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RESEARCH ARTICLE

Spatial Variation of Sediment Grain Size and Its Environmental Implications in the Anoi Itam Coastal Waters, Pulau Weh, Indonesia

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Abstract

This study investigates the grain-size distribution and sediment characteristics of the Anoi Itam coastal waters, Sabang City, Aceh Province, Indonesia. Sediment samples were collected from three stations representing different hydrodynamic energy zones using a Van Veen grab sampler. Grain-size analysis was performed through dry sieving and classified according to the Wentworth and Folk Ward scales. The results show clear spatial variability reflecting a hydrodynamic energy gradient. Station 1 was dominated by coarse to very coarse sand, indicating high-energy conditions, whereas Station 2 exhibited mixed coarse and medium sands under moderate energy. Station 3 consisted mainly of medium to fine sands, characteristic of low-energy depositional settings. The progressive fining trend supports hydrodynamic sorting control on sediment distribution and provides essential baseline data for coastal management.

Keywords: Sediment Composition, Grain-Size Distribution, Hydrodynamic Energy, Anoi Itam Waters, Pulau Weh, Coastal Processes.

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1 Introduction

Aquatic coastal environments, such as those surrounding Pulau Weh, Indonesia, provide valuable natural laboratories for understanding sediment dynamics, particularly in settings characterized by volcanic sand deposits such as Anoi Itam. Sedimentary processes in these systems are closely controlled by local hydrodynamic conditions, which influence geomorphological evolution and benthic habitat structure. Among sediment properties, grain size is a key indicator of hydrodynamic energy and sediment transport mechanisms in intertidal and nearshore environments [1,2]. Grain-size distribution analysis therefore serves as a fundamental approach for interpreting depositional environments and identifying sediment transport pathways. Coarser sediments typically dominate high-energy settings where wave action and tidal currents inhibit fine-particle deposition, whereas finer sediments accumulate under low-energy conditions that promote settling and stability [5].

The volcanic origin of Pulau Weh, combined with complex hydrodynamic interactions driven by tidal currents and seasonal monsoonal winds, generates highly dynamic sedimentary conditions along the Anoi Itam coastline. Variations in wind regime, wave intensity, and current velocity can substantially alter sediment transport patterns and depositional gradients [6,7]. In addition to natural processes,

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anthropogenic activities such as coastal infrastructure development and land-use modification may further influence sediment balance and potentially accelerate shoreline change [6,7]. Despite its ecological and geomorphological significance, sedimentological research in the Anoi Itam region remains limited. Detailed grain-size assessments are therefore essential to establish baseline data supporting coastal monitoring, erosion assessment, and habitat management initiatives [8,9].

Understanding spatial variability in sediment texture can elucidate the interaction between hydrodynamic forcing and geomorphic controls that regulate sedimentation patterns. Such knowledge is critical for environmental management, as sediment composition influences nutrient dynamics, contaminant retention, and ecosystem stability in coastal systems [10,11]. Accordingly, this study aims to analyze the grain-size distribution of coastal sediments at three sampling stations in the Anoi Itam waters. The specific objectives are to (a) quantify the proportional composition of sediment fractions (gravel, sand, and mud), (b) evaluate spatial variations in grain size in relation to hydrodynamic energy conditions, and (c) interpret the depositional characteristics and sedimentary processes governing sediment distribution in the study area. The findings are expected to enhance understanding of sediment dynamics in volcanic island coastal systems and to provide a scientific foundation for sustainable coastal management and conservation strategies in Pulau Weh.

2 Methodology

2.1 Study Area

This study was conducted in the coastal waters of Anoi Itam, Sabang City, Aceh Province, Indonesia, located along the eastern coast of Pulau Weh at the northernmost tip of the Indonesian archipelago. Field sampling was carried out on April 14, 2018, between 08:00 and 18:00 Western Indonesian Time. The Anoi Itam coastline is distinguished by its volcanic-origin black sand, a geomorphological feature unique within the region, reflecting the island's volcanic history and active sediment supply. The study area is situated within a tropical maritime climate zone, where hydrodynamic conditions are strongly influenced by seasonal northeast and southwest monsoon systems. The region experiences semi-diurnal tidal regimes characterized by alternating high and low tides, which contribute to periodic sediment resuspension, transport, and redistribution. Coastal morphology is dominated by gently sloping sandy substrates interspersed with localized rocky outcrops, forming a dynamic nearshore system shaped by wave action, tidal currents, and terrestrial inputs. Following field collection, sediment identification and grain-size analyses were conducted on May 10, 2018, at the Marine Chemistry Laboratory, Faculty of Marine and Fisheries, Universitas Syiah Kuala, Darussalam, Banda Aceh. All samples were processed under controlled laboratory conditions to ensure analytical accuracy, consistency, and reproducibility.

2.2 Field Sampling Procedures

Sediment samples were collected from three stations (Station 1, Station 2, and Station 3) distributed along the Anoi Itam coastal zone to capture spatial variability in hydrodynamic energy and depositional conditions. Each station represented a distinct environmental setting: Station 1 corresponded to a nearshore high-energy zone, Station 2 represented a transitional moderate-energy area, and Station 3 reflected a relatively sheltered low-energy environment. At each station, three replicate samples (Plot 1, Plot 2, and Plot 3) were obtained using a Van Veen grab sampler with an effective sampling area of approximately 0.05 m^2. The upper 2 cm of surface sediment was carefully subsampled to represent the actively reworked layer influenced by recent hydrodynamic processes. Samples were placed in pre-labeled polyethylene bags, stored in a cooled container, and transported to the laboratory for processing. Upon arrival, sediments were air-dried at ambient temperature, gently disaggregated using a porcelain mortar and pestle, and manually cleaned of visible organic debris and shell fragments prior to grain-size analysis to ensure analytical consistency.

2.3 Grain-Size Analysis

Grain-size distribution was determined through the dry-sieving technique, following the standard procedure de- scribed by Folk and Ward (1957) and Wentworth (1922). Approximately 100 g of each dried sediment sample was placed in a nest of stainless-steel sieves arranged in decreasing mesh size order: 2 mm, 1 mm, 500 μm, 250 μm, 125 μm, 63 μm, and 38 μm. The sieve stack was subjected to mechanical agitation for 15 minutes using a Retsch mechanical shaker to ensure complete separation of particle sizes. Each retained fraction was weighed with a precision digital balance ($\pm$0.01 g), and the mass of each fraction was converted into percentage composition relative to the total dry weight of the sample.

2.4 Sediment Classification

Grain-size fractions were classified according to the Wentworth scale into the following categories: (a) gravel (>2 mm), (b) very coarse sand (1–2 mm), (c) coarse sand (500–1000 µm), (d) medium sand (250–500 µm), (e) fine sand (125–250 µm), (f) very fine sand (63–125 µm), and (g) mud (silt + clay; <63 µm). For each sediment sample, the percentage weight of each grain-size fraction was determined relative to the total dry weight. Based on these data, sediment textural parameters, including mean grain size (Mz), sorting (), skewness (Sk), and kurtosis (K) were calculated using the graphical moment method of Folk and Ward. These statistical parameters provide quantitative measures of central tendency, distribution spread, asymmetry, and peakedness of the grain-size distribution, allowing interpretation of depositional energy conditions and sediment transport processes.

2.5 Data Analysis and Visualization

Results from the three replicate plots at each station were averaged to obtain representative mean percentage compositions, and corresponding standard deviations were calculated to quantify variability. Data visualization was performed using Python (Matplotlib and Seaborn libraries) to generate stacked bar charts and grouped comparative plots illustrating the relative proportions of sediment size fractions across sampling stations. Statistical summaries were computed using Microsoft Excel and R (version 4.3). Descriptive statistical analyses were applied to assess spatial variations in grain-size distribution among stations. These analyses provided the quantitative basis for interpreting hydrodynamic energy gradients and depositional patterns within the Anoi Itam coastal system.

2.6 Quality Assurance and Control

To ensure analytical reliability, all sieves were thoroughly cleaned after each run to prevent cross-contamination, and each sediment sample was processed in duplicate. Variations between repeated measurements were maintained below 2%, indicating high analytical precision. The analytical balance was calibrated daily using certified standard weights to maintain measurement accuracy. Additionally, randomly selected subsamples were reanalyzed to verify reproducibility of the grain-size measurements. All laboratory procedures followed established sedimentological protocols and quality control standards, ensuring consistency and comparability of results across sampling stations.

2.7 Data Interpretation Framework

The interpretation of grain-size data was conducted in accordance with established sedimentological principles, whereby coarser sediment fractions are generally associated with higher hydrodynamic energy conditions, while finer fractions reflect deposition under relatively low-energy environments. Accordingly, spatial variations in sediment texture among the three sampling stations were used to infer differences in sediment transport intensity, depositional mechanisms, and prevailing energy regimes along the Anoi Itam coastline. The grain-size distribution patterns provided a basis for delineating sedimentary facies and identifying hydrodynamic gradients across the study area. By integrating textural parameters with spatial trends, the analysis enabled interpretation of sediment transport pathways and depositional stability within the coastal system. These interpretations further support the evaluation of environmental implications related to sediment redistribution, shoreline dynamics, and coastal morphological evolution in the Anoi Itam region.

3 Results

3.1 Sediment Analysis

The grain-size distribution of sediments in the Anoi Itam coastal waters exhibited distinct spatial variability among the three sampling stations, reflecting differences in hydrodynamic energy and depositional regimes. Grain-size analysis was performed across seven sieve classes (2 mm, 1 mm, 500 µm, 250 µm, 125 µm, 63 µm, and 38 µm), and results were expressed as percentage weight of total sediment. Station 1 was dominated by coarse materials, with the 500 µm (coarse sand) and 1 mm (very coarse sand) fractions comprising approximately 74–81% of total sediment across plots. Gravel (2 mm) contributed about 10–11%, while medium sand (250 µm) accounted for 10–22%. Finer fractions (<125 µm) were negligible, collectively representing less than 1%. This distribution indicates a high-energy nearshore environment where strong wave and current action limit fine-particle accumulation.

At Station 2, sediment texture shifted toward slightly finer material. Coarse sand (500 µm) remained dominant (65–79%), followed by very coarse sand (16–27%). Gravel content decreased substantially (1–4%), while finer fractions remained minimal (<3%). These characteristics suggest a moderate-energy transitional setting with reduced

Table 1. Percentage of sediment weight by grain-size fraction across Stations 1–3.

Station	Plot	2 mm	1 mm	500 µm	250 µm	125 µm	63 µm	38 µm
Station 1	1	10.38766	20.51256	45.63882	22.60101	0.798526	0.054648	0.006825
	2	11.32458	28.85758	47.46149	10.39599	1.896325	0.056925	0.007116
	3	9.426642	32.91477	53.46502	4.08399	0.097731	0	0
Station 2	1	3.699313	20.447474	0.024695	73.09725	2.563343	0.158048	0.009878
	2	3.366956	27.262395	64.75825	3.684235	0.767154	0.146801	0.014207
	3	1.331646	16.284044	79.25102	1.352736	1.750422	0.030128	0
Station 3	1	0.643636	1.454545	55.39636	39.63636	2.585455	0.283636	0
	2	1.305006	3.328543	59.00105	35.27401	1.068086	0.023304	0
	3	1.828397	4.795002	68.41111	24.00649	0.871818	0.087182	0

but persistent hydrodynamic influence. In addtion, Station 3 displayed further fining, although coarse sand (55–68%) continued to predominate. Medium sand increased markedly (24–40%), whereas very coarse sand and gravel declined to less than 5%. Fine fractions remained low (<3%), indicating a relatively sheltered, lower-energy depositional environment that permits partial settling of finer sands. A clear offshore fining trend was observed across stations. Gravel decreased from 10.38% at Station 1 to 1.26% at Station 3, and very coarse sand declined from 27.43% to 3.19%. Conversely, coarse sand increased from 31.04% to 60.94%, and medium sand showed a moderate rise offshore. Overall, sediments were overwhelmingly sand-dominated, with minimal silt and clay content (<2%). The progressive textural transition from gravel-rich nearshore deposits to finer offshore sands reflects a decreasing hydrodynamic energy gradient along the Anoi Itam transect.

4 Discussion

The sediment size distributions across the three sampling stations at Pulau Weh reveal a distinct spatial gradient from coarse- to fine-grained textures, reflecting systematic variations in hydrodynamic energy and depositional settings within the study area. Station 1 is characterized by the dominance of coarse sand (500 µm), very coarse sand (1–2 mm), and appreciable gravel content, indicating a high-energy environment where intense wave and current activity preferentially transport and retain coarse particles while removing finer fractions (Figure 1). Such sedimentary characteristics are typical of exposed nearshore zones or channel margins subjected to strong hydrodynamic forcing [12]. In comparison, Station 2 exhibits a more intermediate grain-size composition, with coarse and medium sands (500–250 µm) predominating. The marked reduction in gravel and the increased proportion of medium sand suggest moderate hydrodynamic conditions, where flow energy remains sufficient to mobilize coarse grains but also allows partial deposition of finer sediments. This station likely represents a transitional depositional setting, such as an inner-shelf or tidal-flat environment, where sediment sorting is influenced by fluctuating energy regimes [13].

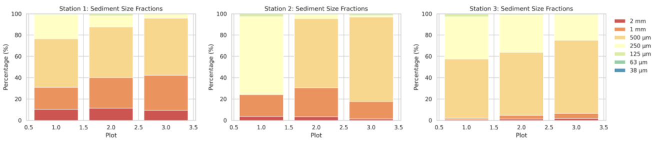

Figure 1. Sediment size fraction on Station 1-3

Station 3 demonstrates further textural fining, with sediments largely composed of medium to fine sands (250–125 µm) and minimal coarse fractions. This pattern reflects a relatively low-energy and more sheltered depositional environment in which hydrodynamic intensity diminishes, permitting greater stability and accumulation of finer particles [14,15]. The consistently low proportions of silt and clay across all stations indicate that sediment transport is dominated by bedload and saltation processes, with limited suspended-load deposition due to frequent reworking by waves and currents. The progressive offshore fining trend is consistent with hydraulic sorting mechanisms, whereby decreasing transport capacity along the flow path results in sequential deposition of progressively finer grains as energy dissipates [16,17]. From a facies perspective, Station 1 corresponds to a coarse-grained, high-energy facies; Station 2 represents a moderately sorted sand facies associated with transitional energy conditions; and Station 3 reflects a finer-grained, better-sorted facies indicative of lower-energy settings [18,19]. This gradational sequence provides compelling evidence of a hydrodynamic energy gradient along the sampling transect.

Sediment provenance patterns further support a unidirectional transport framework governed by a dominant detrital source. The concentration of coarse materials at Station 1 suggests proximity to sediment input sources, such as coastal erosion or localized terrestrial contributions. With increasing distance from this source, finer sediments are progressively deposited in more distal and protected areas, reinforcing the observed fining trend [20]. The predominance of sand-sized fractions throughout the study area indicates that spatial variability is primarily controlled by grain-size sorting processes rather than mineralogical differences [21].

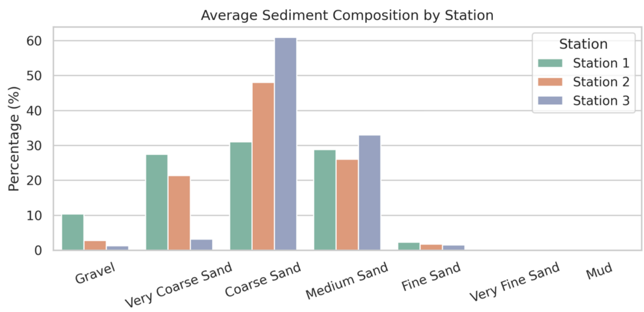

Figure 2. Average sediment composition

Mean sediment compositions across stations corroborate these interpretations: coarse sand remains the principal fraction overall, gravel and very coarse sand are concentrated nearshore, and medium to fine sands increase toward Station 3. This distribution reflects a classical grading sequence associated with declining hydrodynamic energy along the transport pathway [22]. Ecologically, the coarse, well-aerated substrates of Station 1 likely support epifaunal communities adapted to turbulent conditions, whereas the finer, more stable sediments at Station 3 are more suitable for infaunal assemblages. The overall fining trend also suggests a net sediment transport direction from Station 1 toward Station 3 under prevailing hydrodynamic conditions [23].

5 Conclusion

The grain-size analysis conducted across the three sampling stations in the Anoi Itam coastal waters of Pulau Weh demonstrates a well-defined spatial gradient associated with variations in hydrodynamic energy and depositional regimes. A clear fining trend is observed from Station 1 to Station 3, transitioning from gravel-rich and coarse sand deposits in the nearshore zone to finer, sand-dominated sediments in more sheltered offshore settings.

The predominance of coarse and very coarse sands at Station 1 reflects intense wave action and active sediment reworking typical of high-energy environments. Station 2 exhibits characteristics of an intermediate energy regime, where coarse and medium sands coexist under transitional hydrodynamic conditions. In contrast, Station 3 is dominated by medium to fine sands with minimal gravel, indicative of a relatively low-energy depositional setting that facilitates the accumulation of finer materials. The observed sedimentary patterns suggest that hydraulic sorting is the primary mechanism controlling sediment distribution, with transport dominated by bedload and saltation processes and only limited suspended-load deposition. The widespread dominance of sand-sized fractions across stations indicates that spatial textural differences are governed more by sorting intensity than by mineralogical variability. From an ecological standpoint, these sediment textures influence benthic habitat structure: coarse, well-aerated substrates in high-energy zones favor epifaunal assemblages, whereas finer, more stable sediments in sheltered areas support infaunal communities and enhanced organic matter retention.

Overall, the results confirm that the Anoi Itam coastal system is structured by a pronounced hydrodynamic energy gradient, where progressive attenuation of wave and current forces produces predictable patterns of sediment fining and sorting. These findings provide essential baseline information for coastal monitoring, sediment management, and ecological assessment in volcanic island shorelines such as Pulau Weh.

Data Availability Statement

Data will be made available on request.

Author Contributions

J.N. contributed to the conceptualization, supervision, and overall coordination of the study. A.N. was responsible for data collection, methodological design, and formal analysis. M.A.R. contributed to data processing, visualization, and software development. All authors were involved in the interpretation of the results, preparation of the manuscript, and critical revision of the final draft. All authors have read and approved the final version of the manuscript.

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This study was conducted in accordance with the academic and ethical guidelines established by the Department of Marine Science, Faculty of Marine and Fisheries, Universitas Syiah Kuala. All field sampling and laboratory procedures were performed following institutional research standards to ensure scientific integrity, environmental responsibility, and data reliability. The study involved only sediment sampling and did not include human participants or protected species; therefore, no specific ethical clearance for biomedical or animal research was required.

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Conflicts of Interest

The authors declare no conflicts of interest.

Ethical Approval and Consent to Participate

Not applicable.

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