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Seasonal Variation in Total Heavy Mineral Concentration Along a Monsoon-Influenced Coast: A Case Study from Kalutara, Sri Lanka

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Abstract

The seasonal variations of heavy mineral concentrations in coastal sediments affect nearshore sediment dynamics, mineral resource potential, and depositional processes. This study investigates the influence of monsoonal wave dynamics on the heavy mineral distribution along the Kaluthara coast in southwest Sri Lanka, which is an active sedimentary environment shaped by the discharge of the Kalu river and is influenced by both Southwest (SW) and Northeast (NE) monsoons. Sediment samples were collected from 10 locations post-SW and post-NE monsoons from the beach face. Bromoform (SG = 2.89 g/cm^3) was used for the separation of heavy minerals from the sediment samples. The results showed significantly higher Total Heavy Mineral concentrations during the post-NE monsoon season, in contrast to the post-SW monsoon season, which is associated with high-energy wave activity, possibly due to erosion and sediment reworking. This highlights the dynamic relationship between seasonal hydrodynamics and heavy mineral enrichment. This study contributes valuable insight to the temporal behavior of heavy mineral accumulation, which can be helpful in mine planning and exploration.

Keywords: Erosion, Geomorphology, Hydrodynamics, Kaluthara, Sediment reworking, Total Heavy Minerals, Wave dynamics

1 Introduction

Coastal environments disseminated worldwide are often enriched with different types of heavy minerals such as ilmenite, rutile, garnet, and zircon [1]. The enrichment of these heavy minerals is associated with geomorphological processes such as erosion, transportation, deposition, and physicochemical properties in sediments [2].

Heavy minerals are mineral grains that typically have a greater density than 2.9 g/cm^3. This value is linked to the specific gravity of bromoform of 2.89 g/cm^3, which is generally used for heavy mineral separation [3].

Studying heavy minerals is imperative for numerous geological and economic applications [4]. It is important to understand transport history and depositional patterns of sediments and identify economic placer deposits, which are natural concentrations of valuable heavy minerals that are formed by selective sorting [3], [5].

In Sri Lanka, over 90% of the geological landscape is underlain by Precambrian rocks, which are divided into five main complexes: the Highland complex, Vijayan complex, Wanni complex, Kadugannawa complex, and Miocene sedimentary formations [6]. The Kaluthara basin is primarily associated with the highland complex [7]. These ancient Precambrian rocks in the island's interior undergo weathering, producing the source material for mineral sands. Rivers transport these weathered sediments to the coast, where wave action, current, and wind will concentrate them into deposits [6].

The distribution and the concentration of heavy minerals in sediments are controlled by an intricate relationship of physical and chemical processes [5]. These processes govern how minerals are eroded, transported and deposited, thereby leading to selective sorting and accumulation [8]. Key factors include density, which is the primary factor, as well as grain size and shape, mineralogy, and durability [3], [9]. For instance, grain size will influence how particles respond to hydraulic conditions, and grain shape will affect how tightly it is packed, which will impact the shear stress that's needed for transport [9].

Seasonal changes that are associated with monsoon periods significantly impact the sediment transport, erosion, accumulation and heavy mineral concentration in specific coasts [10]. Sri Lanka is primarily affected by two main monsoonal seasons, which bring distinct weather patterns to different parts of the island. The Southwest (SW) monsoon occurs from May to mid-September, while the Northeast (NE) monsoon lasts from December to February.

Longshore sediment transport rates vary seasonally with a northerly transport during the SW monsoon and a southerly transport during the NE monsoon [2]. Areas affected by the monsoon experience rapid sediment erosion and transportation during rainy periods, while accumulation and segregation occur during the drier seasons [10]. A study along the Govindampalli–Durgarajupatnam coast in India found that the total heavy mineral (THM%) was higher during the pre-monsoon season compared to the post-monsoon season [10].

Waves, currents, and tides are the primary agents that lead to selective sorting based on size and density in coastal environments [5]. Strong wave action concentrates heavy minerals on beach faces by carrying lighter minerals back into the sea [3]. Grains that are found together in a sediment layer that is deposited by currents generally have the same settling velocity, commonly known as hydraulic equivalence. Therefore, a deposit will contain low-density grains as well as high-density heavy minerals, where the low-density minerals will be projected above the sediment layer [4], [5]. Hence, high-energy currents will selectively remove the larger grains from the deposits due to smaller pivoting angles and drag forces. As a result, these deposits become increasingly enriched in heavy minerals, ultimately forming placer deposits [4].Generally, heavy minerals settle closer to their source than light minerals and so the composition of heavy minerals will shift with the transport distance [8].

Understanding the seasonal variations in heavy mineral concentration along monsoon-influenced coasts is essential for refining paleoenvironmental interpretations, improving the exploitation of economic placer deposits and for a comprehensive understanding of coastal morphodynamics in regions that are impacted by seasonal climates [3], [4]. The Kaluthara coast is a geomorphologically diverse shoreline with active fluvial and marine interactions due to the Kalu river discharge. Hence, it serves as a representative case for a monsoon-influenced system.

The present study aims to evaluate the seasonal variation of heavy mineral concentrations in coastal sediments along the Kaluthara coast to determine how monsoonal wave regimes influence the enrichment or depletion of heavy minerals in this environment.

2 Methodology

2.1 Study area

2.1.1 Geographical setting

The study area encompasses the coastal region of Kaluthara, which is located along the southwestern coast of Sri Lanka. This stretch of coastline extends from Waskaduwa from north of the Kalu river, to Payagala in the south, with a natural division created by the Kalu river estuary. The specific sampling locations span from the Panadura area to the Kalamulla area, which covers approximately 18.5 kilometres of coastline. This region represents a dynamic coastal environment, and its sediment supply is significantly influenced by Kalu Ganga, one of Sri Lanka's major rivers.

2.1.2 Monsoon changes

The study area is affected by the northeastern and southwestern monsoon seasons. Heavy rainfall brought on by the southwest monsoon occurs from May to mid-September, while light to moderate rainfall can be observed from December to February during the northeast monsoon.

The interaction between riverine discharge and other marine processes, such as cross-shore currents and longshore currents, creates a complex depositional environment [11],[12]. For example, at the river mouth estuary, the outflowing river currents, existing sea waves, modified waves, and turbulence due to mixing of fresh water and saltwater take place. This interaction shapes the coastal environment by continuously altering sediment movement and influencing the formation and evolution of landforms near the river mouth [12].

2.2 Sampling

Sampling was conducted at ten distinct locations within the study area with different geomorphological features. Four locations were situated towards the north of the Kalu river (L1, L2, L3, L9) discharge, and four locations were situated towards the south (L4, L5, L6 L7). The two remaining locations were at the estuary itself (L8-1, L8-2). This targeted distribution of sampling locations facilitated the examination of seasonal variation across the Kalutara coastal region as shown in Figure 1.

The samples were collected at two different times to understand the seasonal variations and their influence on heavy mineral accumulation. The first set of samples was collected in October 2024, following the Southwestern monsoon, and the second set of samples was collected in May 2025, post-inter-monsoon season, which follows the Northeastern monsoon.

Figure 1: Sampling locations across the Kaluthara coastal region

2.3 Testing and analytical procedures

Bromoform (SG = 2.89 g/cm^3) was used for the separation of heavy minerals from the sediment samples, following the standard procedures [3]. After the separation, the samples were oven dried at temperatures between 105^{0}C - 110^{0}C and the weights of the heavy mineral fraction were measured. These weights and the total weight of the sample before the bromoform separation were used to calculate the total heavy mineral percentages.

3 Results

Table 1 shows the results of the heavy mineral separation of post Southeast monsoon and post Northeast monsoon along with a description of the beach. A comparison of the THM% contents is graphically represented in Figure 2.

Table 1: THM concentrations of post Southeast monsoon and post Northeast monsoon

Locations	Description of sampling locations	THM% Post southwest monsoon	THM% Post northeast monsoon
LO1 Beach face	Linear shoreline. Location is near a breakwater	8.52	58.45
LO2 Beach face	Moderately wide and straight beach.	42.35	82.21
LO3 Beach face	Linear beach with a wide sandy stretch	5.69	8.21
LO4 Beach face	Between two distinct breakwaters, a curvy beach	48.86	19.05
LO5 Beach face	Between two breakwaters, curvy sandy beach	41.70	58.84
LO6 Beach face	Relatively straight beach stretch, near a breakwater	32.46	53.15
LO7 Beach face	Sandy exposed coastline, wide and relatively straight beach	33.24	13.90
LO7 Swash		31.68	11.68
LO7 Berm		43.55	16.67
LO8 (1) Sea side	At the river mouth, an estuary, on a large sand bar towards, the sea side	1.63	7.51
LO8 (2) River side	At the river mouth, an estuary, on a large sand bar, towards the river side	16.60	23.06
LO8 Berm	At the river mouth, an estuary, on a large sand bar, on the berm	66.23	22.73
LO9 Beach face	Moderately linear shoreline	24.86	56.25

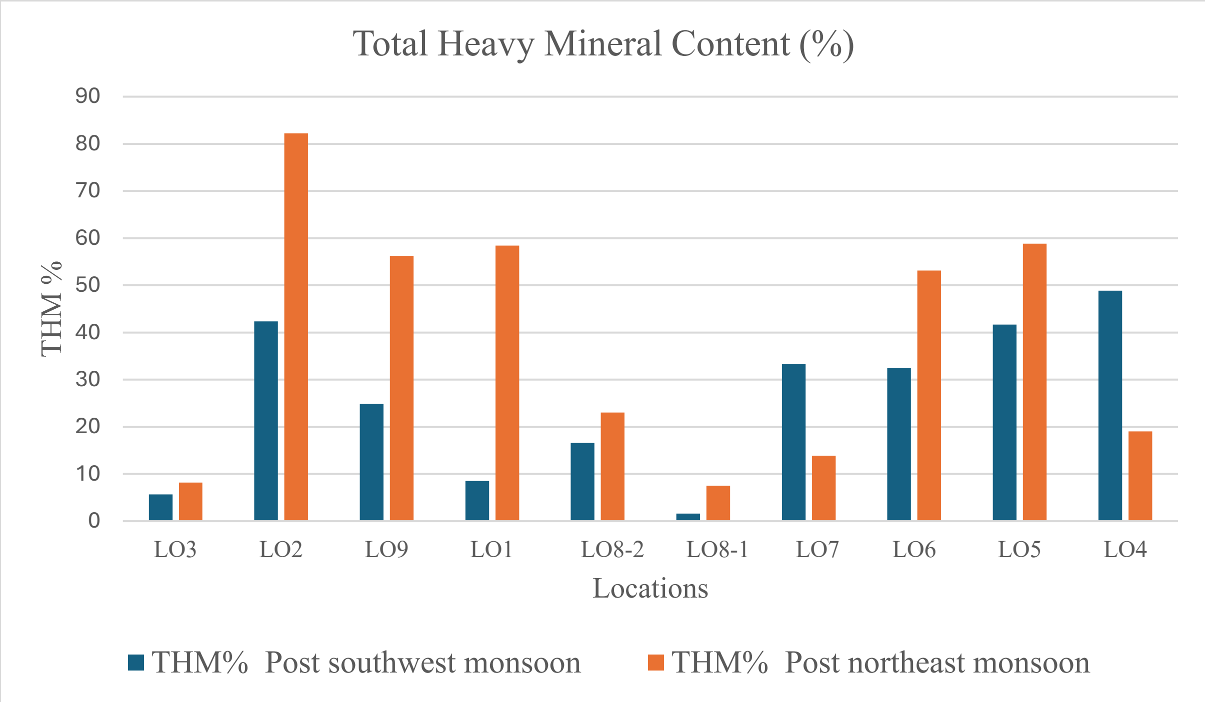

Figure 2: Graphical comparison of THM% contents in the sampling locations

4 Discussion

This study investigated the variation of heavy mineral concentration and distribution in beach sediments along the coast of Kaluthara in the southwestern coast of Sri Lanka, focusing on the contrasting conditions following the SW and NE monsoon periods. The obtained results reveal a distinct seasonal trend with consistently higher total heavy mineral percentages observed following the NE monsoon period when compared to the post-southwest monsoon period across most of the sampling locations.

The wave energy flux during the inter-monsoon period is considerably lower when compared to the SW monsoonal energy flux [13]. The increased THM concentrations post-inter-monsoon period can be attributed to the reduced wave energy conditions prevailing during this season in the Kaluthara coast. Sampling the post-inter-monsoon period captures the sediment deposition during a low-energy phase. This suggests a seasonal variation in sediment supply that favours heavy mineral accumulation. Heavy mineral content tends to increase with a decrease in grain size [3]. The low wave energy environments promote selective sorting processes. Lighter minerals such as quartz and feldspar are winnowed away, thereby allowing the denser, heavy minerals such as ilmenite, garnet, and zircon to concentrate. These will accumulate in the nearshore and berm zones. During this period, beach accretion is dominating, creating a relatively stable surface where heavy minerals can settle and be preserved.

Conversely, due to the higher wave energy and active longshore currents during the Southwest monsoon season, the heavy mineral enrichment appears to be limited. Sampling post SE monsoon allows to assess the impact of the high-energy phase on heavy mineral concentration. In a study conducted on the distribution of particles in a water column showed that the bottom boundary layer primarily consisted of resuspended particles, among which the largest particles were highly concentrated [14]. This resuspension directly implies turbulence and reworking of deposited material. The cross-shore and longshore transport is enhanced due to the increased turbulence, which possibly leads to erosion and reworking of the heavy mineral deposits and their removal.

The spatial patterns in the heavy mineral distribution further suggest that local geomorphological features, anthropogenic features, and the estuarine influence contribute to sediment retention and mineral sorting. For an example, the locations within the proximity of the Kalu river estuary (L1 and L7) show a relatively low total heavy mineral content in both seasons. This can be due to the influx of finegrained alluvial sediments and the dynamic mixing zone at the river mouth. The increase in such sediments may dilute the heavy mineral accretions. In contrast, the locations that are farther from the estuary, such as L2 and L5, recorded a higher heavy mineral percentage.

5 Conclusion

This study examined the seasonal variation of THM content along the Kaluthara coast of Sri Lanka. This is a region that is influenced by contrasting monsoonal regimes. The results show that the THM concentrations are notably higher during the post-inter monsoonal period compared to the post-Southwest monsoon season.

This reflects the strong seasonal influence of wave energy on coastal sediment dynamics. During the SW monsoon, the high-energy conditions promote sediment reworking, dilution, erosion, and offshore transport, which reduces the retention of heavy minerals whereas, the calmer wave conditions during the NE monsoon and low energy regime during the inter-monsoonal period allow for effective segregation and sorting, thereby winnowing lighter minerals and allowing for the denser heavy minerals to accumulate. Despite the spatial heterogeneity in the THM concentrations, the seasonal patterns are monsoon-controlled. 80% of the locations show higher THM concentrations during the post-inter-monsoonal season. LO4 and LO7 show reverse patterns, which could indicate local override mechanisms. Hence, the predominant pattern of increased THM post-intermonsoonal period suggests that regional monsoon-driven processes have control over the heavy mineral distribution.

The spatial distributional variations of THM concentrations suggest that the heavy mineral enrichment or depletion is affected by localized hydrodynamic conditions and beach morphology, in the proximity of the Kalu river mouth.

Importantly, this research also provides insights for coastal placer mining and mine planning. For example, by identifying the seasonal windows during which the heavy mineral concentrations are the highest, resource assessment can be timed better. LO1, LO2, and LO9 have extremely high variations through the periods, which demonstrates that single-season sampling could provide misleading assessments in heavy mineral resources in such environments. In addition, by understanding the spatial distribution patterns for enrichment and depletion of heavy minerals can help identify more reliable zones for mineral extraction while minimizing environmental disruption.

The consistently low heavy mineral concentrations at the river mouth (LO8-1 and LO8-2) indicate that the riverine sediment influx dilutes heavy mineral accumulations, which creates a persistently low concentration zone. This further suggests that heavy minerals tend to accumulate more optimally at intermediate distances from major sediment sources.

Overall, this research outlines the importance of seasonal and localized geomorphological analysis in understanding and predicting the potential of placer minerals in coastal environments.

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