

Sediment Characterisation in an Estuary - Beach System

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Abstract

Spatial sedimentological characteristics of surface and shallow intertidal sediments at an estuary-beach system (using the Hayle-St lves system as a case study) is presented in this study. Short sediment cores obtained from 80 samples are sliced at 1cm intervals and the grain size analysis is undertaken on these subsamples, using a Malvern MasterSizer 2000. The resulting distributions are processed to yield a range of grain size statistics through the GRADISTAT software package. Grain size parameters are examined to explore the evidence for the system's sediment mixing and extensive sediment transport processes. Sediment statistics at the coastlines/beaches (Carbis Bay, Black Cliff and Godrevy Towans) show that sediments are well sorted, near symmetrical/positively skewed medium-coarse sand while the inner estuary samples are predominantly medium sand, well sorted, symmetrical and only negatively skewed at 10-15 cm depth. A Principal Component Analysis, supported by a cluster analysis, shows that 82% of the variance in the grain size distribution is represented by fine-medium-coarse sand, and 14% is represented by the coarse/very coarse sand component. Comparison of grain-size statistics and cluster analysis shows that sediment characteristics can be discriminated clearly by sub-environments, but not on the basis of sub-surface shallow depth.

Keywords: Grain size statistics; Estuary-coast interaction; Sediment grain size; Principal component analysis; Hayle estuary; St Ives bay

Introduction

The study of grain size remains significant in the understanding of transport process pattern because grain-size trends seem to be the natural result of dynamic sediment transport processes [1,2]. The early studies have suggested that the grain size, occasion by the effects of abrasion and selective sorting, decreases in the direction of transport [3-5]. By the use of grain-size statistics, investigation and definition of sediment transport paths have been made evident in environmental studies [6], in sedimentology [7] and in dredging schemes [8].

The erosion, transportation, entrainment or deposition of sediment particles by any medium/fluid is partly controlled by the chemical and physical properties of the particles themselves and also that of the driving mechanisms [9]. Sediment characteristics may be changed during the transport processes and be sorted according to size, shape, mineralogy and density [10]. Grain size is one of the most important of the physical properties of sediments, and can reveal important information about the sediment source, transport history and depositional situation [11-13]. The influence of heterogeneous sediment properties on coastal processes was shown by Holland and Elmore [14] to be commonly underestimated due to difficulties in characterising and quantifying the various types of sediments. The application of extended and multivariate statistical analyses of grain size distributions are effective at identifying discrete similarities and differences between mixed sediment populations [15]. The aim of this study is to examine the sedimentary linkages between the beach and estuarine system using the St Ives Beach and Hayle Estuary in southwest England as case study. Focus here is the investigation of the similarities and differences in sediment texture so as to understand

how closely related the coast/beach and estuary sediment populations are, and gain a better understanding of the controls on sediment supply and transport within and between beach and estuary.

Materials and Methods

Study area description

The Hayle Estuary lies within St Ives Bay in the Penwith District of Cornwall in Southwest England (Figure 1). St Ives Bay is approximately 6.5 km wide, and the Hayle inlet lies just west of the centre of the bay.

The tide range is macrotidal (mean spring range 6.6 m), and the bay is exposed to a predominantly westerly wave climate with a 10% annual exceedance wave height of 2.5-3 m, and a 1 in 50-year extreme offshore wave height of 20 m [16]. The bedrock geology of St Ives Bay and the Hayle catchment is largely composed of Devonian metasediments (mudstones, siltstones, slates and sandstones). Permian granitic intrusions bound the bay to the west (at St Ives), and border the Hayle catchment to the south and southeast. Wave heights regularly exceed 5m@15s during the winter [16]. The bay is considered to be a closed sediment cell, suggesting that over the mesoscale, the sediment budget is balanced by morphodynamic adjustment across the estuary, inlet, beaches and nearshore [16].

Site A, in the inner estuary (Lelant water/Carrack Gladden; Figures 1 and 2) is a broad intertidal flat, the surface of which is characterised by sandy megaripples (wavelength $\lambda = 10\text{-}20$ m) and irregular small scale ($\lambda = 1\text{-}2$ m) hollows (scour features) in muddier unconsolidated sediments. The sandy planar upper foreshore of St Ives Bay beaches (sites B and D) merge with a broader and flatter beach at the inlet of the Hayle estuary (site C) where megaripples ($\lambda = 10\text{-}20$ m) and transverse wave-current ripples ($\lambda = 10\text{-}25$ m) persist (Figure 2).





Figure 1: The St Ives Beaches - Hayle Estuary sites sampled for sediment analysis.



Figure 2: Photographs showing surface conditions in the four main sedimentary environments surveyed. Sites are A – Lelant/Carrack Gladden, B – Carbis Bay/Barrepta Cove, C – Black Cliff and D – Godrevy Towans (Figure 1).

Field sampling

A total of 80 short cores were collected from four different zones within the Hayle estuary and St Ives Bay's intertidal sedimentary environments (Figure 1). Sample locations were located randomly within allowed key sites, and positioned using a hand-held Global Positioning System (GPS), (± 3 m rms error). Some parts of St Ives Bay and Hayle Estuary have been designated as a Site for Specific Scientific

Interest (SSSI) [17]. This means that the sites sampled for this study were those allowed by the conservation authority in the District with the limit of 15cm core permitted to be excavated at the sites. Cores acquired at low tide, were sealed, tagged and returned to the laboratory intact. Short (15cm) sediment cores obtained from 80 sample sites using a 65 mm diameter tube were sliced at 1cm intervals and the grain size analysis was undertaken on these subsamples, using a Malvern MasterSizer 2000 particle analyser, which uses a laser diffraction principle, detecting sizes across the range of $0.02 - 2000 \,\mu m$ [18]. No sediment coarser than sand (>2,000 µm) was present. Grain size distributions are processed to yield a range of Folk and Ward [11] grain size statistics (median, sorting and skewness) through the GRADISTAT software package [12]. Grain size analysis has been widely used to statistically examine spatial changes in sediment size properties. It was pioneered by McLaren [19], improved by McLaren and Bowles [20], and further modified by Gao and Collins [21]. Recent applications include the studies by Jitheshkumar et al. [22], Balsinha et al. [23], Garwood et al. [24] and Ordóñez et al. [25].

Principal Component Analysis (PCA) was used to reduce the grain size distributions across all samples into a smaller number of key variables. Hierarchical cluster analysis (using Euclidean distance and average linkage) was applied to the grain size distribution to organise samples into groups comprising similar sedimentological characteristics, specifically for each of the system. These calculations were undertaken in Matlab.

Results and Discussion

This section presents the results and discussion of the analyses carried out on the sediment. It qualitatively and statistically describes the spatial variation in grain size characteristics and the vertical/ stratigraphical variations in sediment texture.

Grain size characterisation: spatial variation

Grain size distributions of sediment sampled from sites A to D are summarised and presented in Figure 3.



Figure 3: Surface sediment characteristics in the St Ives Bay - Hayle estuary system. Grain size distributions are shown for all samples obtained within the depth range 0-15 cm at locations in the 4 main sedimentary environments examined: sediment at each site is also summarised as a mean distribution (solid black line). Sites are A – Lelant/Carrack Gladden, B – Carbis Bay/Barrepta Cove, C – Black Cliff and D – Godrevy Towans.

Sediment at sites A and D are dominated by particles in the medium sand range (250-500 μ m) while sites B and C comprise, in comparison, a mixture of medium sand and coarser distribution (500-1000 μ m). The grain size distribution here illustrates the clear consistency in sediment sampled in sites B with the modal size lying within the

Coarser Sand (CS) region of the size spectrum (around 600 µm). The mean distribution at site C is very similar to that at site B, but site C lacks consistency between samples which range between medium coarse and very coarse sand. Site D comprises mostly Medium Sand (MS) population, again with a broad consistency between samples. Site A in the inner estuary is distinct in the significance presence of finer material, either as a distinct clay population, a silty population or a silty tail to a dominant sandy population. Clay and silt are not present in the surface samples obtained at sites B-D. The beach samples (sites B - D) suggests the mixture of coarse/very coarse sand population. The presence of the fine-medium sand population in all of the sites however suggests that sediment exchange is active between sites.

Descriptive sediment statistics (Figure 4) show that surface sediments of the beach and inlet (Carbis Bay, Black Cliff and Godrevy Towans - Sites B, C and D) are generally moderately well (MWSo)/ Moderately Sorted (MSo) and largely symmetrical.

These sites do show some discrete differences. Site B is moderately sorted whilst C and D are moderately well sorted. Sites B and D are generally coarser than site D which is primarily medium sand (MS). The inner estuary samples (Lelant/Carrack Gladden, Site A) are a mix of silts, very fine (VFS), and medium sands (MS) that are poorly (PSo)/ very poorly sorted (VPSo), and are largely negatively (fine) skewed (FSk).

The combination of grain-size statistical parameters such as the median, sorting and skewness, obtained from the analyses of grain-size distribution in this study have been used in understanding the pattern of estuary - beach sediment exchange. From the grain size composition/distribution perspective (Figure 3), the sand population in the beaches in the system is composed of similar single particle-size population with minor variation in systematic characteristics. The simple interpretation which can be given to this form of distribution is that the major sand population in the beach is derived from a seaward source (possibly from the Celtic sea where the system is exposed to) with small contributions from the fluvial/river borne sediments. The overlap of marine derived and fluvial-derived sediment populations is evidenced in identifiable areas where there is exchange between the estuary and the beach (coast), for example the samples from the inlet (Figure 3C).



Figure 4: Exploratory sediment analysis – grain-size statistics – (A) Mean vs. Sorting (B) Mean vs. Skewness (C) Median vs. Sorting, and, (D) Median vs. Skewness.

This means that to a large extent, there is at least some exchanges between the inner estuary and the beach, evidenced by the sediment at, and close, to the surface. The continual presence of the medium - fine sand population within the near-surface deposits throughout the outer and the mid/inner of the estuaries suggests that sediment exchanges remains quite active between the sub-environments (beach and the estuarine environments). The processes operating in the environment might include the selective sorting, winnowing and transportation of medium to fine sand populations from the open coast/beach area. This has probably reflected the characteristics of the primary sediment source for this region, which could be marine, largely derived from glacigenic shelf sand which contribute a fine - medium sand population to a wide range of coastal sedimentary environments in northwest Europe [26].

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Considering the grain size statistics of both beach and estuarine environments' sediment samples, there is a possibility that the beach and coastal sands in the vicinity of the bays (especially those at the entrance channels) are caught up by the ebb and flood of the tide, then carried in and out of the estuaries. The large-scale tidal current forced bedforms noticed in the inlet and inner- sub-estuarine environments of the study sites (Figure 2A and 2C), which demonstrates that tidal forcing is clearly significant in the region especially in transferring sediments within and between the sedimentary systems, therefore enabling the delivery of core fine-medium sand to most parts of the estuaries (Figure 4). However, it should be noted that the sand circulation in the system does not appear to be in equilibrium as the greater amounts of sand entering the estuarine environments are transported to the beach, thereby producing a landward extension of the sand inlet into the estuaries (Figure 2C).

Tidal currents alone are not responsible for sediment transport other energies are also important in maintaining the estuary - beach sediment exchanges. Prominent of these forcings is the wave energy [27]. Wave energy constantly transports and sorts sediment in coastal zones thereby maintaining constant sand population in the beach/ coastal areas for the estuarine transport pathway as evidenced in St Ives-Hayle system. The combination of tidal and wave energies is of great influence and is enhancing the flood tide erosion in the processes, and this tend to increase the supply of sand to the estuarine environments. Within the estuarine environments, however, there is a possibility of a prolonged downstream bedloads transport of sediments as a result of low tide thereby causing the remixing of sand populations with other sediment populations presumably sourced locally or representing locally specific processes (Figure 4A).

In the system here, river flow is active. The beds and the banks of the River Hayle and its tributaries entering the estuaries do carry wide range of materials including but not limited to considerable amount of mud and organic matter. Although under the normal condition of flow, these materials may be inhibited thereby resulting into lower/ small quantities of sand being delivered into the estuaries as bedloads. However, during the higher flow velocities, the large amounts of medium and fine sand (M/FS) can be transported into the estuary. The significant departure of the inner estuarine environment (from the results presented in Figures 3-5) from other environments (e.g. Beach/ Coastline and inlet) is an indication there is a reduction in wave energy regime in this environment.

Sand transport processes are the predominant sediment movement and dynamics between estuary and beach in this study site. Mud and gravel are present, primarily at the margins of the inner Hayle estuary. Mud is certainly important to the development of inner estuary tidal

flats and saltmarshes, whereas gravel is likely an inherited (relic) sediment along estuarine margins. But the beach and estuary sediment system is dominated by sand. Based on the spatial patterns in particle size of surface sediments, two dominant populations can be used to determine the nature of sediment linkage between the estuary and beach – marine and fluvial.

Marine sand, which is predominantly of medium-coarser sand population (Figure 3B-3D), has limited exchange with the estuaries (Figure 3A). Sediments sampled from open coast beaches show the predominant well sorted medium-coarse/very coarse sand population across the beach environment (Figure 4A) - can be characterised as marine [28]. Within this sub-environment, there is possibility of sand being transferred from the inner shelf to the beaches, either by the prevailing south westerly west to east longshore currents induced by wave activity or by tidal currents that counter-balance the littoral drift in the sub-tidal zone. The heterogeneity of the intertidal deposits in this mainly marine category, especially in the mixing of sand populations across the main beach environment, shows that the onshore/offshore movement of sand plays a significant role in the morphodynamics of this open coast zone. This applies to the beaches of St Ives Bay. The lack of the coarse sediment population from the Hayle estuarine environment (Figures 3A and 4A) implies transport processes connecting the beach with the estuary are either unable to transport this grade of material, or that the transport linkage does not exist.

In most cases however, the beach (St Ives Bay) sediment populations do comprise a significant fine-medium sand population that is also present within the estuaries. Inlet sediments, but also those associated with the flood tidal delta, comprise this fine-medium population (Figure 3C). This is considered here as evidence of a sediment linkage between the estuary and beach. The spatial analyses of the composition reveal that the medium-fine sand population is found just landward of the inlet in the Hayle estuarine valleys, marking the boundary between the beach and the estuary. The predominant sand deposits here are likely derived from the adjoining beaches.

A silty population is present in the inner estuary sample site, particularly the area in sheltered inner embayment, close to estuary margins or close to the estuary head (Figure 3A). Despite the compartmentalisation of sediments in Hayle system, it is clear that the sediment populations indicative of one depositional environment or rouse are found at other sedimentary locations, i.e. beyond their dominant sub-environment. This shows that mixing is important throughout this system. Interaction between estuarine and coastal processes leads to the mixing of the sediment populations.

Grain size characterisation: vertical/stratigraphic variations in sediment texture

Figure 5 presents a summary of grain size statistics obtained from the sites.

Comparison of grain size statistics grouped by site (sedimentary environment) and sample depth (0-5 cm, 5-10 cm and 10-15 cm from the intertidal sediment surface) reveals little systematic variation in grain size parameters with depth. However, differences between subenvironments are evident, with the estuarine samples (Site A) being finer, less well sorted, and more strongly negatively skewed. Kruskal Wallis analysis of variance shows that differences between sites are significant (at the 99% level) for the median (μ m), sorting (μ m) and skewness statistics (Table 1).



Figure 5: Summary of sediment statistics for sedimentary environments at the Hayle Estuary. Data are divided based on Site (A - D, stated in figures 1 and 2) and depth (using 0-5 cm, 5-10 cm and 10-15 cm stratigraphic units).

This is primarily driven by the properties of sediments from site A which is significantly different from all other sites for all metrics except skewness (for site B) and sorting (for site D). There is no significant difference between the median grain sizes at sites B and C, and no significant difference between skewness at sites C and D. Perhaps more interesting is the lack of significant difference in grain size statistics between sample depth (at the 99% level). The results show the consistency in sediment characteristics with depth suggesting that the depositional environments are well mixed to at least 15cm depth. The analysis shows that variability in sediment size characteristics within the St Ives Beach - Hayle intertidal system is the product of sedimentary environment, not sample depth. Multivariate analyses were undertaken to explore patterns in the full particle size distribution. A Principal Component Analysis (PCA) reduced the data to two Principal Components (PCs) which in combination, account for 96% of the total variance (Figure 6).

Group	D50	Sorting	Skewness
Site	<0.001	<0.001	<0.001
Depth	0.793	0.562	0.076
Site A & Depth	0.685	0.44	0.025
Site B & Depth	0.67	0.817	0.782
Site C & Depth	0.484	0.075	0.841
Site D & Depth	0.186	0.277	0.738
0-5cm & Site	<0.001	<0.001	0.006
5-10cm & Site	<0.001	<0.001	0.007
10-15cm & Site	<0.001	<0.001	<0.001

Table 1: Results (p-value) of one-way analysis of variance of selected sediment statistics, considering groupings based on sample site and depth, using the Kruskal Wallis non-parametric method.

PC1 (82% of the variance) reflects the presence of Medium Sand (MS), to a lesser extent coarse/Very Coarse Sand (CS/VCS), and some Fine Sand (FS), but a distinct lack of material smaller than this. PC2 (14% of variance) relates to a coarser component (presence of coarse

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and very coarse sand), and a lack of a fine-medium sand. PC1 is strongly correlated (negatively) with sorting, whereas PC2 is very strongly correlated (positively) with median grain size. Biplots of these PCs (Figure 7B) show that samples are distinctly separated on the x axis (PC1) and spread across a large range on the y axis (PC2).





Samples from sites B and D (west and east extent of the open coast) are strongly separated on PC2: samples from B are associated with positive PC2 scores (coarser sand) compared to negative scores for D (fine-medium sand), but both are associated with mid-high PC1 scores (relatively well sorted). Only samples from site A (estuary) show any significant distribution along PC1, reflecting a mix of well to poorly sorted sediments at this site, in addition to the presence of very fine material. Samples from site C (inlet) suggest a mix of sediment characteristics from sites B (west bay) and the better sorted sediments from A (estuary).

The PCA provides no evidence of association between sediment characteristics and sample depth (Figure 7C), but again highlights the strong association with sedimentary environment. Cluster 1 refers to medium to high values on both PC1 and PC2, indicating a dominance of the coarser grain sizes and small contribution of finer material to these distributions. This cluster generally characterises the beach environments.

Cluster 2 refers to high PC1 and low PC2 values, which corresponds to a dominance of fine and medium sand in the grain size distribution. This cluster largely represents estuarine sediments, though several beach samples also exist in this group. Cluster 4 refers specifically to low PC1 and PC2 values, representing those samples containing a mix of fine material (silt and very fine sand) and limited coarser component: cluster 4 comprises entirely estuarine samples (Figure 7A and 7B). The clusters identified are closely associated with site (sedimentary environment), which is a significantly more effective discriminator of sediment characteristics (Figure 7B) than stratigraphic depth (Figure 7C). The results reveal that the open coast environment is predominantly characterised by a mixture of mediumcoarse sand while the estuarine intertidal is characterised by a mixture of medium to fine sand and some finer material. Stratigraphically, there appears to be a high degree of consistency in the PC-based sample clustering from surface through to 15 cm deep (Figure 7C). These results also suggest that sediment characterisation in this physical context is relatively insensitive to the sampling depth within the near-surface zone.



Figure 7: Combined plots of PCA and cluster analysis of the grain size distribution (A), comparing the relative sub-environment (B) and relative stratigraphic depth (C).

The principal component and cluster analyses of the sediments in the estuaries have been used to decompose the grain-size distributions into four main clusters of sediments compositions. In St Ives-Hayle system, there appears to be a degree of consistency in sediment distribution pattern from surface through the 15 cm depth in all of the sample sites, except at Site B where there is a composition of silt at 6 – 7 cm below the surface. This observation does support the inference that both the compartmentalisation and partial exchange between the beach/coastal sediments and estuarine sub-environments can be attributed to the contemporary processes in the region. These findings suggest that sediment characterisation in this physical context is relatively insensitive to the sampling depth within the near-surface zone.

The spatial sedimentology concurs with many previous studies of sediments in beach and estuarine environments [29]. The energy regime in the St Ives-Hayle is at a maximum within the beach environment, which is dominated by higher energy wave-driven processes. In this environment, the sediment population is characterised by the medium-coarse sands. The energy levels decreases within the estuarine environment: although the system is macrotidal, the tidal prism here is limited by the narrow accommodation space, and open coastal waves are unable to propagate into the estuaries. The transport pathway exhibits well-defined erosional-deposition processes with clear flood and ebb dominance. Sandy sediments derived from the beach are carried to the inlet as swash bars (or equivalents) and then pass into and through the inlet via spits and extending bars in the upper foreshore. These are mainly littoral (wave-driven) processes, but the flood tidal current is also capable of bringing sand-sized sediment into the estuary, and this is preferentially deposited landward of the narrow inlets (where flood tide energy drops) across the flood-tidal delta. In this lower energy zone, a finer sand population exists, and toward the upper reaches and margins of the estuary, where energy levels decrease further, very fine sediments are also found. In the beach areas, the tidal erosion, particularly via flood currents that have a tendency to enter the inlet via marginal flood channels [27], may have been enhanced by wave action while there is absence of such an

enhancement in the estuarine environment. Ebb currents play their own role in the transport of sediment, but this is primarily through lateral erosion associated with channel migration. The final destination of sediments released through this process is mixed. Certainly, coarser sediments will likely be returned to the beach or ebb delta environment, but finer sediments will not be deposited until they reach a low energy zone, which might simply be the estuary on return via flood tidal currents.

It would seem that there is an imbalance in sediment transport processes, with more sand entering the estuarine environment over time, leading to the building-up of sand deposits within the estuary. Broadly speaking, the estuarine intertidal seems to have exhibited a stronger accretionary signal over the contemporary time scale. It is also possible that selective transportation of finer sand populations towards the estuary from a probably "heterogenous sea-bed source" [30] also drive the compartmentalisation observed. The higher energy processes of the outer beaches might have led to the deposition of the coarser sand population and removal of the finer population, leading to a moderately well sorted sand population here. Throughout the majority of the estuary, there is a relatively consistent, core - fine medium sand population. This is locally modified where mixing with other sediment populations; presumably either sourced locally or representing locallyspecific processes.

Fluvially-sourced riverine materials are another category of sediments observed in the sediment system morphodynamics of the system here [28]. Most of the samples within the Hayle estuary are fine, poorly sorted and negatively skewed. Within the inner part of the estuary, a silt/clay population combines with the fine-medium sand, and it is thought that this very fine population is fluvially-sourced material.

The morphodynamic processes operating in the estuarine environment might have entailed selective sorting, winnowing and transportation of medium to fine/very sand populations. The sizesorting concept discussed by Flemming [31], which suggests that sediment sorting improves with decreasing grain size, is not supported by these results, which show that the beach environment is better sorted but coarser than the rest of the estuarine system. The interaction between the estuarine and coastal processes leads to the mixing of sediment populations. Sediment mixing at each site is evident throughout the 15cm stratigraphic depth sampled, and there is very little evidence of systematic variation in sedimentology with depth.

Conclusion

Based on grain-size parameters, there is some degree of homogeneity in the sediment populations specific to the subenvironments sampled and analysed in this study, but also there is a suggestion of mixing of the sediments between estuarine and beach environments. Sediments across the St Ives beach are mostly mediumcoarse and moderately well sorted. This likely reflects the combination of a marine sediment source and higher energy processes. Most of the samples within the estuary are finer, more poorly sorted and negatively skewed reflecting the mixture of marine and fluvially-sourced material. Sediments at the west of the bay are characteristically slightly different from the samples at the east of the open coast sites, while the inlet of the estuary shows a mix of both estuary and beach characteristics these are clearly separated on the PCA. The processes operating in the estuarine environment might involve selective sorting, winnowing and transportation of medium to fine sand populations. Particle sizes are largely consistent across the top 15cm of the sediment profile. The analyses have been useful as they indicate that a robust grain-size characterisation of estuarine and beach environments can be obtained through spatial sampling of the surface sediment, and that sampling from any depth within the top 15cm achieves a comparable result. The findings in this study collaborate what was discovered in other similar systems in southwest England reported by Oyedotun, et al. [32,33].

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