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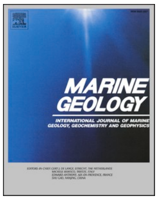

The contribution of sand and mud to infilling of tidal basins in response to a closure dam

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ABSTRACT

Human interventions and climate change can heavily influence the large-scale morphological development of tidal basins. This has implications on sediment management strategies, as well as ecological and recreational purposes. Examples of heavily impacted tidal basins are those in the Western Dutch Wadden Sea. The closure of a large sub-basin in 1932 triggered a shift in the sediment budgets of the remaining basins, leading to sediment infilling that is still ongoing. This paper presents a quantitative analysis of the post-closure sediment volumes, differentiating between sand and mud. Analysis of historical sediment composition data combined with bathymetry data revealed that the intervention caused a redistribution of sand and mud sedimentation. The responses of both sediment types differ spatially and temporally. The total infilling of the basins over the last century was substantially caused by mud (~32%, which is much larger than the average mud content in the bed). Initially, large mud volumes accreted in abandoned channels. At present, mud sedimentation along the mainland coast is still ongoing with nearly constant sedimentation rates over the past century, while the net import of sand significantly decreased over time and has been fluctuating around 0 over the last two decades. This research shows the importance of distinguishing between the response of sandy and muddy sediments when analysing the morphodynamic impact of an intervention, since they operate on different time and spatial scales. Sea level rise is currently a major threat for the existence of the Wadden Sea; its future fate will depend on whether the tidal flats are able to keep pace. Our results show that the supply of mud is sufficient to keep pace with the current sea level rise rates.

1. Introduction

Coastal wetlands and tidal basins are unique ecosystems providing nature, navigation, recreation and flood safety services (Barbier et al., 2011). At present, many tidal basins are under pressure by climate change and increasing human activities, threatening their ecological value and role in protecting the hinterland (e.g., Yang et al., 2011; Syvitski et al., 2005; Wang et al., 2012; de Vriend et al., 2011; Wang et al., 2015; Monge-Ganuzas et al., 2013). While climate change is mostly a slow and continuous process (such as the gradual rise in sea level), anthropogenic interventions have caused many abrupt system transitions worldwide, some of which irreversibly influence the morphological development and the large-scale sediment budgets of tidal basins. Examples of such interventions are closures, land reclamations and coastal protection structures. Preservation of the multiple purposes of coastal wetlands and tidal basins requires thorough understanding of the morphodynamic impact of human interventions. An indicator reflecting the dynamics of tidal basins, and the impact of human interventions, is its sediment composition.

The sediment composition of the bed is an important characteristic of tidal environments: it governs sediment mobility, hence sediment transport and morphological evolution (Geleynse et al., 2011). In addition, the substrate influences its suitability for local biological activity, which in turn also influences bed level morphodynamics. Bed sediments in most tidal basins are a mix of sand (non-cohesive) and mud (cohesive). Sand and mud are typically differentially deposited and preserved in the bed stratigraphy, but their deposition also varies horizontally, which is usually referred to as *sand-mud segregation* (van

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Ledden, 2003). Sand-mud segregation is influenced by local hydrodynamics and sediment supply, but also by the interaction of sand and mud, greatly influencing sediment dynamics (Jacobs, 2011; van Ledden, 2003; Winterwerp and van Kesteren, 2004).

The Western Dutch Wadden Sea provides examples of tidal basins that have been heavily impacted by anthropogenic changes. The partial closure of the South Sea (*Zuiderzee*) in 1932 still influences the morphodynamics of the Wadden Sea basins (Elias et al., 2003; Elias et al., 2012; Wang et al., 2018), including the overall sediment budget. Previous studies on the sediment budget of the Wadden Sea did not differentiate between sand and mud fractions. However, understanding the contribution of both sediment types to the morphologic evolution is crucial for unravelling the processes responsible for the observed bathymetric changes. This is especially relevant if we want to predict future change, under the influence of climate change or local human interventions.

Previous studies elsewhere have demonstrated that the (partial) closure of tidal basins can result in large accumulation of fines (i.e., mud). Elias et al. (2016) showed that the closure of an estuary in the Dutch Southwest Delta, in combination with an extension of the nearby Port of Rotterdam, created a sheltered environment transforming a predominately sandy coast (van Alphen, 1990; Hendriks et al., 2020; Piekhaar and Kort, 1983) into a muddy area. Williams et al. (2014) showed that construction of the Yeongsan Estuarine Dam (Korea) resulted in local distinctive scouring and a dramatic increase of sedimentation rates in the Yeongsan Estuary by at least an order of magnitude over average Holocene sedimentation rates. Construction of the Noksan Dam in the Nakdong Estuary (also South Korea) significantly reduced flow velocities and caused a severe depletion of coarse grained sediment in the West Nakdong River, resulting in the accumulation of fine-grained sediments advected from the estuary and offshore (Williams et al., 2013). These examples show the impacts of a dam on estuary sedimentation and shifts in sediment composition, but a quantitative analysis of the post-closure sediment budgets in all these estuaries is still lacking.

The objective of this study is to better understand the contribution of sand and mud to the morphodynamic evolution of tidal basins in response to human interventions. The tidal basins of the Western Dutch Wadden Sea provide an ideal case study for this purpose, because of the long and well documented response period following the 1932 closure of the South Sea. Unique long-term datasets of bathymetry and bed sediment composition provide detailed information on the response of sand and mud over the past century. We use this information to understand the effect of human interventions on sand- and mud transport and how this affects morphological response timescales and sediment budgets.

The structure of this paper is as follows: In Section 2 we present the general setting of the Western Dutch Wadden Sea, its historical morphodynamic evolution and the current conditions. Subsequently, we present our bathymetric and sediment composition datasets in Section 3, and we introduce our method for the sediment volume analysis of the basins. In Section 4, we first analyse the long-term evolution of the bed composition, after which we combine this evolution with the bed level changes to derive the sediment volume changes of sand and mud. In addition, we present a sensitivity analysis to test the assumptions of the method. The implications of our findings for a general understanding of sand- and mud responses to human interventions are discussed in Section 5. Concluding remarks are summarised in Section 6.

2. Study area

2.1. General setting

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 and Winter, 2019; Elias et al., 2012; Pedersen and Bartholdy, 2006). The tidal basins of the Wadden Sea - which are separated from the North Sea by barrier islands - contain extensive systems of branching channels, sand- and mudflats and salt marshes. These provide important habitats for numerous species of fish, mammals and birds. Therefore, in 2009 the Wadden Sea became a UNESCO world heritage site, requiring preservation of its characteristics.

Sea level rise (SLR) has been a primary driver in the formation of the current Wadden Sea morphology. In the early Holocene, the sea level was many 10's of meters below the current level and the Wadden Sea did not yet exist. However, the subsequent rapid rise of the sea level (Beets and van der Spek, 2000; Zagwijn, 1986), in combination with land subsidence, caused a gradual expansion of the North Sea. Consecutive cycles of marine ingression and subsequent basin sedimentation, and sufficient sediment supply to retain or prograde the coastline, filled in the entire western part of the Dutch coastal plain. The sediment supply along the Wadden Sea was sufficient to retain the extensive systems of tidal flats and salt marshes over the past 7000 years, but insufficient to fill in the basin completely (Wang et al., 2018).

Human interventions have been influencing the evolution of the system since the Middle Ages, partly fixing the basin dimensions with dike constructions, land reclamation, peat excavations and salt marsh accretion works. Later, the closures of the Middel Sea (*Middelzee*, 1600), the South Sea (*Zuiderzee*, 1932) and the Lauwers Sea (*Lauwerszee*, 1969) largely impacted the morphological evolution of the Wadden Sea (Elias et al., 2012; Oost, 1995; van der Spek, 1995).

2.2. Morphodynamic evolution of the Western Dutch Wadden Sea

In this study we focus on the Western part of the Dutch Wadden Sea, consisting of the inlets: Texel inlet, Eijerlandse Gat inlet and Vlie inlet. Fig. 1 provides an overview of the morphology before closure of the South Sea and and the present-day situation. This closure was motivated by a large flood in 1916 and the famine in 1918, which led to the construction of the 30 km closure dam 'Afsluitdijk' to protect the land along the former South Sea against flooding and to create a fresh water lake and new polders with agricultural land. This resulted in a considerable reduction of the total basin area (from 4000 km^2 to 712 km^2) and of the basin length (from 130 km to 30 km) (Elias et al., 2003). The tidal range, however, increased nearly instantaneously with approximately 15% at Den Helder and almost 100% in front of the closure dam at Den Oever, leading to a 20% increase of the tidal prism.

The disturbance of morphological equilibrium led to morphological changes inside and outside the tidal basins. Large infilling rates have been observed in disconnected channels and along the basin shoreline, while ebb tidal deltas and adjacent coastlines eroded (Fig. 1). Elias et al. (2012) show that the sedimentation of the basins has been primarily a response to the closure of the South Sea and not an adaptation to SLR. See Schoorl (1973; 1999; 2000a; 2000b; 2000c) and Elias and Van Der Spek (2006) for more detailed historical reconstructions of the morphodynamic evolution of the Wadden Sea.

2.3. Prevailing conditions

The Wadden Sea is a mixed energy environment (Davis and Hayes, 1984), influenced by tides and waves. The tidal range at Den Helder (Texel inlet) is 1.4 m and increases in eastward direction. Offshore, the mean significant wave height is 1.3 m, with a corresponding mean wave period of 5 s and a WSW direction (Elias et al., 2012; Wijnberg, 1995). During storms, wind-waves can reach heights of over 6 m, accompanied by surges of over 2 m. Fresh water supply by rivers is limited, and dominated by discharges from Lake IJsselmeer (former South Sea) through drainage sluices in the closure dam (yearly average discharges of 450 m^3/s).

The basins have relatively large channels and small intertidal areas, with a channel/shoal ratio of 0.3 and 0.4 at the basins of Texel and Vlie inlet (Oost, 1995). Many Wadden Sea basins are separated by tidal

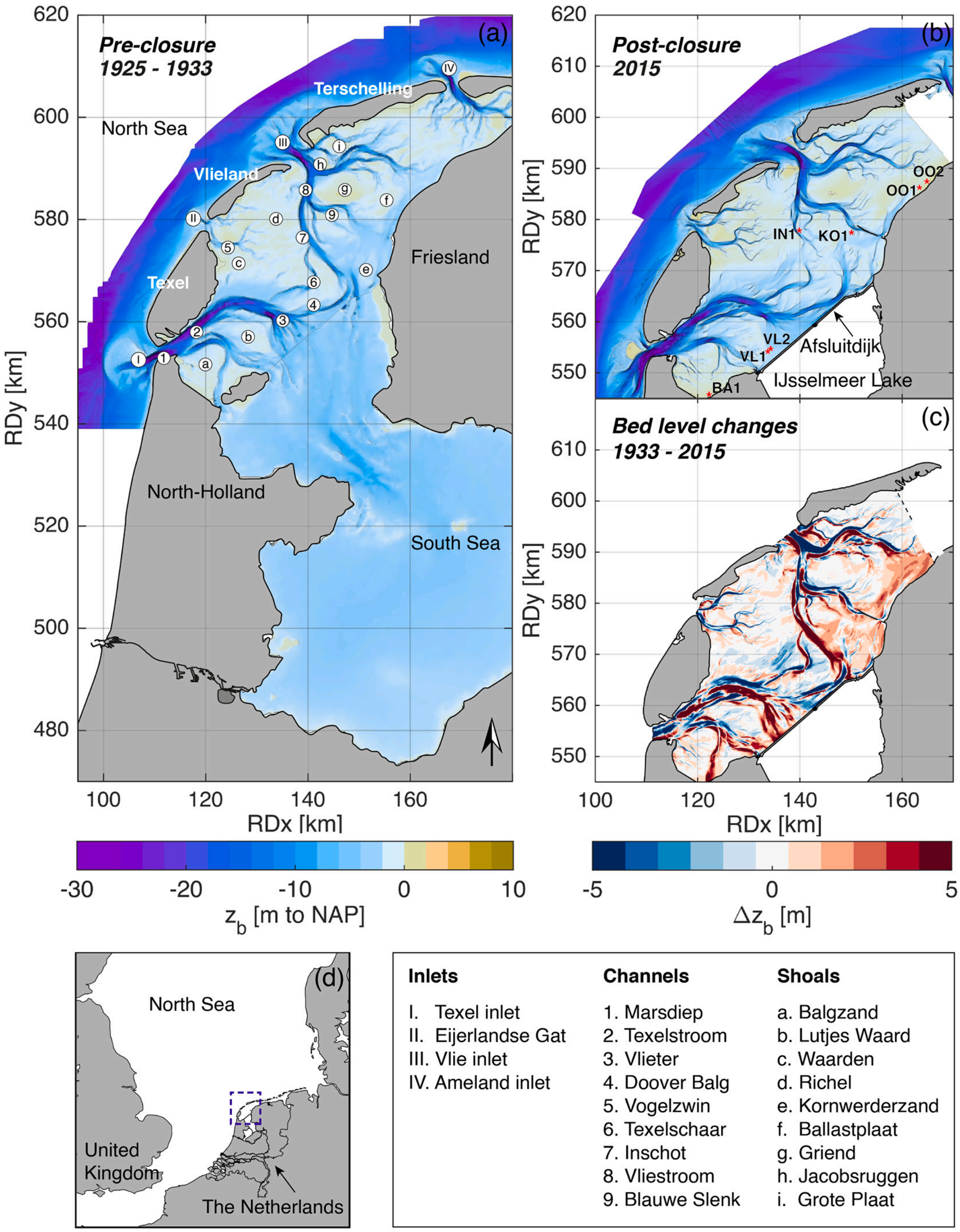

Fig. 1. Location map of (a) the Western Dutch Wadden Sea, pre-closure and (b) post closure, Panel (c) shows the total bed level changes and panel (d) shows the location of the Wadden Sea. The names of the main inlets, channels and shoal are indicated in panel (a). In panel (b) we also show the locations of sediment cores (red) analysed in Fig. 8. Bed levels are shown in meters relative to NAP (the Dutch Ordnance Level, equivalent to MSL). (For interpretation of the references to colour in this figure legend, the reader is referred to the web version of this article.)

divides minimising the flow and sediment exchange between the basins. However, an important characteristic of the present-day Western Wadden Sea is that Texel and Vlie basins are not solitary closed systems, but share a connection on their landward side, allowing exchange between the two basins (Duran-Matute et al., 2014; Duran-Matute et al., 2016; Elias and Van Der Spek, 2006; Ridderinkhof, 1988).

3. Methods

3.1. Datasets

3.1.1. Bathymetry

The bathymetry of the Western Dutch Wadden Sea has been monitored for over 400 years for nautical reasons (because of the presence of shipping lanes and harbours), with nautical maps dating back to the 16th century that indicate the main morphological features. Since 1925, the bathymetry has been monitored consistently and regularly, with a resolution and accuracy progressively increasing in time, by the Navy (Hydrografische Dienst) and the Dutch Ministry of Transport, Public Works and Water Management (the so-called *Vaklodingen* data). This data includes Wadden Sea bathymetry, currently measured on a six-year interval using single-beam echo sounders. Until 1987, the data was published as analogue maps, which were later digitised in 250 × 250 m resolution. More detailed measurements after 1987 have been interpolated to a 20 × 20 m grid (see De Kruif (2001) for a detailed overview of the Vaklodingen dataset).

The accuracy of the Vaklodingen data has been estimated to range between 0.11 m and 0.40 m (Perluka et al., 2006; Wiegmann et al., 2005). According to Marijs and Parée (2004), the total error of the data originates from three sources: stochastic errors due to individual data outliers, systematic errors introduced by the measuring instruments and variable systematic errors consisting of user errors in measuring and handling the data. To enable reliable estimates of sedimentation-erosion trends and volume budgets, we have inspected the data in detail manually. Maps showing unrealistic trends have been excluded from the analysis.

3.1.2. Bed sediments

We analyse the long-term evolution of the bed sediment composition (measured in summer) using four datasets that span over 125 years (Fig. 2). The first synoptic map of the bed composition in the Wadden Sea was produced by Lely (1892), as part of impact studies for the closure of the South Sea and other potential land reclamations. Extensive measurement campaigns were set-up in the summers of 1889 and

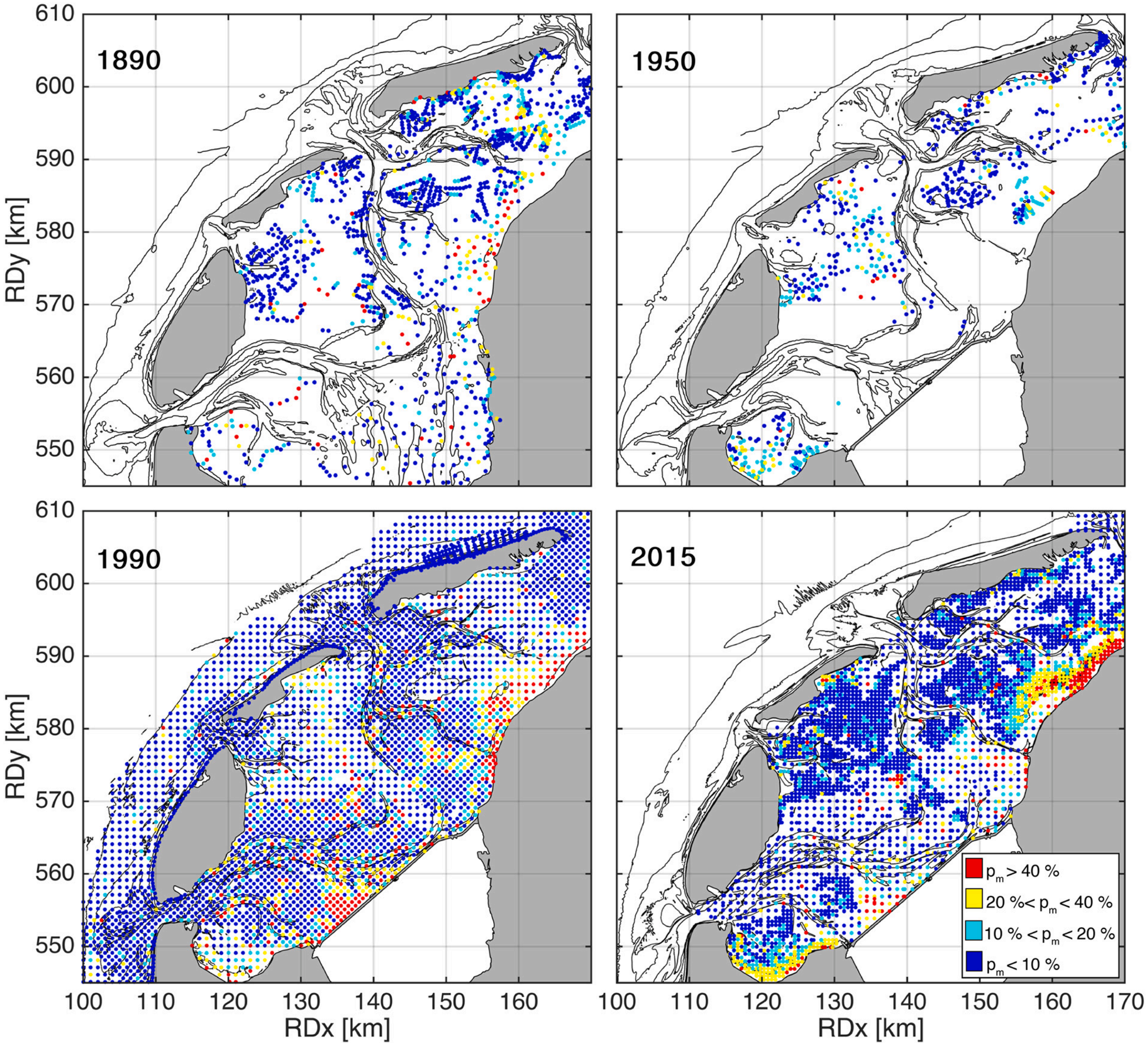

Fig. 2. Bed sediment composition of the upper layer plotted against the depth contours of the Western Wadden Sea. The colored dots indicate the mud content p_m in percentages, based on Lely's classification.

1890, in which cores were taken up to one meter depth in subtidal and intertidal zones of the Wadden Sea basins and the former South Sea. After removing organic matter and calcium carbonate, the grain size was determined and the samples were classified based on the sand content (4 sediment classes). We digitised the resulting map making use of ArcGIS Software.

In the 1950's, about 2500 cores were taken at 0–25 cm depth, as part of an effort to better understand the mud dynamics in the Wadden Sea (de Glopper, 1967). Again, samples were treated to extract organic matter and calcium carbonate (Hofstee, 1980) prior to gravimetric analysis. This work was later digitized (Zwarts, 2004).

Between 1989 and 1996, sediment samples were taken of the top layer of the sediment (up to 10 cm depth), with measurements at 500–1000 m distance covering the whole Dutch Wadden Sea, as well as the ebb-tidal deltas and the coastal zone along the North Sea side of the barrier islands. These samples were analysed with a Malvern Laser Particle Size Analyser (without prior treatment) and complete grain size curves were stored in the publicly available *Sediment Atlas Wadden Sea* (Rijkswaterstaat, 1998).

The most recent and detailed set is the Synoptic Intertidal Benthic Survey (*SIBES*) dataset, which contains samples from approximately 4500 sites, taken at 500–1000 m intervals every year since 2008. The samples are analysed with a Coulter LS 13 320 (optical module 'grey', grain sizes from 0.04 to 2000 μm in 126 size classes), without prior treatment to extract organic matter and calcium carbonate. A detailed description of the measuring campaign and the sediment analysis method is given by Bijleveld et al. (2012) and Compton et al. (2013).

The data of the sediment composition is interpolated to the grid of the Vaklodingen bathymetric data using the Natural Neighbor Interpolation method by MATLAB. We have performed tests with other interpolation methods (Linear and Nearest Neighbor interpolation), resulting in negligible differences between the results ($\leq$2%). Note that the interpolation method becomes more important for small-scale analysis (morphological features with dimensions smaller than 1000 m), or for a similar analysis with a less detailed dataset. In that case, a Co-Kriging approach correlating the sediment composition to the bed level is probably a better alternative (Leecaster, 2003; Meiliand et al., 2011; Park and Jang, 2014).

The Geological Survey of the Netherlands (TNO-NITG) provides borehole data (several meters deep) which is stored in the database *DINO* and is publicly available. We make use of the their lithostratigraphic data containing classified borehole information.

3.2. Sediment volume analysis

We separate the contributions of sand and mud to volume changes in

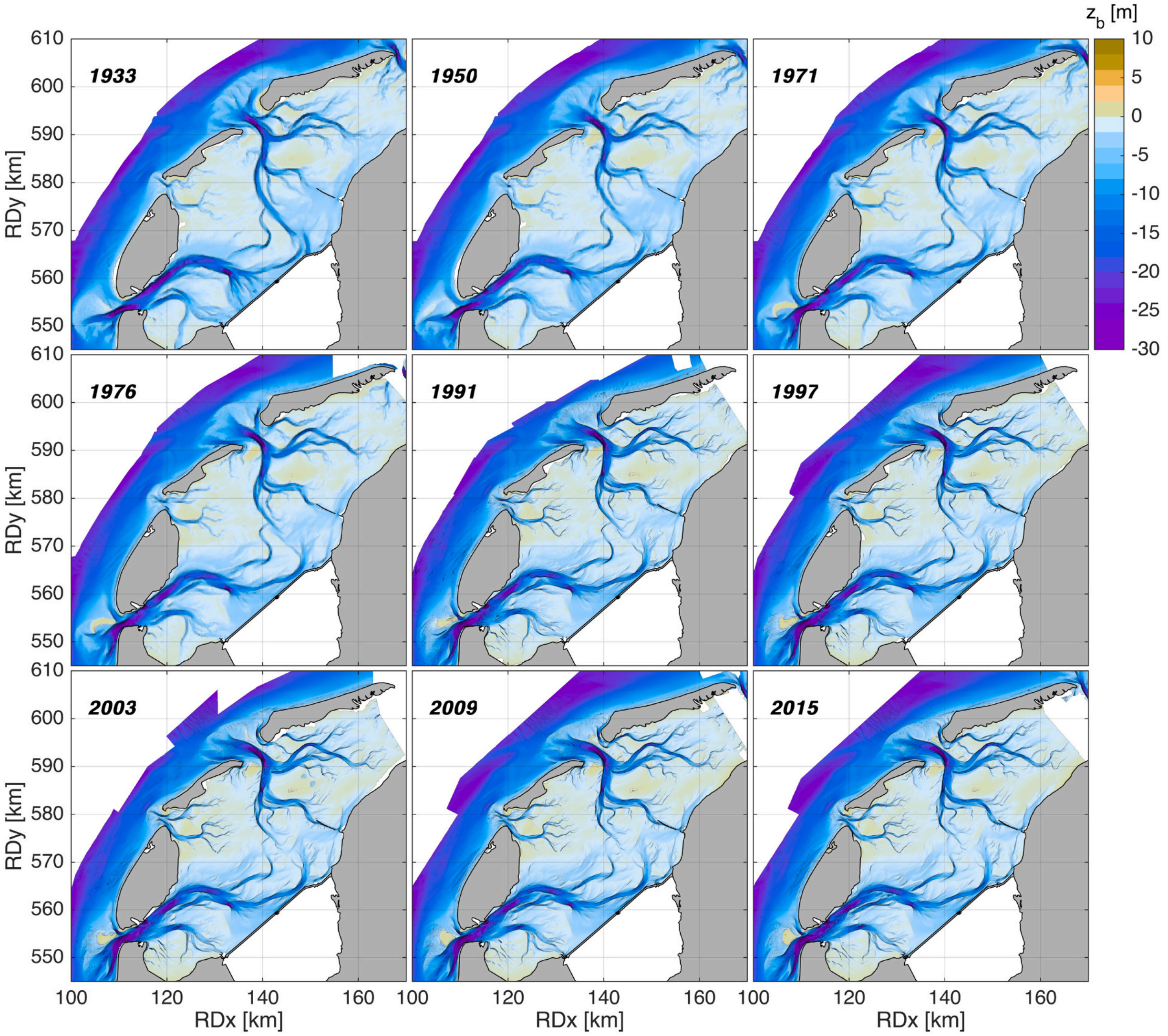

Fig. 3. Overview of available bathymetric charts of the Western Wadden Sea used in this paper. Bed levels are shown in meters relative to NAP (the Dutch Ordnance Level, equivalent to MSL).

Table 1
Overview of the assumptions included in the volume balance. The assumptions included in the *best guess* are marked in bold. The grey options are used to determine the sensitivity of the results.

Bed sediment data	Dry density formulation	Correction V_{mud}<15%
Sediment Atlas	**van Rijn, 2019**	**no**
SIBES, mean		
SIBES, max	Mulder, 1995	yes
SIBES, min		

the basins using the available datasets on bathymetry and sediment composition. Mud is herein defined as a mixture of clay and silt particles (with a particle size diameter $D < 63\mu m$), including organic and calcareous materials. The contributions of sand and mud are separated as follows: First, total sedimentation/erosion volumes (ΔV) are calculated based on the bathymetric data of the *Vaklodingen* dataset (as presented in Figs. 1 and 3). Next, these volumes are multiplied with the sand/mud content in volume fractions f_V (see Fig. 2), to obtain the relative volumetric contribution of the two sediment fractions:

$$\Delta V_{sand} = \Delta V * f_{sand,V}, \tag{1}$$

$$\Delta V_{mud} = \Delta V * f_{mud,V}. \tag{2}$$

This approach requires a number of assumptions:

1 **Bed sediment data:** We use a single bed composition dataset for separating the sand and mud contribution through time (rather than the various historic bed composition data) for the following reasons: (1) the spatial density of the various bed composition datasets varies, and (2) the methodologies applied to pre-treat and analyse the samples differ. With this, we implicitly assume that one sediment composition distribution is representative for the entire period of time, implying a vertical homogeneity of the sediment distribution. Closure of the South Sea caused an abrupt transition, but since then sedimentation/erosion trends of most individual morphological features are approximately constant. This is in line with Wang et al. (2014a; 2014b), who show that bed sediment grain size changes much faster than the bed elevation, such that a new equilibrium distribution of bed sediment can be rapidly attained after interruptions. Besides, no large changes have been observed in the large-scale sand-mud patterns (see Section 4.1). Therefore the use of a single dataset is the most accurate approach for analyses on basin scale.

We use the data of the Sediment Atlas Wadden Sea, since this has the largest spatial extent and was collected halfway the majority of our bathymetric observations. The SIBES data is collected at identical locations for consecutive years since 2015, allowing a sensitivity analysis (minimum, maximum and mean values of each data point). Quantitative use of data before the 1990s (1890, 1950) is not possible because of poor spatial coverage.

2 **Dry density of sand-mud mixtures:** The Sediment Atlas Wadden Sea provides data on the mass fractions which need to be converted into in situ volume fractions, requiring the use of density relations of sand-mud mixtures. Both Mulder (1995) and van Rijn and Barth (2019) derived equations relating the dry density to the sediment composition. Eq. 3 by Mulder (1995) is based on unconsolidated sediment in the Ems Estuary (East of the Dutch Wadden Sea) while Eq. 4 by van Rijn and Barth (2019) uses dry density data from the Wadden Sea subjected to a primary consolidation period (Migniot, 1968; Migniot, 1989). These equations are:

$$\rho_{dry} = 450 + 4.5 * p_{sand} + 0.063 * p_{sand}^2, \tag{3}$$

where p_{sand} is the sand content in weight-percentages, and

$$\rho_{dry} = \left(1 - \frac{p_{org}}{100}\right)\left[400\left(\frac{p_{clay}}{100}\right) + 800\left(\frac{p_{silt}}{100}\right) + 1600\left(\frac{p_{sand}}{100}\right)\right] \tag{4}$$

where p_{org} is the organic content, p_{clay} the clay content and p_{silt} the silt content, all in weight-percentages. van Rijn et al. (2018) show that this relation also well predicts the dry density of Wadden Sea sediments when ignoring the contribution of organic matter.

We use the relation derived by van Rijn and Barth (2019) with $p_{org} = 0$ since this equation was derived for Wadden Sea sediments, best resembling our conditions. We estimate the sensitivity of the computed sediment volumes to the density formulation by comparing the results with those using the relation of Mulder (1995).

To convert the sediment mass percentages into sediment volume fractions, we use the following relations:

$$p_{mud,V} = 100 - \left(p_{sand} * \frac{\rho_{dry}}{\rho_{dry,sand}}\right), \tag{5}$$

$$f_{mud,V} = \frac{p_{mud,V}}{100}, \tag{6}$$

$$f_{sand,V} = 1 - f_{mud,V}. \tag{7}$$

3 **Negligible contribution of small mud contents:** Not all fines that settle on top of the bed contribute to the long-term sediment volume increase, since mud can be reworked into the pores between sand grains by bioturbation and mixing. According to Winterwerp and van Kesteren (2004), the sand skeleton is not affected by mud particles up to 15% mud. On the other hand, field measurements show that the density of pure sand is higher than that of sand-mud mixtures (Mulder, 1995; van Rijn and Barth, 2019). This is contrast with the findings of Winterwerp and van Kesteren (2004), which would result in the highest densities for sand-mud mixtures. Therefore we assume that mud always contributes to the sediment volume, even when the mud weight percentage is below 15%. However, we evaluate the effect of this assumption by also executing our analysis without the contribution of mud to the total volume when the local mud content is below 15%.

Based on the assumptions above, we define a *best estimate* setting to compute the sand and mud volumes (see Table 1 for an an overview). Alternatives to these primary settings are evaluated as part of a sensitivity analysis to evaluate the robustness of this method. The results are subsequently validated through a comparison with additional sediment cores from the DINO database.

4. Results

First, we briefly summarize the morphodynamic evolution of the Western Dutch Wadden Sea and changes in sediment composition, in response to the closure of the South Sea. We refer to Fig. 1 for the names of the channels and shoals. This is followed by a quantitative analysis of sand and mud deposition rates over time (for both the study area as a whole, and for subsections), validation of the results, and a sensitivity analysis.

4.1. *Long-term changes in the bed sediment composition*

In order to qualitatively compare the different sediment composition maps, the various datasets need to be converted to the same classification scheme. Lely's (1892) data is already classified, providing ranges of sand content rather than absolute numbers. As it is impossible to extract the exact sand content from these classified ranges, all data points have been classified using Lely's (1892) scheme (Fig. 2). Blue dots indicate sandy sediments with either very little mud ($p_{mud} < 10\%$, dark blue) or $10 - 20\%$ of mud (light blue). The yellow dots show the sites that are around the transition between non-cohesive/cohesive behaviour ($p_{mud} = 30\%$ according to van Ledden et al. (2004)). Fully cohesive, muddy areas ($p_{mud} > 40\%$) are marked in red.

The overall sediment distribution in the Western Dutch Wadden Sea is characterized by a strong sand-mud segregation, which has also been observed and described in various earlier studies (e.g. Postma, 1954; van Straaten and Kuenen, 1957; de Glopper, 1967; Zwarts, 2004; van Ledden, 2003). The central parts of the basins mainly consist of sandy channels with low mud content (<10%). The mud content sharply increases to more than 40% near the mainland coastlines. In addition to this pattern, many local patches with high mud content are observed in areas with otherwise relatively low mud content.

Despite significant bathymetric changes in the Wadden Sea basins (see Elias et al., 2012; Wang et al., 2018, and also Fig. 1c), the bed sediment composition has remained relatively stable over the last century. Only three areas show large-scale changes: 1) the sheltered embayment of Balgzand, 2) abandoned channels at the seaward side of the closure dam, and 3) the tidal divide behind Terschelling Island.

Prior to the closure, Balgzand area was a sandy tidal flat, surrounded by Texel inlet and access channels to the South Sea. Only a few local mud patches could be distinguished. Since the closure, the bed has become more muddy, with increasing mud content closer to land. The sudden accumulation of fines here is explained by the sheltered environment that was created by the closure and the land reclamation. The flow velocities in the channel connecting this area to the South Sea abruptly decreased. This channel filled in, and the surrounding shoal accreted. Because of its location, this area is relatively sheltered from off-shore waves entering the basin, allowing fine-grained sediments to deposit.

The former access channels to the South Sea — which were previously in equilibrium (Elias, 2006) — used to be predominantly sandy, but became muddy after closure. The tidal divide behind Terschelling seems to have become more sandy over the past century. The mud content exceeded 20% along the entire tidal divide in the early 20th century, but all observations after closure of the South Sea reveal a mud content over most parts of the tidal divide below 20%. The reason for this could be the alterations in the tidal regime after the closure. This will be part of future research.

4.2. Morphological changes: the contribution of sand and mud

The bed composition data is combined with historic bathymetric charts (Fig. 3) to separate the contributions of sand and mud to the long-term morphodynamic development, following the methodology described in Section 3.2. Pronounced sedimentation/erosion patterns of sand (Fig. 4a) are observed in the main channels of the Texel and Vlie inlets, resulting from lateral channel migration. Sedimentation rates are large in the terminal parts of the channels that connected the Texel and Vlie basins to the South Sea. Here, the tidal currents reduced to almost zero, which led to rapid accretion (Elias et al., 2003). Whereas the sedimentation of the main channel connecting the Vlie basin to the South Sea (*Inschot*) filled in with sand, the access channels of Texel basin (such as *Vlieter*) largely filled in with mud (Fig. 4b). This infilling was a rapid response to the closure and mostly occurred before 1971, after which the sedimentation rates in the channels significantly decreased. The mudflat and salt marsh area along the mainland coast of Friesland has been another notable mud sink. Historical data shows no clear trend breaks in the bed composition, since this was a muddy environment already before closure. However, this area has been, and still is, rapidly accreting and expanding, providing a large mud sink.

4.3. Sediment volume changes

Fig. 5a shows the net volume changes (the sum of the total sedimentation and erosion) in the basins for the period 1933–2015. The blue line provides the total volumetric changes and is based on topographic data only. We first discuss the volume changes by sand (red line) and mud (yellow) resulting from the *best estimate* procedure (see Section 3.2) indicated with the solid lines. The total volume changes reveal a rapid initial response of the basins after closure but slowed down after 1971, as observed earlier by e.g. Wang et al. (2018). The contribution of mud to net infilling is large (over 30%), and its relative contribution is also increasing in time. The sensitivity of these computed net volume changes is evaluated by also computing volume changes using alternative assumptions (related to the density formulation or grain size

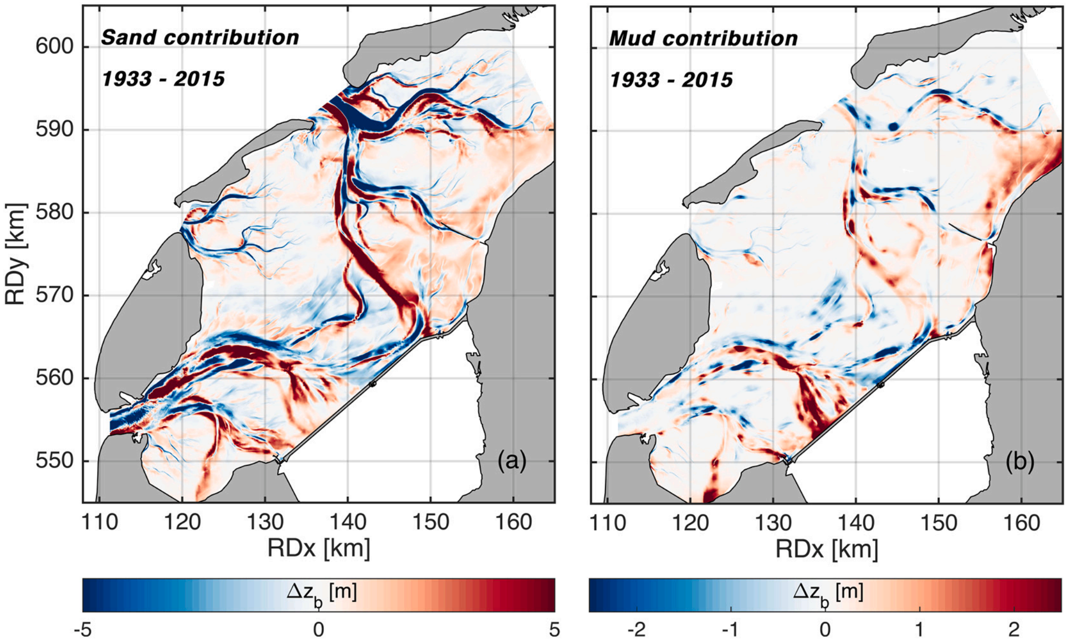

Fig. 4. The contribution of sand (left panel) and mud (right panel) to the bed level changes of 1933–2015 inside the basins of the Western Dutch Wadden Sea.

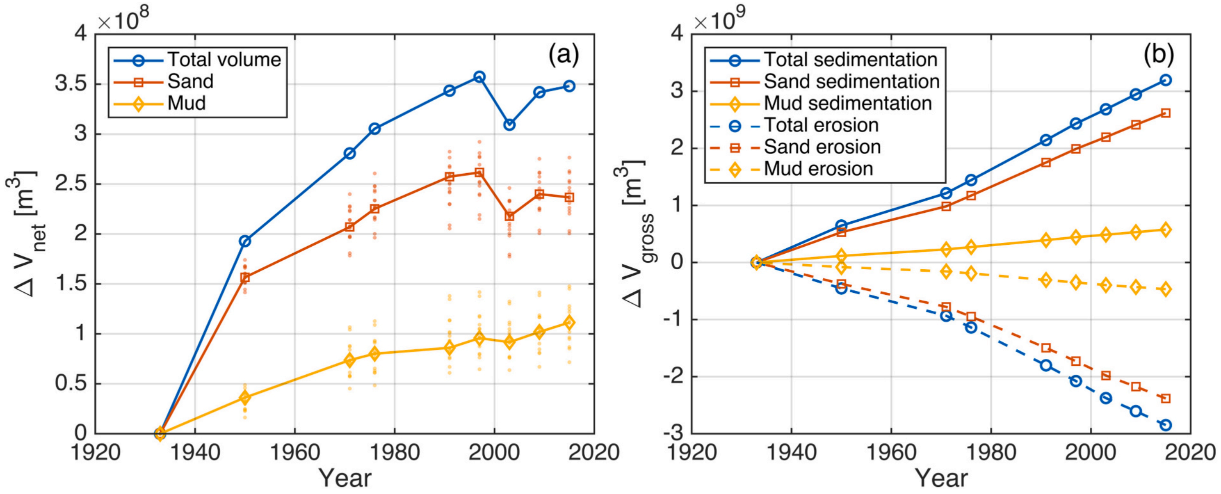

Fig. 5. Volume changes by sand (red) and mud (yellow) to the bed level changes: a) Net volume changes for 1933–2015. Lines show the results following the *best estimate* procedure, based on the assumptions of Section 3.2. The scattered dots show the range of the results for different assumptions. b) Gross volume changes consisting of a separate analysis of the sedimentation and erosion patterns.

distribution dataset). These results (shown with the scatter points in Fig. 5) reveal that the assumptions do not influence the observed trend, but only (and fairly limitedly) the relative contribution of sand and mud. The sensitivity of the results to original assumptions of the method is discussed in more detail in Section 4.6.

The contribution of mud to the total net volume changes is 21–42% (32% for the best estimate), which is significantly larger than the current mud content in the upper bed of the Western Wadden Sea (11.8% on average, but with a median mud content of only 3.6% resulting from sand-mud segregation). The much larger contribution of mud to the total infilling results from preferential settling of mud in areas where net sedimentation prevails.

The total accretion rates of sand started decreasing after 1950, and even reverted to erosion after 1997. Mud accretion, on the other hand, slowed down two decades later, and continues to date. Examining the mud volume changes in more detail reveals that infilling was approximately linear until 1971 and after 1991, but sedimentation stagnated in-between these periods. However, this observation may also be a data-artefact, becoming prominent as a result of the low frequency of observations. However, the decreasing rate of net volume changes is not the result of a reduction in bed level dynamics. Fig. 5b shows the gross sediment volume changes, consisting of the cumulative sedimentation and erosion volumes. While the net volume change rate clearly decreases in time, the gross volume changes have increased since 1971. This increase — both for sand and for mud — is observed in both the sedimentation and the erosion volumes, although it is more pronounced in the latter. Apparently, bed level changes without a residual component (i.e. lateral migration of channels) becomes more pronounced relative to net changes (e.g. net infilling), suggesting the morphology is gradually adapting to the closure of the South Sea.

The relative contribution of sand and mud to the volume changes in the basins has not been constant over the evaluated period, as is evident from the normalised contribution of sand and mud (Fig. 6a). The cumulative contribution of mud to infilling volumes has increased from 19% to 32% since the closure of the South Sea (with present-day mud sedimentation volumes exceeding sand deposition volumes - see Fig. 5a). The reason for this relative increase in mud deposition is that initially, net bed level changes were primarily a response to closure of the South Sea (impacting both sand and mud). In later stages, net sedimentation continued on the tidal flats, which are very muddy.

The more depositional character of mud is also evident from the ratio between the sedimentation and the erosion volumes (Fig. 6b). A ratio larger than one represents sediment import and a ratio smaller than one export (with a ratio equal to 1 representing a closed sediment system

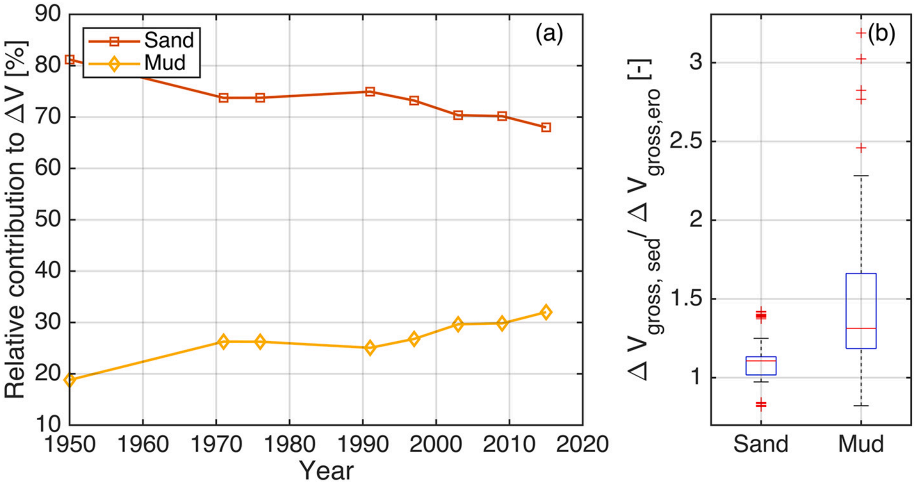

Fig. 6. a) Relative cumulative contribution of sand and mud to the net volume changes. b) Boxplots showing the sedimentation/erosion ratio for sand and mud based on the gross volume changes of all years, calculated for all possible combinations of methodologies to separate the sand and mud contribution.

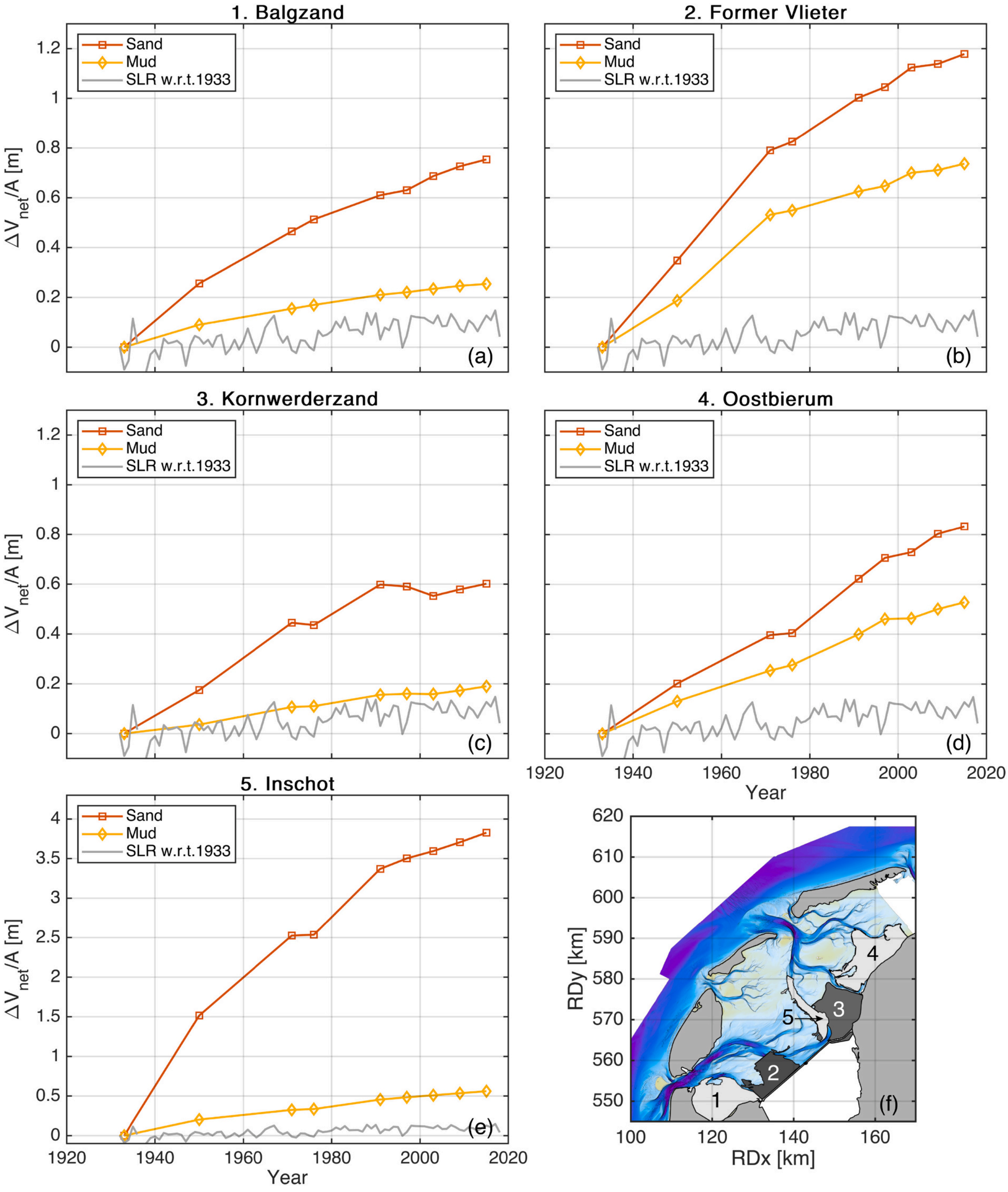

Fig. 7. Volume changes of distinct net accumulation areas, plotted as net volume changes divided by area (m^3/m^2) to enable a comparison between the study areas. The local SLR with respect to the mean sea level in 1933 (measured at Texel inlet) is plotted in grey. Note the different y-axis in panel (e). Panel (f) shows the polygons of the analysed sub-areas.

without external sediment exchange). The ratio of sand has a median value of 1.1 and a relatively low spread (between 0.97 and 1.25, depending on assumptions required for separating sand and mud). The ratio for mud however, has a larger median (1.3, showing the more depositional behaviour within the basin) but also a greater spread, with minimum values around 0.82 and maximum realistic values up to 2.3.

4.4. Local analyses of net accumulation areas

To examine the response of fines to the closure of the South Sea in more detail, the evolution of five main areas that have acted as pronounced sediment sinks is further analysed. To compare these sites, we compute an average accretion per site by dividing their volume change by their area (Fig. 7). For comparison, we have added the SLR since 1933 (same unit as the normalized volume changes), allowing direct assessment to what extent the areas can keep pace with SLR).

Both in the Balgzand embayment and in the abandoned Vlieter Channel we observe a gradual decrease in sedimentation rates for both sediment fractions. These volume changes reveal that the local response was fastest in the Balgzand area, where maximum sedimentation rates occurred in the first 20 years. In the abandoned Vlieter net sedimentation rates increased until 1971. This difference could be related to the distance to the main inlet, which is less for Balgzand since it is closer to the sediment source. However, more accommodation space was created at Vlieter Channel: Note that the presented response of the Balgzand polygon is determined by the infilling of a former channel (small compared to Vlieter Channel) and the heightening of the Balgzand flats (see also Fig. 1). The larger accommodation space explains the larger sedimentation rate at Vlieter Channel.

In Kornwerderzand, sand infilling continued until 1990, after which net infilling was primarily with mud. However, on the adjacent tidal flat area of Oostbierum we still observe an almost linear accretion of both sand and mud. Infilling rates are higher here for both sediment types, with averaged mud accretion rates twice those in Kornwerderzand. Inschot Channel on the other hand, shows a preferential infilling with sand, and although sedimentation rates of sand have decreased over time, they exceed sand sedimentation rates in the other areas. Mud sedimentation rates in Inschot Channel are similar to those in Balgzand area, already sufficient to keep up with SLR.

4.5. *Validation*

To verify our methodology, we compare the calculated accretion volumes and sediment type to the sediment classes derived from sediment cores (see Fig. 8). At the location core BA1, the bathymetric charts suggest a sedimentation rate of 1.85 m in the period 1933–1951, consisting mostly of muddy sediment. Core BA1 (taken in 1946) supports our assumption that the sediment composition depositing in response to closure was constant in time. We analyse two cores taken at the former Vlieter channel. At the location of VL1 we calculated about 1.5 m net accretion in the period 1933–1951, with a mud contribution of about 50%. Since we know this site used to be sandy previous to the closure (see Fig. 2), we can derive from the core that 1.6 m of predominantly fine sediment accreted since the closure until 1946. At the location of VL2 (at a distance of 150 m from VL1) we calculated higher accretion rates of 2.5 m of which 60% mud. The core taken at this location shows that mud was found up to a depth of 3.5 m. We assume that large volumes of mud already deposited before 1933, in the four years between closure (1929) and the bed level observations (1933), and in the years prior to the closure in which construction of the side works had already started. Calculated sedimentation rates over a shoal in Kornwerderzand area also match the findings from core KO1. This area only has a few spots where mud had a large contribution to the sedimentation, which is also reflected in Fig. 4. Cores OO1 and OO2 reveal that mud was already present in the tidal flat area of Oostbierum before the closure (in line with Lely's observations). Core IN1 shows that indeed, Inschot Channel has been filling in with mostly sand (medium fine to fine). Summarizing, the accumulated sediments shown by the deep cores match well with the calculated sedimentation of sand and mud. There are no indications that the long-term deposits significantly differ from the short-term deposits regarding the sediment composition.

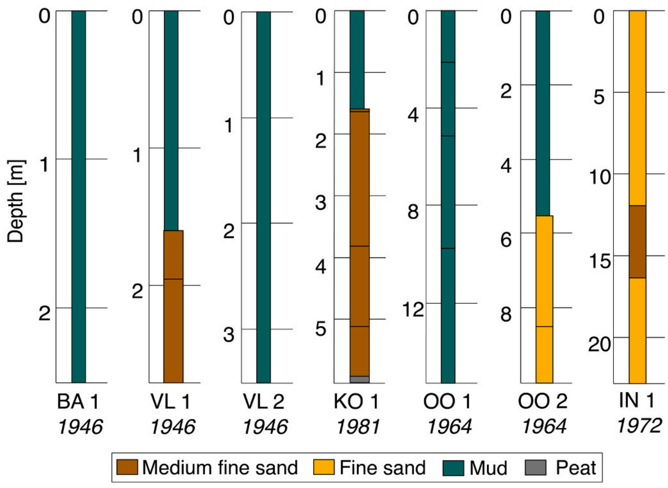

Fig. 8. Lithology of sediment cores, retrieved from *www.dinoloket.nl*. The locations where the cores were taken are indicated in Fig. 1. For each core its is shown when it was taken.

4.6. *Sensitivity analysis*

As already briefly discussed, the calculated total contribution of mud may vary between 21% and 42%, depending on the used dataset, density formulation, and definition of the contribution of fines. In this section, we determine the sensitivity of the computed volumes to these assumptions in more detail. Fig. 9 shows the contribution of each individual parameter/ assumption to the mean volume evolution of mud in the basin. An important observation is that our assumptions do not influence the temporal patterns in mud and sand volume changes. The greatest uncertainty is introduced by the sediment composition data. Depending on the choice of the dataset, the computed net mud sedimentation volumes range between 90 and 131 million m^3, corresponding to a mud contribution of 26–38% to the total sedimentation. Computing volume changes with data of the Sediment Atlas is comparable to using the mean value of SIBES data, except for the period 1980–2000, when using *Mean SIBES* data would lead to an overestimation of the mud accretion volumes. Collecting more frequent data will not improve this, since mud contents in the upper bed show a large variability, even in the short term (Hendriks et al., 2020; Herman et al., 2018; van der Wal et al., 2010; Yang et al., 2008). This shows that the absolute values of our findings should be interpreted carefully. The effect of the dry bed density formulation is much smaller. The formulation by van Rijn and Barth (2019) predicts higher bed densities compared to the formulation by Mulder (1995), resulting in smaller net mud volumes. The effect of the correction factor for small mud contents is minor compared to the other assumptions. Excluding the contribution of small mud fractions on bed level changes results in a small decrease of the mud volume results (less than 10%).

5. Discussion

5.1. *Relation to long-term hydrodynamic changes*

The evaluated morphodynamic evolution results from local human interventions and changing hydrodynamic conditions, such as SLR. Local measurements of the mean sea level during the past century reveal a fairly constant SLR rate of 2 mm/yr along the Dutch coast and 1.2–1.4 mm/yr in the Dutch Wadden Sea (Baart et al., 2012; Deltacommissie, 1960; Vermeersen et al., 2018). Fig. 10b shows the yearly averaged sea level at the tidal gauge of Den Helder, located at Texel inlet. To determine which part of the morphodynamic evolution in the Western Wadden Sea may be attributed to SLR, we have calculated the required sediment volumes to keep pace with the sea level changes (by multiplying the total area with the sea level changes, see the right axis of Fig. 10b). The total observed volume gain in the basins (350 million m^3) is more than the volume required to compensate for SLR (around 150 million m^3).

Fig. 5b shows a distinct increase in gross volume changes between 1970 and 1980 (both sedimentation and erosion rates suddenly increased). This sudden increase in sedimentation corresponds to an increase in tidal range observed during this period, which originates

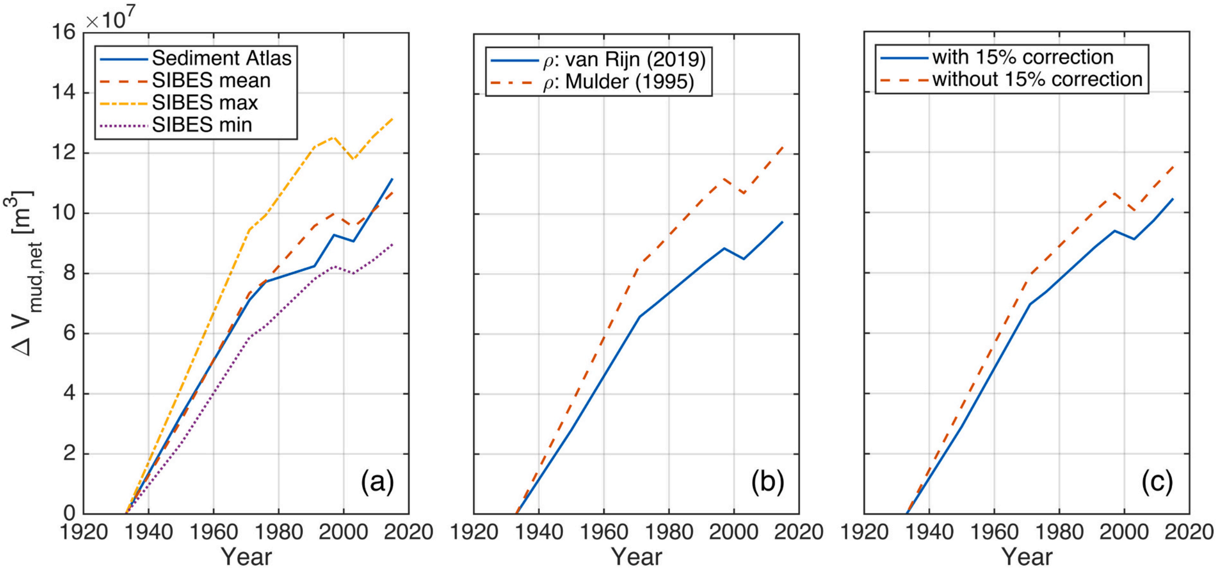

Fig. 9. Sensitivity analysis showing the mean evolution of mud volumes in the basin, calculated for each assumption of a) sediment composition data, b) dry bed density formulation and c) correction factor for the contribution of small mud contents.

from an increase in M2 amplitudes (panels c and d of Fig. 10). In five tidal stations in the Western Dutch Wadden Sea the M2 amplitude increased 3 to 8% between 1970 and 1980. The reason for this increase in tidal range still remains unknown (Hollebrandse, 2005), but it extends into the adjacent North Sea (i.e. it is not caused by changes in the Wadden Sea). A larger tidal range influences sediment transport in two ways: First, the sediment transport capacity increases, leading to larger erosion and deposition rates. This is reflected in the increase of the gross volumes of especially sand (e.g. increased channel migration), without necessarily leading to a change in the net sediment volume. Secondly, larger tidal amplitudes increase the tidal accommodation space for sediment to deposit. This increase in accommodation space is especially illustrated with High Water (HW) levels which increased approximately 20 cm, especially between 1960 and 1990 (see Fig. 10, panels e-i). This increase in HW substantially enlarges the intertidal area where fine-grained sediments may deposit.

5.2. Balance between accommodation space and sediment supply

The rate at which a coastal system evolves is controlled by sediment supply (the rate at which sediment can be transported towards a certain location) and accommodation space (the space available for sediment to deposit) (Beets et al., 1992). Here, we interpret the post-closure large-scale evolution of the Dutch Wadden Sea in terms of both controls. In short basins a closure would result in a smaller tidal prism, corresponding to reduced relative channel cross-sectional areas (e.g., Eysink and Biegel, 1992; Yu et al., 2014), resulting in lower flow velocities and therefore channel infilling. However, the pre-closure Western Dutch Wadden Sea was a long basin, where the tidal prism did not decrease, but even slightly increased after closure (Elias et al., 2003). Still, the closure caused sediment deficits, which has driven sediment import into the basins.

Sediment supply is determined by the sediment availability and the transport capacity (Beets and van der Spek, 2000). Sediment availability is regulated primarily by sediment sources, being the adjacent coastlines and ebb-tidal deltas for sand and the North Sea for mud. Elias et al. (2012) analysed all major ebb-tidal delta systems in the Dutch Wadden Sea, revealing a landward retreat of the outer rim of the deltas and rapidly decreasing volumes since closure of the South Sea. Our results show that also large amounts of mud deposited after closure. Along the Dutch Coastal Zone fines are transported in a residual north-easterly direction, with a yearly flux estimated at 22 ± 10 MT/yr (van der Hout et al., 2015). These suspended sediments originate from sources south of the Dutch Coastal Zone (Hendriks et al., 2020). This coastal mud flux is transported eastward along the Wadden Sea islands, some of which enters the tidal basins through their inlets. Gross exchange rates between the North Sea and each of the tidal basins are in the order of 50 MT/yr (Herman et al., 2018).

Construction of the closure dam created accommodation space in abandoned channels, in addition to the existing accommodation space provided by the intertidal areas along the Frisian mainland coast. In absence of accumulation potential (i.e. when conditions for accumulation are not favourable) no fines permanently deposit (Hendriks et al., 2020). The closure changed the local conditions, probably creating calm areas thereby affecting the accumulation potential, which facilitated permanent deposition of fines. It is unlikely that the present-day deposition rates are natural, i.e. pre-dating closure, because that would have resulted in fairly rapid infilling of the Wadden Sea. However, an alternative explanation for the large deposition rates is related to supply. Before closure, the South Sea provided a large sink for fine sediments to deposit. This sink disappeared after closure, resulting in a greater availability of fine sediment in the remaining basins, and therefore an increase in suspended sediments and deposition elsewhere (van Maren et al., 2016).

In addition, accommodation space has been created by relative sea level rise, consisting of rising sea levels (see Fig. 10) and land subsidence. Natural subsidence over the past century, mainly caused by postglacial isostasy and tectonics, has been estimated around 0.564–0.611 mm/yr for the Western Dutch Wadden Sea (Hijma and Kooi, 2018a; Hijma and Kooi, 2018b). This component is included in the SLR measurements of Fig. 10. Human induced land subsidence, because of gas- and salt mining, takes place on local scale and is estimated around 0.001–0.026 mm/yr in the Western Dutch Wadden Sea. In total, land subsidence should have caused an extra 89 million m^3 increase in water volume in the basins over the past century, of which 1.9 million m^3 caused by mining activities (Hijma and Kooi, 2018b). However, no indications of subsidence of the seabed have been observed, which suggests that this increase in accommodation space in the basins has quickly been filled in with sediment (Wang et al., 2018). By multiplying the additional volume created by subsidence with the mean sand and mud content in the basins, we can estimate how much of this has been filled in with sand and mud, as shown by the dashed lines in Fig. 11. The

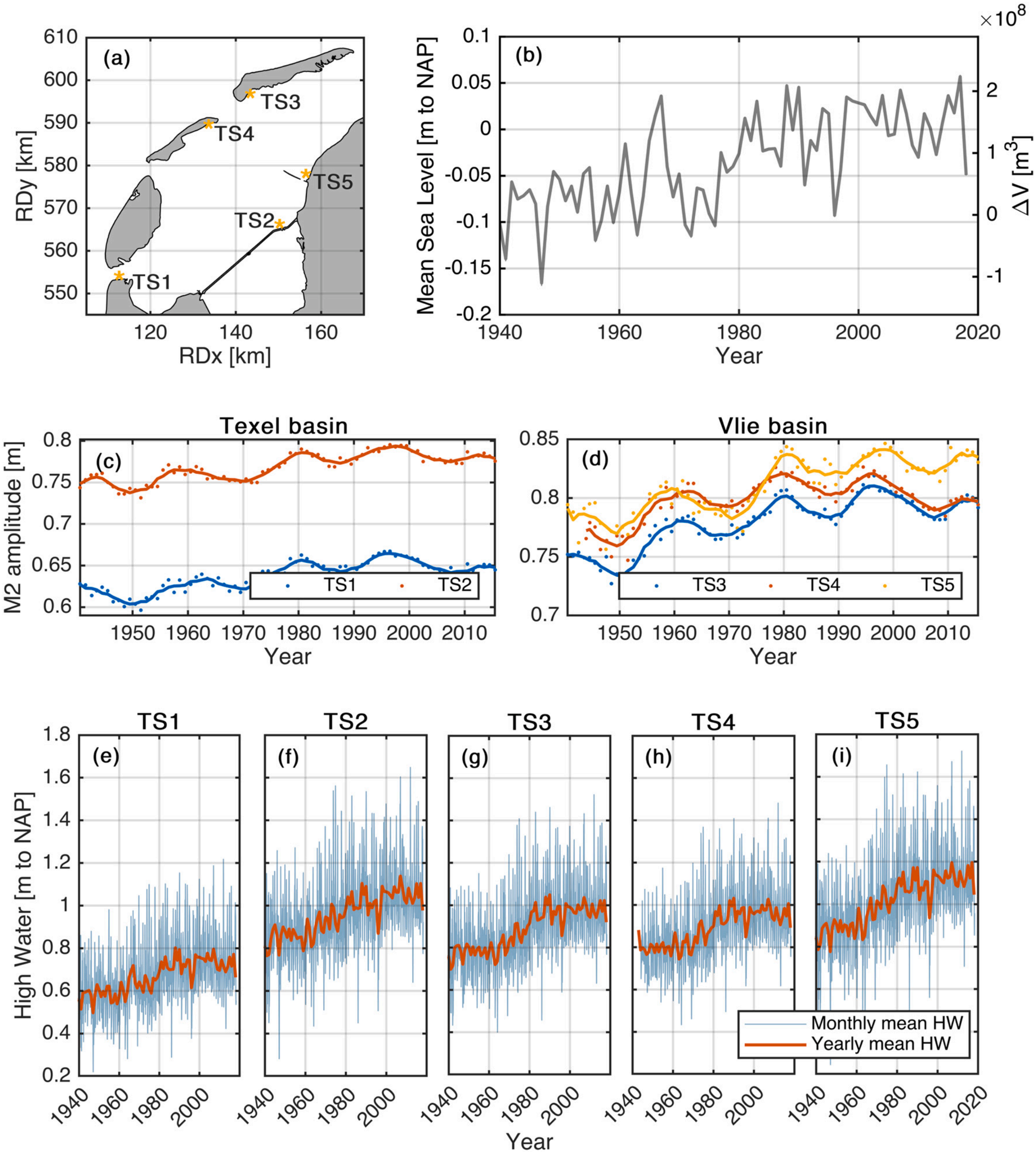

Fig. 10. Long-term hydrodynamic changes in the Western Dutch Wadden Sea. (a) Locations of the Tidal Stations (TS). (b) Tide-gauge observations of the local mean sea level at Den Helder (station TS1). The right axis shows the sediment volume required to directly compensate for SLR. In panels (c) and (d) we present a tidal analysis of the M2 component, after Nederhoff et al. (2017), showing the 18.6-year lunar nodal cycle and an additional increase between 1970 and 1980. Panels (e)-(i) show the evolution of the HW levels (monthly and yearly average).

bandwidth shows the uncertainty range, as calculated by Hijma and Kooi (2018b). To determine the total sediment infilling, these contributions must be added to the observed volume changes, as shown by the red and yellow lines of Fig. 11.

Our results show that the infilling of accommodation space by sand and mud differs spatially: while some abandoned channels mainly filled in with mud (e.g. Vlieter channel) others have filled in with sand (e.g. Inschot channel). This shows the complexity of the morphodynamic response when differentiating between the two sediment classes. Using only the conceptual framework where sedimentation is a balance between accommodation space and sediment supply, it is difficult to predict where sand and mud will deposit. Moreover, we have shown that the contribution of mud to net infilling is much larger than the average mud content in the top layer of the bed. Therefore, the bed composition before or after an intervention is not necessarily a good indicator for the contribution of the different sediment types to the net morphological changes.

5.3. Response timescales

The response of sand and mud does not only vary spatially, but also the involved timescales are different. Since the closure of the South Sea, the availability of both sand and mud has been sufficient to adapt the Wadden Sea morphology. However, the transport capacity of sand and mud, and therefore response timescales, is markedly different. Both Elias et al. (2012) and Wang et al. (2018) state that the response of the Wadden Sea is limited by the transport capacity, even though sediment sources and accommodation space can be abundant. Therefore, the

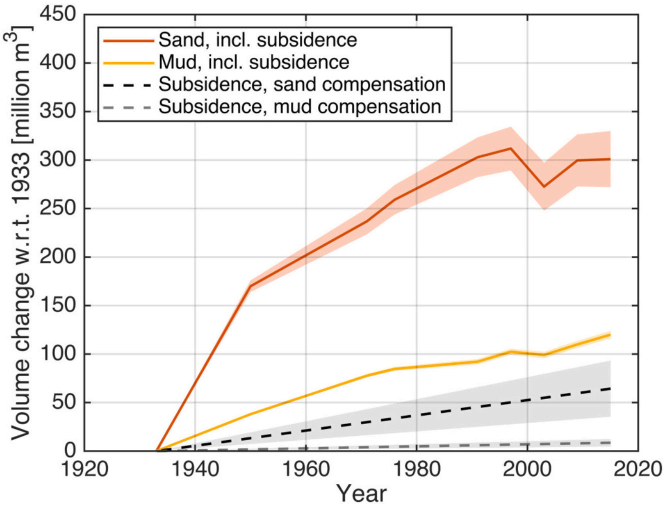

Fig. 11. Calculated volume changes of sand and mud in the Western Dutch Wadden Sea basins including corrections for land subsidence [following Hijma and Kooi, 2018a,b]. The bandwidth shows the uncertainty range of the land subsidence component.

sandy system will be able to compensate for the intervention over longer timescales. Sediment concentrations of mud, on the other hand, may be up to 10's of kg/m^3 (Colosimo et al., 2020). This implies mud is not transport-limited, and as long as a sediment source and accommodation space where mud can settle are available, the response will be fast.

Dastgheib (2012) simulated 2100 years of evolution of the Wadden Sea after closure of the South Sea, and showed that the sediment import of the basins would mainly take place during the first 300 years after the intervention, with a maximum sand infilling rate through Texel Inlet of about 3 million m^3/yr in the first 40 years. However, he based these calculations on sand transport only, without accounting for the contribution of mud in the infilling. Our results show average sand infilling rates are two times higher (6.2 million m^3/yr, including corrections for subsidence) during the first 40 years for the entire Western Dutch Wadden Sea and an additional mud deposition of 2 million m^3/yr. Therefore, we expect the total response timescale to be shorter than Dastgheib's estimates.

Although sand and mud have different response timescales, their contribution to the total response time of the system cannot be considered separately. Mud sedimentation on the tidal flats, for example, reduces the tidal prism, which may subsequently promote infilling of sand-dominated tidal channels. On a smaller scale, interaction of sand and mud influence their mutual erosion rate (van Ledden et al., 2004). This interdependency of the morphodynamic response by both sediment types makes it very difficult, if not impossible, to strictly separate the sandy and muddy response of the system. Yet, we have shown that for sand-mud systems, it is crucial to study the response of both sediment types simultaneously and mutually when addressing large-scale morphological changes. Therefore, we advocate collection of detailed sediment distribution data in the vicinity of large scale past or future interventions, and use of this data in combination with available historic topographic data.

5.4. Sea level rise

SLR is one of the major future threats for the preservation of the Wadden Sea. Keeping pace with SLR requires two things: first, sufficient sediment supply, and second (especially for fine sediment) low-energetic accommodation space. The previously discussed limitation in sand transport capacity may become limiting for morphological adaption to SLR if SLR is faster than a critical rate. Over time, this would result in an eventual disappearance of the intertidal morphology (Wang et al., 2018). On the other hand, our results show that the current supply of mud is sufficient to keep pace with the current SLR rates, and there are no indications showing that future concentrations of suspended matter will significantly decrease. Therefore, we hypothesise that for a critical increase of the sea level the system can only keep up by means of predominant mud sedimentation. This could trigger a shift from a sand-dominated system towards a mud-dominated system.

However, mud deposition requires low-energetic accommodation space. Therefore only low-energy shoals (intertidal and upper subtidal) are presently muddy, and it seems unlikely that the energetic central channels will become muddy as well. When sand import becomes a limiting factor, the channels will not be able to keep pace with the rising sea levels while the muddy shoals can keep up with SLR. This would result in an overall steepening of the coastal profile. Steepening leads to higher wave energy over the flats, and thereby a reduction of mud deposition. This steepening therefore provides a mechanism leading to the shoals no longer being able to keep up with SLR.

6. Conclusions

Closure of the South Sea in 1932 largely changed the morphology of the remaining tidal basins in the Western Dutch Wadden Sea, including the bed composition: it induced local transitions in bed sediments, although the rest of the basins show little large-scale variation on timescales of decades to centuries. The closure triggered an infilling of the basins, that is still partly ongoing. By differentiating between the contribution of sand and mud in this infilling, we have shown that the response was substantially caused by mud (21–42%, with a best estimate of 32%). This contribution of mud is much larger than the average mud content in the bed. The responses of sand and mud to the intervention have been very different in time and in space. During the initial response of the basins, large sand and mud volumes accreted in abandoned channels. At present, mud sedimentation along the mainland coast is still ongoing with fairly constant import rates, while the net import of sand significantly decreased over time and has been fluctuating around 0 in the past two decades. Although we can differentiate between the total contribution of sand and mud to the import volumes, it is not possible to derive independent response timescales for the sandy and the muddy response, since their morphological development is interdependent.

In the future, sea level rise (SLR) will be a major threat for the existence of the Wadden Sea; tidal flats may drown depending on their ability to keep pace. We have argued that for slow, gradual changes, both sand and mud sediments are likely to be able to keep pace. Yet, for rapid changes (such as increased SLR rates) only the transport capacity of mud will be sufficient to compensate directly, as long as the sediment source remains sufficient.

Our study shows the importance of differentiating between sand and mud in sediment budget studies. We have shown that both human interventions and natural hydrodynamic changes can induce major changes in the bed sediment composition of tidal basins, having implications for sediment management strategies, and affecting ecological and recreational values.

Data availability

Open access to the bathymetry data of the Vaklodingen dataset is provided at: https://svn.oss.deltares.nl/repos/openearthrawdata/trunk/rijkswaterstaat/vaklodingen/ The Sediment Atlas is publicly available at: https://svn.oss.deltares.nl/repos/openearthrawdata/trunk/rijkswaterstaat/sedimentatlas waddenzee/ SIBES sediment data is available upon request, see also: https://www.nioz.nl/en/about/cos/coastal-dynamics/sibes. Sediment cores can be downloaded from: https://www.dinoloket.nl/. Hydrodynamic data is publicly available and can be requested at https://www.rijkswaterstaat.nl/water/waterdata-en-waterberichtgeving/waterdata

Declaration of Competing Interest

The authors declare that is no known conflict of interest.

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