S	M	0	0.1	1.7	63.1	37.3
M.B.	0.13	FB	S	M	0.2	0.3	1.4	60.6	37.3
F.A./M.	0.13	FB	S	M	0	0.1	0.7	56.6	42.1
H-1m	0.13	FB	S	M	0.1	0.4	0.9	48.6	49.5
H-3m	0.11	B	S	M	0.2	0.1	0.8	26.2	70.5
H-5m	0.091	RB	AP	L	0.1	0.2	1.2	11.6	73.2
H-7m	0.083	B	S	L	0	0	1.1	7.4	75
H-10m	mud								
Average	0.12					0.3	1.1	48.8	48.4

Over the decade from 2008 to 2018, sea level measurements were taken from the mechanical tide gauge at Constanta port. This instrument continuously records sea levels, providing a dependable and consistent dataset for the area. Between 2008 (17.4 cm) and 2018 (30.76 cm), the average annual sea level measured in the Port of Constanța recorded significant fluctuations, with no clear upward trend. Although the trend line indicates a slight increase (approx. +1.5 cm/decade), this is not statistically significant (Fig. 3).

However, variations in the sea level play an essential role in shaping the coastline. It is important to note that the data were primarily used to test the applicability of the Bruun rule to the Romanian coastline. While the maregraph provides useful information, the main objective was to verify the model's applicability at the local level rather than conducting a detailed study of sea levels.

The observed trend aligns with Bruun's theoretical framework, which explains how sea level rise leads to shoreline retreat. According to this theory, as the sea level rises, the upper beach areas are eroded, and the resulting sediment is transported offshore and deposited in deeper zones. This process modifies the coastal morphology by offsetting the erosion of the upper beach through offshore sediment accumulation, resulting in the gradual retreat of the shoreline.

To assess flood vulnerability and monitor vertical coastal changes, LIDAR technology was used to study all low-lying areas of the Danube Delta, including the Musura barrier island, in a long-term session in 2010 (Fig.4).

Measurements revealed the formation of a sand belt at an elevation of almost 1 m above sea level, which is influenced by Danube River discharge in this area. Successive LIDAR measurements and annual shoreline mapping sessions were conducted to monitor the barrier's dynamics under the dual influence of the river and sea waves, particularly during storm surges, which induce landward translation.

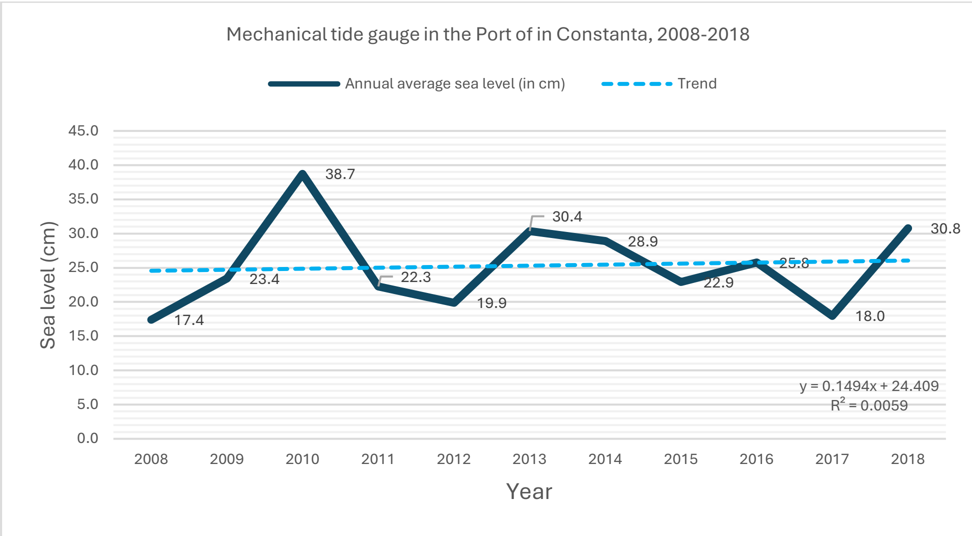

Fig. 3. Annual average sea level (cm)

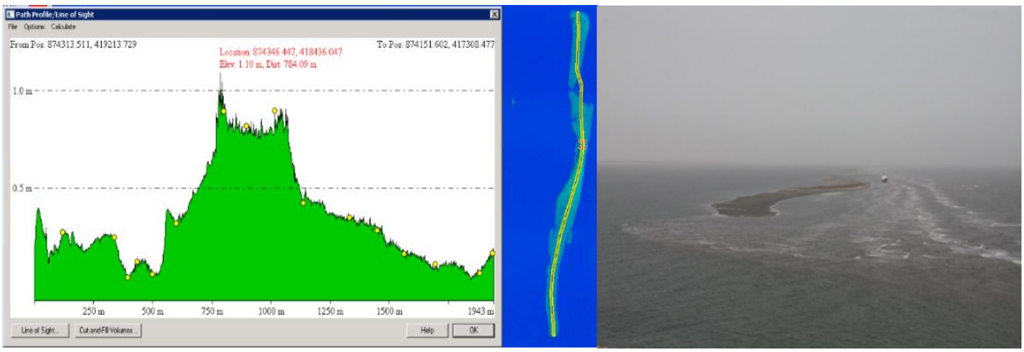

Fig. 4. Cross profile on the DTM of the Musura barrier island
(2010 - data obtained through DDNI courtesy)

In a decadal evaluation, the island reached its maximum size, controlled by the discharge from Musura Bay near the northern jetty of the channel. Its gradual translation averaged approximately 2.8 m per year, based on comparative measurements across four monitored sections (M1–M4).

Some sections narrowed, such as M2 (from 89 m to 50 m) and M4 (from 139 m to 97 m), while others, especially M3, grew significantly (from 102 m to 144 m). On average, the island's width increased from 101.25 m in 2008 to 129.25 m in 2018, a total gain of 28 m over 10 years, indicating sediment accumulation and shoreline migration.

The island is expanding, particularly in the M1 and M3 areas (Table 2 and Figure 5), indicating an increase in sediment and a shifting shoreline.

Table 2. Width of Musura Island – 2008 vs. 2018

Section	Width 2008 (m)	Width 2018 (m)	Difference (m)
M1	75	78	+3
M2	89	50	-39
M3	102	144	+42
M4	139	97	-42
Average	101.25	129.25	+28

This growth corresponds with the average annual sea-level data collected during our study, which showed fluctuations over the years. Notably, significant spikes occurred in 2010 and 2013 (Fig. 3). These sea-level changes are important for understanding the predictions made using the Bruun Rule, offering valuable insights into the physical transformations we're witnessing on the island.

In this study, calculations were performed to determine the value of R (shoreline retreat) using an empirical coefficient. This approach considers actual field conditions such as surface roughness, irregular shapes of the cross-section, and other local factors, providing a realistic estimate of how the system behaves.

The coastline retreat for 2008 and 2018 was estimated using the Brun model . For 2008, the following parameters were taken into account: sea state considered to be 4 on the Beaufort scale, and sea level (S empirical = 0.25 m) was calculated as the average of measurements for 2008 based on data recorded by the tide gauge in the port of Constanta.

The Bruun Rule also takes into account several physical characteristics of the beach profile to estimate coastline retreat. In the case of 2008, the width of the active profile (101.25 m), which represents the horizontal distance over which sediment is redistributed by wave action, was used. Additionally, the closure depth was considered to be 10 m, referring to the depth beyond which wave-induced sediment transport becomes negligible. The height of the berm, a natural ridge formed by wave deposition at the upper part of the beach, was taken as 0.75 m. These parameters, together with the empirical sea-level rise (0.25 m), were used in the Bruun Rule to estimate a coastline retreat of approximately 2.25 metres for the year 2008.

Although the berm height was not measured on-site, it was estimated based on visual observations and general geomorphological descriptions of the area. This figure should be regarded as a reasonable approximation, intended to illustrate how the Bruun Rule can be applied in practice. In the absence of detailed scientific measurements or specific studies documenting the berm in this region, its height was assumed to lie between 0.5 m and 1 m, with an average value of 0.75 m used in the calculation.

The same approach was applied to the 2018 calculation, following the same methodology as in 2008 and using the Bruun Rule. For this year, slightly different parameters were used, including an active profile width of 129.5 m, while the closure depth and berm height remained the same (10 m and 0.75 m respectively). Taking into account the observed sea-level rise, the Bruun model estimated a coastline retreat of approximately 3.01 metres for 2018.

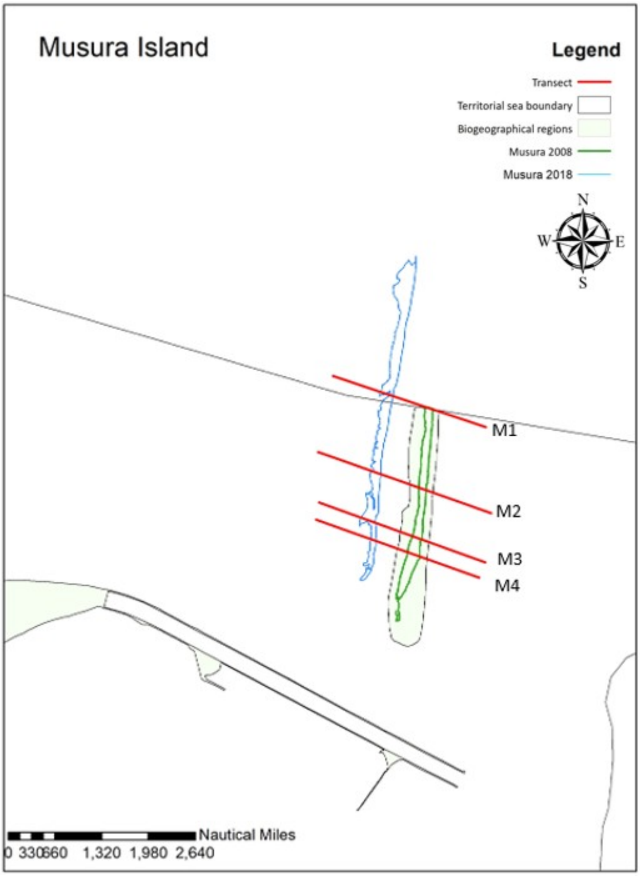

Fig. 5. Changes in Musura Island over time (2008 and 2018)

These findings connect closely with the broader discussion on modelling shoreline changes, particularly when using the Bruun Rule to predict the impacts of sea-level rise. The Bruun Model is sensitive to input sea-level values and generally assumes shoreline retreat is driven solely by sea-level rise and sediment reworking within a stable coastal profile. However, real-world cases such as Musura Island reveal much more complex dynamics.

Musura Island experienced drastic morphological changes over time — it was completely eroded in the M2 sector between 2005 and 2008, shrinking from 128 m in width to zero.
Yet, between 2008 and 2018, the island expanded once again, increasing in surface area and shifting position.The Bruun Model predicted only a minor shoreline retreat (about 2.41 m based on empirical data), which did not reflect the dramatic changes observed. This discrepancy arises because the model does not account for multiple influencing factors such as sediment supply from the Chilia branch, longshore drift, sandbank merging, or complex sediment transport processes.

Therefore, while the Bruun Rule offers a useful theoretical baseline for shoreline retreat in relatively stable coastal environments, it falls short in highly dynamic deltaic systems like the Danube Delta. This study highlights the necessity of using more advanced, adaptable models that incorporate sediment transport, hydrodynamics, and fluvial inputs to realistically predict shoreline evolution in such complex settings.

While some sections, such as M2 and M4 (Tabel 2), narrowed, others, especially M3, grew significantly. On average, the island widened, which suggests sediment accumulation and a shifting shoreline. This growth coincided with fluctuations in the sea level, as recorded at the Constanta tide gauge. Notable peaks occurred in 2010 and 2013, which may have contributed to sediment redistribution and morphological changes.

The Bruun Rule provides a quantitative framework to estimate shoreline recession based on sea-level rise. For instance, studies have applied this rule to the Romanian Black Sea coast, revealing varying rates of shoreline retreat depending on local conditions. These estimates are crucial for identifying areas at high risk of erosion and for prioritizing intervention measures (Niculescu *et al*., 2021; Bruun, 1962).

The applicability of the Bruun Rule in Romanian coastal areas is influenced by factors such as existing protection structures, lateral sediment transport, and variability in wave regimes. These factors may lead to an underestimation or overestimation of shoreline retreat, highlighting the need to use the rule as a preliminary estimate, complemented by detailed analyses and local data (Ranasinghe, 2007).

Bruun's rule can be applied to an arbitrary beach profile for which horizontal inundation dominance is caused by sea-level rise under conditions of sand-volume conservation.

A flooding situation caused by large level fluctuations induced by sudden variations in atmospheric pressure was recorded on 8 July 2025 in Costinesti (Fig. 6).
For the equilibrium profile that takes into consideration the variability of the beach sediment grain size, in particular the Dean relation, on Mamaia beach, the evolution of the profiles of the emerged sandy beach can be frequently monitored in the second phase of the sanding of the Mamaia sector, finalized in 2021.

Thus, the differences induced on the nourished beaches compared to adjacent sectors where no nourishment has been carried out are evident (Fig. 7 a and b), both in terms of the emerged beach profile and especially in terms of its modification in the vicinity of the water edge, by changing the submerged slope and reducing the wave breaking and swash area.

Fig 6. The flooding of Costinesti beach on July 8, 2025
(Source: https://www.replicaonline.ro/fenomen-rar-pe-plaja-din-costinesti-marea-a-inundat-zona-de-plaja-630882)

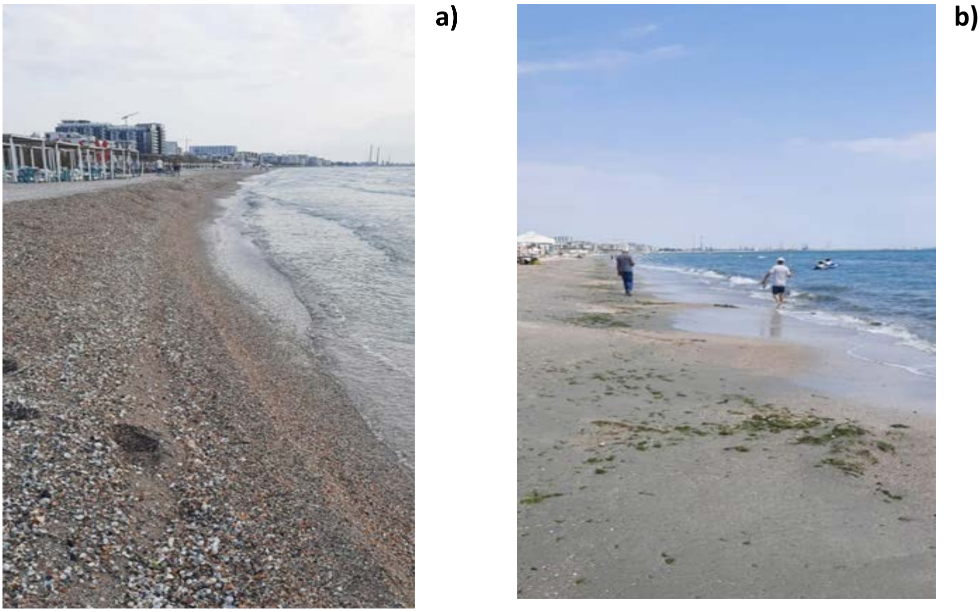

Fig. 7 a and b Beach profiles of the natural/non-nourished beach a)versus the nourished beach; b) in the Mamaia North area

CONCLUSIONS

The evaluation of Bruun's law in studies of the evolution of natural and artificial beaches remains valid, despite the emergence of a number of models superior to the geometric approximation involved in the Brunn model.

Bruun's rule has played a fundamental role in advancing our understanding of how the coast responds to rising sea levels, providing a simple and scalable method for predicting beach erosion and the inland migration of coasts. However, six decades of empirical research and coastal observations have revealed significant limitations in the rule's application, particularly in complex environments where sediment redistribution alone cannot explain the observed changes. The case studies presented in this analysis, including the Musura study in the Danube Delta, demonstrate that the Bruun rule often significantly underestimates shoreline retreat when processes such as longitudinal transport, sediment supply variability and human intervention are not considered.

In light of the growing uncertainty surrounding accelerating sea level rise, the Bruun rule should only be used for preliminary risk assessments or in regions where geomorphological data is lacking. Effective coastal zone management must be based on a combination of empirical observations, site-specific calibration and advanced modelling tools. Future research should focus on combining classical models with high-resolution numerical simulations and localised data sets, especially in sediment-rich deltaic areas where morphological changes are highly dynamic. To reduce vulnerability to sea level rise and the resulting amplification of coastal erosion, it is necessary to accurately quantify the sediment balance and implement specific intervention methods, as well as studying the long-term impact of climatic variations.

This study highlights the limitations of applying the Bruun Rule to a highly dynamic and active environment such as Musura Island in the Danube Delta. While the rule provides a simple framework to estimate shoreline retreat due to rising sea levels, the actual situation on the ground tells a very different story. Between 2008 and 2018, rather than shrinking as the model predicted—by around 2 to 3 m —the island actually expanded, increasing in width by 28 m. This clearly indicates sediment build-up rather than erosion.

This contrast reveals a major shortcoming of the Bruun Rule: it assumes a stable coastal profile and uniform sediment redistribution, which is not the case here. Musura Island is shaped by a complex mix of factors including sediment supply from the Chilia branch, longshore drift, wave action, and climatic variations. These forces interact in unpredictable ways, constantly reshaping the coastline.

In such a complex setting, the Bruun Rule fails to capture critical processes like three-dimensional sediment transport, storm impacts, and the influence of natural features such as sandbanks. While the rule might still be a useful general guide in more stable coastal regions, it is clearly insufficient for highly dynamic deltaic systems.

This underscores the importance of combining detailed field observations, local knowledge, and more sophisticated, adaptable models that reflect actual conditions.

Acknowledgement. This work was carried out within the framework of the Horizon 2020 - DANSER project – "DANube SEdiment Restoration", aligned with the European Mission "Restore our Oceans and Waters" and the Nucleu Project PN23230102 – "Prevention and management of risks associated with hazardous marine physical and hydrological phenomena through the development of innovative, energy-independent, and environmentally friendly solutions". We sincerely acknowledge the support provided by the Ministry of Education and Research, which enabled the successful implementation of this research.

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