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Granulometric Analysis And Sediment Transport Patterns At Kondura And Wayangani Beaches, Sindhudurg Coast, India

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Abstract: This study investigates the granulometric characteristics and sediment transport processes at Kondura and Wayangani Beaches along the Sindhudurg coast, Maharashtra, India. A total of 62 sediment samples were collected during the southwest monsoon in 2023. The grain size distribution, sorting, skewness, and kurtosis were analysed using GRADISTAT software. Kondura Beach exhibited poorly sorted sediments with mean grain sizes ranging from 1.03φ (fine sand) to 1.92φ (coarse sand), and skewness values between -0.384 and 0.139, indicating a prevalence of coarse particles and high-energy depositional events, such as monsoons and storms. In contrast, Wayangani Beach showed better sorting, with mean grain sizes ranging from 1.19φ to 1.92φ, and skewness values between -0.246 and 0.203, suggesting more stable, wave-driven sedimentation processes. The study highlighted that Kondura Beach's sediment composition is influenced by episodic high-energy events, while Wayangani Beach experiences consistent wave action leading to moderate sorting and more balanced sediment distribution. These results provide valuable insights into the hydrodynamic forces at play and the impact of local environmental factors on sediment dynamics. The findings have implications for coastal management, particularly in understanding beach erosion, sediment transport, and the effects of climate variability on coastal systems.

***Keywords* - Granulometric, Grain-size, GRADISTAT, Sediment transport, Beach sediment.**

I. Introduction

Beaches are dynamic geomorphological landscapes shaped by the interplay of natural forces such as wind, river discharge, precipitation, ocean waves, and sediment sources. These environments are highly sensitive to climate change, with factors such as atmospheric pressure variations and wind patterns influencing wave dynamics, tides, and currents, all of which contribute to the shaping of beach features (Simmonds 1996; Vila-Concejo 2020) action. These sediments, which range from clay to coarse sand, provide valuable clues regarding depositional conditions, transport mechanisms, and local hydrodynamics, contributing to the diversity in grain size (Vila-Concejo 2020; Friedman 1978; Putra 2017).

The textural analysis of these sediments has been a focus of significant research, enabling the examination of sediment transport and sorting processes across different coastal environments (Hanamgond 2017; Folk 1957). Estuary and bay beaches (BEBs), in particular, are distinct from open-ocean beaches due to the reduced wave energy, which is influenced by local morphology and the prevailing wave climate, thus affecting sediment characteristics and depositional patterns (Vila-Concejo 2020). Grain size analysis plays a critical role in identifying sediment types and their distribution, while also providing insight into the dynamics and energy conditions of depositional environments (Putra 2017; Carrranza 2005; Randa 2021). Coastal systems are complex and involve intricate interactions between erosion, transport, and deposition, occurring across varying spatial and temporal scales (Nugroho 2014; Short 1999; Hegge 1996; Kennedy 2002). Coarser grains, such as sand and gravel, settle more quickly in areas with high energy, whereas finer grains like silt require specific hydraulic conditions for sorting (Marfai 2021). These grain size variations serve as an indicator of the environmental processes that drive sediment deposition and transport (Nugroho 2014).

In coastal systems like the Sindhudurg coast in Maharashtra, the local geomorphology plays a crucial role in shaping sediment transport and shoreline dynamics. Similar to Formosa Bay, Rio de Janeiro, where rocky outcrops and headlands influence hydrodynamics and sediment transport (Short 1999), the varying coastal features in Sindhudurg, such as embayment and rocky outcrops, may impact sediment dynamics and transport pathways.

India's long coastline is home to diverse depositional environments, particularly in the intertidal zones of its sandy beaches. These areas, shaped by the constant influence of waves and tidal currents, provide a unique opportunity to study the processes of beach sedimentation. As highlighted in Coastal Environments of India (Chapter on Granulometry of Beach Sands) (Das 2022), the composition of beach materials, including both lithogenic and biogenic constituents, is essential for interpreting beach characteristics and the processes that govern them. Studying the textural variations in beach sediments can deepen our understanding of sediment transport, deposition, and the evolution of coastal environments.

Grain size and shape are fundamental properties of sediments that offer valuable insights into their transport history, depositional environment, and sedimentary processes (Visher 1969). Grain size has long been used as a method for characterizing sedimentary environments and transport mechanisms (Krumbein 1938; Dyer 1986; McLaren 1981). While grain size distribution provides important information about sediment transport modes - such as suspension, saltation, and traction - grain shape also significantly influences sediment movement by affecting sorting, abrasion, and transport in fluid environments (Dyer 1986; McLaren 1981). Though grain shape's role in sediment dynamics has been extensively studied in aeolian environments, its influence in coastal systems, particularly on beaches, is less explored (Anderson 1996; Wilson 1988).

The combined analysis of grain size and shape has proven effective in distinguishing between transport modes and sedimentary environments, with potential applications for coastal management and understanding sediment transport mechanisms (Norton 2008; Sanchez 2018). For example, different grain size-shape curve distributions in beach sediment studies can reflect varying sediment transport processes and hydrodynamic conditions (Sanchez 2018). These combined characteristics of grain size and shape are especially relevant in understanding sediment behaviour in embayed and estuarine coastal environments, where hydrodynamics play a pivotal role in sediment transport and deposition patterns (Friedman 1978).

Numerous studies have focused on sediment distribution along the east and west coasts of India, providing valuable insights into textural characteristics and seasonal variations in sediment composition (Chakrabati 1977; Nayak 1996; Gao 1991). However, there remains a lack of comprehensive spatiotemporal studies on nearshore sediment dynamics, particularly in regions like Chennai. Research on sediment grain size distribution, transport, and their relationship with hydrodynamic conditions has been a key focus of coastal studies (McLaren 1981; Gao 1991). This study aims to fill this gap by investigating the sedimentary environment of Chennai's nearshore region through sediment texture analysis and hydrodynamic modelling to enhance our understanding of transport patterns and beach evolution.

This study aims to analyze the granulometric and textural characteristics of beach sediments along the western coast of India, specifically in the Sindhudurg district of Maharashtra. By examining sediment properties such as mean grain size, sorting, skewness, and kurtosis, the study seeks to investigate the depositional and erosional environments influenced by dynamic coastal processes. The study also aims to use comprehensive sediment sampling and statistical analysis to further our understanding of sediment transport pathways, identify sediment sources, and evaluate the impact of environmental conditions on the morphological evolution of the beach landscapes.

II. Study Area

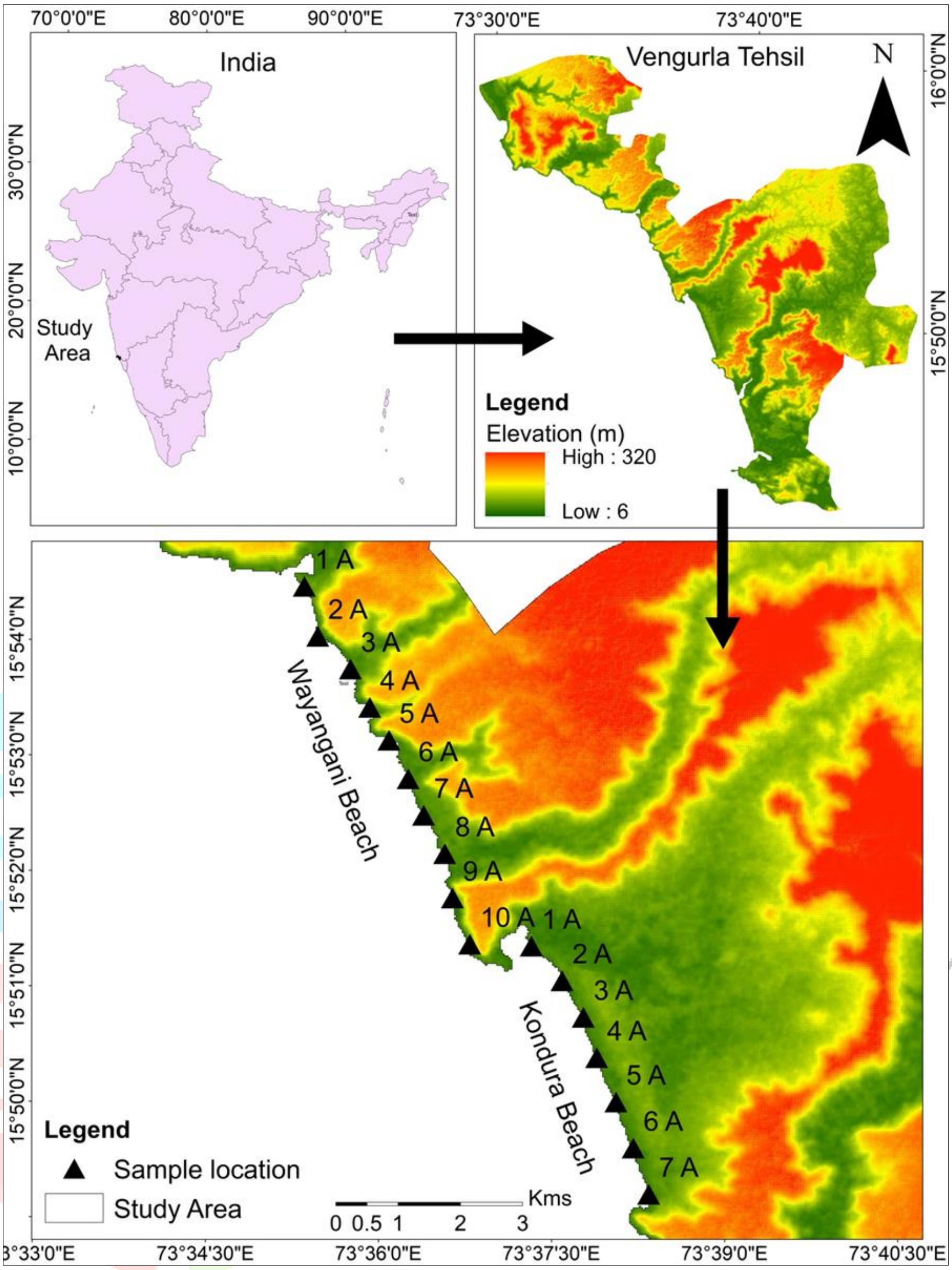
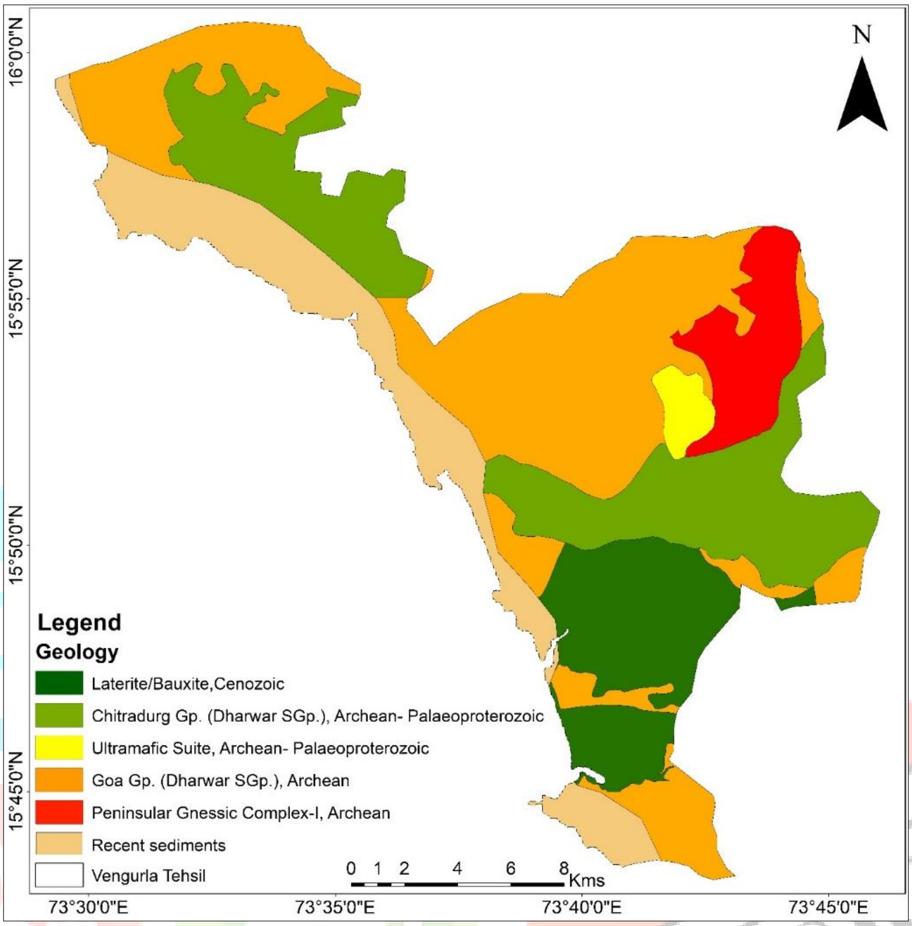


Figure.1 Location map of the Study Area. The map depicts the sample location and elevation variation in the study area.

The study area is located along the coast of Maharashtra, India, in the Sindhudurg district, which features a coastline of approximately 121 km. Specifically, the region under investigation extends from Kondura to Wayangani Beach, covering about from 15°54'38" - 15°49'0" N, 73°34'30" - 73°39'0" E (Fig.1). The study area has maximum elevation of 320 meters (m), whereas the minimum elevation is 6 meters above mean sea level (Fig.1). This coastal stretch runs in a northeast direction and is characterized by relatively flat terrain. This research targets an untouched area where no prior sediment studies have been conducted, although geo-electrical studies have been carried out on the inland sides. The broader littoral lowland, known as the "Konkan," stretches from the Arabian Sea to the Western Ghats escarpment, extending from north of Mumbai to north of Goa (Hanamgond 2008). The region is shaped by several processes, including tectonics, fluvial systems, and coastal dynamics, as noted in geological studies. The rocky coastal stretch of the Konkan region is one of the most geologically significant terrains in western India (Mutaqin 2017). Historically, this area experienced tectonic activity, particularly during the Mio-Pliocene epoch (Gupta 2014). As part of the Deccan volcanic province, the landscape is influenced by significant tectonic and volcanic activity, resulting in its current form. Except for the coastal plains, the region has an undulating topography (Mutaqin 2017).

The area experiences semidiurnal tides with micro-tidal beach dynamics and is heavily influenced by the Southwest monsoon (June-September) and a fair-weather period (October-May). The coastal zone is hilly and narrow, dissected by transverse ridges of the Western Ghats, which often extend into the Arabian Sea as promontories. Alluvial deposits, primarily beach sand, are present in small areas near the shore (Tandale 1993; CGWB 2009), while clay is a prevalent lithology in the coastal region. Features such as cliffs, sea notches, caves, estuaries, creeks, and embayment contribute to an irregular shoreline, shaped by both tectonic and erosional processes.



Marine conditions in the Konkan region, influenced by the Southwest monsoon and semidiurnal tidal patterns, exhibit seasonal fluctuations that align with the distinct phases of the monsoon and fair-weather periods. However, detailed chronologies of sea-level fluctuations are lacking (Maiti 2012). Remote sensing studies of beaches in the area, conducted by (Karlekar 2001; Kunte 1993; Kunde 1994; Hanamgond 2007), have enhanced the understanding of the region's dynamic coastal development.

2.1 Geology and Geomorphology of the Study Area

Figure. 2 Geological map of Vengurla tehsil, Sindhudurg district (redrawn after bhukosh.gsi.gov.in).

The geology of the Vengurla tehsil in Sindhudurg district is defined by lithological units ranging from Archean basement rocks to Cenozoic laterites and bauxite deposits (Fig.2), which has been modified after the Geological Survey of India (GSI 2024). The Peninsular Gneiss Complex-I (Fig.2), composed of granitic gneisses and migmatites, forms the foundational rocks of the region, representing high-grade metamorphism during the Archean era. These rocks bear evidence of igneous intrusions and subsequent tectonic deformation. Proterozoic units, including quartzites and schists, reflect sedimentary deposition in shallow marine conditions, later subjected to regional metamorphism. The presence of ultramafic rocks indicates tectonic settings associated with mantle-derived materials, possibly remnants of ancient subduction or rift zones. Lateritic and bauxite deposits (Fig.2), prevalent along the coastal plateaus, were formed during the Cenozoic under humid tropical conditions. Intense leaching of parent rocks during monsoonal periods led to residual accumulations of iron and aluminium oxides, characteristic of the region's weathering profile (Fig.2). The influence of tectonic uplift and prolonged erosion further contributed to the formation of these deposits. The Mio-Pliocene epoch saw significant tectonic activity as part of the Deccan volcanic province, marked by volcanic outpourings and crustal reactivations. While the primary Deccan basalts are absent in this region, tectonic uplift during this period shaped the current landscape, including the coastal plains and transverse ridges of the Western Ghats. The lithology and tectonic history of the region play a crucial role in sediment supply to the beaches. Archean gneisses and granites contribute coarse detrital minerals like quartz and feldspar, while lateritic weathering products add fine-grained clay minerals and iron-rich particles. The combination of fluvial transport and coastal dynamics results in a unique sediment assemblage, influencing the granulometric characteristics of the study area.

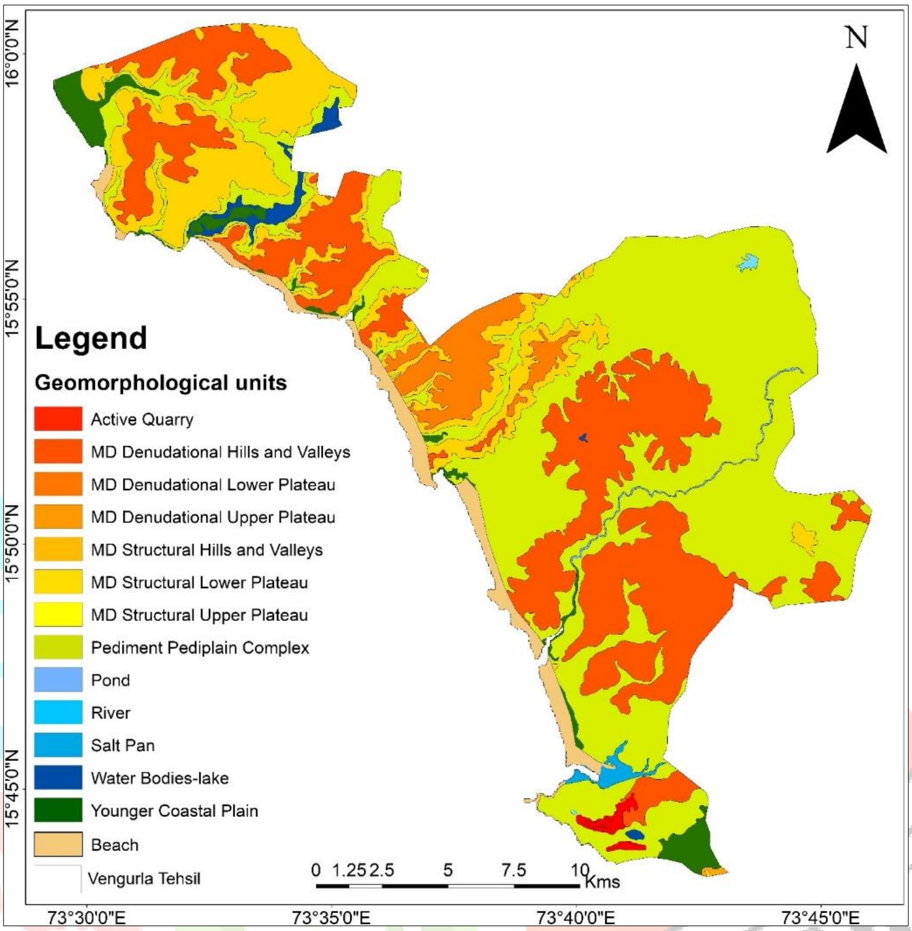


Figure.3 Geomorphological map of Vengurla Tehsil, Sindhudurg district (redrawn after bhukosh.gsi.gov.in).

The geomorphology of the study area, located in Vengurla tehsil, Sindhudurg district, Maharashtra, reflects a complex interplay of tectonic, fluvial, and coastal processes that have shaped its diverse landforms over time. Along the coastline, the Younger Coastal Plain dominates, characterized by depositional environments primarily composed of beach sands (Fig.3), which has been modified after the Geological Survey of India (GSI 2024). This zone is shaped by dynamic interactions between marine and fluvial processes, including wave action, tidal influence, and sediment transport, which contribute to the region's evolving shoreline. Inland, the terrain transitions to denudational hills and valleys, which are remnants of ancient erosional landscapes. These features are further classified into Moderately Dissected (MD) moderately Denuded Structural Hills and Valleys, representing residual ridges and dissected valleys with structural control, and MD Denudational Upper and Lower Plateaus, which highlight the stepped morphology of former peneplains, shaped by tectonic uplift and prolonged erosion (Fig.3). The Moderately Dissected Structural Upper Plateau reflects advanced stages of erosion; characterized by relatively flat to gently undulating surfaces (Fig.3).

At the interface of the highlands and low-lying plains lies the Pediment-Pediplain Complex (Fig.3), a gently sloping erosional surface that marks the transitional zone formed by the retreat of the surrounding hills. The fluvial network in the region plays a crucial role in sediment transport, giving rise to features like estuarine and deltaic formations that further influence the geomorphology of the coastal plain. Anthropogenic and semi-natural features such as ponds, salt pans, and active quarries are also present, reflecting both natural processes and human interventions in the region. Additionally, while not explicitly mapped, coastal features such as cliffs, sea notches, and embayment are likely prominent in the area, shaped by wave action, tectonic activity, and erosional processes.

III. METHODOLOGY

The research involved collecting sediment samples from seventeen different sites (Fig.1) along the western coast of India during the southwest monsoon period in May and June 2023. The samples were taken from the upper 4-5 cm of the surface sediment to capture recent depositional material. A total of 62 samples were obtained from various locations to assess the textural properties of the beach sediments and understand the depositional and erosional environments influenced by the alternating wind and current patterns.

After collection, the sediment samples are dried in a hot air oven, and a 100-g portion of each bulk sample is designated for laboratory analysis. Organic matter and ferruginous coatings were removed from the samples using a treatment of 30% H_2O_2 and $SnCl_2$. The samples were then sieved at 0.50ø intervals using ASTM sieve sets with a Ro-Tap sieve shaker for 20 minutes, with sieve aperture sizes (1108 to 75) and sieve sizes 16µm, 30µm, 50µm, 100µm, and 200µm. The sediments collected from each sieve were weighed using an electronic balance, and cumulative weight percentage frequencies were calculated.

The Gradistat 8.0 Software (Hanamgond 2017) is used to compute statistical parameters, including Mean, Sorting, Skewness, and Kurtosis, which were delineated using the graphical method of Folk and Ward (Folk 1957). This allowed for the interpretation of the depositional environments.

To analyze the sediment characteristics at Kondura Beach and Wayangani Beach, several graphs were generated using Golden Grapher software to examine key sediment properties and the processes influencing them. These include Standard Deviation vs. Mean Grain Size, Mean Grain Size vs. Skewness, Mean Grain Size vs. Sorting, Standard Deviation vs. Skewness, Skewness vs. Kurtosis, Sorting vs. Skewness, and Mean Grain Size vs. (Standard Deviation + Skewness). The graphs reveal how varying energy conditions at both beaches impact sediment characteristics. At Kondura Beach, there is greater variability in grain size and sorting, indicating high-energy events like storms that mix coarse and fine particles. These visualizations helped explain the influence of wave energy and depositional processes on sediment structure and composition at each location.

IV. RESULTS

Granulometric analysis involves measuring and classifying sediment particle sizes, offering insights into sediment dynamics and depositional environments (Table 4.1) (Blott 2001). Sediments are categorized into classifications such as 'Unimodal,' 'Moderately Well Sorted,' 'Moderately Sorted,' and 'Poorly Sorted' (Ribeiro 2020). This classification is essential for understanding sediment transport, deposition, and the ecological implications of varying sediment types along beach environments (Buscombe 2006).

Sediments classified as 'Unimodal' indicate a predominant grain size distribution, typically found in environments with consistent energy levels, such as beaches experiencing steady wave action (Schlacher 2008). For example, the designation "Unimodal, Moderately Well Sorted" (Table 4.1), suggests that sediment particles are relatively uniform in size, reflecting selective sorting processes in stable depositional settings. This indicates a stable energy environment where similarly sized particles are transported and deposited uniformly (Said 2016). Conversely, 'Bimodal, Poorly Sorted' sediments (Table 4.1) signify a more complex depositional environment characterized by a mixture of different grain sizes (Holland 2008). This variation results from fluctuating energy conditions, such as those encountered during storm events or from sediment input from diverse sources, which can adversely impact coastal stability and habitat diversity.

Table 4.1: Classification of Beach Sediments Based on Textural and Granulometric Properties

Sample no	Sample type	Sediment Name	Sample no	Sample type	Sediment Name
1 A KB	Unimodal	Moderately Well Sorted Medium Sand	1 A WB	Unimodal	Moderately Sorted Medium Sand
1 B KB	Unimodal	Moderately Well Sorted Medium Sand	1 B WB	Unimodal	Moderately Well Sorted Medium Sar
1 C KB	Unimodal	Moderately Well Sorted Fine Sand	1 C WB	Unimodal	Moderately Well Sorted Medium Sar
1 D KB	Unimodal	Well Sorted Medium Sand	2 A WB	Unimodal	Moderately Sorted Medium Sand
2 A KB	Unimodal	ModeratelySorted Medium Sand	2 B WB	Unimodal	Moderately Sorted Medium Sand
2 B KB	Unimodal	Moderately Well Sorted Medium Sand	2 C WB	Unimodal	Moderately Well Sorted Medium Sar
2 C KB	Unimodal	ModeratelySorted Medium Sand	3 A WB	Unimodal	Moderately Well Sorted Medium Sar
2 D KB	Unimodal	Moderately Well Sorted Fine Sand	3 B WB	Unimodal	Moderately Well Sorted Medium Sar
2 E KB	Unimodal	ModeratelySorted Medium Sand	3 C WB	Unimodal	Moderately Well Sorted Medium Sar
3 A KB	Unimodal	ModeratelySorted Medium Sand	4 A WB	Unimodal	Moderately Sorted Medium Sand
3 B KB	Unimodal	ModeratelySorted Medium Sand	4 B WB	Unimodal	Moderately Well Sorted Medium Sar
3 C KB	Unimodal	ModeratelySorted Medium Sand	4 C WB	Unimodal	Moderately Sorted Medium Sand
3 D KB	Unimodal	ModeratelySorted Medium Sand	5 A WB	Unimodal	Moderately Well Sorted Medium Sar
3 E KB	Unimodal	ModeratelySorted Medium Sand	5 B WB	Unimodal	Moderately Sorted Medium Sand
4 A KB	Unimodal	ModeratelySorted Medium Sand	5 C WB	Unimodal	Moderately Sorted Medium Sand
4 B KB	Unimodal	ModeratelySorted Medium Sand	6 A WB	Unimodal	Moderately Sorted Medium Sand
4 C KB	Unimodal	ModeratelySorted Medium Sand	6 B WB	Unimodal	Moderately Well Sorted Medium Sand
4 D KB	Unimodal	ModeratelySorted Medium Sand	6 C WB	Unimodal	Moderately Well Sorted Medium Sand
4 E KB	Unimodal	Moderately Well Sorted Fine Sand	7 A WB	Unimodal	Moderately Sorted Medium Sand
5 A KB	Unimodal	ModeratelySorted Medium Sand	7 B WB	Unimodal	Moderately Sorted Medium Sand
5 B KB	Unimodal	Moderately Well Sorted Fine Sand	7 C WB	Unimodal	Moderately Well Sorted Medium

					Sand
5 C KB	Unimodal	Moderately Sorted Medium Sand	7 D WB	Unimodal	Moderately Well Sorted Medium Sand
5 D KB	Unimodal	Moderately Sorted Medium Sand	8 A WB	Unimodal	Moderately Well Sorted Fine Sand
5 E KB	Unimodal	Moderately Sorted Fine Sand	8 B WB	Unimodal	Moderately Sorted Medium Sand
6 A KB	Unimodal	Moderately Sorted Medium Sand	8 C WB	Unimodal	Moderately Well Sorted Medium Sand
6 B KB	Unimodal	Moderately Well Sorted Medium Sand	9 A WB	Unimodal	Moderately Sorted Medium Sand
6 C KB	Unimodal	Moderately Sorted Medium Sand	9 B WB	Unimodal	Moderately Well Sorted Medium Sand
6 D KB	Bimodal	Poorly Sorted Coarse Sand	9 C WB	Unimodal	Moderately Well Sorted Medium Sand
7 A KB	Unimodal	Moderately Well Sorted Medium Sand	10 A WB	Unimodal	Moderately Well Sorted Medium Sand
7 B KB	Unimodal	Moderately Well Sorted Fine Sand	10 B WB	Unimodal	Moderately Well Sorted Medium Sand

In beach sedimentology, textural analysis focuses on grain size distribution, shape, and sorting of sediment particles (Ayodele 2019). The classifications derived from this analysis elucidate the mechanisms of sediment transport along beaches. Well-sorted samples, like those labelled 'Moderately Well Sorted Medium Sand' (Table 4.1), indicate transport primarily driven by wave action (Huisman 2016), where energy levels are sufficient to remove finer particles and create a uniform size distribution. In contrast, poorly sorted sediments suggest a mixed depositional history influenced by storm events or high-energy conditions that lead to the accumulation of various particle sizes (Woodruff 2021; Amrouni 2007).

The samples indicate varying grain sizes, including descriptors such as "Medium Sand," "Fine Sand," and "Coarse Sand" (Table 4.1). Grain size is a primary factor influencing sediment behaviour and transport. For instance, medium sands in many beach environments are typically well-sorted due to consistent wave action and current regimes that facilitate selective transport. This aspect is significant, as the degree of sorting in the sediments reflects the energy conditions of the depositional environment (Buscombe 2006). "Well Sorted" sediments imply consistent energy levels, often found in high-energy zones like surf zones, where wave action effectively segregates particles by size (Table 4.1).

In contrast, 'Poorly Sorted' sediments, such as those categorized as 'Bimodal, Poorly Sorted' (Table 4.1), suggest variable energy conditions (Costas 2006), often associated with environments experiencing rapid sediment input or high-energy events like storms or flooding. The relationship between sediment sorting and energy conditions underscores the dynamics of sediment transport and deposition, providing crucial insights into the ecological implications of sedimentary processes in coastal environments. Thus, the interplay between granulometric characteristics and environmental conditions is vital for understanding beach sediment dynamics.

4.1 Statistical measurements and Grain morphology

Tables 4.2 and 4.3 show the granulometric and textural characteristics of various beach sediment samples measured using the Fork and Ward method (Folk 1957). The analysis includes parameters such as mean grain size (in phi units), sorting coefficient, skewness, and kurtosis, which together provide insights into the sediment's physical properties and transport dynamics.

Table 4.2: Granulometric and Textural Analysis of Kondura Beach Sediments

Sample no.	Fork and Ward Method				Sorting	Skewness	Kurtosis
	Mean	Sorting	Skewness	Kurtosis			
1 A KB	1.774	0.657	-0.116	0.75	Moderately Well	Coarse	Platykurtic
1 B KB	1.774	0.657	-0.116	0.75	Moderately Well	Coarse	Platykurtic
1 C KB	1.881	0.640	-0.249	0.84	Moderately Well	Coarse	Platykurtic
1 D KB	1.263	0.441	0.139	1.11	Well	Fine	Leptokurtic
2 A KB	1.575	0.773	-0.018	0.96	Moderately	Symmetry	Mesokurtic
2 B KB	1.258	0.606	-0.011	1.46	Moderately Well	Symmetry	Leptokurtic
2 C KB	1.533	0.822	-0.064	0.97	Moderately	Symmetry	Mesokurtic
2 D KB	1.839	0.644	-0.194	0.78	Moderately Well	Coarse	Platykurtic
2 E KB	1.524	0.709	0.096	1.01	Moderately	Symmetry	Mesokurtic
3 A KB	1.520	0.819	-0.048	0.96	Moderately	Symmetry	Mesokurtic
3 B KB	1.667	0.727	-0.059	0.87	Moderately	Symmetry	Platykurtic
3 C KB	1.682	0.751	-0.119	0.90	Moderately	Coarse	Mesokurtic
3 D KB	1.416	0.879	-0.072	1.00	Moderately	Symmetry	Mesokurtic
3 E KB	1.559	0.836	-0.087	1.00	Moderately	Symmetry	Mesokurtic
4 A KB	1.533	0.804	-0.031	0.99	Moderately	Symmetry	Mesokurtic
4 B KB	1.660	0.762	-0.095	0.92	Moderately	Symmetry	Mesokurtic
4 C KB	1.401	0.872	-0.049	1.00	Moderately	Symmetry	Mesokurtic
4 D KB	1.438	0.799	0.020	1.09	Moderately	Symmetry	Mesokurtic
4 E KB	1.921	0.675	-0.332	1.05	Moderately Well	Very Coarse	Mesokurtic
5 A KB	1.573	0.823	-0.108	0.93	Moderately	Coarse	Mesokurtic
5 B KB	1.878	0.640	-0.242	0.83	Moderately Well	Coarse	Platykurtic
5 C KB	1.553	0.820	-0.048	0.96	Moderately	Symmetry	Mesokurtic
5 D KB	1.485	0.868	-0.100	0.93	Moderately	Symmetry	Mesokurtic

5 E KB	1.818	0.800	-0.384	1.02	Moderately	Very Coarse	Mesokurtic
6 A KB	1.535	0.779	0.002	0.98	Moderately	Symmetry	Mesokurtic
6 B KB	1.802	0.656	-0.171	0.76	Moderately Well	Coarse	Platykurtic
6 C KB	1.712	0.748	-0.161	0.88	Moderately	Coarse	Platykurtic
6 D KB	1.031	1.010	0.132	0.63	Poorly	Fine	Very Platykurtic
7 A KB	1.786	0.674	-0.177	0.79	Moderately Well	Coarse	Platykurtic
7 B KB	1.819	0.653	-0.173	0.77	Moderately Well	Coarse	Platykurtic
7 C KB	1.612	0.757	-0.028	0.92	Moderately	Symmetry	Mesokurtic

The mean grain size for both beaches ranges from fine to coarse sand. At Kondura Beach (Table 4.2), the mean grain size varies between 1.031 (fine) to 1.921 (very coarse) (Folk 1957). Similarly, Wayangani Beach (Table 4.3) exhibits a range from 1.192 (fine) to 1.920 (very coarse). The wide range in grain size across both beaches reflects the influence of varying energy conditions (Carranza 2005), with finer sands typically deposited in lower-energy environments and coarser sands indicative of higher-energy zones such as wave-dominated surf areas.

Sorting, which measures the uniformity of grain sizes, is a key indicator of the depositional processes at both sites (Putra 2017). At Kondura Beach, sediments are predominantly "Moderately Sorted" to "Moderately Well Sorted," with a few "Poorly Sorted" samples indicating variable energy levels. The sorting values range from 0.441 to 1.010 (Table 4.2), reflecting a general trend towards uniform particle size but with occasional mixing due to storms or tidal events. In contrast, Wayangani Beach exhibits slightly better sorting overall, with the majority of samples classified as "Moderately Well Sorted" and a narrower sorting range of 0.614 to 0.919 (Table 4.3). The improved sorting suggests that Wayangani Beach experiences more consistent energy conditions, where wave action plays a dominant role in continuously reworking the sediments.

Table 4.3: Granulometric and Textural Analysis of Kondura Beach Sediments

Sample no.	Fork and Ward Method				Sorting	Skewness	Kurtosis
	Mean	Sorting	Skewness	Kurtosis			
1 A WB	1.684	0.704	-0.049	0.829	Moderately	Symmetry	Platykurtic
1 B WB	1.415	0.630	0.146	1.270	Moderately Well	Fine	Leptokurtic
1 C WB	1.769	0.660	-0.102	0.744	Moderately Well	Coarse	Platykurtic
2 A WB	1.533	0.719	0.081	1.004	Moderately	Symmetry	Mesokurtic
2 B WB	1.634	0.716	0.011	0.871	Moderately	Symmetry	Platykurtic
2 C WB	1.436	0.663	0.131	1.296	Moderately Well	Fine	Leptokurtic
3 A WB	1.749	0.678	-0.098	0.770	Moderately Well	Symmetry	Platykurtic
3 B WB	1.650	0.676	0.059	0.791	Moderately Well	Symmetry	Platykurtic

3 C WB	1.742	0.657	-0.068	0.739	Moderately Well	Symmetry	Platykurtic
4 A WB	1.546	0.735	0.055	0.999	Moderately	Symmetry	Mesokurtic
4 B WB	1.539	0.655	0.174	0.920	Moderately Well	Fine	Mesokurtic
4 C WB	1.471	0.796	0.025	1.058	Moderately	Symmetry	Mesokurtic
5 A WB	1.662	0.683	0.019	0.803	Moderately Well	Symmetry	Platykurtic
5 B WB	1.659	0.703	-0.011	0.837	Moderately	Symmetry	Platykurtic
5 C WB	1.468	0.726	0.075	1.143	Moderately	Symmetry	Leptokurtic
6 A WB	1.268	0.729	0.013	1.333	Moderately	Symmetry	Leptokurtic
6 B WB	1.583	0.680	0.111	0.872	Moderately Well	Fine	Platykurtic
6 C WB	1.634	0.685	0.054	0.823	Moderately Well	Symmetry	Platykurtic
7 A WB	1.192	0.919	-0.032	0.921	Moderately	Symmetry	Mesokurtic
7 B WB	1.699	0.714	-0.100	0.847	Moderately	Coarse	Platykurtic
7 C WB	1.444	0.618	0.180	1.190	Moderately Well	Fine	Leptokurtic
7 D WB	1.571	0.630	0.203	0.811	Moderately Well	Fine	Platykurtic
8 A WB	1.920	0.614	-0.246	0.869	Moderately Well	Coarse	Platykurtic
8 B WB	1.577	0.785	-0.024	0.949	Moderately	Symmetry	Mesokurtic
8 C WB	1.802	0.651	-0.161	0.759	Moderately Well	Coarse	Platykurtic
9 A WB	1.534	0.745	0.042	1.020	Moderately	Symmetry	Mesokurtic
9 B WB	1.800	0.641	-0.133	0.753	Moderately Well	Coarse	Platykurtic
9 C WB	1.607	0.634	0.161	0.774	Moderately Well	Fine	Platykurtic
10A WB	1.694	0.658	0.042	0.740	Moderately Well	Symmetry	Platykurtic
10B WB	1.748	0.649	-0.054	0.739	Moderately Well	Symmetry	Platykurtic
10C WB	1.587	0.763	-0.022	0.943	Moderately	Symmetry	Mesokurtic

Skewness provides insight into the dominance of finer or coarser particles. Kondura Beach shows skewness values ranging from -0.384 to 0.139, indicating that the sediments are generally coarser (Clark 1981), with negative skewness being more common. This suggests that higher-energy events such as storms may have deposited coarser materials. On the other side, Wayangani Beach exhibits skewness values between -0.246 and 0.203 (Table 4.3), with a more balanced mix of positive and negative skewness. This indicates that while coarser sediments dominate in some areas, there are also regions with finer materials, suggesting a mix of depositional environments with more dynamic energy conditions compared to Kondura Beach.

Kurtosis values range from platykurtic (broad distribution) to leptokurtic (narrow distribution), indicating a spread of grain sizes (Hanamgond 2017). At Kondura Beach, kurtosis values range from 0.63 to 1.46 (Table 4.2), with a predominance of mesokurtic and platykurtic samples. This indicates a spread of grain sizes, likely resulting from fluctuating energy conditions and sediment input from various sources. Similarly, Wayangani Beach shows kurtosis values ranging from 0.739 to 1.333 (Table 3), with many samples also being platykurtic or mesokurtic. The improved sorting suggests that Wayangani Beach experiences more consistent energy conditions, where wave action plays a dominant role (Holland 2008).

4.2 Bi-Variant Plot and Graph

Standard Deviation vs. Mean Grain Size:

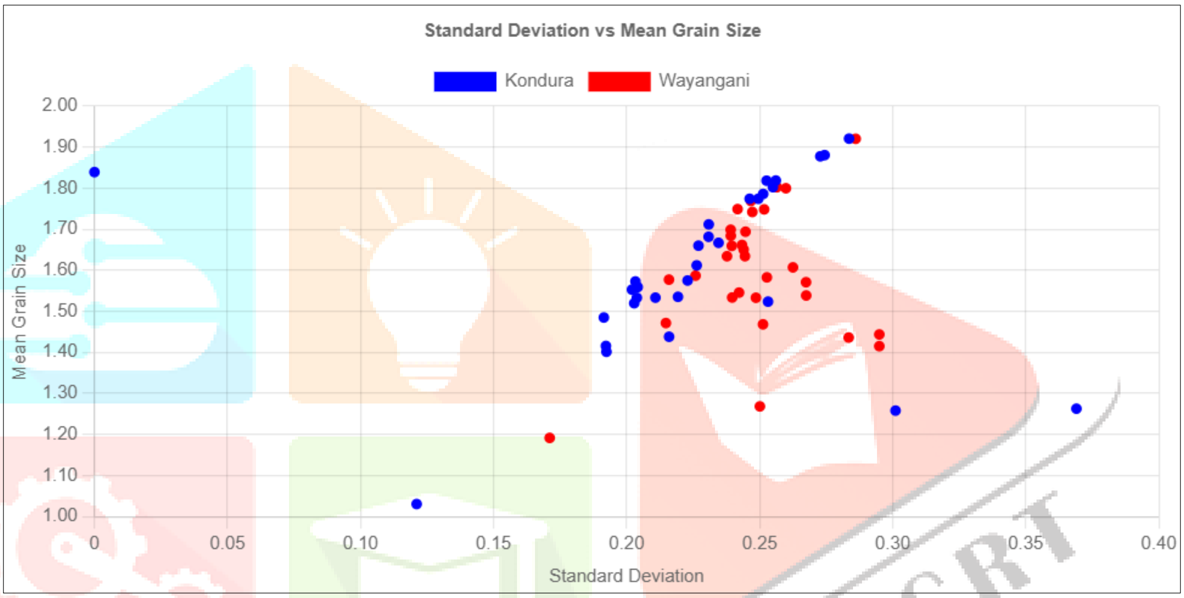
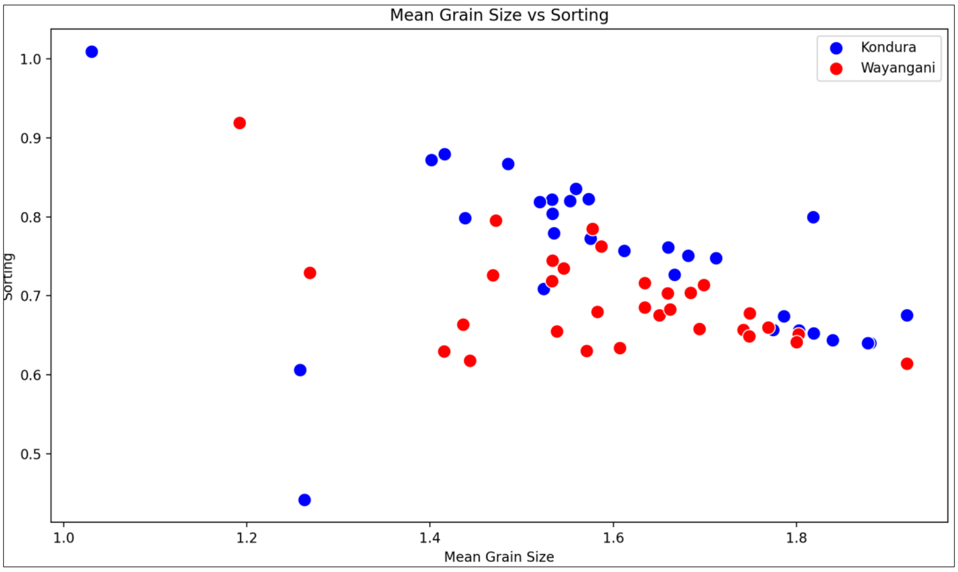


Figure.4 Standard deviation vs. Mean grain size. The figure shows the relationship between sediment sorting and energy conditions at Kondura and Wayangani Beaches.

The mean grain size ranges from 1.0φ to 2.0φ (Fig.4), with standard deviation values extending up to 1.0 (Fig.4). This broad spread reflects moderate to poor sorting, indicating variable energy conditions at this beach. Coarser grains are poorly sorted, reflecting high-energy events such as storms that mix grain sizes. In contrast, Wayangani's data shows a tighter clustering around 1.6φ (Fig.4), with standard deviation values below 0.7 (Fig.4). This indicates better sorting and more consistent wave energy, which selectively removes finer particles and leads to a more uniform grain size distribution. Kondura Beach experiences greater variability in grain size and sorting due to episodic high-energy events, while Wayangani Beach reflects more consistent sorting due to steady wave action.

Mean Grain Size vs. Skewness:

Figure.5 Mean grain size vs. Skewness. This figure compares grain size distributions and skewness

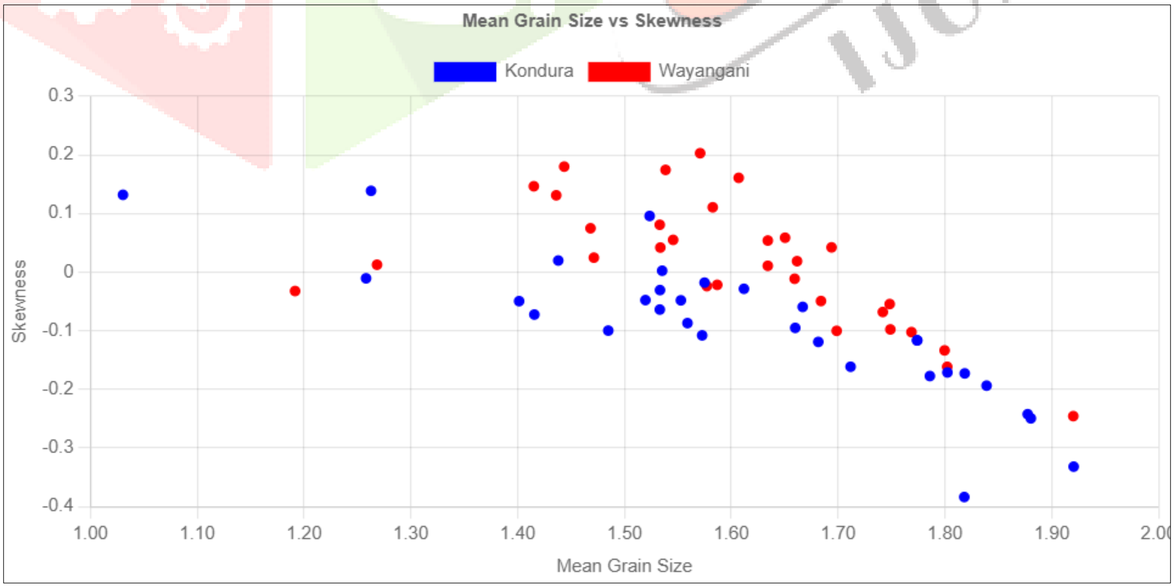


at Kondura and Wayangani Beaches to illustrate depositional environments.

The skewness values range from -0.384 (coarse-skewed) to 0.139 (fine-skewed) (Fig.5), with mean grain sizes between 1.0φ and 2.0φ (Fig.5). Most of the data points indicate negative skewness, reflecting coarser particles deposited by high-energy conditions such as storms. Skewness values at Wayangani range from -0.246 to 0.203 (Fig.5), with mean grain size clustering around 1.6φ (Fig.5). This more balanced skewness distribution reflects a uniform depositional environment, with the energy levels sufficient to transport and deposit both fine and coarse particles. Kondura Beach tends towards coarse-skewed sediments, indicating turbulent depositional conditions, while Wayangani Beach shows more symmetrical skewness, reflecting balanced sediment transport.

Mean Grain Size vs. Sorting:

Figure.6 Mean grain size vs. Sorting. Displays the variability in grain sorting and its relationship with mean grain size for the two beaches.



The mean grain size ranges from 1.0φ to 2.0φ (Fig.6), with sorting values extending up to 1.0 (moderately to poorly sorted) (Fig.6). This suggests variable energy conditions, where coarser particles are mixed with finer particles during high-energy events. Mean grain size here clusters around 1.6φ, with sorting values below 0.7 (well to moderately well sorted) (Fig.6). This indicates better sorting, driven by consistent wave action that effectively separates the particles by size. Kondura Beach exhibits more variable sorting, reflecting fluctuating energy levels, while Wayangani Beach shows better sorting, indicating a stable wave-dominated environment.

Standard Deviation vs. Skewness:

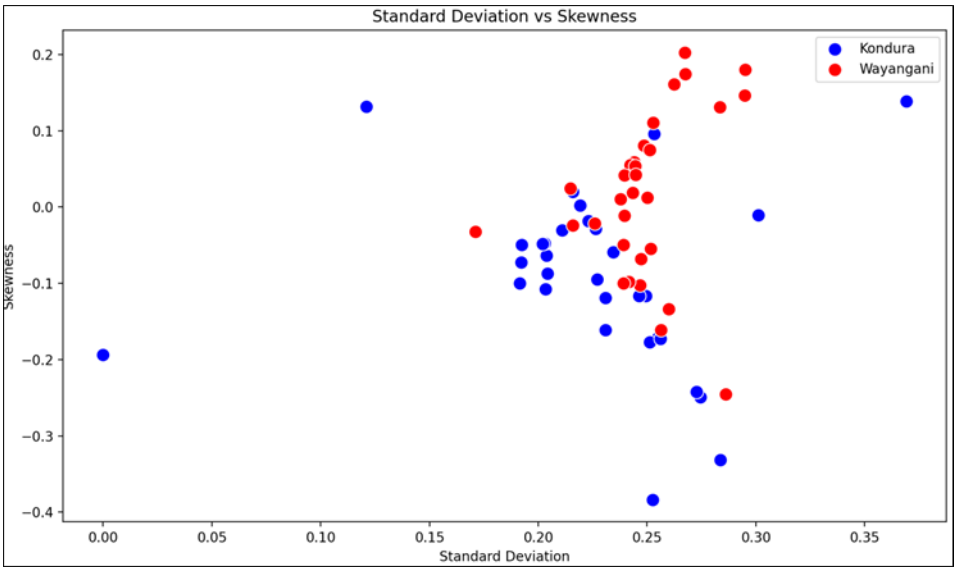


Figure.7 Standard deviation vs. Skewness. This figure highlights the variation in sediment distribution patterns between Kondura and Wayangani Beaches.

Sorting ranges from moderate to poor (standard deviation ~1.0) (Fig.7), with most skewness values being negative (coarse-skewed), indicating the dominance of coarse particles in the sediment. This is typical of high-energy depositional events, where poorly sorted sediments include a range of particle sizes. The sorting is better (standard deviation ~0.6) (Fig.7), and skewness values range from negative to neutral. This reflects more balanced energy conditions, where the sediment is better sorted, and the energy levels allow for more even deposition of particle sizes. Kondura Beach shows poorer sorting and coarser- skewed sediments, indicating episodic high-energy events, while Wayangani Beach shows better sorting and more symmetrical sediment distributions.

Skewness vs. Kurtosis:

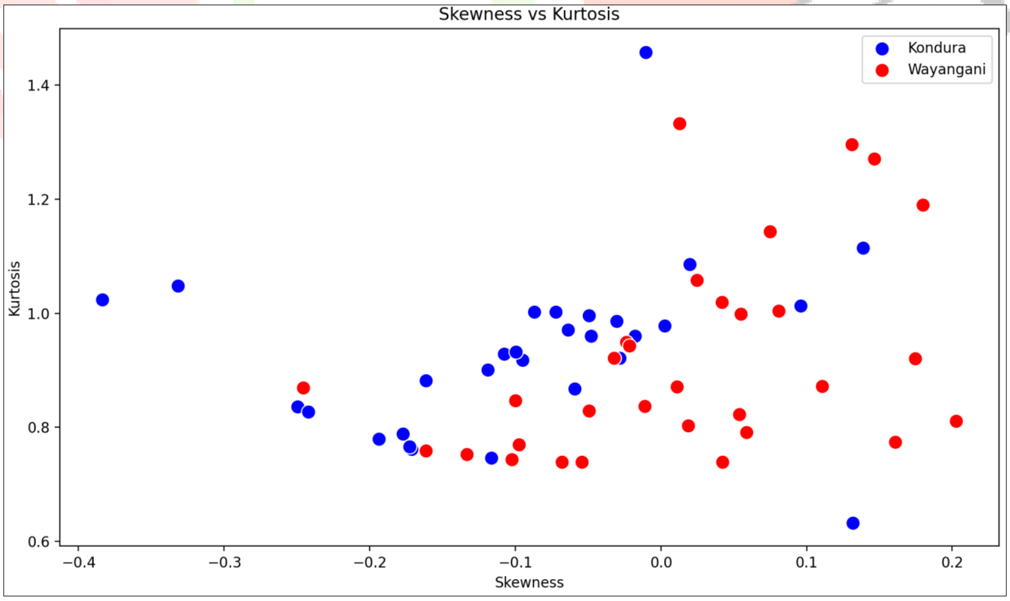


Figure. 8 Skewness vs. Kurtosis. Depicts grain distribution shape characteristics for both beaches.

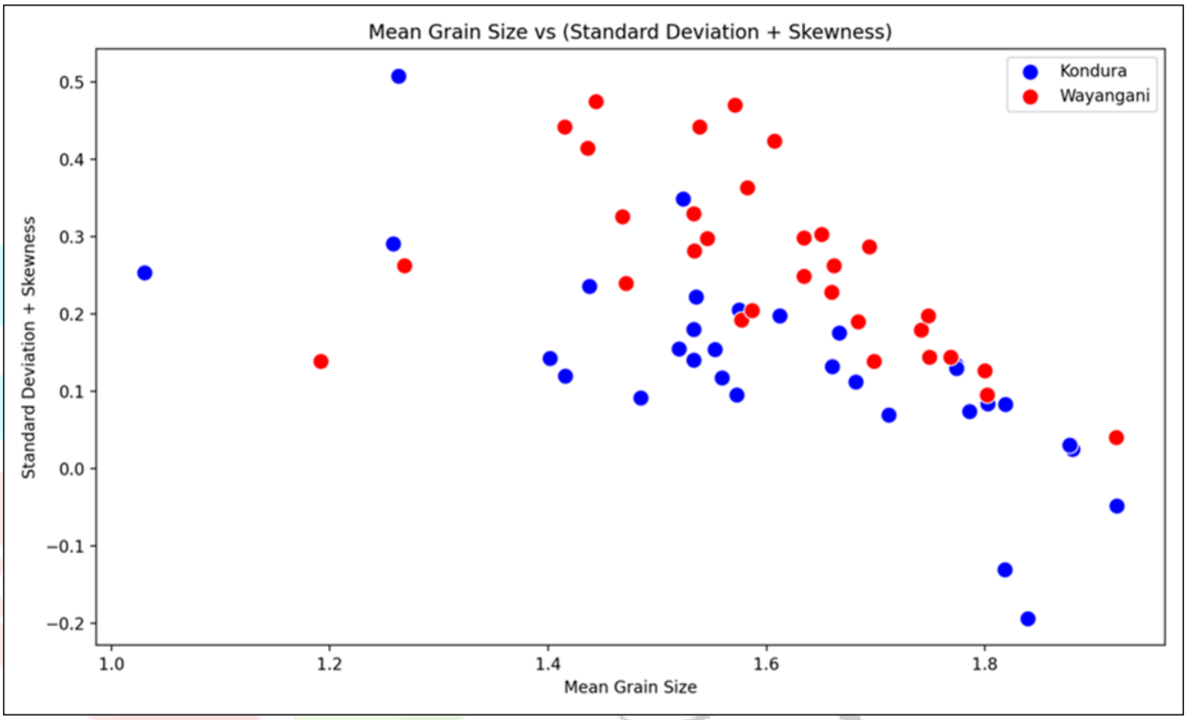
The kurtosis values range from platykurtic (~0.63) to leptokurtic (~1.46) (Fig.8), with most of the skewness values being negative (coarse-skewed). This indicates a broad grain size distribution, where high-energy conditions result in the deposition of coarser materials. Kurtosis values are more consistent and mesokurtic (~1.0) (Fig.8), with skewness values closer to neutral. This suggests a narrower grain size distribution due to more consistent energy conditions, where the sorting processes are effective. Kondura Beach shows more variability in both skewness and kurtosis, reflecting variable depositional environments, while Wayangani Beach has more consistent skewness and kurtosis, indicating a stable energy environment.

Sorting vs. Skewness:

Figure.9 Sorting vs. Skewness. Represents sediment sorting and skewness patterns at both locations.

The sorting is poorer (up to 1.0) (Fig.9), and most samples are coarse-skewed, indicating that high-energy events lead to the deposition of coarse, poorly sorted particles. The mixed energy conditions are responsible for the variable grain size distribution. The sorting is better (~0.65) (Fig.9), and skewness is closer to neutral, reflecting more balanced conditions where both fine and coarse particles are deposited more evenly. The wave energy consistently sorts the sediment. Kondura Beach shows poor sorting and coarse-skewed sediments, reflecting high-energy events, while Wayangani Beach shows better sorting and more symmetrical grain size distribution, indicating steady wave action.

Mean Grain Size vs (Standard Deviation + Skewness):



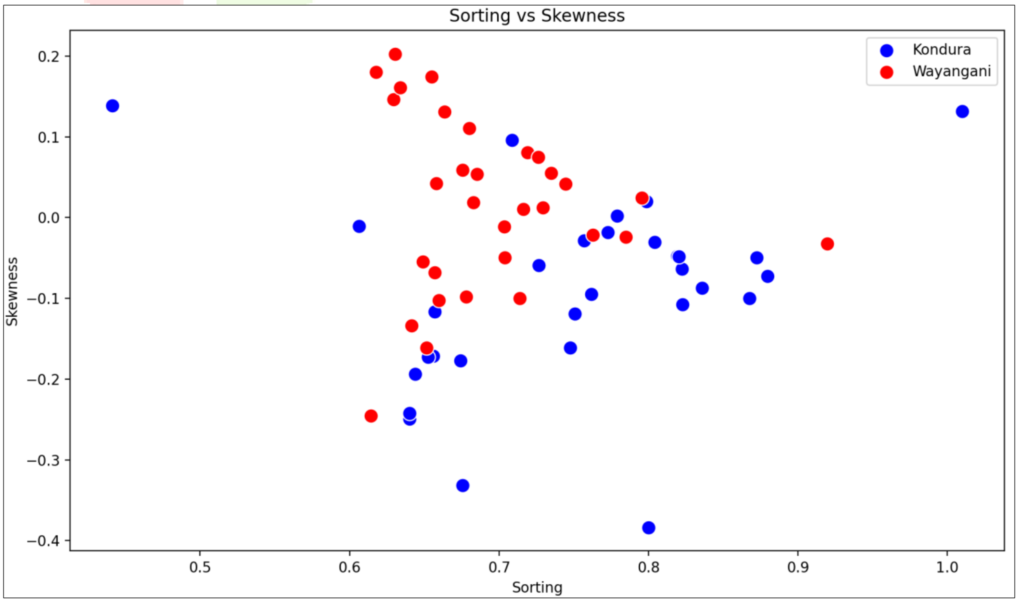
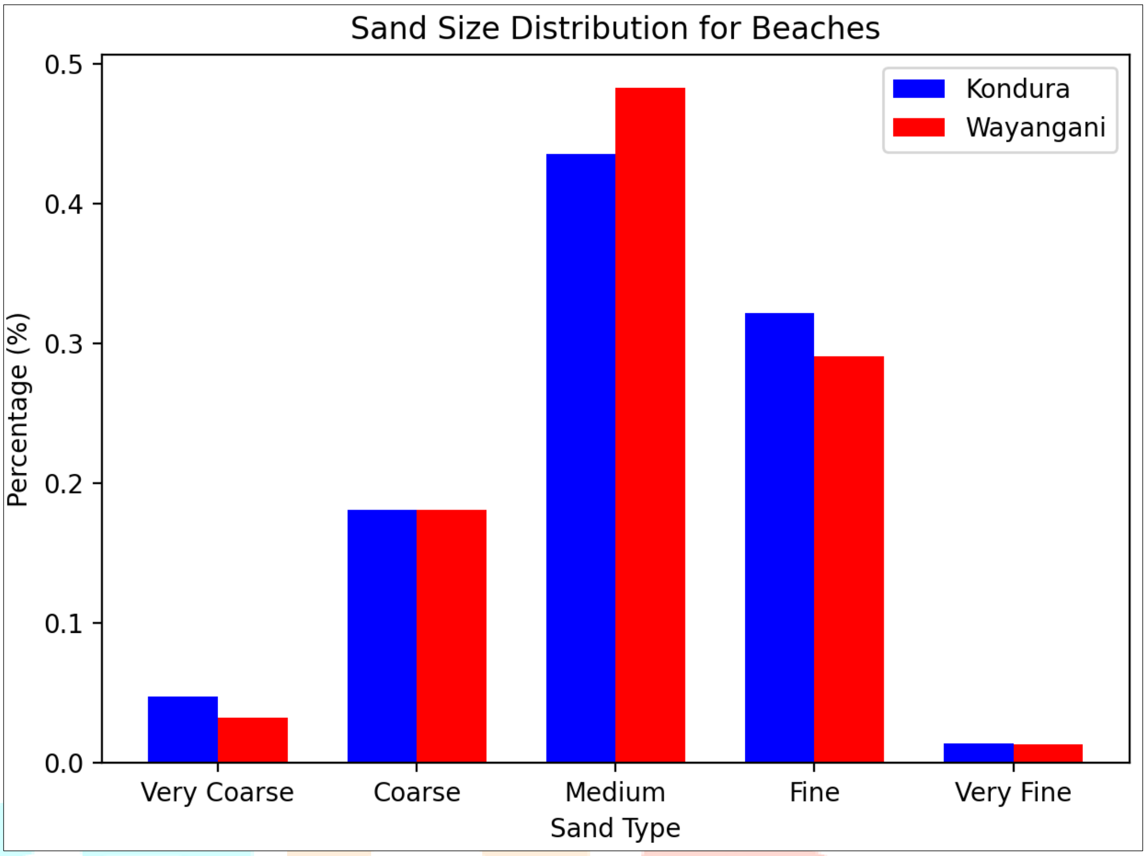


Figure.10 Mean grain size vs. Standard deviation and Skewness. Shows combined sediment distribution parameters at Kondura and Wayangani Beaches.

The mean grain size ranges from 1.0φ to 2.0φ (Fig.10), with most samples showing negative



skewness and higher standard deviation (up to 1.0) (Figure 10), reflecting coarse-skewed, poorly sorted sediments deposited by high-energy conditions. The data for Wayangani clusters around 1.6φ (Fig.10), with better sorting (lower standard deviation) and neutral skewness, indicating a more uniform energy environment where the sediment is better sorted and more evenly distributed. Kondura Beach tends toward coarse-skewed, poorly sorted sediments, while Wayangani Beach reflects better sorting and a more balanced grain size distribution.

Sand Size Distribution:

Figure.11 Sand type vs. Percentage (%). Illustrates the proportion of sand types in relation to their percentages at the two beaches.

The sand composition indicates a higher percentage of coarse and medium sand, suggesting a more robust sediment structure, which may be influenced by wave action and sediment transport dynamics (Fig.11). The presence of finer sand types suggests a different depositional environment, possibly indicating calmer waters or finer sediment sources. Medium sand dominates the distribution, but a significant proportion of coarse sand is also present, reflecting high-energy depositional events that introduce larger particles into the beach system. Medium sand makes up the majority of the distribution, with only a small percentage of coarse sand. This indicates consistent wave action, which efficiently sorts and deposits medium sand particles. Kondura Beach has a higher proportion of coarse sand, reflecting episodic high-energy events (Fig.11), while Wayangani Beach is dominated by medium sand (Fig.11), indicating more uniform wave energy conditions.

V. DISCUSSION

This study aims to analyze the textural and granulometric characteristics of beach sediments along the Sindhudurg coast of Maharashtra, specifically comparing Kondura Beach and Wayangani Beach. The interpretation of various plots and graphs reveals distinct depositional environments and energy dynamics at these two beaches, providing insights into sediment transport processes, sorting mechanisms, and morphological evolution.

From the analysis of the Standard Deviation vs. Mean Grain Size plot (Fig.4), it is clear that Kondura Beach experiences variable energy conditions, as evidenced by the broad range of grain sizes and poor sorting, with standard deviation values extending up to 1.0. This variability suggests episodic high-energy events, such as storms or seasonal monsoon influences, where coarser particles are deposited and poorly sorted, similar to findings (Putra 2017) on dynamic sediment distribution in coastal environments. In contrast, Wayangani Beach exhibits more consistent sorting, with better-organized grain sizes and a narrower spread of standard deviation values, indicating stable wave action that maintains uniform depositional processes.

The Mean Grain Size vs. Skewness plot (Fig.5) reinforces these findings. Kondura Beach shows predominantly coarse-skewed sediments (negative skewness), reflecting high-energy events that deposit larger grains, confirming the impact of dynamic environmental forces on sediment distribution. This is consistent with (Friedman 1961), who highlighted the relationship between high-energy coastal processes and coarse-skewed distributions. Wayangani Beach, however, shows more balanced skewness, indicating a stable depositional environment with relatively consistent energy levels throughout the year, aligning with previous studies on stable coastal zones with predictable sediment transport pathways.

The Mean Grain Size vs. Sorting plot (Fig.6) provides further evidence of Kondura Beach's variability, with a wide range of poorly sorted sediments. This suggests multiple sediment input sources (e.g., rivers, wind, and wave action), leading to fluctuating energy conditions that fail to sort the sediment effectively. Conversely, Wayangani Beach demonstrates better sorting, indicative of wave-dominated processes that consistently rework the sediments, removing finer materials and leading to a more uniform grain size distribution. This pattern aligns with (Riberio 2020), who emphasized the role of wave action in improving sediment sorting in beach environments.

The Skewness vs. Kurtosis plot (Fig.8) illustrates that Kondura Beach has a mix of platykurtic and leptokurtic sediments, reflecting a broad grain size distribution. This variability is indicative of multiple sediment transport pathways, including wave action, river deposition, and wind-driven processes, which lead to a mixture of coarse and fine particles being deposited at different times. Wayangani Beach shows more mesokurtic distributions, indicative of a narrower grain size range and consistent energy conditions, supporting the conclusion that wave action is the primary sorting mechanism on this beach.

The Sorting vs. Skewness plot (Fig.9) further differentiate the two beaches. Kondura Beach has poorly sorted, coarse-skewed sediments, suggesting episodic high-energy events, while Wayangani Beach shows moderately well-sorted and symmetrically skewed sediments, indicative of continuous wave-driven sediment transport that results in more even sorting of grain sizes.

Lastly, the Sand Size Distribution plot (Fig.10) reveals that Kondura Beach has a significant proportion of coarse sand, indicating high-energy deposition, while Wayangani Beach is dominated by medium sand, reflecting the steady reworking of sediment by wave action. This distribution pattern is consistent with studies (Hanamgond 2017; Carranza 2005), which highlighted how sediment size and sorting are linked to local hydrodynamics and energy regimes.

VI. CONCLUSION

The granulometric analysis of sediments from Kondura and Wayangani beaches has revealed significant differences in sorting, grain size distribution, skewness, and kurtosis, reflecting the varying energy conditions and sediment transport mechanisms at these two locations. Kondura Beach exhibits poor sorting, with coarse-skewed, poorly sorted sediments. These characteristics are indicative of episodic high-energy events such as storm surges or monsoonal influences, which introduce coarse materials into the beach system, disrupting the regular sorting processes typical of wave-dominated environments. Wayangani Beach, on the other hand, shows better sorting and more symmetrical grain size distributions, reflecting stable, continuous wave action that consistently reworks the sediment. The dominance of medium sand and the lack of extremely coarse material suggest a steady, predictable energy regime, which maintains uniform depositional conditions.

Future research could further explore the seasonal variability in sediment dynamics, particularly focusing on how monsoonal cycles and climate change might influence long-term coastal evolution along the Konkan coast of India.

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