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Seasonal Granulometric Variability and Sediment Dynamics of Kondura and Wayangani Beaches, Sindhudurg Coast, Maharashtra India: A Comparative Pre- and Post- Monsoon Investigation

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Abstract

Variability in the granulometric properties of beach sediments from season to season serves as an excellent indicator of the hydrodynamic energy available, sediment transport processes, shoreline changes, source mixing, and the erosion-deposition cycle of beaches that are affected by the monsoons. The current study highlights the granulometric attributes of the Kondura and Wayangani beaches of Sindhudurg coast, Maharashtra, India. The analysis is based on three seasons: post-monsoon 2023, pre-monsoon 2024, and post-monsoon 2024. The analyses of grain-size distributions were done based on the graphical parameters of Folk and Ward, namely mean size (Mz), inclusive graphic standard deviation/sorting (σI), inclusive graphic skewness (SkI), and graphic kurtosis (KG). The beaches consist mainly of medium to fine sands but differ in their seasonal behavior. At post-monsoon 2023, there was 63.3% of medium and 36.7% fine sand at Kondura while there was 83.3% of medium and 16.7% fine sand at Wayangani. At Pre-Monsoon 2024, there was an increase in medium sand to 70.3% at Kondura and 94.1% at Wayangani. By Post-Monsoon 2024, Kondura became increasingly heterogeneous with 56.2% of medium sand, 40.6% fine sand and 3.1% coarse sand. There were still 70% medium sand and 30% fine sand at Wayangani. Kondura had relative stability in the beach scale mean grain size for the three surveys (around 1.86–1.93 φ) while there was increased seasonality in the beach scale mean grain size of Wayangani from 1.59 ± 0.18 φ at pre-monsoon 2024 to 1.93 ± 0.14 φ at post-monsoon 2024. There was improved sorting from 0.76 ± 0.12 φ to 0.62 ± 0.09 φ at Wayangani together with coarse-skewing from near-symmetrical (−0.08 ± 0.15) to distinctly coarse-skewed (−0.25 ± 0.06). The bivariate plots show improved sorting toward finer grain sizes and widespread negative skewness, indicating repeated hydraulic selection, swash–backwash winnowing, and episodic mixing. The Results drawn from the findings indicate that the southwest monsoon influences the sedimentary cycle on an annual basis while coastal setting influences the number of sediments redistributed. Kondura is considered a more heterogeneous geomorphically constrained sedimentary system while Wayangani maintains a more coherent medium sand framework yet experiences more seasonal reorganization.

Keywords: Granulometry, Beach Morphodynamics, Coastal Sedimentology, Sediment Sorting, Kondura Beach; Wayangani Beach

1.Introduction

Coastal sandy beaches are one of the most dynamic systems in terms of sediments as they keep on modifying their morphology and physical properties according to wave action, tides, currents, storms, sand supply, shoreline direction, geological setting, river flow, and climatic forces (Komar, 1998; Short, 1999; Masselink & Hughes, 2003; Cooper et al., 2020). Grain size analysis is thus used extensively to assess sediment movement, hydraulic energy, source diversity, textural maturity, and erosion-deposition processes. Such a change is especially noticeable in the case of tropical coastlines where seasonal changes from active monsoonal to fair weather climates create periodic cycles of erosion, redeposition, and reworking. Statistics of grain-size parameters offer a quantitative basis for the interpretation of such sedimentary adjustments. Mean grain size is the measure of the central tendency of the grain size distribution and indicates the combined effect of sediment supply and transportation capability. Sorting or inclusive graphic standard deviation is a measure of hydraulic sorting, while skewness is a measure of skewness resulting from the enrichment of finer or coarser tails of the distribution. Kurtosis is a measure of the clustering of grains about the mode compared to the tails (Folk & Ward, 1957; Folk, 1966; Friedman, 1967, 1979). Since no individual statistical parameter can uniquely

identify a deposition process, the best interpretation is achieved by assessing all these parameters together and taking into account the geomorphology and seasonality of processes (Moiola & Weiser, 1968; McLaren & Bowles, 1985).

The graphical technique put forth by Folk & Ward in 1957 still stands out as the basis of most of the contemporary studies of granulometry. In addition, the GRADISTAT software developed by Blott & Pye (2001) offered consistency in calculating grain size statistics and textural characterization to allow comparative study of different sedimentary settings. Bivariate plots for average grain size, sorting, skewness, and kurtosis were also widely used to delineate transport populations and relative energy conditions (Mason & Folk, 1958; Friedman, 1961; Martins, 1965; Visher, 1969; Rajganapathi et al., 2013). In the west coast of India, the southwest monsoon results in a clear seasonal cycle in wave climate and precipitation. High energy monsoonal waves may cause erosion of the beach profile, formation of coarser lag deposit, deposition of sediments in offshore and alongshore directions and widening of the grain size distribution, while low energy waves might help in sediment migration in landward direction and beach profile reconstruction (Wright & Short, 1984; Komar, 1998; Prakash et al., 2022). Research in the central and south-west coast of India has shown that grain size composition is highly influenced by seasonal forcing; however, adjacent beaches may behave differently due to the reasons stated above (Dora et al., 2021; Kumar et al., 2023).

Previous investigations into the Indian coast using sedimentology have shown the importance of grain size analysis in coastal process interpretation. Rajganapathi et al. (2013) utilized textural variables in identifying the coastal sediments of the Tamil Nadu coast, whereas Santhiya et al. (2022) highlighted the importance of bivariate analysis in differentiating depositional environments in the Indian peninsula. Regional syntheses have further revealed that sediments of Indian beaches tend to vary from well-sorted fine sand to poorly sorted medium and coarse sediments depending on varying hydrodynamic energy, sources, and seasonality (Nageswara Rao et al., 2020; Vespremeanu-Stroe et al., 2021).

The Sindhudurg coast of Maharashtra is an appropriate choice to make such a comparison due to its formation of sandy beaches with rocky outcrops and small embayments and creek mouths separating them. The formation of the coastline could lead to sediment compartmentalization and altered wave refraction, littoral transport, and rip current dynamics. Kondura and Wayangani beaches are close geographically but differ in their geomorphology. While Kondura is relatively narrow and shows variation locally, Wayangani is more open sandy beach where alongshore and swash backwash dynamics could work effectively on the beachface. In the current study, three seasonal states have been considered namely post-monsoon 2023, pre-monsoon 2024, and post-monsoon 2024, to assess whether both beaches react in the same manner to regional monsoon influences and whether consecutive post-monsoon surveys can yield similar sedimentological states. The primary purposes include (i) understanding sediment grain size and sedimentation statistics of both beaches; (ii) determining seasonal variability in grain size, sorting, skewness, and kurtosis; (iii) comparing percentages of course, medium, and fine sand; (iv) examining significant bivariate relations; and (v) discussing the different sediment dynamic behavior of a restricted beach and an open beach.

2. Study Area

Kondura and Wayangani beaches occur along the coastline of Sindhudurg in south Maharashtra state within the eastern rim of the Arabian Sea (Figure 1). The Sindhudurg coast belongs to the Konkan physiographic province and is marked by a combination of rocky headlands, sandy pocket and open beaches, tidal creeks, estuaries, and coastal plain areas. Irregular nature of this coastline heavily affects nearshore wave transformation and sediment transport processes. The area features a monsoonal climatic regime where the southwest monsoon season, usually extending between June and September, contributes to the majority of the precipitation and wave energy. Waves and currents in the monsoonal period could lead to beach face erosion, sediment sorting, and nearshore reorganization, whereas the period before and after monsoons is known for lower wave energy. Seasonal forcing is a proven control of sediment composition along the western Indian coast (Dora et al., 2021; Prakash et al., 2022).

Kondura Beach is a relatively constrained coastal environment that is controlled by its surrounding rocky geology and drainage systems. Headland influence may serve to increase refraction and reflection of waves, reduce longshore sediment transport, and create uneven rip and swash currents. In comparison, Wayangani Beach is relatively more unconstrained and laterally continuous, allowing for better re-working of sediments as well as accumulation of a dominant sand type.

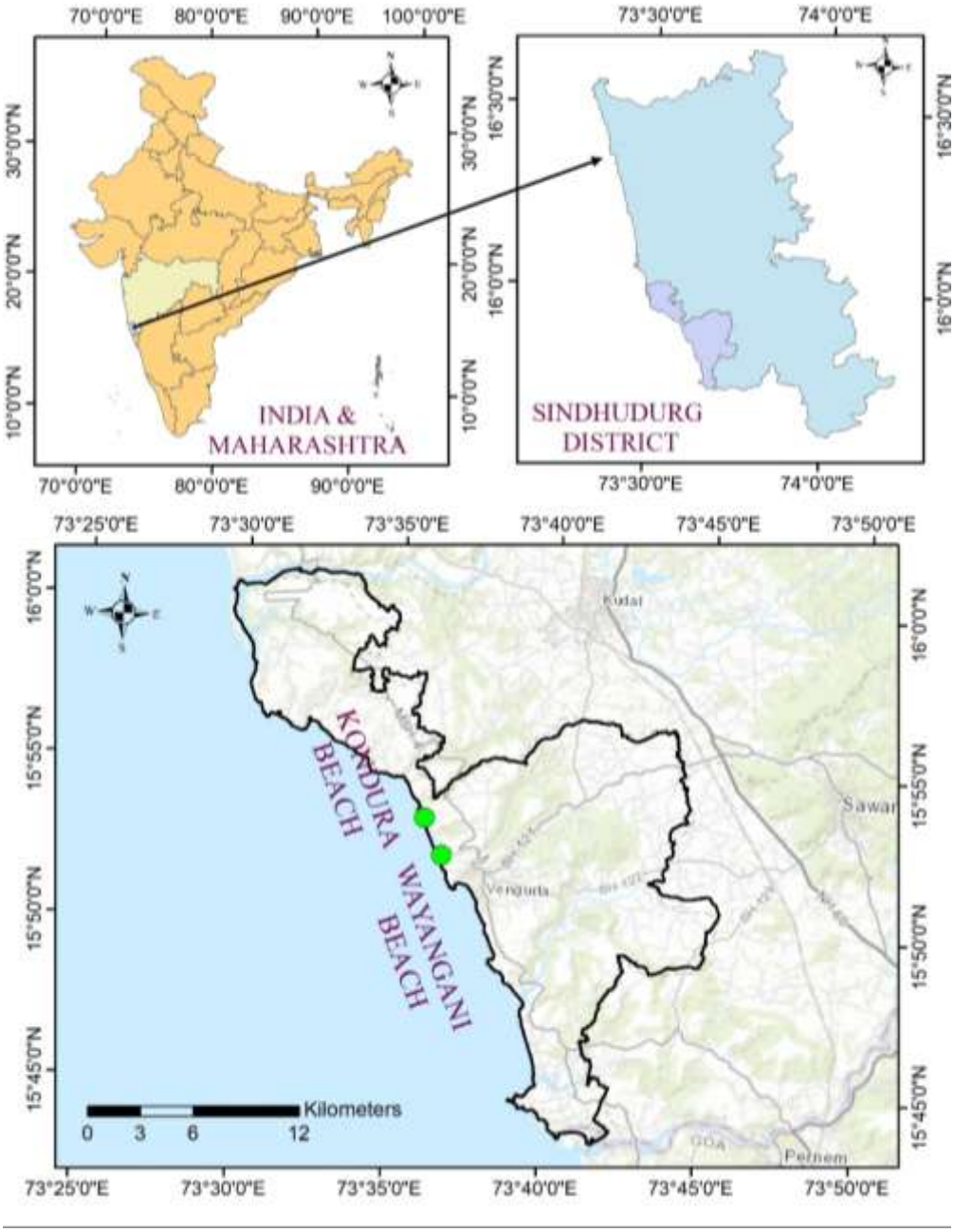


Figure 1 Location Map of Study Area

3. Materials and Methods

3.1 Seasonal Sampling framework

Samples of beach sediments collected from the surface at Kondura and Wayangani beaches have been analysed for three monitoring phases; post-monsoon 2023, pre-monsoon 2024, and post-monsoon 2024. Sampling sites have been selected at different locations on the two beaches to examine the variability of sediments along and across the beach.

Table 1: Seasonal sampling and comparative analytics framework used in the study

Survey Phase	Kondura Beach	Wayangani Beach	Purpose of Comparison
Post Monsoon 2023	Multiple Stations / Transect	Multiple Stations / Transect	Initial post-monsoonal sediment state
Pre Monsoon 2024	Multiple Stations / Transect	Multiple Stations / Transect	Fair weather Seasonal adjustment
Post Monsoon 2024	Multiple Stations / Transect	Multiple Stations / Transect	Response after a second monsoonal cycle

3.2 Grain Size parameters and classification

Grain size was expressed in the φ scale in accordance with the formula φ = −log2 d, where d is the grain diameter in millimeters (Krumbein, 1934). The interpretation of textural statistics was performed by means of the Folk & Ward (1957) graphical approach and Blott & Pye (2001) GRADISTAT classification system. The principal parameters were graphic mean grain size (Mz), inclusive graphic standard deviation (σI), inclusive graphic skewness (SkI), and graphic kurtosis (KG).

$$Mz = (\varphi16 + \varphi50 + \varphi84) / 3$$

Graphic mean grain size, representing the central grain-size tendency.

$$\sigma I = (\varphi84 - \varphi16) / 4 + (\varphi95 - \varphi5) / 6.6$$

Inclusive graphic standard deviation, used as the principal measure of sorting.

$$SkI = [(\varphi16 + \varphi84 - 2\varphi50) / 2(\varphi84 - \varphi16)] + [(\varphi5 + \varphi95 - 2\varphi50) / 2(\varphi95 - \varphi5)]$$

Inclusive graphic skewness, describing the asymmetry of the grain-size distribution.

$$KG = (\varphi95 - \varphi5) / [2.44(\varphi75 - \varphi25)]$$

Graphic kurtosis, describing the relation between the central part of the distribution and its tails.

3.3 Bivariant Granulometric Analysis

Seven combinations or bivariate relationships were evaluated: (A) standard deviation to mean grain size, (B) mean grain size versus skewness, (C) mean grain size versus sorting, (D) standard deviation versus skewness, (E) skewness versus kurtosis, (F) sorting versus skewness, and (G) mean grain size versus the combine (σI + SkI). In addition, each seasonal composite also consists of panel H, showing the percent distribution of sand textural types. Relationships like this help in determining systematic grain-size distributions and variation in mixing and hydraulic sorting of sediments (Friedman, 1961; Martins, 1965; Visher, 1969; McLaren & Bowles, 1985).

4.Results

4.1 Seasonal Variations in sand texture

The textural composition of both the beaches consists of predominantly medium and fine sand, although their ratios differ significantly from beach to beach and from season to season (Table 2). In 2023 post-monsoon, the percentage of medium sand at Kondura was 63.3%, while fine sand constituted 36.7%. On the other hand, Wayangani had 83.3% of medium sand and 16.7% of fine sand. The percentage of medium sand increased for both beaches in 2024 pre-monsoon, with 70.3% at Kondura and 94.1% at Wayangani. In the 2024 post-monsoon study, Kondura registered a maximum textural variety: the ratio of medium sand dropped to 56.2%, while fine sand increased to 40.6%; 3.1% of coarse sand emerged.

Table 2: Seasonal variation in Sand-textural composition at Kondura and Wayangani beaches

Survey	Beach	Coarse sand (%)	Medium Sand (%)	Fine Sand (%)
Post-Monsoon 2023	Kondura	0.0	63.3	36.7
Post-Monsoon 2023	Wayangani	0.0	83.3	16.7
Pre-Monsoon 2024	Kondura	0.0	70.3	29.7
Pre-Monsoon 2023	Wayangani	0.0	94.1	5.9
Post-Monsoon 2024	Kondura	3.1	56.2	40.6
Post-Monsoon 2024	Wayangani	0.0	70.0	30.0

The sustained predominance of medium sand in Wayangani is evidence of efficient accumulation of preferred grain size populations. Kondura still contains a range of sand sizes, and by post-monsoon 2024, a small component of coarse sand was present. The presence of coarse sand in this particular Kondura seasonal population is evidence of high energy erosion leading to either a coarse basal population being exposed or storm lag deposition.

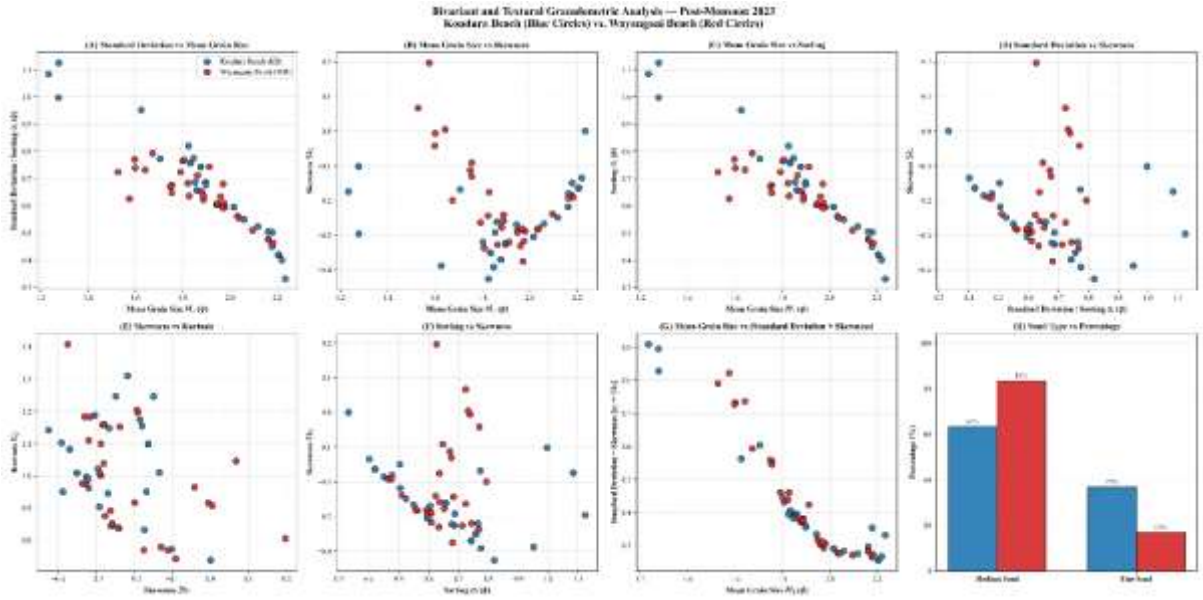


Figure 2: Comprehensive bivariate granulometric suite (A–G) and sand textural distribution (H) for Post-Monsoon 2023 comparing Kondura Beach (blue circles) and Wayangani Beach (red circles).

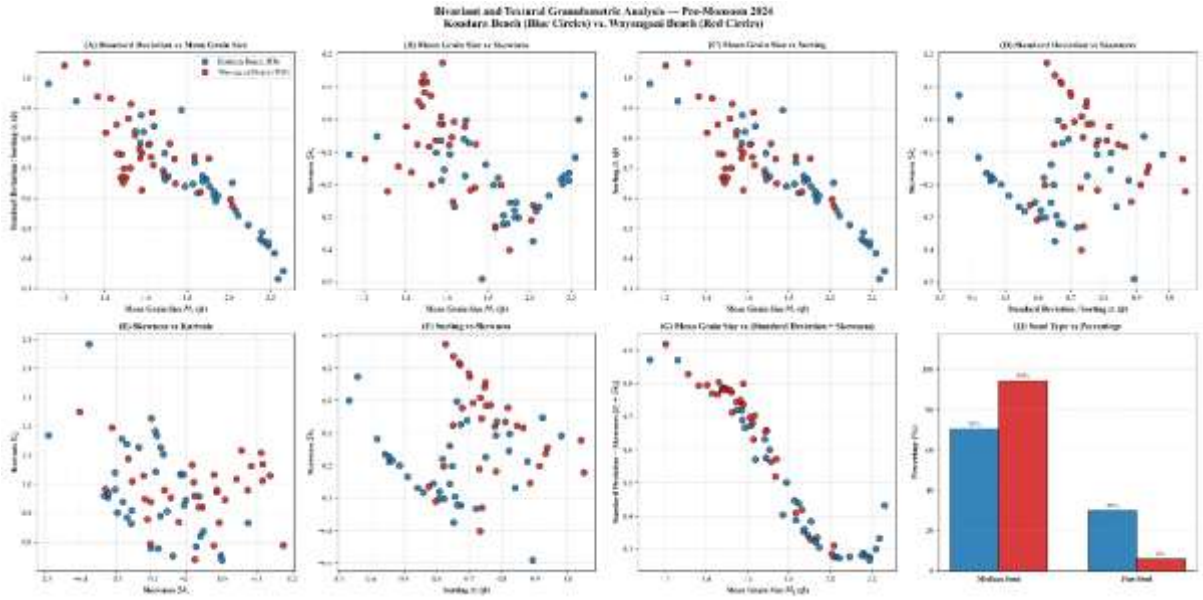


Figure 3: Comprehensive bivariate granulometric suite (A–G) and sand textural distribution (H) for Pre-Monsoon 2024 comparing Kondura Beach (blue circles) and Wayangani Beach (red circles).

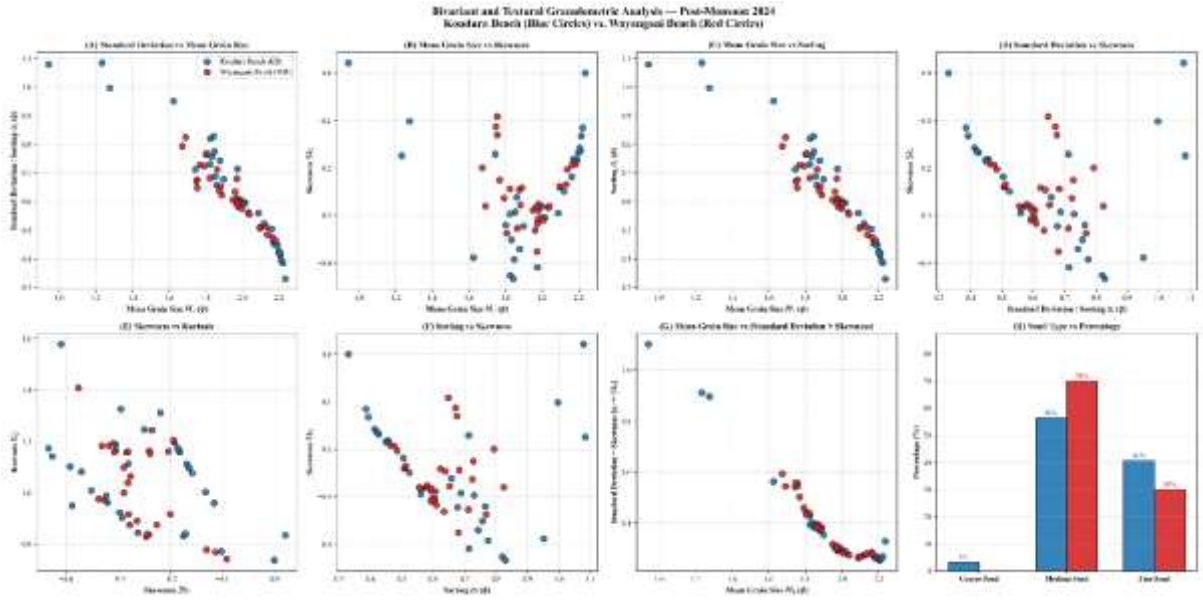


Figure 4: Comprehensive bivariate granulometric suite (A–G) and sand textural distribution (H) for Post-Monsoon 2024 comparing Kondura Beach (blue circles) and Wayangani Beach (red circles).

4.2 Seasonal summary of Grain-Size Statistics

This is evident in the seasonal mean data presented below (Table 3). There is relatively little variation in mean grain size at the beach level for Kondura while Wayangani beach displays significant variation between pre- and post-monsoon seasons. In the year 2023, Kondura had an average mean grain size of about 1.90 ± 0.27 φ in post-monsoon, 1.86 ± 0.26 φ in pre-monsoon 2024, and 1.93 ± 0.30 φ in post-monsoon 2024. Sorting remained close to 0.64–0.67 φ and skewness remained consistently negative.

Wayangani had a mean of 1.86 ± 0.17 φ in post-monsoon 2023; was coarser at 1.59 ± 0.18 φ in pre-monsoon 2024; and became finer at 1.93 ± 0.14 φ in post-monsoon 2024. Sorting degraded to 0.76 ± 0.12 φ in the pre-monsoon season and improved to 0.62 ± 0.09 φ post-monsoon. Skewness changed from almost symmetrical in the pre-monsoon mean (−0.08 ± 0.15) to a distinctly coarse-skewed post-monsoon mean (−0.25 ± 0.06).

Table 3: Comparative seasonal mean granulometric characteristics of Kondura and Wayangani beaches

Beach	Survey	Mz φ	Sorting σI (φ)	Skewness SkI	Kurtosis KG	General character
Kondura	Post-Monsoon 2023	1.90 ± 0.27	0.67 ± 0.20	−0.26 ± 0.10	Mesokurtic dominant	Medium sand; moderate to moderately well sorted; coarse skewed
Kondura	Pre-Monsoon 2024	1.86 ± 0.26	0.64 ± 0.16	−0.19 ± 0.12	0.98 ± 0.16	Medium sand; moderately well sorted; coarse skewed
Kondura	Post-Monsoon 2024	1.93 ± 0.30	0.64 ± 0.20	−0.24 ± 0.11	1.06 ± 0.18	Medium–fine sand; moderately well sorted; coarse skewed
Wayangani	Post-Monsoon 2023	1.86 ± 0.17	0.65 ± 0.08	−0.20 ± 0.13	0.99 ± 0.16	Medium sand; moderately well sorted; coarse skewed
Wayangani	Pre-Monsoon 2024	1.59 ± 0.18	0.76 ± 0.12	−0.08 ± 0.15	—	Coarser medium sand; moderately

						sorted; near symmetrical
Wayangani	Post-Monsoon 2024	1.93 ± 0.14	0.62 ± 0.09	−0.25 ± 0.06	1.03 ± 0.17	Finer medium sand; moderately well sorted; coarse skewed

4.3 Mean Grain size versus sorting

Figure 2A/C, 3A/C, and 4A/C show an inverse curvilinear relationship between the mean grain size and sorting. The samples with Mz close to 2.0-2.3 φ typically show σI of about 0.35-0.55 φ, which implies good to moderate sorting of fine sand. On the other hand, coarser sands with Mz close to 0.9-1.5 φ typically show σI above about 0.75 φ and occasionally reach 1.0 φ. It implies that the fine sand population is subjected to a better hydraulic selection compared to coarse sediment population, which is characterized by a mixture of transport populations. Similar observations on sorting of wave reworked beach sediments in favor of modal population have been reported before (Folk & Ward, 1957; Friedman, 1967; McLaren & Bowles, 1985).

4.4 Relation of mean grain size versus skewness

The graphs relating mean size and skewness (Figures 2B, 3B, and 4B) show that they follow a V-shape trend. Most samples are negatively skewed, with some of the greatest negative values found in the medium-sand category. The occurrence of negative skewness suggests that there is a coarse tail in the distribution. This is because there has been a selective sorting of the finer sediments due to swash and backwash processes. The Wayangani samples in pre-monsoon 2024 season have slightly symmetrical or positive values.

4.5 Sorting vs Skewness

Sorting-Skewness diagrams (Figures 2D/F, 3D/F, and 4D/F) separate a fairly compact well-sorted population from a widely scattered poorly sorted population. The former have σI in the vicinity of 0.35-0.55 φ maintaining negative skewness, whereas the latter have σI above 0.65 φ covering a considerably wider range of skewness values. This difference has been explained to show that certain sediments are composed of relatively homogeneous populations of grains reworked by waves, and others have mixed sediments developed under varied conditions (Friedman, 1961; Martins, 1965; Visher, 1969).

4.6 Comparison between skewness and kurtosis and composite index

The majority of samples fall in the region between mesokurtic and leptokurtic areas, with only a few samples falling in the region of platykurtic distribution. This variability is due to the varying sorting of the modal population compared to its tails. The composite relation of Mz versus (σI + SkI) helps distinguish coarse populations with poor sorting from texturally mature fine sand populations. Coarse samples show high values of the combination of both parameters, while fine samples of approximately less than 2.0 φ show low values.

5.Discussion

5.1 Monsoonal control on Seasonal sediment dynamics

From the three-survey series, it is clear that southwest monsoon-driven wave activity is the major control on the sedimentary cycle at a local level. The high-energy nature of the waves and strengthened nearshore currents associated with the monsoon could mobilize the beach face, transport sands alongshore and offshore, expose coarse sediments, and change the ratio of the grain size distributions. Low-energy phases favor hydraulic sorting and beach rebuilding. This process is in agreement with beach morphodynamic processes in literature and in monsoon-controlled regions of the Indian west coast (Wright & Short, 1984; Komar, 1998; Dora et al., 2021; Prakash et al., 2022).

Grain size analysis further reveals that even though regional forcing produces similar effects on adjacent shorelines, the responses are not exactly the same for both beaches. Wayangani Beach becomes highly concentrated in medium sand in pre-monsoon 2024 while Kondura Beach remains relatively heterogeneous throughout the research period. This suggests that the geomorphology, geological setting, and nearshore environment significantly affect the typical monsoon signal (Cooper et al., 2020; Kumar et al., 2023).

5.2 Kondura Beach: local variability within the stable beach scale

Kondura shows higher local variation in terms of granulometry compared to the other beach. In post-monsoon 2024, 56.2% of Kondura consists of medium sand, 40.6% of fine sand, and 3.1% coarse sand. Presence of course, medium,

and fine sand simultaneously can be related to sediment mixing due to scouring, storms, wave action, current action, or even temporary input from the land or creeks. In bivariate plots, coarsest samples of Kondura show highest sorting, indicating that they may be younger or less mature than others. Despite the mentioned spatial heterogeneity, the statistical averages of the beach at Kondura are extremely repeatable. The average post-monsoon grain size increased by less than 0.03 φ from 2023 to 2024 (from 1.90 to 1.93 φ), while sorting decreased from around 0.67 to 0.64 φ, and skewness from around −0.26 to −0.24. Consequently, the local stations may experience significant changes in their composition while the sediment of the beach overall tends to approach the typical post-monsoon statistical parameters range. This process may be explained by the theory of dynamic equilibrium when the constant sediment exchange occurs.

5.3 Wayangani Beach: seasonal reorganization enhancement

There is a more evident seasonality in the mean size of the sediment at Wayangani. In contrast with Pre-Monsoon and Post-Monsoon 2024, Mz changed from 1.59 to 1.93 φ (fining); sorting decreased from 0.76 to 0.62 φ; and skewness became distinctly negative, from −0.08 to −0.25. The combined effect points to hydraulic sorting and greater presence of coarser material within the post-monsoon population.

Also, Wayangani contains more medium sand than Kondura during all three seasons: 83.3% vs. 63.3% in post-monsoon 2023, 94.1% vs. 70.3% in pre-monsoon 2024, and 70.0% vs. 56.2% in post-monsoon 2024. The dominance of the medium sand component indicates wave-based sorting around the preferred size while changes in mean size and skewness point to reorganization of the distribution extremes.

5.4 Hydraulic winnowing, sediment mixing, and textural maturity

Negatively skewed data is common in most data and therefore constitutes one of the most identifiable sedimentological characteristics of both beaches. Within beach settings, finer sediments may stay in suspension for a longer duration during backwash and nearshore circulation while relatively larger sediments may be more easily retained within the beach face. This process may result in the formation of negatively skewed data and a coarse distribution tail through repeated processes of selective removal (Duane, 1964; Friedman, 1967). The identification of negatively skewed data is made even more reliable since it comes with better sorting of fine sand sediments.

The sorting pattern is another source of information for textural maturity. Fine sands with Mz in the range of 2.0-2.3 φ tend to be better sorted than coarse sediments. This pattern is consistent with the process of continuous reworking of selected grain-size fraction by waves. Unsorted coarse sediments, especially from Kondura, are more likely mixed sediments resulting from high-energy episodes than sediments formed by low-energy processes (Folk & Ward, 1957; McLaren & Bowles, 1985).

5.5 Interannual post-monsoonal equilibrium

The intercomparison of post-monsoon 2023 and post-monsoon 2024 is especially important because it can reveal if the seasonal cycle brings the beaches back to comparable sedimentary states. Post-Monsoon values of Kondura are very similar to each other. At Wayangani, the Post-Monsoon values of 2023 and 2024 are also comparable: Mz increases from approximately 1.86 to 1.93 φ and sorting decreases from 0.65 to 0.62 φ. Such results imply that intense seasonal sorting processes take place in addition to the repeated post-monsoonal equilibrium.

It should be noted that the term 'equilibrium' does not mean immobility of the system. The 'equilibrium' is a dynamic phenomenon characterized by permanent transformation of the local stations and grain size populations whereas some parameters of beaches vary in a certain range. It is especially crucial to distinguish the two cases during the coastal monitoring since a single seasonal survey will either overestimate or underestimate the actual textural state of a monsoon-beach.

5.6 Conceptual seasonal model for sediment dynamics

These can be described in terms of disturbance due to the monsoon, sediment mixing and movement, post-monsoon recovery, and new sorting due to hydraulics. The annual cycle results from wave and climatic forcing in the region, while the local geomorphology determines the expression of the cycle at each beach. Kondura displays more local variability and occasional occurrence of coarse storm lag sediments, while Wayangani maintains its medium sand framework with a more pronounced seasonal variation in grain size, sorting, and skewness.

6. Conclusions

The granulometric comparison of Kondura and Wayangani beaches indicates that both beaches undergo strong seasonality in sediment redistribution, but there are differences in intensity and spatial characteristics. Medium and fine sands form the basis of sediment composition on both beaches. Wayangani always has more proportion of medium sand,

while Kondura beach preserves textural variability and forms a small amount of coarse sand after the 2024 monsoon. Kondura beach displays relatively stable mean grain-size characteristics for beach scale during three surveys with Mz varying from 1.86 to 1.93 φ. The Wayangani beach displays stronger seasonality, starting from relatively coarse, moderately sorted, nearly symmetrical population before monsoon and ending with finer, well-sorted, distinctly coarse skewed population after the monsoon. Bivariate plots show that finer sediments are well sorted, while coarse sediments are poorly sorted. The presence of negative skewness, increased sorting into finer grains, and seasonal variations in textural fractions clearly demonstrate multiple episodes of hydraulic sorting, winnowing through swash/backwash, and periodic mixing of sediments. Thus, the obtained evidence proves a model that takes into account a southwest monsoon influence on the sedimentation process in the region as well as an influence of a local coastal morphology on the nature of sedimentation. A remarkable similarity in textural fractions of beaches after each monsoon implies the formation of a stable seasonal balance in the sediments of these areas. This result is important for coastal research since measurements of sediment texture performed only during one season may provide information only about partial behavior of the beach. Therefore, continuous investigation that includes not only sediment texture but also beach morphology, wave characteristics, etc. will help to understand better the connection between sedimentary processes and morphology of the Sindhudurg coast.

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