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Morphosedimentary dynamics of the Moulay Bousselham coast in responses to seasonal and extreme hydrodynamic forces

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ABSTRACT

This study investigates the morphodynamic and sedimentary processes of the Moulay Bousselham coastline, a sandy stretch interrupted by the Merja Zerga lagoon inlet, designated a RAMSAR site. Conducted between 2017 and 2018, the research employs topographic profiling and sediment sampling to assess beach morphology, sediment distribution, and the influence of hydrodynamic forces. The results demonstrate marked spatial and temporal variability in beach morphology, with profiles exhibiting distinct responses to both seasonal and extreme hydrodynamic conditions. Northern beaches exhibit intermediate morphodynamic states, balancing energy dissipation and reflection, while southern beaches near the lagoon inlet display dissipative characteristics, absorbing wave energy and promoting sediment accumulation. The study highlights the protective role of a rocky platform in mitigating wave energy and supporting sediment retention. However, annual sediment budgets indicate a general erosion trend, amplified by extreme hydrodynamic events, including the February 2018 storm, which caused extensive sediment loss. Sediment analysis reveals a uniform granulometric structure, dominated by well-sorted medium sands shaped by hydrodynamic processes. This research fills a critical gap in understanding the interplay of sediment dynamics and hydrodynamic forces in this region, providing a scientific basis for sustainable coastal management and highlighting vulnerabilities to natural and anthropogenic pressures.

Keywords: Moulay Bousselham coastline, morphosedimentary dynamics, beach profiles, granulometry, sediment budget, coastal erosion, morphodynamic states, hydrodynamic forces.

INTRODUCTION

Beaches are dynamic interfaces between land and sea, playing a crucial ecological, economic, and protective role for coastal areas. Their morphology and evolution primarily depend on coastal sediments, making in-depth studies essential for understanding their dynamics and resilience to both natural and anthropogenic pressures.

The composition, grain size, sorting, and homogeneity of sediments are key indicators of the hydrodynamic processes acting on beaches. For instance, sandy beaches with finer grains are often more susceptible to erosion, whereas gravel beaches exhibit greater resistance to high-energy waves (Carter, 1988; Komar, 1976). These sedimentary characteristics directly influence the width, slope, and shape of beaches, which also vary depending on hydrodynamic conditions such as waves, currents, and tides (El Khalidi et al., 2009; Masselink and Pattiaratchi, 2001).

Analyzing the morphological units of beaches is equally vital to assess their response to external forces. For example, gently sloping beaches better dissipate wave energy, reducing erosion, whereas steep beaches are more exposed to marine submersion events (Aangri et al., 2024; Short, 1999). Additionally, seasonal variations and annual sediment budgets help identify trends in erosion and accretion, providing valuable insights into beach stability and their adaptation to environmental forcings (Nordstrom, 2000; Pinot, 1998).

The last three decades have been particularly fruitful in advancing the fundamental understanding of coastal processes. Various techniques have been developed to analyze sediments, classify beach types, and map beach profiles. Concerning sediments, studies focus on the relationship between grain size and their distribution on sandy beaches. Research by (Anthony et al., 2006; Short, 1992) demonstrates that these variations directly influence erosion and deposition processes, thereby shaping coastal morphology. For beach classification, the Iribarren number is a widely used method, linking beach slope and wave height to determine whether a beach is dissipative, intermediate, or reflective (Aouiche, 2016; Aouiche et al., 2016). This approach bridges hydrodynamic and morphological characteristics, enabling predictive analysis of beach responses to external forcings. Lastly, topographic surveys conducted with modern technologies such as DGPS, drones, and other remote sensing tools provide precise and repeatable measurements of beach profiles, facilitating the identification of temporal variations.

Although these approaches target distinct objectives, they share a common goal: to understand the complex interactions between hydrodynamic, sedimentary, and morphological processes. For instance, sediment grain size influences the beach type identified through the Iribarren number, while profile measurements validated by modern technologies confirm the established relationships between sediment dynamics and morphological features. The integration of these methods offers a comprehensive understanding of beaches from a dynamic perspective.

The Moulay Bousselham coast, which is part of the Moulay Bousselham site designated as a RAMSAR area since 1980, has yet to be the subject of a morphosedimentary study. The aim of the present work is to tackle a significant challenge by integrating laboratory experiments, field observations, and theoretical developments, in order to provide scientific insights and engineering solutions to coastal sediment issues. Specifically, our vision for the Moulay Bousselham site is to develop a comprehensive understanding of its coastal dynamics. This area has not been the subject of similar studies in the past, which emphasizes the unique and critical importance of this research. This includes examining the composition, grain size, sorting, and homogeneity of sediments, which are primarily influenced by hydrodynamic factors. Additionally, we focus on the morphological characteristics of each beach unit such as width, slope, and profile shape and how these features vary in response to hydrodynamic conditions. Finally, we aim to analyze the annual sediment budget by tracking vertical movements to assess trends in erosion and accretion driven by hydrodynamic forces. By studying these interconnected elements, we seek to gain valuable insights into the site's sedimentary processes and morphological evolution, ultimately contributing to more effective management and preservation strategies for this dynamic coastal area.

STUDY AREA

The Moulay Bousselham coast lies on Morocco's northern Atlantic shore, approximately 80 km from the city of Kénitra. It features a straight sandy coastline interrupted by the Merja Zerga lagoon inlet, a 35 km² area designated as a RAMSAR site.

The sandy beach spans 150–200 meters in width but narrows considerably, ranging from 50 to 100 meters near the lagoon inlet. A 900-meter-wide dune system, rising to elevations of 10–30 meters, borders the beach (Belrhaba et al., 2024). This dune system gradually disappears to the north near the inlet, where an ancient consolidated dune forms a cliff overlooking the beach (Benmohammadi et al., 2007; Mhamdi Alaoui, 2009). A part of the town of Moulay Bousselham is constructed on this fossil dune, featuring commercial, touristic, and residential areas (Figure 1). Residences parallel to the coast stretch over approximately 2 km in the area most severely impacted by erosion (Belrhaba et al., 2024). Moulay Bousselham remains the only urban presence along this otherwise pristine coastline, though new development projects are underway.

Except for the Moulay Bousselham lagoon environment, which has been the subject of a few sedimentological and structural studies, the hydrosedimentary dynamics of the beach at Moulay Bousselham remain largely unknown. The study area covers 12 km, including the beaches north (2nd Pool beach and 1st Pool beach) and south of the Moulay Bousselham lagoon inlet (Hawai beach) (Figure 1). The coastline faces energetic NW waves, generated by depressions in the North Atlantic (Belrhaba et al., 2024; Hakkou et al., 2019). The most intense waves occur in winter (December to March), reaching heights of 7 to

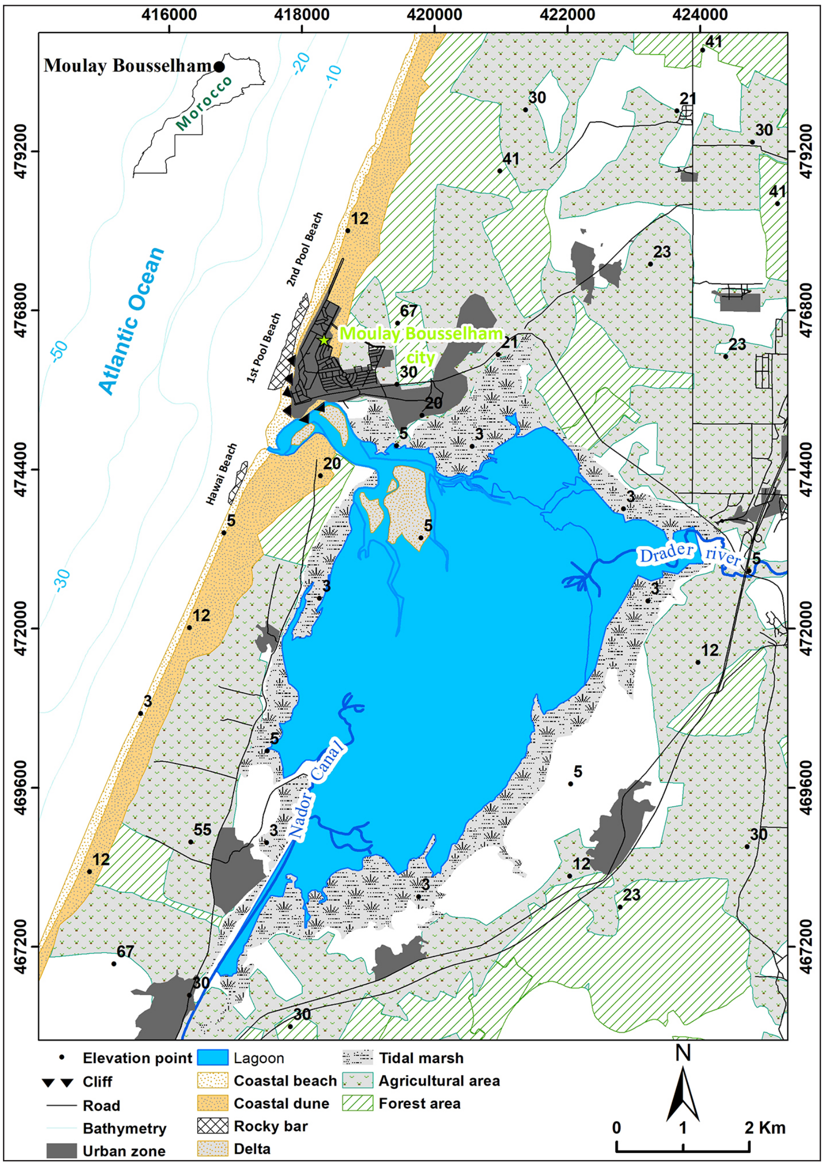

Figure 1. Moulay Bousselham coast, Morocco

9 meters during severe storms (DPDPM, 2014; Hakkou et al., 2011).

The tide is meso semi-diurnal, with an average tidal range of 2.2 meters. This range varies between 0.9 and 3.5 meters during neap and spring tides, respectively (Carruesco, 1989; Sogreah, 1961). Tide-induced currents on the continental shelf measure around 0.2–0.3 m/s, generally flowing northward during ebb and southward during flow (Charrouf, 1989; Jaaidi, 1981). Coastal currents, which are highly variable and influenced by seasonal changes and local bathymetry, range between 0.1 and 0.5 m/s (Cirac et al., 1993; Jaaidi, 1981). In the nearshore region of Moulay Bousselham, except near the lagoon entrance, coastal and tide-induced currents are negligible compared to wave-driven currents, classifying the beaches as wave-dominated. The Moulay Bousselham lagoon receives inflow from a small river (Drader river) and an artificial canal (Nador canal); however, no studies have quantified the sand export from the lagoon to the ocean.

MATERIALS AND METHODS

Topographic survey

The morphological variations of beaches were analyzed using repeated beach profile measurements. Comparing measurements from different dates allowed tracking of profile evolution. A detailed survey included nine cross-shore profiles covering the intertidal zone of Moulay

Bousselham to represent its morphological characteristics. from April 2017 to August 2018, 45 beach profiles were recorded to describe longitudinal variability and key seasonal changes. These included four profiles at the northern corniche of Moulay Bousselham (2nd Pool beach), four at the north of the inlet (1st Pool beach), and one at Hawaii Beach to the south of the inlet (Figure 2).

All topographic measurements were performed using a CHC X90 differential GPS (DGPS) with a UHF radio transmitter/receiver (450–470 MHz). The mobile receiver operated in repeater mode, allowing measurements up to 5 km from the base station. Local DGPS setup points were connected to cadastral and topographic service benchmarks, with precisely determined XY and Z coordinates serving as the reference station base. Distance adjustments were made according to weather conditions and the topographic characteristics of the sector. The receiver continuously tracked GPS constellations for both the base and mobile receivers. The DGPS operated in RTK mode to establish control points, allowing for precise real-time corrections. Files were then downloaded directly in Excel (CSV) format, including XY and Z coordinates for each point. Beach profiles were taken in continuous topographic mode, automatically recording a point every 0.50 m as the mobile receiver moved. Each point was acquired over 5 seconds.

DGPS data were referenced to the Lambert Conformal Conic projection system, Zone 1, Clarke 1880. To reduce user error on sandy ground (± 2 cm due to rod penetration), a thin horizontal plate was placed at the mobile station base to prevent sinking. The precision of topographic measurements, both horizontally and vertically, was established using reference points and profile

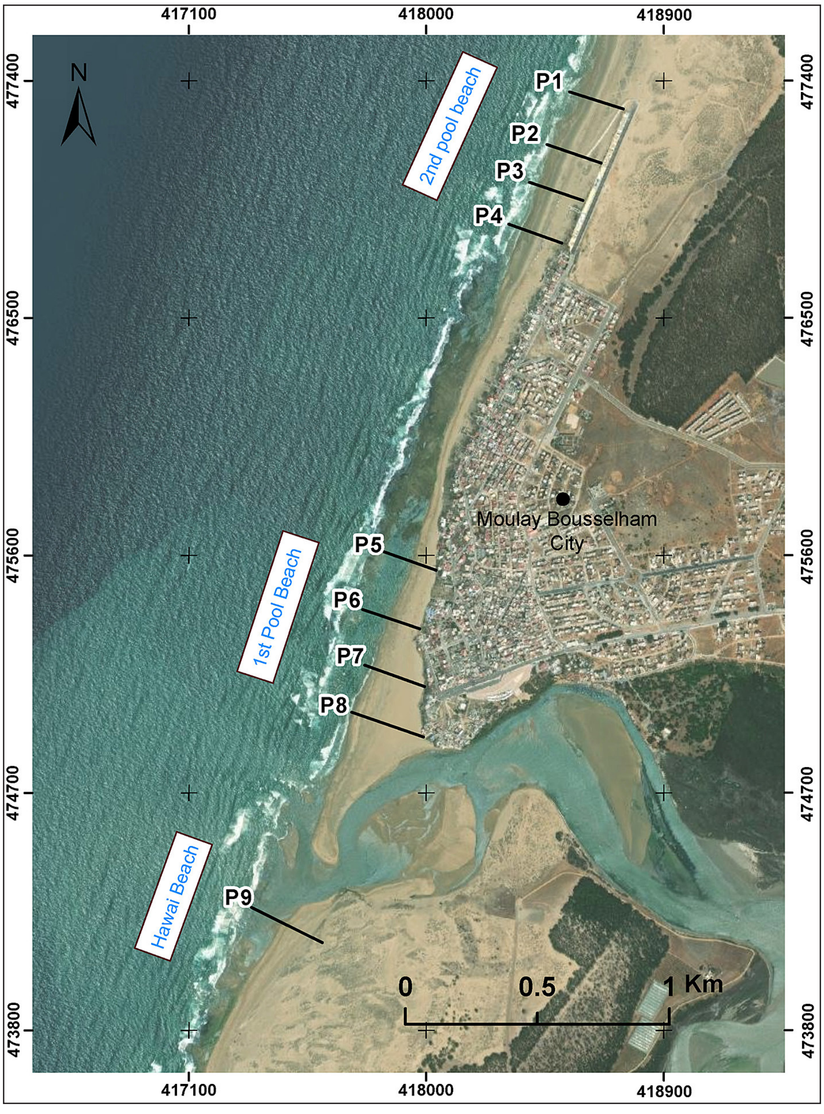

Figure 2. Location of profiles in the study area

heads at each study site (Table 1). Measurement quality was considered good, with an accuracy of around 2 cm for XY and less than 1 cm for Z.

Topographic profiles were taken during spring tide periods, when sea levels were at their lowest. This allowed for a full description of beach morphology, from the lower foreshore to a fixed reference point on the dune. Cross-shore profiles were aligned to be approximately perpendicular to the shoreline. This ensured an accurate temporal record of morphodynamic evolution. Significant morphological elements, such as dune foot, slope breaks, sediment structures, and inflection points, were carefully recorded to accurately represent the observed topography. Table 2 summarizes the main geographic characteristics of the different profiles.

Morphodynamic characterization of the beaches

The different beach compartments are in constant interaction with various external forces, resulting in distinct morphological features. In this study, a morphodynamic characterization of the Moulay Bousselham beaches was conducted to understand their profile response to incoming waves.

A beach's behavior can be characterized by its ability to reflect or dissipate wave energy. (Wright and Short, 1984) developed a conceptual model distinguishing six morphodynamic beach states, ranging from reflective to dissipative beaches, with intermediate states. This model allows beaches to be represented in a spatial-temporal morphodynamic continuum based on indices that synthesize key parameters related to sedimentological, hydrodynamic, and topographic characteristics (Anthony, 1998). The Iribarren number ξb (Battjes, 1974) is one of the most commonly used indices and is defined by the following formula:

$$\xi b = tan\beta \;/\; (Hmo \;/\; Lo)^{1/2} \qquad (1)$$

where: Hmo – wave height at breaking (m), Lo – offshore wavelength (m), β – beach slope (°). The slope values used for each survey and beach correspond to the mean slope of each profile.

According to this index, a beach is considered dissipative when $\xi b < 0.4$, reflective if $\xi b > 2$, and intermediate when $0.4 < \xi b < 2$ (Fredsoe and Deigaard, 1992).

Sedimentological materials and methods

Sampling was conducted in August 2017 and February 2018, alongside topographic surveys. Each mission included nine profiles during low tide. Sand samples were collected over a 200 cm² area (20 × 10 cm) at a depth of approximately 5 mm, covering the entire "active layer" (Abuodha,

Table 1. Accuracy of topographic measurements

Beach name	X (cm)	Y (cm)	Z (cm)
2nd Pool beach	2.2	2.3	0.8
1st Pool beach	1.8	2.0	0.4
Hawai beach	1.6	1.9	0.7

Table 2. Geographical characteristics of the beach profiles analyzed

Coast name	Beach name	Profile N°	Coordinates (m)		Altitude (m)	Average profile length (m)
			X	Y		
Moulay Bousselham	2nd Pool beach	1	418604,445	477630,988	34,718	218
		2	418537,064	477474,957	29,356	246
		3	418480,285	477342,95	29,817	227
		4	418419,833	477197,598	27,345	154
	1st Pool beach	5	417848,583	475730,285	6,76	115
		6	417796,587	475587,737	7,042	110
		7	417826,312	475463,323	6,874	145
		8	417815,184	475240,362	5,046	201
	Hawai beach	9	417507,56	474465,637	32,121	266

2003; Chauhan, 1992). Five samples were collected per profile, each representing a specific geomorphological beach unit (dune, upper beach, upper foreshore, mid-foreshore, and lower foreshore). In total, 90 surface samples were obtained.

The methodology builds on previous studies exploring the relationship between sediment grain size and its distribution on sandy beaches (Kroon and Wetenschappen, 1994; Masselink and Hegge, 1995). In the laboratory, 100 g sand samples were dried, weighed, and mechanically sieved for 20 minutes using an Afnor sieve series, with mesh openings ranging from 2000 µm to 63 µm.

A semi-logarithmic cumulative curve was plotted for each sample to show cumulative retention percentages against sediment grain diameter. Using these curves and an Excel-based program, grain size parameters were calculated, including mean size (Mz), sorting coefficient (σ), and skewness coefficient (Sk). The grain size parameters were calculated according to the (Folk and Ward, 1957) method and are expressed in Phi (ϕ), recognized for providing the most meaningful results.

RESULTS

Alongshore variations in beach morphology

The spatial and temporal variability of beach profiles provides insights into the seasonal and interannual behavior of beaches along the Moulay Bousselham coast. Volume fluctuations are expressed in m³/m. Figures 3, 4, and Table 3 show average profiles, maximum and minimum envelopes, and beach measurements for the nine transects monitored.

2nd Pool beach

The profiles at 2nd pool beach display a concave shape, with an intertidal zone exceeding 80 meters in width. The well-defined upper beach transitions into a well-developed dune reaching heights of 25 to 35 meters, structured to support the Moulay Bousselham corniche. The average, maximum, and minimum profiles show minimal variation, especially in the supratidal zone (Figure 3). The average slope of the intertidal zone

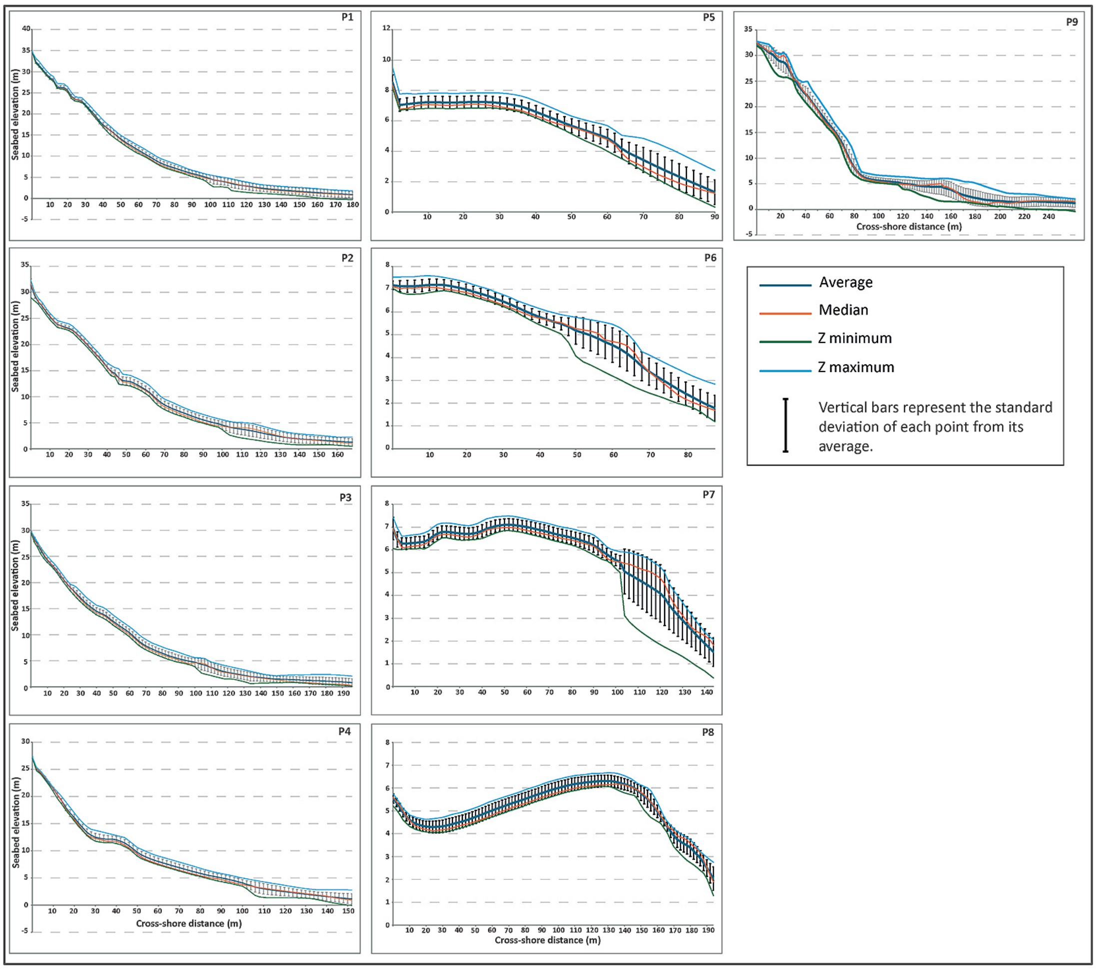

Figure 3. Average profile and envelopes for the nine transects analyzed

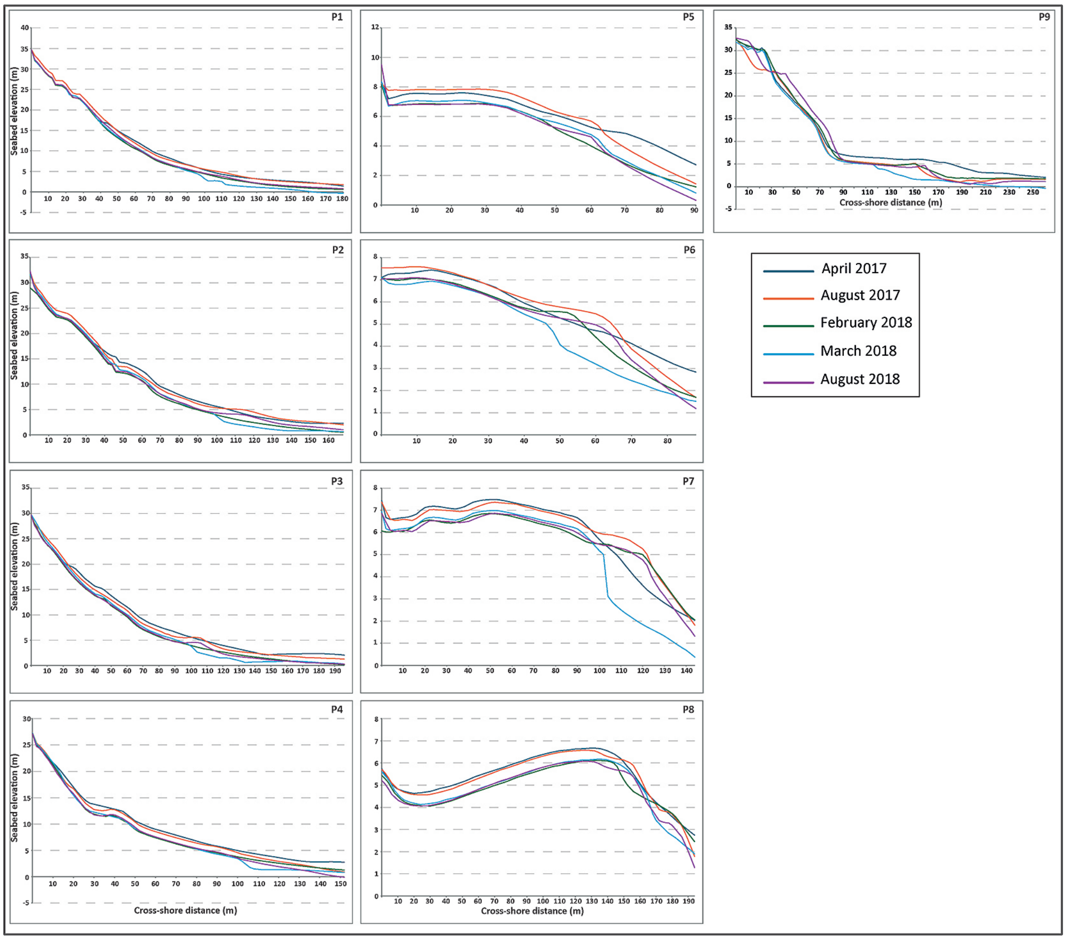

Figure 4. Superposition of measured profiles for the three beaches

Table 3. sediment budgets (in m³/m) for the three beach profiles

Periods	P1	P2	P3	P4	P5	P6	P7	P8	P9
April – August 2017	+35.28	+5.94	-92.44	-84.71	-8.07	+6.11	+25.83	-14.7	-378.6
August 2017 – February 2018	-223.8	-244.9	-200.6	-110.7	-88.69	-46.32	-62.91	-85.2	+171.3
February – March 2018	-66.3	+14.63	-4.28	-42.82	+15.39	-42.09	-88.10	-0.82	-361.3
March – August 2018	+111.1	+64.13	+10.64	+9.93	-20.97	+44.41	+79.01	-10.9	+343.3
April 2017 – March 2018	-254.9	-224.3	-297.4	-238.3	-81.38	-82.30	-125.2	-100.7	-568.6
August 2017 – August 2018	-179	-166.1	-194.3	-143.7	-94.28	-44.00	-72.00	-97.00	+153.3

is about 5.63%, with the maximum envelope at approximately 5.51% and the minimum envelope at about 5.65%.

The annual evolution of profiles 1 to 4 at 2nd Pool beach shows a negative sediment balance for both annual cycles, with an average deficit of -253.72 m³/m during the April 2017 to March 2018 cycle and an average deficit of -170.77 m³/m during the August 2017 to August 2018 cycle (Figure 4).

Seasonally, between April and August 2017, the northern profiles (P1 and P2) showed an average accumulation of 20.61 m³/m. In contrast, the southern profiles (P3 and P4) experienced an average erosion of -88.57 m³/m. Between August 2017 and February 2018, all four profiles show a general erosion trend, with an average deficit of -195.04 m³/m. This trend continued from February to March 2018, except for P3, which showed a sand accumulation of 14.63 m³/m, while the other profiles recorded an average erosion of -37.81 m³/m. From March to August 2018, the profiles displayed an average accumulation of 48.96 m³/m.

1st Pool beach

This 1.5 km beach is bordered to the south by the lagoon inlet and lies adjacent to the urban center of Moulay Bousselham, which is established on consolidated dunes. Four profiles (P5 to P8) were taken along this beach, spaced no more than 200 m apart. Unlike 2nd Pool beach, 1st Pool beach features convex profiles with a gradually decreasing slope from P5 (7.19%) to P8 (0.23%), the latter being the gentlest slope in the Moulay Bousselham sector. Figure 3 shows that the most significant variations are concentrated in the intertidal zone. The average slope across the four profiles is about 4.24%, with minimum envelopes at 4.99% and maximum envelopes at 3.65%.

The two annual cycles (April and August) exhibit significant sediment deficits across the four profiles. The April 2017 to March 2018 cycle concluded with an average deficit of -97.39 m^3/m, while the August 2017 to August 2018 cycle recorded a smaller deficit of -76.82 m^3/m. Seasonal dynamics of profiles P5 to P8 display different behaviors across profiles during the summer periods (April to August 2017 and March to August 2018). From August 2017 to February 2018, erosion affected all profiles with an average deficit of -70.79 m^3/m. Between February and March 2018, only profile P5 showed sand accumulation of 15.39 m^3/m, while the other profiles recorded an average erosion of -43.67 m^3/m. Between March and August 2018, profiles showed variable dynamics requiring further analysis for a comprehensive understanding of their morphological evolution.

Hawaii beach

Due to difficult access and recurrent GPS signal loss, monitoring in this sector was limited to a single profile, P9. This profile has a concave shape, starting from the dune crest (over 35 m high at a cadastral marker) and characterized by an intertidal zone about 300 meters wide at low spring tide with a gentle slope. The transition from the intertidal zone to the upper beach occurs through a well-developed berm reaching up to 5 meters in August. Analysis of the average profile and maximum and minimum envelopes shows limited variations in the intertidal zone (Figure 3). The average intertidal slope is 3.30% for the mean profile, 3.64% for the minimum envelope, and 3.25% for the maximum envelope.

Annual evolution of P9 at Hawaii Beach displays different dynamics compared to other beaches in the Moulay Bousselham sector, with a negative sediment balance of -568.62 m^3/m for the April 2017 to March 2018 spring cycle, while the summer cycle (August 2017 to August 2018) shows an accumulation of 153.32 m^3/m (Figures 4 and Table 3).

Seasonal dynamics for this profile reveal significant erosion between April and August 2017, with a loss of -378.65 m^3/m. However, between August 2017 and February 2018, the profile accumulated 171.3 m^3/m. During the high-energy period from February to March 2018, associated with a storm on February 28, the beach experienced a total erosion of -361.27 m^3/m. From March to August 2018, the profile accumulated 343.29 m^3/m.

Beach state

Table 4 presents the parameters used for calculating the Iribarren number for beaches along the Moulay Bousselham coast. Morphodynamic characterization of coastal profiles reveals intermediate beach states to the north, while profiles near the lagoon inlet exhibit a dissipative beach type.

Table 4. Morphodynamic characteristics and calculation of the Iribarren number for Moulay Bousselham beaches

Coast name	Beach name	Profile N°	Coordinates (m)		Altitude (m)	Average profile length (m)
			X	Y		
Moulay Bousselham	2nd Pool beach	1	418604,445	477630,988	34,718	218
		2	418537,064	477474,957	29,356	246
		3	418480,285	477342,95	29,817	227
		4	418419,833	477197,598	27,345	154
	1st Pool beach	5	417848,583	475730,285	6,76	115
		6	417796,587	475587,737	7,042	110
		7	417826,312	475463,323	6,874	145
		8	417815,184	475240,362	5,046	201
	Hawai beach	9	417507,56	474465,637	32,121	266

Dissipative beaches are notable for their ability to efficiently dissipate wave energy. These beaches have gentle slopes where waves break over long distances, often structured by a system of linear sandbars that cause multiple wave breaks, enhancing their dissipative nature. Conversely, reflective beaches have steep slopes between the wave breaking zone and the top of the swash zone, which prevents wave energy absorption and instead reflects it seaward. Unlike more dissipative beaches, reflective beaches lack sandbars, significantly affecting sediment dynamics in these environments (Short, 1999).

Sediment dynamics of the beaches

Transverse sediment distribution was described based on samples collected during August 2017 and February 2018 missions on Moulay Bousselham's beaches. Grain size analysis and sorting results (Figure 5) indicate that most samples are classified as medium sands (1ϕ < Mz < 2ϕ), suggesting a uniform sand source across Moulay Bousselham's coastline. This granulometric homogeneity is observed across different morphological units of the beach and is primarily marine in origin. However, it is worth noting potential additional contributions from cliff and rock bar erosion near the lagoon outlet and adjacent coastal erosion.

Coarse sands (Mz < 1ϕ), which are less frequent, are mainly concentrated in the submerged beach units, notably in the lower and mid-foreshore. Most samples are well to moderately sorted (σ between 0.4 and 0.7), indicating effective sorting by beach hydrodynamic processes. Dune and upper beach sands are generally better sorted, reflecting more stable depositional conditions with less disturbance from waves and currents. In contrast, sands in the foreshore (upper, mid, and lower) show greater sorting variability, indicating more dynamic and energetic hydrodynamic conditions.

Comparison across morphological units reveals that dune and upper beach sands tend to be well sorted, indicating regular depositional processes less influenced by marine dynamics. In contrast, sands in the upper, mid, and lower foreshore exhibit greater sorting variability, reflecting the hydrodynamic forces they experience.

These trends underscore the role of hydrodynamic processes in sand distribution and sorting on Moulay Bousselham's beaches. The presence of well-sorted medium sands indicates effective sorting, while differences in sand sorting across morphological units reflect the specific hydrodynamic conditions in each zone. The dunes and upper beach, being better sorted, reflect calmer and more stable depositional conditions, while the foreshore, with more variability in sand sorting, reveals more energetic conditions.

DISCUSSION

The analysis of the results reveals a high variability in beach profile responses to hydrodynamic conditions, illustrating the complexity of sedimentary processes in this region. Profiles P1, P2, P6, and P7 follow a classic seasonal pattern, as described by (Shih and Komar, 1994), where

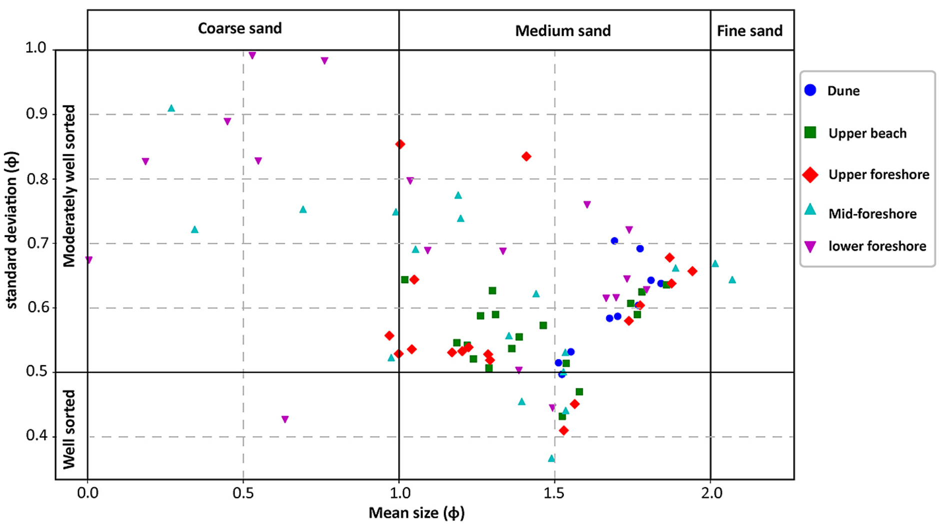

Figure 5. Granulometric characteristics of morphological units of the Moulay Bousselham coast

beaches exhibit an accretionary shape during low-energy conditions in fair weather and an erosive shape during high-energy waves conditions in stormy weather (Shepard et al., 1963). This observation aligns with traditional morphodynamic models, suggesting a degree of morphological stability despite seasonal variations.

A key factor contributing to this stability is the presence of a rocky platform that protects these profiles from dominant northwestern swells (Figure 6). By reducing wave energy reaching the beach, this platform also limits sediment transport capacity, thus reducing erosion and promoting sediment accumulation in the intertidal zone. This natural wave attenuation mechanism is comparable to the effects of artificial breakwaters, which are often used to protect beaches vulnerable to erosion. However, despite this natural protection, annual sediment budgets indicate a general trend of erosion, highlighting the impact of extreme hydrodynamic events, such as storms, on regional sediment dynamics.

The annual budgets across profiles show widespread erosion on all beaches within the Moulay Bousselham sector for both the April 2017 to March 2018 cycle (Figure 7) and the August 2017 to August 2018 cycle (Figure 8). Profile P9 experienced the highest recorded erosion, with sediment losses reaching -568.62 m^3/m. Underscores the destructive impact of winter storms, particularly the February 28, 2018 storm. This event caused massive sediment loss from the intertidal zone and frontal dunes, with sand volumes that could not be replenished naturally during the

Figure 6. Rocky platform appears at low tide north of the 1st Pool beach at Moulay Bousselham

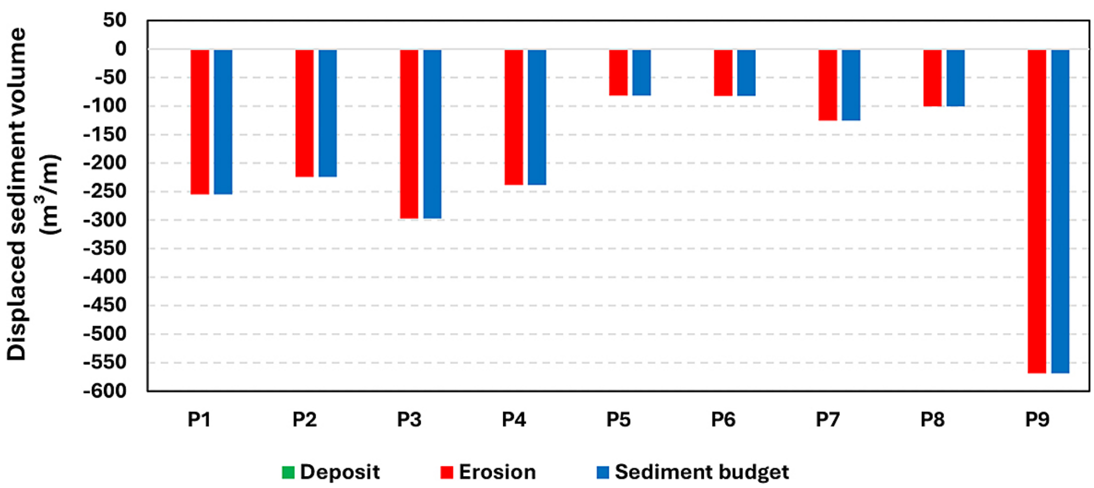

Figure 7. Sediment volumetric balance across the different profiles of the Moulay Bousselham coastline during the annual cycle "April 2017–March 2018"

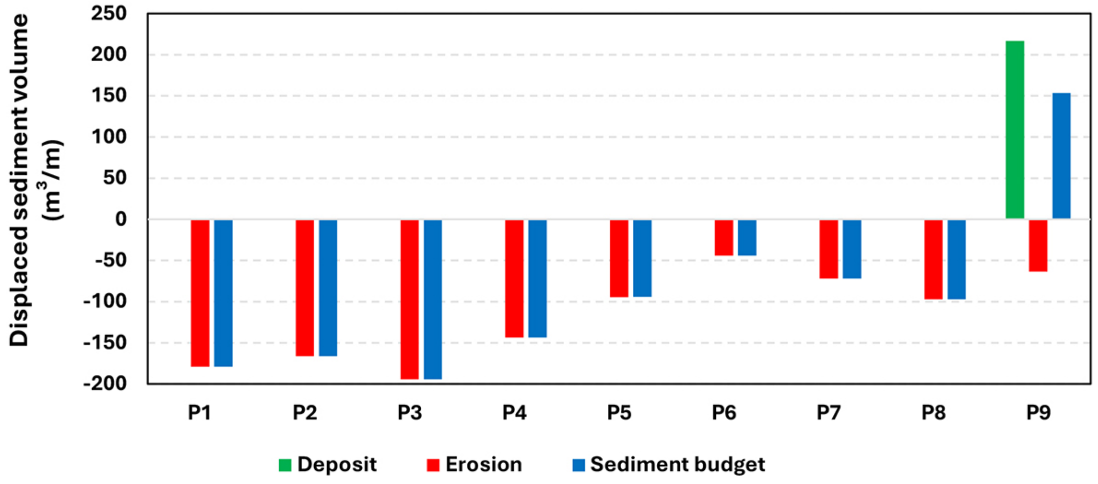

Figure 8. Sediment volumetric balance across the different profiles of the Moulay Bousselham coastline during the annual cycle "August 2017– August 2018"

summer season. Nevertheless, sediment dynamics are not uniform across all beaches. For instance, profile P9 at Hawaii beach demonstrated relative resilience with a positive sediment balance of 153.32 m^3/m during the August 2017 to August 2018 annual cycle (Figure 8). This accumulation may be attributed to sediment redistribution processes facilitated by milder hydrodynamic conditions or external sediment inputs from adjacent areas or littoral transport.

Comparing the two annual cycles reveals distinct morphological changes, particularly between April and August, where the profiles from the August 2017 to August 2018 cycle exhibit lower erosion compared to those of the April 2017 to March 2018 annual cycle. This trend is primarily linked to generally weaker wave conditions during fair-weather periods, accompanied by offshore winds, which promote sediment accumulation in the intertidal zone and the formation of berms.

The morphodynamic characterization of the Moulay Bousselham beaches, based on the (Wright and Short, 1984) model, reveals diverse morphodynamic states. These include reflective beaches, where wave energy is reflected, and dissipative beaches, where wave energy is dissipated.

Beaches on the northern coast tend to exhibit intermediate states, demonstrating a balance between dissipation and reflection of wave energy. These intermediate beaches are characterized by shallow sandbar systems and concave profiles, suggesting a continuous modulation of their morphology in response to varying hydrodynamic conditions.

Conversely, beaches near the lagoon inlet, such as Hawaii beach, display a more dissipative character. This type of beach is characterized by a gentle slope, where waves break over a long distance, dissipating a significant amount of energy before reaching the shore. This dissipation results in greater sediment accumulation, partially explaining the resilience observed at profile P9. However, these beaches remain vulnerable to high-energy events, as evidenced by the impact of the February 2018 storm.

In summary, the diversity of morphodynamic states along the Moulay Bousselham beaches underscores the complexity of their sediment dynamics. Differences between dissipative beaches and those with intermediate characteristics reflect spatial variations in hydrodynamic conditions and local geomorphological structures, such as the rocky platform.

CONCLUSIONS

This study provides the first detailed investigation of the morphosedimentary dynamics of the Moulay Bousselham coastline, offering insights into the interactions between hydrodynamic forces and sedimentary processes specific to this region. It reveals distinct spatial and temporal variability in beach morphology, sediment distribution, and morphodynamic states, driven by both seasonal changes and extreme events.

For the first time, this research characterizes the northern Moulay Bousselham beache's as having intermediate morphodynamic states, balancing energy dissipation and reflection through shallow sandbar systems and concave profiles. In contrast, southern beaches near the lagoon inlet, such as Hawaii beach, display dissipative characteristics, with gentle slopes that effectively absorb wave energy and promote sediment accumulation. These findings fill a critical gap in the understanding of morphosedimentary processes along the Moulay Bousselham coast, a site previously lacking systematic analysis.

The protective role of the rocky platform in attenuating wave energy is highlighted, contributing to localized sediment retention and mitigating the impact of hydrodynamic forces. Additionally, sediment analyses reveal a homogeneous granulometric structure dominated by well-sorted medium sands, showing up the role of marine-origin sediments in shaping beach morphology.

Despite these natural defenses, the study reveals a predominant erosion trend across the region, with significant sediment losses recorded during high-energy events, particularly the February 2018 storm. This highlights the vulnerability of the Moulay Bousselham coastline to extreme natural events and anthropogenic pressures.

By addressing a previously unexplored coastline, this study provides a scientific foundation for sustainable coastal management in the region. It emphasizes the importance of integrating natural defenses, such as rocky platforms, into targeted erosion mitigation strategies. Continued monitoring and a deeper understanding of sediment dynamics will be essential for enhancing the resilience of this coastline against future challenges.

Building on these findings, future research should explore sediment transport pathways and the impact of long-term climatic trends on sediment dynamics, using numerical modeling. Such efforts will further refine coastal management strategies and help assess the socio-economic implications of shoreline change for the sustainable development of this region.

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