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DOI
10.1029/2024EF005080

Publication date
2024

Document Version
Final published version

Published in
Earth's Future

Citation (APA)
Schrijvershof, R. A., van Maren, D. S., Van der Wegen, M., & Hoitink, A. J. F. (2024). Land Reclamation Controls on Multi-Centennial Estuarine Evolution. *Earth's Future*, *12*(11), Article e2024EF005080. https://doi.org/10.1029/2024EF005080

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Earth's Future

RESEARCH ARTICLE
10.1029/2024EF005080

Land Reclamation Controls on Multi-Centennial Estuarine Evolution

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Key Points:

- Land reclamation in the Ems estuary was followed by progressive subtidal infilling and degeneration of separated ebb-flood channels
- Loss of intertidal areas distorts the estuary-scale channel-flat configuration, which is partly restored by subtidal infilling
- Tidal asymmetry-based equilibrium theory can serve estuarine management by predicting estuary evolution in response to land reclamation

Supporting Information:

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

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Citation:

Schrijvershof, R. A., van Maren, D. S., Van der Wegen, M., & Hoitink, A. J. F. (2024). Land reclamation controls on multi-centennial estuarine evolution. *Earth's Future*, *12*, e2024EF005080. https://doi.org/10.1029/2024EF005080

Received 11 JUL 2024
Accepted 14 OCT 2024

Author Contributions:

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Abstract Land reclamations influence the morphodynamic evolution of estuaries and tidal basins, because an altered planform changes tidal dynamics and associated residual sediment transport. The morphodynamic response time to land reclamation is long, impacting the system for decades to centuries. Other human interventions (e.g., deepening of fairways or port construction) will add more morphodynamic adaptation timescales. Our understanding of the cumulative effects of anthropogenic interference with estuaries is limited because observations usually do not cover the complete morphological adaptation period. We aim to assess the impact of land reclamation works and other human interventions on an estuarine system by means of digital reconstructions of historical morphologies of the Ems Estuary over the past 500 years. Our analysis demonstrates that the intertidal-subtidal area ratio altered due to land reclamation works and that the ratio partly restored after land reclamation ended. The land reclamation works have led to the degeneration of an ebb and flood channel system, transitioning the estuary from a multichannel to a single channel system. We infer that the 20th-century intensification of channel dredging and re-alignment works accelerated rather than caused this development. The centennial-scale observations show that the Ems estuary evolution corresponds to a land reclamation response following tidal asymmetry-based stability theory as it moves toward a new equilibrium configuration with modified tidal flats and channels. Considering the long history of land reclamation in the Ems Estuary, it provides an analogy for expected developments in comparable tidal systems where land reclamations were recently carried out.

Plain Language Summary Reclaiming land along the margins of estuaries and tidal basins leads to loss of intertidal areas, impacting the remaining underwater landscape for decades to centuries. This influences the patterns, dimensions, and functionalities of the channels and tidal flats. Observations are usually not available for such a long period, limiting our capacity to study the impact of land reclamation. Here, we overcome this limitation by reconstructing the landscape adaptation in the Ems estuary since land reclamation accelerated in the 16th century, when flooding by storms reshaped the estuary. Historical and recent topo-geographical sources were used to reconstruct the centennial-scale developments of the tidal channels and tidal flats. Results show that, after reclamation works stopped, the tidal flats reduced in area and the tidal channels filled up. The tidal channel patterns and dimensions permanently changed, impacting, for example, shipping waterways. The observed estuary-scale land reclamation response can be qualitatively predicted on the basis of descriptive parameters. This suggests that we can anticipate on the future evolution of comparable tidal systems that are recently impacted by land reclamation.

1. Introduction

Estuaries and tidal basins are biodiverse coastal landscapes that are often intensely used by humans, offering services such as navigation routes, fisheries, and protection against flooding. These services are influenced by estuarine morphology because the channel-flat pattern and geometry (hypsometry) determine hydrological connectivity (Hiatt & Passalacqua, 2015) and ecological connectivity (Olds et al., 2017). The morphological configuration controls future morphodynamic evolution because of the link with tidal asymmetry and residual sediment transport (Dronkers, 1986; Z. B. Wang, et al., 1999). Large-scale human alteration of estuarine planform and channel dimensions influences tidal dynamics, sediment transport, and ultimately the basin's long-term evolution. Engineering works and construction of embankments restrain intertidal dynamics. This process of "coastal squeeze" affects the accommodation space available for dynamic adaptation to sea level rise (Borchert et al., 2018). Understanding and predicting the combined impact of global climate change and anthropogenic

10.1029/2024EF005080

Writing – review & editing:
D. S. van Maren, M. Van der Wegen, A. J. F. Hoitink

pressure requires grasping the complex interaction between the tidal channels and the adjacent intertidal areas (Hoitink et al., 2020; Z. Wang et al., 2015).

Tidal channels dynamically interact with tidal flats and associated salt marshes. Tidal flat development influences tidal propagation characteristics (Dronkers, 1986) and channel mobility (Kleinhans et al., 2022), which in turn affect the channel dynamics and the system-scale morphodynamic development (Hibma et al., 2004; Braat et al., 2017; J. R. Leuven & Kleinhans, 2019; Van der Wegen et al., 2008). Important hydrodynamic mechanisms linked to the tidal flats are the temporal storage of mass and dissipation of momentum (Alebregtse, 2015; Friedrichs & Aubrey, 1988; Zhou et al., 2018). Both influence tidal propagation, leading to asymmetric sea surface elevations and velocity distribution (e.g., Friedrichs, 2010). An asymmetric tidal motion drives a net sediment transport flux (Groen, 1967; Van de Kreeke & Robaczewska, 1993), while the long-term, residual transport determines morphological evolution (Dronkers, 1986). Large-scale changes in the channel-flat configuration therefore disrupt the net sediment transport magnitudes and directions (import vs. export) and steer the morphodynamic evolution of an estuary or tidal basin (Chen et al., 2020; Guo, Zhu, et al., 2022; Van Der Wegen, 2013).

In many tidal systems worldwide, the loss of intertidal area due to land reclamation and channel deepening due to dredging have been the major anthropogenic interferences over the past and present century (Talke & Jay, 2020). The construction of embankments (artificial levees) for flood protection and land reclamation purposes effectively alters the tidal regime, because the basin's geometry (i.e., depth, width, length) is essentially changed (Talke & Jay, 2020). Tidal flat loss reduces the embayment's intertidal storage volume, decreasing the tidal prism and enhancing flood dominance (Speer & Aubrey, 1985). An increased sediment import will lead to basin infilling, which will continue until the channel geometry has re-established to new equilibrium conditions, in which the sediment transport capacity can maintain the new channel-flat configuration (Dronkers, 2016). Tidal-asymmetry based equilibrium theory can be useful to assess the evolutionary trajectory of an estuarine system responding to land reclamations (Zhou et al., 2018).

An example of a well-studied response to fairly recent human interventions is Hangzhou Bay, China. Large-scale coastal land reclamations since the 1950s triggered high sediment deposition rates, despite a simultaneous drastic reduction in fluvial sediment supply (Xie et al., 2017). A 25% reduction in tidal prism led to shoaling of the seabed and increasingly flood-dominated tidal currents, further promoting infilling of the bay. The reduction in tidal prism was partly compensated by an increase in tidal range (Li et al., 2019). The continued transportation of marine sediment toward the inner bay causes progressive infilling of the tidal channels with fine-grained non-cohesive silt (Jiyu et al., 1990), further reducing the tidal prism. Similar developments are observed in the Keum river estuary, Korea, where an increased flood directed sediment flux (Figueroa et al., 2020) doubled sedimentation rates in response to the construction of a dam that closed the upstream reaches of the estuary in the 1990s (Kim et al., 2006). The combination of dam construction and land reclamation, as implemented in the Nakdong estuary, Korea, concurrently impacts the sedimentary regime (Williams et al., 2013), albeit as a result of different mechanisms (Chang et al., 2023). The general response of the human-impacted systems described above is an estuary-scale tendency of increased sedimentation. This infilling is presumed to continue until a new equilibrium channel-flat configuration is reached. The morphological response to the original intervention thus extends far beyond the implementation timespan.

As part of the lagged response to large-scale human interventions, a morphodynamic feedback loop can develop that may influence the system-scale sediment budgets (Donatelli et al., 2018; Guo, Xie, et al., 2022), trigger a transition to hyper-concentrated flow conditions (Van Maren et al., 2016; Van Maren, Winterwerp, & Vroom, 2015; Winterwerp et al., 2013), and influence channel migration and avulsion (Dai et al., 2016). In the Ganges-Brahmaputra-Meghna (GBM) mega delta, for example, large-scale land reclamation (>5,000 km^2) in the 60's and 70's of the 20th century has led to a significant change in the hydro-sedimentary regime, drastically increasing flood risk (Auerbach et al., 2015), persistent infilling of the tidal channels (Wilson et al., 2017), and, as a result, a reorganization of the tidal channel network (Bain et al., 2019; Van Maren, Beemster, et al., 2023). Large-scale human interventions may thus impact delta system functioning for decades to centuries through non-linear feedback loops, exceedance of thresholds, and time-lags (Coco et al., 2013; Liu et al., 2007). The observed and widely varying developments of tidal systems impacted by land reclamation cannot exclusively be predicted on the basis of estuarine equilibrium theory. To date, it remains unclear to what extent these developments are driven by the land reclamations or other human interference.

Isolating the impact of a single intervention is challenging, because each intervention triggers a morphodynamic response within a system that may still be adapting to one or more previous interventions. The response time depends on the magnitude of the intervention, the size of the system, and the sediment transport rates, and may typically be several decades or more (Van Maren, Colina Alonso, et al., 2023). As a result, multiple interventions may interactively impact the system within the time period in which the system morphodynamically adapts to the principal intervention (Z. Wang et al., 2015). Long-term observations documenting morphological adaptation to tidal flat reclamations in a real-world tidal system may be used to verify the validity of theoretical frameworks describing its evolutionary trajectory toward morphological equilibrium.

The aim of this paper is to understand how loss of intertidal area by land reclamations influences estuarine morphodynamic development. We focus on the Ems estuary (Figure 1), located on the border between the Netherlands and Germany and part of the Wadden Sea tidal lagoon, which represents a heavily human-modified tidal system. The most important anthropogenic pressures in the Ems include large-scale tidal flat reclamation of storm-surge formed embayments, which started in the beginning of the 16th century. This was followed by fairway re-alignment, deepening, and maintenance dredging since the 20th century (Van Maren et al., 2016). First, we reconstruct the land reclamation history (Section 3.1). Second, we reconstruct and analyze the historical and contemporary development of the estuarine channels and tidal flats over the past 500 years (Section 3.2). A multichannel system with distinct ebb and flood channels (Van Veen et al., 2005) in the estuary has degenerated into a single channel in the 20th century (Gerritsen, 1952), which is still poorly understood. Two hypotheses exist explaining these channel pattern changes: (a) channel system instability due to fairway deepening and related sediment disposal (Van Veen, 1950; Van Veen et al., 2005), and (b) tidal prism decrease as a result of intertidal storage loss due to land reclamation (Gerritsen, 1952). We discuss the controls of land reclamation versus channel deepening on the observed channel pattern changes and interpret these findings using tidal asymmetry-based estuarine equilibrium relationships (Section 4). The Ems estuary thus provides an analogy for applying such theory in predicting the evolution of comparable tidal systems impacted by recent land reclamations.

2. Material and Methods

Reclaimed land surface area was reconstructed from several data sources described below, and archived in Schrijvershof (2024). The main sources for the reconstructions on the Dutch shore of the Ems estuary are geospatial data sets with the location of historical embankments (Provincie Groningen, 2024) and the National Historical Culture registry (Rijksdienst voor het Cultureel Erfgoed, 2024). This information was supplemented with information from maps presented by Knottnerus (2013a) and Van Maren et al. (2016), to determine the year in which a reclamation was completed. Digital elevation models (DEMs) of the surface topography, aerial imagery (allotment pattern), and paleogeographical reconstructions (P. C. Vos & Knol, 2013, 2015) were used to detail the maximum extent of storm-surge-formed bays, to include the oldest (poorly documented) reclaimed lands. The maximum extent of the Dollard Bay, in particular, increased through this approach, leading to a reclamation reconstruction that largely agrees with the map presented by Knottnerus (2013a). The reclamation history on the German part of the Ems estuary is digitized from maps presented by Homeier (1962) and Homeier et al. (1969). The reclamation history of Sielmönken bay could not be reconstructed but the approximate maximum extent of the embayment is derived from DEMs and aerial imagery. The lands reclaimed along the tidal river (landwards of the port of Emden) are not included in the land reclamation database (Schrijvershof, 2024) because the focus of this paper is on the mouth and transitional regions of the Ems estuary.

The morphological evolution of the Ems estuary is reconstructed for the period with intensive anthropogenic interventions since the 16th century. A unique long-term record of geospatial data sets is compiled that almost completely covers this time-period (Table 1). The data sets were collected from published literature (Gerritsen, 1952; Homeier, 1962; Lang, 1954; Stratingh & Venema, 1855), published data sources (H. Pierik, 2019; Sievers et al., 2021), or collected from national archives, and were provided in digitized format (De Jong, 2006; Herrling & Niemeyer, 2007, 2008) or, otherwise, digitized using GIS software. The recent gridded topo-bathymetrical data sets (1985-2020) are publicly available at Rijkswaterstaat (https://www.rijkswaterstaat.nl/formulieren/contactformulier-servicedesk-data) and WSA Emden (https://www.wsa-ems-nordsee.wsv.de/Webs/WSA/Ems-Nordsee/DE/00_Startseite/startseite_node.html). The data sets can be divided in three categories: (a) historical reconstructions of channel and tidal flat planform, based on a large variety of written and illustrated sources, but interpreted and compiled in the 20th century, (b) digitized nautical charts originally collected in hydrographic surveys for military and water way organizations, and (c) recent (1937, 1985–2020) full coverage

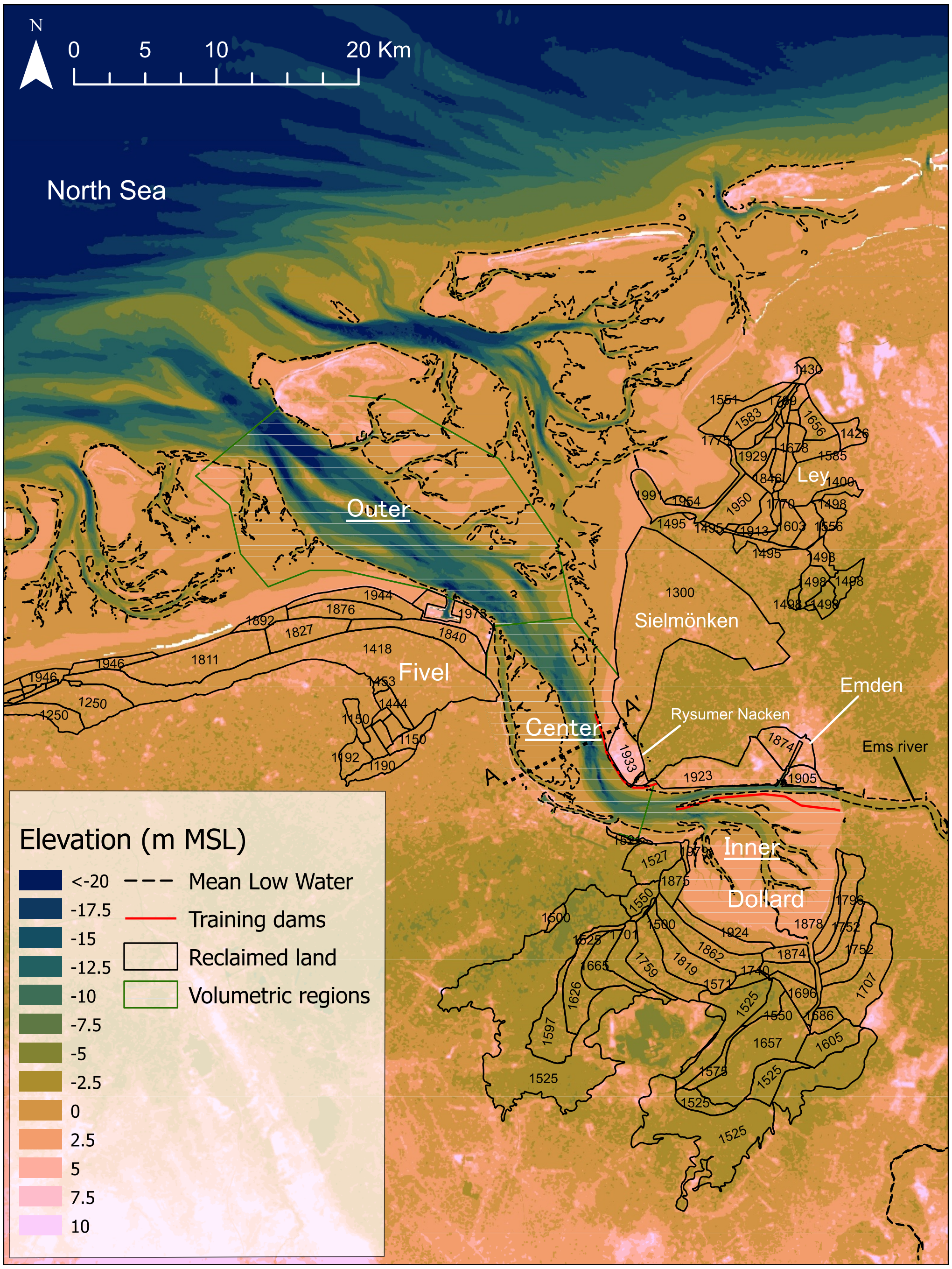

Figure 1. Land surface reclaimed in the region of the Ems estuary, with the year of completion indicated in the reclaimed area. The background color-scale visualizes the present-day topo-bathymetric Digital Elevation Model, compiled from multiple sources (see Open Research section, Section 5).

digital elevation models (DEM) collected through (echo) sounding observations. All geospatial data sets were provided or converted in a digitized format (Table 1) and published with this paper (Schrijvershof, 2024). The three types of data sets provide different kind of geospatial information. The historical reconstructions only reveal the geographical location of the Mean Low Water line (MLW), Mean High Water line (MHW) and fixed bank lines; the nautical charts provide a DEM of the subtidal (below MLW) domain; and the recent sounding observations provide a full DEM of the subtidal, intertidal and supratidal domain. Contour lines of MLW and MHW are derived from the recent DEMs using an along-estuary averaged value for MLW (NAP −1.50 m) and MHW

Table 1
Overview of the Type and Sources of the Geospatial Data Sets Gathered and Digitized for This Study

Year	Format & resolution	Original source	Digitized source
1580	MLW contours	Hist. reconstruction Lang (1954)	This article
1650	MLW contours	Hist. reconstruction Lang (1954)	This article
1650	MLW, MHW and supratidal contours	Hist. reconstruction Homeier (1962)	Herrling and Niemeyer (2007)
1720	MLW contours	Hist. reconstruction Lang (1954)	This article
1750	MLW, MHW and supratidal contours	Hist. reconstruction Homeier (1962)	Herrling and Niemeyer (2007)
1790	MLW contours	Hist. reconstruction Lang (1954)	This article
1812	LLW contours	Hist. reconstruction Gerritsen (1952)	This article
1833	Gridded (100 × 100)	Nautical chart Dutch dep. of defense	H. J. Pierik et al. (2022), H. Pierik (2019)
1855	MLW, MHW and supratidal contours	Hist. reconstruction Stratingh and Venema (1855), Gerritsen (1952)	De Jong (2006)
1860	MLW contours	Hist. reconstruction Lang (1954)	This article
1860	MLW, MHW and supratidal contours	Hist. reconstructions Homeier (1962), Gerritsen (1952)	Herrling and Niemeyer (2007)
1873	MLW contours	Hist. reconstruction Gerritsen (1952)	This article
1888	Gridded (100 × 100)	Nautical chart Dutch dep. of defense, Hist. reconstruction Relative change of the subtidal Homeier (1962)	H. J. Pierik et al. (2022), H. Pierik (2019)
1898	Gridded (20 × 20)	Nautical charts Ems Mündung (1:50,000) & Die Ems Von Delfzijl Bis Pogum (1:25,000) von Reichs Marine Amt	This article
1901	MLW contours	Hist. reconstruction Gerritsen (1952)	This article
1928	Gridded (100 × 100)	Nautical chart Dutch dep. of defense	H. J. Pierik et al. (2022), H. Pierik (2019)
1930	MLW contours	Hist. reconstruction Lang (1954)	This article
1937	Gridded (5 × 5)	Depth soundings (German marine, RWS, Waterway agency Emden & Meppen)	Herrling and Niemeyer (2008)
1953	Gridded (100 × 100)	Nautical chart Dutch dep. of defense	H. J. Pierik et al. (2022), H. Pierik (2019)
1960	MLW, MHW and supratidal contours	Hist. reconstructions Homeier (1962), Gerritsen (1952)	Herrling and Niemeyer (2007)
1985	Gridded (20 × 20)	Echo soundings	Rijkswaterstaat
1990	Gridded (20 × 20)	Echo soundings	Rijkswaterstaat
1996	Gridded (10 × 10)	Echo soundings	Sievers et al. (2021)
1997	Gridded (20 × 20)	Echo soundings	Rijkswaterstaat
2001	Gridded (20 × 20)	Echo soundings	Rijkswaterstaat
2005	Gridded (20 × 20)	Echo soundings	Rijkswaterstaat
2008	Gridded (20 × 20)	Echo soundings	Rijkswaterstaat
2010	Gridded (25 × 25)	Echo soundings	WSA Emden
2014	Gridded (20 × 20)	Echo soundings	Rijkswaterstaat
2016	Gridded (10 × 10)	Echo soundings	Sievers et al. (2021)
2020	Gridded (20 × 20)	Echo soundings	Rijkswaterstaat

(NAP +1.30 NAP), following Arcadis (2011). The spatial extent of the geospatial data sets varies and do not all cover the full extent of the estuary. Data sets with incomplete coverage are not used for all analyses. The accuracy and precision of the geospatial information are lower for older data sets than for more recent data sets. The historical reconstructions of pre-19th-century morphology (made in the 20th century), in particular, are constructed with considerable interpretation of the original authors who drafted the maps. The inaccuracies of older maps therefore introduce uncertainty in the metrics we develop as part of our morphological analysis. We minimize the impact of such uncertainties by collecting data from multiple sources and authors, and by focusing on morphological trends based on a wide range of independent data sets.

We identify and quantify the main morphological changes in the estuary over the past 500 years. Subtidal surface area (A_s) and intertidal surface area (A_i) are derived from enclosed areas formed by MLW, MHW, and fixed bank lines. These surface area metrics are, due to data availability, quantified for a defined region that includes the Dollard Bay and the central estuary, but excludes the mouth zone with the tidal inlets (see Figure S4 in Supporting Information S1). Channel geometry metrics (area, depth, volume) are derived as spatial mean values for areas defined in the outer, central, and inner estuary and along a defined cross-section covering the central-estuary channels (Figure 1).

Contextual background information on the historic landscape developments and the most important human-landscape interaction in the Ems estuary is provided in Supporting Information S1. Palaeogeopgraphical reconstructions, presented by P. Vos et al. (2020); P. C. Vos and Knol (2015, 2013), were modified to show and describe the inherited geological setting and Holocene evolution (Cleveringa, 2000) of the Ems estuary region influenced by relative sea level rise (Meijles et al., 2018) (Text S1.1 in Supporting Information S1). The historic evolution is particularly relevant to understand the formation of the storm surge-formed embayments that were reclaimed (Text S1.2 in Supporting Information S1). The 20th-century human-landscape interactions, particularly relevant for the recent observed morphological developments, include channel dredging (Boon et al., 2002), port construction (Talke & de Swart, 2006), and channel-realignments (Gerritsen, 1955; Oberrecht & Wurpts, 2014). An overview of these anthropogenic works is presented in Text S1.3 in Supporting Information S1.

3. Results

3.1. Land Reclamation Reconstruction

Land reclamation works started probably in the 11th century in the Ems estuary region (Behre, 1999; Homeier et al., 1969). The former "Sielmönken bay" (Figure 1), a former sea ingression that reached its largest extent between 800 and 950 A.D., was already completely reclaimed in the 13th century. The Fivel bay (Figure 1) started to silt-up prior to human settlement because outflow of the Fivel river was hampered by expanding shore ridges (P. Vos & van Kesteren, 2000). The process was accelerated because, from the 12th century onwards, embankments were constructed and the flow from the Fivel river was redirected to artificial tidal shipping canals (Knottnerus, 2013b). Reclamation of the Fivel bay continued until the 15th century, after which the seaward shoreline extension continued in the 19th century with improved reclamation techniques. The most recent coastal reclamation was the construction of a large seaport in the 1970's. The Ley bay reclamations started in the 15th century and continued until the 20th century (Figure 1). The Dollard bay reclamations are the largest reclamation works in the estuary (Figure 1), starting at the beginning of the 16th century (Figure 1) and continuing far into the 20th century. The land surface elevations of the Dollard reclamations clearly show the decrease in land surface level with reclamation age (Figure 1), because older reclaimed areas subsided more due to peat oxidation and compaction. The Dollard bay was never completely reclaimed (≈20% remained) and is nowadays highly valued and protected as a unique tidal flat and salt marsh landscape. Reclamations near the port city of Emden were executed to relocate the city harbor toward the river (Figure 1), after it lost its access due to a meander bend cut-off (see Text S1.2 in Supporting Information S1). In an effort to narrow and deepen the Emden access fairway, the tidal flats west of Emden were reclaimed as well. The most recent reclaimed land in the inland part of the estuary is the construction of the "Rysumer Nacken" (Figure 1). The 1933 completion of a bended longitudinal training dam, constructed to redirect the navigational channel (Die Bautechnik, 1938), was followed-up by landfill deposits on the sheltered tidal flats with dredged material (https://de.wikipedia.org/wiki/Rysumer_Nacken).

The total cumulative amount of land surface reclaimed in the region of the Ems estuary since the start of reclamation works (12th century) is approximately 700 km^2 (Figure 2). The Dollard Bay reclamations constitute half (≈360 km^2) of the total reclaimed land. The reclamation rate in Dollard Bay decreased halfway through the 19th century, while the Fivel Bay and Ley Bay reclamations accelerated slightly around this time. Including all reclamation regions, there has been a continuous reclamation rate of ≈100 km^2 per century since the Dollard reclamations started in the beginning of the 16th century. The extent of the Ems estuary was largest after the formation of Dollard Bay in 1509 (≈1,750 km^2) and decreased due to the land reclamation works to a present-day

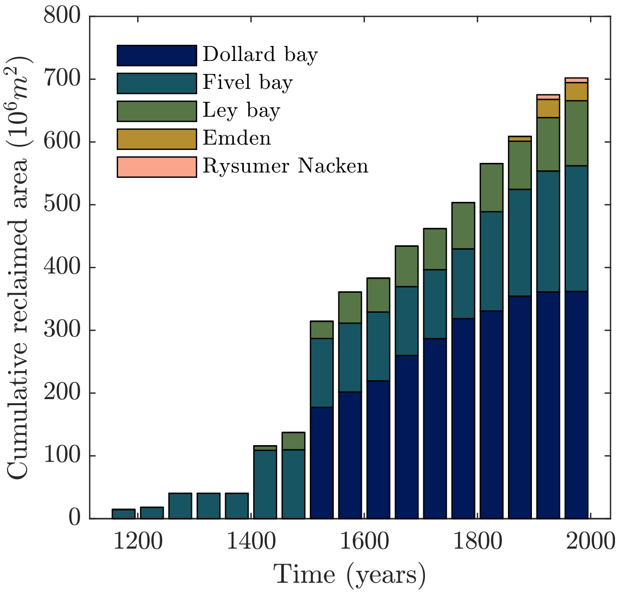

Figure 2. Cumulative area reclaimed since the 12th century, summed over half-century periods and subdivided for each defined land reclamation region.

size of ≈1,200 km^2. The reclamation works reshaped the estuary outline and decreased $\approx \frac{1}{3}$ of the total basin extent. The Dollard Bay reclamations make up 65% of this reduction.

3.2. Morphological Reconstruction

3.2.1. Channel-flat configuration

The 16th-century morphology consisted of multiple tidal channels and tidal flats consisting of fringing flats and mid-channel bars, or shoals (Figure 3a). A double inlet system flanking the barrier island Borkum, connected the estuary and the North Sea. The two inlets had approximate equal planform sizes, yet the western inlet was more efficiently connected to the central-estuary (see Figure 1 for demarcation) channels. The eastern inlet also drained the tidal volume of the Ley Bay, most of which was not yet reclaimed in the 16th century (Figure 1). The central part of the estuary is bisected by a western and an eastern channel, hereafter referred to as the western channel and eastern channel (see Figure 3e). In the 16th-century the western channel dominates over the eastern channel and connects via a meander bend to the western inlet in the outer estuary. In the 18th century (Figure 3b) the orientation of the channel connecting the eastern tidal inlet with the central-estuary channels changes while shrinking in size. A mid-channel shoal develops in the outer estuary western inlet. The central-estuary shoal complex migrates westward, resulting in an increase of the size of the eastern channel at the expense of the western channel. Despite this, the western channel remains to be the main channel. Subtidal bathymetries, available from the start of the 19th century (Figure 3c, Figure S5 in Supporting Information S1), reveal the depths of the main estuarine channels. The main channel route starts from the western inlet via the western channel into Dollard Bay. The sinusoidal meandering pattern with mid-channel shoals confirms the multichannel ebb-flood pattern reported by Van Veen (1950) and Gerritsen (1952).

The connection of the eastern inlet to the central-estuary channels degenerated from a well-connected channel in the 16th century into a tidal divide in the 18th century to the beginning of the 19th century (see Figures 3b and 3c). The main tidal channels are filling in with sediments in the 20th century (compare Figure 3c with d and e) while degeneration of the former connection with the eastern tidal inlet progresses until it is completely disconnected in the 21th century (Figure 3f). The tidal shoal complex in the central-estuary zone becomes larger and migrates further westward. At the same time, the western channel degenerates (becoming shallower and narrower) while the eastern channel deepens and widens. During the 20th century, the meander bend connecting the outer estuary channels with the central-estuary channels (see Figure 1) is straightened, resulting in a reduction of channel sinuosity (H. J. Pierik et al., 2022). The southern section of the central-estuary eastern channel moves westward (Figure 3d), presumably forced by the construction of a longitudinal training wall (Figure 1). The present-day situation shows that the western channel has now degenerated into a minor channel (Figure 3f).

The land reclamation works and the channel and tidal flat pattern developments illustrated in Figure 3 influence the surface areas occupied by tidal channels (A_s) and tidal flats (A_i). Up to the end of the 19th century, A_i decreased (Figure 4), which is a result of land reclamation in Dollard Bay (Figure S4 in Supporting Information S1). Since the beginning of the 20th century the tidal flat surface area gradually increased because of expansion of the central-estuary shoal complex, and degeneration of the eastern inlet connection to the central-estuary channels (Figure S4 in Supporting Information S1). A_s is more variable over the reconstructed time period but shows, in general, a decreasing trend. This decrease is due to the loss of tidal channels in the progressively reclaimed Dollard Bay (up till the 20th century), and the central-estuary channel transition from a double to single channel system. The estuary-scale A_i/A_s ratio decreases up to the beginning of the 20th century, and since then increases again (Figure 4). The decrease in A_i/A_s is mostly attributed to a loss in A_i (due to land reclamations works) whereas the increase in A_i/A_s is mostly attributed to a loss of subtidal area A_s (resulting from subtidal infilling).

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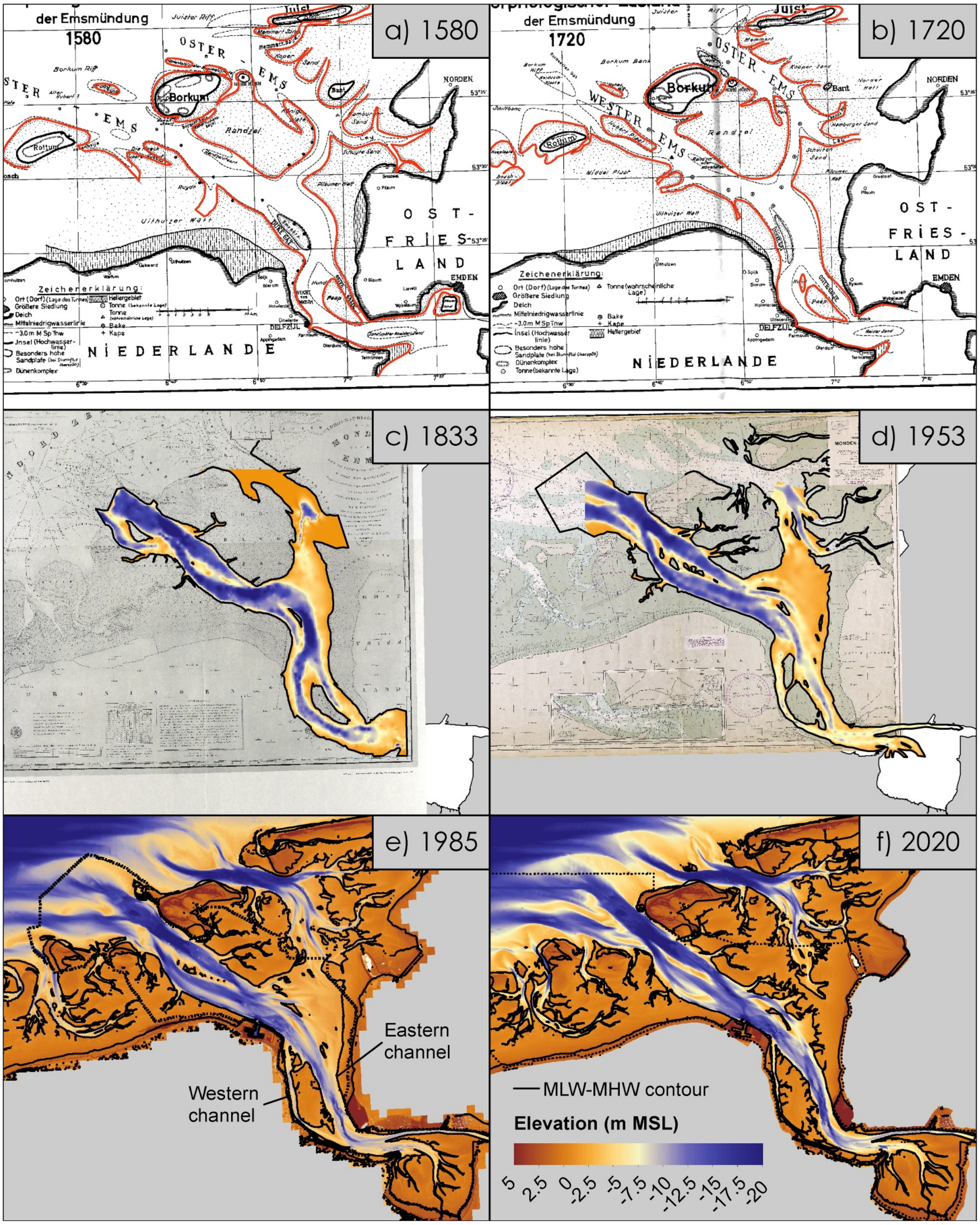

Figure 3. Centennial morphological evolution of the Ems estuary, based on: historical reconstructions of Lang (1954) (a), (b); reconstructed subtidal bathymetry from H. J. Pierik et al. (2022); H. Pierik (2019) (c), (d); and compiled data sets of echo sounding observations from the years 1985 and 1996 (e) and the years 2016 and 2020 (f). The Mean Low Water line is shown in red (a), (b) and black (c, d, e, f). On the two most recent maps (e), (f) the present-day outline of the estuary is shown and the dotted lines indicate the extent of the Rijkswaterstaat data sets.

3.2.2. Channel dimensions

Metrics of channel geometry, derived since the first available subtidal bathymetry in 1833, show that in the period 1833–1900 the total central-estuary channel area decreased (Figure 5a). The channels became shallower (Figure 5b), and as a combined result, the channel volume decreased (Figure 5c). After 1900, the subtidal area further decreased (Figures 4 and 5a). The remaining single channel, however, deepened (Figure 5b) and, as a result, the subtidal volume of the central-estuary channels remained mostly constant during the 20th century

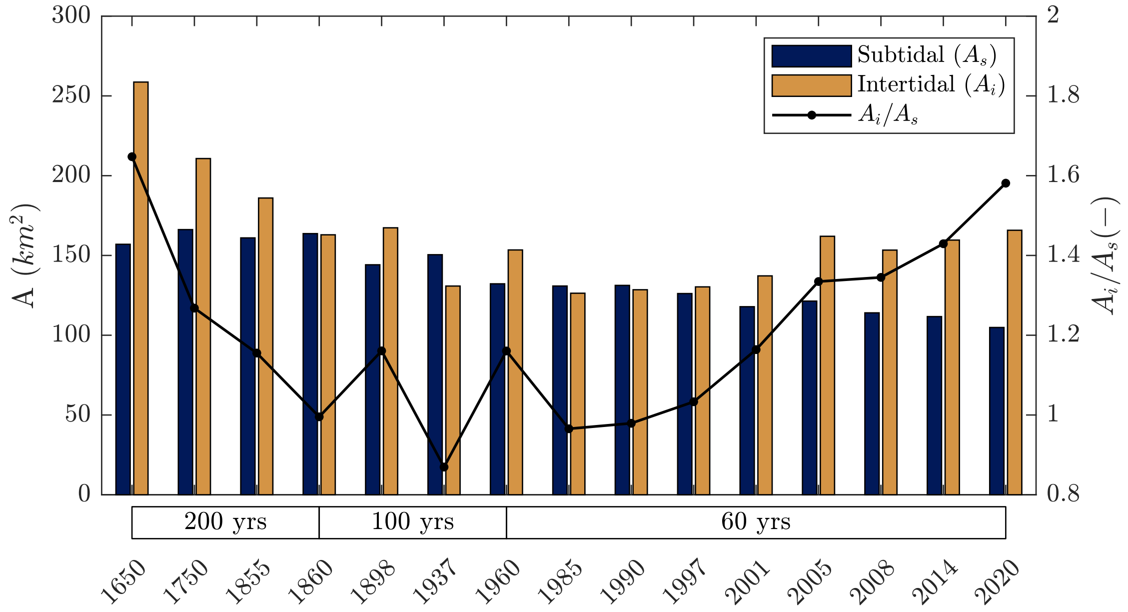

Figure 4. Subtidal and intertidal surface area (A) and subtidal to intertidal surface area ratio (A_i/A_s) in the estuarine zone, excluding the mouth zone (see Figure S4 in Supporting Information S1 for the spatial distribution of the surfaces). The boxes on the *x*-axis highlight that there is a time-scaling discontinuity between the available reconstructions.

(Figure 5c). This deepening is partly natural, but since the 1970's deepening accelerated by increasing maintenance dredging for navigation purposes (Figure S3 in Supporting Information S1). In the inner estuary, the subtidal volume has been nearly constant since 1888, because a decrease in subtidal area was compensated for by an increase in channel depth (Figure 5b). The subtidal volume of the outer estuary inlet increased (Figure 5c) and expanded (Figure 5a), presumably because the western inlet accommodated the tidal volume exchange of the disconnected eastern inlet. The depth of the outer estuary western inlet first decreased and later increased, which may be the result of the dynamic character of the inlets, influenced by tidal discharge, and wave-driven alongshore (eastwards) sediment transport.

Cross-sectional geometry metrics (see Figure 1 for the location of cross-section A-A') show that the width (W_{cs}) of the central-estuary channels (Figure 6a) has been changing very consistently since the oldest available historical reconstruction from 1580. The western channel width decreased steadily with ≈300–400 m/century up to 1900, after which the channel width abruptly narrowed. In the past decades the rate of change decreased again, but channel width continues to decrease up till present. The eastern channel width steadily increased with ≈250 m/century over the reconstructed period. The cross-sectional deepest point (Figure 6b) and cross-sectional area (Figure 6c) both show consistent trends of channel shoaling in the western channel and channel deepening in the eastern channel since the beginning of the 19th century. The change in the deepest point in the cross-section appears, similarly to channel width, to accelerate in the 20th century.

4. Discussion

4.1. Adaptation Timescales to Land Reclamation

The centennial-scale morphological reconstructions of the Ems estuary show that since the beginning of the land reclamation works in the 16th century the morphology of the estuary has been changing. The loss of estuarine tidal flats resulted in pronounced infilling of tidal channels. The channels and tidal flats in the central area and Dollard Bay clearly show this morphological response, despite 20th-century intensified channel dredging favoring an increase in subtidal volume. The channel and tidal flat adaptation demonstrates that the response time of estuaries to large-scale ($\frac{1}{3}$ of basin extent) and continued land reclamation is in the order of centuries. This response time to human interventions depends on the processes driving the change, the size of the system, and the magnitude of the intervention (Van Maren, Colina Alonso, et al., 2023) as well as accommodation space and sediment supply (Beets et al., 1992).

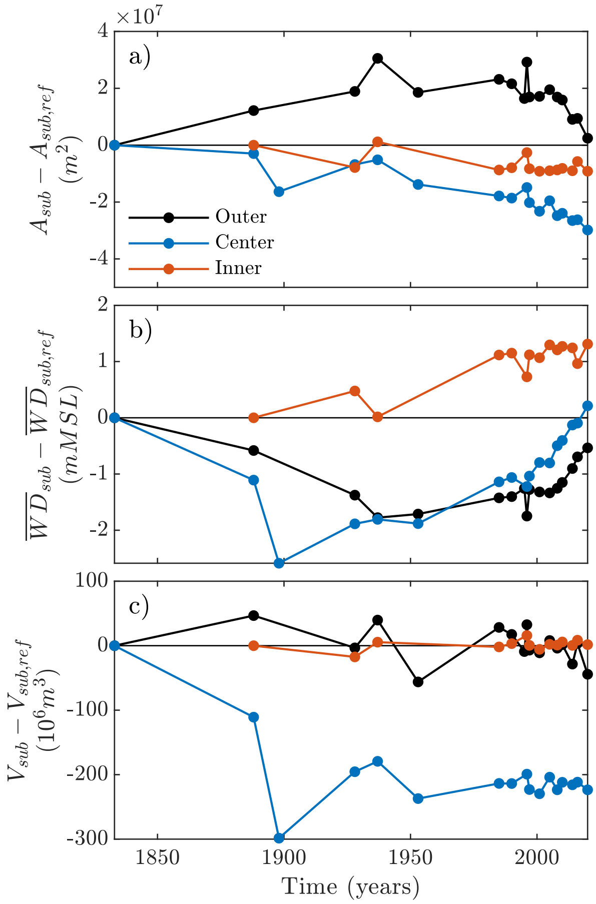

Figure 5. Relative change of the subtidal (below Mean Low Water) area A_{sub} (a), mean water depth $\overline{WD}_{sub}$ (b, with negative values implying shallower channels) and volume V_{sub}(c) with respect to the same properties derived from the first available subtidal bathymetry (1833 or 1888), depending on the region.

Intertidal storage volume decreased due to the reclamation of tidal flats. The decrease will lead to a smaller tidal prism conveyed through the tidal channels (Friedrichs & Aubrey, 1988; Speer & Aubrey, 1985), and channel infilling because the channel dimensions correspond to a pre-reclamation tidal volume exchange (Dronkers, 2016). In short tidal basins, the basin geometry change (Dronkers, 1986; Friedrichs & Aubrey, 1988; Ridderinkhof et al., 2014) and a reduction in friction (Fortunato & Oliveira, 2005) increase tidal asymmetry-driven import of sediment. In the Ems estuary, the main source of sediment is of marine origin (the Wadden Sea and/or North Sea), and the sediment load carried by the Ems river is small (Van Maren, van Kessel, et al., 2015). With abundant supply of sand from the adjacent shallow sandy seabed (Van der Molen & De Swart, 2001) and of mud supplied by the nearby Meuse and Rhine rivers, the tidal embayments along the Dutch coast filled up rapidly during the Holocene (De Haas et al., 2018; Van der Spek, 1994).

Despite the abundant sediment supply, the Ems Estuary requires centuries to adapt to human interventions. The observed trends in channel dimensions (Figures 4–6) show, up till present, no clear tendency toward stabilization. Therefore, we infer that the system-scale adaptation of the Ems estuary to tidal flat reclamation is ongoing. The continued trend of subtidal infilling in the center and inner estuary is particularly relevant for estuarine ecosystem services. Maintenance of the fairway may, therefore, face increasing dredging operations. Dredging volumes in the Ems estuary have increased substantially in the 1960s through the 1980s (Van Maren et al., 2016). This increase is, however, mostly related to channel deepening to accommodate heavier ship traffic and increased ship sizes (Essink et al., 1992).

Globally, dredging activities have accelerated in the past century (Talke & Jay, 2020). The hydro-morphodynamic conditions of estuaries and tidal basins in the pre-dredged era are often taken as a reference to study the impact of channel deepening (Bao et al., 2022; Ralston et al., 2019; Siemes et al., 2023), maintenance dredging and disposal (Jeuken & Wang, 2010; Van Dijk et al., 2021; Vellinga et al., 2014), or a combination (Van Maren, van Kessel, et al., 2015). Our results demonstrate that estuaries along which land was reclaimed are unlikely to be in morphological equilibrium. Pre-19th-century land reclamation may still impact the present-day morphodynamic evolution, which needs to be considered when differentiating between natural controls and recent human modifications (Dai et al., 2016; Monge-Ganuzas et al., 2013; Zhu et al., 2019).

Estuaries and embayments where tidal flats were reclaimed in the past century will likely experience a delayed morphodynamic response in the upcoming century, similar to the Ems Estuary. This applies to many estuaries in fast developing Asian countries; see (e.g., Chu et al., 2022; Kim et al., 2006; Wilson et al., 2017; Xie et al., 2017). Such an anticipated response (often estuarine infilling, conflicting with the typical navigational demand for deeper channels) should be part of sediment management strategies in the face of climate change. In many land reclamation impacted tidal systems, including the recently impacted Asian systems, tidal flat restoration efforts are proposed as a nature-based solution to improve ecological functioning, coastal flood protection, and to mitigate the impact of sea level rise (e.g., X. Wang et al., 2021; Jing et al., 2023; Cox et al., 2006; Weisscher et al., 2022). Tidal flat restoration adds intertidal area to the impacted system, partially offsetting the land reclamation effects. As a consequence, it can be expected that the system evolves at a faster rate toward a new equilibrium channel-flat configuration that in turn is subject to sea level rise and a river discharge regime altered by climate change.

4.2. Tidal Asymmetry and System Resilience

The loss of intertidal area due to tidal flat reclamation distorts the estuary-scale configuration of channels and tidal flats, which is quantified with a ratio A_i/A_s. Land reclamations resulted in a decrease in A_i/A_s over several

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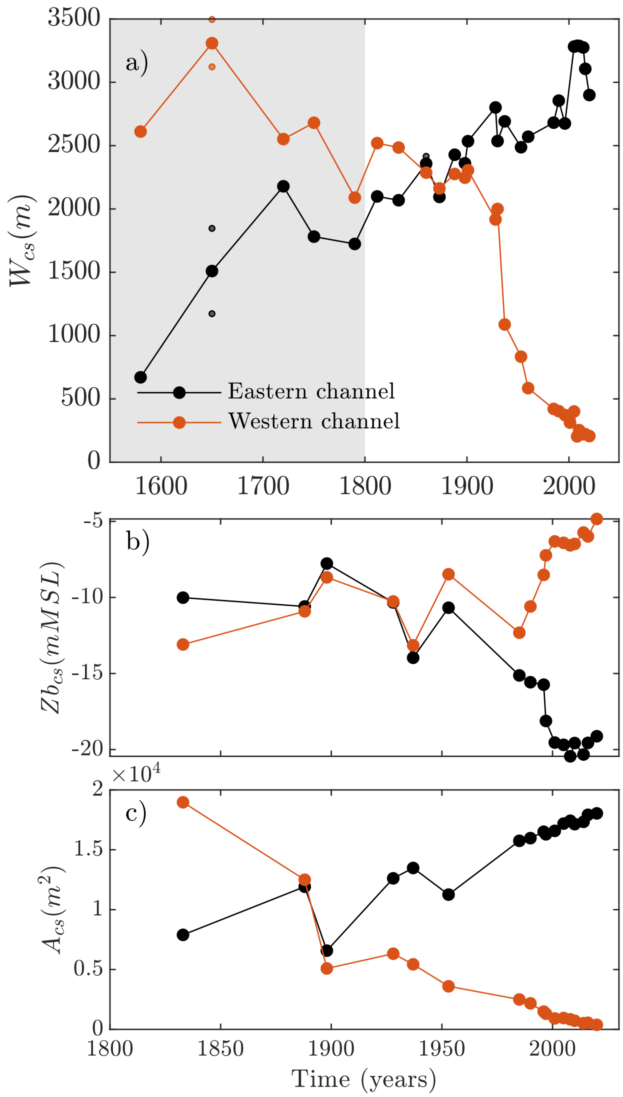

Figure 6. Channel width W_{cs} (a), deepest point Zb_{cs} (b), and cross-sectional volume V_{cs} (c) along the cross-section A-A' in Figure 1. Note that the channel geometry metrics are shown for time periods with data availability, leading to a longer time span in panel (a) (indicated by a gray patch) than in panels (b) and (c). Channel width in panel (a) shows averaged values for years with multiple sources available.

centuries, but the ratio increases again after 1937 (Figure 4). The reason for this change is stabilization of the tidal flat area (no more reclamations) while the subtidal area continued to decrease due to infilling in response to a smaller tidal prism. The reconstructed channel-flat ratio in the Ems estuary provides a unique long-term record, which allows testing stability theory.

Tidal inlet stability theory typically relates a metric for residual sediment transport (the type and degree of tidal asymmetry) to a metric representing the relative importance of flow over flats and channels. The type of tidal asymmetry is the result of a competition between frictional interaction between the tide and the channel bed (captured in the tidal amplitude over channel depth ratio, a/h) and the relative intertidal water storage capacity (captured in the intertidal volume over channel volume ratio, V_i/V_s) (e.g., Friedrichs & Aubrey, 1988; Dronkers, 2016; Z. B. Wang et al., 1999). Various types of tidal asymmetry-based stability relationships have been developed, which are quite consistent, as demonstrated by Zhou et al. (2018). Comparisons between the stability relationships and field-based conditions of real-world systems (Dronkers, 2016; Zhou et al., 2018), however, shows considerable discrepancy. The discrepancy is due to the assumptions that inevitably have to be made to facilitate the analytical solutions (e.g., simplifications of the cross-sectional geometry) and uncertainties in real-world observations (Zhou et al., 2018).

To apply existing equilibrium realtionships to the Ems Estuary, the subtidal and intertidal surface areas are converted to subtidal and intertidal volumes, following Zhou et al. (2018) and assuming a rectangular cross-sectional geometry:

$$V_i = 2a(S_{HW} - S_{LW}) \quad (1)$$

$$V_s = h(S_{LW}) \quad (2)$$

Here, S_{HW} and S_{LW} are the surface area at high water and low water, respectively. The surface area at low water is equal to the reconstructed subtidal area ($S_{LW} = A_s$) and the surface area at high water results from addition of the subtidal and intertidal areas ($S_{HW} = A_s + A_i$). The parameter a is the tidal amplitude at the mouth of the estuary (equal to 1.2 m; see Herrling and Niemeyer (2007)) and assumed constant for the reconstructed period (H. J. Pierik et al., 2022). The mean water depth h is taken as the average channel depth, following Zhou et al. (2018), and can only be computed since the availability of subtidal DEMs (beginning of the 19th century). Linear interpolation and extrapolation provide the values of h at the moments the channel-flat configuration is known (Figure 4). The evolutionary trajectory of the reconstructed Ems estuary (Figure 7) in the stability diagram shows that up till the beginning of the 20th century, the system evolved toward a more flood dominant regime (increasing a/h), but became more ebb dominant since then (decreasing a/h and increasing V_i/V_s). Such an evolutionary trajectory from an increasingly flood dominant system to ebb-dominant conditions agrees with the theoretical trajectory of an estuarine system responding to land reclamation (Dronkers, 2016). The agreement between the observed and theoretical trajectories suggests a certain resilience of the morphodynamic system, because there is system tendency toward a morphodynamic equilibrium state.

A delta system is defined as resilient when it has the capacity to recover from an extreme forcing at one of its boundaries and is largely self-sustaining (i.e., not in need of high maintenance) (Hoitink et al., 2020). In this case, the anthropologically disturbed channel-flat configuration is the forcing and the morphodynamic system response through tidal asymmetry-driven import of sediment restores this configuration. The recovery capacity of an estuarine system impacted by land reclamation will thus primarily depend on sediment availability. The future

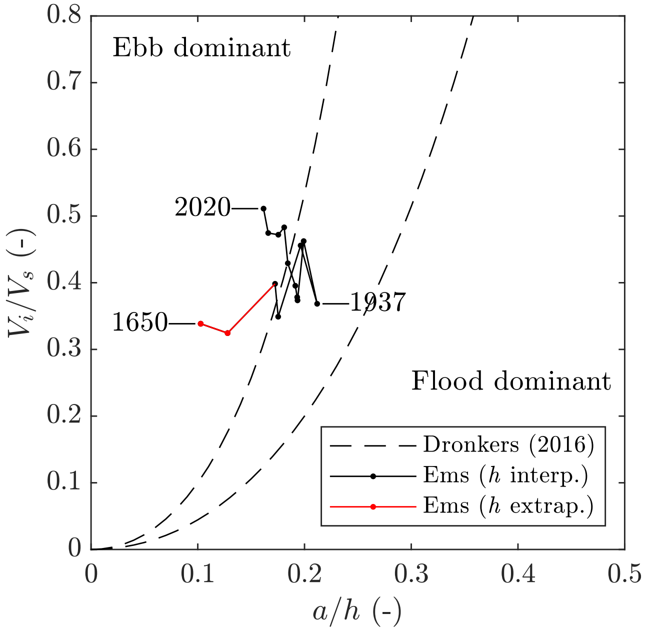

Figure 7. Tidal asymmetry based on the stability diagram in Zhou et al. (2018). For the Ems estuary data, V_i/V_s is derived by applying Equations 1 and 2 on the surface areas from the morphological reconstructions, the tidal amplitude a is assumed constant at 1.2 m, and the mean water depth h is derived from linear interpolation and extrapolation (red data points) on the subtidal DEMs. The stability curves represent the analytical expressions derived by Dronkers (2016) with $\gamma = [1, 2]$.

development of a land reclamation impacted system like Hangzhou bay, for example, can therefore be expected to follow a similar evolutionary trajectory as the Ems estuary, and tidal asymmetry-based equilibrium theory can be useful to anticipate on future estuarine evolution. Based on equilibrium theory, the system-scale morphodynamic trends of Hangzhou Bay are expected to include increased subtidal infilling of channels, and continued aggradation of the tidal flats.

4.3. Controls on Channel-Flat Dynamics

The channel-flat pattern in the Ems estuary transitioned from a double-inlet multichannel system with mutually evasive ebb and flood channels separated by shoals, toward a channel system consisting of a single inlet with a main channel and less pronounced ebb and flood channels. The degeneration of the connection with the eastern Ems inlet and the central-estuary channel system change are the most pronounced channel pattern developments. These channel dynamics can be observed since the 16th century (Figure 3) until present, indicating a permanent channel pattern change with no tendency of re-establishment of the multi-channel system. Considering that these developments started in the 16th century, the loss of the characteristic multichannel pattern is not caused by channel re-alignment and dredging works in the 19th and 20th centuries (Van Veen, 1950; Van Veen et al., 2005). The past decadal developments of channel geometry do show a clear signature of dredging activity (Figures 5 and 6) but these changes are superimposed on the long-term system-scale response to the loss of intertidal areas (Figures 4 and 7). The most likely trigger for the channel pattern change is thus the loss of intertidal areas landward of the central-estuary channels and the resulting decrease of the tidal volume exchange (Gerritsen, 1952), predominantly caused by reclamation of Dollard Bay.

The loss of a naturally stable multichannel ebb and flood system has previously been related to dredging and disposal activities (Monge-Ganuzas et al., 2013), because a change in flow and sediment distribution can lead to bifurcation instability and subsequent channel degeneration (avulsion) (Z. B. Wang & Winterwerp, 2001; Jeuken & Wang, 2010; Gao et al., 2024). Here, we present a system in which the degeneration of the multichannel system is not primarily caused by dredging and disposal activities but by land reclamation, although dredging works may have accelerated the response to land reclamations. This points to a relation between the tidal prism and the number of channels in an estuary or tidal basin.

The cross-sectional area (A) of a tidal inlet is linearly correlated to the tidal prism (P) (Jarrett, 1976; O'Brien, 1931). This well-known tidal prism-area (P-A) relationship is argued to be applicable along the entire length of the tidal channel (D'Alpaos et al., 2010), although it seems to have upper and lower limits (Hibma et al., 2004). In the Western Scheldt estuary, a channel will bifurcate into more channels if the cross-sectional area exceeds 25,000–30,000 m^2 (Allersma, 1992; Voorsmit, 2006). Interestingly, the total cross-sectional area of the central-estuary channels in the Ems estuary equaled this critical value in the 19th century (Figure 6c), shortly after which the multichannel system degenerated. This supports that the loss of the multichannel system results from a reduction in cross-sectional area, which in turn is the result of channel infilling due to lower tidal flow velocities. The range in the critical cross-sectional area found in the Western Scheldt is, however, not universally constant, but depends on the size of the system and type of sediment in the estuary (Allersma, 1994). The number of channels is limited by the width to depth ratio of the estuary cross-section, with an increasing number of channels with increasing estuary width (Stive & Wang, 2003). Numerical morphodynamic modeling confirms that, indeed, the development of a multichannel system is controlled by the tide and basin geometry (Gundlach et al., 2021). The development of quantitative relationships between the number of tidal channels and the tidal prism, the cross-sectional area, and the width to depth ratio of the estuary is, however, a contemporary challenge that is crucial in making future predictions for estuarine morphology.

4.4. Future Estuarine Evolution

The multi-centennial evolution of the Ems estuary demonstrates that, provided that sufficient sediment is available, land reclamation-impacted estuaries can adapt toward a new equilibrium channel-flat morphology through tidal asymmetry driven import of sediment. In the past centuries, the impact of human interference often exceeded allogenic controls, such as sea level rise or changes in the wind and wave climate (Talke & Jay, 2020; Vellinga et al., 2014). It is anticipated that a faster rise in global sea level (Intergovernmental Panel on Climate Change (IPCC), 2021) will increase the influence of sea level rise on prevailing tidal characteristics in estuaries (Haigh et al., 2020). The associated morphodynamic response will depend on the estuary's size, planform, and bathymetry (J. R. F. W. Leuven et al., 2019) because the basin hypsometry controls the tidal response to a mean water level change (Dronkers, 1986).

The tidal prism is directly influenced by the increased intertidal storage volume caused by sea level rise. The increased tidal prism enhances the transport capacity in the tidal channels to supply the sediment for accretion of the intertidal areas (e.g., Dronkers, 2016; Elmilady et al., 2022; Khojasteh, Chen, et al., 2021). Still, tidal flat aggradation lags behind sea level rise (Elmilady et al., 2019; Huismans et al., 2022). In estuaries where the intertidal dynamics are restrained, the extent of the intertidal areas, therefore, may decrease initially despite an intertidal storage volume increase. This enhances flood dominance and sediment import. Estuaries that still adapt to recent land reclamations currently have a channel-flat morphology and channel dimensions that are unlikely to sustain under the occurring tidal forces. Therefore, these systems are faced with an increasing sediment demand from both autogenic (land reclamation) and allogenic (sea level rise) controls.

The capability of an estuary to reach an equilibrium topography in response to land reclamation and sea level rise will thus not only depend on the availability of an external sediment influx to satisfy the additional sediment demand (Reeve & Karunarathna, 2009), but also on the change in transport capacity with sea level rise and alteration of the river discharge regime subject to climate change. Fundamental insight on the change in sediment dynamics under sea level rise and climate change is thus required to inform estuarine management decisions (Khojasteh, Glamore, et al., 2021), because the effects are highly site-specific. Numerical modeling of the impacts of sea level rise on estuaries in a changing climate will help to gain more detailed insight into the expected hydrodynamic changes (Huismans et al., 2022; Jordan et al., 2021; Khojasteh, Glamore, et al., 2021).

5. Conclusion

The land reclamation history and the morphodynamic evolution of the Ems estuary were reconstructed since the 16th century. The reconstructions show that the morphodynamic evolution of the Ems estuary is heavily influenced by land reclamation works, particularly by those carried out in the Dollard Bay. The loss of intertidal storage volume as a result of tidal flat reclamation reduces the tidal prism, which leads to subtidal infilling. Interpretation of the long-term change in tidal channels and flats shows that the system-scale morphodynamic adaptation is controlled by the effects of land reclamation. Channel deepening and maintenance dredging in the 20th century cumulatively impacted the system, while still adapting to the land reclamation works. The disconnection of a tidal inlet to the main estuarine system, and the transition from a multichannel-shoal complex toward a single channel configuration with fringing flats, is shown to be primarily forced by the effects of land reclamation. Dredging works and channel re-alignment have likely accelerated these developments.

The centennial-scale historical analysis shows that the land reclamation response of the Ems estuary corresponds to the evolutionary trajectory predicted by tidal asymmetry-based stability theory as it moved toward a new equilibrium configuration with modified tidal flats and channels. This demonstrates that stability theory can be applied to predict the evolutionary trajectory of real-world estuaries responding to land reclamation, serving as a valuable tool to aid for the future management of estuaries. The channel pattern transition - from a multichannel to single channel system - is argued to be related to the changes in tidal prism and the width to depth ratio of the estuary.

Data Availability Statement

Figure 1 is compiled from various sources of topo-bathymetric data to construct a full coverage DEM, all sources are publicibly available. The data sources include the land surface topography at 30 m resolution provided by

Copernicus (2016), sub-aqueous bathymetry of the North Sea at ≈90 m resolution provided by the European Marine Observation and Data Network (EMODnet Bathymetry Consortium, 2016) and the coastal bathymetry which was requested through the servicedesk data of Rijkswaterstaat (https://www.rijkswaterstaat.nl/formulieren/contactformulier-servicedesk-data). Figures 1 and 2 use the color blind-friendly batlow color scale provided by Crameri et al. (2020). The main sources for the reconstruction of the land reclamation history are geospatial data sets with the location of historical embankments (Provincie Groningen, 2024) and the National Historical Culture registry (Rijksdienst voor het Cultureel Erfgoed, 2024). The land reclamations reconstructions are published (Schrijvershof, 2024) and available at 4TU.ResearchData (https://data.4tu.nl/datasets/78ac0cf9-e9f7-47c7-8c4e-93f7fb2c633e/1). The morphological reconstructions are based on a large number of historical maps, reconstructions and data sources, all listed in Table 1. All maps that were georeferenced and digitized (MLW, MHW, and supratidal contours) in this study (Gerritsen, 1952; Lang, 1954) and the maps of Homeier (1962) are included in Schrijvershof (2024). The digitized reconstructions made by Herrling and Niemeyer (2007) from the maps of Homeier (1962) were provided by the Niedersächsischer Landesbetrieb für Wasserwirtschaft, Küsten- und Natur-schutz (NLWKN) and can be contacted for the data (https://www.nlwkn.niedersachsen.de/). The digitized reconstruction of the maps of Stratingh and Venema (1855) and available from De Jong (2006). The gridded (subtidal) bathymetry data sets (see Table 1) are available from H. Pierik (2019) (data sets 1833, 1888, 1928, 1953), Schrijvershof (2024) (data set 1898), Herrling and Niemeyer (2008) (data set 1937), Rijkswaterstaat (https://www.rijkswaterstaat.nl/formulieren/contactformulier-servicedesk-data) (data sets 1985, 1990, 1997, 2001, 2005, 2008, 2014, 2020), Sievers et al. (2021) (data sets 1996 and 2016), and WSA Emden (https://www.wsa-ems-nordsee.wsv.de/Webs/WSA/Ems-Nordsee/DE/00_Startseite/startseite_node.html) (data set 2010).

Acknowledgments

This work was funded by the Netherlands Organisation for Scientific Research (NWO) within Vici project "Deltas out of Shape: Regime Changes of Sediment Dynamics in Tide-Influenced Deltas" (Grant NWO-TTW 17062) and Deltares Research Funds. This study is based on and relied on an enormous quantity of historical data sources compiled from old literature, that is often not well-disclosed. We want to thank all involved that supported the collection of the required data sets that made this study possible. In particular the colleagues from Niedersächsischer Landesbetrieb für Wasserwirtschaft, Küsten-und Natur-schutz (NLWKN) for providing the digitized reconstruction of Homeier (1962) and our colleague Joris Beemster who generously helped on gathering and digitizing the 1898 Nautical Charts from the Reichs Marine Amt.

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