

Article

Context-Dependent Control of Erosion Resistance in Intertidal Flats: The Central Role of Bulk Density Across Natural and Restored Systems

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Abstract

Intertidal flats are highly dynamic coastal environments that provide vital ecosystem services. Despite their importance, intertidal flats are declining worldwide. In response, a range of restoration and management measures are increasingly being applied to enhance sediment accumulation and stabilize the bed surface. However, the effectiveness of these interventions ultimately depends on how sediment properties and bed stability develop over time. Quantitative understanding of these properties in natural and restored intertidal areas remains limited because field measurements are scarce, spatial heterogeneity is high, and hydrodynamic forcing is highly variable. Here, we quantify differences in key sediment properties between natural and restored intertidal flats to identify bed stability. We sampled sediments and measured key in situ bed characteristics at 16 intertidal sites in the Dutch Eastern and Western Scheldts, spanning multiple restoration strategies (i.e., managed realignments, groynes, and sediment nourishments) and natural locations. Our results show that restoration sites differ in sediment characteristics, with bulk density as the most consistent predictor of critical shear stress, an indicator of bed stability. These findings provide new insights into erosion thresholds in intertidal environments and can help inform adaptive coastal management of restoration measures under accelerating intertidal loss.



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1. Introduction

Intertidal flats are among the world's most dynamic and productive coastal ecosystems, providing essential ecological functions such as nutrient cycling [1], carbon storage [2], and habitat provision for benthic communities [3] and migratory birds [4], while also supporting important socio-economic activities including fisheries and tourism [5]. Despite

their ecological and socio-economic importance, these systems are declining globally [6] due to sea level rise [7], coastal engineering [8], and increased hydrodynamic stress [9,10]. In response, a range of restoration interventions, including sediment nourishments [11], groynes [12], managed realignments [8,13], dune reinforcement, saltmarsh restoration, and hybrid nature-based solutions are increasingly implemented to counteract habitat loss and restore intertidal functioning [14]. This study focuses on the first three interventions.

Each restoration strategy modifies intertidal morphology and hydrodynamics in distinct ways [14]. Sediment nourishments directly increase bed elevation by adding sediment to intertidal flats, aiming to create a new habitat surface [11]. Groynes reduce local hydrodynamic energy by altering flow paths and trapping sediment, thereby aiming to promote gradual sediment accretion. The groynes examined in this study are predominantly low-crested rock groynes that become submerged during high tide, with one exception consisting of wooden piles. Managed realignment involves the intentional breaching or relocation of coastal defenses, allowing tidal inundation to alter previous terrestrial areas into tidal habitat [15]. This creates space for natural sedimentation processes, though initial erosion can be substantial before equilibrium is reached [16,17]. While all three approaches aim to enhance ecological functioning by increasing habitat availability for benthic organisms and foraging birds, they simultaneously alter sediment dynamics in ways that can promote either long-term stability or erosion over time. Ultimately, their success depends on whether restored intertidal surfaces can maintain or improve biophysical conditions for key species [15].

Erosion in intertidal environments is driven by a combination of tidal currents, wave action, sediment properties [18], and biological stabilization (e.g., microphytobenthos, roots) [19,20]. Resistance to this erosion is commonly quantified using the standard metric of critical shear stress, which has traditionally been linked to grain size distribution [18], organic matter content [21], and surface stabilization by microphytobenthos [22]. These properties, however, primarily describe sediment composition rather than structure: they capture what the sediment is made of, but not how its particles are arranged in situ. An underexplored property that integrates grain packing, compaction, and pore structure is bulk density [23,24]. Because it reflects this in situ arrangement [24], bulk density helps explain why sediments with similar grain size distributions can differ substantially in mechanical behavior, depending on packing density and grain shape effects (e.g., angular versus rounded particles) that influence resistance to erosion [25–27].

Despite the growing recognition of bulk density association with bed stabilization [24], the controlling factors of critical shear stress remain incompletely understood, and bulk density has not been systematically evaluated as a primary predictor of erosion resistance across natural-to-restored intertidal gradients under field conditions. We address this gap with a 16-site field campaign across natural intertidal flats and three restoration strategies in the Eastern and Western Scheldt estuaries (the Netherlands). We combine in situ sediment measurements with paired flume experiments on undisturbed field cores. Additionally, laboratory mixtures of controlled bulk density allowed us to isolate the effect of bulk density from covarying sediment properties. Specifically, we quantify how sediment properties differ between natural and restored intertidal flats and how these properties, particularly bulk density, control erosion resistance. We hypothesize that (i) sediment properties differ significantly between natural and restored intertidal flats; (2) restoration modifies erosion resistance indirectly through changes in bulk density as a proxy for compaction; and (iii) bulk density explains a significant proportion of spatial variability in erosion resistance compared with traditional sediment descriptors.

Understanding how restoration strategy reshapes sediment structure and governs erosion resistance is essential for predicting long-term stability and improving restoration design, ultimately safeguarding the ecosystem services these systems provide.

2. Materials and Methods

This study quantifies sediment properties and erosion resistance across contrasting tidal flats, ranging from mud, sandy mud, and muddy sand to sand, while covering natural flats and three restoration strategies. The methodological choice was guided by the primary aims of this research: to compare sediment property differences across restoration practices and to identify the role of bulk density as a key driver of bed stability in intertidal environments. Given these objectives, logistical and methodological constraints of the field campaign required prioritizing broad spatial coverage of core physical sediment characteristics across restoration settings.

2.1. Study Area and Sampling Design

Sampling was carried out on tidal flats in the Eastern and Western Scheldt estuaries (The Netherlands). The Eastern Scheldt is a mesotidal basin varying from 2.5 m at the mouth to 3.5 m at the northern branch [10]. The Western Scheldt is a mesotidal to weakly macrotidal basin with an average tidal range of 3.8 m at the mouth (Vlissingen) increasing landward (Antwerp) to 5.2 m, with a maximum tidal range reaching 5.4 m [28]. The Eastern Scheldt has undergone major hydrodynamic reconfiguration due to the Delta Works [29,30]. The construction of the storm-surge barrier and upstream damming significantly reduced tidal prism and peak current velocities, leading to a wave-dominated and sediment-deficit environment in which reduced resuspension and limited sediment import has strongly led to intertidal erosion [31–33]. In contrast, the Western Scheldt is an openly connected estuary characterized by a larger tidal range, strong tidal asymmetry, and energetic channel–shoal interactions [31]. High bed shear stresses, persistent along-channel transport gradients, and elevated suspended sediment concentrations create a highly dynamic system in which erosion and deposition continuously rework intertidal flats [31]. Together, these contrasting estuaries provide a strong environmental gradient in hydrodynamics, sediment supply, and thereby consolidation potential, which is essential for evaluating spatial differences in erosion resistance.

Selected sampling sites included natural sites (Ns) and three restoration strategies: sand nourishments (SNs), groynes (Gs), and managed realignments (MRs) (Figure 1). Each restoration strategy was represented by multiple sampling sites. Sand nourishment sites included the Roggenplaat [34,35] and Oesterdam [36] in the Eastern Scheldt. Groyne sites included Knuitershoek, Baalhoek [37], Bath, Zimmerman, and Ossenis in the Western Scheldt. Managed realignment sites included Hedwige-Prosperpolder [38] and Perkpolder [37] in the Western Scheldt. To span a full intertidal sediment gradient from mud-dominated to sand-dominated flats, natural sites were selected in the Eastern (Slikken van Dortsman, Slikken van Vianne, and an unnourished part of the Roggenplaat) and Western (Zandkreek, Zuidgors, Hellegat, and Paulinapolder) Scheldts (Table A1). The natural locations were selected due to having similar exposure levels to the managed areas. Within each sampling site, bare sediment was sampled from the high intertidal zones located close to the dike or vegetation edge (Table A1).

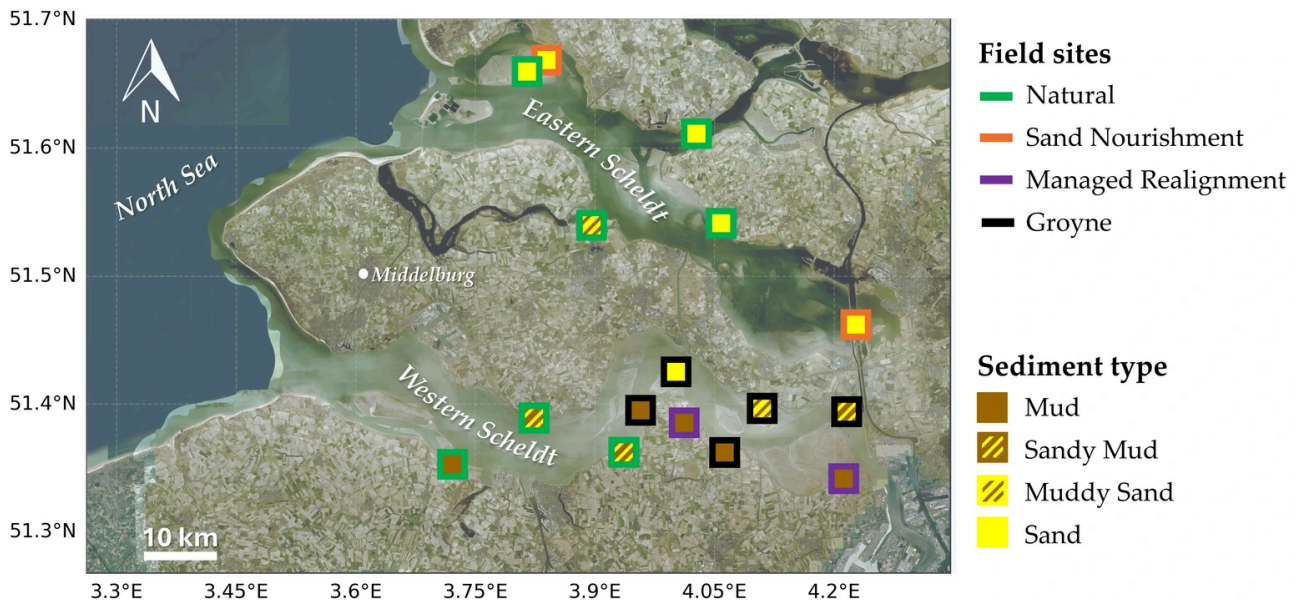


Figure 1. Sample locations on the tidal flats of the Eastern and Western Scheldts. Locations are colored by sediment type (mud, sandy mud, muddy sand, and sand) and bordered by the corresponding restoration strategy type colors.

To quantify the role of sediment properties in controlling erosion resistance, sediment cores (3 cm diameter, 3 cm depth; $n = 2$) were collected at each site, while sediment surface shear strength and compaction was measured in situ.

Bulk density (g cm^{-3}) was determined by measuring the wet weight of the sediment cores, after which they were frozen at $-20\text{ }^{\circ}\text{C}$, before freeze-drying them for 72 h until constant mass was reached and subsequently reweighing them. Bulk density was calculated as the dry mass divided by the core volume. The same sample was used to determine the grain size distribution using a Malvern laser diffraction particle size analyzer (Mastersizer 2000, Malvern, UK) following standard dispersion procedures. Freeze-dried samples were pre-sieved to 2 mm to remove aggregates and stirred to ensure full particle separation, allowing high-resolution quantification of the complete particle size spectrum. To quantify the spread of grain size distribution, Span was calculated using the formula

$$\text{Span} = \frac{D90 - D10}{D50}, \quad (1)$$

where D10, D50, and D90 represent the 10th, 50th (median), and 90th percentile grain-size diameters, respectively [39]. Lower Span values indicate a narrower distribution (higher homogeneity), and higher Span values represent a wider particle size distribution (lower homogeneity). To capture in situ sediment mechanical resistance, sediment surface shear strength was measured at each sampling site using a handheld surface shear vane (Eijkelpkamp, The Netherlands). Measurements were taken immediately adjacent to core collection points to represent near-surface conditions. The vane was inserted 1 cm into the upper sediment layer until its base was aligned with the sediment surface, then rotated at a constant rate until the sediment started moving. Maximum torque was recorded and converted to surface shear strength (kPa) following the manufacturer's calibration. Additionally, penetration resistance was measured to a depth of 80 cm using a penetrometer (Eijkelpkamp, Giesbeek, The Netherlands). For this study, only the maximum penetration resistance (in mPa) up to 3 cm depth was used, corresponding to the 3 cm sediment cores. All in situ mechanical measurements were replicated five times and averaged.

Furthermore, elevation was measured at every sampling site, together with the x and y coordinates with a dGPS (Trimble TSC5, R780, Westminster, CO, USA), referenced to NAP (Amsterdam Ordnance Datum), with a vertical accuracy of approximately 3 cm.

All measurements were conducted within a 1 m radius by the same investigator to minimize operator-induced variability.

2.2. Flume Measurements of the Erosion Resistance of Sampled and Lab-Mixed Sediments

To quantify differences in erosion resistance among the different restored and natural sites, undisturbed rectangular sediment cores ($20 \times 12.5 \times 10$ cm, $n = 2$ per site) were extracted from the same sampling sites as those used for the sediment properties and transported to the laboratory. These cores were used to measure critical shear stress (τ_{cr}) using the Oscillatory Sediment Erosion Assessment System (OsCaR) flume [40]. This flume simulates wave-induced shear stress by moving water back and forth over the sediment surface. During the experiment, bed shear stress was incrementally increased by gradually increasing the peak flow velocity at the sediment surface in 15 steps from 5 to 75 cm s^{-1} , with each step lasting 60 s. The flow velocity was determined from vertical water movement measured by a 25 Hz pressure sensor (Druck 1800 series; Druck, Groby, UK), and critical bottom shear stress, defined as the stress at which sediment begins to resuspend, was calculated following the established method of [41], as described in both [40,42]:

$$\tau_{cr} = \frac{1}{2} \rho f_w u_{cr}^2, \quad (2)$$

where ρ represents density of seawater (1027 kg m^{-3}), u_{cr}^2 is the critical flow velocity at which sediment resuspension begins, and f_w represents the dimensionless friction factor:

$$f_w = a A_{max}^{-0.52}, \quad (3)$$

where a is a constant value estimated for the OsCaR flume ($a = 0.0076$) [40], and A_{max} is the maximum variation in the water level (in m) during a single oscillation.

The erosion threshold was identified as the point where the rate of turbidity increase exceeded a set value, according to the method described in [42].

To isolate the effect of bulk density on sediment erosion, a mixture of different sediment grain sizes was made in the laboratory and mixed with different amounts of seawater to manipulate bulk densities. Cores were made from these mixtures and analyzed in the OsCaR flume. This experimental setup does not reproduce the biological activity, natural sediment stratification, or long-term consolidation processes present in field environments, and therefore represents a simplified analog of physical intertidal field conditions.

2.3. Data Analysis

The statistical analyses were structured to evaluate differences in sediment properties and erosion resistance across natural sites and restoration strategies. The dataset comprises 16 sites distributed across two estuarine systems, with an uneven representation of restoration strategies (S1). Within this structure, estuarine context is also reflected in site-level variability and is therefore inherently embedded in the data rather than explicitly modelled as a separate factor.

The estuary identity was initially explored during the early stages of the analysis as a potential explanatory factor; however, it did not show significant effects and did not improve model fit or explanatory power. This outcome is consistent with the structure of the dataset, where substantial within-estuary variability across sites already captures a large portion of the environmental heterogeneity relevant to sediment properties and

erosion resistance. This allows the analyses to focus on patterns associated with sediment properties and restoration strategies across the observed environmental gradient.

According to this data structure, we applied a set of complementary, well-established statistical approaches, including univariate tests, multivariate ordination, and regression-based models. Together, these methods provide multiple, converging perspectives on the same dataset and allow assessment of the consistency of observed patterns across different analytical representations.

2.3.1. Sediment Property Correlations

To quantify how sediment properties differ between natural and restored intertidal flats, we conducted two correlation analyses: (1) for the fieldwork-acquired dataset and (2) for the laboratory sediment mixes. The following variables were included in the analysis: critical shear stress, silt percentage, Span, bulk density, surface shear strength, elevation, and penetration resistance. Restoration strategy was treated as a categorical grouping variable for visualization purposes.

Pairwise Pearson correlation coefficients were calculated using the `rcorr()` function from the `Hmisc` package in R. Correlation coefficients and associated *p*-values were computed using only restoration strategies with more than two sites (which excludes the sand nourishment strategy). Relationships among variables were visualized using a scatterplot matrix generated with the `GGally` package (`ggpairs`).

To test for differences in the distribution of sediment properties among restoration strategies, we additionally performed non-parametric Kruskal–Wallis tests for each variable. Where significant effects were detected, post hoc pairwise comparisons were conducted using Dunn's test with Benjamini–Hochberg adjustment to control for false discovery rate in multiple testing. Effect sizes were calculated using the effect size (η^2) to quantify the magnitude of differences among restoration strategies.

All analyses were performed in R (version 4.5.1), using the packages `dplyr`, `Hmisc`, `GGally`, `ggplot2`, `readxl`, `FSA`, and `rstatix` for correlation analysis, visualization, non-parametric group comparisons (Kruskal–Wallis and Dunn post hoc tests), and effect size estimation (η^2) (S2).

2.3.2. Sediment Property Differences Among Restoration Strategies

Non-metric multidimensional scaling (NMDS) ordination based on a Euclidean distance matrix was used to assess differences in sediment properties among restoration strategies. Upon identification of collinearity with the previous correlation matrixes, a set of variables was chosen to assess differences in sediment properties between natural and restoration strategies. Hence, the analyses included critical shear stress, silt percentage, Span, bulk density, surface shear strength, elevation, and penetration resistance. Variable ordination was performed using the `metaMDS` function (`vegan` package, $k = 2$, `trymax` = 100). Group variability was visualized using 95% confidence ellipses, representing the expected dispersion around each cluster centroid. The ellipses were constructed from the covariance of site scores within each group, providing a visual interpretation of clustering patterns. Environmental vectors were fitted using `envfit` to evaluate relationships between sediment variables and sample distribution in multivariate space, and group centroids were included to visualize restoration strategy clustering.

To test differences among clustered groups, Permutational Multivariate Analysis of Variance (PERMANOVA) was conducted using the `adonis2` function in the R package `vegan`, based on the same distance matrix. Homogeneity of multivariate dispersion was assessed using the `betadisper` function. *p*-values were adjusted using the Benjamini–Hochberg correction, and significance was evaluated using 999 permutations ($p < 0.05$).

To further evaluate differences among restoration groups, the most explanatory variables were identified using non-parametric tests. A variable-wise Kruskal–Wallis test was applied to detect sediment property differences across all groups. Subsequently, pairwise Wilcoxon rank-sum tests were used to rank sediment properties according to the magnitude of differences between groups. To control for inflated Type I error rates due to multiple comparisons, Benjamini–Hochberg correction was again applied to adjusted p -values. All analyses were conducted in R (version 4.5.1) (S3).

2.3.3. Interaction Drivers of Critical Shear Stress

To investigate the drivers of critical shear stress across sampling sites, we fitted a multiple linear regression model using ordinary least squares. Critical shear stress was included as the response variable, while bulk density, silt percentage, Span, and restoration strategy were included as explanatory variables. As Span varies per restoration strategy (Figure A1, S6), an interaction term was incorporated into the model:

$$\text{Critical Shear Stress} \sim \text{Bulk Density} + \text{Silt percentage} + \text{Span} + \text{Restoration Strategy} + (\text{Span} \times \text{Restoration Strategy}) \quad (4)$$

The predictor selection was guided by ecological hypotheses and mechanistic understanding of sediment–hydrodynamic controls and was restricted to a reduced set of key variables identified as having statistical significant correlations with critical shear stress (Figure 2), avoiding purely stepwise procedures that may introduce selection bias and reduce interpretability. To evaluate model structure, candidate models representing increasing ecological complexity (from sediment-only to full interaction formulations) was compared using information-theoretic criteria (AIC and AICc), ensuring that final model selection reflected both statistical support and mechanistic interpretability.

Model assumptions were evaluated through graphical inspection of residuals, together with formal tests of residual normality (Shapiro–Wilk test) and homoscedasticity (Breusch–Pagan test). Multicollinearity among predictors was assessed using generalized variance inflation factors (GVIFs), accounting for the inclusion of interaction terms. Model robustness was further evaluated by comparing alternative model formulations, examining influential observations using Cook’s distance and leverage diagnostics, and estimating heteroscedasticity-consistent (HC1) robust standard errors to assess the stability of regression coefficients.

Model performance was evaluated using adjusted R^2 , F-statistics, coefficient estimates, and analysis of variance (ANOVA). Statistical significance was assessed at $\alpha = 0.05$.

To further examine how the relationship between Span and critical shear stress differed among restoration strategies, estimated marginal trends were calculated using the emmeans package. These analyses provided restoration-specific slopes for Span. To compare the relative importance of continuous predictors, predictor variables were standardized to z-scores prior to fitting an additional regression model. Standardized variables included bulk density, silt percentage, and Span. Variable effects were then quantified using a perturbation-based sensitivity approach, in which each standardized predictor was incrementally increased by 0.1 units while holding all other variables constant. The resulting change in predicted critical shear stress was divided by the perturbation magnitude to estimate standardized effect sizes. Diagnostic inspection of residual distributions and model assumptions was conducted using standard linear model diagnostics.

This analysis was conducted in R (version 4.5.1), using the packages tidyverse, dplyr, ggplot2, car, emmeans, lmttest, sandwich, MuMIn, corrplot, patchwork, gridExtra, tidyr, and readxl (S4).

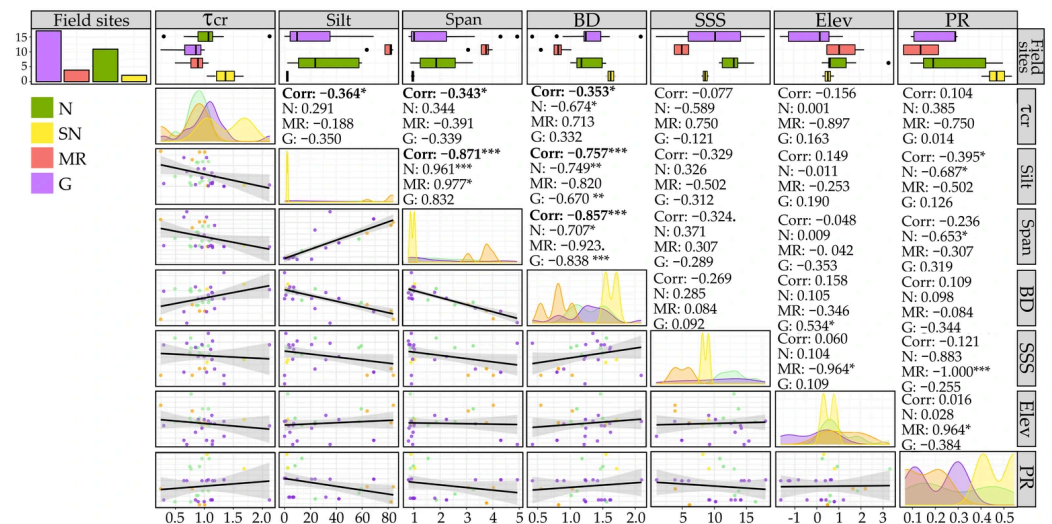


Figure 2. Correlation matrix of field sediment properties with supplementary visualizations: critical shear stress (τ_{cr}), silt percentage (Silt), Span (Span), bulk density (BD), surface shear stress (SSS), elevation (Elev), and penetration resistance (PR). The left panel displays scatterplots and a black fitted tendency line with 95% confidence grey bands to illustrate bivariate relationships among sediment properties. The right panel presents the correlation of natural and restoration strategies together in a matrix (Corr) with correlation coefficients and significance indicators. Statistically significant correlations are in bold. The correlation among natural (N), managed realignment (MR), and groynes (G) is also stated below. Above the correlation matrix, boxplots are shown by restoration strategy to summarize the distributions of each property across groups, and a stacked bar plot provides an overview of the data composition. Significant relationships are signaled with asterisks indicating significance levels: high significance $p < 0.001$ (***), moderate significance $p < 0.01$ (**), and low significance $p < 0.05$ (*). Restoration strategies are color-coded as natural (N) in green, sand nourishment (SN) in yellow, managed realignment (MR) in orange, and groynes (G) in purple.

2.3.4. Field and Lab Sediment Mix Comparison

To test whether relationships differed between laboratory mixed sediments and field sediments, critical shear stress was analyzed using linear regression models with bulk density, environment (laboratory vs. field), and silt percentage as predictors. Interaction effects between bulk density and environment were included to test whether relationships differed between laboratory and field sediments. This comparative framework allows mechanistic evaluation of sediment properties across environments, while recognizing that laboratory and field sediments differ in structural complexity.

Model assumptions were evaluated using diagnostic residual plots, including assessments of normality and homoscedasticity. Because heteroscedasticity and non-normal residual distributions were detected, response and predictor variables were log-transformed prior to analysis. To avoid undefined values, a small constant (0.01) was added to bulk density values before log transformation.

To evaluate the robustness of the results, several complementary statistical approaches were applied. Heteroscedasticity-consistent robust standard errors (HC3 estimator) were calculated for the linear models. In addition, robust regression models were fitted using M-estimation to reduce sensitivity to outliers and deviations from normality. Generalized least squares (GLS) models with variance structures grouped by environment were also fitted to explicitly account for heteroscedasticity between laboratory and field conditions.

Finally, non-parametric Spearman rank correlations were performed between critical shear stress and sediment properties as an additional robustness check. Consistency in coefficient direction and significance across approaches was used to assess the stability of the model results.

The analyses were conducted in R (version 4.5.1), using the packages stats, sandwich, lmttest, MASS, and nlme (S5).

3. Results

3.1. Sediment Property Correlations

Correlation analyses revealed several strong relationships among sediment characteristics across natural (N) and restoration strategy sites (SN, MR, and G) (Figure 2).

Critical shear stress was negatively correlated with silt percentage ($r = -0.364$, $p < 0.05$) and Span ($r = -0.343$, $p < 0.05$), while showing a positive correlation with bulk density ($r = 0.353$, $p < 0.05$) for natural and restored tidal flats. As higher critical shear stress indicates greater resistance to erosion, sediments with higher bulk density generally exhibited greater erosion resistance across all sites. However, within natural sites only, critical shear stress was negatively correlated with bulk density ($r = -0.674$, $p < 0.05$), indicating an opposite relationship between bulk density and erosion resistance.

To better understand the drivers of critical shear stress, we further explored the relationships among the statistically significant variables. Silt percentage was positively correlated with Span ($r = 0.871$, $p < 0.001$) and negatively correlated with bulk density ($r = -0.757$, $p < 0.001$), while Span ($r = -0.871$, $p < 0.001$) was also negatively correlated with bulk density for all natural and restored tidal flats. These relationships indicate that higher bulk density was associated with lower silt percentage and lower Span values.

Boxplots and density distributions reveal a mixed pattern of separation and overlap among natural sites and restoration strategies, rather than uniform divergence across all variables. MR consistently showed the most distinct separation from the other restoration strategies across multiple variables, particularly silt percentage (Kruskal–Wallis $\eta^2 = 0.337$, $p < 0.01$), bulk density ($\eta^2 = 0.205$, $p < 0.05$, $\eta^2 = 0.205$), and shear strength ($\eta^2 = 0.217$, $p < 0.05$), with additional contributions from peak penetration resistance showing a marginal effect ($\eta^2 = 0.152$, $p = 0.056$). In contrast, N, G, and SN generally exhibited more overlapping distributions across these variables, with no consistent pairwise separation and mostly non-significant or weak differences in Span ($p > 0.05$) and critical shear stress ($p > 0.05$). Among all restoration strategies, G showed intermediate behavior, differing significantly from MR for silt percentage ($Z = -3.12$, $p\text{-adj} < 0.01$), bulk density ($Z = 2.27$, $p\text{-adj} < 0.05$), surface shear strength ($Z = 2.08$, $p\text{-adj} < 0.05$), and elevation ($Z = -2.14$, $p\text{-adj} < 0.05$). In contrast, SN and N were generally more similar to each other and exhibited broader overlap with G, with few significant pairwise differences and mostly non-significant comparisons across silt content, bulk density, Span, and penetration resistance (Table A2). These results indicate that there are differences among natural and the different restoration strategies in terms of sediment composition and sediment strength.

3.2. Sediment Property Differences Among Restoration Strategies

To explore multivariate patterns in sediment characteristics, non-metric multidimensional scaling (NMDS) analysis was performed to visualize similarities among samples and to assess whether natural and restored sites exhibit distinct clustering in sediment property space (Figure 3). NMDS produced a two-dimensional solution with a stress value of 0.151, which indicates good representation of the underlying multivariate structure (stress < 0.20 ; [43,44]) (Figure 3). Ordination analyses showed sediment-characteristic space organization according to restoration strategy. Specifically, samples from sand nourishment and MR occupy distinct regions of the ordination space, whereas natural intertidal sites and groyne-affected sites show major partial overlap. However, groyne sites exhibited a comparatively wider spread across the ordination space. This dispersion reflects internal heterogeneity within groyne sampling sites, driven in part by the Ossenisse site, which is

situated in a highly dynamic, sand-dominated environment. Ossensisse also differs in construction from the other groyne locations, as rock groynes are used instead of wooden pole structures. This distinction was further supported by a supplementary analysis in which Ossensisse was treated as a separate category, yielding consistent results while clarifying its intermediate position in the ordination space (Figure A2).

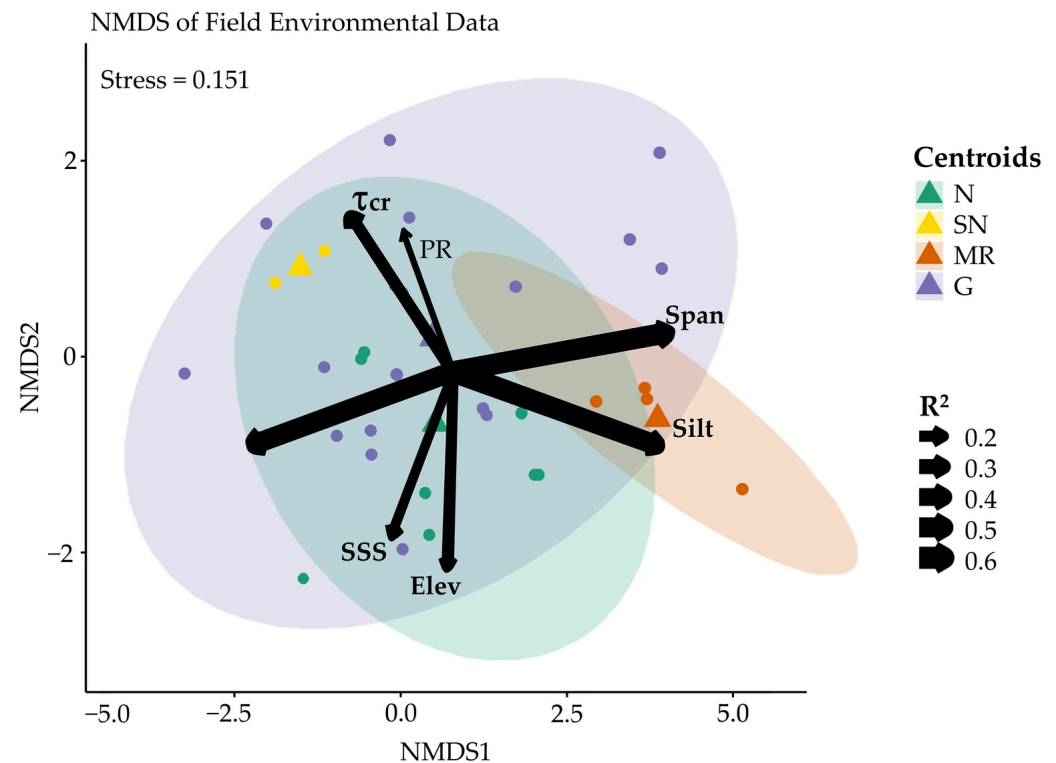


Figure 3. NMDS ordination illustrating patterns among sampled sediment properties, including critical shear stress (τ_{cr}), silt percentage (Silt), Span (Span), bulk density (BD), surface shear stress (SSS), elevation (Elev), and penetration resistance (PR). Data points are colored and clustered according to restoration strategy: natural (N) in green, groynes (G) in light purple, managed realignment (MR) in orange, and sand nourishment (SN) in yellow. The thickness of the arrows (env vectors) represents the strength of the environmental-variable loadings, with thicker arrows denoting larger $|R^2|$ contributions of the vectors to the NMDS solution. Triangles represent the centroid hulls, and circles represent the data points. The overall NMDS stress value is 0.151, which is within the commonly recommended threshold of 0.20 for acceptable ordination ([43,44]).

Sand nourishment does not overlay any other clustered group, and the data points were positioned close to the Ossensisse groyne site; however, as fewer than three collection sites were included, they did not form group ellipses.

Pairwise PERMANOVA analyses further confirmed structured differences among restoration strategies. The strongest separation was observed between N vs. MR ($R^2 = 0.404$, p -adjusted = 0.006) and between G vs. MR ($R^2 = 0.264$, p -adjusted = 0.006), indicating that MR is the most distinct restoration strategy, showing significant differences from multiple groups (p -adjusted < 0.05) (Table A2). In contrast, no significant differences were found between SN vs. G and SN vs. MR (p -adjusted > 0.05), indicating substantial overlap in multivariate environmental conditions among these restoration types after multiple-testing correction. Natural (N) also differed significantly from both SN (p -adjusted = 0.024) and G (p -adjusted = 0.024), although with weaker effect sizes compared to contrasts involving MR. Overall, SN and G showed no significant difference and clustered more closely in

ordination space, suggesting broadly comparable environmental conditions between these restoration strategies (Table A3).

The NMDS pattern was, then, consistent with the univariate correlation analyses, where MR showed the strongest differences in sediment characteristics, particularly silt percentage, bulk density, and sediment strength variables. In contrast, groyne sites were more dispersed across the ordination space, reflecting greater variability in sediment characteristics among groyne locations.

The sediment characteristics contributing most strongly to the clustered differences among restoration strategies were identified using Kruskal–Wallis tests. By order of significance, silt percentage showed the strongest difference among restoration strategies (p -adjusted < 0.01), followed by bulk density, Span, peak penetration resistance, elevation, and surface shear strength (p -adjusted < 0.05) (Table A4).

3.3. Interaction Drivers of Critical Shear Stress

While correlation and clustering patterns of sediment variables already suggest strong interdependence among sediment properties, the multiple linear regression model analyses clarify how these relationships are structured (Table 1).

Table 1. Linear model results (Critical Shear Stress $\sim$ Bulk Density + Silt percentage + Span + Restoration + (Span $\times$ Restoration Strategy)) showing relationships between environmental variables and critical shear stress as the response variable. Effect sizes are presented as regression coefficients ($\beta \pm$ SE) with associated p -values. Significance is indicated with standard markers: marginal ($\cdot$), significant ($* p < 0.05$, and $** p < 0.01$), and non-significant (n.s.). Where applicable, 95% confidence intervals (95% CI) are reported for estimated marginal trend slopes (emttrends), indicating the range of plausible values for group-specific effects of Span across restoration categories. The interaction between Span and restoration is tested using an F-statistic ($F_{3,10}$), where the subscripts denote the degrees of freedom for the model [3] and residual error [10], respectively.

Variable	LM Result	Statistical Support (from LM/Emttrends)
Bulk density	Significant negative main effect	$\beta = -0.761$, SE = 0.291, $p = 0.024$ *
Silt percentage	Weak/marginal effect	$\beta = -0.011$, SE = 0.0071, $p = 0.140$ $\cdot$
Span	No significant global main effect	$\beta = -0.101$, SE = 0.112, $p = 0.386$ (n.s.)
Restoration strategy	Strong significant main effect (differences among types)	$F_{3,11} = 7.391$, $p = 0.0055$ ** - Emttrends slopes: N = 0.90 (n.s.); SN = 8.69 (95% CI: 2.33–8.65) *; MR = 0.70 (n.s.); G = 1.05 (n.s.)
Span $\times$ restoration (interaction)	Strong significant interaction indicating restoration-dependent sensitivity	- Interaction: $F_{3,10} = 7.007$, $p = 0.0067$ ** - emttrends slopes: N = 0.22 (n.s.); SN = 5.49 (95% CI: 2.49–8.75) **; MR = 0.31 (n.s.); G = -0.10 (n.s.)

Bulk density shows a strong and significant negative relationship with critical shear stress ($\beta = -0.761$, $p = 0.024$). Silt percentage, by contrast, shows only a weak and marginal effect ($\beta = -0.011$, $p = 0.140$). Similarly, Span does not exhibit a significant overall effect on critical shear stress ($\beta = -0.101$, $p = 0.386$). However, its role becomes highly structured when restoration context is considered, where the Span $\times$ restoration interaction shows statistically significant results ($F_{3,10} = 7.007$, $p = 0.0067$). This interaction is further expressed in the differing response slopes across restoration strategies. Sand nourishment sites show a strong positive relationship between Span and critical shear stress (emttrends slope = 5.49, 95% CI: 2.49–8.75), whereas natural, groyne-influenced, and managed realignment sites show weak or negligible responses (0.22, -0.10 , and 0.381 respectively). Finally, restoration strategy exerts a strong and significant effect on critical shear stress ($F_{3,11} = 7.391$, $p = 0.0055$),

with sand nourishment systems exhibiting substantially higher adjusted mean values (EMM = 8.69) compared to groynes (1.05), natural sites (0.90), and managed realignment systems (0.70).

Model diagnostics indicated no major violations of linear model assumptions. Multicollinearity analysis using generalized variance inflation factors (GVIFs) showed higher values for restoration categories and the Span $\times$ restoration interaction, reflecting expected correlation structures in field-based sediment–hydrodynamic systems where predictors are not fully independent. Coefficient signs and effect directions remained stable, and inference was consistent under heteroscedasticity-robust (HC1) standard errors, confirming the robustness of the main results.

3.4. Bulk Density as a Consistent Driver of Critical Shear Stress

Bulk density consistently emerges as a strong predictor of critical shear stress, as indicated by both the correlation matrix of field sites and the multiple linear regression analyses (Figure 4). At natural sites, critical shear stress increases with decreasing bulk density ($p < 0.05$), indicating an inverse relationship between sediment compaction and erosion resistance. In other words, sediments with higher pore space and lower bulk density require more force to be eroded, corresponding to higher critical shear stress values and thus greater erosion resistance. Along this gradient, sediment structure also varies, with higher Span values occurring at lower bulk densities, while Span decreases progressively as bulk density increases. This indicates that sediment grain size heterogeneity and compaction covary across natural sites. In contrast, restored sites show the opposite pattern, where critical shear stress increases with increasing bulk density ($p < 0.01$), meaning that more compact sediments require greater force to initiate erosion. Nevertheless, Span remains highest at lower bulk densities across both natural and restored conditions, indicating that sediment heterogeneity is consistently associated with less compacted sediment states across environments.

Clustering of natural and restoration strategy datapoints further highlights sediment property differences observed in the NMDS analysis: MR sites are characterized by relatively higher Span values and lower critical shear stress, indicating more heterogeneous sediments that require less force to be eroded, and therefore exhibit lower erosion resistance. In contrast, SN sites tend to exhibit lower Span values combined with higher critical shear stress, meaning that more homogeneous sediments that require greater force to initiate erosion and thus show higher erosion resistance. Natural sites occupy an intermediate position across both variables, bridging the patterns observed in restored conditions. G display the widest spread, covering a broad range of both Span and critical shear stress values.

The comparison between field correlations and laboratory sediment mixture relationships confirmed the overall consistency of sediment property control of critical shear stress, with the exception of silt percentage and Span, which showed opposing trends between environments. In laboratory mixtures, critical shear stress increased with both silt percentage and Span, whereas field measurements indicated negative relationships for these variables (Figure A3). The generalized least squares (GLS) model helped reconcile these contrasting patterns. The intercept was not significant (Estimate = 0.005, SE = 0.316, $t = 0.015$, $p = 0.988$), indicating no inherent baseline difference in critical shear stress once predictors were accounted for (Table A3). The GLS analysis identified bulk density as the strongest predictor of critical shear stress across both field and laboratory datasets (Estimate = 0.680, SE = 0.209, $t = 3.26$, $p = 0.0016$). Silt percentage also showed a weaker but significant positive contribution (Estimate = 0.005, SE = 0.0025, $t = 2.19$, $p = 0.0308$), while neither environment nor the interaction between environment (lab) (Estimate = 0.470,

SE = 0.413, $t = 1.14$, $p = 0.2586$) and bulk density (Estimate = -0.420 , SE = 0.316, $t = 1.33$, $p = 0.1875$) was significant.

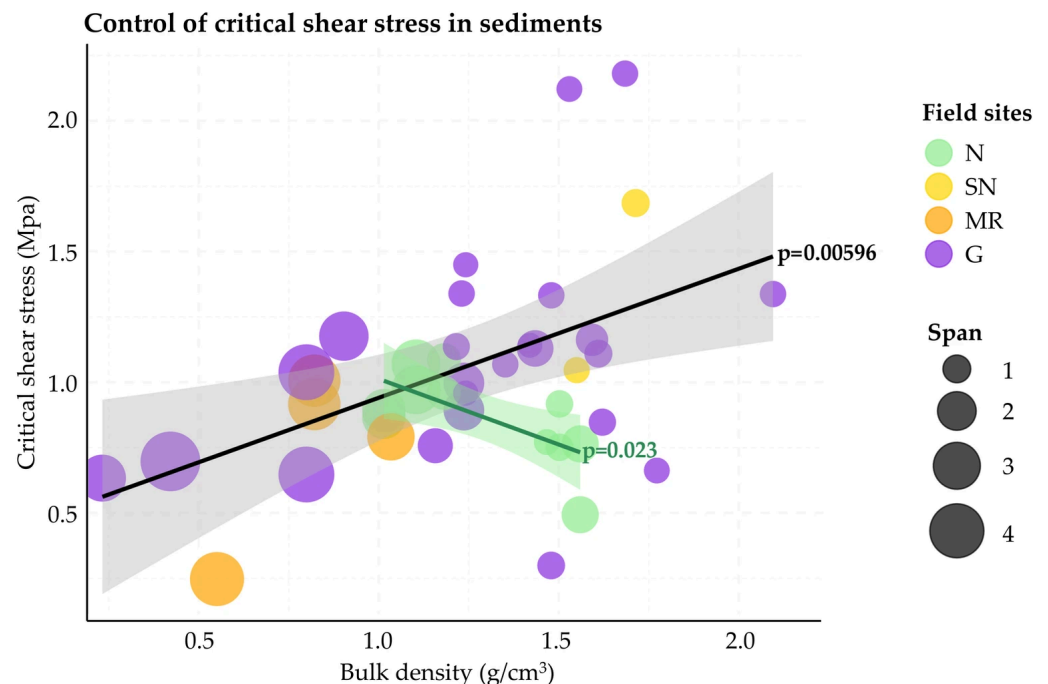


Figure 4. Relationship between bulk density and critical shear stress in the field across natural and restored sites. Critical shear stress is represented on the y-axis and bulk density on the x-axis. Field data are depicted as circles, and colors denote the different restoration strategies: natural (N) in green, groynes (G) in purple, managed realignment (MR) in orange, and sand nourishment (SN) in yellow. Symbol size encodes Span values (smaller symbols = lower Span, higher sediment homogeneity; larger symbols = higher Span, higher sediment heterogeneity). A black trend line is shown with a grey 95% confidence interval band and the respective p -value in black font for the restored sites; while a green trend line with a green 95% confidence interval band and the respective p -value in green is shown for natural sites.

4. Discussion

What emerges from this study is not a simple separation between natural and restored intertidal flats, but rather a more subtle restructuring of how sediment properties interact to produce erosion resistance. Instead of clear categorical differences between systems, the data reveal a landscape of shifting relationships, where the meaning of a sediment property depends less on its absolute value and more on the environment in which it is embedded. This is reflected in the partial overlap of groups in multivariate space, the context-dependent reversal of key correlations, and the dominance of bulk density as a functional predictor across environments.

4.1. A Landscape of Sediment States Rather than Fixed Categories

At first glance, the multivariate structure tells a story that restoration does leave a fingerprint on intertidal sediments. The NMDS ordination (stress = 0.151) [43,44] shows that sand nourishment, managed realignment, groyne-affected areas, and natural flats each occupy partially distinct regions in sediment space, suggesting that restoration strategies do indeed create sediment development in different directions. Yet this separation is not absolute: the sites overlap rather than forming bounded clusters, suggesting that restoration shapes sediment properties. In general, restored intertidal flats do not converge toward a single “ideal state”, but instead follow multiple trajectories shaped by hydrodynamic

exposure, sediment supply, and geomorphic feedbacks [20,45,46]. What appears at first to be variability is, in fact, structure—an indication that each restoration strategy is governed by a distinct set of formative processes.

Natural sites are most strongly associated with higher surface shear strength, elevation in the tidal frame, and a higher proportion of fine sediments. This reflects their position in relatively stable, longer-established intertidal zones where prolonged exposure, biological mediation, and repeated reworking promote cohesive surface layers and structured vertical gradients. Elevated surfaces experience reduced inundation stress and longer consolidation times, which enhances bed surface stability [24], while fine sediment fractions contribute to cohesive behavior through electrochemical binding [41] and biofilm development [47,48]. Together, these characteristics are typical of mature intertidal flats where bed stability is strongly mediated by both physical and biological processes.

Managed realignment sites, in contrast, are most strongly associated with Span and silt percentages, reflecting greater sediment heterogeneity and a finer-grained depositional environment. This pattern is consistent with the early to intermediate stages of intertidal flat development following local re-inundation, where sediment deposition is often episodic and spatially variable [46,49]. The resulting sediment fabric tends to be less consolidated and more heterogeneous, reflecting fluctuating hydrodynamic conditions and ongoing adjustment toward a new equilibrium state [45,46,49]. Such variability is a hallmark of systems undergoing active geomorphic reorganization, where sediment sorting and surface smoothing have not yet stabilized [50].

Groyne-influenced sites exhibit a distinct sedimentary signature compared to the other intertidal environments. They are characterized by bulk density, critical shear stress, and Span values. This combination of sediment properties reflects the geomorphic role of groynes as flow-modifying structures. By reshaping local hydrodynamics and reducing lateral energy, they redistribute near-bed velocities, encouraging a more spatially even pattern of deposition [51]. In sheltered zones where near-bed flow is weakened, groynes promote sediment accumulation and consolidation, resulting in denser deposits that are more resistant to erosion [52]. Several studies from engineered tidal environments have reported that flow obstruction promotes sediment trapping and increases bed stability through physical packing and consolidation processes [52]. Within this broader groyne category, Ossensisse represents a functionally distinct hydrodynamic and sedimentary sub-environment. In contrast to sites such as Bath, Zimmerman, Baalhoek, and Knuitershoek—which are generally characterized by more sheltered intertidal flats situated in the lee of groyne structures, where tidal energy is partially attenuated and fine-grained sediments can accumulate more consistently—Ossensisse is strongly influenced by its proximity to deeper navigation channels and more direct exposure to the main tidal current axis [53]. As a result, near-bed flow velocities are higher and more variable, producing increased temporal fluctuations in bed shear stress and a stronger coupling between erosion and deposition events [53,54]. This enhanced hydrodynamic forcing limits sustained fine sediment accumulation, promotes sediment reworking, and leads to coarser sediment composition compared to the other groyne sites [31,54]. Consequently, its characteristics were more similar to the sand nourishment restoration strategy due to its coarser sediment type. This is the reason why there were consistently two distribution peaks in the correlation matrix of groynes.

Sand nourishment sites are most distinctly characterized by critical shear stress. These areas receive externally supplied sediments that are often more uniformly graded and initially loosely structured, but which undergo rapid post-depositional consolidation under tidal forcing [55]. As a result, their erosion resistance is strongly governed by physical compaction processes rather than long-term biological or geomorphic structuring [55].

Taken together, these results suggest that restoration primarily reshapes sediment composition rather than directly prescribing erosion resistance. Natural flats emerge as biologically and physically stabilized systems dominated by fine sediments and surface cohesion; managed realignment reflects dynamic, heterogeneous early-to-mid-stage development; groynes create structurally complex, density-driven mosaics; and sand nourishment produces systems where physical consolidation governs stability.

4.2. Bulk Density as a Hidden Thread Linking Structure and Erosion

Across all analyses, one pattern remains remarkably persistent: bulk density consistently emerges as one of the strongest predictors of critical shear stress, outperforming grain size descriptors and composite texture measures (silt percentage and Span, respectively). However, its effect is strongly context-dependent and varies in both magnitude and direction between natural and restored sites. In restored environments, higher bulk density aligns with higher critical shear stress, reflecting a direct and intuitive relationship: more compact sediments resist erosion more effectively. In natural flats, however, the relationship reverses, with higher bulk density associated with lower erosion resistance. This reversal is not a contradiction, but a clue. It indicates that bulk density is not a universal measure of “strength”, but a proxy whose meaning shifts depending on sediment context. In restored systems, sediments are often newly deposited, relatively unstructured, and weakly biologically modified. Here, bulk density primarily reflects physical consolidation: how tightly particles have settled under gravity and reduced disturbance [52,56]. In this setting, density becomes a direct expression of stability. We hypothesize that, in natural systems, the observed reversal arises because sediments are living and reworked landscapes shaped by tides, organisms, and time. Even though they were not directly quantified in this study, bioturbation, biofilms, and repeated re-suspension are well-established processes known to continuously reshape the sediment fabric [57,58] of natural intertidal flats. In such environments, higher bulk density may not indicate stronger material, but rather coarser or reworked deposits with reduced cohesion [19,24]. The result is a decoupling of density and resistance: structure is no longer simply a function of packing, but of biological and hydrodynamic history [45,50,59].

This duality is central. It explains why a single variable—bulk density—can appear both strongly predictive and directionally inconsistent, depending on context. It is not the sediment that changes meaning, but the system that defines it. In newly restored or engineered intertidal environments, physical sediment properties such as bulk density initially dominate erosion resistance, making them critical indicators to monitor in restoration trajectories until longer-term biological and biogeochemical feedbacks become established and increasingly intertwined with the physical structure of the system. This interpretation fits within established bed stability theory, in which erosion thresholds arise from the interaction among grain packing, cohesion, and biological reinforcement [24,51,60]. More recent work has similarly shown that sediment erodibility cannot be reduced to grain size alone, but arises from integrated bed properties, including density, structure, and biogenic cohesion [61].

4.3. When Laboratory Simplicity Meets Field Complexity

One of the most intriguing outcomes of this study is the comparison between laboratory mixtures and field observations. Most tendencies, including those involving bulk density, as well as silt percentage with critical shear stress, remain directionally consistent across both environments for the overall correlation analysis. The main exception is the relationship between Span and critical shear stress, which shows the opposite trend in field conditions compared to laboratory mixtures, possibly due to natural human handling

errors during sediment mixing in the lab. However, the generalized least squares model reveals that, despite the contrasting pairwise correlation, bulk density remains the dominant predictor of erosion resistance across both laboratory and field datasets. Neither environmental setting nor interaction effects significantly alter this relationship. This suggests that the laboratory does not fundamentally misrepresent field behavior; rather, it isolates different parts of the same underlying system, which helped confirming the functional role of each variable in the field, while inherently lacking any biological activity, natural stratification, and long-term consolidation processes that characterize field conditions. In this sense, bulk density becomes a translation layer between simplified experimental systems and the complexity of natural environments. Future studies could further explore this relationship under more complex and biologically active sediment conditions in controlled laboratory settings.

4.4. Conceptual Ecological Implications for Benthic Organisms and Migratory Birds

While biological responses were not measured in this study, the observed differences in sediment properties provide a basis for discussing potential ecological implications in light of established relationships reported for intertidal ecosystems.

Sediment is not just a physical substrate, but the foundation on which intertidal life is organized [62,63]. As bulk density, critical shear stress, and sediment texture covary across restoration strategies, they are expected to quietly determine whether a habitat is stable enough to persist in the tidal frame or too dynamic to sustain long-term ecological function [51]. In this way, sediment mechanics become a potential hidden link between restoration design and habitat quality.

For benthic organisms, this link is well established in the literature to be immediate and physical [23]. Where sediments are densely packed and erosion-resistant—associated with higher bulk density and surface shear strength—burrowing becomes more difficult, oxygen exchange is restricted, and access to food resources is constrained, particularly for deposit feeders [64]. Yet when sediments are too loose and weakly consolidated, conditions shift in the opposite direction: colonization may be easier at first, but frequent disturbance prevents communities from stabilizing. The result is a delicate balance, where the most favorable conditions for benthic diversity emerge not at either extreme, but at intermediate sediment bed stability, where structure is strong enough to persist but still permeable enough to support life [65]. This physical balance then cascades upward through the food web. Migratory shorebirds, which depend on predictable access to infaunal prey, are commonly understood to be directly influenced by how easily they can penetrate and extract organisms from the sediment [66]. High bulk density and shear resistance can limit prey accessibility, while overly soft sediments increase energetic costs and reduce foraging efficiency through substrate instability [66]. Sediment heterogeneity adds another layer to the story. Moderate variability can open up a wider range of niches, supporting more diverse communities, but excessive or unstable heterogeneity reduces predictability and can disadvantage specialist feeders. As a result, changes in sediment structure driven by restoration practices can translate into changes in the carrying capacity of intertidal flats along major migratory routes such as the East Atlantic Flyway [67].

Together, these dynamics suggest how restoration shapes not only the physical stability of intertidal flats, but also the ecological conditions that determine whether those flats function as productive and reliable habitats for benthic communities and migratory birds.

5. Conclusions

Bulk density emerges as a key indicator of present-day erosion resistance of restoration strategies, reflecting the coupled influence of physical structure and biological processes shaping sediment behavior at both natural and restored sites. Its consistent explanatory power across restored systems suggests that it should be prioritized in monitoring frameworks for intertidal restoration, as it captures how quickly sediments consolidate, how they respond to hydrodynamic forcing, and how systems evolve from physically dominated conditions toward more integrated states where physical, biological, and chemical processes jointly regulate stability.

Across restoration strategies, erosion resistance is not primarily controlled by uniform shifts in critical shear stress, but by differences in how sediment systems are organized. Groyne-influenced areas show the widest variability due to dynamic sediment trapping and redistribution, managed realignment reflects intermediate and still-developing structure, and sand nourishment is comparatively constrained by more uniform depositional conditions. In contrast, natural and more mature intertidal flats follow a different trajectory, where erosion resistance is increasingly shaped by longer-term biogeochemical stabilization, biological activity, and sediment reworking processes inferred from established intertidal sediment dynamics [23]. These processes decouple stability from purely physical properties and embed it within a more complex sediment–ecosystem framework. These differences in sediment organization and stabilization pathways directly influence benthic and higher trophic level organisms, as they determine substrate accessibility, habitat stability, and prey availability. Consequently, restoration does not simply modify erosion resistance, but reshapes the environmental conditions that structure ecological functioning. This highlights the need for future restoration strategies to prioritize bulk density as a central indicator of physical sediment development, while also accounting for the future gradual emergence of biological and biogeochemical controls that are ultimately expected to govern long-term ecosystem performance.

Supplementary Materials: The following dataset and scripts can be downloaded at: <https://www.mdpi.com/article/10.3390/jmse14141271/s1>, S1: dataset; S2: Sediment_property_correlations; S3: NMDS; S4: Field_vs_Lab; S5: Controls_Critical_Shear_Stress; S6: Span_PR_Map.

Author Contributions: Conceptualization, R.P.T., T.J.B., J.v.B., B.W., and G.S.F.; methodology, R.P.T., T.J.B., and B.W.; software, R.P.T. and G.S.F.; validation, R.P.T., T.J.B., and B.W.; formal analysis, R.P.T. and B.W.; investigation, R.P.T. and L.B.; resources, T.J.B.; data curation, R.P.T.; writing—original draft preparation, R.P.T.; writing—review and editing, R.P.T., B.W., T.G., J.v.B., J.v.d.K., S.T., and T.J.B.; visualization, R.P.T.; supervision, J.v.B., J.v.d.K., S.T., T.J.B., and B.W.; project administration, T.J.B.; funding acquisition, T.J.B. All authors have read and agreed to the published version of the manuscript.

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Data Availability Statement: The processed datasets used for statistical analyses and figures are available as Supplementary Materials, along with the accompanying R (version 4.5.1) and Python (version 3.12.4) scripts. Raw data is available from the corresponding author upon reasonable request.

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Conflicts of Interest: The authors declare no conflicts of interest.

Abbreviations

The following abbreviations are used in this manuscript:

BD	Bulk density
Elev	Elevation
G	Groyne
MR	Managed realignment
N	Natural site
PR	Penetration resistance
SSS	Surface shear strength
Silt	Silt percentage
SN	Sand nourishment
τ_{cr}	Critical shear stress

Appendix A

Appendix A.1. Sampling Sites

Table A1. Geographic coordinates (latitude and longitude), sampling site names, identification of natural vs. restored sites, and estuarine location of the field sampling sites included in this study. Restored habitats included sand nourishment (SN), managed realignment (MR), and groynes (G), while natural habitats are represented as N. Latitude and longitude are indicated with WGS84 coordinate system. “Scheldt” refers to the corresponding Eastern Scheldt (ES) and Western Scheldt (WS).

Latitude	Longitude	Sampling Site	Natural vs. Restored	Scheldt
51.5415178	3.8964257	Zandkreek	N	WS
51.5453735	4.0582680	Slikken van Dortsman	N	ES
51.6676700	3.8341000	Roggenplaat	N	ES
51.3516095	3.7180219	Paulinapolder	N	WS
51.3869635	3.8233574	Zuidgors	N	WS
51.6634990	3.8165760	Roggenplaat	SN	ES
51.4653010	4.2219630	Oesterdam	SN	ES
51.3885500	4.0198190	Perkpolder	MR	WS
51.3445350	4.2141120	Hedwige-prosperpolder	MR	WS
51.3659383	4.0699771	Baalhoek	G	WS
51.3968650	4.2251160	Bath	G	WS
51.3657785	3.9424038	Hellegat	G	WS
51.4202096	3.9931657	Ossensisse	G	WS
51.4011310	4.1173730	Zimmerman	G	WS

Appendix A.2. Spatial Distribution of Sediment Properties

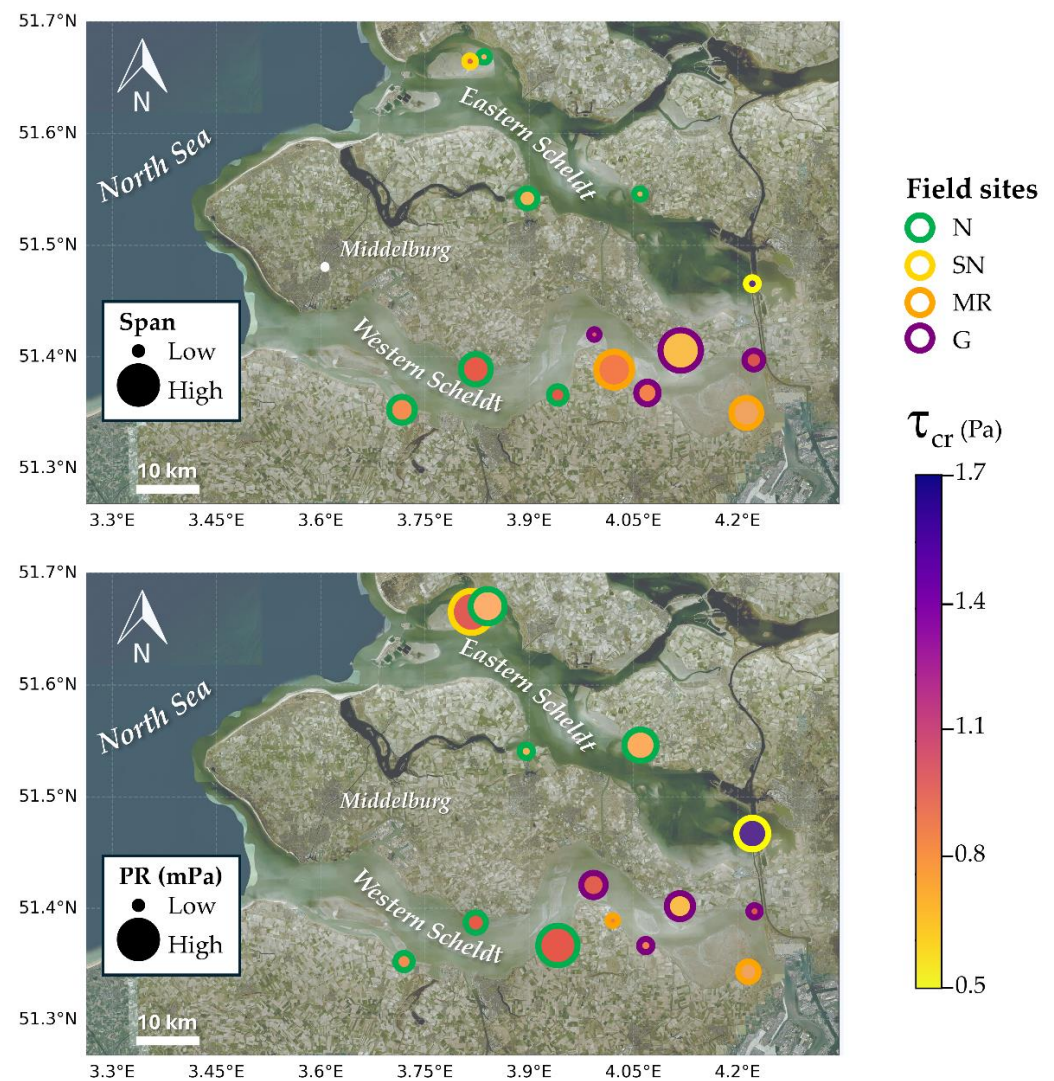


Figure A1. Spatial distribution of sediment property drivers of critical shear stress in the Eastern Scheldt (ES) and Western Scheldt (WS), The Netherlands. The panels show Span and peak penetration resistance. Circles indicate the presence and magnitude of each driver at sampling locations, with circle size proportional to the measured value (small to large values). Circles are encircled by a colored outline that denotes restoration type: natural (green), groynes (purple), managed realignment (orange), and sand nourishment (yellow). A separate, continuous color ramp represents critical shear stress, with yellow corresponding to the lowest critical shear stress values and purple to the highest critical shear stress values. Each panel corresponds to a single sediment property driver of critical shear stress, and the same geographic domain is used across panels for direct comparison.

Appendix B.

Appendix B.1. Sediment Property Correlations

Table A2. Differences in sediment characteristics among natural (N) and restoration strategies (sand nourishment, SN; managed realignment, MR; and groyne, G), based on boxplots and density distributions, including critical shear stress (τ_{cr}), silt percentage (Silt), grain size span (Span), bulk density (BD), surface shear stress (SSS), elevation (Elev), and penetration resistance (PR). Group differences were evaluated using Kruskal–Wallis tests, with effect sizes reported as η^2 . Overall statistical significance is indicated by asterisks (* $p < 0.05$, and ** $p < 0.01$). Pairwise differences between restoration types are based on Dunn post hoc tests with Benjamini–Hochberg adjusted p -values ($p_{adj} < 0.05$). Only statistically significant pairwise comparisons are shown; non-significant comparisons are indicated as “n.s.”.

Variable	Kruskal–Wallis χ^2	p -Value	Effect Size (η^2)	Sig Pairwise Differences (Dunn, $p_{adj} < 0.05$)	Sig
Silt	13.10	0.004	0.337	G vs. MR ($Z = 3.12$, $p_{adj} = 0.0018$); MR vs. SN ($Z = -3.13$, $p_{adj} = 0.0017$); MR vs. N ($Z = 2.28$, $p_{adj} = 0.0224$)	**
Elev	10.01	0.018 *	0.234	G vs. N ($Z = 2.81$, $p_{adj} = 0.0049$); G vs. MR ($Z = -2.14$, $p_{adj} = 0.0325$)	*
SSS	9.51	0.023	0.217	MR vs. N ($Z = 2.91$, $p_{adj} = 0.0036$); G vs. MR ($Z = -2.27$, $p_{adj} = 0.0233$)	*
BD	9.15	0.027	0.205	G vs. MR ($Z = -2.27$, $p_{adj} = 0.0233$); MR vs. SN ($Z = 2.87$, $p_{adj} = 0.0041$); MR vs. N ($Z = 2.14$, $p_{adj} = 0.0324$)	*
PR	7.57	0.056	0.152	MR vs. SN ($Z = 2.57$, $p_{adj} = 0.0103$)	n.s.
τ_{cr}	7.34	0.062	0.145	n.s.	n.s.
Span	7.08	0.069	0.136	G vs. MR ($Z = 2.42$, $p_{adj} = 0.0154$)	n.s.

Appendix B.2. Structured Differences Among Restoration Strategies

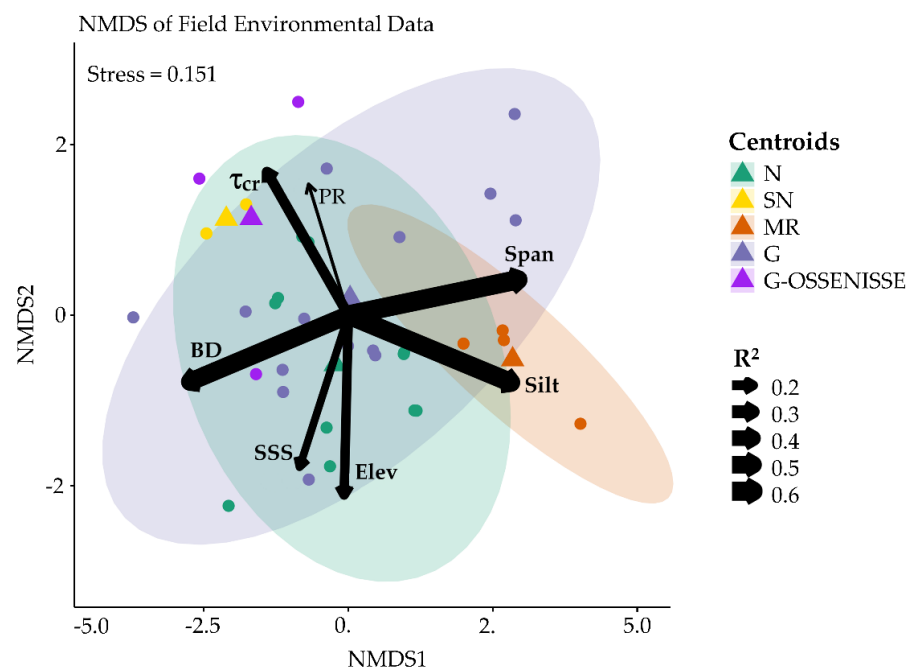


Figure A2. NMDS ordination illustrating patterns among sampled sediment properties, including critical shear stress (τ_{cr}), silt percentage (Silt), Span (Span), bulk density (BD), surface shear stress (SSS), elevation (Elev), and penetration resistance (PR). Data points are colored and clustered according to restoration strategy: natural (N) in green, groynes (G) in light purple, the Ossenisse groyne site in dark purple (G-OSSENISSE), managed realignment (MR) in orange, and sand nourishment (SN) in yellow. The thickness of the arrows (env vectors) represents the strength of the environmental variable loadings, with thicker arrows denoting larger $|R^2|$ contributions of the vectors to the NMDS solution. Triangle shapes represent the centroid hulls, and circles represent the data points. The overall NMDS stress value is 0.151, which is within the commonly recommended threshold of 0.20 for acceptable ordination ([43,44]).

Table A3. Pairwise PERMANOVA assessing among-NMDS cluster distances differences across restoration types: natural (N), groynes (G), managed realignment (MR), and sand nourishment (SN). The table reports R^2 , F.Model, p -value, and adjusted p -value (p -adj) for each pairwise comparison between restoration types. Significance is indicated as follows: significant (* $p < 0.05$, and ** $p < 0.01$), and non-significant (n.s.).

Comparison	R^2	F.Model	p -Value	p -Adjusted	Sig
N vs. MR	0.404	8.800	0.002	0.006	**
G_vs_MR	0.247	6.230	0.002	0.006	**
N_vs_SN	0.228	3.252	0.016	0.024	*
N vs. SN	0.228	3.252	0.016	0.024	*
N_vs_G	0.098	2.829	0.016	0.024	*
SN_vs_G	0.103	1.955	0.074	0.074	n.s.
SN_vs_MR	0.778	14.049	0.067	0.074	n.s.

Table A4. Sediment characteristics contributing to differences among restoration strategies identified using Kruskal–Wallis tests applied to each variable separately. The table reports the raw p -values, Benjamini–Hochberg (BH) adjusted p -values to control for false discovery rate due to multiple comparisons, and significance levels based on adjusted p -values (n.s. for non-significant p -value, marginal (.) p -value, significant (* $p < 0.05$, and ** $p < 0.01$)). Variables represent sediment characteristics, including critical shear stress (τ_{cr}), silt percentage (Silt), grain size distribution (Span), bulk density (BD), surface shear strength (SSS), elevation (Elev), and penetration resistance (PR). These parameters collectively describe differences in sediment structure, stability, and geomorphological conditions among restoration strategies.

Variable	p -Value	p -Adjusted (BH)	Sig
Silt	0.00443	0.0310	**
BD	0.0274	0.0480	*
Elev	0.0185	0.0480	*
SSS	0.0232	0.0480	*
PR	0.0557	0.0695	.
Span	0.0695	0.0695	n.s.
τ_{cr}	0.0619	0.0695	n.s.

Appendix B.3. Laboratory Mixture Sediment Property Correlations

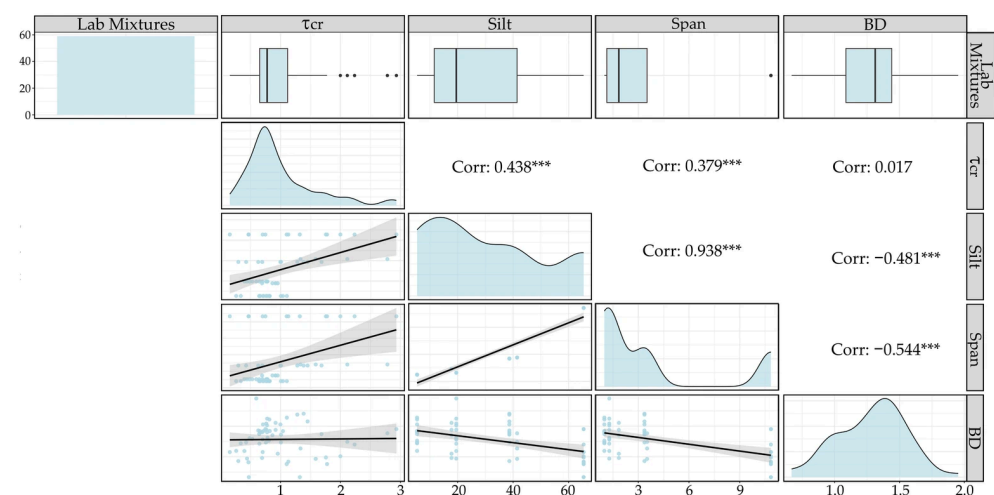


Figure A3. Correlation matrix of the laboratory mixtures sediment properties with supplementary visualizations. The left panel displays scatterplots and a fitted tendency line with 95% confidence bands to illustrate the bivariate relationships among sediment properties. The right panel presents the correlation. Above the correlation matrix, boxplots are shown by restoration strategy to summarize the distribution of each property across groups, and a stacked bar plot provides an overview of the data composition. Significant relationships are signaled with asterisks indicating high significance level (***).

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