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Key Points:

- Mud contents in the sediment bed can be bimodally distributed, resembling preferential sand-mud segregation
- Bimodality represents the existence of two stable equilibrium conditions, which are a result of the deposition fluxes of sand and mud
- Bimodality is expected for a large range of suspended sediment concentrations in sand-mud systems

Supporting Information:

Supporting Information may be found in the online version of this article.

Correspondence to:

A. Colina Alonso,
A.ColinaAlonso@tudelft.nl

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Author Contributions:

Conceptualization: A. Colina Alonso, D. S. van Maren, P. M. J. Herman, R. J. A. van Weerdenburg, Y. Huismans, S. J. Holthuijsen, L. L. Govers, A. I. Bijleveld, Z. B. Wang
Data curation: A. Colina Alonso, S. J. Holthuijsen, L. L. Govers, A. I. Bijleveld
Formal analysis: A. Colina Alonso, P. M. J. Herman, R. J. A. van Weerdenburg
Funding acquisition: D. S. van Maren, Z. B. Wang
Investigation: A. Colina Alonso, D. S. van Maren, P. M. J. Herman, R. J. A. van Weerdenburg, Y. Huismans, S. J. Holthuijsen, L. L. Govers, A. I. Bijleveld, Z. B. Wang

The Existence and Origin of Multiple Equilibria in Sand-Mud Sediment Beds

A. Colina Alonso[1,2], D. S. van Maren[1,2,3], P. M. J. Herman[1,2], R. J. A. van Weerdenburg[2], Y. Huismans[1,2], S. J. Holthuijsen[4,5], L. L. Govers[4,6], A. I. Bijleveld[4], and Z. B. Wang[1,2]

[1]Faculty of Civil Engineering and Geosciences, Delft University of Technology, Delft, The Netherlands, [2]Department of Marine and Coastal Systems, Deltares, Delft, The Netherlands, [3]State Key Lab of Estuarine and Coastal Research, East China Normal University, Shanghai, China, [4]Department of Coastal Systems, NIOZ Royal Netherlands Institute for Sea Research, Den Burg, The Netherlands, [5]Waardenburg Ecology, Culemborg, The Netherlands, [6]Conservation Ecology Group, Groningen Institute for Evolutionary Life Sciences (GELIFES), University of Groningen, Groningen, The Netherlands

Abstract The sediment composition of the seabed governs its mobility, hence determining sediment transport and morphological evolution of estuaries and tidal basins. Bed sediments often consist of mixtures of sand and mud, with spatial gradients in the sand/mud content. This study aims at increasing the understanding of processes driving the sediment composition in tidal basins, focusing on depositional processes. We show that bed sediments in the Wadden Sea tend to be either mud-dominated or sand-dominated, resulting in a bimodal distribution of the mud content where the two modes represent equilibrium conditions. The equilibria depend primarily on the sediment deposition fluxes, with bimodality originating from the dependence of suspended sand/mud concentrations on the local bed composition. Our analysis shows that bimodality is a phenomenon that is not only specific for the Wadden Sea; it can be expected for a wide range of suspended sediment concentrations and thus also in other systems worldwide.

Plain Language Summary The bottom of coastal seas is often composed of two sediment types, namely sand and mud. The evolution of the seabed, and thus of our coasts, depends on how these sediment types move. A correct representation of the spatial sand-mud patterns in the bed is therefore essential if we want to understand and predict coastal evolution. Studying a large data set we found that sediment beds tend to be either sandy or muddy, with lower chances of finding something in between (i.e., bimodality). Although segregation of sand and mud has often been attributed to erosion processes, we found that this is mainly the result of depositional processes, and especially of the suspended sediment concentrations. Sand concentrations largely depend on local conditions, while local mud concentrations are much more affected by conditions elsewhere and/or earlier. The difference in the suspended sand and mud concentrations leads to multiple equilibria in the bed composition—resulting in the previously mentioned bimodality—for a very wide range of conditions. Therefore, we also expect bimodality and sharp sand-mud transitions in other systems worldwide.

1. Introduction

Most bed sediments in estuaries and tidal basins are a mixture of sand and mud, with spatial gradients in the sand/mud content, typically with sandy outer areas near the inlet and fining in the landward direction. These gradients may be gradual or abrupt, and cover large spatial scales (e.g., a tidal basin) or small spatial scales (e.g., individual shoals). Especially at small spatial scales the transition in sediment composition may be abrupt (Braat et al., 2017; de Glopper, 1967; de Vet, 2020; Oost, 1995; van Straaten & Kuenen, 1957). The sediment composition in turn governs sediment mobility, hence sediment transport and morphological evolution (Geleynse et al., 2011; Jacobs et al., 2011; Le Hir et al., 2008; Mitchener & Torfs, 1996; van Rijn, 2020). It may also influence hydrodynamics, introducing complex morphodynamic feedback loops (van Maren et al., 2015; Winterwerp & Wang, 2013). Moreover, the bed sediment composition strongly influences biological activity and habitat suitability for many benthic organisms (Brückner et al., 2020). Therefore, understanding and correctly predicting the distribution of sand and mud in tidal basins is important for sustainable management of these systems.

Grain size fractions in the sediment bed of tidal basins are generally sorted along an energy gradient, with a decreasing trend in hydrodynamic energy and grain size from the inlet to the landward side (e.g., Chang et al., 2006; Flemming & Nyandwi, 1994). Above a threshold bed shear stress the mud content is generally low (mud contents <10%), but the mud content may vary anywhere between 0% and 100% below this threshold

Methodology: A. Colina Alonso, D. S. van Maren, P. M. J. Herman, R. J. A. van Weerdenburg, Y. Huismans, Z. B. Wang
Project Administration: A. Colina Alonso, D. S. van Maren, P. M. J. Herman, Z. B. Wang
Resources: A. Colina Alonso, D. S. van Maren, S. J. Holthuijsen, L. L. Govers, A. I. Bijleveld, Z. B. Wang
Software: A. Colina Alonso, D. S. van Maren, R. J. A. van Weerdenburg
Supervision: D. S. van Maren, P. M. J. Herman, Y. Huismans, S. J. Holthuijsen, L. L. Govers, A. I. Bijleveld, Z. B. Wang
Validation: A. Colina Alonso, D. S. van Maren, P. M. J. Herman, R. J. A. van Weerdenburg, Y. Huismans, Z. B. Wang
Visualization: A. Colina Alonso, R. J. A. van Weerdenburg
Writing – original draft: A. Colina Alonso
Writing – review & editing: D. S. van Maren, P. M. J. Herman, R. J. A. van Weerdenburg, Y. Huismans, S. J. Holthuijsen, L. L. Govers, A. I. Bijleveld, Z. B. Wang

condition (Braat, 2019; van Ledden, 2003). Spatial segregation of sand and mud has often been attributed to erosion processes, identifying a cohesive erosion regime (high mud content) and a non-cohesive erosion regime (low mud content) (see e.g., Jacobs et al., 2011; Torfs, 1995; van Ledden, 2003; van Rijn, 2020). Within both regimes, erosion is a bulk process (dominated by mud in the former, by sand in the latter). An implication of this mutual coupling is—as will be discussed in more detail in this paper—that erosion processes do not lead to sand-mud segregation. Depositional processes, on the other hand, have received much less scientific attention as a driver of sand-mud segregation.

The main objective of this study is to increase our understanding of processes driving the sediment composition in tidal basins, focusing on depositional processes. For this purpose, we analyze a large data set containing over 50,000 bed sediment samples collected in the Dutch and German Wadden Sea (WS). The Wadden Sea is the world's largest uninterrupted system of barrier islands and tidal flats, spanning over a distance of nearly 500 km along the North Sea coasts of the Netherlands, Germany and Denmark (Benninghoff & Winter, 2019; Elias et al., 2012; Pedersen & Bartholdy, 2006). Being a mixed-energy tidal system, both tides and waves play an important role in shaping its morphology. The tidal amplitude increases from 1.4 m in the western Wadden Sea to 3 m in the east. The offshore wave climate mainly consists of locally generated wind waves with an average significant wave height of 1.4 m and corresponding peak wave period of 7 s. The back-barrier basins contain extensive sand- and mudflats (see Figure 1) that provide great ecological value. The bed composition is annually sampled on a high spatial resolution, providing a unique data set that, as will be explored in this paper, provides a signature of sand-mud distribution (bimodality) which has not yet been documented in literature. These data give important insight into sand-mud patterns and segregation in tidal basins, thereby influencing long-term morphology. The mechanisms responsible for this bimodality will be explored within a theoretical framework supported by numerical models.

2. Methods

2.1. Field Data

The Synoptic Intertidal Benthic Survey (SIBES) data set contains samples from approximately 7,400 locations, covering the entire Dutch and part of the German Wadden Sea, and most of the Ems Estuary. The Dutch intertidal areas have been annually sampled since 2008, while the Dutch subtidal areas and the German parts of the Wadden Sea have been sampled only once. Sediment samples have been taken with a small core (with a diameter of 33 cm) up to 4 cm depth and freeze dried at −20°C. After homogenization the samples have been analyzed with a Coulter LS 13 320, without prior treatment to extract organic matter or calcium carbonate (see also Bijleveld et al., 2012; Compton et al., 2013). Based on the grain size distribution we derive the clay content (p_{clay}, <4 μm), silt content (p_{silt}, 4–63 μm) and sand content (p_{sand}, >63 μm). Mud is defined as all sediment with a grain size smaller than 63 μm (i.e., silt and clay), such that:

$$p_{clay} + p_{silt} + p_{sand} = p_{mud} + p_{sand} = 1. \quad (1)$$

By analyzing the averaged sediment composition of the (homogenised) upper layer, we ignore the smaller-scale stratigraphy which is largely determined by the short-term dynamics (caused by for instance spring-neap tide variations) which is out of the scope of this research.

In addition, we make use of the suspended sediment concentration (SSC) data collected in the Wadden Sea since 1973 within the long-term monitoring program (MWTL) of the Dutch Ministry of Transport, Public Works and Water Management (Rijkswaterstaat). Measurements have been carried out in over 50 stations on a monthly to bimonthly basis, although currently only 10 station are still actively maintained. Shipboard measurements are performed at 1 m water depth, where water samples are taken and filtered. After drying, the filter is weighed to determine the amount of suspended sediment. This data gives insight in the overall SSC trends in the Dutch Wadden Sea and more specifically in the large-scale variation of the suspended mud concentrations.

2.2. Numerical Models

We use two numerical models to determine how concentrations vary in space and how they are related to the local bed composition. First, we use the depth-averaged hydrodynamic model of the Dutch Wadden Sea developed by

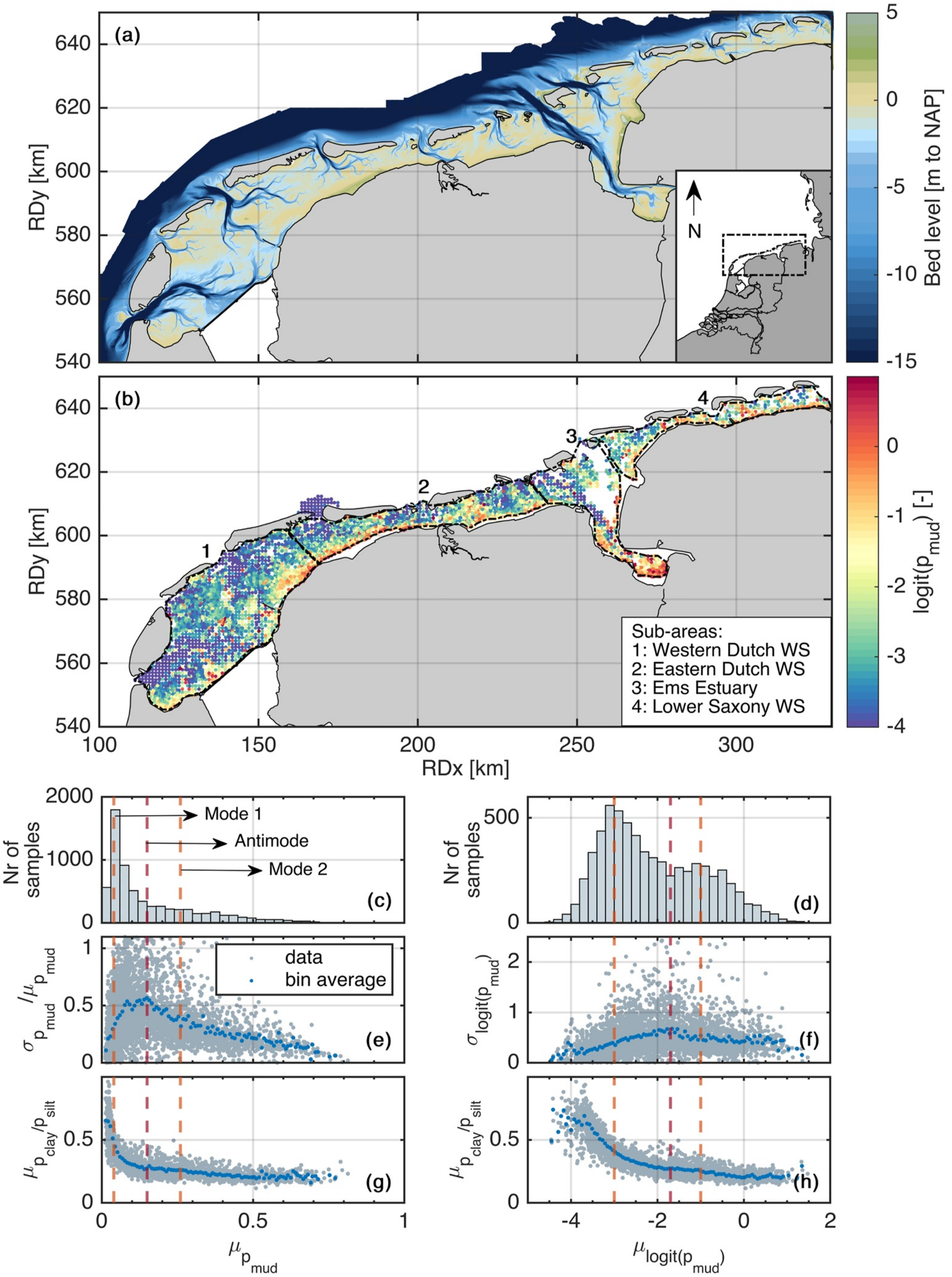

Figure 1. (a) Bathymetry of the Wadden Sea (WS) including the Ems Estuary in m to NAP (Dutch Ordnance Datum). (b) Mean mud content for each location, after logit transformation, over the period 2009–2018. (c–d) Number of samples per mud content (prior to and after logit transformation). (e) Coefficient of variation of the mud content. Standard deviations $(\sigma_{p_{mud}})$ and means $(\mu_{p_{mud}})$ are computed for each sample site (every gray dot represents one site). Bin average values (blue dots) have been calculated for 300 bins. (f) Standard deviation of $logit(p_{\mathrm{mud}})$. (g–h) Dependence of the clay/silt ratio on the mud content.

van Weerdenburg et al. (2021) in Delft3D Flexible Mesh. Near bed sand concentrations during a tidal cycle are calculated using the transport formulations by van Rijn (2007a, 2007b).

In addition, we have set up a generalized, schematized depth-averaged (2DH) Delft3D morphodynamic model (Lesser et al., 2004) of a tidal inlet. The model domain consists of a tidal inlet in between two islands and a back-barrier basin with dimensions of 15 × 10 km and a rectangular computational grid with a mesh size of

100 × 100 m. The initial topography is a gradually sloping bed with a uniform sediment composition ($p_{sand} = 0.95$, $p_{mud} = 0.05$). The model has a stratified bed with an active transport layer of 0.1 m. Below the transport layer, 20 Eulerian sediment layers of 1 m thickness are prescribed. Initially, all bed layers have the same sediment composition. The model is run for a period of 50 years, forced by a semi-diurnal and quarter-diurnal tide with an amplitude of 1.5 m (S2 + S4) prescribed at the northern open boundary (15 km from the inlet), and a wave-climate created by locally generated wind-waves of varying strength and direction. Sand-mud interaction is accounted for using the formulations by van Ledden (2003), in which non-cohesive sediment transport is calculated with Van Rijn transport formulations (van Rijn, 1993), and cohesive sediment transport with the Partheniades-Krone formulations (Partheniades, 1965). Details on the model settings of both models are provided in Supporting Information S1.

3. Field Data Reveal a Bimodal Mud Content

3.1. The Composition of the Sediment Bed Is Strongly Segregated

The overall sediment distribution in the Wadden Sea and Ems Estuary is characterized by a pronounced sand-mud segregation. Sandy channels with a low mud content ($p_{mud} < 10\%$) dominate the central part of the basins (see Figure 1b). The mud content sharply increases to more than 40% on the mudflats bordering the mainland coastlines, in sheltered bays and across the tidal divides behind the islands.

The statistical distribution of the mud content in the Wadden Sea bed is positively skewed with mostly sandy samples (see Figure 1c). Because of this log-normal distribution, we convert the mean mud content p_{mud} using a logit transformation ($logit(p_{mud})$). We use the logit transformation rather than a conventional log transformation ($\log(p_{mud})$), because the range of p_{mud}/p_{sand} can be infinite whereas p_{mud} is bounded between 0 and 1. This transformation is defined as:

$$logit(p_{mud}) = ln(p_{mud} / (1 - p_{mud})) = ln(p_{mud} / p_{sand}) . \quad (2)$$

Logit-transformed mud contents reveal a striking bimodality: most frequent observations occur for either low or high $logit(p_{mud})$, with fewer observations in between (see Figures 1d and 2). This bimodality is not simply the result of large-scale spatial segregation, which would for instance be the case in a system with mainly sandy channels and muddy shoals. This is evidenced by its presence in both the subtidal and the intertidal areas (Figure 2). Especially the mud content in the intertidal areas shows that flats tend to be either sand-dominated or mud-dominated. The Eastern Wadden Sea, the Ems estuary and Lower Saxony have an approximately equal number of sandy and muddy flats, but the intertidal areas in the Western Dutch Wadden Sea are largely sandy. The subtidal areas in the Wadden Sea are mainly sand-dominated but in the Ems Estuary the subtidal areas are as frequently muddy as they are sandy, showing that also channels may be muddy.

The location of the first mode is remarkably stable: all sub-systems show a mode corresponding to approximately 4% mud. In contrast to the first mode, the mud content (value of $logit(p_{mud})$) and frequency of occurrence of more muddy areas (i.e., the second mode) can largely vary per sub-area of the Wadden Sea (as defined in Figure 1b). Comparison with data from the 1990's (Rijkswaterstaat, 1998) reveals that the bimodal distribution of the mud content in the Wadden Sea has remained largely stable over the past decades (see also Colina Alonso et al., 2021). Apparently, the second mode is more sensitive to local conditions compared to the first mode, but does remain fairly constant over time.

3.2. Two Equilibrium States

The intertidal locations in the Dutch Wadden Sea (n = 5,935) are sampled every year, allowing the determination of the variability of $logit(p_{mud})$ using a standard deviation. Beds with a mean mud content close to any of the modes ($\mu_1 \approx -3$, $\mu_2 \approx -1$) are relatively stable in time, reflected in a relatively lower standard deviation (Figures 1e and 1f); the standard deviation of samples with a mean mud content in between the two modes is substantially higher. Apparently, the two frequently occurring modes are fairly constant in time, while sediments with a mud content in between tend to switch to either of the modes. We believe this reflects the stability of the different states, where both modes can be characterized as stable conditions (equilibrium mud contents),

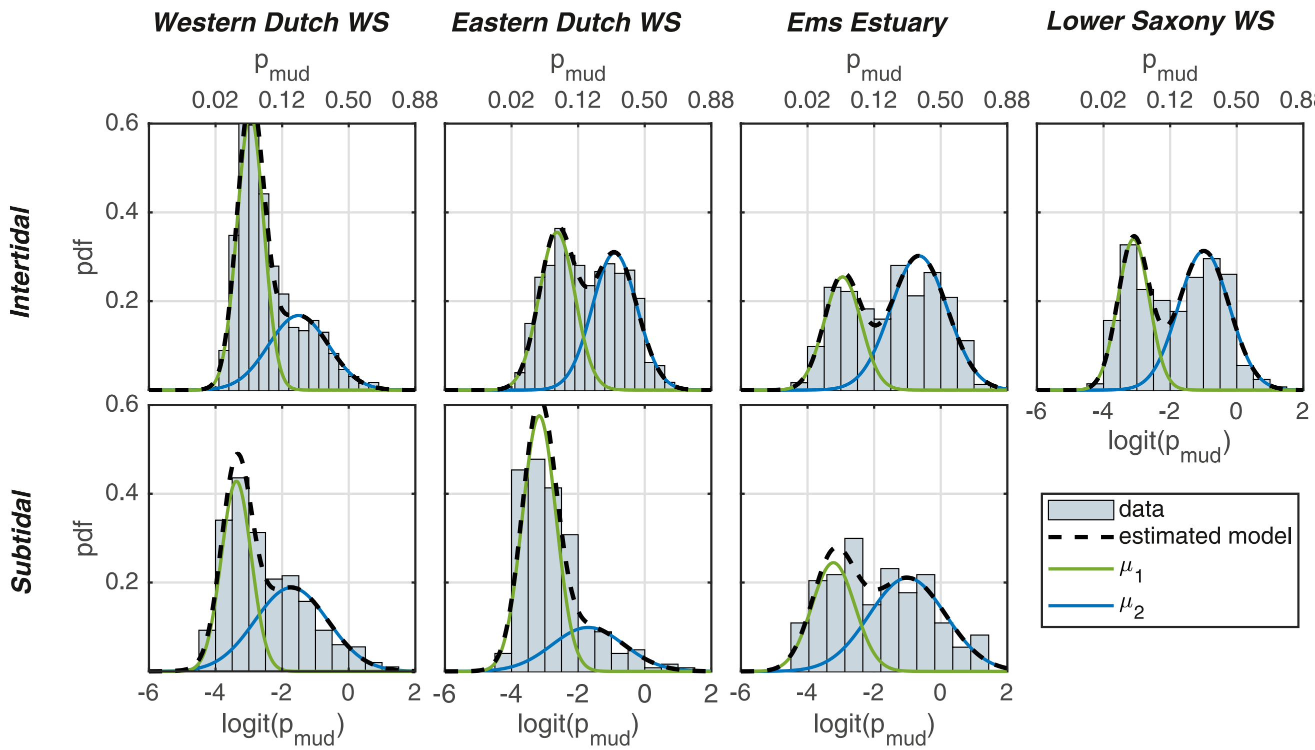

Figure 2. Distribution of the mud content p_{mud} [-] after logit transformation and data-fit for the sub-areas (of which the polygons are defined in Figure 1b). The upper panels show the results for the intertidal areas, the lower panels for the subtidal areas (no subtidal data is available for the German Lower Saxony Wadden Sea). The bin size is based on the number of observations. Distributions are fitted with a Gaussian mixture model using the Expectation Maximization algorithm (Roughan, 2021).

whereas a mud content in between the two modes is unstable. In the next section, we investigate the mechanisms controlling the existence of multiple equilibria.

4. Theoretical Analysis on the Bed Sediment Composition

4.1. Sediment Bed Dynamics

Bed sediments are continuously eroded, transported and deposited, resulting in bed level and bed composition changes. The change of the sediment composition, expressed as the change in mud content, can be described by:

$$\frac{\partial p_{mud}}{\partial t} = \frac{\partial \frac{M}{M+S}}{\partial t} = \frac{S}{(M+S)^2}\frac{\partial M}{\partial t} - \frac{M}{(M+S)^2}\frac{\partial S}{\partial t} \tag{3}$$

in which M is the total mass of mud in the bed and S the total mass of sand. Equilibrium corresponds to $\frac{\partial p_{mud}}{\partial t} = 0$. Since

$$M + S > 0 \tag{4}$$

and

$$\frac{S}{(M+S)} = p_{sand} = 1 - p_{mud} \tag{5}$$

and

$$\frac{M}{(M+S)} = p_{mud}, \tag{6}$$

equilibrium corresponds to:

$$(1 - p_{mud})\frac{\partial M}{\partial t} - p_{mud}\frac{\partial S}{\partial t} = 0. \tag{7}$$

For both mud and sand, the change of mass in time ($\frac{\partial M}{\partial t}$, $\frac{\partial S}{\partial t}$) is given by the sum of the deposition rate (D_{mud}, D_{sand}) and the erosion rate (E_{mud}, E_{sand}). Herein, with deposition and erosion we refer to the gross sediment fluxes, which can occur simultaneously (Winterwerp, 2007), and of which the net result can be either accretion or erosion. Equilibrium is defined by:

$$(1 - p_{mud})(D_{mud} - E_{mud}) - p_{mud}(D_{sand} - E_{sand}) = 0. \tag{8}$$

The deposition of sand and mud can be treated as two independent processes when neglecting flocculation interaction (Manning et al., 2011; Spearman et al., 2011), which we do here for simplicity reasons, and as long as the near bed concentration c_b is less than the gelling concentration (Torfs et al., 1996), which is the case for most tidal systems including the Wadden Sea. However, erosion of sand and mud in the bed is generally coupled and proportional, as elaborated in the next section.

4.2. Interactive Erosion of Sand-Mud Mixtures

Sand-mud mixtures are either non-cohesive or cohesive, depending on the small-scale structure of the bed. In a sand-dominated bed (non-cohesive), the internal structure is determined by the inter-particle locking of sand grains. For a high mud content, sand grains lose contact and sand particles become part of a (cohesive) mud matrix (Jacobs et al., 2011; Torfs, 1995; van Ledden et al., 2004).

The erosion behavior of sand-mud mixtures has been topic of several experimental studies (e.g., Jacobs, 2011; Mitchener & Torfs, 1996; van Rijn, 2020) and parameterized in erosion models (e.g., Le Hir et al., 2011; van Ledden, 2003). This earlier work reveals that for non-cohesive mixtures, erosion of both sand and mud depends on the erosion properties of sand, as sand determines the skeleton structure. In the cohesive regime, erosion of sand and mud is determined by the erosion properties of mud. Consequently, the gross erosion fluxes of sand and mud are proportionally coupled (Chen et al., 2021; Jacobs et al., 2011; Le Hir et al., 2011; Mitchener & Torfs, 1996; van Ledden et al., 2004; Winterwerp & van Kesteren, 2004). Therefore we can express erosion of mud as follows:

$$E_{mud} = E_{sand}\frac{p_{mud}}{(1 - p_{mud})}. \tag{9}$$

This equation reveals that erosion of sand and mud is coupled following a ratio governed by p_{mud}, which strikingly implies that p_{mud} remains constant. Erosion does therefore not lead to a change in mud content $\frac{\partial p_{mud}}{\partial t}$. Field observations in which higher bed shear stresses lead to coarsening of the bed are therefore not the result of preferential erosion of mud relative to sand, but reflect a reduction in the deposition of the mud particles relative to sand particles after erosion. The equilibrium mud content (Equation 8) is therefore redefined as:

$$(1 - p_{mud})D_{mud} - p_{mud}D_{sand} = 0. \tag{10}$$

4.3. Deposition of Sand-Mud Mixtures

The sediment deposition rate can be approximated as the product of the near-bed settling velocity ($w_{s,b}$) and the near-bed SSC (c_b). In general, the settling velocity of sand is at least an order of magnitude larger than that of mud. Local sand concentrations mostly depend on the local hydrodynamic conditions, whereas local mud concentrations are often supply limited and (because of the small settling velocity) determined by conditions elsewhere or by the hydrodynamic history (Colosimo et al., 2020; Pearson et al., 2021). This typically results in high sand concentrations in the channels and low sand concentrations over the flats, while the suspended mud concentration is more uniformly distributed over the channels and the flats. We can simplify this to an overall constant mud concentration, regardless of the local mud content in the bed, whereas sand concentrations in the water column would decrease with increasing mud content in the bed. This is supported by the findings of Colosimo et al. (2020) and Pearson et al. (2021), combined with the fact that muddy beds mainly prevail in calm

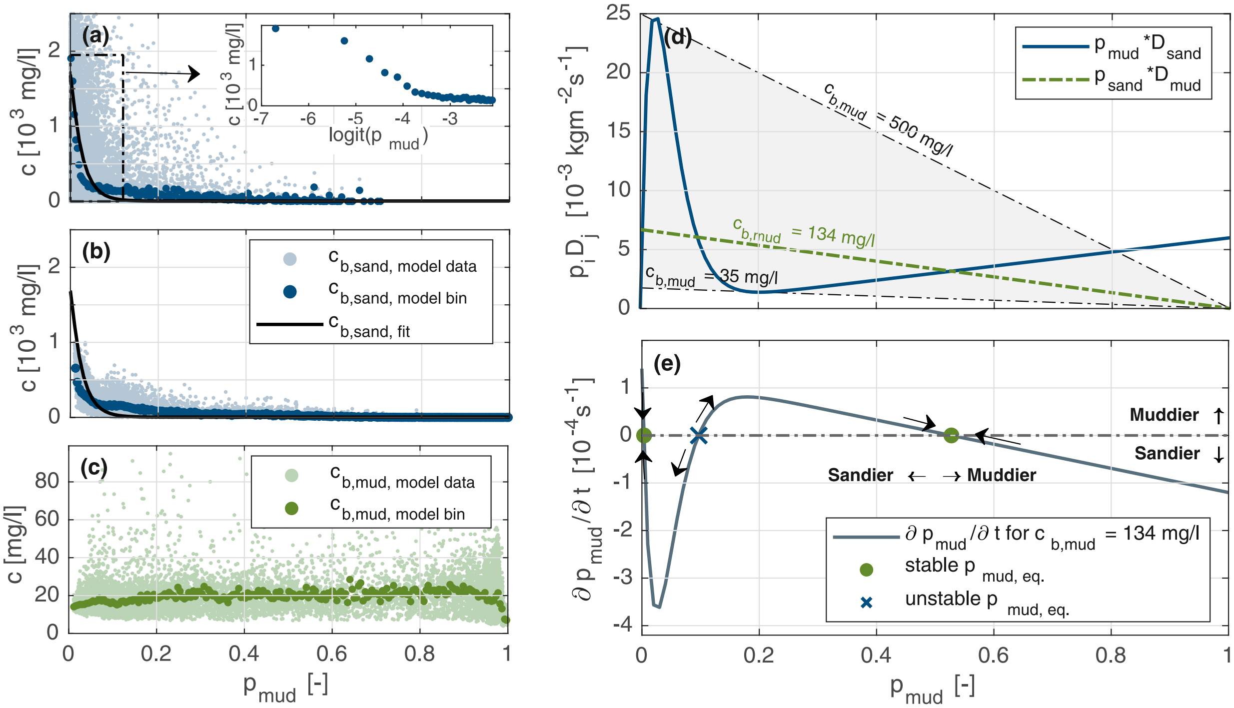

Figure 3. Suspended sediment concentrations, deposition fluxes and corresponding equilibrium sediment composition. (a) Relation between p_{mud} in the bed (derived from SIBES data) and the tide averaged $c_{b,\mathrm{sand}}$ in the Wadden Sea (calculated with a numerical model, see (b) for legend). (b–c) Relation between p_{mud}, $c_{b,\mathrm{sand}}$, and $c_{b,\mathrm{mud}}$, derived from a schematized model. (d) Product of the deposition fluxes (fits based on model data) and the local sediment composition (Equation 10). Multiple equilibria are possible for 35 mg/l < $c_{b,\mathrm{mud}}$ < 500 mg/l. (e) $\frac{\partial p_{mud}}{\partial t}$ for $c_{b,\mathrm{mud}}$ = 134 mg/l and the theoretical fit of c_{sand}, and corresponding equilibria of p_{mud} at $\frac{\partial p_{mud}}{\partial t} = 0$.

environments. In the next section we test this simplification of the deposition fluxes, for the Wadden Sea and for tidal basins in general, and we explore its relevance for the observed bimodality of p_{mud} in the sediment bed.

5. Analysis of Sand-Mud Deposition Fluxes

5.1. Dependency of the Deposition Fluxes on the Local Conditions

We illustrate the spatial variability of $c_{b,\mathrm{sand}}$ and $c_{b,\mathrm{mud}}$ with two numerical models (one model of the Wadden Sea and one model of a generalized tidal basin) in combination with field data (see also Section 2). The Wadden Sea model (van Weerdenburg et al., 2021) is used to calculate tide-averaged near-bed sand concentrations. These are compared to the observed mud content in the bed, derived from SIBES data. Figure 3a shows that $c_{b,\mathrm{sand}}$ indeed sharply decreases for increasing p_{mud}. However at very small p_{mud} values, $c_{b,\mathrm{sand}}$ seems to reach a maximum, revealing a sigmoidal type of relation rather than a purely inverse one. This is especially clear after logit transformation (see the inset plot in Figure 3a). The results of the schematized model, in which both $c_{b,\mathrm{sand}}$ and p_{mud} are computed, show a very similar relation (Figure 3b, see bin-averaged values for a comparison with Figure 3a). In both models sand concentrations are very low for high mud contents, but still exceed 0. For both the model and the data, the sigmoidal relation between $c_{b,\mathrm{sand}}$ and p_{mud} can be described with the same sigmoid fit. Our model data shows slight deviations from a purely sigmoidal character around $0.1 < p_{\mathrm{mud}} < 0.15$, but we believe this may originate from model artifacts rather than having a physical cause.

The schematized model also gives insight into the tide-averaged mud concentrations: these are more or less constant, regardless of the local sediment composition (Figure 3c). But although $c_{b,\mathrm{mud}}$ does not depend on local p_{mud}, long-term SSC observations in the Dutch Wadden Sea reveal that there is considerable variation over larger spatial scales (see Figure S5 of Supporting Information S1). Concentrations are generally lower in the western part and higher in the eastern part and the Ems Estuary, and are around 67 mg/l on average. Since SSC is herein measured close to the water surface in relatively deep areas (depth >5 m), the observed suspended sediment is assumed to be mainly mud. The near-bed mud concentrations are assumed to be a factor 2–3 higher, following a

Rouse profile (see e.g., van Maren et al., 2020). The observations in the Wadden Sea illustrate that the concentrations computed with the schematized model (Figure 3c) reasonably represent the mud concentrations in the western part of the Wadden Sea.

As shown above, a local dependency exists between D_{sand} and p_{mud}. In order to determine the spatial scale associated with D_{sand} we calculate a transport length scale as:

$$L = \frac{hu}{w_s}, \tag{11}$$

in which h is the depth, u the depth-averaged velocity and w_s the settling velocity of the corresponding sediment type. This length scale is compared against the variogram of p_{mud}, representing the inter-dependency of the observed mud content as a function of distance (for details, see Supporting Information S1). The distance at which the sediment data are no longer spatially correlated is 5,464 m. This value is much larger than the 95 percentile transport length scales of coarse and fine sand (which are in the order of 400 and 1,400 m, respectively), showing that transport of sand is determined by local conditions. This validates the assumption of correlation between local D_{sand} and p_{mud}. The transport length scale of mud is an order of magnitude larger. This confirms our findings in Figure 3 that sand concentrations largely depend on local hydrogeomorphic conditions (explaining the correlation between D_{sand} and p_{sand}), while local mud concentrations are much more affected by conditions elsewhere and/or earlier (since mud can be transported over much larger distances).

5.2. Equilibrium Mud Contents

The theoretical fits of $c_{b,\mathrm{sand}}$ (sigmoid) and $c_{b,\mathrm{mud}}$ (constant, using 134 mg/l) to p_{mud} are subsequently used to calculate $p_{\mathrm{mud}} \times D_{\mathrm{sand}}$ and $p_{\mathrm{sand}} \times D_{\mathrm{mud}}$ (Equation 10, Figure 3d) and the resulting temporal change in p_{mud} (Figure 3e). Figure 3e reveals three equilibrium conditions in the Wadden Sea, of which two are stable and one is unstable. Stable equilibrium conditions are characterized by convergence: an increase in p_{mud} leads to a negative $\frac{\partial p_{mud}}{\partial t}$ while a decrease in p_{mud} results in a positive $\frac{\partial p_{mud}}{\partial t}$. Unstable conditions prevail in-between, in agreement with our theory but also suggested by the large standard deviation of the mud content for conditions in-between the bimodal peaks (Figures 1e and 1f). We believe that the bimodality in the bed sediment of the Wadden Sea is the result of these stable equilibrium conditions. Our analysis then suggests that bimodality is expected for many $c_{b,\mathrm{mud}}$ conditions (tide averaged values of 35–500 mg/l), which is a much wider range than the conditions observed in the Wadden Sea.

The first equilibrium condition is in all cases located near $p_{\mathrm{mud}} \approx 0$, showing that this condition is not sensitive to the suspended sediment concentrations. Note that in reality we observe a mode at slightly higher values of $p_{\mathrm{mud}} \approx 0.04$ (see Figure 2). We believe this results from mud-burial mechanisms such as the trapping of mud in local bedforms and bioturbation, which are beyond the scope of our analysis (Kristensen et al., 2012; Le Hir et al., 2007; Terwindt & Breusers, 1972). In contrast, the location of the second stable equilibrium condition is sensitive to the suspended sediment concentrations.

For an increasing mud concentration $c_{b,\mathrm{mud}}$, the second stable equilibrium shifts to higher values of $p_{\mathrm{mud},eq.}$. This corresponds well with our data, where $c_{b,\mathrm{mud}}$ increases in the eastern direction (Western Dutch Wadden Sea to Eastern Dutch Wadden Sea to Ems Estuary) while the second mode of the bimodal distribution shifts to the right (Figure 2). A second factor influencing the location of the second equilibrium is the sand concentration above muddy beds. The higher $c_{b,\mathrm{sand}}$ at high p_{mud} (Figure 3a), the lower the value of the second stable $p_{\mathrm{mud},eq.}$ in Figure 3e. Sand transport rates over muddy beds will differ per system because it is probably mostly influenced by sand characteristics (D_{50}) and storm conditions. During storms sand may be transported to low-energy (muddy) locations, so the second bimodality peak is expected at lower p_{mud} values when the muddy areas are close to energetic sandy shorelines.

Our analysis explains the occurrence of bimodality, but also spatial trends in bimodality for a range of sedimentary conditions in the Wadden Sea. In this environment the time and spatially average SSC varies (from East to West) by a factor of ∼2. Therefore we strongly encourage to expand this analysis to field conditions covering a wider range in SSC (both more and less turbid environments).

5.3. Criteria for Bimodality

Based on our findings, we can define three general criteria for the suspended sediment concentrations with respect to p_{mud}, in order to have two stable equilibria, and thus a bimodal mud content in the bed:

1. $c_{b,\mathrm{mud}} > 0$ at $p_{\mathrm{mud}} = 0$: mud is always available for deposition, also in fully sandy environments.
2. $c_{b,\mathrm{sand}} > 0$ at $p_{\mathrm{mud}} = 1$: sand is always available for deposition, also in fully muddy environments. This likely suggests transport of fine sand, since hydrodynamic conditions here are mostly not sufficiently energetic to transport coarse sediments.
3. The lines $p_{\mathrm{mud}} \times D_{\mathrm{sand}}$ and $(1 - p_{\mathrm{mud}}) \times D_{\mathrm{mud}}$ should cross three times: two crossings will define the stable equilibria and one crossing in between will define the unstable equilibrium. This gives requirements for the character of the relations between $c_{b,\mathrm{sand}}$ and p_{mud} (in our case sigmoid), $c_{b,\mathrm{mud}}$ and p_{mud} (in our case constant) and for the magnitude of $c_{b,\mathrm{mud}}$. The latter should be within a range in which three crossings are possible.

6. Conclusion

Bed sediments in estuaries and tidal basins are often a mixture of sand and mud. The sediment composition is a key component influencing morphological evolution, hydrodynamics, biological activity and habitat suitability. Consequently, understanding the distribution of sand and mud in tidal basins is important for sustainable management. Analysis of bed sediments in the Wadden Sea has revealed that the mud content is bimodally distributed, with sediment mixtures being either sand-dominated or mud-dominated. Beds with a mean mud content close to one of the modes are relatively stable in time, whereas those with a mean mud content in between are more variable in time. This suggests that the system is bistable with an unstable state between the two stable equilibrium conditions.

Using numerical models and field data, we have shown that the existence of multiple equilibrium conditions can be explained theoretically with the gross sediment deposition flux. Since in most cases gross sand and mud erosion fluxes are interdependent (erodibility interaction), the equilibrium mud contents depend primarily on the sediment deposition fluxes. The deposition fluxes are the product of the near-bed SSC and the settling velocity. Model simulations show that suspended concentrations of mud only weakly depend on the local bed composition, whereas we observe a sigmoidal relation between the concentrations of sand and the local mud content in the sediment bed. Herein, sand concentrations rapidly decrease with increasing mud content, but never become zero.

The difference in the suspended sand and mud concentration leads to multiple equilibria in bed composition—of which two are stable and one is unstable—for a wide range of conditions. This explains why bimodality is observed in the entire Wadden Sea system, even though average suspended sediment concentrations may largely differ per sub-system. The value of the first equilibrium (sandy mode) is relatively robust and stable, whereas the second equilibrium (muddy mode) may largely vary depending on the local mud concentrations and the mobility of sand in muddy areas. Our analysis shows that bistability is a generic phenomenon, so it can be expected in other systems as well. We advocate to study this for other systems worldwide in which sufficient bed sediment data is available to determine a representative statistical distribution of the sediment composition.

Our conclusion that sand-mud segregation results from deposition processes has implications for the understanding of sediment transport processes and modeling of coastal evolution. Predicting the sediment composition in the bed not only requires accounting for sand-mud erodibility interaction, but also a realistic spatial distribution of SSC (and hence the deposition flux). Our findings advance on our understanding of the distribution of sand and mud in tidal basins, and we recommend further analysis of these interaction processes using numerical morphological models.

Data Availability Statement

Bathymetry data of the Dutch Wadden Sea and the Ems Estuary are available at: https://svn.oss.deltares.nl/repos/openearthrawdata/trunk/rijkswaterstaat/vaklodingen/. For access, first register at: http://oss.deltares.nl/. Bathymetry data of the German Wadden Sea are available at: https://doi.org/10.48437/02.2020.K2.7000.0002. Bed composition data, suspended sediment data and input files of the numerical simulations are available at the 4TU.ResearchData repository: https://doi.org/10.4121/19519861.

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