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ABSTRACT

Storm surge barriers and closure dams influence estuarine morphology. Minimizing consequential ecological impacts requires a thorough understanding of the morphological adaptation mechanisms and associated time scales. Both are unraveled using three decades of morphological measurements on the adaptation of the Eastern Scheldt estuary (The Netherlands) to a storm surge barrier and closure dams. Both the storm surge barrier (through a decrease in cross-sectional area) and closure dams (inducing a reduction in surface area of the estuary) contributed to a reduction in tidal prism. As a smaller tidal prism implies a smaller equilibrium volume of the channels, the channels demand sediment to adjust. Consequently, by providing sediment to the channels, the intertidal flats erode. Erosion rates decreased while the sediment demand of the channels attenuated. This attenuation in sediment demand resulted mainly from tidal prism gains, caused by intertidal flat erosion and sea level rise. Erosion rates of the intertidal flats decreased further while they flattened to adapt to the reduced tidal velocities. Furthermore, storms caused erosion events, after which the long-term adaptation pace of intertidal flats suddenly reduced. Despite decreasing erosion, sea level rise enhances the drowning of intertidal flats in sediment-scarce estuarine systems, thereby pressuring these estuarine ecosystems and raising the need for mitigation measures.

1. Introduction

In the era of climate change and biodiversity loss, preserving the world's precious estuarine ecosystems is crucial (Barbier et al., 2011; Kennish, 2002). Nonetheless, estuarine ecosystems suffer from the impact of engineering works (Meire et al., 2005; Van Wesenbeeck et al., 2014; Ezcurra et al., 2019; Murray et al., 2019). Engineering works constructed to enhance safety against flooding – such as closure dams and storm surge barriers (SSBs) – modify hydrodynamics and thereby estuarine morphology (Renger and Partenscky, 1980; Eysink, 1990; Wang et al., 2015; Orton et al., 2023) which results in ecological losses, especially for wading birds when tidal flat erosion reduces the emergence duration of the tidal flats (Nienhuis et al., 1994; Van Wesenbeeck et al., 2014). To assess the long-term fate of estuaries, to enable better designs of future barriers (e.g., considered in the United States, Sweden, China, and Singapore; Jonkman and Merrell, 2024), and to support effective mitigation of ecological consequences (e.g., with sand nourishments; Van der Werf et al., 2019), underlying morphological adaptation mechanisms need to be unraveled.

Estuarine morphology generally strives for equilibrium of the volume of the channels and intertidal flats (e.g., Eysink, 1990). A change in tidal prism induced by engineering works leads to an adaptation of estuarine morphology to a new equilibrium state, typically taking decades–centuries (Renger and Partenscky, 1980; Eysink, 1990; Van Dongeren and De Vriend, 1994; Van Maren et al., 2023). As equilibria change over time, for example by sea level rise (SLR), an actual

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equilibrium may never be reached (Zhou et al., 2017). Apart from directly altering channel volume and exposure duration of flats, SLR impacts the equilibrium volume of channels through tidal prism changes (Becherer et al., 2018; Hofstede et al., 2018). Furthermore, storms can impose substantial spatiotemporal variations in morphological evolution (Anderson et al., 1981; Fan et al., 2006; De Vet et al., 2020). As storm impacts depend on local hydrodynamics on the flats (e.g., velocities and tidal range; Le Hir et al., 2000; Green et al., 1997), changes in hydrodynamics imposed by engineering works are another trigger for estuarine morphology adaptation. These mechanisms adapt estuarine morphology after the construction of engineering works at different time scales.

This study unravels and compares the importance of these concurring morphological mechanisms from extensive field measurements, using the Eastern Scheldt (The Netherlands) as case study. Various engineering works were constructed in the 1980s in this estuary, and its morphological adaptation has been monitored over different spatial and temporal scales. Specifically, changes in (equilibrium) volume of channels, adaptation of intertidal flat elevation and steepness, and storm impacts are analyzed. Moreover, we identified the relative contributions of intertidal flat erosion and SLR to changes in sediment demand of the channels, considering both the associated changes in equilibrium channel volume (through changes in tidal prism) and channel volume. Combining all insights, the initial and long-term fate of estuaries facing SSBs, closure dams and SLR are addressed.

2. Study Site

The present-day Eastern Scheldt basin (southwest of The Netherlands; Fig. 1a) has a ~350 km^2 surface area and a tidal range of 2.5–3.5 m. Engineering works were initiated after the 1953 flood to increase the safety of the hinterland against flooding (Louters et al., 1998; Eelkema et al., 2009) and were completed in 1986. The landward branches of the Eastern Scheldt estuary have been dammed, while the SSB in the mouth (8 km long and 62 gates; Fig. 1b) only closes during severe storm surges (less than once a year on average so far). Maintaining tides inside the basin limited short-term ecological consequences (Smaal and Nienhuis, 1992) for this ecologically important area (protected by European Natura 2000 regulations).

Still, the SSB reduced – through its decrease in cross-sectional area – the tidal prism by 25 % (Vroon, 1994). The tidal range was predicted to decrease by ~25 % as well, which was considered to have an

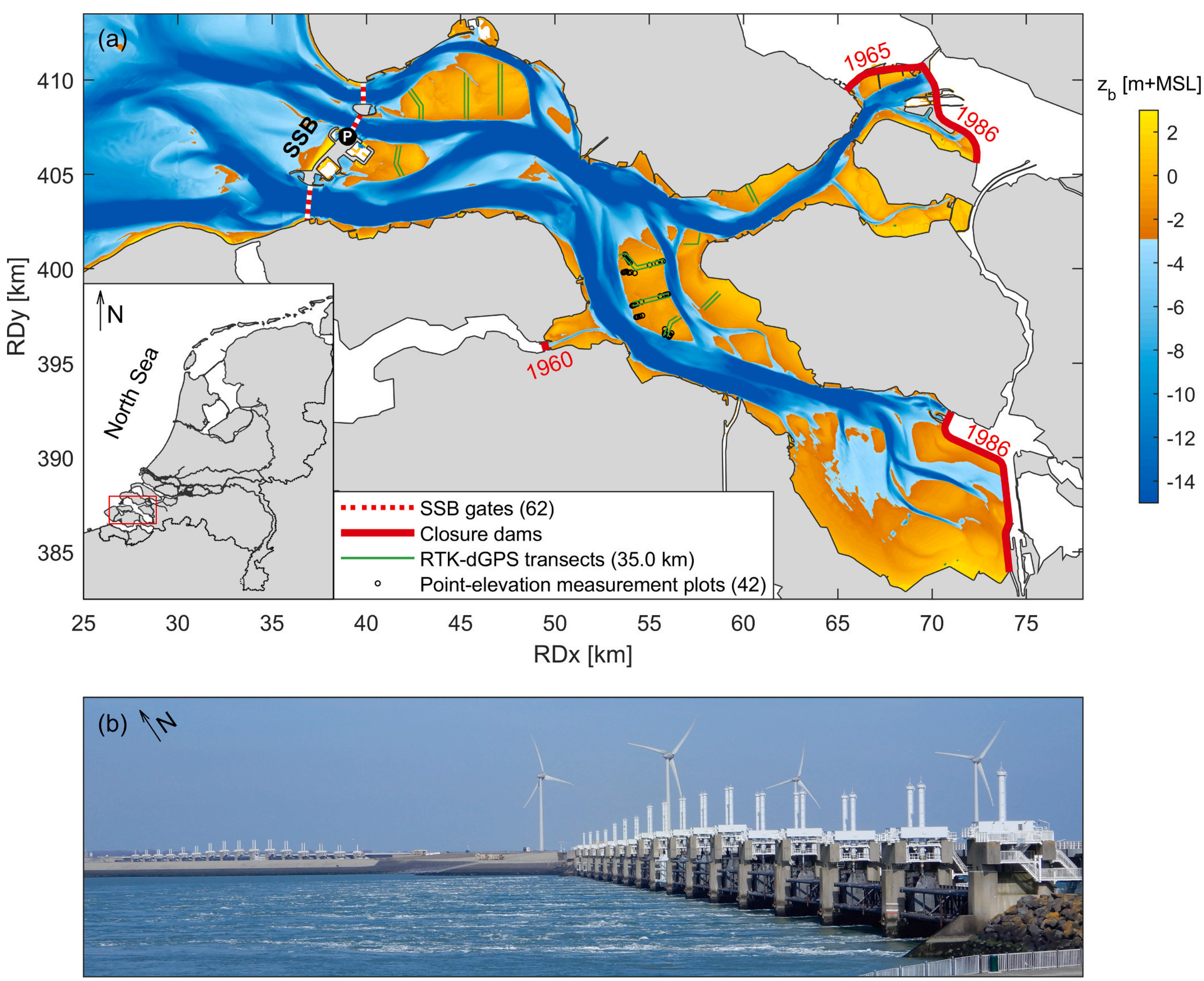

Fig. 1. Bathymetry of the Eastern Scheldt of 2019 (a) with the storm surge barrier (SSB), closure dams (years of closure indicated in red) and the location of the RTK-dGPS transects and point-elevation measurements. The maximum depth of the channels exceeds the color scale, see Fig. 3a for the full elevation distribution. A photo of the SSB gates is provided in (b), taken on 23 March 2017 at location *P* in (a) looking at the NNE.

unacceptable negative impact on ecology (Vroon, 1994). This motivated the construction of the closure dams at the landward end of the Eastern Scheldt, reducing the surface area of the basin by 22 % and limiting the tidal range reduction to 13 % (despite reducing the tidal prism with another 5 %; Vroon, 1994). Altogether, the engineering works reduced the tidal prism by 30 % and with that also the equilibrium volume of the channels, i.e., the channels desire sedimentation to adapt to the reduced tidal prism. This sediment demand of the over-sized channels equaled initially 400–600 million m^3 (~500 million m^3 is considered hereafter), as calculated by Mulder and Louters (1994) based on equilibrium relationships.

As the SSB blocks sediment import to the basin (Huisman and Luijendijk, 2009; Louters et al., 1998), the neighboring North Sea coastal zone can barely contribute to this sediment demand (i.e., contrary to open tidal basins, the Eastern Scheldt is considered mostly a decoupled system in the sediment budget of the Dutch coast; Lodder and Slinger, 2022; Lodder, 2024). Specifically, sand exchange through the SSB is negligible, among other reasons, due to the steep slopes of the scour holes at both sides of the SSB (Huisman and Luijendijk, 2009), while suspended fine sediments could possibly still contribute to an import of 1 million m^3/year to the Eastern Scheldt (Smaal and Nienhuis, 1992; Louters et al., 1998). This amounts to a possible attenuation of the sediment demand up to 0.2 %/year. Therefore, the eroding intertidal flats of the Eastern Scheldt provide a key source of sediment feeding its channels.

Before the engineering works, the flats were gaining elevation while the channels were deepening (Mulder and Louters, 1994). Contrarily, sediment has been eroding from the flats to the channels ever since the construction of these works (Louters et al., 1998; De Vet et al., 2017). There are indications that erosion is slowing down (De Vet et al., 2017), suggesting that the Eastern Scheldt morphology is attaining a new equilibrium. However, the total sediment volume originally present in the intertidal flats (~126 million m^3 in 1983) is only less than one-third of the initial sediment demand of the channels as estimated by Mulder and Louters (1994). Whether or not the decay in erosion rates of the flats will persist is yet unknown.

3. Methods

Three independent datasets capture the morphological adaptation of the Eastern Scheldt to the SSB and closure dams. First, the *Vaklodingen* dataset (accuracy of individual samples of ±25 cm; Wiegmann et al., 2005) is a composition of single beam and LiDAR measurements (and more primitive techniques before 2000) covering the complete basin morphology typically once every four years since 1983. Second, *RTK-dGPS transects* (±3 cm) capture the intertidal flat elevation every year since 1988 (Fig. 1a). Third, at 42 *point-elevation measurement plots* (Fig. 1a), bed elevations have been measured (averaging 15 samples within a 2 m radius) every ~29 days for 1986–2003, resulting in centimeter-precision time series. Considering different datasets allows for cross-validation of observations. Furthermore, differences in spatiotemporal coverage between the datasets complement insights on the morphological adaptation of the basin.

The response of the Eastern Scheldt is evaluated using aggregated parameters such as average bed slope and intertidal flat elevation for which random errors in the measurements average out. Analyses are restricted to the present-day geometry of the Eastern Scheldt (i.e., excluding former branches). The channel volume is defined as the volume below MSL (mean sea level) for all areas below MLW (mean low water). The intertidal flats are defined as all areas between MLW and MHW (mean high water). Local (spatially varying; constant in time) post-barrier estimates of MLW, MSL and MHW are derived from a validated model simulation (De Vet et al., 2017), from which also the tidal prism was computed. Note that considering a spatially varying MSL is of minor importance, as the MSL estimate varies by less than 5 cm across the Eastern Scheldt.

For the computation of the tidal flat elevation from the Vaklodingen data, only years with at least 98 % coverage of the flats are considered and only cells with data in all those years are included. Data after 2019 are omitted to exclude effects from a sand nourishment in 2020. To derive time series from the intertidal flat RTK-dGPS transects, data are binned in 10 m segments and interpolated to the middle of each year. Segments not covering 1988–2019 are excluded, after which 35 km of segments remains (Fig. 1a). Elevations of segments lacking data in specific years are interpolated from neighboring years. Years with less than 85 % segments measured are omitted. When computing the bed slope, the transect data are smoothed with an averaging window of 50 m to capture the main morphology of the flats. The absolute bed slope is then determined for each segment and averaged over all 35 km of segments.

4. Morphodynamic changes

The morphological changes of the intertidal flats and implications for the channels of the Eastern Scheldt are first considered with respect to a constant in time (present-day) MSL to focus on morphodynamic changes. Consequences of SLR are considered in the subsequent section.

After the completion of the SSB, the intertidal flats have been eroding, providing sediment to the channels. The evolution of the average elevation of the intertidal flats is shown in Fig. 2a and b, derived from three independent datasets. The Vaklodingen data, covering the spatial extent of the flats, suggest a decay in elevation with possibly smaller erosion rates in the last decade (Fig. 2a). However, this observation is based on a time series with only seven samples and relatively inaccurate data. The 35 km of annual RTK-dGPS transect measurements support the observation of smaller erosion rates over the last decade (Fig. 2a). The flats lowered 24 cm so far which is 30 % less compared to a linear extrapolation of the first years of evolution (until 1995, after which the evolution deviated from the initial linear trend). Furthermore, the transect time series indicate a relatively gradual evolution over most years and larger changes over some years. The reasons for this variability can be inferred from the 42 monthly-measured point-elevation plots (Fig. 2b), even though these observations are predominantly located on the lower edges of a tidal flat (Fig. 1). In 1990, a sudden drop in bed elevation occurred – coinciding with some of the largest storms of these decades – after which the average erosion rate over these plots reduced by 24 %. Despite this change in erosion rate, erosion occurred relatively gradually (r-squared above 0.95 and root-mean-squared-error below 1 cm) both before (over 3 years) and after this drop (over 12 years). These relatively constant erosion rates for clusters of multiple years are also visible in the transect data (Fig. 2a). The 1990 bed level decay is less pronounced in the system-wide transect data (Fig. 2a), indicating storm-impacts are not uniform across the flats.

While eroding, the intertidal flats became flatter, evidenced by the evolution of the average bed slope derived from the RTK-dGPS transect data (Fig. 2c). Since 1988, the average steepness of the intertidal flats covered by the transects has been decreasing by ~19 % (i.e., the shape of the intertidal flats has been adapting). Furthermore, this dataset suggests a reduction of the rate at which the flats flattened: half of the reduction in average steepness of the flats occurred approximately within the first five years.

Sediment is transported from higher to lower elevated areas. The elevations at which net erosion and sedimentation occurred are derived from the Vaklodingen data in Fig. 3 for two 18-years periods (1983–2001 and 2001–2019). Most changes occurred in the intertidal zone and some meters below (i.e., limited changes in the deeper channels). The elevation above which the losses and gains in area balanced was MSL-3.5 m for both periods (i.e., sedimentation especially in the shallow edges/zones of the channels). Consistently for both periods, a reduction in tidal flat surface area is observed over the upper half of the tidal window (roughly between MSL and MHW) whereas an increase in surface area is observed below (especially around MLW). This supports a

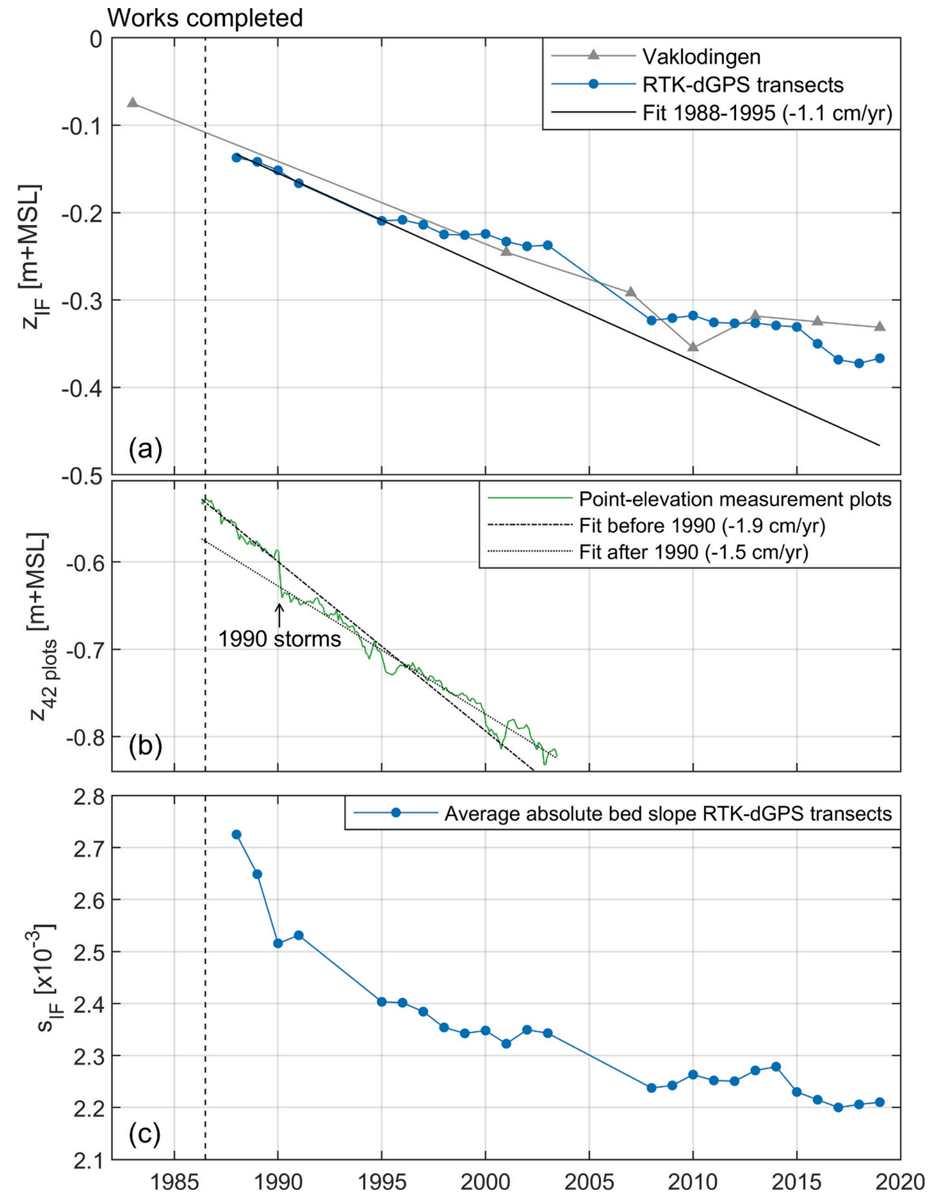

Fig. 2. Evolution of the intertidal flats (bounded by MLW and MHW) with respect to a constant MSL. The evolution of the average elevation of the flats is visualized in (a) derived from the Vaklodingen and the 35 km of RTK-dGPS transects. A time series of the average evolution of the 42 point-elevation measurement plots is provided in (b). The evolution of the average absolute bed slope of the intertidal flats is shown in (c), based on the transects measurements. Locations of included transect segments and measurement plots are shown in Fig. 1. Linear fits to the transect data in (a) and the plot measurements in (b) are provided over the periods indicated in the legends (extrapolation illustrates deviation from linear evolution).

general flattening of the intertidal flats as suggested with Fig. 2c. Despite the similar pattern in areal changes over depth classes for both periods, the magnitude of the changes reduced over time. The sum of the absolute changes in area for all elevation classes of Fig. 3 halved from the first to the second period. Aligned with Fig. 2a and c, this indicates not only a reduction in the erosion rate of the intertidal flats but also a reduction in the rate at which the intertidal flats flattened.

The volume of sediment present in the intertidal flats between MLW and MHW – the source of sediment for the channels – is computed from the Vaklodingen data. In 1983, ~126 million m^3 of sediment was present in the intertidal flats, which reduced by roughly a fifth to ~98 million m^3 in 2019. As this lessened the volume of the channels, it attenuated their initial sediment demand of ~500 million m^3 by 6 % (*Component 1* in Fig. 4). At the same time, this volume reduction of the flats corresponds to a ~3.1 % increase of the tidal prism (initially equal to ~908 million m^3). Considering the equilibrium volume of the channels to be proportional to the tidal prism to the power 3/2 (Eysink, 1990), this implies a ~4.7 % increase of the initial equilibrium volume of ~2250 million m^3, i.e., another 21 % attenuation of the sediment demand of the channels (*Component 2* in Fig. 4). Altogether, the sediment demand of the channels reduced by 27 % over these three decades through morphodynamic changes of the flats (*Components 1* + *2* in Fig. 4a).

5. Consequences of sea level rise

Even without morphodynamic activity, SLR alters the state of tidal basins. The present-day SLR in this region amounts to ~2.7 mm/year (Steffelbauer et al., 2022) which means that the intertidal flats of the Eastern Scheldt have drowned 8 cm by SLR alone over the three post-barrier decades. Therefore, the total relative elevation change of the flats (including SLR) was one-third larger than the morphodynamic

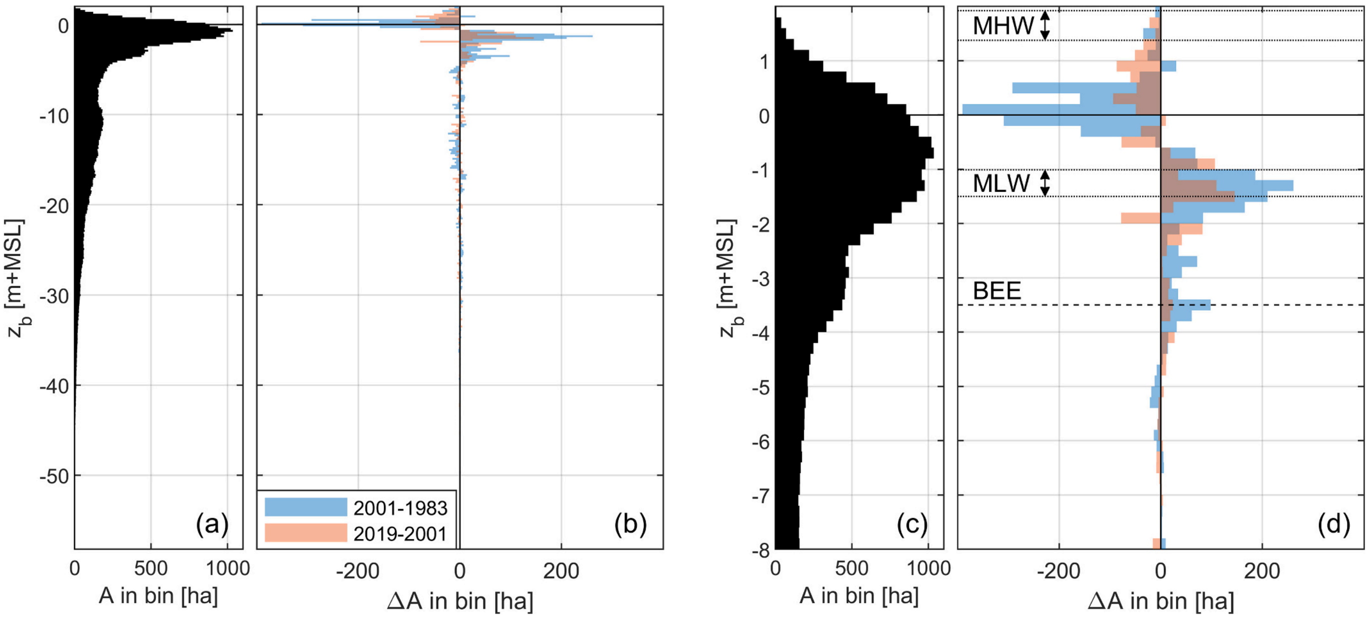

Fig. 3. The area within vertical bins of 0.2 m is shown for different vertical limits in (a) and (c), for the Vaklodingen elevation data (averaged over 1983, 2001 and 2019). Changes in area within these bins from 1983 to 2001 and 2001 to 2019 (18 years interval) are shown in (b) and (d) for vertical limits corresponding to (a) and (c), respectively. Only parts of the domain are included with data in all three considered years (96 % of the domain). The dotted lines in (d) illustrate the spatially varying MLW and MHW levels across the estuary. Data above the local MHW level are excluded from the analysis. The elevation above which the net area change equals zero (break-even elevation; BEE) is indicated in (d) with the dashed line (MSL-3.5 m for both periods).

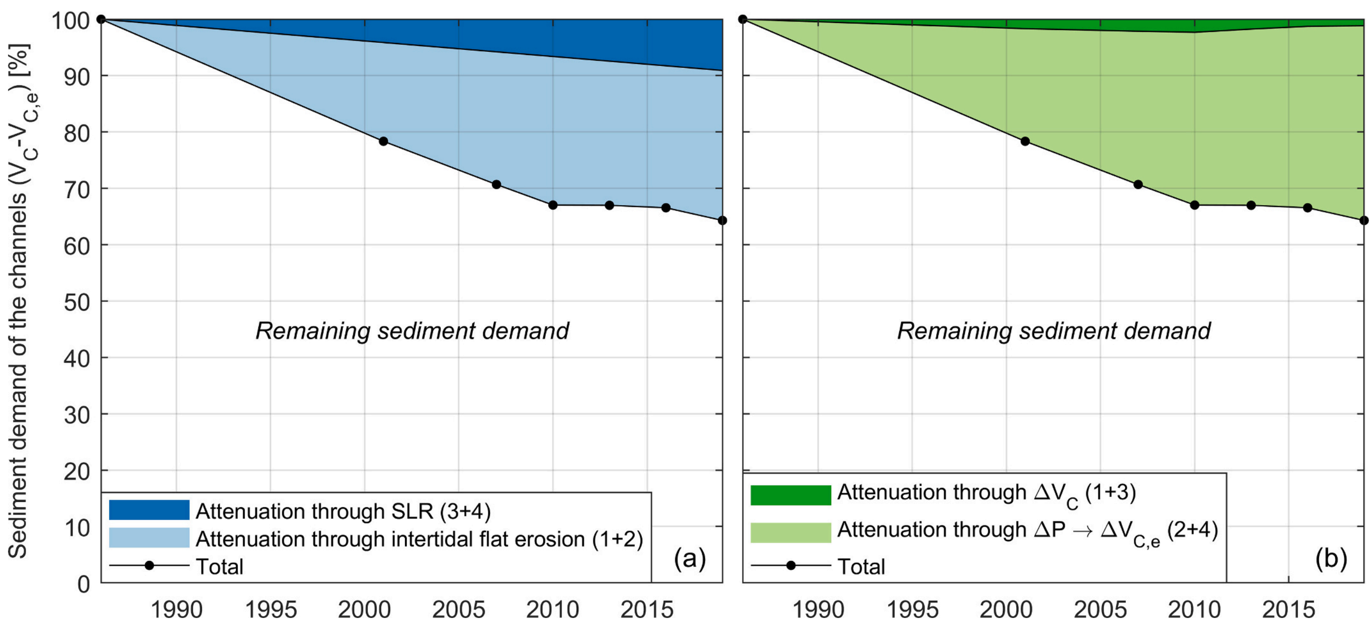

Fig. 4. Evolution of the sediment demand of the channels as the difference between the channel volume V_c and the equilibrium channel volume $V_{c,e}$. In (a) the attenuation of the sediment demand is divided to the contributions by SLR and intertidal flat erosion. In (b) the attenuation is decomposed through changes in V_c and through changes in $V_{c,e}$ (following gains in tidal prism P). The dots indicate years with volume data of the intertidal flats. The 1983 data is used as an estimate for 1986 (completion of storm surge barrier and closure dams). The numbers between brackets refer to the distinct components numbered in the results section.

lowering of the flats alone over this period (24 cm; Fig. 2a).

Another effect of SLR is the alteration of the sediment demand of the channels through two mechanisms. First, SLR increases the volume of the channels. Given a surface area of the channels of ~250 km^2, their volume increases by ~0.7 million m^3/year through SLR alone. This amplifies the sediment demand (initially equal to ~500 million m^3) by 0.14 %/year (*Component 3* in Fig. 4).

Second, the tidal prism increases (i.e., attenuating the sediment demand instead) with SLR. Jiang et al. (2020) estimated – with a hydrodynamic model excluding morphological changes (i.e., not incorporating morphodynamic feedback on the tidal range) – the tidal range to increase in the Eastern Scheldt with 11.5 % for every meter of SLR (i.e., 0.03 %/year for the present-day SLR-rate). This induces a proportional increase in tidal prism. Additionally, with the net-drowning of the flats by SLR alone, the tidal prism increases another 0.03 %/year for present-day SLR-rates (considering ~100 km^2 of flats). Following Eysink (1990), the annual 0.06 % tidal prism gain relates to an increase in equilibrium volume of the channels of 0.09 %/year. This implies an annual attenuation of the sediment demand of 0.41 % (*Component 4* in Fig. 4).

Considering both mechanisms (amplification through *Component 3* and attenuation through *Component 4*), SLR imposes a net attenuation of the sediment demand of 0.27 %/year. Accumulating over the three considered decades, SLR attenuated the sediment demand of the channels by 8 % (Fig. 4a).

6. Discussion

The morphological response of estuaries to the construction of SSBs and closure dams is shown to involve substantial temporal variations. A variety of mechanisms affect the morphology on different time scales. In the Eastern Scheldt, the intertidal flats have been eroding consistently after the construction of the SSB and closure dams, but the erosion pace decayed over time and involved sudden changes.

The reduction in erosion rates of the intertidal flats over the three post-barrier decades (~30 %) was proportional to the attenuation of the sediment demand of the channels by sediment transport from the flats and SLR over this period (~35 %; Fig. 4). Additionally, the sediment demand of the channels may have been attenuated by another 6 % over this period as 1 million m^3/year of fine sediments have possibly been imported through the SSB (Smaal and Nienhuis, 1992; Louters et al., 1998). As the adaptation pace of estuaries decays with decreasing imbalances (Renger and Partenscky, 1980; Eysink, 1990), the erosion of the flats is expected to remain attenuated. So far, the sediment demand of the channels has been attenuating predominantly through intertidal flat erosion (Fig. 4a). However, attenuation through SLR is becoming increasingly important (possibly even dominant) when erosion rates of intertidal flats reduce (e.g., last decade in Fig. 4a) and SLR accelerates. The attenuation of the sediment demand of the channels resulted almost completely from tidal prism gains (i.e., gains in equilibrium volume of the channels), whereas the actual channel volume barely changed (Fig. 4b). Thus, achieving equilibrium of channels requires a sediment volume equal to only a fraction of their initial sediment demand if tidal prism changes occur (e.g., through intertidal flat erosion and SLR). However, even when the sediment demand of channels would be closed, intertidal flats will still face a sediment demand themselves to cope with SLR (i.e., to avoid drowning), even more under reduced sediment imports and increasing SLR-rates (Elmilady et al., 2022; Benninghoff and Winter, 2019; Huismans et al., 2022).

After the SSB and closure dams were constructed, the intertidal flats have not only been facing a yet unabridged sediment demand from the channels, but also a related reduction in tidal flow velocities (Vroon, 1994; Louters et al., 1998; Eelkema et al., 2009). The modified balance in hydrodynamics on the flats enforced changes in tidal flat shape (Friedrichs, 2011). As the flattening involved a migration of sediment from the intertidal to the subtidal elevations (Fig. 3; Louters et al., 1998), this change in shape of the intertidal flats inherently implied a net lowering of these flats. After approximately a decade, the shape-related morphological adaptation had decayed (Figs. 2c and 3). As milder bed slopes favor smaller bed level changes (e.g., wave dissipation spreads over larger distances; De Vet et al., 2020), morphodynamic activity reduced even further.

Complementary to these relatively gradual adaptation mechanisms, storms introduce sudden changes in intertidal flat evolution. For example, the major drop in elevation observed in the point measurements (1990; Fig. 2b) related to some of the most extreme storms on record, which involved three succeeding closures of the SSB, while to date it was closed on average less than once each year. During closures of the SSB with several hours of relatively constant water levels inside the basin, the energy of locally generated storm waves focuses on specific elevations of the intertidal flats, enhancing the erosion potential (De Vet et al., 2020). As the erosion event was followed by a persisting change in erosion pace, storms can – likely through changes in shape of the flats (Yang et al., 2003) – have long-lasting morphological consequences. However, storm impacts can be a local phenomenon (e.g., the 1990 storms had less impact on the system-wide evolution; Fig. 2a). This results from the non-uniform character of storm erosion within intertidal areas (De Vet et al., 2020) and local deposition of eroded sediments (Yang et al., 2003). But even then, storms may impose net erosion of the flats, affecting their average elevation (e.g., steps in Fig. 2a).

Hence, the morphological adaptation of intertidal flats to human interventions is generally forced by a combination of (1) the sediment demand of the channels following interventions which attenuates with tidal flat erosion and SLR mainly through tidal prism gains, (2) the adaptation of the shape of the flats to adjustments in local hydrodynamics, and (3) sudden but potentially persisting consequences from storm-impacts. These mechanisms have different degrees of importance over time, implying multiple time scales are involved. Other mechanisms, such as influences of macrobenthos (Widdows et al., 2004; Shi et al., 2020) and grain-size-varying adaptation time scales (Colina Alonso et al., 2021), make morphological responses even more complex.

The future ecological fate of estuaries facing SSBs, closure dams and SLR is largely influenced by the response of intertidal flat morphology. Although erosion rates of intertidal flats can attenuate over time, SLR will further reduce emergence duration of the flats. Intertidal areas that remain will typically be lower and more gently sloped. As this implies less morphological diversity (similarly observed in Venice Lagoon; Tognin et al., 2022) and shorter emergence duration of the flats, this can have severe ecological consequences (e.g., reducing the foraging potential for migratory birds; Nehls and Tiedemann, 1993; Mu and Wilcove, 2020). The extent to which an estuary will face these consequences largely depends on sediment availability (Orton et al., 2023). For example, if import of (fluvial) sediments is preserved, the estuary would remain coupled to the neighboring sedimentary system, which could improve the tidal flats' ability to cope with consequences from SSBs and SLR (Ralston, 2023; Huismans et al., 2022; Lodder, 2024). Knowing the estuarine morphological response allows for better engineering work designs (Jonkman and Merrell, 2024), minimizing morphological consequences (e.g., minimizing changes in tidal prism and velocities). Moreover, measures to mitigate resulting ecological consequences (e.g., tidal flat nourishments; Van der Werf et al., 2019) can be optimized for the coexisting adaptation mechanisms.

7. Conclusions

Estuarine channels and intertidal flats adapt their morphology to storm surge barriers (SSBs), closure dams and sea level rise (SLR). SSBs and closure dams impose instant changes in estuarine hydrodynamics. Intertidal flats adapt their shape, especially in the first years after construction, to the lower flow velocities on the flats. Estuarine channels face a long-term sediment demand imposed by the suddenly reduced tidal prism. This sediment demand of the channels induces erosion of the intertidal flats. The sediment demand of the channels (and hence the erosion of the flats) attenuates with sediment transport from the flats to the channels and SLR. This is mainly due to tidal prism gains. Therefore, the sediment demand of the channels can be closed even if the volume of sediment in the flats is only a fraction of the initial sediment demand and sediment import from sea is obstructed. However, even when the sediment demand of channels closes, intertidal flats face a sediment demand themselves when coping with SLR (i.e., drowning of flats is increasingly SLR-driven). In addition to these gradual mechanisms, storms can suddenly boost the adaptation of intertidal flats. Maintaining precious estuarine ecosystems requires holistic system management strategies incorporating the various morphological mechanisms following SSBs, closure dams and SLR.

CRediT authorship contribution statement

P.L.M. de Vet: Writing – review & editing, Writing – original draft, Visualization, Formal analysis, Conceptualization. **B.C. van Prooijen:** Writing – review & editing, Investigation, Conceptualization. **P.M.J. Herman:** Writing – review & editing, Investigation, Conceptualization. **T.J. Bouma:** Writing – review & editing, Investigation, Conceptualization. **D.S. van Maren:** Writing – review & editing, Investigation, Conceptualization. **B. Walles:** Writing – review & editing, Investigation, Conceptualization. **J.J. van der Werf:** Writing – review & editing, Investigation, Conceptualization. **T. Ysebaert:** Writing – review & editing, Investigation, Conceptualization. **E. van Zanten:** Writing – review & editing, Investigation, Conceptualization. **Z.B. Wang:** Writing – review & editing, Investigation, Conceptualization.

Declaration of competing interest

The authors declare the following financial interests/personal relationships which may be considered as potential competing interests: P.L.M. de Vet reports financial support was provided by Royal Netherlands Academy of Arts and Sciences (KNAW). P.L.M. de Vet reports financial support was provided by Deltares. P.L.M. de Vet reports financial support was provided by Rijkswaterstaat. If there are other authors, they declare that they have no known competing financial interests or personal relationships that could have appeared to influence the work reported in this paper.

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Data availability

All data analyzed in this study have been measured and provided by Rijkswaterstaat (Dutch Ministry of Infrastructure and Water Management). These data are available on the 4TU.nl Research Data Repository as De Vet (2024) under doi:10.4121/33e9810b-d211-4e0a-bd6c-f17e36de0cd3.

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