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Spatio-Temporal Dynamics of Beach Morphology and Sediment Textural Properties in the Mandarmani Coast, East Medinipur, West Bengal

Sujata Dutta, Subhamita Chaudhuri, Swetangee Chowdhury, Pritam Sarkar, Arpan Roy Chowdhury, Manika Mandal and Dipankar Paul

Department of Geography, West Bengal State University, Barasat, Kolkata-700126
E-mail:sujataduttawbsu@gmail.com (*Corresponding author*)

Abstract: *The Mandarmani coast of East Medinipur, West Bengal is experiencing rapid and complex transformations driven by both natural forces and human interventions. This study provides an integrated assessment of spatio-temporal changes in beach morphology and sediment textural properties along ~13 km meso-tidal coastal areas of Pichaboni, Dadanpatrabar, and Jaldha. Investigations of 26 beach profiles and systematic sediment collection processes were conducted during pre-monsoon, monsoon, and post-monsoon periods. The study revealed noticeable seasonal variability.The monsoon season is marked by intense beach erosion, vertical elevation loss especially in Jaldha sectors and cross-shore beach narrowing due to high-energy wave and current dynamics, while post-monsoon phases exhibit partial morphological recovery and sediment re-accumulation. Sedimentological analyses indicate a shift from texturally heterogeneous and bimodal distributions in the pre-monsoon and post-monsoon to tightly unimodal and well-sorted fine sands during the monsoon, reflecting strong hydrodynamics. Sector-wise, Pichaboni is the most dynamic in nature. Jaldha shows abrupt textural and morphological shifts influenced by dune-beach interactions, where Dadanpatrabar is relatively stable but is disrupted by anthropogenic obstructions. Statistical grain-size parameters underscore the interplay between wave energy, sediment supply, and human activities. The findings highlight the dynamic feedbacks connecting beach profile change, equilibrium conditions, and sediment dynamics under varying seasonal forcings and land-use pressures.*

Keywords: *Beach Morphology; Sediment Texture; Equilibrium beach profile; Beach erosion. Mandarmani*.

Introduction

Coastal zones represent one of the most dynamic geomorphic environments on earth, characterised by continuous interactions between marine and terrestrial processes. Beaches, as essential components of these environments, undergo significant morphological changes under varying spatial and temporal scales due to complex factors such as wave climate, tides, storm events, sediment supply, human interventions, and relative sea-level changes (Masselink *et al.,* 2014; Anthony *et al.,* 2015). Understanding beach morphology and associated sediment dynamics is crucial for effective coastal management, especially in the context of increasing anthropogenic pressures and climate change. As coastal urbanisation intensifies, the extent of human intervention within the littoral zone progressively increases over time. A comprehensive understanding of beach dynamics requires recognition of the cumulative effects of deliberate and unintended anthropogenic modifications (Kennedy *et al.,* 2025).

The east coast of India, particularly the coastal stretch of West Bengal, exhibits a rich diversity of beach forms, sedimentological characteristics, and dynamic processes (Mishra *et al.,* 2001; Kumar *et al.,* 2006). The Mandarmani coast in East Medinipur district of West Bengal has emerged as a critical zone owing to its rapid transformation over the past few decades (Nath *et al.,* 2020; Bose and Bardhan, 2023).Population showing rapid growth and urbanization is taking place in this coastal area, which is continuously altering the coastal processes.

A relatively stable Mandarmani coast has witnessed accelerated rates of coastal erosion, beach retreat, and morphological alterations since the late 20th century, exacerbated by both natural forces and intensified human activities (Chakraborty, 2017).Several controlling factors govern the morphodynamics of the Mandarmani beach. Natural drivers include the semi-diurnal meso-tidal regime, seasonal monsoon influences, episodic tropical cyclones, and longshore sediment transport shaped by prevailing wave directions (Bal and Paul, 2023). In addition, relative sea-level rise (SLR), attributed partly to global warming and regional subsidence processes, poses a significant threat to the stability of this coast (Dasgupta *et al.,* 2022). Superimposed on these natural dynamics are human-induced stresses, particularly unregulated tourism development (Dey and Mazumder, 2023). The mushrooming of hotels and resorts close to the active beach zone has led to construction activities without adequate setback regulations, resulting in disruption of natural sediment pathways, increased wave reflection, and accelerated erosion (Mondal *et al.,* 2023).Beach erosion along the Mandarmani coast has been increasingly documented over the last two decades. Reports suggest that several sections have experienced shoreline retreat rates exceeding 3 m/year, particularly near densely built-up areas (Paul *et al.,* 2024).Majumder and Fatma, 2025 also tried to estimate shoreline shift to predict future shoreline movement of Mandarmani coastal belt.Furthermore, the construction of semi-permanent structures and embankments to protect properties has, paradoxically, enhanced localised scouring and downdrift erosion, a phenomenon consistent with patterns observed globally (Nordstrom, 2000). The lack of integrated coastal zone management (ICZM) initiatives and weak enforcement of Coastal Regulation Zone (CRZ) guidelines have further compounded the vulnerability of this region (Chatterjee and Bhandari, 2022). The textural character of the sand-sized particles is also seasonally changed by the dynamic nature of the nearshore wave climate. The erosion of the beach is not only dependent on wind intensity or blowing time but also the beach grain size, where the beach is composed of finer grains, there will be greater chance of backshore topographic variation (Lamy *et al.,* 2024). Thus, Grain size analysis is a fundamental approach to sediment characterization which serves as a valuable tool for interpreting the hydro-morphodynamic behavior of coastal environments (Dasgupta, 2025).

A substantial body of research along India's eastern coastline has examined beach dynamics and associated sedimentological processes. For instance, multi-decadal shoreline changes analyses using Digital Shoreline Analysis System (DSAS) and remote sensing have revealed alternating erosion and accretion patterns across regions such as Odisha, West Bengal, and Tamil Nadu, driven by monsoonal wave climates, cyclonic events, and sediment transport disruptions (e.g., Jana *et al.,* 2014; Velsamy *et al.,* 2020). However, Sandy coasts, directly exposed to storm activity undergo continuous adjustment to wave energy through alternating phases of erosion and deposition (Vandenhove *et al.,* 2025).

The present study aims to address the spatio-temporal variability in beach morphology and sediment textural properties of the Mandarmani coast. The study seeks to understand how the beach profile and sediment characteristics vary across different seasons, particularly between the pre-monsoon, monsoon, and post-monsoon periods. In addition, it aims to assess the nearshore wave climate and associated hydrodynamic conditions throughout the year. By integrating these datasets, the research endeavours to establish the linkages between seasonal variability in beach-sediment dynamics and the prevailing nearshore hydrodynamic forces, thereby providing a comprehensive understanding of the physical processes controlling coastal change in the region.

Material and methods

Study area

The Mandarmani coast is located in the East Medinipur district of West Bengal, India, represents a dynamic and rapidly evolving coastal stretch along the northwestern margin of the Bay of Bengal. Geographically, it lies between 21°36'N to 21°39'N and 87°42'E to 87°45'E (Fig. 1), covering approximately a length of 13 km shoreline (Chakraborty, 2017). This coastal segment is characterized by a wide and gently sloping sandy beach, backed by low-lying areas, tidal creeks, and mudflats, forming part of the larger deltaic environment shaped by the Subarnarekha-Rasulpur-Haldi estuarine system (Bhattacharya, 2017). Considering the heterogeneous morphology and human-induced pressures along the 13 km coastal stretch of Mandarmani (Table 1), the area has been divided into three sectors: Pichaboni (eastern end, influenced by the Pichaboni tidal inlet), Dadanpatrabar (central zone), and Jaldha (western sector, influenced by the Jaldha tidal inlet) (Fig. 2). Mandarmani experiences a tropical monsoonal climate, with distinct seasonal variations. The region receives most of its annual rainfall during monsoon period (June–September), significantly influencing coastal processes through enhanced wave energy, sediment influx, and morphological adjustments (Dasgupta *et al.,* 2022). Tidal fluctuations are semi-diurnal with an average tidal range of about 3 to 4 m, classifying it as a meso-tidal coast (Sahoo and Bhaskaran, 2018). The dominant wave regime is shaped by the southwest monsoon winds and periodic cyclonic disturbances generated in the Bay of Bengal (Paul *et al.,* 2022). In recent decades, Mandarmani has undergone rapid socio-economic transformation driven primarily by tourism-led development. The unregulated construction of hotels, resorts, and infrastructure along the active beach zone has disrupted natural sediment transport pathways and accelerated beach erosion (Dasmahapatra, 2023). Coupled with regional sea-level rise and extreme weather events, the Mandarmani coast now exhibits pronounced morphological instability, making it an important location for research into coastal dynamics and management interventions.

Beach profile survey

To assess the seasonal variability in beach morphology along the Mandarmani coast, 26 beach profiles (Fig. 2) were considered

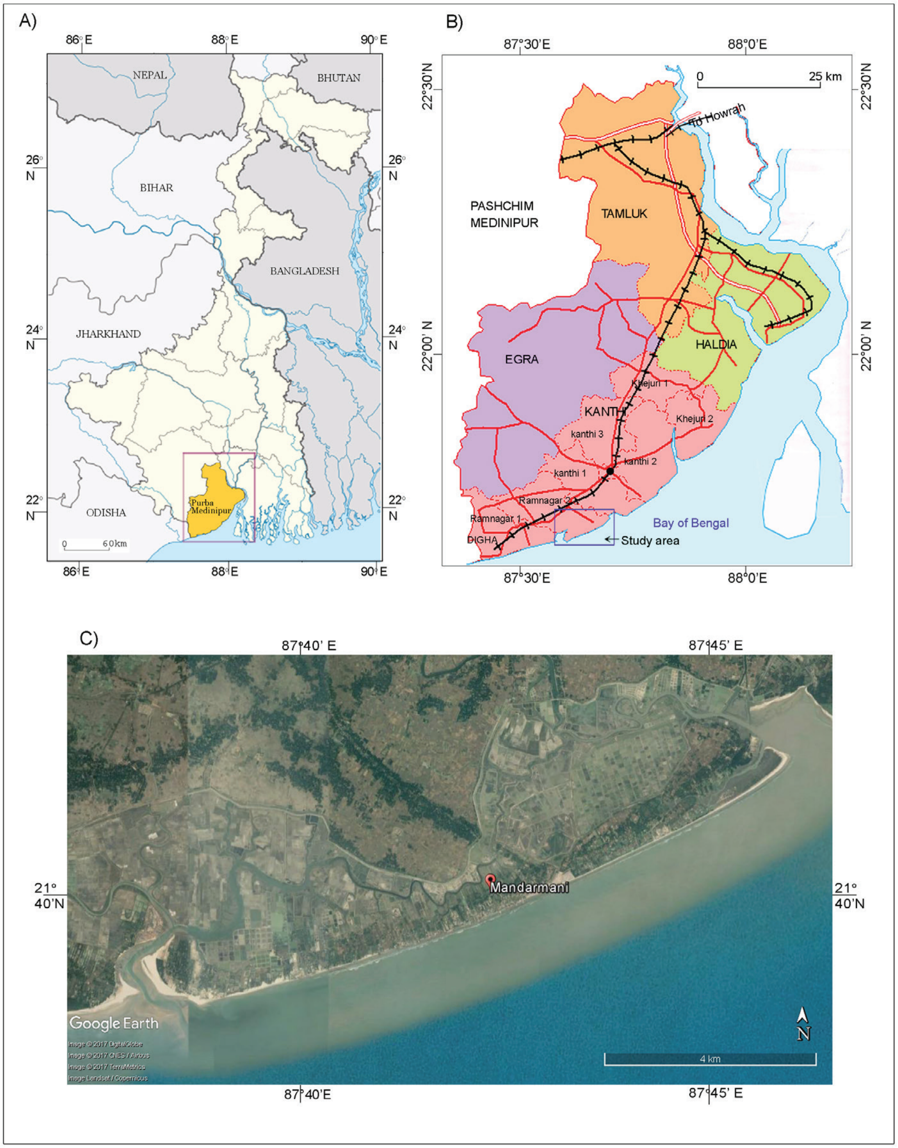


Figure 1. Location of the study area. (a) location of Purba Medinipur within West Bengal, (b) location of Mandarmani within Purba Medinipur, (c) 13 km long Mandarmani coastal stretch. Image Source (c): Google Earth Image, YoA: 2017.

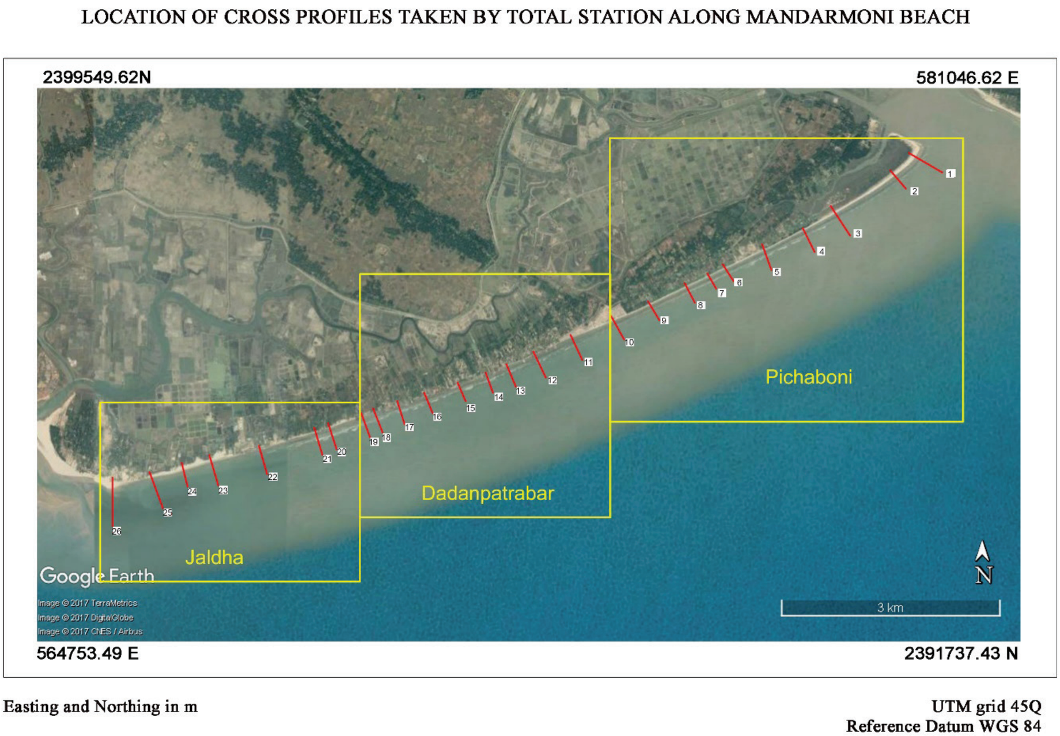


Figure 2. Location of 26 beach profiles surveyed in 2018.

perpendicular to the shoreline, extending from the dune crest to the lowest low tide line. Each profile was georeferenced using a handheld GPS device (Garmin Etrex10) to ensure spatial consistency across surveys. Topographic measurements were conducted using a Total Station (Leica TS06) during three distinct seasons in 2018 i.e. pre-monsoon (April), monsoon (July), and post-monsoon (December) for capturing intra-annual morphological variations driven by differing hydrodynamic regimes.Although the study area does not feature engineered coastal protection structures such as seawalls and unregulated tourism infrastructure below the high tide line. These unplanned interventions were recorded during fieldwork, as they influence sediment dynamics and local beach morphology. The multi-seasonal profiling approach offers a detailed understanding of short-term erosion and accretion trends along the human-impacted open coast.

Sediment sample collection and analysis

To investigate the sedimentological characteristics of the Mandarmani beach, surface sediment samples were collected from alternate profiles (i.e., Profiles 1, 3, 5, etc.) among the 26 beach profiles considered for the morphological survey (Fig. 2). From each of these 13 profiles, 5, 6 and 7 sediment samples (approximately 200 g each) were systematically collected from the cross-shore transects, covering the zone between the dune crest (or wall crest) and the low tide line. Sampling was conducted during the same seasonal intervals and months as detailed in Section 3.2, ensuring consistency with the corresponding topographic data. All sediment samples were oven-dried at 80 °C for 24 hours to eliminate moisture. The dried samples were sieved at 0.50 ϕ intervals across a size range from 0.0 ϕ to 4.25 ϕ. The grain size fractions were weighed, and granulometric parameters were computed using GRADISTAT software (version 9.1), with a focus on median grain size (d_{50}). These sedimentological data, integrated with the corresponding elevation profiles, were used to assess cross-shore sediment sorting patterns and to evaluate deviations from theoretical equilibrium beach profiles under seasonal forcing conditions.

Equilibrium Beach Profile (EBP)

Equilibrium beach profile is used to express balance of destructive and constructive forces acting on the beach (Dai *et al.,* 2007). A quantitative understanding of the equilibrium beach profile (EBP) is fundamental for coastal engineering applications and interpreting nearshore morphodynamics, especially in the context of beach nourishment and sediment stability (Dean, 1991). As originally proposed by Bruun (1954), the equilibrium profile extends seaward until a theoretical "closure depth," beyond which net sediment transport is negligible. Dean (1977) mathematically formulated the equilibrium profile as:

$$h\,(y) - Ay^{n} \;\ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots \text{(Eq. 1)}$$

Where, h is the water depth at an offshore distance y, A is the profile scale factor related to sediment characteristics, and n is an exponent that defines the energy dissipation pattern across the profile. A value of n = 2/3 implies uniform energy dissipation per unit volume of the water column, whereas n = 2/5 corresponds to uniform energy dissipation per unit area of the seabed (Dean, 1977). While early studies considered A to be a complex function of wave energy dissipation, it has been more practically estimated using empirical relationships derived from sediment characteristics. Based on the formula after Dean and Dalrymple (2002), A can be expressed as:

$$A = 0.067W^{0.44} \ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots \text{(Eq. 2)}$$

Where, W is the sediment fall velocity (cm/s). The fall velocity W is empirically related to the median grain size (d_{50}) by the equation proposed by Hallermeier (1981):

$$W = 14{d_{50}}^{1.1} \ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots \text{(Eq. 3)}$$

In the present study, three representative beach profiles such as profile 5, profile 13, and profile 22 (Fig. 1) were selected for EBP modelling. Although hydrodynamic parameters such as wave climate may be relatively consistent along this ~13 km stretch, sediment properties exhibit significant variation, particularly across the cross-shore gradient from the upper beach to the low water line. To account for this variability, at least five representative d_{50} values from each selected profile were used in the computation of the equilibrium beach profiles.

Results

Variability of beach profiles

Seasonal dynamics of beach profiles

The seasonal variation in beach morphology across the 26 shore-perpendicular profiles, covering three sectors reveals pronounced beach-face changes between pre-monsoon, monsoon, and post-monsoonseason. In the Pichaboni sector (Fig. 3), beach profiles during the monsoon exhibit marked lowering across almost all transects, indicating pronounced erosion. The profiles of 1, 2 and 3 show significant vertical loss in elevation of about 2 m, especially in the mid to lower beach-face, suggesting seaward sediment

Table 1. Anthropogeomorphic basis for dividing the Mandarmani coast into three sectors i.e. Pichaboni, Dadanpatrabar, and Jaldha.

Geomorphic variables	Different Sectors		
	Pichhaboni	Dadanpatrabar	Jaldha
1. Beach gradient[1]	Varies from 0.003–0.001	0.02	0.02–0.03
2. Beach width[1]	Wide beach (>350 m)	Narrow beach segment (250 m–300 m)	Narrow beach segment (250 m–300 m)
3. Grain size[1]	Very fine to fine	Fine to moderate fine	Very fine to fine
4. Condition of natural dune[1]	Dune lowering due to natural wave processes	Dune replacement due to building construction	Dune replacement due to building construction
5. Shoreline shifting (1972–2024)[2]	Maximum 836 m shifted towards sea.	20–50 m towards land	Shifted almost 80 m inward.
6. Mud layer exposition[1]	Partially viewed in monsoon period	Partially present	Relative abundance of mud layer exposition
7. Wave refraction pattern[3, 4]	Divergence of wave orthogonals	Convergence of wave orthogonals	Convergence of wave orthogonals
8. Shape of the coastline[2]	Straight coastline	Crenulated coastline	Crenulated coastline
9. Presence of red crab[1]	Known as red crab zone with high abundance	Absent of red crab	Absent of red crab
Anthropogenic variables			
1. Dune Agriculture[1]	Present	Absent	Absent
2. Hotel and resorts construction[1]	Generally absent but now very few are seen	Abundance of hotels and building construction	Abundance of hotels and building construction
3. Tourist crowdedness[1]	Less crowded	Overcrowded	Overcrowded
4. Sewage inclusion[1]	Absent	Direct inclusion of sewage to the beach	Direct inclusion of sewage to the beach

Source: [1]Primary field survey; [2]1972-SoI topographical sheet (1:50000), Landsat 9, DoA: 28/12/2024, Path/Row: 139/45; [3]Bathymetry: Indian Naval Hydrographic Office, Chart No. 351, Scale: 1:300000 and Wave climate: INCOIS (2018).

transport under high-energy wave conditions. In most of the profiles, the post-monsoon lines are situated above the monsoon profiles, reflecting partial sediment recovery. Profiles such as 5, 6, and 7 highlight clear beach building processes in post-monsoon, with steeper gradients indicating re-accumulation of sediments over the beach. The pre-monsoon profiles generally lie between monsoon and post-monsoon lines but are close to the post-monsoon profiles in upper and mid-beach regions. In some profiles (e.g., profile 8, 9, and 10), seasonal variability is less pronounced, pointing to local geomorphic or wave energy controls.

In the Dadanpatrabar sector (Fig. 4), seasonal variability in beach morphology reveals a dynamic interplay between accretion and erosion. Profile 11 exhibits a striking monsoonal elevation gain of ~1.15 m compared to the pre-monsoon, suggesting substantial storm-driven deposition or berm formation. In contrast, profile 12 records a ~0.6 m decline in elevation during the monsoon and increase of elevation duringpre-monsoon marking, indicating dominant erosion during the monsoon. Profiles of 13 and 14 show a relatively consistent morphology with minimal seasonal fluctuation, highlighting beach stability. Similarly, profiles 15 and 16 display limited variability (<0.3 m), although the monsoon profiles remain the lowest, indicating at subdued but persistent seasonal erosion. In profiles 17, 18 and 19, pre-monsoon consistently marks the lowest elevation, where monsoon and post-monsoon profiles occupying intermediate and upper positions respectively, but the overall seasonal variation remains within 1 m. A critical observation is the monsoonal beach shortening, particularly pronounced in profiles 14, 15, 16, 17, 18 and 19, where the active beach retreats by approximately 50 m compared to pre-monsoon. On average, the longest beach widths (~270 m) are recorded during the pre-monsoon, highlighting seasonal sediment buildup prior to monsoonal reworking. Collectively, these trends indicate a cyclical pattern of pre-monsoonal progradation, monsoonal erosion and beach narrowing, followed by partial post-monsoonal recovery, with the mid-to-lower profiles being more vulnerable to seasonal energy shifts.

In the Jaldha sector (Fig. 5), seasonal beach profile dynamics reveal moderate to high morphological variability. Profile 20 shows negligible elevation changes across seasons, indicating a stable beach face. Profile 21 is characterised by a prominent dune (~9 m), which remains morphologically stable across seasons, suggesting minimal wind or wave-induced reworking. Profile 22 indicates slight monsoonal elevation drop (~0.4 m), while both pre-monsoon and post-monsoon maintain same levels, reflecting limited sediment exchange. Profile 23 shows a sudden elevation drop of nearly 1 m at the upper beach near the high tide line from pre-monsoon to monsoon, indicating sharp erosion likely due to wave action. Profile 24 reflects dune retreat during monsoon, with the eroded material being re-deposited at the upper foreshore, resulting in an irregular and elevated beach profile. Profile 25 reveals the formation of a runnel in the mid-beach zone during monsoon, likely carved by wave scouring or swash processes; where this feature is subdued or nearly absent in the post-monsoon, indicating profile smoothening and sediment redistribution. Profile 26 shows marked monsoonal erosion, with over 1.5 m elevation loss and only partial post-monsoonal recovery. Profile 26 shows a seasonal variability, where the monsoon profile drops by nearly 1.5 m below the post-monsoon, suggesting intense sediment removal, while the post-monsoon profile exhibits increased elevation and progradation. On a contrary, profile 26 shows marked monsoonal beach shortening (from ~320 m to 160 m) and ~1 m lowering, followed by post-monsoonal recovery in both elevation and lateral extent.

Seasonal dynamics of equilibrium beach profile

In pre-monsoon, monsoon and post monsoon season the equilibrium beach profile of profile 5 tend to be concave in upward beach face. The actual beach is steeper in upper beach face than equilibrium beach profile which suggests erosion in lower foreshore and deposition near the berm. During all seasons the actual beach of profile 11 consistently shows higher than equilibrium near the upper beach, indicating sediment building process upward, whereas towards offshore zone sediment deficit were observed. In pre-monsoon and post-monsoon season the profile 15 shows that actual and equilibrium beach profile are very close but actual beach is still slightly higher in upper foreshore indicating that it has not fully adjusted yet.

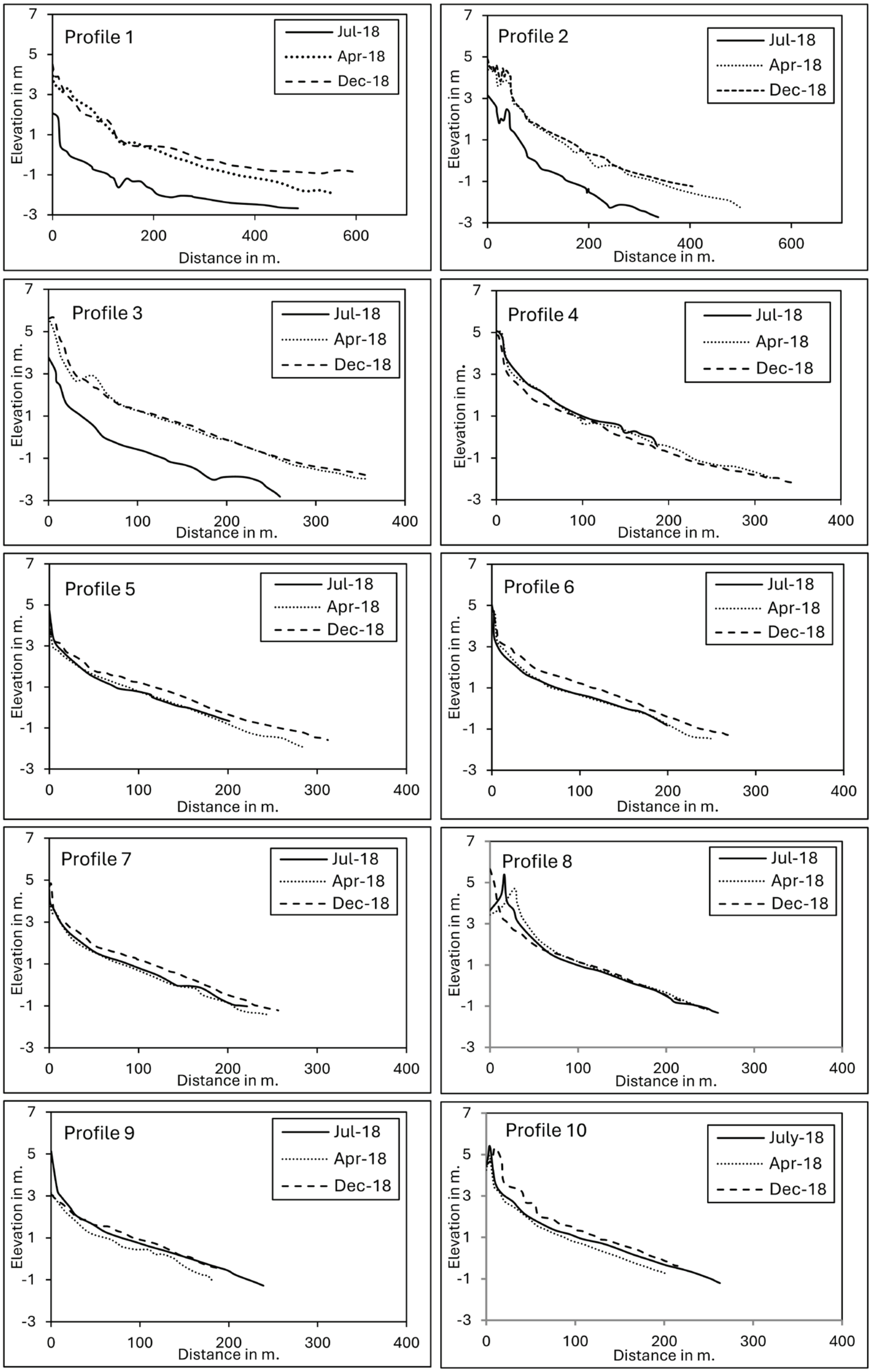


Figure 3. Spatio-temporal variation of beach profiles in Pichaboni sector.

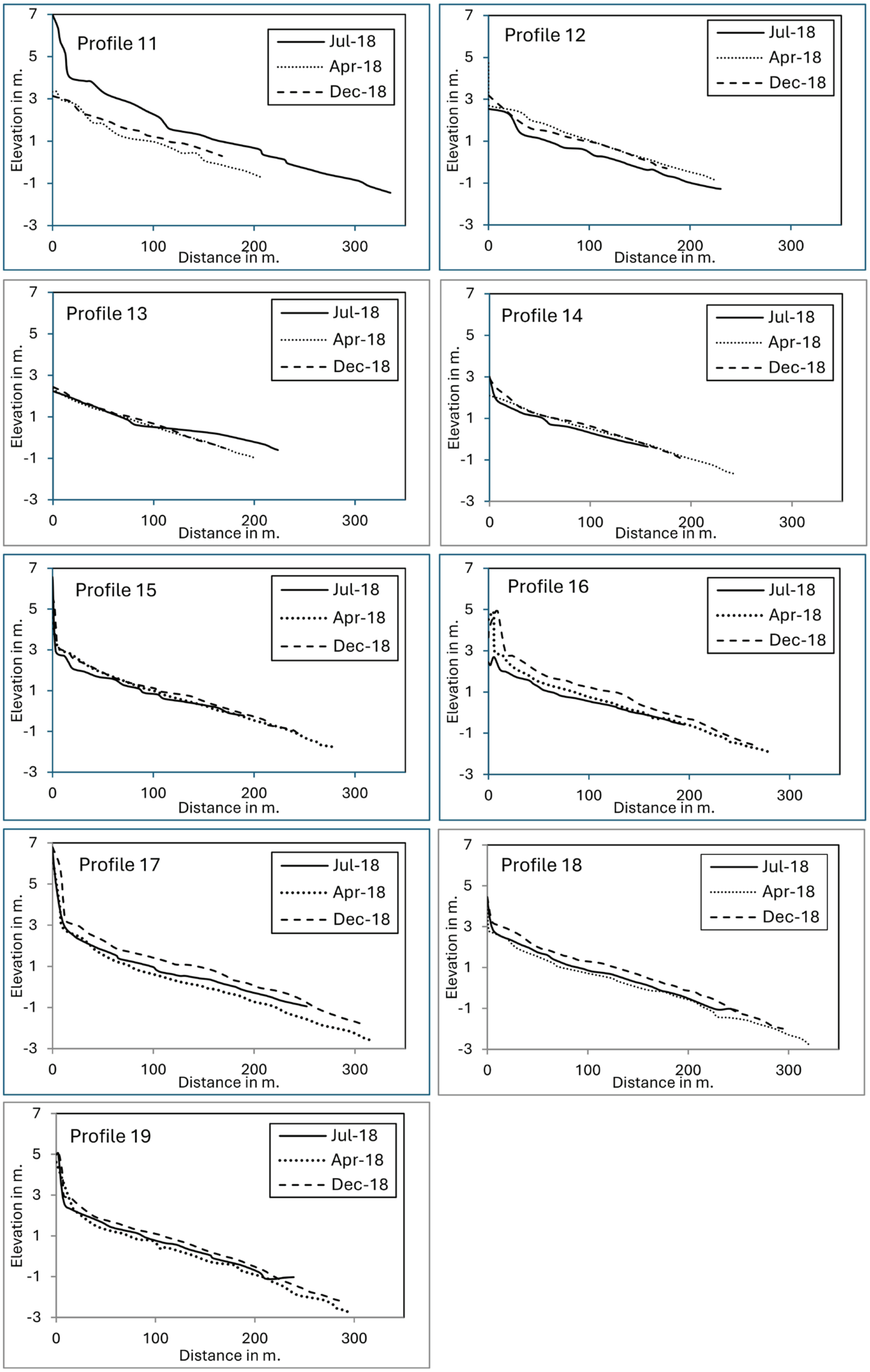


Figure 4. Spatio-temporal variation of beach profiles in Dadanpatrabar sector.

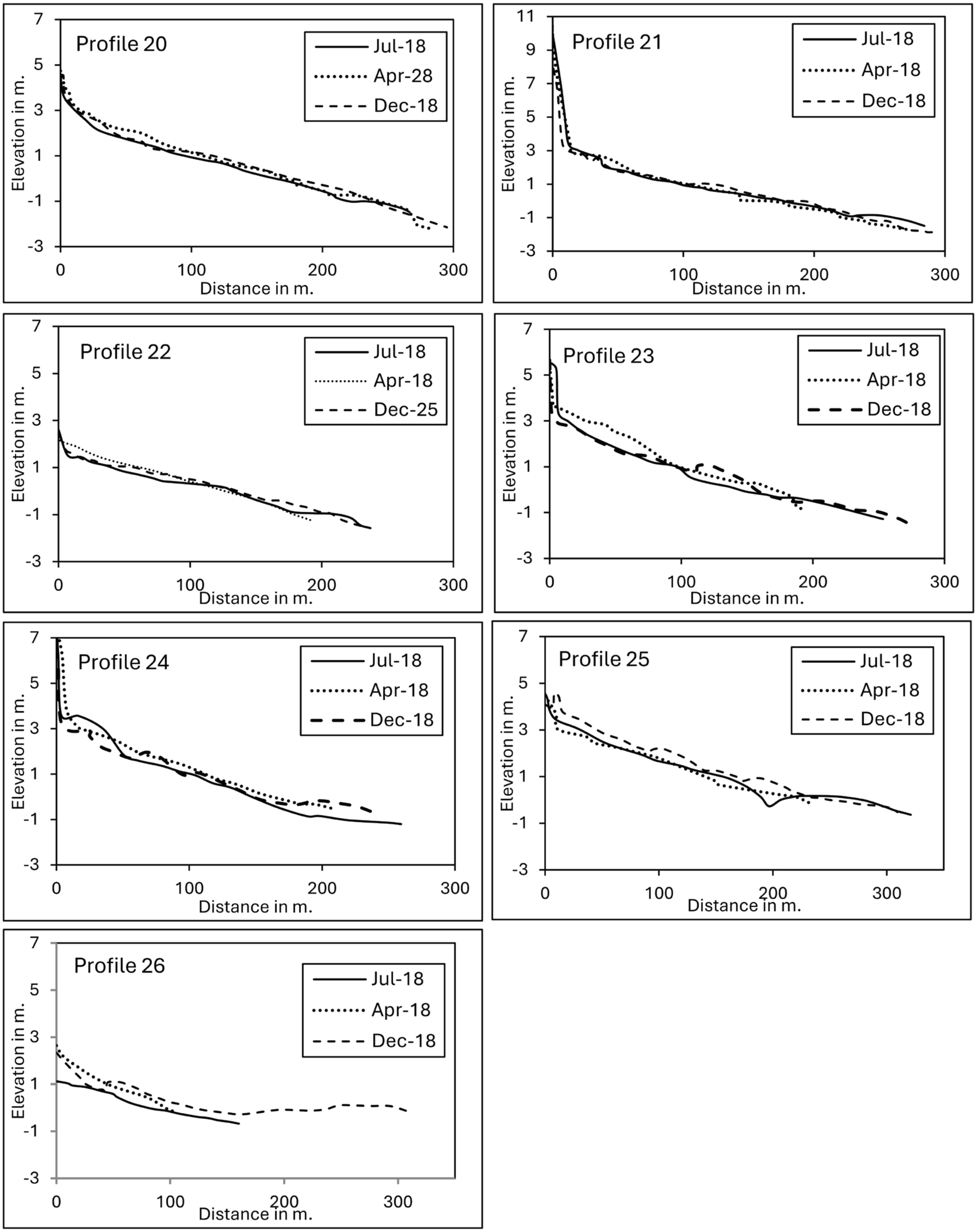


Figure 5. Spatio-temporal variation of beach profiles in Jaldha sector.

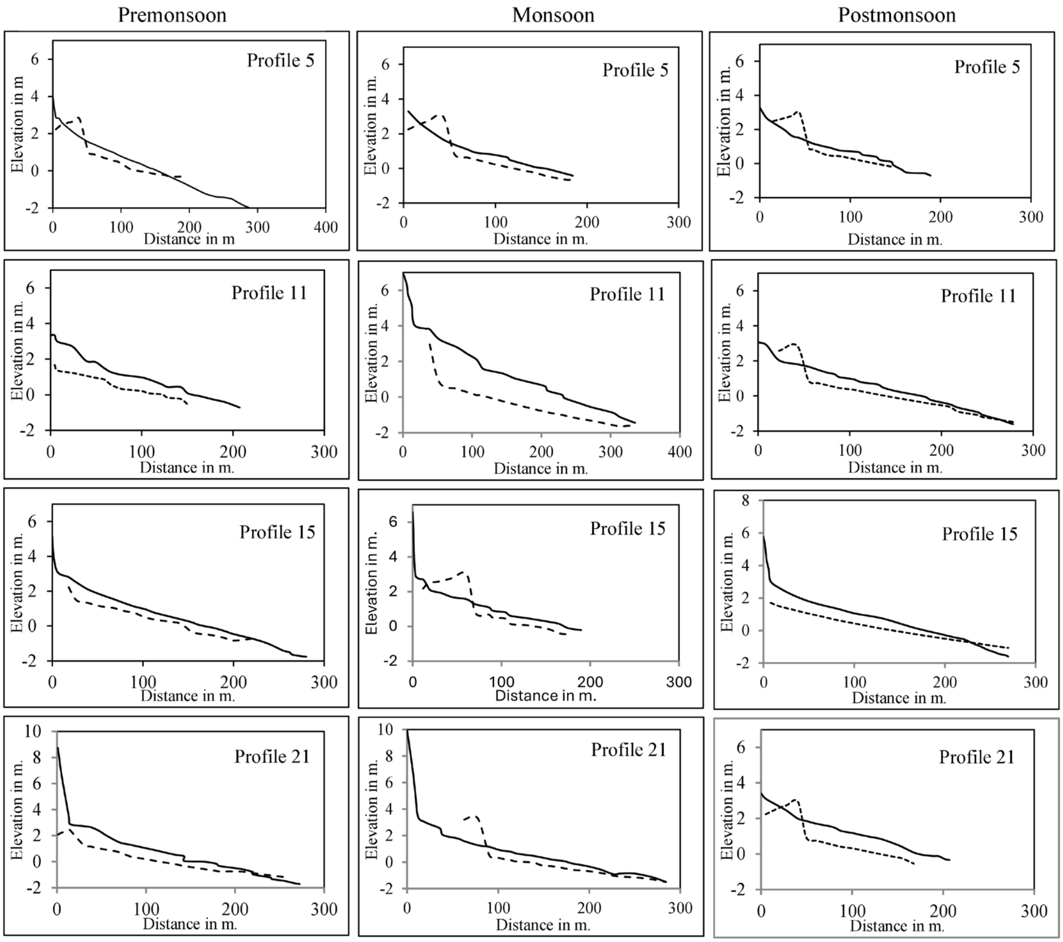


Figure 6. Deviation between observed and equilibrium beach profiles of some selected profiles.

Actual cross shore transects of profile 15 started from a seawall where the upper beach face shows high deviation from equilibrium condition especially in monsoon season. The mid-shore zone is close to equilibrium indicating natural adjustment. In case of profile 21, the upper beach face continues to show higher than equilibrium profile. In pre-monsoon season and post-monsoon season, the actual profile lies between 50 m and 200 m which is close to the equilibrium profile, but characterised as sediment rich beach. Beyond 200 m the actual and equilibrium profiles nearly match, showing offshore region is closer to equilibrium condition. In monsoon season, the actual profile is much steeper than the equilibrium profile. This suggests that erosion of the dune is caused due to high energy wave events in monsoon season. In middle beach, the equilibrium profile shows a small bar while the actualprofile is flatter, which indicates departure from equilibrium dominated by erosion (Fig. 6).

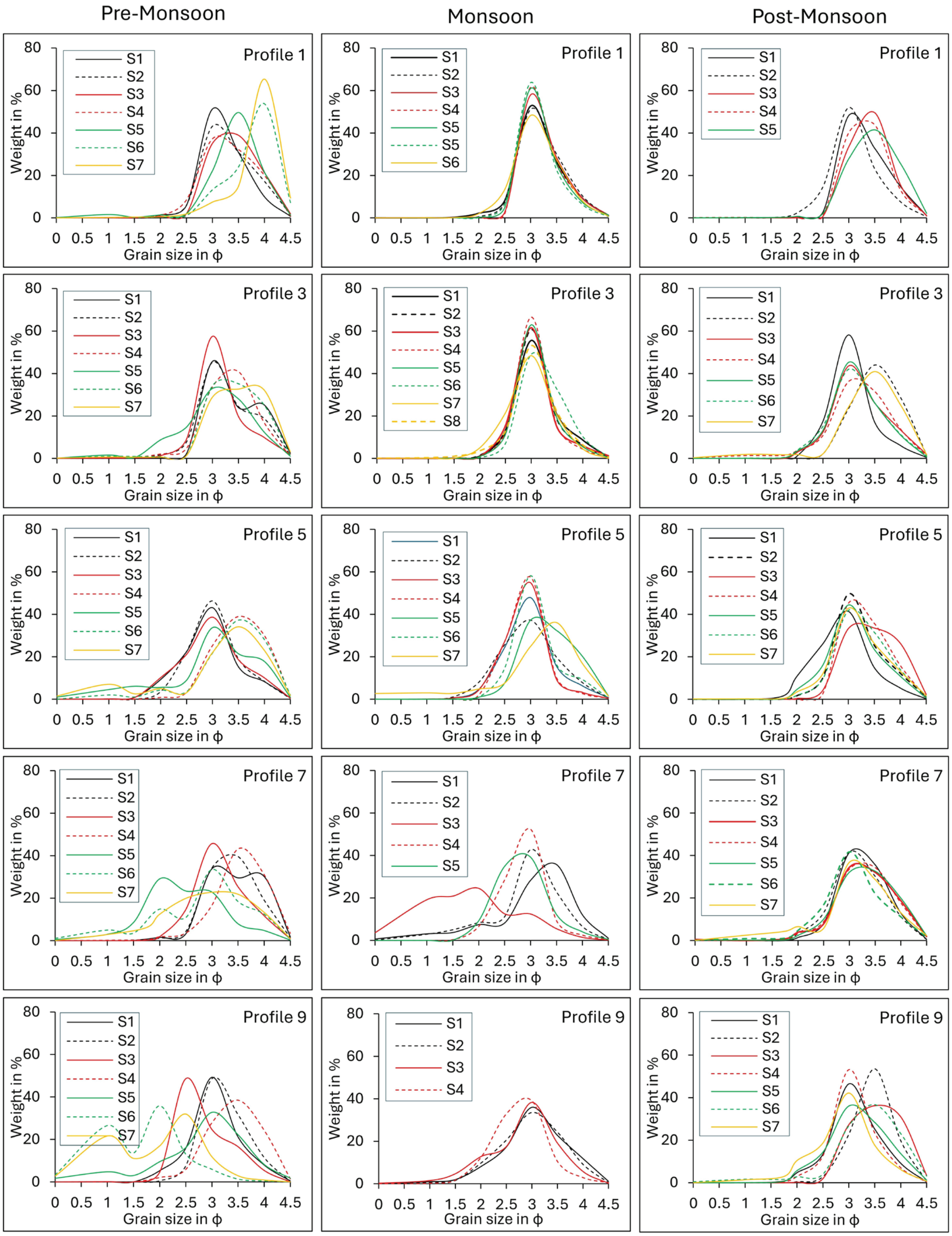
Seasonal dynamics of sediment character

The seasonal grain size distribution

patterns in the three sectors reflect marked spatial and temporal variability driven by hydrodynamic conditions, sediment sources, and beach morphology. Across all sectors, a general trend of textural homogenization was observed during monsoon, contrasting with the higher variability and bimodality evident duringpre-monsoon and post-monsoon seasons. However, inter-sectoral differences remain pronounced, especially in the degree of sorting and modal shifts across the beach face. At Pichaboni (Fig. 7), pre-monsoon samples reveal bimodal curves in profiles 1, 3, 5, and 7, particularly evident in samples from the mid to lower foreshore (S4–S7), indicating dual sediment sources or reworking of older deposits. Profile 3 displays a sharp peak at ~2.5 ϕ and a secondary peak near 1.5 ϕ in S4–S5, reflecting the influx of moderately sorted medium sand and some coarser fractions, possibly associated with active swash zone processes. In contrast, during monsoon season, unimodal and well-sorted distributions dominate across all profiles, especially in profiles 1 and 3, where grain size peaks are tightly clustered between 2.5 and 3.2 ϕ across S1–S6. This reflects enhanced suspension and redistribution of sediments due to high wave energy and onshore-offshore sediment fluxes. Post-monsoon distributions regain bimodality in several profiles, with profile 5 showing renewed textural heterogeneity along the mid-beach (S3–S5), likely due to reworking of swash and partial recovery of beach face materials.

At Dadanpatrabar (Fig. 8), the sedimentological patterns show a slightly different narrative. Pre-monsoon profiles are often characterised by poorly sorted and multimodal curves, especially evident along the profiles of 11, 15, and 17. Profile 11, for instance, demonstrates overlapping but distinct peaks near 2.2 ϕ and 3.5 ϕ in S1–S4, suggesting a mix of medium and fine sand fractions with varying depositional histories, possibly from aeolian dune or storm-derived over-wash fans. The monsoon period yields sharper, better-sorted unimodal peaks centered around 2.7–3.2 ϕ across most profiles, including profiles 11, 13, 15, and 17, showing stronger hydrodynamic control and homogenised sediment input. Post-monsoon profiles, however, reflect increased variability again. Notably, profile 15 displays a broadened peak distribution from 2.2 to 3.7 ϕ across S3–S7, indicating beach rebuilding through deposition of finer sand and reestablishment of transitional zones. The presence of fine skewness in some shoreward samples (S1–S3) during post-monsoon (e.g., profile 19) may imply aeolian redistribution or mild backshore flooding during retreating monsoonal tides.

The Jaldha sector (Fig. 9) presents some of the most irregular and morphodynamically sensitive sediment curves. Pre-monsoon distributions, especially along the profiles of 21, 22, and 24, show distinct bimodal peaks, notably in profile 21 (S3–S6), with one dominant mode at ~2.5 ϕ and a secondary one near 1.2 ϕ. This might reflect sediment inputs from both fluvial and aeolian sources, as the sector is flanked by dunes and vegetated backshore zones. Monsoon curves transition toward sharp, unimodal forms, particularly in profile 24 and 26, which show tight clustering between 2.8–3.3 ϕ, indicating energetic winnowing and offshore-directed sediment transport. Interestingly, profile 26's monsoonal samples (S1–S2) exhibit a distinctive peak separation of nearly 1 ϕ compared to pre-monsoon, indicating strong removal of coarser material. Post-monsoon



Sample IDs (S1–S7) represent sediment collected along a shore-normal transect, with S1 consistently located near the high tide line and increasing numerically toward the low tide line (S7)

Figure 7. Seasonal grain-size distribution curves along shore-normal transects in the Pichaboni sector.

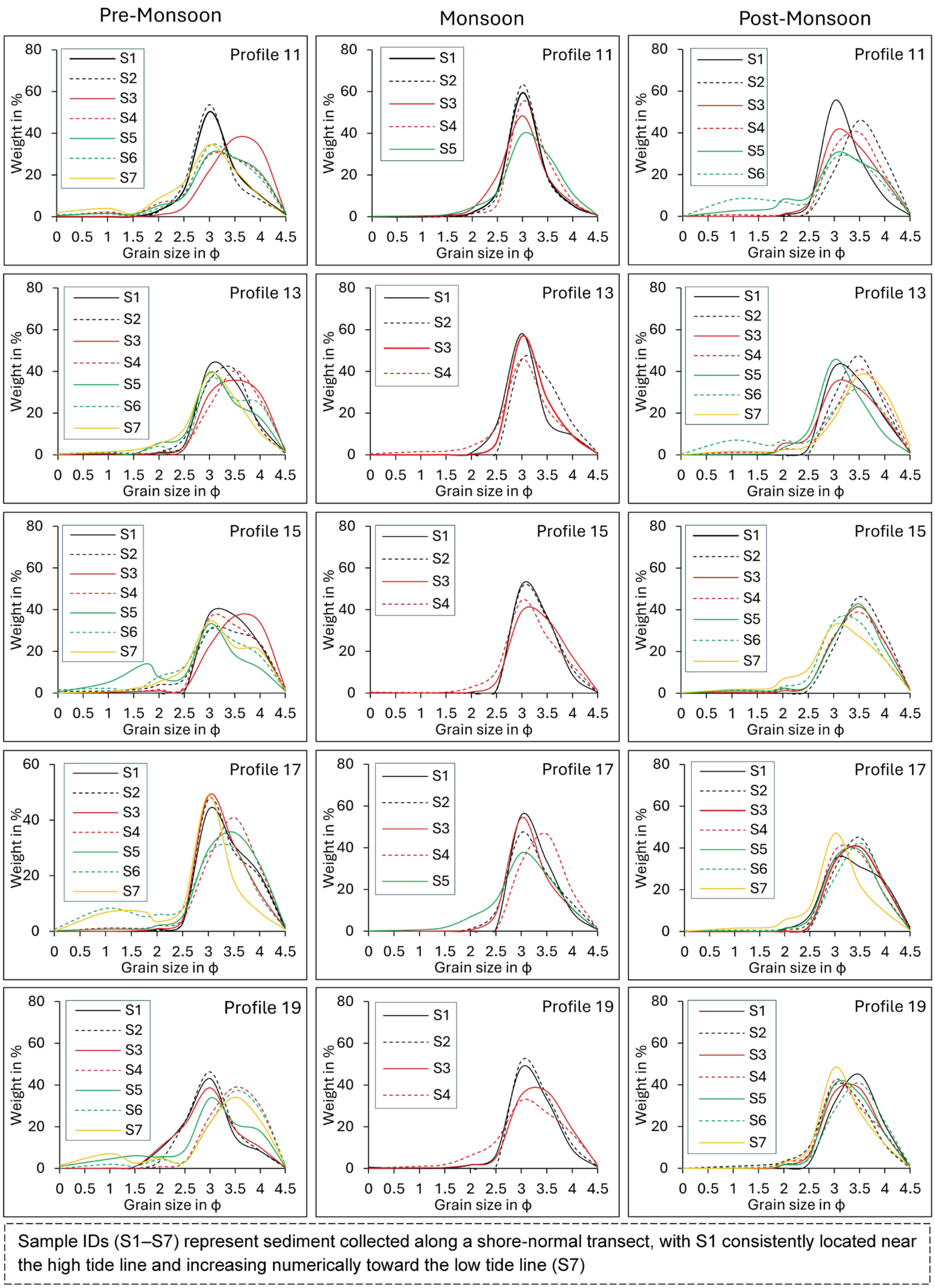


Figure 8. Seasonal grain-size distribution curves along shore-normal transects in the Dadanpatrabar sector.

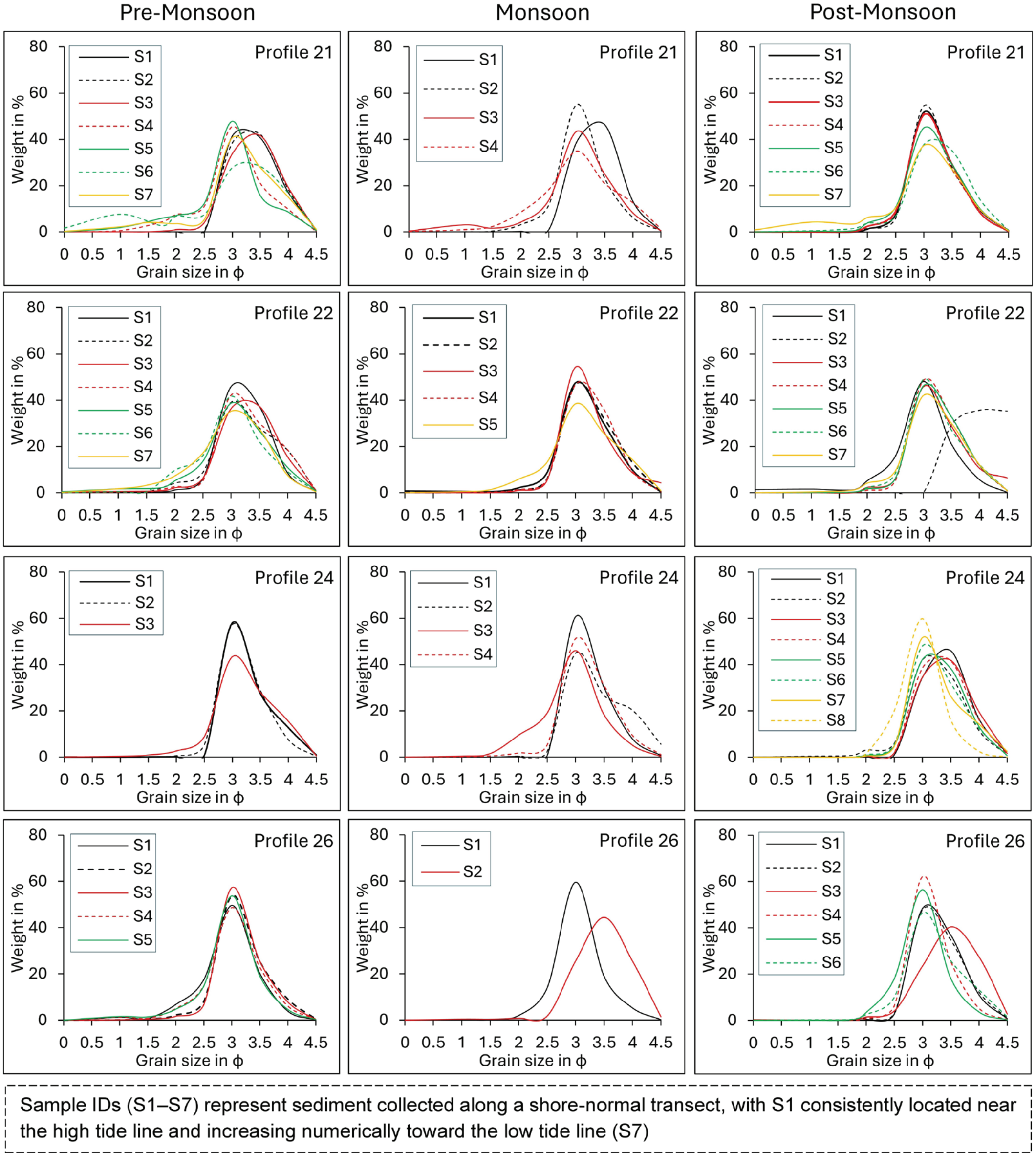


Figure 9. Seasonal grain-size distribution curves along shore-normal transects in the Jaldha sector.

curves suggest partial recovery, especially in profile 21 and 24, with wide modal ranges and resumption of bimodal tendencies in S5–S7, pointing toward swash deposition and alongshore drift influence. Across all three sectors, monsoon emerges as the most sorting-dominated season, producing tight, unimodal, and centrally peaked distributions between 2.5 and 3.2 ϕ, consistent with well-sorted fine to very fine sand. Pre-monsoon, with lower energy conditions and sediment input from aeolian and local transport sources, fosters more textural heterogeneity and bimodality. Post-monsoon reflects a transitional state—combining monsoonal sorting with gradual reintroduction of sediment diversity.Pichaboni area demonstrates the most dynamic pre-monsoon variability and strongest monsoonal sorting signature, aligning with its morphologically complex beach-face and higher wave exposure. Dadanpatrabar, while showing similar monsoonal sorting, retains higher pre- and post-monsoon modal consistency, reflecting a relatively stable profile and moderate hydrodynamic energy. Jaldha, with its pronounced beach-dune interactions and morphological variabilities (e.g., runnels, berms), exhibits the most abrupt seasonal shifts in both peak modes and grain-size distributions, pointing to sediment fluxes heavily influenced by local topography and episodic storm activity.

Statistical parameters of sediment grain size distribution

Mean grain size

The spatial distribution of mean grain size (ϕ) in Jaldha, Dadanpatrabar, and Pichaboni sectors exhibits clear seasonal variation during pre-monsoon, monsoon, and post-monsoon seasons. In pre-monsoon, sediments are uniformly fine to very fine sand across the profiles, with ϕ values ranging from 2.9 to 3.3. The central Dadanpatrabar sector records very fine sediments, with ϕ values exceeding 3.3, while Jaldha and Pichaboni sectors show slightly coarser values, generally between 2.9 and 3.1. In monsoon, a shift in texture is evident, where Jaldha sector dominated by finer sediments (ϕ ~3.3–3.5), as indicated by lighter tonal values, whereas Pichaboni sector contains relatively coarser sediments (ϕ ~2.5–2.9). The Dadanpatrabar sector again remains intermediate, with values of around 2.9–3.1. By the post-monsoon, mean grain size increases across most of the profiles, particularly in the Dadanpatrabar and Pichaboni sectors, where values ranges from 3.1 to 3.3, indicating finer sediment accumulation. In contrast, Jaldha sector becomes relatively coarser again, with ϕ values of around 2.8. The observed grain size trends indicate a dynamic seasonal reorganization of sediment textures, with finer material accumulating in different sectors depending on the season (Fig. 10).

Sorting

The sediment sorting in the study area, based on Folk and Ward's classification, ranges from very well sorted (ϕ <0.35) to moderately sorted (up to approximately 1.0 ϕ), with no instances of poorly or extremely poorly sorted material in any season. During pre-monsoon, sediments are generally well to very well sorted across all the profiles, reflecting deposition under relatively low-energy and stable hydrodynamic conditions. A clear cross-shore zonation is evident in Mandarmani coastal area of West Bengal. The upper beach which is closer to the high tide line, exhibits the best sorting, with extensive areas under very well sorted class (<0.35 ϕ). This pattern is strongest at Dadanpatrabar sector (Fig. 11), where both alongshore and shore-normal sorting is consistently high. The middle and lower beach zones transition into well sorted (0.35–0.5 ϕ) and moderately well sorted (0.5–0.71 ϕ) textures, particularly evident in the lower beach, indicating greater grain size variability because of more frequent inundation and swash-zone turbulence. This upper-to-lower beach deterioration in sorting is observed in all three sectors but most pronounced in Pichaboni. In the monsoon season, sorting visibly degrades, particularly in the middle and lower beach zones across all the profiles. The Dadanpatrabar sector shows the highest deterioration of sorting values (ϕ ~0.7–1.0) in these zones, indicating a shift to moderately sorted conditions, especially toward the lower beach. Despite this, the upper beach zones across all three sectors continue to maintain very well to well sorted conditions (ϕ < 0.5), highlighting their relative insulation from high-energy wave turbulence. In contrast, Jaldha sector retains more uniform sorting across the beach profile, with large areas showing well to moderately well sorted sediments, and less pronounced vertical variability compared to Dadanpatrabar. The Pichaboni sector, while more variable alongshore, follows a similar trend, with relatively poorer sorting in the lower beach during the monsoon. The post-monsoon sorting pattern shows greater spatial uniformity across the entire beach system. Most of the beach across all three sectors is characterised by well to moderately well sorted sediments (ϕ ~0.35–0.7), with no presence of moderate or poor sorting. The Dadanpatrabar sector displays a clear gradient from well sorted upper beach to moderately well sorted lower beach. The Pichaboni sector is highly uniform, with widespread well sorted sediments dominating the entire beach face and only minor variation near the low tide line (LTL). The Jaldha sector contains an extensive zone of well to moderately well sorted textures, with slightly more lateral variation, and no zones of moderate or poor sorting.

Kurtosis

In the pre-monsoon, Jaldha sector is dominated by mesokurtic (0.90–1.11) and leptokurtic (1.11–1.50) values, particularly along the upper and middle beach zones (Fig. 12). A few small patches of very leptokurtic (1.50–3.00) sediments appear in localized middle to lower beach areas. The Dadanpatrabar sector features a combination of mesokurtic and platykurtic (0.67–0.90) distributions, especially across the upper and middle beach. Occasional leptokurtic zones occur along the central reach. In the Pichaboni sector, most of the area is classified as platykurtic to mesokurtic, with limited occurrences of leptokurtic zones toward the inner beach margin. In the monsoon, the kurtosis pattern becomes more heterogeneous. The Jaldha sector displays alternating zones of mesokurtic and leptokurtic values across all beach levels, with increased spatial spread of very leptokurtic patches, especially in the lower beach. The Dadanpatrabar sector exhibits a broader presence of leptokurtic areas in the middle and lower beach, while the upper beach remains largely mesokurtic. Patches of platykurtic sediments are scattered in transition zones. In the Pichaboni sector, a wider range of values appears, with dominant mesokurtic conditions and scattered zones of leptokurtic and platykurtic sediments. In the post-monsoon, the kurtosis pattern becomes more uniform. The Jaldha sector predominantly shows leptokurtic to mesokurtic values, with larger, continuous patches of leptokurtic sediment along the middle and lower beach. The upper beach displays mainly mesokurtic distributions. The Dadanpatrabar sector is characterised by widespread mesokurtic conditions, with narrow bands of leptokurtic values confined to the lower beach. No very leptokurtic or platykurtic zones are prominently developed. The Pichaboni sector reflects mostly mesokurtic distributions across the entire profile, with minor platykurtic zones scattered in the lower beach and isolated occurrences

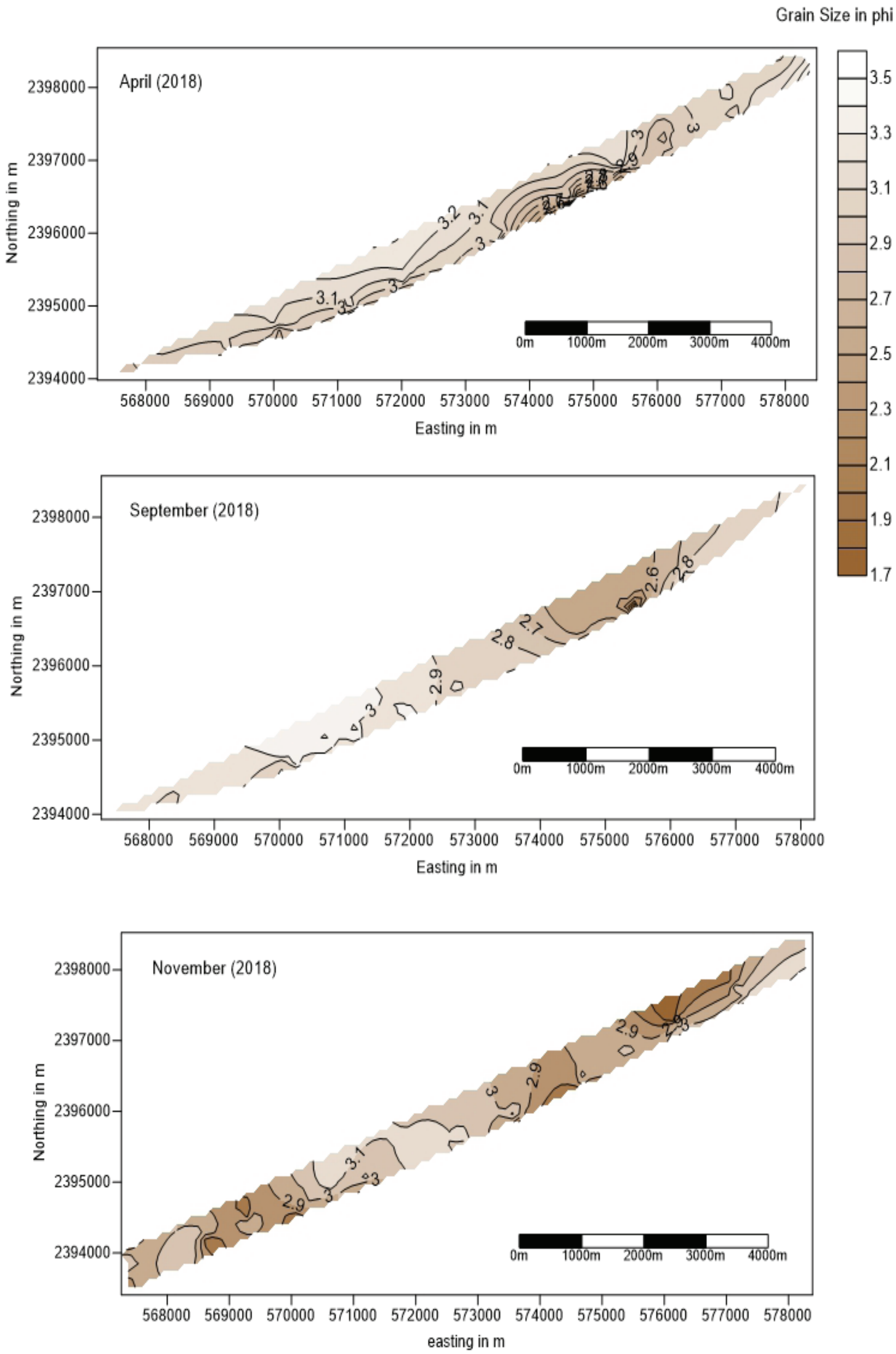


Figure 10. Spatial variation in mean grain size (in ϕ) across the Mandarmani coast during pre-monsoon, monsoon, and post-monsoon of 2018.

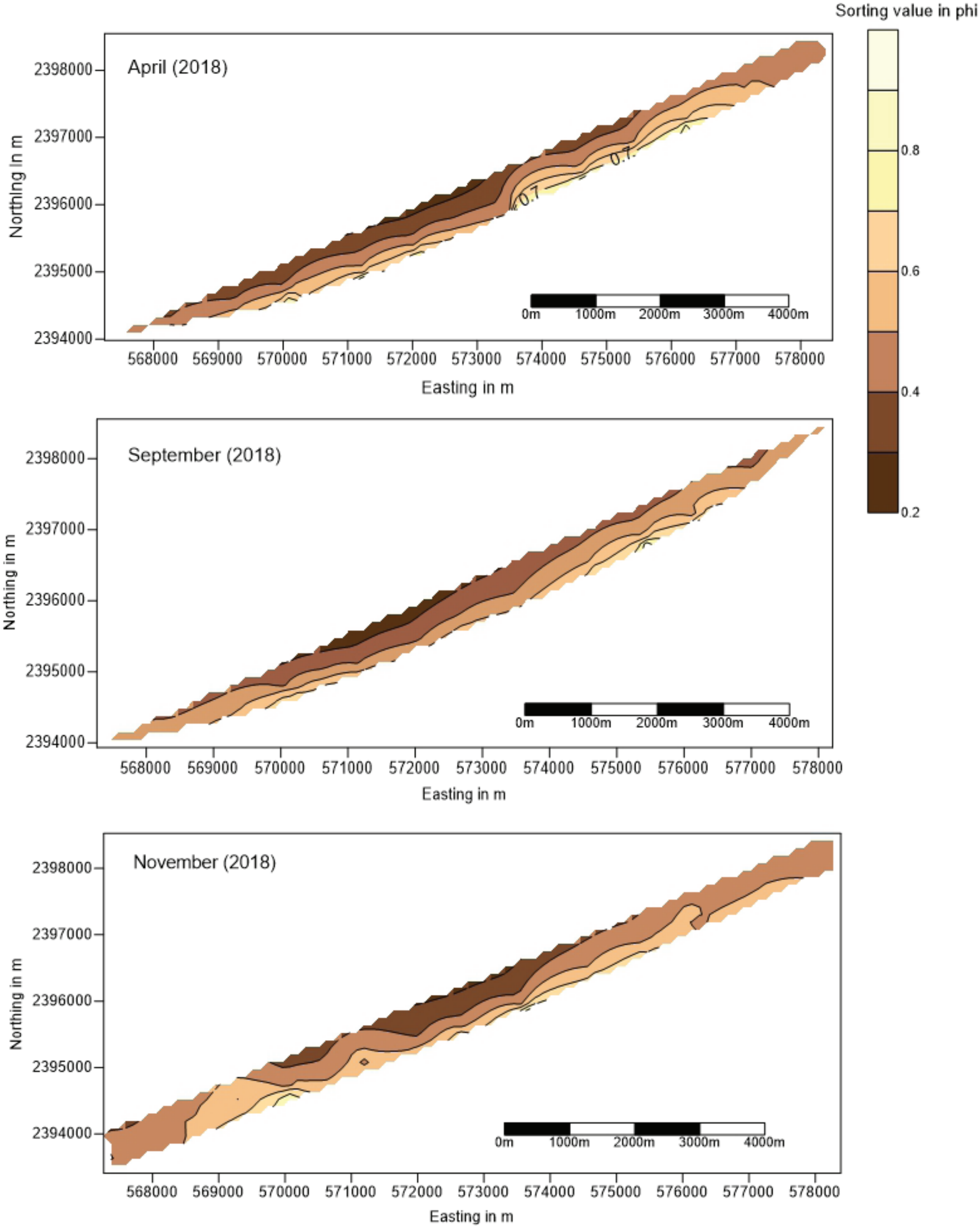


Figure 11. Spatial variation in sediment sorting (in ϕ) across the Mandarmani coast during pre-monsoon, monsoon, and post-monsoon of 2018.

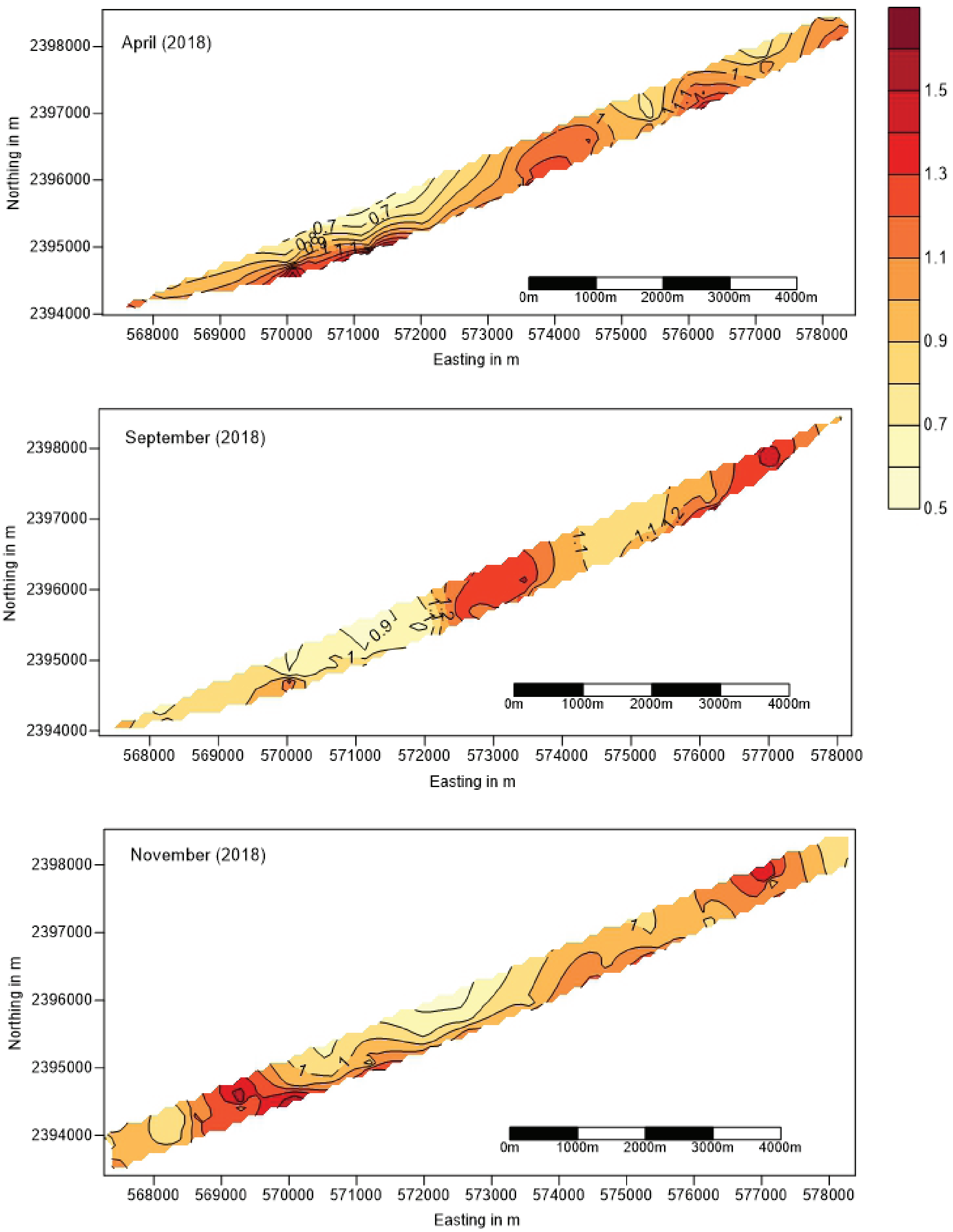


Figure 12. Spatial variation in Kurtosis across the Mandarmani coast during pre-monsoon, monsoon, and post-monsoon of 2018.

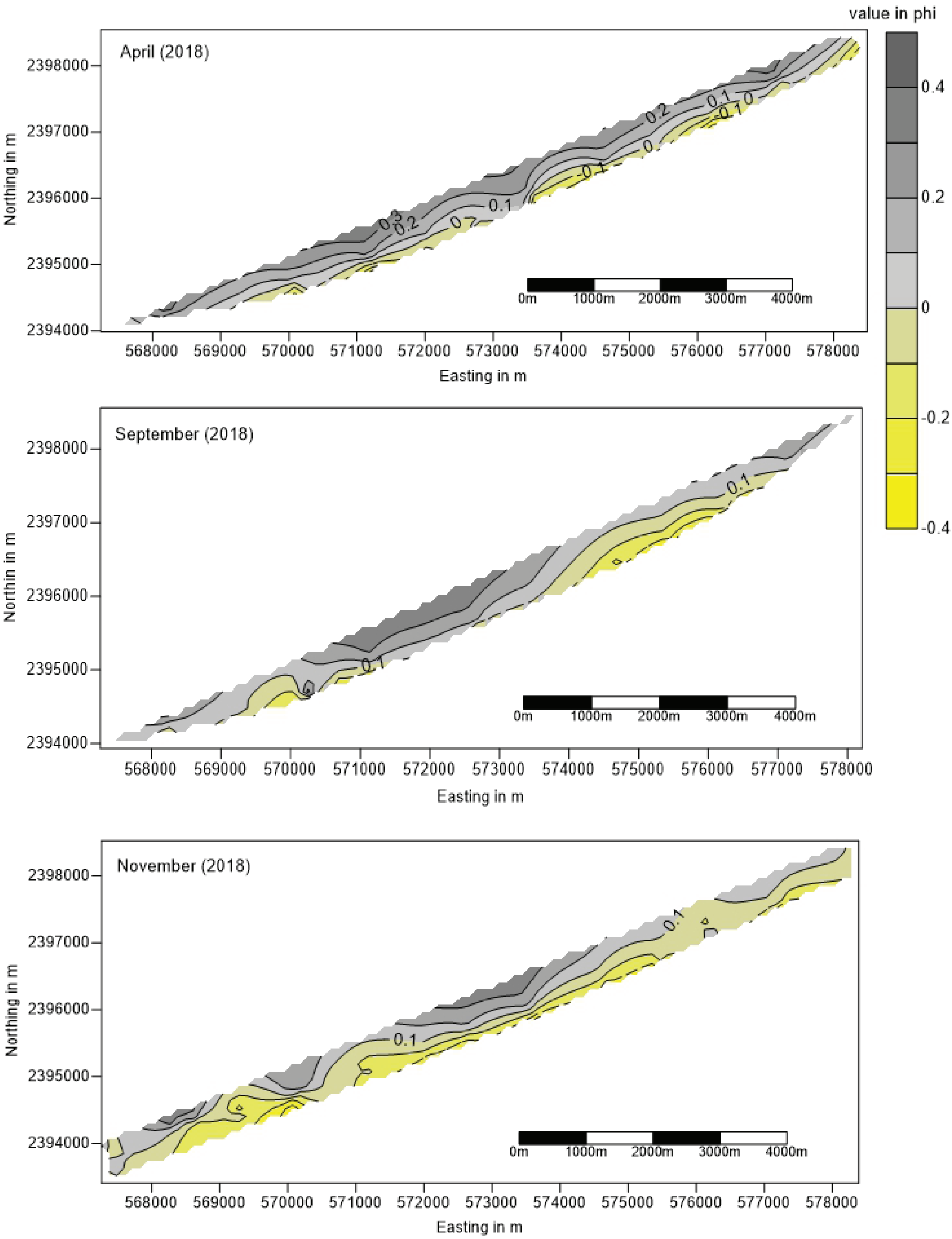


Figure 13. Spatial variation in skewness across the Mandarmani coast during pre-monsoon, monsoon, and post-monsoon of 2018.

of leptokurtic values in the middle beach. No extremely leptokurtic or very platykurtic values are observed in any season.

Skewness

The spatial variability of skewness of sediment distribution revealed that the pre-monsoon skewness distribution is predominantly fine skewed (+0.10 to +0.30) to near symmetrical (+0.10 to –0.10) across most parts of the study area (Fig 13). In Jaldha sector, the entire beach profile is largely covered by fine skewed sediments, where upper and middle beach zones consistently maintaining values ranges from +0.2 to +0.3. The Dadanpatrabar sector shows a central swath of near symmetrical sediment extending along the mid-beach, flanked by fine skewed zones toward the upper beach. A narrow belt of coarse skewed (–0.10 to –0.30) sediments appear in the lower beach. In Pichaboni sector, a similar cross-shore gradient exists, with fine skewed sediment in the upper beach and transitions to near symmetrical and coarse skewed zones closer to the LTL. In the monsoon, the skewness pattern becomes more spatially variable. The Jaldha sector retains a continuous stretch of fine skewed conditions in the upper and middle beach zones, while the lower beach introduces patches of coarse skewed values, primarily near the LTL. The Dadanpatrabar sector contains a wider distribution of coarse skewed sediments along the mid to lower beach, while upper portions remain near symmetrical. A few localized patches of strongly coarse skewed (–0.30 to –0.40) values appear in the central zone. The Pichaboni sector shows the highest concentration of coarse skewed sediments, particularly in the lower beach, whereas the upper beach still retains near symmetrical to fine skewed textures. During the post-monsoon period, the Jaldha sector displays a clear shore-normal gradient, where the lower beach is dominated by coarse to strongly coarse skewed sediments (–0.10 to –0.40) and the upper beach exhibits near symmetrical values (–0.10 to +0.10). The Dadanpatrabar sector is characterised by a uniformly near symmetrical distribution across the upper and middle beach zones, gradually transitioning into coarse skewed sediments (–0.10 to –0.30) toward the lower beach. The Pichaboni sector shows a more extensive dominance of coarse to strongly coarse skewed sediments (–0.20 to –0.40) across the entire beach profile, where some pockets in the upper beach is characterised as near symmetrical.

Discussion

Spatio-seasonal transformation of beach morphology

The Mandarmani coast represents a monsoon-dominated, mesotidal beach system where morphological variability arises from the seasonal interplay of wave energy, tidal range, and sediment circulation within a semi-enclosed littoral environment. Together, the three morphodynamic sectors—Pichaboni, Dadanpatrabar, and Jaldha form an integrated sediment-sharing system within the Mandarmani coastal tract, operating as an interlinked continuum of erosion and accretion zones that maintain an overall sediment balance. Despite localized variations in shoreline response due to inlet dynamics, wave convergence, and nearshore current reversals, these sectors exhibit synchronized adjustments to seasonal monsoonal forcing. During the high-energy southwest monsoon, sediment transport intensifies eastward, nurturing depositional features near the Pichaboni inlet, whereas the post-monsoon period witnesses subdued transport and partial redistribution of beach material westward. This cyclical exchange of sediment, governed by the alternating dominance of littoral drift and tidal exchange, ensures morphological coherence across the 13 km Mandarmani beach, signifying the functional unity of a single, dynamic littoral cell that evolves through subtle shifts in hydrodynamic and sedimentary processes (Mandal and Chaudhuri, 2023).

Seasonal oscillations between erosional and accretional phases are pronounced across all 26 profiles. During the monsoon, high-energy waves with increased obliquity, coupled with elevated tidal levels, induce significant foreshore erosion and vertical beach lowering. The predominance of high-energy bearing breakers and enhanced longshore currents trigger active sediment displacement seaward, leading to beach loss. The mean profile lowering of 1–2 m and lateral retreat up to 40–50 m recorded during this period are indicative of a high-energy regime where sediment is redistributed offshore to form nearshore bars. Following the monsoon, the post-monsoon season marks the initial phase of morphological recovery. As storm energy subsides, low-amplitude swell waves begin to migrate sediment landward from the nearshore bars, resulting in partial profile infilling and smoothing. The foreshore regains elevation gradually. The pre-monsoon phase represents the culmination of this recovery cycle. Under persistently calm hydrodynamic conditions onshore sediment transport dominates, facilitating beach reformation and gentle beach steepening. The enhanced beach width (up to ≈ 270 m on average) and elevation increase characterise a constructive phase during which the coastline approaches equilibrium before the next monsoonal reworking. This cyclic pattern—erosion during monsoon, partial restoration post-monsoon, and full accretion pre-monsoon—exemplifies the open-cell sediment exchange typical of the eastern Indian littoral drift corridor (Komar, 1998; Shankar and Shetye, 2001).

Spatially, each sector's response to seasonal forcing highlights subtle yet significant deviations attributable to local morphology and exposure. In the Pichaboni sector, monsoon erosion is most severe, often exceeding 2 m in vertical lowering, accompanied by pronounced concave profile development. Wave refraction patterns (Paul *et al.,* 2022) indicate that Pichaboni functions as the downdrift end of the littoral cell, with oblique waves generating strong south-to-north littoral drift. The prevalence of erosional equilibrium and the thicker post-monsoon accretional layer confirm this sector as a prime example of a natural beach-dune complex. In contrast, the Dadanpatrabar sector, situated at the mid-cell position (Mandal and Chaudhuri, 2023), reflects a more balanced morphodynamic regime, yet anthropologically affected. Here, the profiles remain relatively stable, with limited vertical oscillation (<1 m), and equilibrium curves closely parallel the measured profiles during calmer seasons. This morphological steadiness corresponds to its position along the mid-cell where sediment inflow from updrift (Jaldha) and outflow toward downdrift (Pichaboni) nearly offset each other, maintaining a quasi-equilibrium state. At the updrift end, the Jaldha sector exhibits a contrasting behaviour characterised by gentler slopes and more consistent sediment supply. The net northeastward sediment transport inferred from morphological trends aligns with the regional drift direction documented along the West Bengal coast (Deb *et al.,* 2017). Human interference increasingly disrupts this natural equilibrium. The construction of concrete ramps, resorts, and temporary seawalls, especially near Dadanpatrabar, alters wave reflection and limits sediment replenishment. The steeper, more reflective upper profiles near these structures indicate local sediment starvation, consistent with observations of anthropogenic narrowing of equilibrium profiles in similar tropical coasts (Anthony *et al.,* 2019).

Sediment texture and its process linkage

The sediment texture of the Mandarmani coastal sector reveals a strong spatio-temporal coherence with prevailing hydrodynamic and morphodynamic conditions. Across all three sectors—Pichaboni, Dadanpatrabar, and Jaldha distinct seasonal grain-size signatures mirror oscillations between high-energy monsoonal reworking and low-energy depositional recovery phases, while inter-sectoral variation reflects their contrasting roles within the local littoral cell.

During the monsoon, the dominance of unimodal and well-sorted fine to very fine sands (2.5–3.3 ϕ) across profiles signifies an energetic regime characterised by intense wave turbulence and longshore current activity. The uniformity of these distributions, particularly evident at Pichaboni and Dadanpatrabar, indicates efficient hydraulic sorting through winnowing of coarser fractions and offshore transport of suspended fines under high energy breakers and strong undertow. The resultant fine-skewed and mesokurtic to leptokurtic distributions demonstrate dynamic yet systematic textural organization driven by high wave energy. This process corresponds to the seaward sediment flux observed in profile lowering and foreshore erosion, as sediments are redistributed into the nearshore bar system. Such selective sorting and offshore-directed sediment transport are consistent with the energetic monsoonal hydrodynamics typical of the northern Bay of Bengal, where the net southwest-to-northeast littoral drift facilitates both cross-shore and longshore sediment exchanges (Komar, 1998; Shankar and Shetye, 2001). In the post-monsoon, attenuated wave energy and reduced breaker obliquity allow gradual sediment return from nearshore bars. Grain-size distributions regain weak bimodality and moderately improved sorting, particularly at Dadanpatrabar and Jaldha, while persistence of fine fractions and partially restored leptokurtic values indicate only partial recovery, with some monsoon-deposited load remaining offshore or advected northward. The pre-monsoon marks a shift toward constructive sedimentation, yet processes vary spatially. At Pichaboni, bimodal curves with coarser secondary peaks (1.5–2.5 ϕ) in the mid and lower foreshore indicate reworking of older deposits under calm swash conditions. The statistical parameters further reinforce the process linkage. Sorting improves with decreasing wave energy, while kurtosis transitions from platykurtic under turbulent monsoonal flows to leptokurtic during depositional recovery, denoting the progressive stabilization of the sediment population. Skewness evolves seasonally from fine-skewed during high-energy suspension dominance to coarse-skewed in the calmer, swash-dominated post-monsoon, marking the directional bias of sediment transport. The strong cross-correlation between beach slope, sorting, and mean grain size indicates that coarser, less sorted profiles correspond to steeper, erosional states, whereas finer and better-sorted sands are associated with accretional phases.

Therefore, the seasonal and spatial insights from Mandarmani's beach dynamics can guide coastal management and erosion mitigation strategies. Understanding monsoonal erosion patterns and post-monsoon recovery helps optimise beach nourishment and dune protection measures. Overall, these findings provide a scientific basis for planning resilient coastal interventions along the north-eastward-drifting sandy coast.

Conclusion

The spatio-temporal dynamics of the Mandarmani coast reveal that beach morphology and sediment texture are highly sensitive to seasonal hydrodynamic forcing, longshore drift, and anthropogenic influences. Across all three sectors—Pichaboni, Dadanpatrabar, and Jaldha a recurrent cycle of pre-monsoonal accretion, monsoonal erosion, and partial post-monsoonal recovery is evident, though the degree of response varies across sectors. Pichaboni, with its estuarine proximity and finer sediment inputs, is most vulnerable to intense monsoonal erosion, while Dadanpatrabar demonstrates relatively moderate variability but is increasingly shaped by human interventions that disrupt natural sediment exchange. The dune-backed Jaldha sector shows greater morphological resilience in some stretches, but localized erosion, runnel formation, and exposure of sub-surface mud highlight its susceptibility to wave convergence zones and storm activity.Sediment textural properties exhibit parallel seasonal adjustments. Monsoon conditions consistently generate unimodal, well-sorted fine sands across all sectors, reflecting strong winnowing and offshore-directed transport. In contrast, pre- and post-monsoon periods retain greater heterogeneity, with bimodal and multimodal distributions linked to aeolian supply, swash reworking, and alongshore drift. Statistical parameters further confirm this pattern: mean grain size shifts seasonally with finer fractions dominating during monsoon and post-monsoon; sorting deteriorates during peak energy months but recovers to well- to moderately-well-sorted conditions afterward; and skewness and kurtosis highlight the role of localised erosional and depositional processes in shaping beach texture. Overall, the Mandarmani coast functions as a dynamic sedimentary environment, where monsoonal hydrodynamics act as the primary driver of erosion and homogenisation, while calm pre- and post-monsoonal phases foster accretion, variability, and partial morphological recovery. However, anthropogenic modifications, particularly at Dadanpatrabar and Jaldha sectors, increasingly constrain natural dune-beach sediment coupling, potentially reducing resilience to future storm surges and sea-level rise. These findings underscore the importance of sector-specific coastal management strategies that account for both natural seasonal rhythms and human interventions in order to maintain the stability of this ecologically and economically significant shoreline.

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