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A mud budget of the Wadden Sea and its implications for sediment management

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The world's coasts and deltas are progressively threatened by climate change and human activities. The degree at which coastlines can adapt to these changes strongly depends on the sediment availability. The availability of muddy sediments is however poorly known. This study aims at developing a mud budget for the world's largest system of uninterrupted tidal flats: the Wadden Sea. The resulting mud budget is nearly closed: ~ 12 million ton/year enters the system on its western end, ~ 1.5 million ton/year is added by local rivers, while ~ 12 million ton annually deposits or is extracted by anthropogenic activities. A mud deficit already exists in the downdrift areas, which will only become more pronounced with increased sea level rise rates. Mud is thus a finite resource similar to sand, and should be treated as such in sediment management strategies. Resolving future challenges will therefore require a cross-border perspective on sediment management.

The world's coasts and deltas are increasingly influenced by human interventions. Deltas are subsiding at alarming rates[1–3], the influx of fluvial sediments is reduced because of upstream dams[4,5] or sand mining[6,7], and the alongshore drift is interrupted by coastal structures[8,9]. Superimposed on these local interventions are global climate change effects, with sea level rise (SLR) progressively threatening coastlines worldwide[10–12]. In the coming century, both human interventions and climate change will put the livelihoods of millions of people at risk[13]. Deltas and coastal environments are dynamic systems in which erosion, transport, and deposition of sediments provide a delicate balance. The degree to which coastlines will be able to adapt to future changes, especially in view of SLR, strongly depends on modifications to coastal sediment budgets.

Coastal systems display a wide variety of types, ranging from exposed high-energy beaches to estuaries and back-barrier lagoons. Sediment budgets along sandy open-coast beaches are strongly driven by the wave climate and adapt relatively quickly to SLR or human interventions[14,15]. Using empirical formulations[16–18], the sediment fluxes along sandy beaches are relatively well known, and their adaptation to SLR can be reasonably predicted when assuming the coastal profile to remain constant[12] (although such a simplification is debated[19]). Sediment transport in estuaries, tidal basins and lagoon systems is primarily driven by tidal transport of both mud and sand. Adaptation of such relatively sheltered systems to SLR requires enhanced sediment trapping. Predicting this enhanced trapping introduces two challenges: one is related to the delicate balance in erosional and depositional processes within the basins, and the other to the availability of sediments[20,21]. In many of such basins, the availability of sand will be a limiting factor, but this may be (partly) compensated with fine-grained sediments (i.e., mud)[22–25]. In contrast to sand-dominated systems, the alongshore fluxes of fine-grained sediments are poorly known. We aim to develop such a fine-grained sediment flux and highlight the importance of knowing it for the world's largest uninterrupted system of barrier islands and tidal flats—the Wadden Sea.

The Wadden Sea spans a distance of nearly 500 km along the coastlines of the Netherlands, Germany and Denmark in the Northwestern European shelf (Fig. 1). As a protected UNESCO world heritage site, it provides crucial habitats for numerous species of fish, mammals and birds. It also plays an important role as a sink for CO_2, in particular by blue carbon storage in its sediments, seagrass and salt marshes[26]. Water motion in the Wadden Sea basins is influenced by tides (with tidal ranges from about 1.5 to over 4 metres), offshore waves generated in the North Sea that penetrate through

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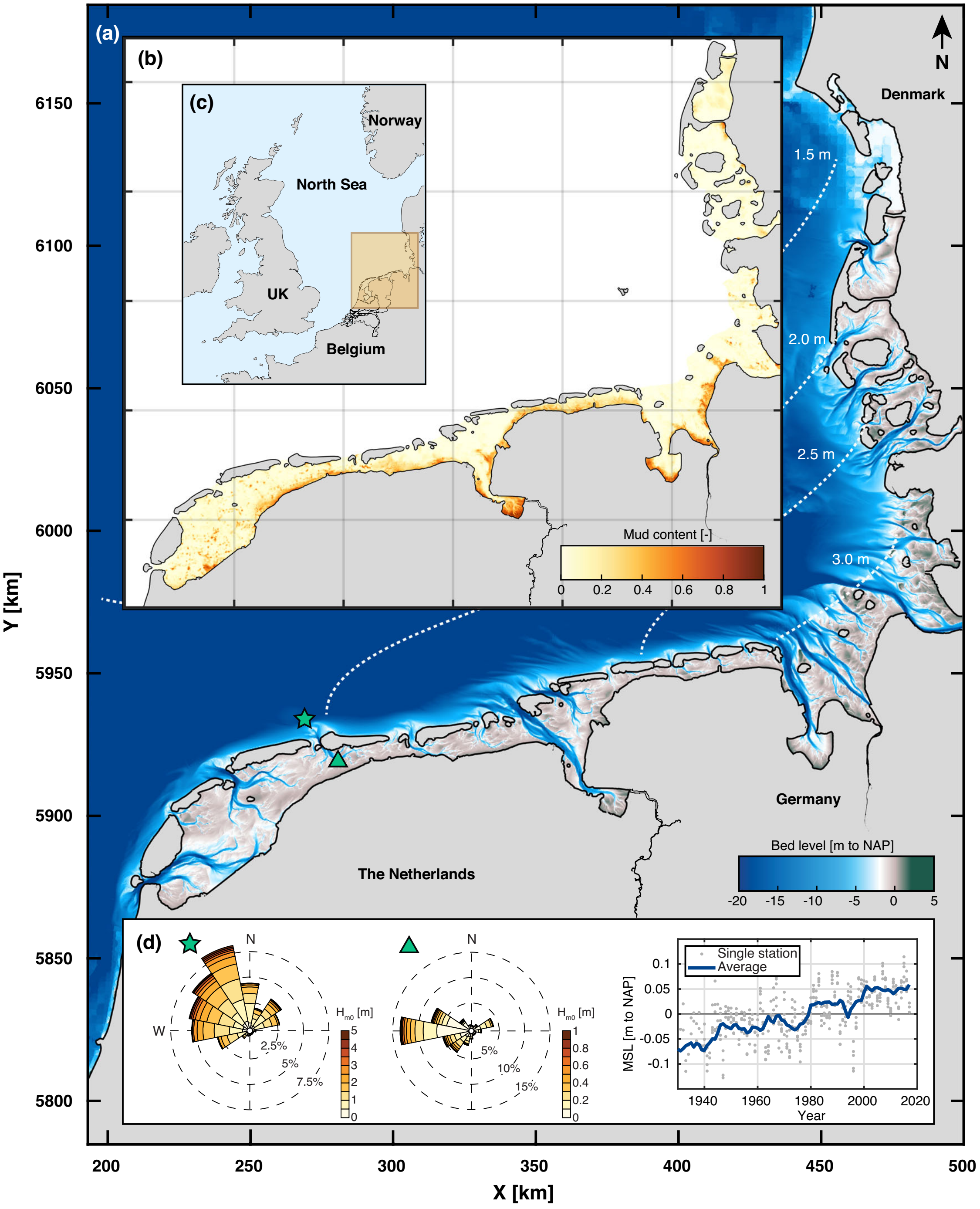

Fig. 1 | Overview map of the Wadden Sea. a Current bathymetry (combined maps of 2015–2021 in m to NAP, Netherlands Ordnance Datum). The white dotted lines indicate the tidal range[105]. **b** Bed sediment composition plotted as the mud content in the upper bed (top 4–10 cm). The Danish part of the Wadden Sea is not included in the plot because there is no available data on this area. **c** Location of the Wadden Sea. **d** Example of a wave climate on an ebb-tidal delta and in a Wadden Sea basin (both calculated over the period 2015–2018), and average yearly mean sea level (MSL) from tide gauge records in the Dutch basins over the past century.

the inlets and smaller locally-generated wind waves (Fig. 1d). Besides, wind-driven currents play an important role in the shallow parts of the basins[27,28]. The main freshwater sources enter the Wadden Sea through the IJssel Lake sluices (average yearly discharge of ~ 450 m^3/s[29]) and the Ems (~100 m^3/s[30]), Weser (~300 m^3/s[31]) and Elbe (~750 m^3/s[30]) estuaries. SLR has so far been limited, with rates of 1.2–2.3 mm/year in the past century[32] (Fig. 1d). Accelerated SLR and subsidence, however, threaten the Wadden Sea's existence: if the sediment import cannot keep up with increased relative SLR rates, this will result in partial loss or even disappearance of the ecologically valuable intertidal areas[33,34].

The sediment bed of the Wadden Sea, as that of many other coasts and deltas (e.g., Yangtze Delta, Mekong Delta, Nakdong Estuary, San Francisco Bay), consists of sand and mud. Despite decades of scientific attention to sandy alongshore sediment budgets[35–37] and sand-mud budgets of fluvial systems[38–40], marine mud budgets remain largely unknown. This is probably related to the inherent difficulties with obtaining such a budget. Transport of mud cannot be predicted with empirical formulae because its transport is supply-limited and therefore needs to be based on observed bathymetric changes or detailed measurements of hydrodynamics and sediment concentrations. The Wadden Sea provides herein a globally unique case, with detailed observations of bathymetric changes and grain size distribution[41–47]. Such observations can be used to quantify the contribution of sand and mud to infilling[48], thereby providing a sediment budget.

In this study, we expand on previous work by developing a complete mud budget for the entire Wadden Sea by carefully quantifying sources and sinks. We synthesise earlier studies to obtain the best estimate for the sources while we compute sinks using extensive bathymetric and grain size distribution data. By demonstrating that this mud budget is nearly closed, we show that mud is, in fact, a commodity that may become a limiting factor under conditions of accelerated SLR.

Results and discussion

Mud sources and sinks

To establish the mud budget, we determine the magnitude of the main sources and sinks, focusing on inorganic particulate matter. The largest mud source is the marine North Sea Continental Flow (NSCF). This flow transports mud from the Dover Strait (in between France and the United Kingdom) along the French, Belgian and Netherlands coasts. Its magnitude at the western end of the Wadden Sea is on average, approximately 10–14.4 million (M) ton/year (see the Methods section). The sediment plume first deflects to the East, after which it turns northward again in the German Bight while interacting with the various tidal basins (Fig. 2a). Although these basins primarily act as sediment sinks, several rivers (from Lake IJssel and the Ems, Weser and Elbe estuaries) constitute an additional sediment source, adding a total amount of mud of 1.5 M ton/year into the Wadden Sea.

The main mud sinks throughout the Wadden Sea can be divided into four categories: deposition in the basins (7.95 M ton/year) and on the salt marshes (1.84 M ton/year), offshore deposition (0.56 M ton/year), and anthropogenic extraction (1.98 M ton/year, see Fig. 2b). Most basin deposition presently takes place in the intertidal areas, especially along the mainland coast, although abandoned channels also acted as major mud sinks in the past[48,49]. The average mud deposition in the basins and on the salt marshes largely varies per basin (see also Supplementary Tables 1 and 2 and Figs. 1 and 2 in the Supplementary Information). The main offshore sink is Helgoland, where continuous deposition rates of about 1.6 mm/year[50] amount to a sink of approximately 0.5 M ton/year. Anthropogenic sediment extraction provides the second biggest sink, even surpassing salt marsh deposition. Hereby we refer to the removal of sediments by dredging without disposing of the sediment within the Wadden Sea or in its vicinity in the North Sea. Although most dredged sediment is redistributed within the Wadden Sea, some of the sediment dredged from the lower Ems[51,52], Weser[53,54], and Elbe estuaries[55–57] is disposed on land (either on disposal sites for contaminated sediments or as coastal protection reinforcement).

The mud budget is nearly closed

The various sediment sources and sinks have been converted into a sediment pathway (Fig. 2c). Starting West (at Den Helder), where the NSCF enters the Wadden Sea, it follows the anti-clockwise rotation of the flow along the barrier islands until the most northern end. With increasing distance from Den Helder, the magnitude of the cumulative sinks increases far beyond the sources along its pathway. With our best estimate for the initial sediment supply and various sources and sinks, there is only about 1.5 M ton/year unaccounted for in the northern end. This can be considered a small amount given the wide range of apparent uncertainties and the possible loss of mud to the offshore areas along its pathway.

The largest uncertainty in our estimate is the magnitude of the flux in the NSCF, followed by the basin deposition, mud extraction and salt marsh sedimentation. The uncertainty in these latter three includes the variability in the mud density and sediment composition over time (see the Methods section). The lower end of the cumulative error band is considered to be unrealistic since this would imply that there is no mud left after the Elbe estuary (basin 22), while mud sedimentation has been observed in the basins and on the marshes to its North. The observation that the mud budget is nearly closed is only limitedly affected by uncertainties in the fluvial sources: even if those would vary by a factor of 2 (which does not seem to be the case when comparing our data to other estimates[58]), the total sources would still only be slightly larger than the sinks.

The spatial variability of the mud sinks is large throughout the entire domain (see Fig. 3a). To compensate for the basin size, we determine the basin deposition per km^2, revealing a distinctive trend (Fig. 3b): mud deposition largely increases with increasing distance from Den Helder until km 224 (basin 14, in East Frisia), after which it sharply drops (especially after the Elbe estuary, km 300). Salt marshes are efficient mud traps. Here, sedimentation rates are up to an order of magnitude larger than in the basins (although their total area is much smaller) and follow the same spatial trend. Most sediment deposits are on the foreland marshes, while a smaller amount accretes on the island- and hallig marshes (Supplementary Fig. 2 in the Supplementary Information). The decline of sedimentation rates in the last 200 km of the Wadden Sea is even more pronounced in these foreland marshes (Fig. 3d). These spatial trends in the basin and marsh sedimentation suggest that there could be a mud shortage in this downdrift part of the Wadden Sea[59,60].

Another indicator of the potential mud shortage in the northern German and Danish parts of the Wadden Sea is the upper bed sediment composition in the basins. Whereas the mean mud content ranges between 5% and 25% in the first 300 km without showing a distinctive spatial trend between the basins, it drops abruptly below 10% afterwards (Fig. 3e). Even more pronounced is the trend in the bimodality of the mud content (Fig. 3f). The mud content in the Wadden Sea tends to be bimodally distributed[61], with the sediment bed being either relatively sandy (mode 1) or relatively muddy (mode 2). This bimodality may disappear if suspended mud concentrations become low (only mode 1 remains) or high (only mode 2 remains)[61]. Figure 3f shows that bimodality disappears after km 300, suggesting that suspended mud concentrations are lower here, and therefore also indicating a potential mud shortage compared to the other Wadden Sea basins. Thus, both the sedimentation rates and the bimodality of the bed sediments indicate that mud sedimentation in the northern parts of the Wadden Sea might be supply-limited, which matches the observation that the cumulative mud budget in these areas is largely reduced. Note, however, that a potential higher energy exposure in these areas could also be a contributing factor to this. The western parts of the Wadden Sea appear to be accommodation space limited (i.e., sediment deposition rates are restricted by available space to deposit and not by the supply of sediments). This also explains the high suspended sediment concentrations observed in many parts of the Western Wadden Sea, exceeding many g/l even on the exposed tidal flats[28].

Fine sediments as a resource

Intertidal areas comprise nearly half of the surface of the Wadden Sea[62] and provide important functions related to safety, ecology and economy. In combination with salt marshes, the intertidal areas protect the mainland coast[63,64]. Intertidal areas also provide habitat for benthic communities and higher trophic levels, acting as e.g., fish nurseries[65] and feeding ground for birds[66]. Their disappearance would lead to a large-scale loss of biodiversity[67]. Their economic importance is also evidenced by other ecosystem services such as fisheries[62,68].

These intertidal systems are composed of sand and mud. Mud plays a crucial role in creating specific habitats for benthic species[45,69,70], and contributing to the current morphological evolution of the intertidal areas[48] as well as their ability to keep pace with relative SLR[71]. The rate at which sand is transported towards the intertidal areas is namely largely dependent on the transport capacity[22] and will become a limiting factor under conditions of accelerated SLR[34,72,73]. The decline in sand supply will increase with increasing distance from the inlet, resulting in partial drowning of the intertidal areas if the sediment deficit is not compensated by mud. Deposition of fine-grained sediments is supply- or accommodation space limited and hardly depending on transport capacity.

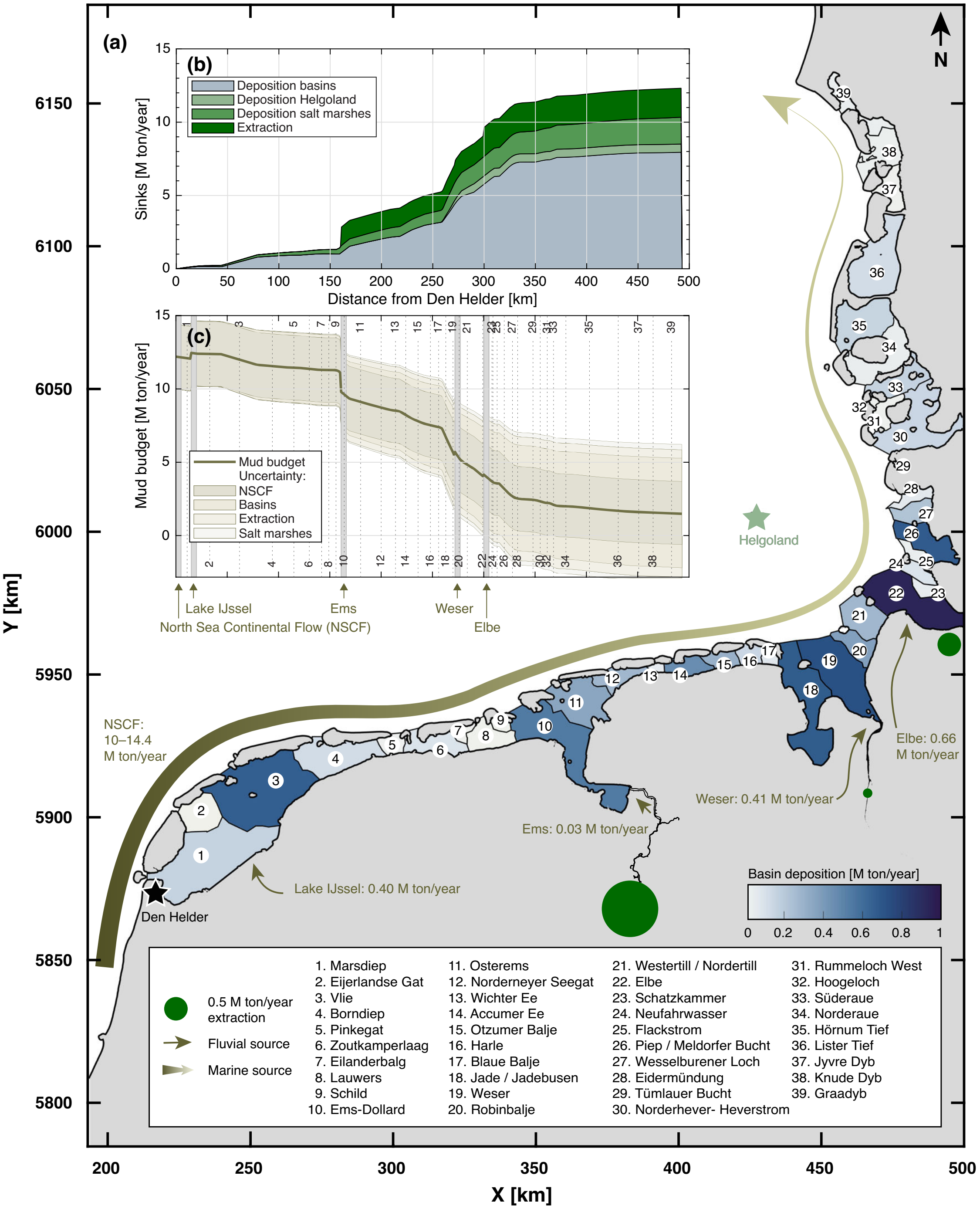

Fig. 2 | Mud budget of the Wadden Sea. a The blue colours show the basin-average mud deposition, calculated for 1996–2015. The brown arrows indicate the main mud sources, and the green dots the average mud extraction from the Ems, Weser, and Elbe estuaries (in which we assume an uncertainty range of 20% originating from a variation in sediment composition of the dredged material). **b** Cumulative alongshore sediment sinks per type. **c** Estimated alongshore mud budget and its uncertainty as a function of distance from Den Helder. The uncertainty initially results from the NSCF flux (10–14.4 M ton/year, darkest brown band) but becomes progressively more influenced by sedimentation in the basins, on salt marshes and through extraction (lighter brown bands). The vertical grey bars indicate the location of sources, and the numbered dotted lines the location of individual basins.

The accretion rates on some of the tidal flats presently outpace SLR[22,48,74,75], but this may change in the future for two reasons: First, it is expected that SLR will accelerate in the coming centuries. The global sea level has risen 2.1 mm/year since 1970, but this speed is accelerating[76,77]. The region-mean SLR in the Wadden Sea has been slower—1.77 mm/year since 1958, most likely due to regional geological, glacio-isostatic and meteorological effects—but projections of SLR rates range from 2.2 to 18.3 mm/year for the year 2100[78]. Secondly, the current accretion rates of the tidal flats do not necessarily represent their ability to keep up with SLR. The present-day development of the Wadden Sea is largely influenced by human interventions, of which the response timescales are long. The observed sedimentation rates are partly a response to these interventions, and given the exponential decay of such a response[49], it is likely that sedimentation rates will slow down in the future. Accretion rates will largely depend on the sediment availability in combination with sediment management strategies.

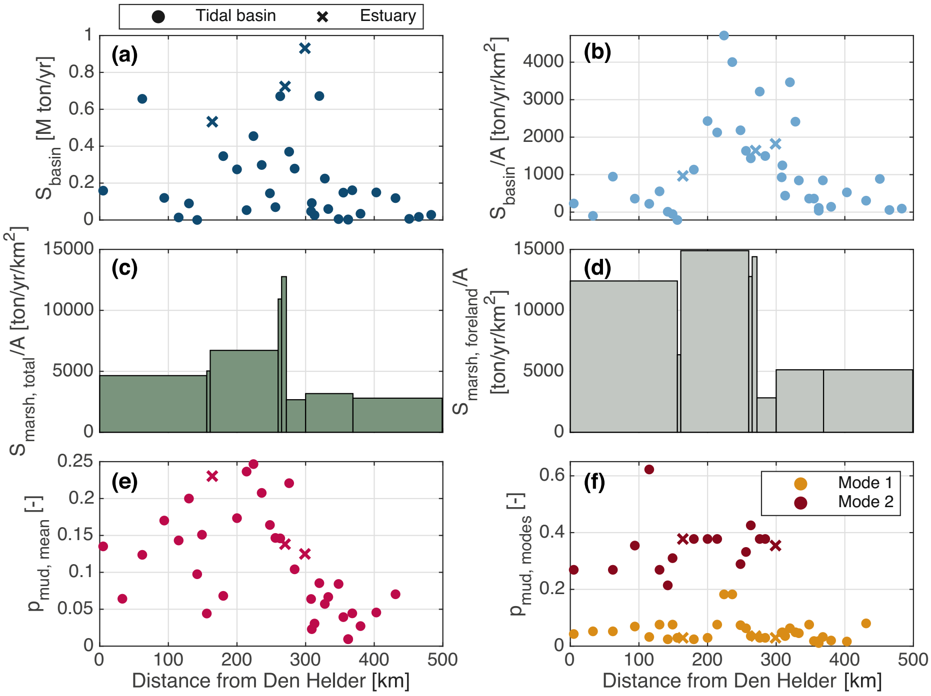

Fig. 3 | Spatial variation of sinks and indicators of a decreasing mud availability. a, **b** Scatter plot of the total mud sinks in the basins. Tidal basins are indicated by a dot, and estuaries by a cross. Basin sinks per km^2 show a clear spatial trend along the Wadden Sea coast. **c** Histogram of the average salt marsh sinks per km^2. **d** Histogram of the salt marsh sinks in foreland salt marshes. This type of marsh has the largest contribution to the total marsh sinks (see also Supplementary Fig. 2 in the Supplementary Information). **e** Average mud content ($p_{\mathrm{mud,mean}}$) in the upper sediment bed of the basins. **f** Modes of the probability density function (PDF) of the mud content in the sediment bed ($p_{\mathrm{mud,modes}}$, plotted per basin), representing the equilibrium mud content in the bed[61]. Bimodality is detected up to km 300 (Elbe estuary).

Implications for future sediment management

Our findings are important for future sediment management of the Wadden Sea specifically[79], but also in general for muddy environments where fine-grained sediments are often assumed to be abundantly available. Our work illustrates that mud is a finite resource, and therefore circularity is key. Mud is abundantly available in the Western Wadden Sea, leading to regular maintenance dredging. Here, even without interventions, SLR will probably lead to higher sedimentation rates over the supra- and intertidal areas because of the increase in accommodation space. But even more, a likely future sediment management strategy will be to progressively trap fine-grained sediments in anticipation of accelerated SLR. SLR, especially when combined with modified sediment management strategies, will then lead to a downdrift reduction of available fine-grained sediments. With the Wadden Sea spanning three different countries, such dependencies illustrate the importance of cross-border sediment management policies.

With mud being a finite resource and SLR inducing shortages over time, some of the policies related to the extraction of mud should potentially be revisited. In the past, sediments were primarily extracted for the construction of flood safety infrastructure (e.g., dikes, dwelling mounds) and roads[80]. Nowadays, the main motivation for extraction is the deepening of navigation channels (and the costs associated with disposal). Although the total extracted mud mass has decreased over time[53,81], it still amounts to 12–17% of the total mud budget. Sediment extraction may provide a relatively cost-effective methodology of dredging and may also lower the suspended sediment concentrations locally[81]. However, the negative impact of sediment extraction over longer timescales and larger spatial scales in the context of climate change is, at present, not considered in policy frameworks. Given the expected future demand for sediments in order to keep pace with SLR, these long-term large-scale impacts should be accounted for when planning sediment extraction. Such planning would also need to account for a delayed response resulting from the system's previous buffer capacity[22,82,83].

Consequently, we stress the need for cross-border sediment management strategies fuelled by our findings that not only sand but also mud is often a finite resource. The accuracy of tools to predict a coastal system's response to SLR is limited, posing a challenge for scientists, coastal engineers, and decision-makers. While numerical models may capture short-term up to decadal morphodynamic evolution—especially after large-scale distortion of the system[84]—their ability to predict (natural) long-term development remains limited[85]. Moreover, the absence of calibration and validation data of system response to future SLR conditions introduces major uncertainties. We believe that understanding this response should start with a sediment budget on a system scale, i.e., crossing international borders and national policy frameworks.

Methods

North Sea mud sources

The biggest source of mud transported into the Wadden Sea is the North Sea, where mud transport follows the long-year residual current patterns. The North Sea Continental Flow (NSCF, sometimes referred to as Continental Coastal Water) is the most relevant path to the Wadden Sea's mud import. We reconstruct an estimate of its magnitude based on data and model results reported in the literature, as explained below.

The mud flux transported by the NSCF originates from the Dover Strait, where a net inflow of water and suspended particulate matter is transported into the North Sea[86,87]. The magnitude of the mud flux has been widely researched, but the results show a large variety originating from the high temporal and spatial variability of mud fluxes in combination with the methodologies that have been used[88]. An extensive recent study, where the net flux was calculated based on satellite images as well as on numerical model simulations, indicates a mud flux through the Dover Strait of 22.26–31.74 M ton/year[88]. Approximately 60% of this flux enters the NSCF, whereas the remaining 40% is transported in the East Anglia Plume (EAP)[88].

As the NSCF travels North, it transports mud along the French and Belgian coasts toward the Netherlands. Transport from France to Belgium is estimated at 15.5 M ton/year, and further on to the SW Netherlands at 12.8–14.5 M ton/year[89]. North of the Netherlands–Belgian border, but before reaching the Wadden Sea, the NSCF encounters mud sinks in the Eastern Scheldt and around the Port of Rotterdam, as well as a fluvial source from the Rhine River. Together, this results in a net sink of 0.1 M ton/year[90], resulting in 12.7–14.4 M ton/year of mud reaching the coastal zone just South of the Wadden Sea. Other research[91] reports slightly lower values of around 10 M ton/year. We therefore assume a range between 10 and 14.4 M tons/year of mud reaching the Wadden Sea.

The EAP is another North Sea current that transports suspended matter from the Dover Strait, the Thames estuary and cliff erosion to the

North East along the southern English coast[88,92]. So far, the amount of suspended matter travelling with the EAP that can reach the Wadden Sea coast seems limited[90,92,93]. Instead, observations and modelling studies indicate that it is transported via the Oyster Grounds directly to the Skagerrak and the Norwegian Channel[93,94].

Main fluvial mud sources

Similar to the marine mud sources, we have collected data from the literature to estimate the average magnitude of the main fluvial sources. These are the freshwater inputs from Lake IJssel (via the sluices den Oever and Kornwerderzand) and the Ems, Weser, and Elbe estuaries. Their magnitudes are shown in Table 1.

Atmospheric deposition

We base our estimate of the atmospheric contribution to the mud sources on previously published data. Studies in the North Sea yielded average atmospheric deposition rates of 1.6–2.2 tons/km^2/year[95]. Applied to the total area of the Wadden Sea (11,400 km^2), this results in a contribution of 0.018–0.025 M ton/year. This contribution is orders of magnitude smaller than that of the marine and fluvial sources. We therefore consider it to be negligible.

Tidal basin sinks

To calculate the average deposited mud mass in the basins, we follow a previously developed approach that makes use of bathymetry change data in combination with sediment composition data to calculate the contribution of mud to the observed morphodynamic evolution[48]. Net sedimentation and erosion volumes (ΔV) are calculated by subtracting measured bathymetries. Next, these volumes are multiplied by the volumetric mud fraction in the upper bed (top 4–10 cm) to obtain the volumetric contribution of mud (ΔV_{mud}). Our sediment composition data provides information about the mass fraction of the sediment, for which we use a density relation for sand-mud mixtures in the Wadden Sea[96] to derive the volumetric mud fraction. We subsequently transform the calculated volumetric mud sinks into a mud mass by assuming that pure mud in the tidal basins has an average density of 700 kg/m^3, while in the estuaries it is slightly lower (500 kg/m^3).

We use Dutch bathymetry data of the Vaklodingen dataset (resolution of 20 × 20 m)[41] and German data collected within the EASY-GSH project (resolution of 10 × 10 m)[42,46]. Sediment composition information is based on the Sediment Atlas (sediment samples taken in the '90s in Netherlands parts of the Wadden Sea, resolution of 500 × 500 m in the channels, and 1000 × 1000 m on the intertidal flats)[43], SIBES (sediment samples taken in 2008–2018 in the Netherlands parts of the Wadden Sea, based on 50,000 surface sediment samples of approximately 7400 locations, with a resolution of 1000 × 1000 m in the channels, and 500 × 500 m on the intertidal flats)[44,45] and EASY-GSH datasets (German parts of the Wadden Sea, based on 45,000 surface sediment samples which are interpolated on a 10 × 10 m grid)[46].

Calculations are performed for the period 1996–2015 (based on data availability) on a computational grid with a resolution of 250 × 250 m. We determine an uncertainty band by assuming that the calculated volumes might vary 40% (20% higher and 20% lower) because of variations in the sediment density of sand-mud mixtures[48] and of sediment composition changes within the observed period (i.e., between Sediment Atlas data and SIBES data). No detailed bathymetric evolution or sediment composition data of the Danish basins is available, for which we have based the results of these mud sinks on existing literature[97].

Table 1 | Main freshwater sources of mud in the Wadden Sea

Source	Basin nr	Magnitude [M ton/year]
Lake IJssel	1	0.4[90]
Ems	10	0.03[101]
Weser	19	0.4[102,103 a]
Elbe	22	0.66[104]

[a] Based on an average discharge of 323 m^3/s and a concentration of 40 mg/l.

The basin numbers refer to Fig. 1. The magnitude of the sources is derived from literature.

Salt marsh sinks

Similarly, we make use of bed composition data in combination with accretion rates[98] to calculate the mud sinks on the salt marshes. The size of salt marshes in the study area was derived from literature[98] and is based on surveys carried out between 2004 and 2014. For sedimentation, we follow the terminology for sedimentation where this is expressed as the amount of sediment that is deposited in the marsh per unit area and time, i.e., kg/m^2/year[99]. No adjustments were made for organic matter since Wadden Sea salt marshes are generally minerogenic and thereby low in organic matter. Salt marsh vegetation does contribute to an enrichment of organic matter in the upper sediment layers of the marsh bed, but this organic matter appears to be lost at greater depth when it is buried by new sediment layers[100]. Similar to the calculations of the basin sinks, we account for an uncertainty range of 40% total in the salt marsh sinks calculations, originating from variations in the sediment density and in the sediment composition.

Data availability

- Bathymetry data of the Dutch Wadden Sea (Vaklodingen) is publicly available and can be requested through the Data Servicedesk of Rijkswaterstaat: https://www.rijkswaterstaat.nl/formulieren/contactformulier-servicedesk-data.
- Bathymetry data of the German Wadden Sea (EasyGSH) are available at (Bundesanstalt Für Wasserbau): https://doi.org/10.48437/02.2020.K2.7000.0002.
- Sediment composition information was obtained from the SIBES data set (to be viewed and downloaded from: https://viewer.openearth.nl/wadden-viewer), the Sediment Atlas Wadden Sea[43] (https://svn.oss.deltares.nl/repos/openearthrawdata/trunk/rijkswaterstaat/, register at oss.deltares.nl), and via the EasyGSH data set[46] (https://doi.org/10.48437/02.2020.K2.7000.0005).
- Salt marsh data was retrieved from: https://qsr.waddensea-worldheritage.org/reports/salt-marshes
- Hydrodynamic data from the Dutch parts of the Wadden Sea and the North Sea (including wave climates and water levels) was retrieved from the Data Servicedesk of Rijkswaterstaat: https://www.rijkswaterstaat.nl/formulieren/contactformulier-servicedesk-data.

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References

1. Syvitski, J. P. et al. Sinking deltas due to human activities. *Nat. Geosci.* **2**, 681–686 (2009).
2. Brown, S. & Nicholls, R. J. Subsidence and human influences in mega deltas: the case of the Ganges-Brahmaputra-Meghna. *Sci. Total Environ.* **527-528**, 362–374 (2015).
3. Minderhoud, P. S. et al. The relation between land use and subsidence in the Vietnamese Mekong delta. *Sci. Total Environ.* **634**, 715–726 (2018).
4. Vörösmarty, C. J. et al. Anthropogenic sediment retention: major global impact from registered river impoundments. *Glob. Planet. Change* **39**, 169–190 (2003).
5. Syvitski, J. P. M., Vo, C. J., Kettner, A. J. & Green, P. Impact of human on the flux of terrestrial sediment to the global coastal ocean. *Science* **308**, 376–381 (2005).
6. Eslami, S. et al. Tidal amplification and salt intrusion in the Mekong Delta driven by anthropogenic sediment starvation. *Sci. Rep.* **9**, 1–10 (2019).
7. Jordan, C. et al. Sand mining in the Mekong Delta revisited—current scales of local sediment deficits. *Sci. Rep.* **9**, 1–14 (2019).

8. Luijendijk, A. et al. The State of the World's Beaches. *Sci. Rep.* **8**, 1–11 (2018).
9. Mentaschi, L., Vousdoukas, M. I., Pekel, J. F., Voukouvalas, E. & Feyen, L. Global long-term observations of coastal erosion and accretion. *Sci. Rep.* **8**, 1–11 (2018).
10. Nicholls, R. J. & Cazenave, A. Sea-level rise and its impact on coastal zones. *Science* **328**, 1517–1520 (2010).
11. Bilskie, M. V., Hagen, S. C., Medeiros, S. C. & Passeri, D. L. Dynamics of sea level rise and coastal flooding on a changing landscape. *Geophys. Res. Lett.* **41**, 927–934 (2014).
12. Vousdoukas, M. I. et al. Sandy coastlines under threat of erosion. *Nat. Clim. Change* **10**, 260–263 (2020).
13. IPCC. *Climate Change 2022: Impacts, Adaptation and Vulnerability. Contribution of Working Group II to the Sixth Assessment Report of the Intergovernmental Panel on Climate Change* (eds H.-O. Pörtner, D.C. Roberts, M. Tignor, E.S. Poloczanska, K. Mintenbeck, A. Alegr) (Cambridge University Press. Cambridge, Cambridge University Press, Cambridge, UK and New York, NY, USA, 2022).
14. Nordstrom, K. F. & Jackson, N. L. Physical processes and landforms on beaches in short fetch environments in estuaries, small lakes and reservoirs: a review. *Earth* **111**, 232–247 (2012).
15. Toimil, A., Losada, I. J., Álvarez-Cuesta, M. & Le Cozannet, G. Demonstrating the value of beaches for adaptation to future coastal flood risk. *Nat. Commun.* **14**, 1–11 (2023).
16. Fredsoe, J. & Deigaard, R. *Mechanics of Coastal Sediment Transport Vol. 3* (World Scientific Publishing Company, 1992).
17. van Rijn, L. C. Unified view of sediment transport by currents and waves. I: Initiation of motion, bed roughness, and bed-load transport. *J. Hydraulic Eng.* **133**, 761–775 (2007).
18. van Rijn, L. C. Unified view of sediment transport by currents and waves. II: suspended transport. *J. Hydraulic Eng.* **133**, 668–689 (2007).
19. Cooper, J. A. et al. Sandy beaches can survive sea-level rise. *Nat. Clim. Change* **10**, 993–995 (2020).
20. Ranasinghe, R., Duong, T. M., Uhlenbrook, S., Roelvink, D. & Stive, M. Climate-change impact assessment for inlet-interrupted coastlines. *Nat. Clim. Change* **3**, 83–87 (2013).
21. Coco, G. et al. Morphodynamics of tidal networks: advances and challenges. *Mar. Geol.* **346**, 1–16 (2013).
22. Wang, Z. B., Elias, E. P. L., Van der Spek, A. J. F. & Lodder, Q. Sediment budget and morphological development of the Dutch Wadden Sea: impact of accelerated sea-level rise and subsidence until 2100. *Neth. J. Geosci.* **97**, 183–214 (2018).
23. Braat, L., Leuven, J. R., Lokhorst, I. R. & Kleinhans, M. G. Effects of estuarine mudflat formation on tidal prism and large-scale morphology in experiments. *Earth Surf. Process. Landf.* **44**, 417–432 (2019).
24. Elmilady, H., Wegen, M., Roelvink, D. & Spek, A. Modeling the morphodynamic response of estuarine intertidal shoals to sea-level rise. *J. Geophys. Res.* **127**, e2021JF006152 (2022).
25. Boechat Albernaz, M., Brückner, M. Z., van Maanen, B., van der Spek, A. J. & Kleinhans, M. G. Vegetation reconfigures barrier coasts and affects tidal basin infilling under sea level rise. *J. Geophys. Res.* **128**, e2022JF006703 (2023).
26. UNESCO. *UNESCO Marine World Heritage: Custodians of the Globe's Blue Carbon Assets* (Paris, France, 2020).
27. van Weerdenburg, R. et al. Field measurements and numerical modelling of wind-driven exchange flows in a tidal inlet system in the Dutch Wadden Sea. *Ocean Coast. Manag.* **215**, 105941 (2021).
28. Colosimo, I. et al. The impact of wind on flow and sediment transport over intertidal flats. *J. Mar. Sci. Eng.* **8**, 1–26 (2020).
29. Duran-Matute, M., Gerkema, T., Boer, G. J. D., Nauw, J. J. & Gräwe, U. Residual circulation and freshwater transport in the Dutch Wadden Sea: a numerical modelling study. *Ocean Sci.* **10**, 611–632 (2014).
30. Gräwe, U. et al. A numerical model for the entire Wadden Sea: Skill assessment and analysis of hydrodynamics. *J. Geophys. Res.* **121**, 5231–5251 (2016).
31. Herrling, G. et al. The effect of asymmetric dune roughness on tidal asymmetry in the Weser estuary. *Earth Surf. Process. Landf.* **46**, 2211–2228 (2021).
32. Wahl, T. et al. Observed mean sea level changes around the North Sea coastline from 1800 to present. *Earth* **124**, 51–67 (2013).
33. Timmerman, A., Haasnoot, M., Middelkoop, H., Bouma, T. & McEvoy, S. Ecological consequences of sea level rise and flood protection strategies in shallow coastal systems: a quick-scan barcoding approach. *Ocean Coast. Manag.* **210**, 105674 (2021).
34. Huismans, Y. et al. Development of intertidal flats in the Dutch Wadden Sea in response to a rising sea level: Spatial differentiation and sensitivity to the rate of sea level rise. *Ocean Coast. Manag.* **216**, 105969 (2022).
35. Bowen, A. & Inman, D. Budget of littoral sands in the vicinity of Point Arguello, California. U.S. Army Corps of Engineers, Coastal Engineering Research Center, Technical Memorandum No. 19. Tech. Rep. (1966).
36. Komar, P. D. The budget of littoral sediments: concepts and applications. *Shore Beach* **64**, 18–26 (1996).
37. Rosati, J. D. Concepts in sediment budgets. *J. Coast. Res.* **21**, 307–322 (2005).
38. Milliman, J. D. & Meade, R. H. World-wide delivery of river sediment to the oceans. *J. Geol.* **91**, 1–21 (1983).
39. Milliman, J. D. & Syvitski, J. P. Geomorphic/tectonic control of sediment discharge to the ocean: the importance of small mountainous rivers. *J. Geol.* **100**, 525–544 (1992).
40. Walling, D. E. & Webb, B. W. Erosion and sediment yield: a global overview. Series of Proceedings and Reports-Intern Assoc Hydrological Sciences. *IAHS-AISH Publ.* **236**, 3–19 (1996).
41. Rijkswaterstaat. Vaklodingen bathymetry request page [Dataset]. www.rijkswaterstaat.nl/formulieren/contactformulier-servicedesk-data (2023).
42. Bundesanstalt Für Wasserbau. EasyGSH-DB: Bathymetrie (1996-2016) [Dataset] (2020).
43. Rijkswaterstaat. Sedimentatlas Waddenzee (CD-Rom). https://svn.oss.deltares.nl/repos/openearthrawdata/trunk/rijkswaterstaat/ (1998).
44. Bijleveld, A. I. et al. Designing a benthic monitoring programme with multiple conflicting objectives. *Methods Ecol. Evolut.* **3**, 526–536 (2012).
45. Compton, T. J. et al. Distinctly variable mudscapes: distribution gradients of intertidal macrofauna across the Dutch Wadden Sea. *J. Sea Res.* **82**, 103–116 (2013).
46. Sievers, J. et al. An integrated marine data collection for the German Bight—Part 1: subaqueous geomorphology and surface sedimentology (1996-2016). *Earth Syst. Sci. Data* **13**, 4053–4065 (2021).
47. Folmer, E. O. et al. Space–time analyses of sediment composition reveals synchronized dynamics at all intertidal flats in the Dutch Wadden Sea. *Estuar. Coast. Shelf Sci.* **285**, 108308 (2023).
48. Colina Alonso, A., van Maren, D. S., Elias, E. P. L., Holthuijsen, S. J. & Wang, Z. B. The contribution of sand and mud to infilling of tidal basins in response to a closure dam. *Mar. Geol.* **439**, 106544 (2021).
49. van Maren, D. S. et al. Adaptation timescales of estuarine systems to human interventions. *Front. Earth Sci.* **11**, 1–18 (2023).
50. Hebbeln, D., Scheurle, C. & Lamy, F. Depositional history of the Helgoland mud area, German Bight, North Sea. *Geol. Mar. Lett.* **23**, 81–90 (2003).
51. Vroom, J., de Vries, B., Dankers, P. & van Maren, D. S. Cumulatieve effecten baggeren en verspreiden op habitattype H1130 in het Eems estuarium. Deel 1: Abiotische effecten. Tech. Rep., Deltares, Delft, The Netherlands (2022).

52. Pierik, H. J., Leuven, J. R. F. W., Busschers, F. S., Hijma, M. P. & Kleinhans, M. G. Depth-limiting resistant layers restrict dimensions and positions of estuarine channels and bars. *Depos. Rec.* **9**, 213–232 (2023).
53. BIOCONSULT & Coastal Defence and Nature Conservation Agency (NLWKN). Sediment Management Strategies in the Weser Estuary—Study in the framework of the Interreg IVB project TIDE Long version. *rapport projet Interreg IVB TIDE* 56 (2012).
54. BIOCONSULT, GbR, S. & Scholle. Umwelt- und naturschutzfachliche Studie zum Sedimentmanagementkonzept für die bremischen Häfen. Tech. Rep. (2018).
55. Netzband, A., Reincke, H. & Bergemann, M. The River Elbe: a case study for the ecological and economical chain of sediments. *J. Soils Sediment.* **2**, 110–116 (2002).
56. Weilbeer, H. & Uliczka, I. Unterbringung von Baggergut in den Bereich der Ausschließlichen Wirtschaftszone AWZ. BAW-report B3955030610003. Tech. Rep., Bundesanstalt für Wasserbau (BAW) (2019).
57. HPA & WSA. River Elbe River Engineering and Sediment Management Concept - Review of sediment management strategy in the context of other European estuaries from a morphological perspective. Tech. Rep. May, Hamburg Port Authority (HPA) & Federal Waterways and Shipping Administration (WSA) (2011).
58. Milliman, J. D. & Farnsworth, K. L. *River Discharge to the Coastal Ocean* (Cambridge University Press, 2011). https://www.cambridge.org/core/product/identifier/9780511781247/type/book.
59. Maan, D. C., van Prooijen, B. C. & Wang, Z. B. Progradation speed of tide-dominated tidal flats decreases stronger than linearly with decreasing sediment availability and linearly with sea level rise. *Geophys. Res. Lett.* **46**, 262–271 (2019).
60. Willemsen, P. W. et al. Modeling decadal salt marsh development: variability of the salt marsh edge under influence of waves and sediment availability. *Water Resour. Res.* **58**, 1–23 (2022).
61. Colina Alonso, A. et al. The existence and origin of multiple equilibria in sand-mud sediment beds. *Geophys. Res. Lett.* **49**, e2022GL101141 (2022).
62. de Jonge, V. N., Essink, K. & Boddeke, R. The Dutch Wadden Sea: a changed ecosystem. *Hydrobiologia* **265**, 45–71 (1993).
63. Temmerman, S. et al. Ecosystem-based coastal defence in the face of global change. *Nature* **504**, 79–83 (2013).
64. Zhu, Z. et al. Historic storms and the hidden value of coastal wetlands for nature-based flood defence. *Nat. Sustain.* **3**, 853–862 (2020).
65. Elliott, M. et al. The guild approach to categorizing estuarine fish assemblages: a global review. *Fish. Fish.* **8**, 241–268 (2007).
66. van Roomen, M. et al. Signals from the Wadden sea: Population declines dominate among waterbirds depending on intertidal mudflats. *Ocean Coast. Manag.* **68**, 79–88 (2012).
67. Laursen, K. et al. Regime shift and changes in sediment morphology driven by sea level rise affect abundance of migratory waders. *J. Ornithol.* **164**, 573–582 (2023).
68. Lotze, H. K. Rise and fall of fishing and marine resource use in the Wadden Sea, southern North Sea. *Fish. Res.* **87**, 208–218 (2007).
69. Ysebaert, T., Meire, P., Herman, P. M. & Verbeek, H. Macrobenthic species response surfaces along estuarine gradients: prediction by logistic regression. *Mar. Ecol. Prog. Ser.* **225**, 79–95 (2002).
70. Singer, A. et al. Long-term response of coastal macrofauna communities to de-eutrophication and sea level rise mediated habitat changes (1980s versus 2018). *Front. Mar. Sci.* **9**, 1–20 (2023).
71. Wang, Z. B. & van der Spek, A. J. F. Importance of mud for morphological response of tidal basins to sea-level rise. In (eds P. Wang, J.D. Rosati, J. C.) *The Proceedings of the Coastal Sediments 2015*, 11–14 (WORLD SCIENTIFIC, San Diego, CA, 2015). http://www.worldscientific.com/doi/abs/10.1142/9789814689977_0208.
72. Dissanayake, D. M. P. K., Ranasinghe, R. & Roelvink, J. A. The morphological response of large tidal inlet/basin systems to relative sea level rise. *Clim. Change* **113**, 253–276 (2012).
73. Lodder, Q. J. et al. Future response of the wadden sea tidal basins to relative sea-level rise—an aggregated modelling approach. *Water* **11**, 2198 (2019).
74. Benninghoff, M. & Winter, C. Decadal evolution of tidal flats and channels in the Outer Weser estuary, Germany. *Ocean Dyn.* **68**, 1181–1190 (2018).
75. Benninghoff, M. & Winter, C. Recent morphologic evolution of the German Wadden Sea. *Sci. Rep.* **9**, 9293 (2019).
76. IPCC. *IPCC Special Report on the Ocean and Cryosphere in a Changing Climate* (eds H.-O. Pörtner, D.C. Roberts, V. Masson-Delmotte, P. Zhai, M. Tignor, E. Poloczanska, K. Mintenbeck, A. Alegría, M. Nicolai, A. Okem, J. Petzold, B. Rama, N.M. Weyer) (Cambridge University Press, Cambridge, UK and New York, NY, USA, 2019). https://doi.org/10.1017/9781009157964.
77. Dangendorf, S. et al. Persistent acceleration in global sea-level rise since the 1960s. *Nat. Clim. Change* **9**, 705–710 (2019).
78. Vermeersen, B. L. et al. Sea-level change in the Dutch Wadden Sea. *Neth. J. Geosci.* **97**, 79–127 (2018).
79. Lodder, Q. & Slinger, J. The 'Research for Policy' cycle in Dutch coastal flood risk management: the Coastal Genesis 2 research programme. *Ocean Coast. Manag.* **219**, 106066 (2022).
80. Vollmer, M., Guldberg, M., Maluck, M., Marrewijk, D. & Schlicksbier, G. Landscape and Cultural Heritage in the Wadden Sea Region—Project Report. Wadden Sea Ecosystem No. 12. Tech. Rep., Common Wadden Sea Secretariat, Wilhelmshaven, Germany (2001).
81. van Maren, D. S., Oost, A. P., Wang, Z. B. & Vos, P. C. The effect of land reclamations and sediment extraction on the suspended sediment concentration in the Ems Estuary. *Mar. Geol.* **376**, 147–157 (2016).
82. Raff, J. L. et al. Sediment delivery to sustain the Ganges-Brahmaputra delta under climate change and anthropogenic impacts. *Nat. Commun.* **14**, 1–13 (2023).
83. Luan, H. L., Ding, P. X., Wang, Z. B., Ge, J. Z. & Yang, S. L. Decadal morphological evolution of the Yangtze Estuary in response to river input changes and estuarine engineering projects. *Geomorphology* **265**, 12–23 (2016).
84. Luijendijk, A. P. et al. The initial morphological response of the Sand Engine: A process-based modelling study. *Coast. Eng.* **119**, 1–14 (2017).
85. Lesser, G. *An Approach to Medium-term Coastal Morphological Modelling*. Phd, Delft University of Technology, UNESCO-IHE Institute for Water Education. http://www.narcis.nl/publication/RecordID/oai:tudelft.nl:uuid:62caa573-4fc0-428e-8768-0aa47ab612a9 (2009).
86. Prandle, D., Loch, S. G. & Player, R. Tidal flow through the straits of Dover. *J. Phys. Oceanogr.* **23**, 23–37 (1993).
87. Gerritsen, H., Boon, J. G., Van der Kaaij, T. & Vos, R. J. Integrated modelling of suspended matter in the North Sea. *Estuar. Coast. Shelf Sci.* **53**, 581–594 (2001).
88. Fettweis, M., Nechad, B. & van den Eynde, D. An estimate of the suspended particulate matter (SPM) transport in the southern North Sea using SeaWiFS images, in situ measurements and numerical model results. *Cont. Shelf Res.* **27**, 1568–1583 (2007).
89. Fettweis, M. & van den Eynde, D. The mud deposits and the high turbidity in the Belgian-Dutch coastal zone, southern bight of the North Sea. *Cont. Shelf Res.* **23**, 669–691 (2003).
90. de Kok, J. Slibtransport langs de Nederlandse kust Slibtransport langs de Nederlandse kust. Tech. Rep. december, RIKZ (2004).
91. van Alphen, J. S. A mud balance for Belgian-Dutch coastal waters between 1969 and 1986. *Neth. J. Sea Res.* **25**, 19–30 (1990).

92. Pietrzak, J. D., de Boer, G. J. & Eleveld, M. A. Mechanisms controlling the intra-annual mesoscale variability of SST and SPM in the southern North Sea. *Cont. Shelf Res.* **31**, 594–610 (2011).
93. van Raaphorst, W., Philippart, C. J., Smit, J. P., Dijkstra, F. J. & Malschaert, J. F. Distribution of suspended particulate matter in the North Sea as inferred from NOAA/AVHRR reflectance images and in situ observations. *J. Sea Res.* **39**, 197–215 (1998).
94. Sundermann, J. Suspended particulate matter in the North Sea: field observations and model simulations. *Philos. Trans. R. Soc. Lond. Ser. A* **343**, 423–430 (1993).
95. McCave, F. N. Mud in the North Sea. In (ed E.D. Goldberg) *North Sea Science*, November, 75–100 (MIT Press, 1973).
96. Mulder, H. P. J. De droge dichtheid als functie van het slibgehalte t.b.v. een sedimentbalans (1995).
97. Pedersen, J. B. & Bartholdy, J. Budgets for fine-grained sediment in the Danish Wadden Sea. *Mar. Geol.* **235**, 101–117 (2006).
98. Esselink, P. et al. Wadden Sea Quality Status Report: Salt Marshes. Tech. Rep. (2017).
99. Nolte, S. et al. Measuring sedimentation in tidal marshes: a review on methods and their applicability in biogeomorphological studies. *J. Coast. Conserv.* **17**, 301–325 (2013).
100. Mueller, P. et al. Assessing the long-term carbon-sequestration potential of the semi-natural salt marshes in the European Wadden Sea. *Ecosphere* **10**, e02556 (2019).
101. Puls, W., Heinrich, H. & Mayer, B. Suspended particulate matter budget for the German Bight. *Mar. Pollut. Bull.* **34**, 398–409 (1997).
102. Grabemann, I. & Krause, G. Response of the turbidity maximum in the Weser Estuary to pulses in freshwater runoff and to storms. In (eds Dronkers, J. & Scheffers, M.) *Physics of Estuaries and Coastal Seas*, 83–92 (Rotterdam, the Netherlands, 1998).
103. Grabemann, I. & Krause, G. On different time scales of suspended matter dynamics in the Weser estuary. *Estuaries* **24**, 688–698 (2001).
104. Ackermann, F. & Schubert, B. Trace Metals as Indicators for the Dynamics of (Suspended) Particulate Matter in the Tidal Reach of the River Elbe. In Springer (ed.) *Sediment Dynamics and Pollutant Mobility in Rivers. An Interdisciplinary Approach*., chap. Trace Meta, 296–394 (2007).
105. Wehrmann, A. Wadden Sea. 933–939. http://link.springer.com/10.1007/978-94-007-6238-1_143 (2016).

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Author contributions

A.C.A., D.S.M., Z.B.W. and A.P.O. designed this study. A.C.A, D.S.M, A.P.O., P.E., R.L., F.K., J.B. and A.I.B. compiled the data. A.C.A. and P.E. conducted the data analyses, with inputs from D.S.M., Z.B.W., A.P.O., R.L., and F.K. A.C.A. led the visualisation of the results and the writing of the paper, to which all co-authors contributed.

Competing interests

The authors declare no competing interests.

Additional information

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