

Chapter

Depositional and Erosional Behaviour of Cohesive Sediments in Estuarine Saltmarsh and Mudflat Environments

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Abstract

Management of aquatic environments relies on the accurate prediction of sediment transport via numerical models. Knowledge of erosional and depositional behaviours in the muddy sediments dominating these environments is therefore required. Erosional and depositional characteristics are complicated due to cohesive sediment processes, influenced by biophysical properties. To enhance the understanding of interactive processes within cohesive sediments from various aquatic environments, this study collated and analysed sedimentary datasets representative of differing dynamical regimes. Sediment stability in intertidal sediments was investigated using data collected during the CBESS (Coastal Biodiversity and Ecosystem Service Sustainability) programme. The CBESS project collected landscape-scale field measurements investigating patterns between biodiversity and ecosystem service flows in coastal wetlands. In CBESS samples from Essex (SE England) and Morecambe Bay (NW England), the highest stability was observed in saltmarsh samples. Significant differences are demonstrated in sediment stability across sites, habitats (saltmarsh/mudflat), and seasons (summer/winter). This chapter provides an extensive background literature review and analysis of sediment characteristics in mudflat and saltmarsh habitats. Analysis of secondary field data explores the variation in erosional properties across varying dynamics and sediment compositions.

Keywords: erosion, deposition, intertidal, cohesive sediment, sediment stability, sediment transport

1. Introduction

This chapter details an investigation of vegetated and non-vegetated sediment in intertidal sediments utilising data from the Coastal Biodiversity and Ecosystem Service Sustainability project (CBESS). The CBESS programme (2012–2016) collected large-scale datasets (UK-wide) investigating biodiversity and the related ecosystem

service provision in intertidal ecosystems, with regional datasets from Essex (south-east England) and Morecambe Bay (northwest England). The overall aim of CBESS was to investigate how biodiversity provides ecosystem services at various scales. This was achieved through biological and physical surveys, alongside *in situ* ecosystem function measurements at more than 600 stations.

The aim of the present study was to address the impact of varying dynamical conditions and sediment compositions on erosion properties, as well as the inter-comparison of physical sediment properties.

Sediment transport prediction in aquatic environments is complicated by variations in sedimentary and dynamic conditions promoting complex cohesive sediment interactions [1, 2]. For context, a discussion of various cohesive sediment behaviours is conducted below. Sections 1.1 and 1.2 give an overview of existing research related to erosion and floc characteristics, demonstrating the general focus on site-specific scenarios in literature, rather than a combination of all aspects of sediment prediction [3, 4]. The following sections discuss research applications, in relation to transport modelling.

1.1 Background

Natural sediment that dominates aquatic environments is characterised by a mixture of constituents, including mud, sand and organic material (**Figure 1**; [7, 8]). Commonly described as muddy sediments, these cohesive mixtures result in complex interactions, due to variations in bio-physical attributes. Since the nature of muddy sediments relies on physical, biological and chemical aspects, each affords equal consideration [3, 9]. A comprehensive review of erodibility in relation to bio-chemo-physical attributes can be found in [6]. Measurement of particle size distribution from a particle sizer (e.g., the Malvern Mastersizer 2000 in [10]), provides insight into sediment composition.

From sedimentary and hydrodynamic interactions, flocculation of muddy sediments arises, the degree of which is described by sediment stability. In turn, sediment stability relies on forces of interaction influenced by suspended particulate matter and turbulent shear stress (τ), the turbulent shear generated within the water column, as well as compositional properties (mineral, biological; [11–14]). Resulting flocs form and break up, determining erodibility and depositional characteristics, therefore, impacting sediment transport processes [11, 15]. Erosion and deposition are commonly considered mutually exclusive processes, an approach deemed invalid for natural sediment [16].

1.2 Erodibility

Erodibility in literature can be expressed by erosion threshold and erosion rate. Spatial variation in cohesive sediment erodibility is highlighted in many studies (e.g., [17–19]). Horizontal variation is present in erodibility, across depth environments, with variation between channel and shoal areas [10]. For instance, towards the Humber Estuary shore, the erosion threshold has been observed to increase [20]. Vertical spatial variation has been observed between surface and sub-surface sediments and vertical sorting of grain size fractions has been modelled [21, 22]. Temporal (including seasonal and tidal) variation is also widely observed in erodibility (e.g., [23–25]).

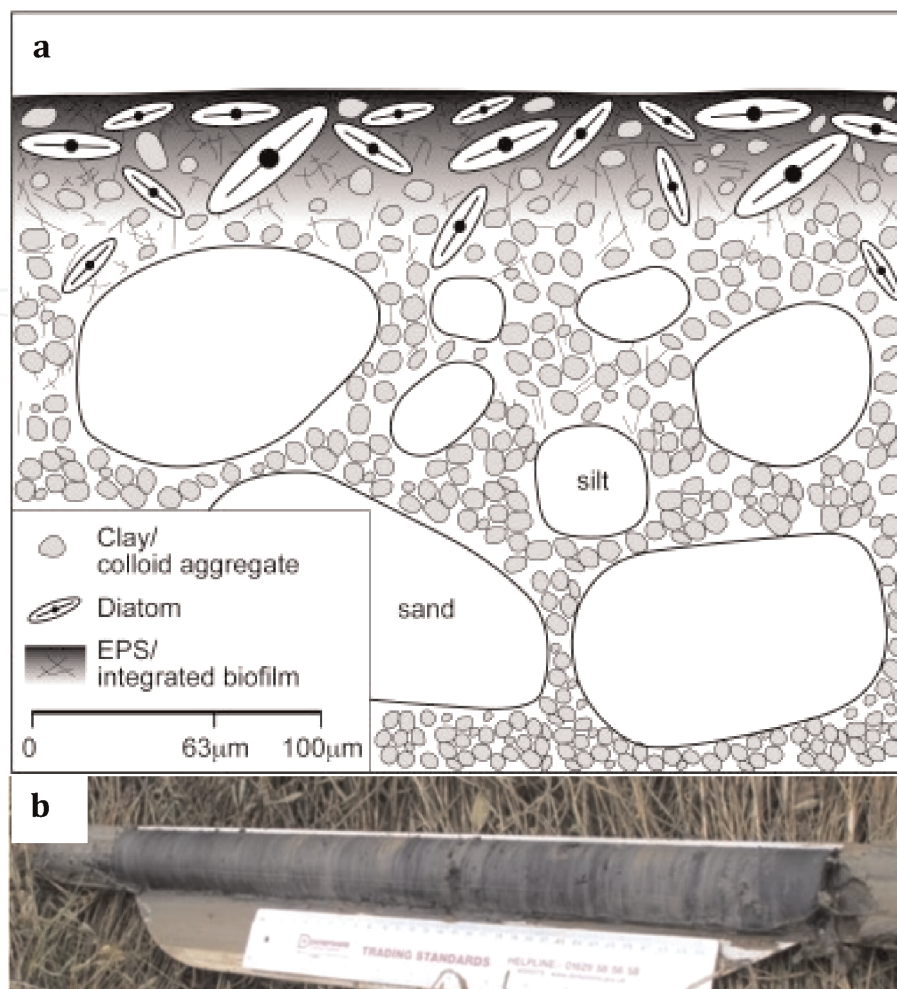


Figure 1.
(a) Diagram representing various components within the microstructure of cohesive sediment, from which abiotic and biotic components can be identified. The extracellular polymeric substances (EPS) may occur at greater depths within the sediment than the integrated biofilms they make up, which occur predominantly on the sediment surface. From [5], reproduced in [6]. (b) Example of a Russian corer sediment core from the CBESS site, Tillingham, Essex. Photo taken by Helen Brooks in February 2017.

1.2.1 Empirical research and instrumentation

1.2.1.1 Estuarine and surrounding areas

The Cohesive Strength Meter (CSM; [26]) is a portable instrument, used extensively for sediment stability erosion threshold measurements, usually represented by τ or critical shear stress, τ_c (Nm^{-2} or Pa, e.g., [27, 28]). A water jet is fired through a chamber onto the surface of the sediment directly below, measuring resuspended sediment with a transmissometer and the force of the jet pulse at which surface cohesive strength of the sediment is overcome ([26, 29]; **Figure 2**). The literature states various pros and cons for this instrumentation (**Table 1**). For cohesive sediments, CSM use is validated by [29], suggesting the best results are obtained for sediments with 4–10% minimum clay content (as per [32]).

Intertidal sediments analysed using the CSM, measuring *in situ* τ , revealed biofilm influence on erosion characteristics. Larger median grain size (D_{50}) correlated with increasing eroding pressure, the water jet pressure at which light transmission in the CSM chamber dropped below 90% (e.g., 1000 μm D_{50} grains eroded at 50 kPa,



Figure 2.
Cohesive strength meter features (e.g., [28, 29]). Image: [30].

Pros	Cons
<i>In situ</i> measurements	Not suitable for underwater deployment—not <i>in situ</i> in deep water
Small, portable, handheld	Unnatural flow structure
Efficient deployment, short tests	Non-cohesive sediment causes over-estimation of erosion threshold
Sensitive sensors	

Table 1.
Pros and cons of the cohesive strength meter [28, 29, 31].

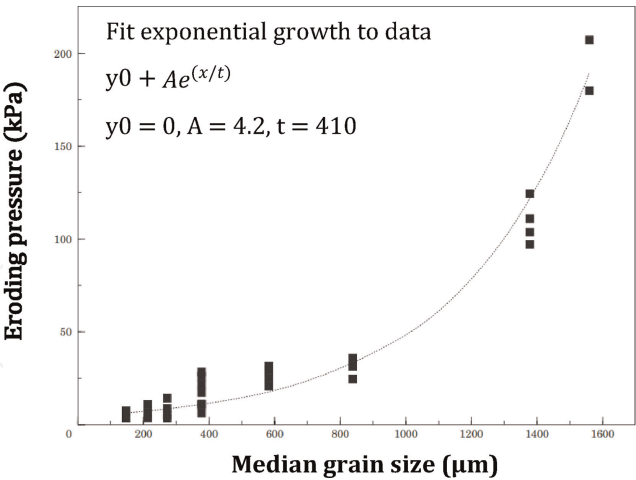


Figure 3.
Critical erosion pressure is required to suspend sand at different grain sizes, where increasing grain size corresponds to an exponential trend for increasing pressure required for sediment suspension. The equation represents the equation for x and y , where A and t are constants, 4.2 and 410, respectively, as indicated (from [28]).

1600 μm required >150 kPa; [28]; **Figure 3**). Experiments on the same sediment type revealed the minimum erosion threshold as 9.08 Nm⁻², increasing rapidly when bio-filmed areas emerged; a lack of biofilm produced lower erosion thresholds [33]. In mesotidal estuarine conditions, erosion thresholds ranged from ~120 to 340 Pa [34]. As a representation of erosion threshold, τ has been reported across various Humber

Estuary (UK) sites varying from ~ 0.5 to 2.5 Nm^{-2} [20]. Similarly, calculations of τ_c ranged from 0.48 to 1.74 Pa in fine-grained Huanghe River estuarine sediment, in China [35].

1.2.1.2 Intertidal (saltmarsh/mudflat)

As saltmarsh and mudflat ecosystems retreat, recent research has focused on various forcing mechanisms and properties responsible for erosion (e.g., hydrodynamic [36, 37], geotechnical/sedimentary [36, 38, 39], and biological factors [20, 37]). At a large scale, factors impacting saltmarsh erosion include wind exposure and vegetation abundance, whereas at local and mesocosm scales, erosional sediment properties and other characteristics become more important [40]. In Britain, northern marsh expansion and southern marsh erosion have been related to a reduced sediment flux and wave sediment resuspension/transport in the south compared to the north [39]. Additionally, biodiversity is crucial, since extracellular polymeric substance (EPS) biofilms play an important role in biostabilisation, causing complex erosional behaviour. One such influence, for example, is increasing τ_c required for erosion [26, 37]. As biodiversity decreases, long-term monitoring is important for the selection of management techniques to maintain species richness [41].

Intertidal sediments were tested in the German Wadden Sea area (tidal flat) using the EROMES (erosion-measurements) device, which works similarly to the CSM by creating artificial turbulence using water to resuspend sediment [42]. In this study, τ_c

Location	Erosion threshold (Nm^{-2})	Mud content (%)	MC (%)	OC (%)	Reference
Microtidal mudflat Kongsmark	0.306			11.8	[43]
Microtidal mudflat Kjelst	0.554			10.3	[43]
Intertidal cohesive sediment	0.360				[44]
Intertidal cohesive sediment	0.470				[44]
Intertidal cohesive sediment	0.580				[44]
Mudflat	0.319	72.3		7.4	[18]
Mudflat	0.140		66.6		[45]
Intertidal sediments	1.105	71.7	38.6	4.1	[42]
Mudflat	0.175				[46]
Tidal flat Site E	0.180				[47]
Tidal flat Site F	0.230				[47]
Tidal flat Site G	0.160				[47]
Intertidal flat	0.776				[48]
Mudflat, A1	0.086	83.0			[49]
Mudflat, A2	0.093	84.0			[49]
Mudflat, A3	0.090	76.0			[49]

MC = Moisture content, OC = organic content.

Table 2.
Summary of mudflat data from the literature.

values of $0.16\text{--}2.05\text{ Nm}^{-2}$ were produced. Other biophysical properties were tested, including mud content (46.32–97.07%), water content (24.7–52.46%), organic content (1.30–6.81%) and chlorophyll-a concentration (8.72–144.19 mg.m^{-2}). Lanuru [42] found that the most important of these factors correlating to τ were chlorophyll-a and organic content ($r = 0.8$ and 0.58 , respectively, $p < 0.01$). Mean biophysical properties in mudflats with mud content ranging from ~ 72 to 84% (clay and silt), include organic matter from ~ 4 to 12% and moisture content $\sim 39\text{--}67\%$, with erosion thresholds from ~ 0.2 to 1.1 Nm^{-2} (**Table 2**). In a CSM study, roots contributed to bank stability in a southern English saltmarsh creek bank [50].

1.3 Transport modelling

The process of sediment transport along the coast is dynamic, complex, and impacted by various dynamical and sedimentological factors [1]. Much research has been undertaken, developing models to predict sediment movement and behaviour (e.g., [51] and following reviews). For reviews on transport models and techniques, see Refs. [1, 2]. Three main theories utilised in numerical modelling include capacity for sediment transport, near-bottom equilibrium concentration and τ_c [52]. Common inputs involve erodibility parameters and sediment properties (floc diameter (spherical equivalent), density, etc., e.g., [53]). Hydrodynamical parameters, such as flow velocity and flow depth, are well-understand, whereas sedimentary parameters inputs, such as bio-physical properties are less well described, due to less developed sediment transport theories and limits on the experimental techniques and data on particle scale interactions [52, 54]. A better understanding of τ has improved numerical modelling, with τ_c being included more comprehensively in recent models [52].

1.4 Summary

Various techniques required in evaluating cohesive sediment properties have been demonstrated, along with the lack of a coherent theory and few models combining erosional and depositional sedimentary processes across environments [3, 53]. While the importance of flocculation and hydrodynamics is highlighted in understanding cohesive sediment behaviour [2], the key knowledge gap identified is understanding τ processes alongside sediment characteristics [16]. The following sections, therefore, utilise various case studies to investigate cohesive sediment interactions across several aquatic environments.

2. Methods and analysis

Aspects of erodibility and deposition were combined, to increase understanding of complex processes of interaction between cohesive and mixed sediment, ensuring these processes are not considered mutually exclusive as seen previously (following [10]).

2.1 CBESS

The CBESS project collected landscape-scale field measurements for biodiversity and ecosystem service flows in coastal wetlands to quantify patterns between

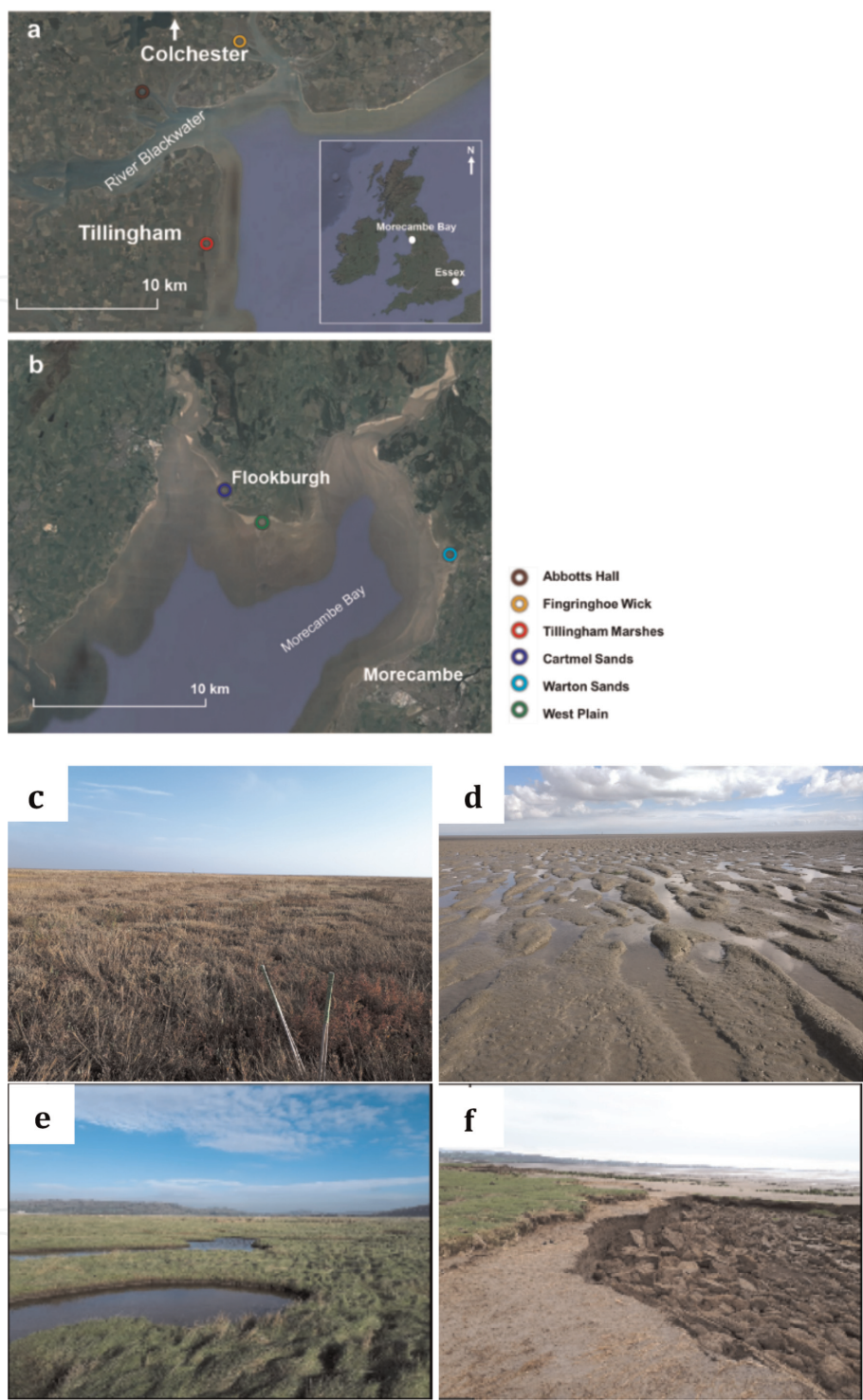


Figure 4. CBESS site locations for (a) Essex and (b) Morecambe Bay [58–60], site examples: Tillingham, Essex, (c) vegetated, (d) non-vegetated; Warton, Morecambe Bay, (e) vegetated, (f) non-vegetated. Photographs taken by Helen Brooks in October 2018 (c, e, f) and by Iris Möller in September 2017 (d).

ecosystem service provision and biodiversity [55]. The CBESS sediment stability dataset from a CSM was obtained to investigate sediment erodibility in intertidal habitats ([56]; **Figure 2**). Colloidal carbohydrate concentration data was also acquired from [57], which were measured from the top 2 mm of surface soil, to quantify the colloidal carbohydrate fraction of EPS (hereafter cEPS).

2.1.1 Study site

The two locations investigated were Essex (SE England) and Morecambe Bay (NW England), with three sites at each, taking vegetated (saltmarsh, SM) and non-vegetated (mudflat, MF) samples at each site (**Figure 4; Table 3**). The locations represent varying inundation frequencies and creek structures, with erosive coast in Essex and deposition in Morecambe Bay, where mudflats characterise higher sand content [56].

2.1.2 Data acquisition and processing

The CBESS field survey was conducted in 2013 (summer and winter) on surface vegetated and non-vegetated samples from 11 quadrats per site. A mean was taken of three to five replicates within each quadrat. The values obtained were at scale D (100 m to site upper limit within site polygons, [56], e.g., **Figure 5**).

Location	Site	Latitude (°N)	Longitude (°E)
Essex	Abbotts Hall	51° 47'	0° 52'
	Fingringhoe Wick	51° 49'	0° 58'
	Tillingham Marshes	51° 41'	0° 56'
Morecambe Bay	Cartmel Sands	54° 10'	−3° 30'
	Warton Sands	54° 8'	−2° 48'
	West Plain	54° 9'	−2° 58'

Table 3.
GPS coordinates for the six CBESS sites [56].

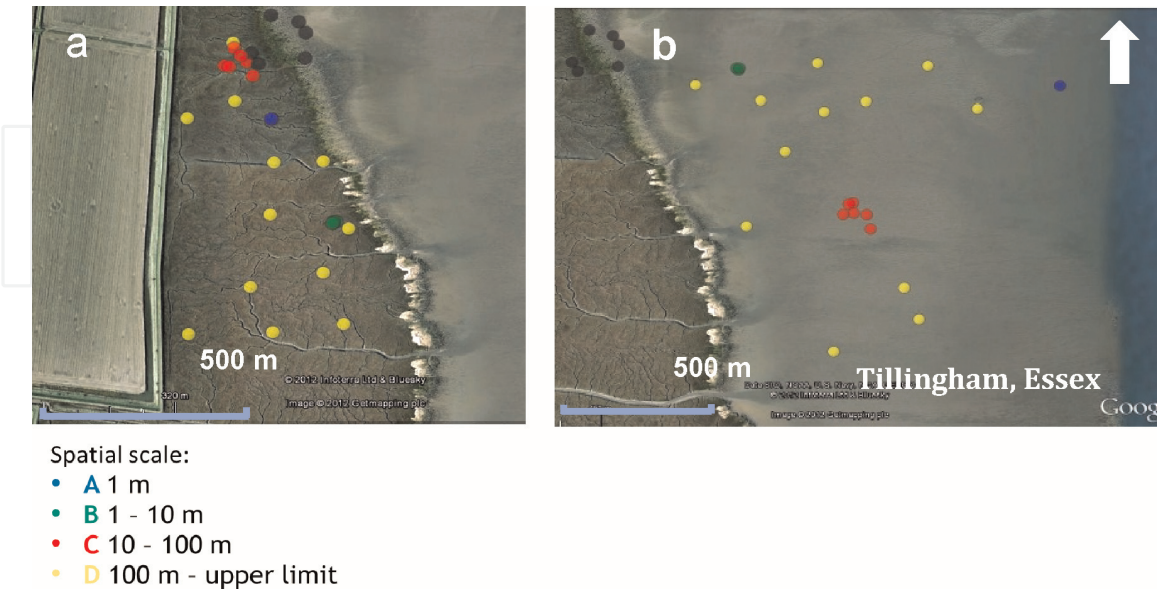


Figure 5.
CBESS field survey example for Tillingham winter quadrats, indicating random distribution within a site polygon for (a) saltmarsh samples and (b) mudflat samples. Twenty-two quadrats (1 × 1 m) are indicated at different spatial scales, with this study focusing on scale D, represented in yellow. The procedure was replicated at each of the six locations and for summer measurements. Site polygons were 400 × 500 m to 1000 × 1000 m ([61, 62], adapted from [56]).

Sediment stability was assessed by measuring the stagnation pressure (Nm^{-2}) of the jet upon the sediment surface as an indication of erosion threshold, a measurement of the energy required to oppose the force of the jet at the sediment surface. CSMs were calibrated for comparability between devices [56, 63]. For broad-scale comparison, mean values for scale D quadrats were calculated at each site (SM, MF samples in summer and winter). Raw measurements from individual quadrats (11, 18) were also taken from Tillingham SM and MF datasets to assess the variability of erosion threshold measurements within quadrats. Hierarchical clustering was utilised to visualise the variation (average, Appendix 1).

The cEPS was determined from dried core subsamples (50–500 mg depending on site from the top 2 mm of the surface) via the DuBois assay, and spectrophotometer readings were compared with regression analysis values of standards for cEPS calculation (see [57]). Analysis in Excel was the same as the CSM procedure above.

2.1.2.1 Statistical analysis

2.1.2.1.1 Tillingham within-site variation

All statistical analysis was performed in standardised statistical software (Minitab LLC, 2020 v19.2020.1 <https://www.minitab.com/en-us/products/minitab/>; Excel, v2002; RStudio 1.3.1093 <https://www.r-project.org/>, vegan 2.5–6 package <https://cran.r-project.org/web/packages/vegan/>) unless stated otherwise. Comparisons across software packages were made on test data to confirm the equivalence of results.

Within-site variation of erosion threshold in vegetated and non-vegetated habitats was utilised to investigate statistical methods. The Anderson-Darling test was carried out on TM summer and winter samples for SM and MF sediments with 95% confidence [64]. The test (coefficient AD) uses Eq. (1) and Eq. (2), with the AD* (adjusted) value determining the equation for the p-value according to [65]. To understand the impact of the inclusion of non-normal datasets, in parametric and non-parametric difference statistics, spatial and seasonal variations were analysed (**Figure 6**; summary in **Table 4**). For these difference statistics, the Bonferroni correction was applied for multiple comparisons, to the 95% confidence interval; thus, the alpha value utilised was 0.0125 (reject null if $p < 0.0125$; [69]).

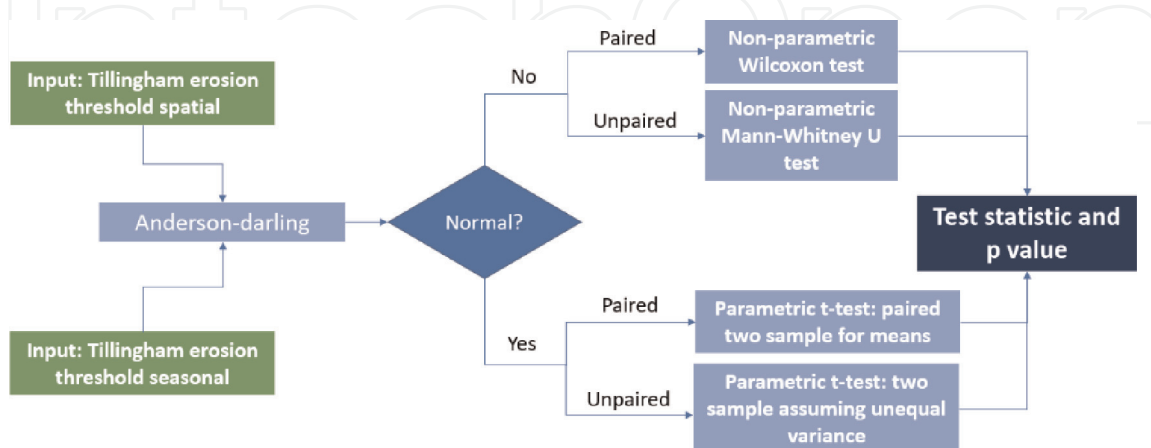


Figure 6. Tillingham within-site variation statistical analysis flowchart where green represents an input, light blue represents processing/analysis, and dark blue is an output. Note: seasonal data is paired and spatial data is unpaired. The single value input for the Wilcoxon test required the difference between the two input variables to be calculated (summer minus winter for mudflat and saltmarsh values).

Test	Test type	Data type	Null hypothesis	Equation/Algorithm [66]
T-test: paired two sample for means	P	Paired	Population mean of differences = 0	$t = \frac{\bar{x} - \mu_0}{s/\sqrt{n}}$
t-test: two sample assuming unequal variance	P	Unpaired	Difference between population means = 0	$t = \frac{\bar{X}_1 - \bar{X}_2}{s}$ where: $s = \sqrt{\frac{s_1^2}{n_1} + \frac{s_2^2}{n_2}}$
Wilcoxon	N-P	Paired	Population median of differences = 0	Algorithm from [67]
Mann-Whitney U	N-P	Unpaired	Difference between population medians = 0	Calculates p, using test statistic (W; sum of ranks of sample 1), adjusted via standard methods.
Kruskal-Wallis	N-P		All medians are equal	E.g. [68]

For the t-tests (t-statistic, t): $\bar{X}_{(y)}$ indicates the sample mean (for the yth sample where a subscript is present); μ_0 indicates the hypothesised population difference; $s_{(y)}$ represents sample standard deviation for the difference between means (for the yth sample where a subscript is present) and $n_{(y)}$ represents the sample size (for the yth sample where applicable).

Table 4.
Summary of statistical test methods, where test type indicates parametric (P) or non-parametric (N-P).

$$AD = -N - \frac{2i - 1}{N} (\ln F(Y_i) + \ln(1 - F(Y_{N+1-i}))) \tag{1}$$

where N is the number of data points, F(Y) represents the cumulative distribution function and i is the sample value at position i when the data is in ascending order.

$$AD * = AD \left(1 + \frac{0.75}{N} + \frac{2.25}{N^2} \right) \tag{2}$$

2.1.2.1.2 Broad-scale variation

Broad-scale analysis was conducted on data from all six sites in Essex and Morecambe Bay, to investigate if there was a significant difference in stability or composition properties across the six sites. Firstly, the Anderson-Darling test was

Site	p-value	
	Erosion	cEPS
TM	0.0005	<0.0005
AH	<0.0005	<0.0005
FW	<0.0005	<0.0005
CS	<0.0005	<0.0005
WP	<0.0005	<0.0005
WS	<0.0005	<0.0005

Calculated using [70]. Sites: Tillingham Marsh (TM) - Abbots Hall (AH), Fingringhoe Wick (FW) and Morecambe Bay (M) - Cartmel Sands (CS), West Plain (WP), Warton Sands (WS).

Table 5.
p-values from the Anderson-Darling test to determine the normality of data distribution for erosion thresholds and cEPS (colloidal carbohydrate concentrations fraction; using data from [56, 57]).

conducted (Section 2.1.2.1.1). All datasets were non-normally distributed at the 95% confidence interval (all $p \leq 0.0005$; e.g., **Table 5**), therefore, non-parametric testing was implemented, using the Kruskal-Wallis test (**Table 4**).

Spatial variation in erosion threshold and cEPS across sites was tested, as well as comparing erosion thresholds across habitats at 95% confidence ($\alpha = 0.017$; [69]). Additionally, seasonal variation in erosion threshold was investigated at 95% confidence ($\alpha = 0.05$).

3. Results

3.1 Intertidal habitats (saltmarsh/mudflat)

Analysis of broad-scale CBESS stability measurements allowed comparison of stability measurements between intertidal habitats, including variation between vegetated and non-vegetated sediments and seasonal variation.

CBESS data were obtained from six sites to investigate comparisons between vegetated and non-vegetated sediment stability.

3.1.1 Tillingham within-site variation

One site, Tillingham (**Figure 4**), was chosen to investigate within-site sediment stability variation. Within Tillingham, 33% of both SM and MF quadrat measurements reveal higher erosion thresholds in summer than in winter (**Figure 7**). In the SM

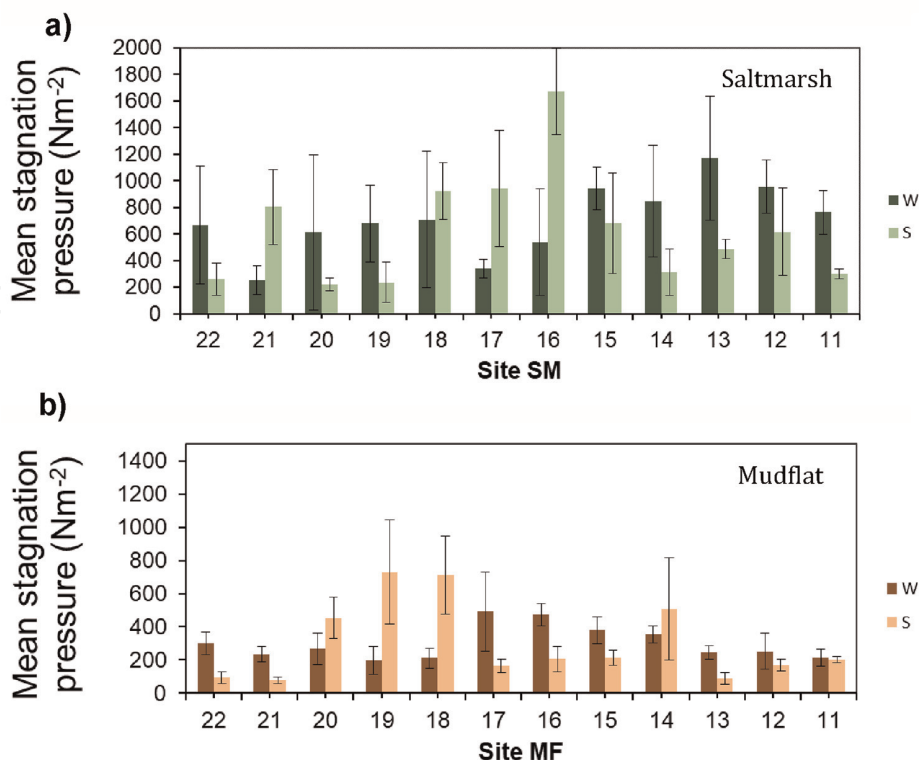


Figure 7. Twelve quadrats in Tillingham marshes, at scale D for (a) saltmarsh (SM), (b) mudflat (MF) with standard deviation indicated, winter (dark) and summer (light) (From [71]; data from [56]). Stagnation pressure = static pressure at the point where fluid velocity is zero.

samples, erosion threshold range was 916 (1450) Nm^{-2} in winter (summer), whereas the MF samples' range was 296 (652) Nm^{-2} , with the maximum stability occurring in summer, reaching 1669 $\pm$ 325 (730 $\pm$ 314) Nm^{-2} thresholds for SM (MF) samples. Average standard deviation was within 40% (31%) of the mean erosion threshold in SM (MF) samples.

3.1.2 Broad-scale variation

Broad-scale spatial and seasonal variation was investigated across six sites (Essex and Morecambe Bay, UK) utilising sediment stability and cEPS data. Essex erosion threshold measurements in summer and winter revealed means of 527 $\pm$ 210 (411 $\pm$ 134) Nm^{-2} in SM (MF) samples (**Figure 8**). Morecambe Bay erosion threshold means were lower at 458 $\pm$ 171 (159 $\pm$ 56) Nm^{-2} in SM (MF) samples. Average standard deviation was within 39% (33%) of the mean erosion threshold in SM (MF) samples.

Essex cEPS measurements in summer and winter revealed means of 4869 $\pm$ 3417 (1320 $\pm$ 373) $\mu\text{g.g}^{-1}$ in SM (MF) samples (**Figure 9**). For Morecambe Bay, cEPS means were higher and lower respectively, at 6893 $\pm$ 3569 (103 $\pm$ 66) $\mu\text{g.g}^{-1}$ in SM (MF) samples. Average standard deviation within 59% (31%) of the mean cEPS in SM (MF) samples.

The largest change in erosion threshold between SM and MF habitats occurred in Morecambe Bay summer samples (73%), corresponding to the second largest cEPS change (98%, **Table 6**). The smallest change in stability (2%) occurred in the Essex summer sample, corresponding to a change in cEPS of 52%.

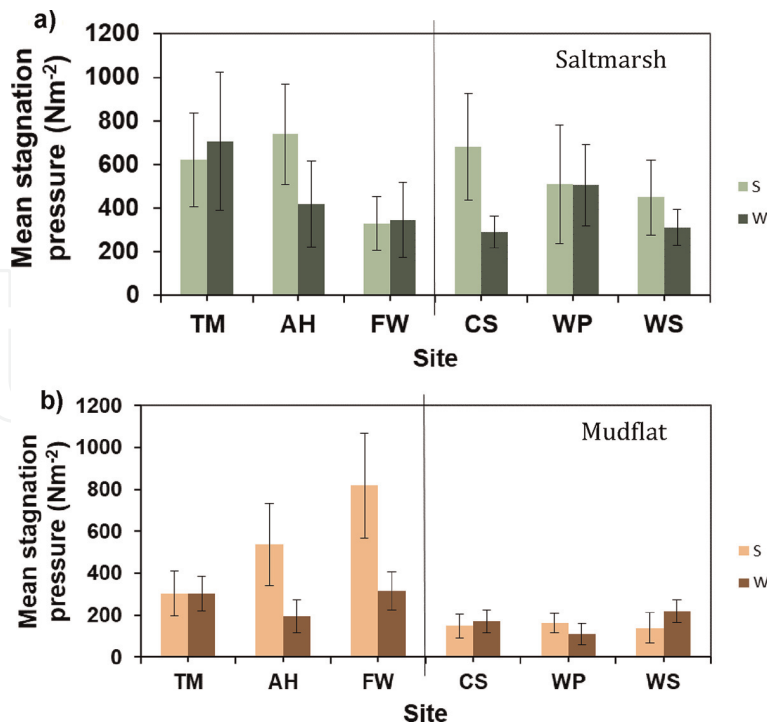


Figure 8. Mean stagnation pressure as an indication of erosion threshold, for summer (S) and winter (W) measurements for (a) saltmarsh and (b) mudflat samples. Erosion threshold values utilise an average for six sites at scale D, with mean values across 12 quadrats ($1 \times 1 \text{ m}$) at each site. Essex (left of divider): Tillingham Marshes (TM), Abbotts Hall (AH), Fingringhoe Wick (FW); Morecambe Bay (right of divider): Cartmel Sands (CS), West Plain (WP), Warton Sands (WS). Data from [56].

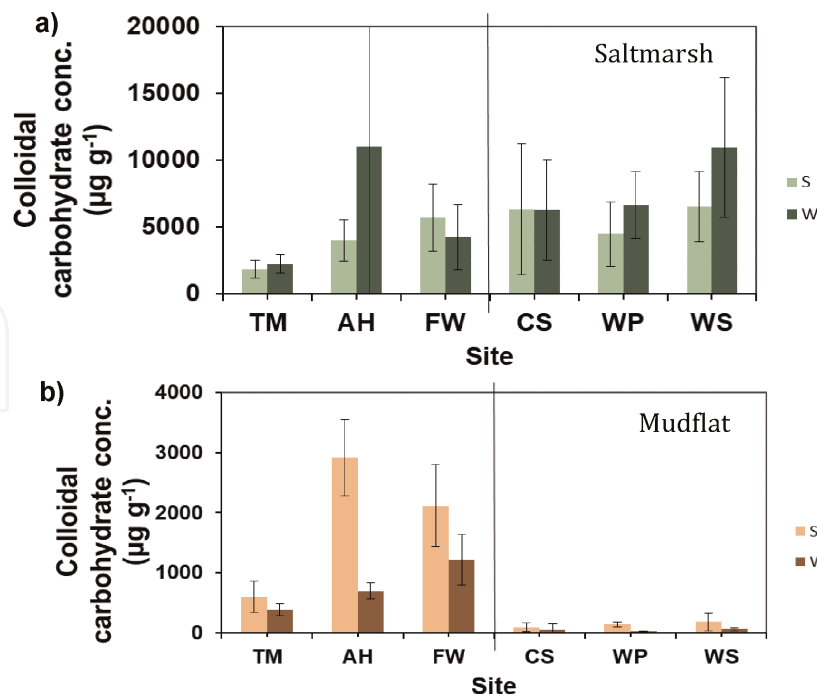


Figure 9. Colloidal carbohydrate concentration (cEPS fraction) for summer (S) and winter (W) measurements for (a) saltmarsh and (b) mudflat samples. cEPS measurements utilise an average for six sites at scale D, with mean values across 12 quadrats (1 × 1 m) at each site. Essex (left of divider); Morecambe Bay (right of divider). Note: Standard deviation error bar for saltmarsh winter AH = −1596 to 23,726 $\mu\text{g.g}^{-1}$ and for mudflat winter CS = −46 to 149 $\mu\text{g.g}^{-1}$. Data from [57].

Location	Season	Erosion difference (%)	cEPS difference (%)
Essex	S	1.90	51.6
	W	44.9	87.2
Morecambe Bay	S	72.5	97.6
	W	54.7	99.4

The mean values of three sites were taken from both Essex and Morecambe Bay. Calculated using data from [56, 57].

Table 6. The percentage decrease from saltmarsh to mudflat samples in erosion threshold (from stagnation pressure) and colloidal carbohydrate concentration (cEPS fraction) in summer (S) and winter (W).

4. Statistical analysis

Statistical analysis of CBESS data was undertaken to investigate apparent trends observed in Section 3, aiding interpretation. The analysis explored statistical approaches, then utilised multivariate statistical visualisation and analysis to explore data, considering the relative influences on sediment stability and cEPS of site, habitat and seasonal characteristics.

Statistical CBESS data analysis illustrated caveats in various methodological approaches for Tillingham samples, justifying methodologies in this study (Section 4.1). To investigate broad-scale spatial and seasonal variation, comparisons of erosion thresholds and cEPS across six sites in Essex and Morecambe Bay were conducted (4.2).

4.1 Tillingham within-site variation

Tillingham stability data distribution is unclear from histograms, for example, observations of winter SM and MF appear normal and non-normal, respectively (Figure 10). Consequently, the Anderson-Darling test was conducted, revealing normal distributions for tested data, except the summer MF sample ($p < 0.05$; Table 7). Example normality plots from a normal and non-normal distribution are presented in Figure 11.

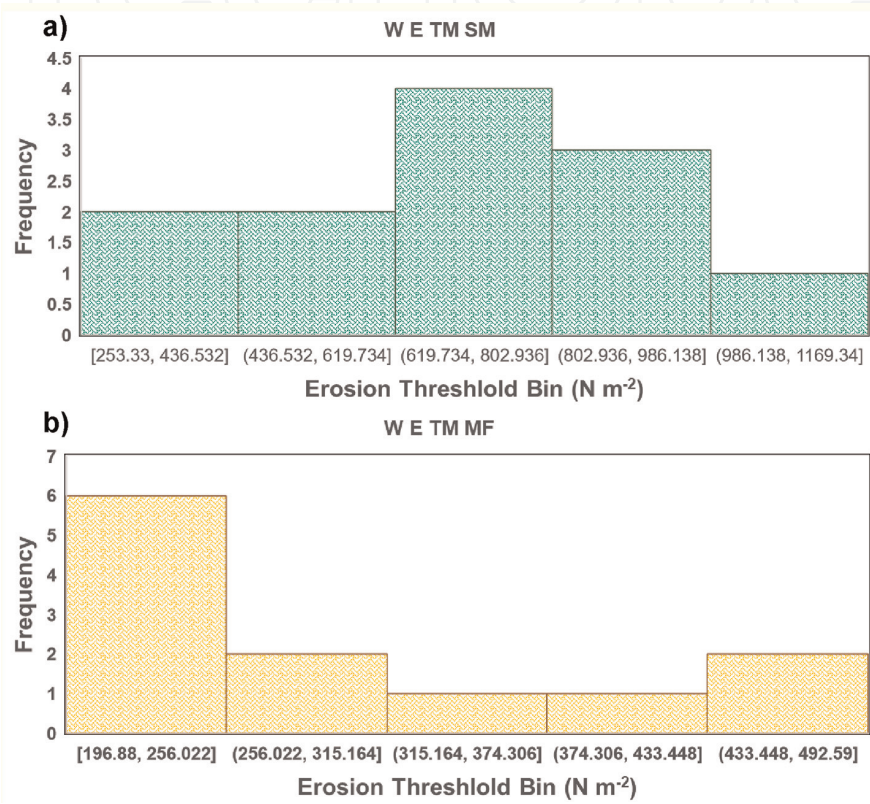


Figure 10. Example histograms for the winter (W) measurements at Tillingham marsh, Essex (TM, E) for (a) saltmarsh (SM) and (b) mudflat (MF) samples. Erosion threshold values were taken from 12 quadrats at scale D (100–1000 m or site maximum) from [56]).

Sample	Mean	SD	n	AD*	p
Winter MF	302	102	12	0.707	0.07
Summer MF	302	237	12	1.022	<i>0.01</i>
Winter SM	706	259	12	0.189	0.90
Summer SM	621	425	12	0.640	0.10

The p -value is highlighted bold, where $p > 0.05$ (normally distributed data) and italic for $p < 0.05$ (non-normal distribution). Calculated using [70] and Minitab LLC, 2020 v19.2020.1; p value threshold from [65]. Data from 12 quadrats at scale D; from [56]).

Table 7. Anderson-Darling test at 95% confidence for Tillingham marshes, Essex data (mudflat (MF) and saltmarsh (SM) samples in winter and summer), indicating the mean, standard deviation (SD), number of samples (n), the Anderson-Darling statistic (AD) and the adjusted Anderson-Darling statistic value for small sample sizes (AD*; $n < 30$).

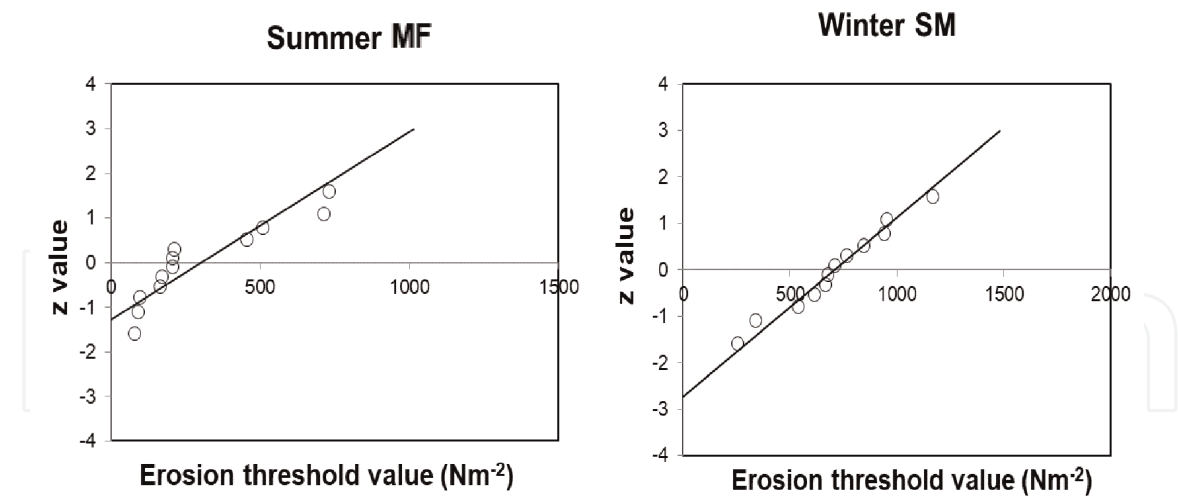


Figure 11. Example normal probability plots of standardised z values (the number of standard deviations a given value x is away from the mean). Tillingham stability measurements: (a) summer mudflat (MF, non-normal) and (b) winter saltmarsh (SM, normal), from the Anderson-Darling test, using [70]. Data from 12 quadrats at scale D; from [56]).

4.1.1 Quadrat variability

Quadrat variability was analysed to illustrate an example of data similarity averaged within each quadrat (Section 2.1.2). Hierarchical clustering created dendrograms, which allocate values to clusters to indicate similarity within the data. Clusters are formed by joining points in order of similarity, where the smallest link height represents the highest similarity (e.g., blue circles, **Figures 12 and 13**).

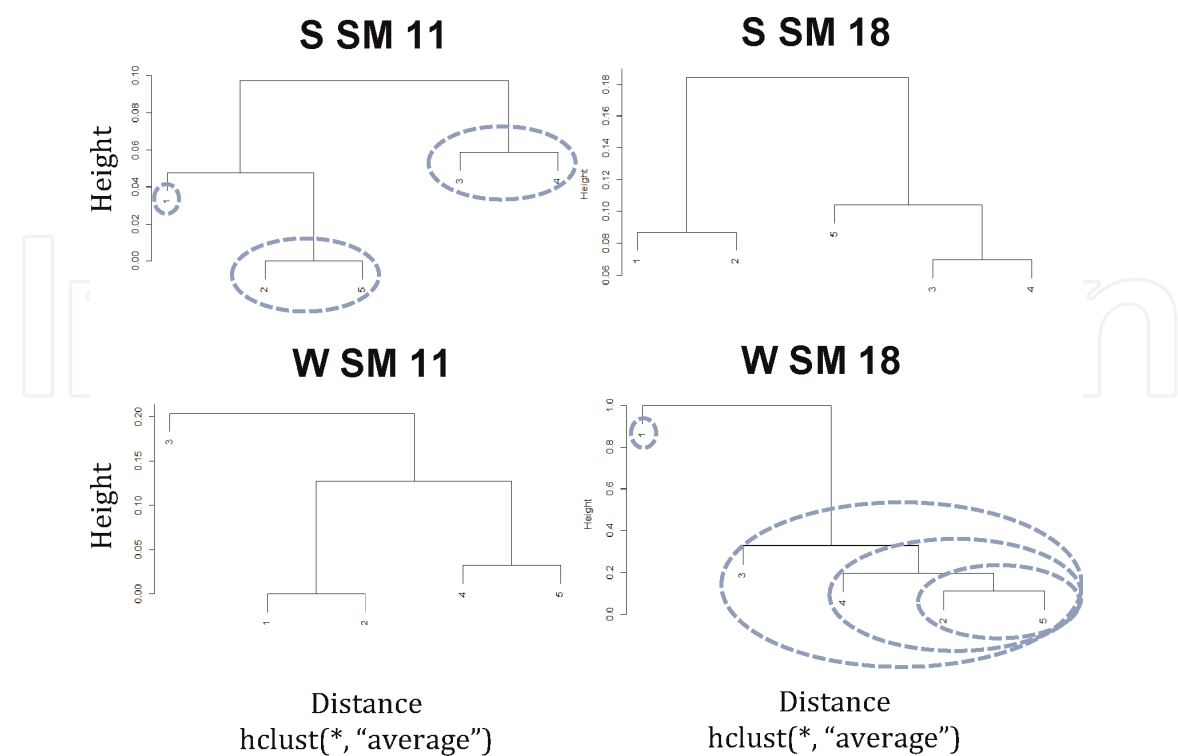


Figure 12. Hierarchical cluster analysis (average) within CBESS Tillingham saltmarsh (SM) quadrats, 11 and 18. Where S = summer, W = winter, numbers 1–5 represent the repeat CSM erosion threshold measurements within each 1×1 m quadrat (Data from [56]). Example clusters – see blue circles.

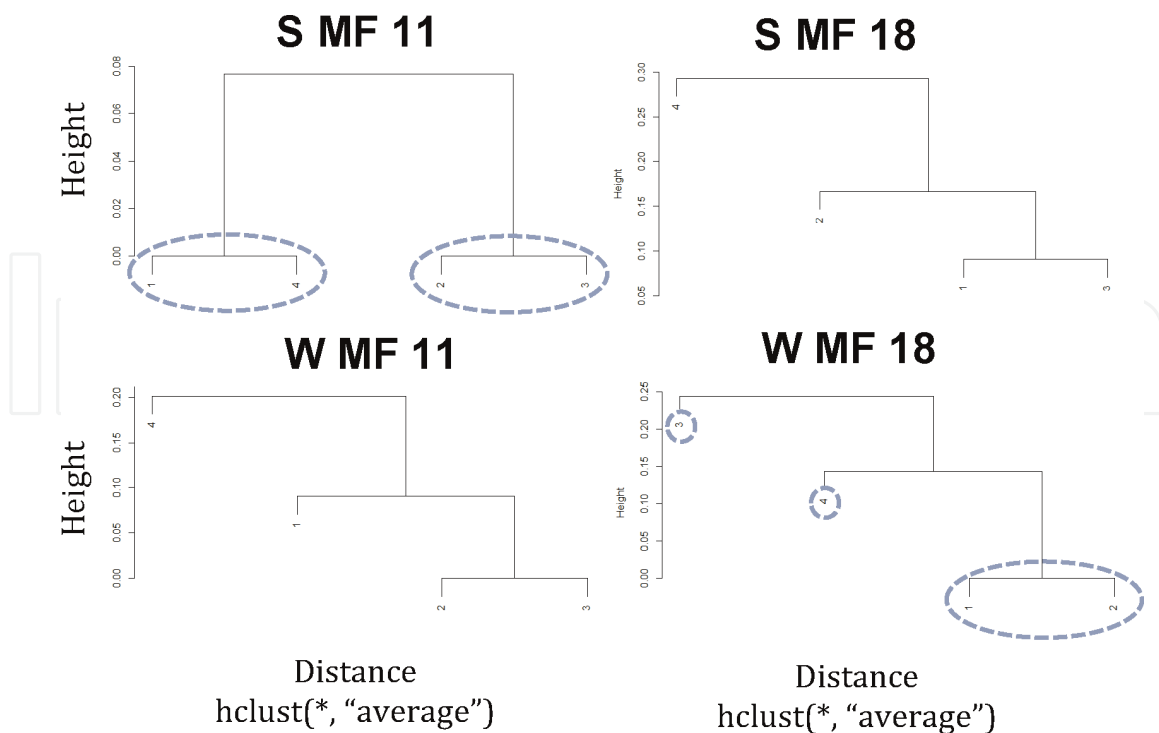


Figure 13. Hierarchical cluster analysis (average) within CBESS Tillingham mudflat (MF) quadrats, 11 and 18. Where, S = summer, W = winter, numbers 1–4 represent the repeat CSM erosion threshold measurements within each 1 × 1 m quadrat (Data from [56]). Example clusters – see blue circles.

Variation within quadrats indicated some clustering in SM and MF quadrats, thus data was deemed similar enough to average in this study (**Figures 12 and 13**).

4.1.2 Spatial variation

The statistical investigation of spatial variation within TM proposed the following question:

- Q1. “Is there a spatial difference in erosion threshold in Tillingham?”

The following null hypotheses were tested:

- Null hypothesis 1. “There is no difference between summer SM and MF erosion thresholds”.
- Null hypothesis 2. “There is no difference between winter SM and MF erosion thresholds”.

The parametric summer results indicated no significant difference, in habitat stability at 95% confidence, between SM and MF habitats ($p = 0.036$; **Figure 7**; **Table 8**). The non-parametric results (more appropriate due to non-normal data) disagreed, revealing a significant difference ($p = 0.0102$), thus the choice between parametric or non-parametric tests was important. Winter results were unaffected by the test type, the habitats’ stability being significantly different at 95% confidence for

Sample	N	Test statistic	p	Test
S MF + SM	12	-2.27	0.4	P
W MF + SM	12	-5.04	<0.01	P
S MF + SM	12	105	0.01	N-P
W MF + SM	12	88.5	<0.01	N-P

N = number of samples, the test statistics are indicated for the parametric t-test: Two sample assuming unequal variance (P) and non-parametric Mann-Whitney U test (N-P). Degrees of freedom for parametric tests: S MF + SM = 17 and W MF + SM = 14 (not available for non-parametric). The p values < alpha = 0.0125 are highlighted bold, for which the null hypothesis is rejected (significant difference). Values where the null is accepted are indicated in italic (no significant difference). S = summer, W = winter, MF = mudflat, SM = saltmarsh. Utilising data from 12 quadrats at scale D; from [56]).

Table 8.
Results summary for spatial difference statistics at 95% confidence (with Bonferroni correction: 98.75%).

both tests ($p < 0.001$). Consequently, for normal data distributions, both parametric and non-parametric approaches produced the same result.

4.1.3 Seasonal variation

The statistical investigation of seasonal variation within TM proposed the following question:

- Q2. “Is there a seasonal difference in erosion threshold in Tillingham?”

The following null hypotheses were tested:

- Null hypothesis 1. “There is no difference between MF summer and winter erosion thresholds”.
- Null hypothesis 2. “There is no difference between SM summer and winter erosion thresholds”.

Mudflat comparisons revealed no significant difference between summer and winter erosion thresholds in both parametric and non-parametric cases ($p = \sim 1.0$, 0.7 respectively; **Table 9**). The inclusion of the non-normal summer MF data set in this case did not cause differing outcomes for parametric and non-parametric tests, however, the parametric test produced a less significant p-value ($\sim 33\%$ higher than non-parametric). Similarly, SM comparisons produced no significant difference between summer and winter stability ($p = 0.6$), thus in this case utilising parametric and non-parametric testing for the normally distributed datasets produced the same outcome.

4.2 Broad-scale variation

Stability and cEPS data were analysed from all six Essex and Morecambe Bay sites to determine whether there were significant differences. Data distributions for each case (spatial and seasonal) were determined using the Anderson-Darling test. None of the tested datasets were normally distributed at the 95% confidence

Sample	N	Test statistic	p	Test
MF S + W	12	−0.003	0.997	P
SM S + W	12	−0.519	0.614	P
MF S + W	12	33	0.666	N-P
SM S + W	12	32	0.610	N-P

N = number of samples, the test statistics are indicated for the parametric t-test: paired two sample for means (P) and non-parametric Wilcoxon test (N-P). Degrees of freedom for parametric tests: MF S + W = 11 and SM S + W = 11 (not available for non-parametric). The p values < alpha = 0.0125 represent the threshold for which the null hypothesis is rejected (significant difference). Values where the null is accepted are indicated in italic (no significant difference). S = summer, W = winter, MF = mudflat, SM = saltmarsh. Utilising data from 12 quadrats at scale D; from [56]).

Table 9.
Results summary for seasonal difference statistics at 95% confidence (with Bonferroni correction: 98.75%).

interval (all $p \leq 0.0005$; e.g., **Table 5**). All analysis in this section therefore utilises non-parametric tests.

4.2.1 Spatial variability

To determine whether there was a significant difference in properties across the six sites in Essex and Morecambe Bay, statistical analysis was undertaken. Median erosion and cEPS across the six sites were compared, implementing Kruskal-Wallis tests for the following null hypotheses:

- Null hypothesis 1. “There is no difference between erosion thresholds across the six sites”.
- Null hypothesis 2. “There is no difference between cEPS colloidal carbohydrate across the six sites”.

Additionally, to determine the difference in median erosion thresholds across habitats, the following hypothesis was tested:

- Null hypothesis 3. “There is no difference between SM and MF erosion thresholds”.

There was a significant difference between some erosion thresholds and cEPS across sites at the 95% confidence interval. Similarly, there was a significant difference in erosion thresholds between SM and MF habitats (95% confidence). Since all p-values for spatial comparisons were less than 0.017 (Bonferroni correction applied; **Table 10**), the null hypotheses were rejected; there are some spatial differences. For context between sites, spatial differences of note may be observed in MF erosion thresholds between Fingringhoe Wick and Morecambe Bay sites (**Figure 8**). Erosion thresholds also differ between habitats from Morecambe Bay SM to MF samples. An example of large differences in cEPS across habitats may be observed between TM and Warton Sands SM samples (**Figure 9**).

4.2.2 Seasonal variability

To assess whether there was a significant difference between summer and winter sediment stability across Essex and Morecambe Bay sites, the Kruskal-Wallis test was

	DF	H	p-value
Site			
Erosion	5	23.29	<0.0005
cEPS	5	30.59	<0.0001
Habitat			
Erosion	3	59.48	<0.0001
Season			
Erosion	1	4.00	0.046

Comparisons included erosion thresholds and cEPS (colloidal carbohydrate concentrations fraction) across sites in Essex and Morecambe Bay, habitats (saltmarsh/mudflat) and seasons (summer/winter). (Using data from [56, 57]).

Table 10.
p-values, degrees of freedom (DF) and test statistic (H) from the Kruskal-Wallis test.

implemented. This tested for seasonal difference in median erosion threshold values with the following hypothesis:

- Null hypothesis: “There is no difference between summer and winter erosion thresholds”.

The null hypothesis was rejected at the 95% confidence interval due to the p-value below 0.05 ($p = 0.046$; **Table 10**); there was a significant difference between some erosion thresholds between summer and winter. As an example, this difference may be partly due to the difference between summer and winter values in Fingringhoe Wick MF or Cartmel Sands SM sediment (**Figure 8**).

5. Discussion

In situ stability from the CBESS programme in two intertidal locations was explored alongside cEPS. This discussion will look at within-site stability variation in Tillingham, Essex, followed by a broad-scale investigation of stability and cEPS across six sites in Essex and Morecambe Bay. Statistical analysis was utilised to illustrate various methodologies and assess stability and cEPS across spatial and seasonal factors.

The within-site investigation in Tillingham revealed higher stability in summer for approximately a third of samples (**Figure 7**), indicating increased biostabilisation in those sites due to microphytobenthos or root stabilisation from vegetation [28]. More erosion could be expected in winter, for example, when biostabilisation may be less effective and in the saltmarsh when vegetation cover is lower (e.g., [72, 73]). Higher stability observed in winter in most Tillingham samples, however, could indicate additional stabilising factors, for example, possible impacts from site-specific changes in grazing and vegetation community [73]. It has been noted that erodibility in intertidal habitats is complex, with both summer and winter exhibiting higher stability, with recommendations that as well as benthic micro-algae, macrofaunal community structure and population density

should be considered [43], agreeing with [74]. There is also a possibility that seasonal trends were impacted by sampling, since the standard deviation was high, indicating variability within quadrats, hence this discussion focuses mainly on spatial variation.

Highest stability occurred in SM samples for both within-site investigations in Tillingham and broad-scale explorations of Morecambe Bay and Essex sites (**Figure 8**). This is expected due to the higher vegetation content, which increases stability via roots (**Figure 4**; [50]). Mean cEPS was highest in Morecambe Bay SM (**Figure 9**), with the lowest concentration in the Morecambe Bay MF sample, coinciding with the lowest stability. EPS, the cEPS fraction of which was higher in SM samples, traps fine sediment, stabilising the bed via cohesive forces [3, 75]. The highest erosion thresholds occurred in Essex SM samples; Morecambe Bay stability was lower, the lowest observed in MF samples. Warton in Morecambe Bay characterises a silty fine sand substrate, while Tillingham in Essex is clayey silt [76], therefore, coarser Morecambe Bay sediment could cause lower stability, due to less cohesion from clay particles. Other factors that further research could address include root content or inundation.

The mean change in stability between SM and MF habitats was largest in Morecambe Bay, alongside the highest changes in cEPS (**Table 6**), therefore, it is beneficial to investigate interactions between stability and EPS, as literature agrees [6]. The smallest decrease in erosion threshold from SM to MF occurs in Essex in the summer (2%), while cEPS still differs by 52%. Conversely, in Essex in winter there was a larger decrease in erosion threshold (44%) alongside decreasing cEPS (87% loss) from SM to MF habitats. This difference could be due to the higher amount of cEPS left in the summer scenario due to the smaller loss of cEPS between habitats, enabling sediment to resist erosion more effectively across the habitats, than in the winter scenario, with the larger decrease in cEPS. A more established microphytobenthos community captures more cohesive sediment, enhancing the process of stabilisation [75]. While cEPS was still reduced between habitats in the summer, the impact of cEPS loss on stability between the sites varied between seasons, potentially due to the retained presence of cEPS compared to the larger loss of cEPS across habitats in winter. This also highlights the influence of other factors (e.g., sedimentology, ecology) on stability variation across habitats in different seasons. The presence of EPS is important as well as the absolute amount, suggesting a threshold at which EPS is sufficient to influence stability [37, 75].

Non-parametric statistical analysis in Tillingham revealed significant spatial differences between the MF and SM. Parametric statistics were not sufficient to resolve the difference when non-normally distributed summer samples were included. This illustrates the need for caution when assuming normality of data, as with advice applied to machine learning cases (e.g., [77]). Since seasonal differences (observed in **Figures 8** and **9**) could not be resolved at all, multivariate statistical analysis (e.g., multidimensional scaling) would be beneficial further work to investigate seasonal and spatial differences in stability (e.g., [75, 78]). Due to some clustering within quadrat measurements, these were averaged in this study (**Figures 12** and **13**). Further assessment of within-quadrat variation could be carried out, using the raw values, to preserve spatial variability. Quadrat variability could be assessed via interpolation, such as Kriging interpolation, minimising prediction errors [79].

Where seasonal variability was not resolved by t-tests/Mann-Whitney U analysis for within-site investigations, broad-scale Kruskal-Wallis tests allowed individual factors to be investigated against a response, with seasonal and site variability retained. Across six sites in Essex and Morecambe Bay, a statistically significant difference in erosion threshold across the sites was found (**Table 10**). Similarly, cEPS was significantly different between sites. It would be expected that differences occur in stability and EPS across sites, as factors such as tidal effects impact biofilms and stability [50]. There are many other influencing factors including substrate composition, grain size distribution and vegetation type, which could explain the larger differences observed, for example between Fingringhoe Wick and Morecambe Bay sites (e.g., [76]). It has been found that cEPS was not as effective for indicating small scale erosion threshold variability, as it was most effective between high and low marsh environments [80]. cEPS difference tests, therefore, focussed on larger spatial variability between sites. Spatial difference in erosion thresholds was identified between SM and MF habitats, for example, Morecambe Bay SM to MF samples. Spatial differences in habitats have been identified due to factors such as morphology and hydrodynamics (e.g., [81]). Finally, a seasonal difference was identified, which may be influenced by various factors, for example, changes in episodic events, such as storms. For instance, frequent cyclic disturbance may encourage new biofilm growth which is supported by eroded organic matter left on the sediment surface and as such, may increase biostabilisation [37]. Changes in vegetation cover, macrofaunal community structure and population density for example also impact seasonal variation and as such seasonal stability is complex and site specific [6, 43, 73]. Further work would be beneficial to identify relative influences of site, season and habitat type, along with EPS concentration on sediment stability. Multivariate testing or ANOVA (analysis of variance) and Tukey's test could be implemented to preserve variability in the data (e.g., [81]).

6. Conclusions

This chapter explores the sediment stability of intertidal sediments in vegetated and non-vegetated habitats. The erosional and depositional characteristics were investigated between habitats, different sites under differing sedimentary and hydrodynamical conditions and seasonally. A background review also explores the erosional and depositional characteristics of intertidal sediments alongside the application of such research to sediment transport modelling. Findings are summarised below along with future recommendations that arise from the investigations.

6.1 CBESS (Essex and Morecambe Bay, UK)

Within-site Tillingham investigations indicated higher sediment stability in approximately a third of summer samples relative to winter, possibly due to increased biostabilisation from microphytobenthos. Higher winter stability for the majority of samples suggests additional stabilising factors. Across within-site and broad-scale studies, highest stability occurred in SM samples, indicating increased biostabilisation from higher vegetation and fine sediment content. Lower stability occurred in Morecambe Bay than Essex, alongside coarser sediment.

The lowest erosion thresholds occurred alongside lowest cEPS in MF samples. The highest cEPS was observed in Morecambe Bay SM samples. Future work could investigate the reasons for the lower stability in Morecambe Bay (e.g., inundation and root content).

Various statistical methods illustrated analysis approaches. Non-parametric statistical analysis within TM revealed significant spatial differences between SM and MF samples, in summer and winter ($p \leq 0.01$). Since parametric statistics, involving non-normally distributed summer samples, did not resolve spatial difference ($p > 0.0125$), this illustrated the caution required in assuming data normality. Seasonal differences could not be resolved at all, illustrating the need for further statistics to investigate spatial and seasonal differences.

Broad-scale statistical comparisons (six sites) revealed significant spatial and seasonal differences in erosion thresholds at the 95% confidence interval. Differences were significant across sites ($p < 0.0005$), habitats (SM/MF, $p < 0.0001$) and seasons (summer/winter, $p = 0.046$). A statistically significant spatial cEPS difference across sites was also identified ($p < 0.0001$; 95% confidence). Further analysis (such as multivariate statistics) would be beneficial to examine where these differences lie and investigate the relative importance of site, habitat and seasonal factors on sediment stability.

6.2 Future recommendations

For intertidal sediments, further multivariate statistical analysis or ANOVA, retaining data variability, through stability comparisons across sites, habitats, seasons and compositional factors would enable assessment of relative importance on stability. Carbonate core data is available from Tillingham, Essex as an additional compositional factor aiding marsh sediment dynamics research.

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Conflict of interest

The authors declare no conflict of interest.

Appendix 1 R dendrogram analysis

Script in R Studio for hierarchical cluster analysis, creating dendrograms to test similarity within CBESS sediment stability quadrat measurements in Tillingham. Example file format for .csv below (**Figure A1**).

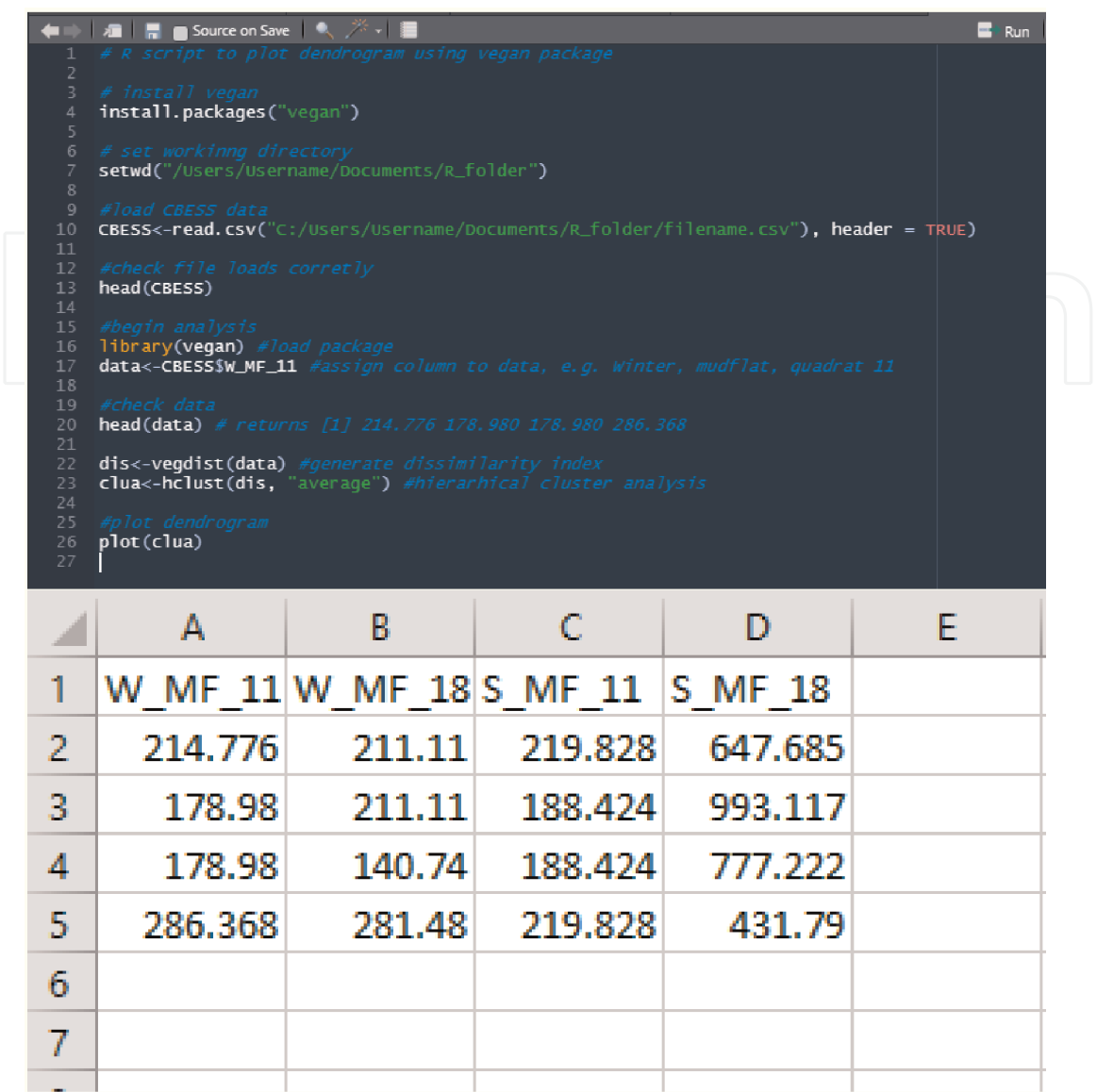


Figure A1.
Top: Example R Studio script utilised to create dendrograms for hierarchical cluster analysis of Winter Mudflat erosion threshold measurements. Below: Example .csv file format required to run the script.

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