Posted on 25 Apr 2024 — The copyright holder is the author/funder. All rights reserved. No reuse without permission. — https://doi.org/10.22541/essoar.171405335.56595430/v1 — This is a preprint and has not been peer-reviewed. Data may be preliminary.

Land Reclamation Controls on Multi-Centennial Estuarine Evolution

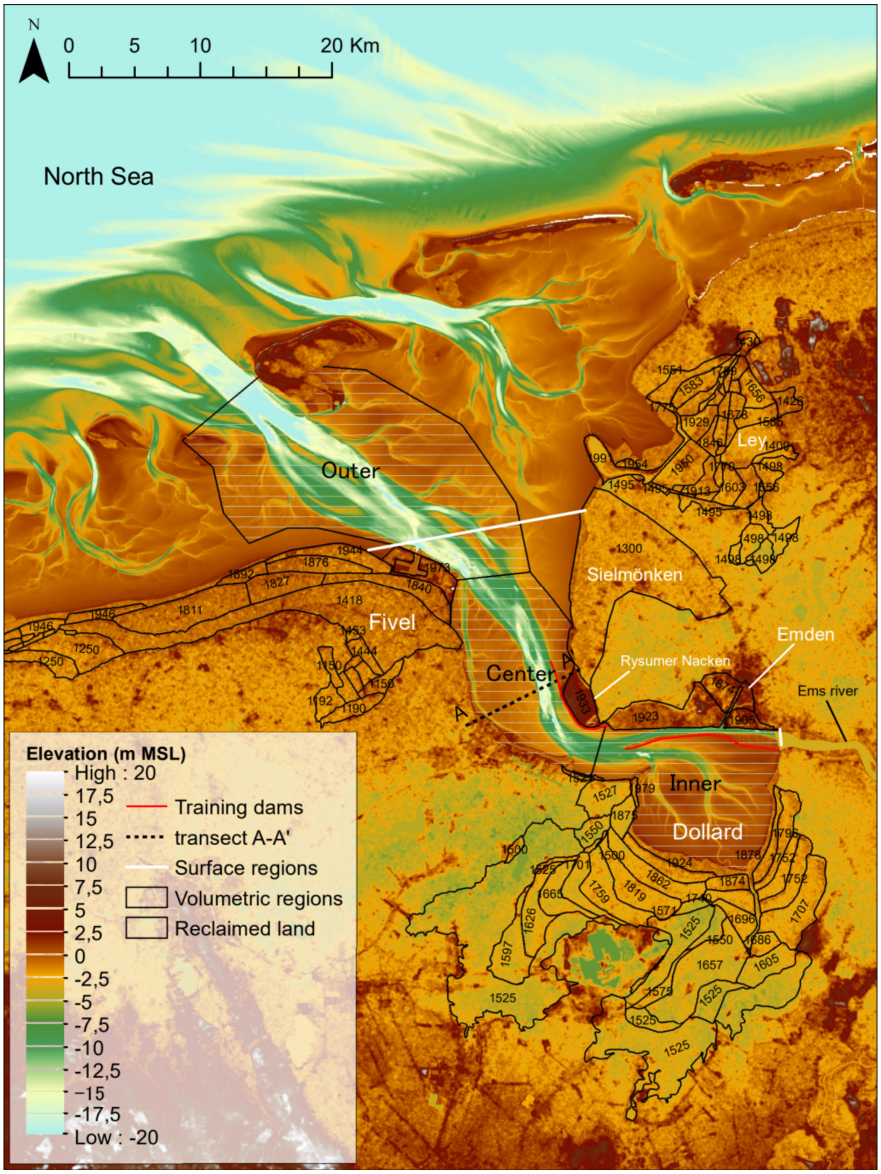
Reinier Schrijvershof[1], Dirk Sebastiaan van Maren[2], Mick van der Wegen[3], and A.J.F. (Ton) Hoitink[4]

[1]Wageningen University and Research
[2]East China Normal University
[3]IHE Delft Institute for Water Education, Delft, Netherlands
[4]Wageningen University

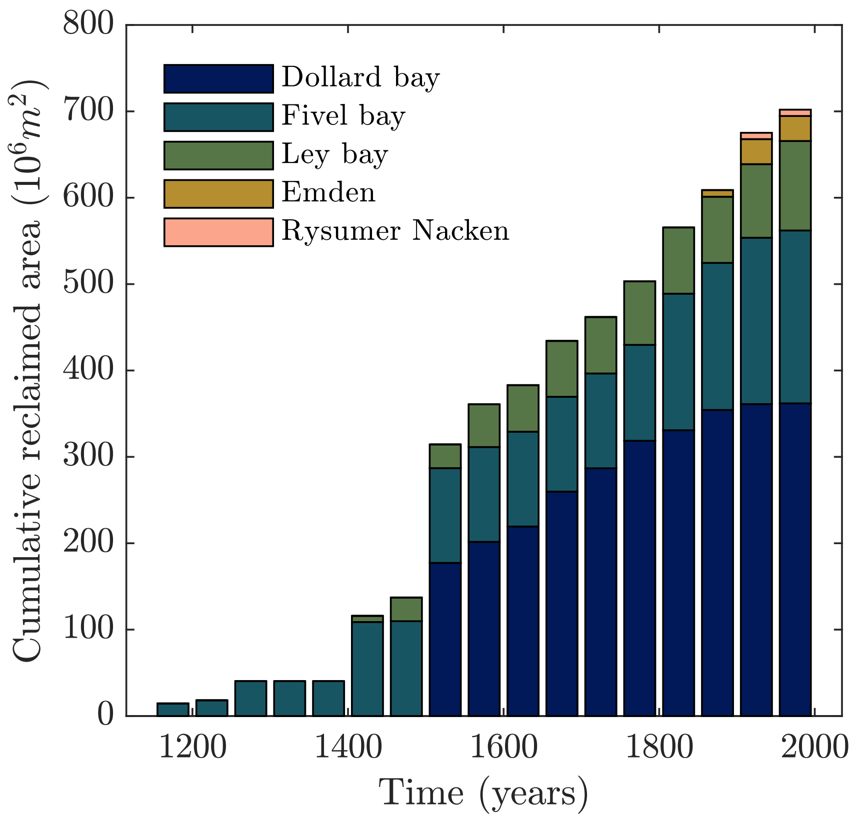
April 25, 2024

Abstract

Land reclamations influence the morphodynamic evolution of estuaries and tidal basins, because 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) add a morphodynamic adaptation timescale to a system that may still adapt as the result of land reclamations. 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 cause this development. The centennial-scale observations suggest that estuarine systems responding to land reclamations follow the evolutionary trajectory predicted by tidal asymmetry-based stability theory as they move towards a new equilibrium configuration with modified tidal flats and channels. Existing estuarine equilibrium theory, however, fails in linking multichannel stability to the loss of intertidal area, emphasizing the need for additional research.

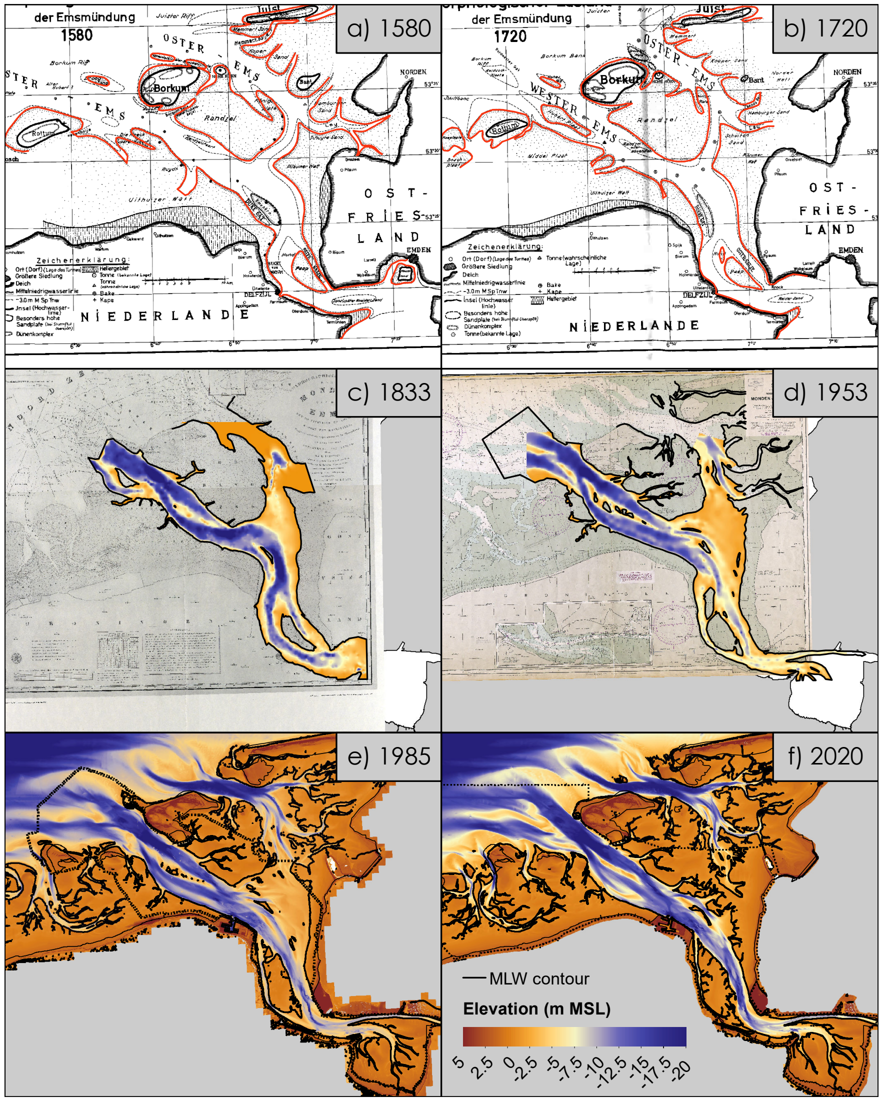


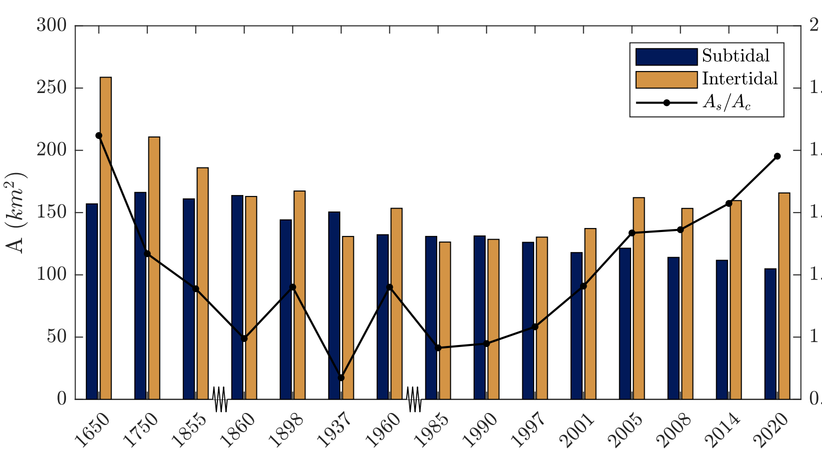
Posted on 25 Apr 2024 — The copyright holder is the author/funder. All rights reserved. No reuse without permission. — https://doi.org/10.22541/essoar.171405335.56595430/v1 — This is a preprint and has not been peer-reviewed. Data may be preliminary.



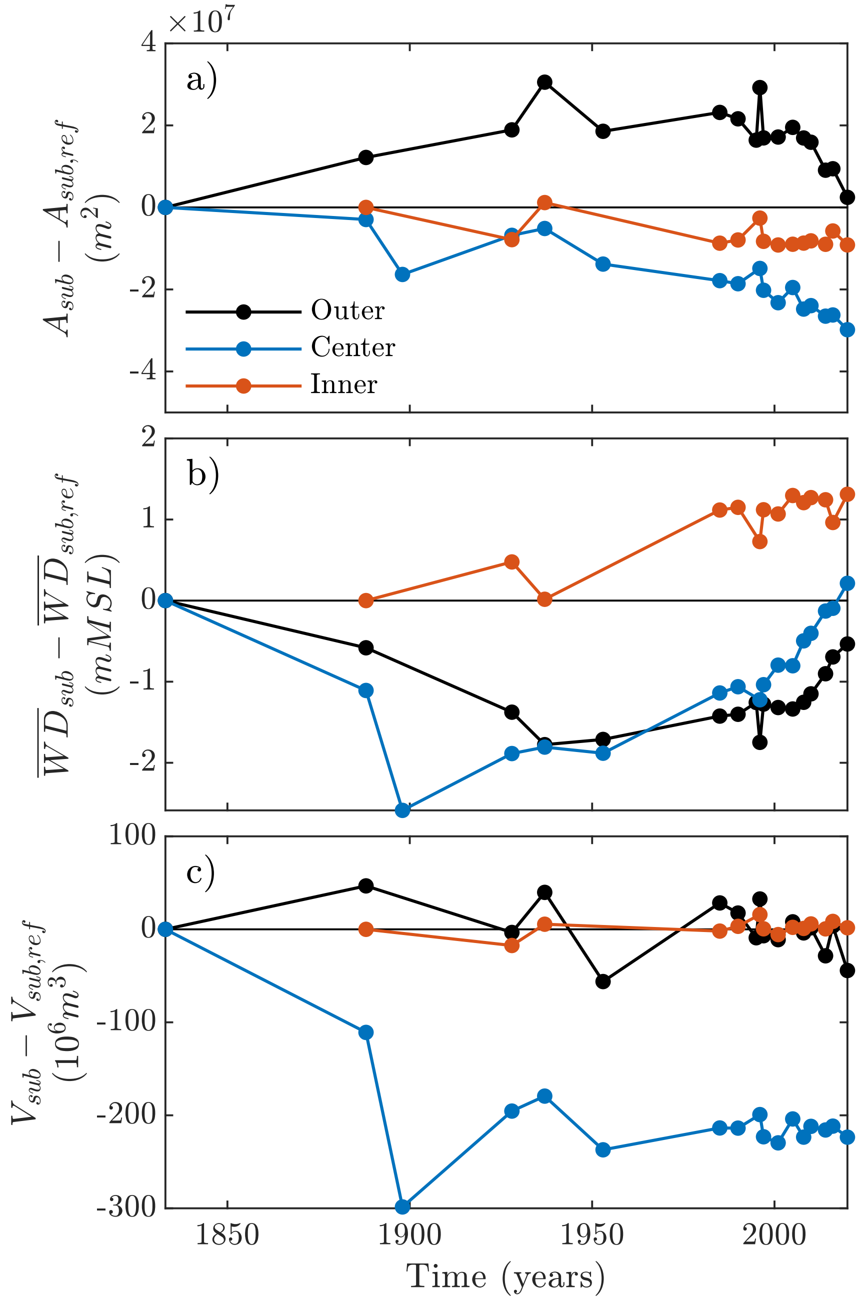
Posted on 25 Apr 2024 — The copyright holder is the author/funder. All rights reserved. No reuse without permission. — https://doi.org/10.22541/essoar.171405335.56595430/v1 — This is a preprint and has not been peer-reviewed. Data may be preliminary.

Posted on 25 Apr 2024 — The copyright holder is the author/funder. All rights reserved. No reuse without permission. — https://doi.org/10.22541/essoar.171405335.56595430/v1 — This is a preprint and has not been peer-reviewed. Data may be preliminary.

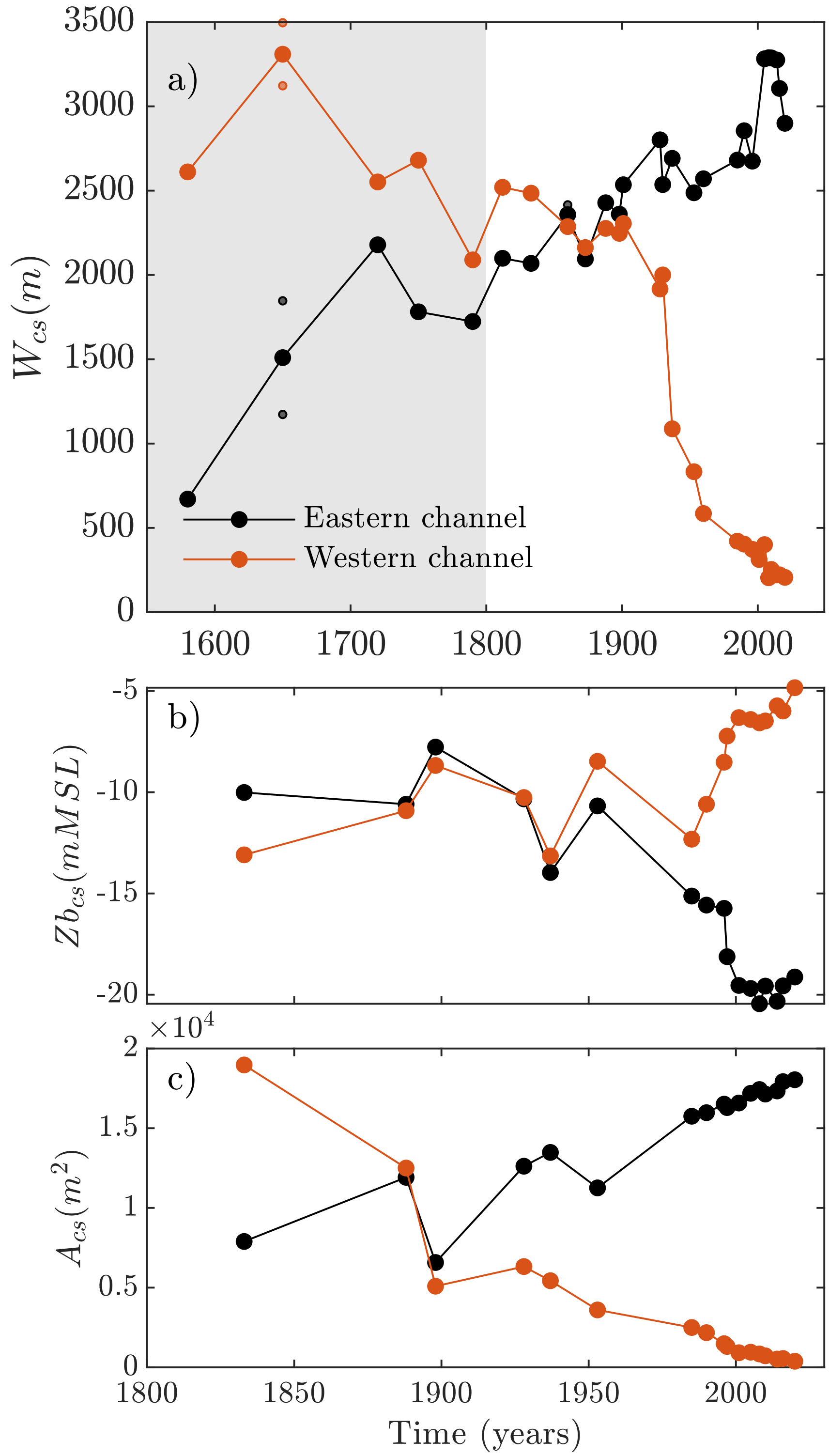




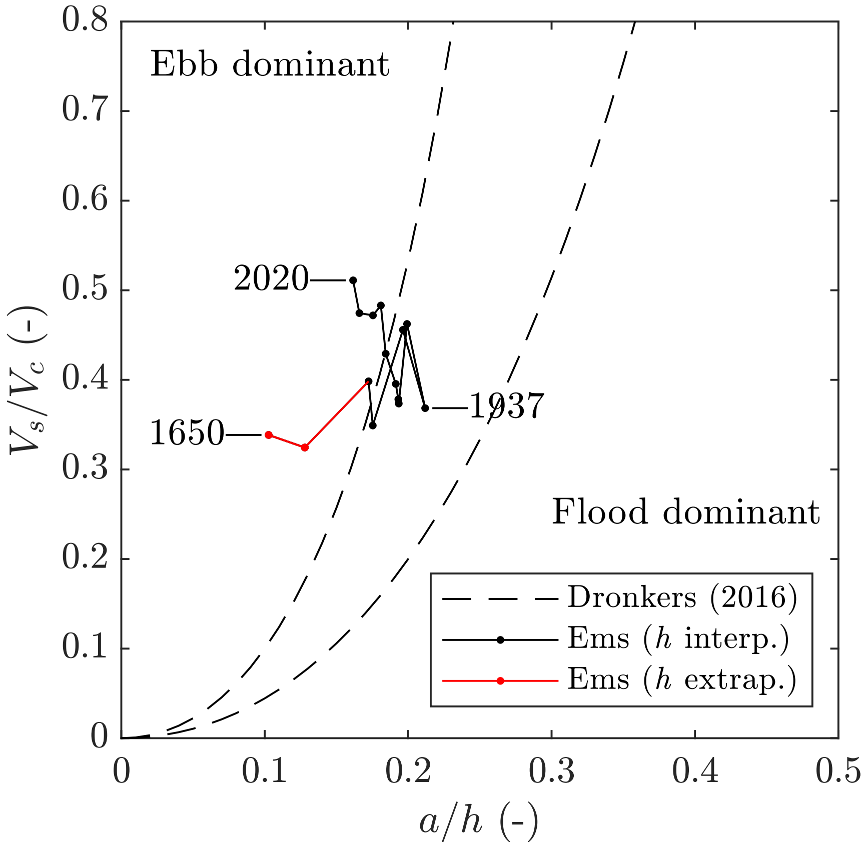
Posted on 25 Apr 2024 — The copyright holder is the author/funder. All rights reserved. No reuse without permission. — https://doi.org/10.22541/essoar.171405335.56595430/v1 — This is a preprint and has not been peer-reviewed. Data may be preliminary.



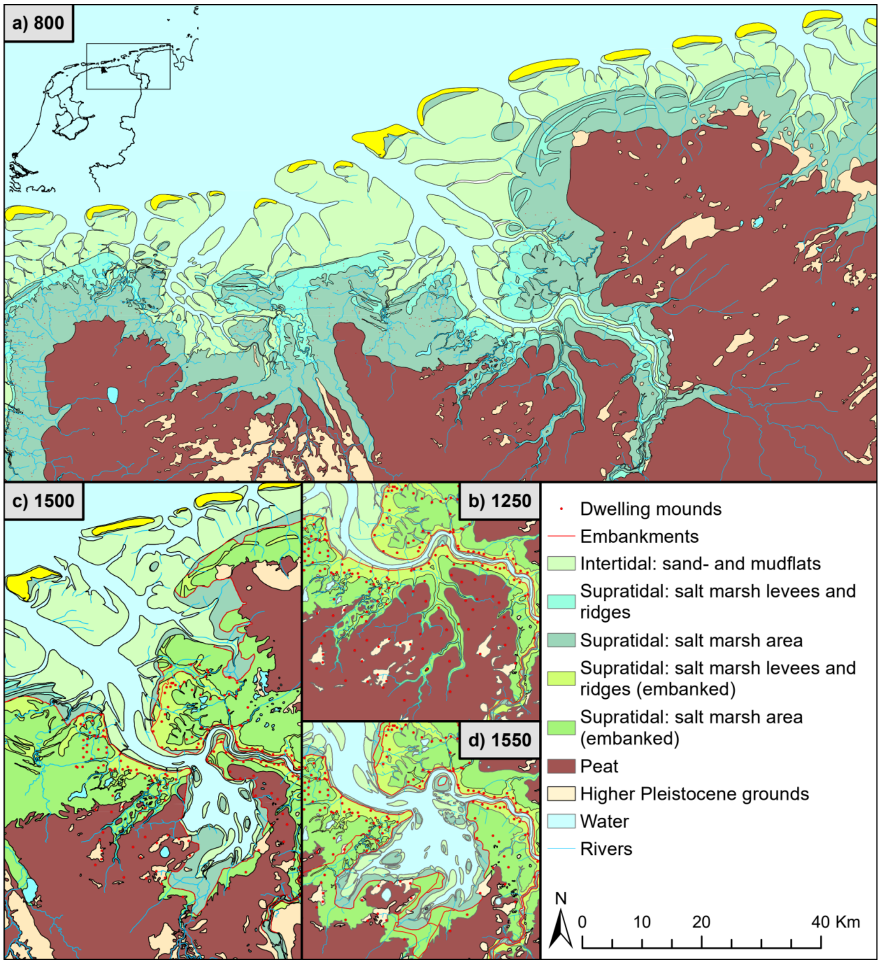
Posted on 25 Apr 2024 — The copyright holder is the author/funder. All rights reserved. No reuse without permission. — https://doi.org/10.22541/essoar.171405335.56595430/v1 — This is a preprint and has not been peer-reviewed. Data may be preliminary.



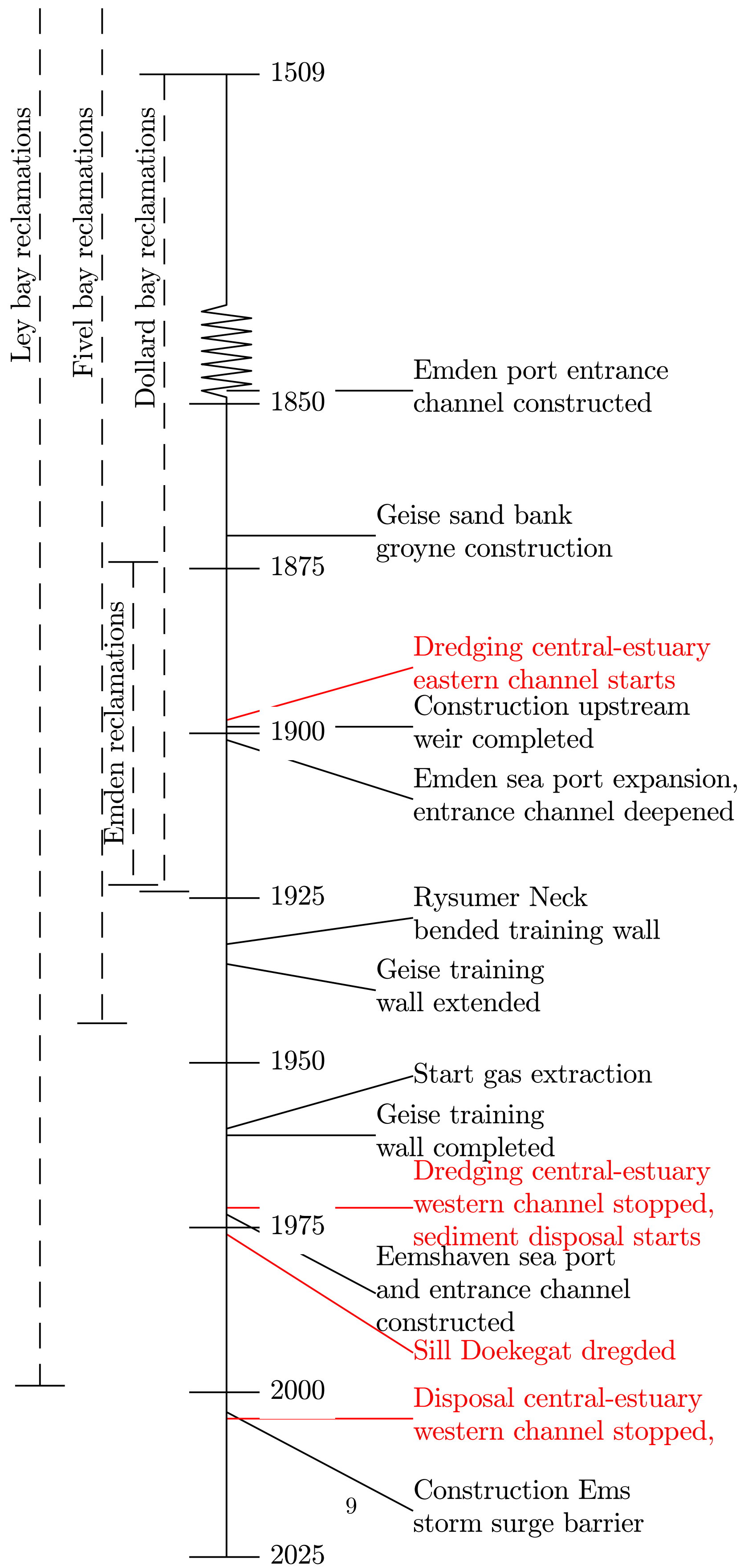
Posted on 25 Apr 2024 — The copyright holder is the author/funder. All rights reserved. No reuse without permission. — https://doi.org/10.22541/essoar.171405335.56595430/v1 — This is a preprint and has not been peer-reviewed. Data may be preliminary.



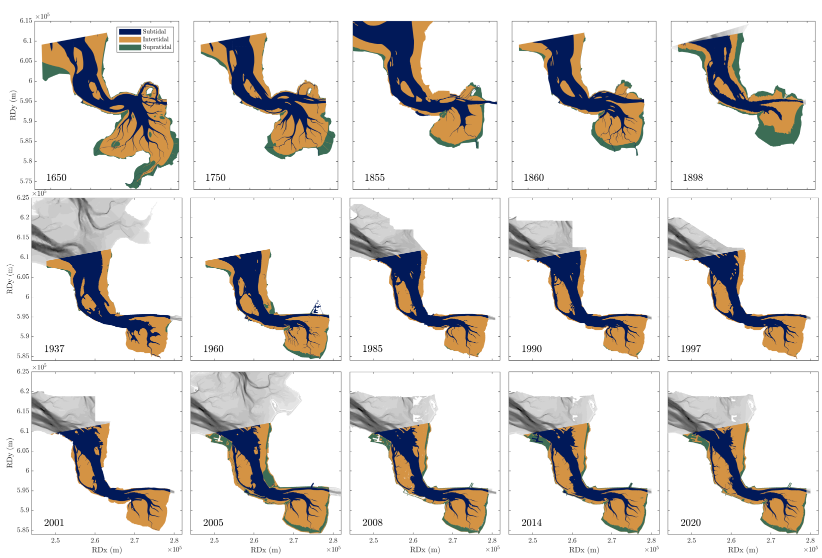
Posted on 25 Apr 2024 — The copyright holder is the author/funder. All rights reserved. No reuse without permission. — https://doi.org/10.22541/essoar.171405335.56595430/v1 — This is a preprint and has not been peer-reviewed. Data may be preliminary.



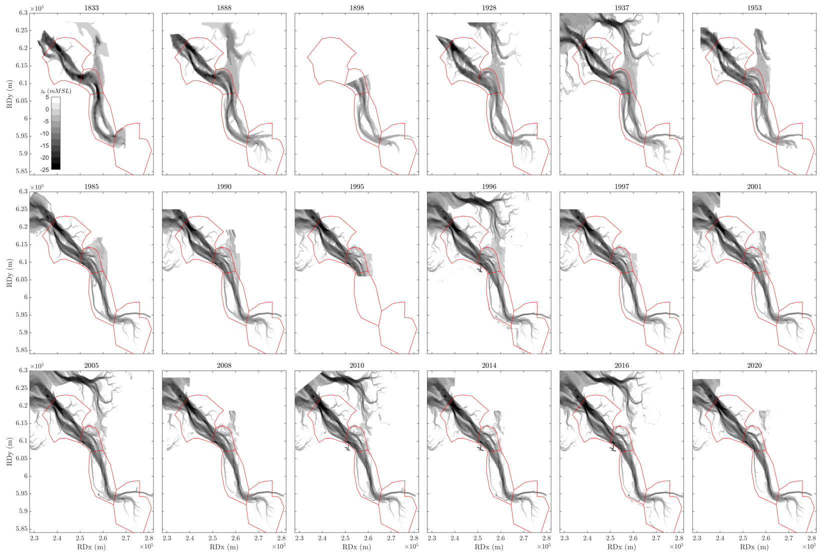
Posted on 25 Apr 2024 — The copyright holder is the author/funder. All rights reserved. No reuse without permission. — https://doi.org/10.22541/essoar.171405335.56595430/v1 — This is a preprint and has not been peer-reviewed. Data may be preliminary.



Posted on 25 Apr 2024 — The copyright holder is the author/funder. All rights reserved. No reuse without permission. — https://doi.org/10.22541/essoar.171405335.56595430/v1 — This is a preprint and has not been peer-reviewed. Data may be preliminary.



Posted on 25 Apr 2024 — The copyright holder is the author/funder. All rights reserved. No reuse without permission. — https://doi.org/10.22541/essoar.171405335.56595430/v1 — This is a preprint and has not been peer-reviewed. Data may be preliminary.



Land Reclamation Controls on Multi-Centennial Estuarine Evolution

R.A. Schrijvershof[1,2], D.S. van Maren[2,3], M. van der Wegen[2,4], A.J.F. Hoitink[1]

[1]Wageningen University & Research, Environmental Sciences Group, Wageningen, The Netherlands
[2]Deltares, Delft, The Netherlands
[3]Delft University of Technology, Faculty of Civil Engineering and Geosciences, The Netherlands
[4]IHE-Delft Institute for Water Education, Delft, The Netherlands

Key Points:

- Land reclamation in the Ems estuary has led to 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 predict the evolutionary trajectory of real-world estuaries responding to land reclamation

Corresponding author: R.A. Schrijvershof, `reinier.schrijvershof@wur.nl`,`reinier.schrijvershof@deltares.nl`

Abstract

Land reclamations influence the morphodynamic evolution of estuaries and tidal basins, because 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) add a morphodynamic adaptation timescale to a system that may still adapt as the result of land reclamations. 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 20$^{\text{th}}$-century intensification of channel dredging and re-alignment works accelerated rather than cause this development. The centennial-scale observations suggest that estuarine systems responding to land reclamations follow the evolutionary trajectory predicted by tidal asymmetry-based stability theory as they move towards a new equilibrium configuration with modified tidal flats and channels. Existing estuarine equilibrium theory, however, fails in linking multichannel stability to the loss of intertidal area, emphasizing the need for additional research.

Plain Language Summary

Reclaiming land along the margins of estuaries and tidal basins leads to loss of intertidal areas. The response of the remaining underwater landscape to the loss of intertidal areas takes decades to centuries. This impacts 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 beginning of the 16$^{\text{th}}$ century, when 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. Further research should address the link between changes in intertidal areas and channel dynamics because we currently lack such a comprehensive understanding. This hampers our ability to predict the effects of future anticipated tidal flat changes, as a result of, for example, sea level rise or tidal flat restoration works.

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 provided by estuarine morphology because the channel-flat pattern and geometry (hypsometry) determine hydrological connectivity (Hiatt & Passalacqua, 2015), ecological connectivity (Olds et al., 2017), and influences future morphodynamic evolution because of the link with tidal asymmetry and residual sediment transport (Dronkers, 1986; Z. 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 pressure requires grasping the complex interaction between the tidal channels and the adjacent intertidal areas (Z. B. Wang et al., 2015; Hoitink et al., 2020).

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 (A. Hibma et al., 2004; van der Wegen et al., 2008; Braat et al., 2017; Leuven & Kleinhans, 2019). Important hydrodynamic mechanisms linked to the tidal flats are the temporal storage of mass and dissipation of momentum (Friedrichs & Aubrey, 1988; Alebregtse, 2015; 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 versus export) and steer the morphodynamic evolution of an estuary or tidal basin (Van Der Wegen, 2013; Guo, Zhu, et al., 2022; Chen et al., 2020).

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 basins' geometry (i.e.; depth, width, length) is essentially changed (Talke & Jay, 2020). Tidal flat loss reduces the embayments' 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).

The morphodynamic response to large-scale interventions, such as tidal flat reclamation is, however, often slow and manifests itself on longer time-scales (Guo, Zhu, et al., 2022). 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). Various concurrent human interventions (reclamation, deepening, construction of hydraulic works) may impact a system. It is difficult to isolate the impact of a single intervention because each intervention adds a morphodynamic adaptation timescale to a system that may still adapt as the result of previous interventions. As a result, multiple interventions may interactively impact the system within the morphodynamic adaptation time, possibly exacerbating or accelerating the system's response to the principle intervention (Z. B. Wang et al., 2015).

Land reclamation and channel deepening may influence system-scale sediment budgets (Guo, Xie, et al., 2022; Donatelli et al., 2018), initiate a transition to hyper-concentrated flow conditions (Winterwerp et al., 2013; Van Maren, Winterwerp, & Vroom, 2015; Van Maren et al., 2016), and influence channel migration and avulsion (Dai et al., 2016). In the Ganges-Brahmaputra-Meghna (GBM) mega delta, for example, large-scale land reclamation (>5000 km^2) in the 60's and 70's of the 20^{th} 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). Such 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 (Liu et al., 2007; Coco et al., 2013). The observed and widely varying impact of land reclamation can not be predicted on the basis of estuarine equilibrium theory. To date, it remains unclear to what extent these developments are driven by land reclamations or other human interference. Based on long-term observations that span the time of morphological adaptation to tidal flat reclamations, here we explore if the evolution of real-world tidal systems agrees with the theoretical frameworks describing the evolutionary trajectory towards 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, 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 16^{th} century. This was followed by fairway re-alignment, deepening, and maintenance dredging since the 20^{th} 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 20^{th} century (Gerritsen, 1952), which is still poorly understood. Two hypotheses exist explaining these channel pattern changes: (1) channel system instability due to fairway deepening and related sediment disposal (Van Veen et al., 2005; Van Veen, 1950), and (2) 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).

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 datasets with the location of historical embankments[1] and the National Historical Culture registry[2]. 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 palaeogeographical reconstructions (P. C. Vos & Knol, 2015, 2013) were used to detail the maximum extent of storm-surge-formed bays, to include the oldest (poorly-documented)

[1] `https://geoportaal.provinciegroningen.nl/portal/apps/experiencebuilder/experience/?id=9e93c75c4e5e47a584829e1deb0ad5f6`

[2] `https://nationaalgeoregister.nl/geonetwork/srv/dut/catalog.search#/metadata/9a9cef3a-2dfc-4aa8-b248-f73f4064d7ad`

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)[3]. 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 intense anthropogenic interventions since the 16$^{\text{th}}$ century. A unique long-term record of geospatial datasets is compiled that almost completely covers this time-period (Table 1). The datasets were collected from published literature (Lang, 1954; Homeier, 1962; Gerritsen, 1952; Stratingh & Venema, 1855), published data sources (H. Pierik, 2019; Sievers et al., 2021), or collected from national archives, and were provided in digitized format (Herrling & Niemeyer, 2007, 2008; De Jong, 2006) or, otherwise, digitized using GIS software. The recent gridded topo-bathymetrical datasets (1985-2020) are publicly available at Rijkswaterstaat[4] and WSA Emden[5]. The datasets can be divided in three categories: (1) historical reconstructions of channel and tidal flat planform, based on a large variety of written and illustrated sources, but interpreted and compiled in the 20$^{\text{th}}$ century, (2) digitized nautical charts originally collected in hydrographic surveys for military and water way organizations, and (3) recent (1937, 1985-2020) full coverage digital elevation models (DEM) collected through (echo) sounding observations. All geospatial datasets were provided or converted in a digitized format (Table 1) and published with this paper (Schrijvershof, 2024). The three types of datasets 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 (NAP +1.30 NAP), following Arcadis (2011). The spatial extent of the geospatial datasets varies and do not all cover the full extent of the estuary. Datasets with incomplete coverage are not used for all analyses. The accuracy and precision of the geospatial information are lower for older datasets than for more recent datasets. The historical reconstructions of pre-19$^{\text{th}}$-century morphology (made in the 20$^{\text{th}}$ 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 datasets.

We identify and quantify the main morphological changes in the estuary over the past 500 years. Subtidal surface area (A_c) and intertidal surface area (A_s) 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 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

[3] https://www.nlwkn.niedersachsen.de/startseite/hochwasser_kustenschutz/kustenschutz/ausgewahlte_projekte/kustenschutz_projekt_leybucht/kuestenschutz-projekt-leybucht-43552.html

[4] https://www.rijkswaterstaat.nl/formulieren/contactformulier-servicedesk-data

[5] https://www.wsa-ems-nordsee.wsv.de/Webs/WSA/Ems-Nordsee/DE/00_Startseite/startseite_node.html

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 interactions 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 of the Ems estuary region (Section 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 (Section S1.2 in Supporting Information S1). The 20th-century human-landscape interactions, particularly relevant for the recent observed morphological developments, include channel dredging, port construction, and channel-realignments. An overview of these anthropogenic works is presented in Section S1.3 in Supporting Information S1.

3 Results

3.1 Land reclamation reconstruction

In the Ems estuary region land reclamation works started probably in the 11th century (Homeier et al., 1969; Behre, 1999). 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 untill 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 ($\approx$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 towards the river (Figure 1), after it lost its access due to a meander bend cut-off (see Section 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[6], was followed-up by landfill deposits on the sheltered tidal flats with dredged material[7].

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 ($\approx$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 $\approx$100

[6] `https://delibra.bg.polsl.pl/Content/22564/heft53_54.pdf`
[7] `https://de.wikipedia.org/wiki/Rysumer_Nacken`

km^2 per century since the Dollard reclamations started in the beginning of the 16$^{\text{th}}$ century. The extent of the Ems estuary was largest after the formation of Dollard Bay in 1509 ($\approx$1750 km^2) and decreased due to the land reclamation works to a present-day size of $\approx$1200 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

Channel-flat configuration

The 16$^{\text{th}}$-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 16$^{\text{th}}$ 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. In the 16$^{\text{th}}$-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 18$^{\text{th}}$ 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 19$^{\text{th}}$ 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 16$^{\text{th}}$ century into a tidal divide in the 18$^{\text{th}}$ century to beginning of the 19$^{\text{th}}$ century (see Figure 3b, c). The main tidal channels are filling in with sediments in the 20$^{\text{th}}$ 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 21$^{\text{th}}$ 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 20$^{\text{th}}$ 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 areas occupied by tidal channels (A_c) and tidal flats (A_s). Up to the end of the 19$^{\text{th}}$ century, A_s decreased (Figure 4), which is a result of land reclamation in Dollard Bay (Figure S4 in Supporting Information S1). Since the beginning of the 20$^{\text{th}}$ 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_c 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 20$^{\text{th}}$ century), and the central-estuary channel transition from a double to single channel system. The estuary-scale A_s/A_c ratio decreases up to the beginning of the 20th century, and since then increases again (Figure 4). The decrease in A_s/A_c is mostly attributed to a loss in A_s (due to land reclamations works) whereas the increase in A_s/A_c is mostly attributed to a loss of subtidal area A_c (resulting from subtidal infilling).

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 (Figure 5a and Figure 4). 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 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 of 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 along-shore (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).

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 (Speer & Aubrey, 1985; Friedrichs & Aubrey, 1988), 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 (van der Spek, 1994; de Haas et al., 2018). Despite the abundant sediment supply, the Ems Estuary required centuries to adapt to human interventions.

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 (Ralston et al., 2019; Bao et al., 2022; Siemes et al., 2023), maintenance dredging and disposal (Vellinga et al., 2014; Jeuken & Wang, 2010; van Dijk et al., 2021), 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-19$^{\text{th}}$-century land reclamation may still impact the present-day morphodynamic evolution, which needs to be taken into account when differentiating between natural controls and recent human modifications (Monge-Ganuzas et al., 2013; Dai et al., 2016; Zhu et al., 2019). The morphodynamic impact of future newly proposed interventions (e.g., Cox et al., 2006; Weisscher et al., 2022) should carefully embed the lagging effects of a still adapting morphology.

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_s/A_c. Land reclamations resulted in a decrease in A_s/A_c over several 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_s/V_c) (e.g., Friedrichs & Aubrey, 1988; Z. Wang et al., 1999; Dronkers, 2016). 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 (for example, 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:

$$V_s = 2a(S_{HW} - S_{LW}) \tag{1}$$

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

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 ($S_{HW} = A_s + A_c$). 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 19^{th} 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 20^{th} century, the system evolved towards a more flood dominant regime (increasing a/h), but became more ebb dominant since then (decreasing a/h and increasing V_s/V_c). 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 towards 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.

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, towards 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 16^{th} century (Figure 3) untill 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 16^{th} century, the loss of the characteristic multichannel pattern is not caused by channel re-alignment and dredging works in the 19^{th} and 20^{th} centuries (Van Veen, 1950; Van Veen et al., 2005). The past decadal developments of channel geometry do show a clear signature of dredging activity (Figure 5, Figure 6) but these changes are superimposed on the long-term system-scale response to the loss of intertidal areas (Figure 4, Figure 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). 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) (O'Brien & P., 1931; Jarrett, 1976). 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 (a. 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 19^{th} 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). 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 a contemporary challenge that is crucial in making future predictions for estuarine morphology.

5 Conclusion

The land reclamation history and the morphodynamic evolution of the Ems estuary were reconstructed since the beginning of 16^{th} 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 20^{th} 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 towards 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 estuarine systems follow the evolutionary trajectory predicted by tidal asymmetry-based stability theory as they move toward a new equilibrium configuration with modified tidal flats and channels. The channel pattern transition - from a multichannel single channel system - is found to be related to the changes in tidal prism and the width to depth ratio of the estuary.

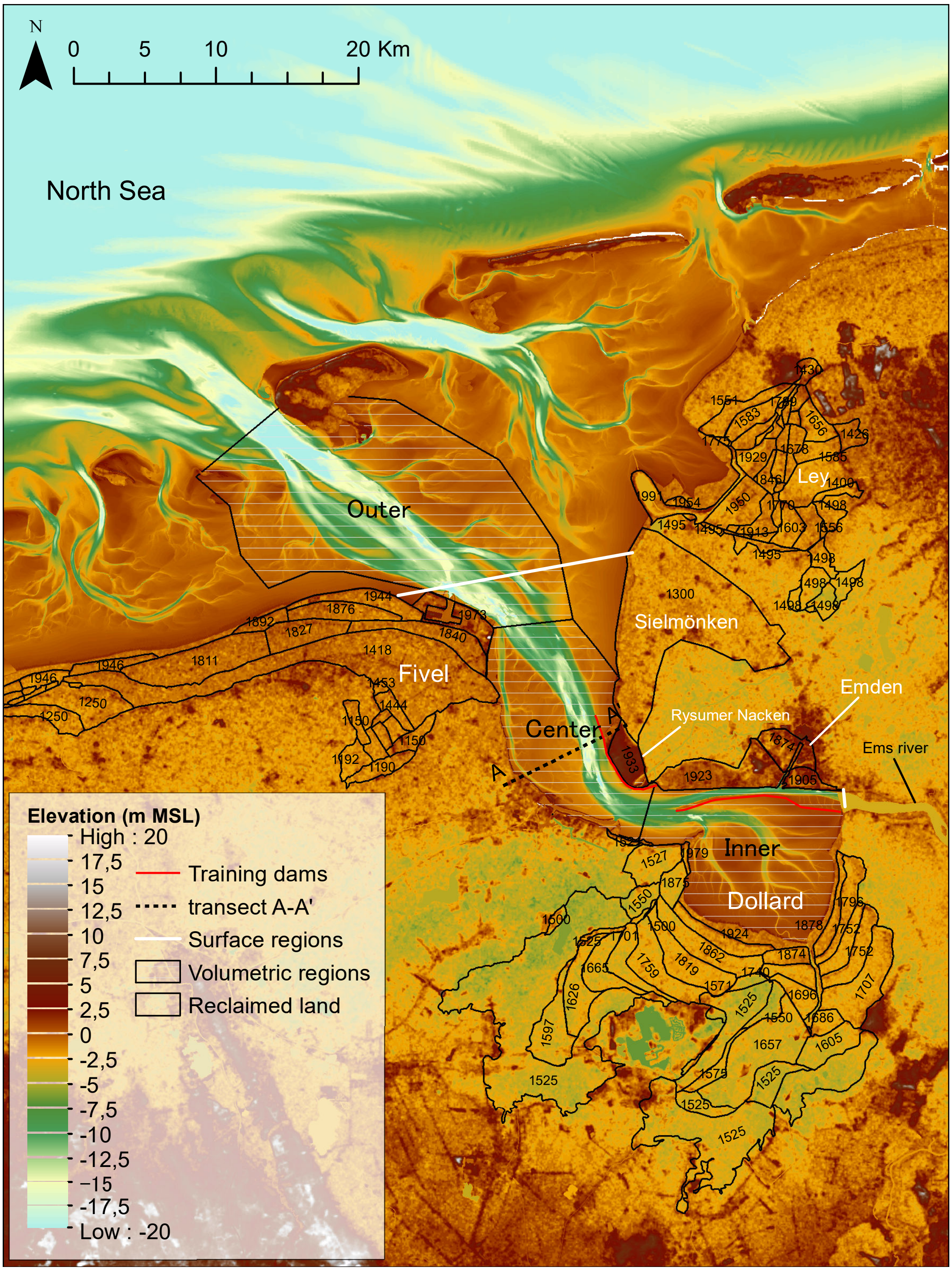


Figure 1. Land surface reclaimed in the region of the Ems estuary, with the year of completion indicated in the reclaimed area. The background color-scale visualizes the present-day topo-bathymetric Digital Elevation Model, compiled from multiple sources (see Open Research section, Section 5)

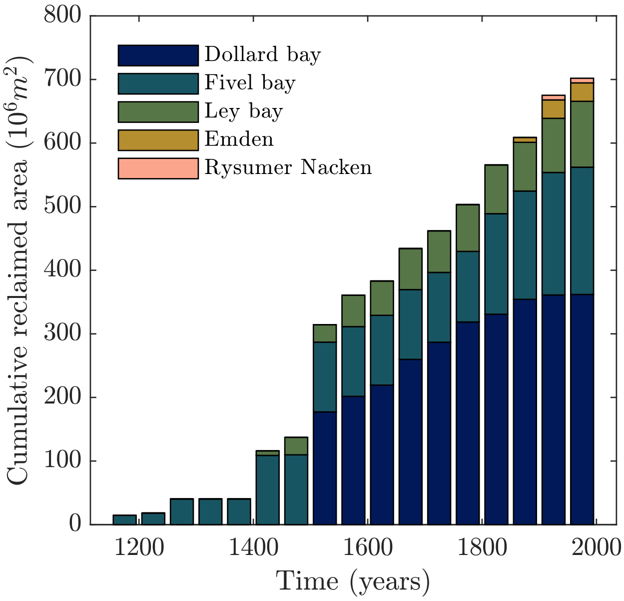


Figure 2. Cumulative area reclaimed since the 12$^{\text{th}}$ century, summed over half-century periods and subdivided for each defined land reclamation region.

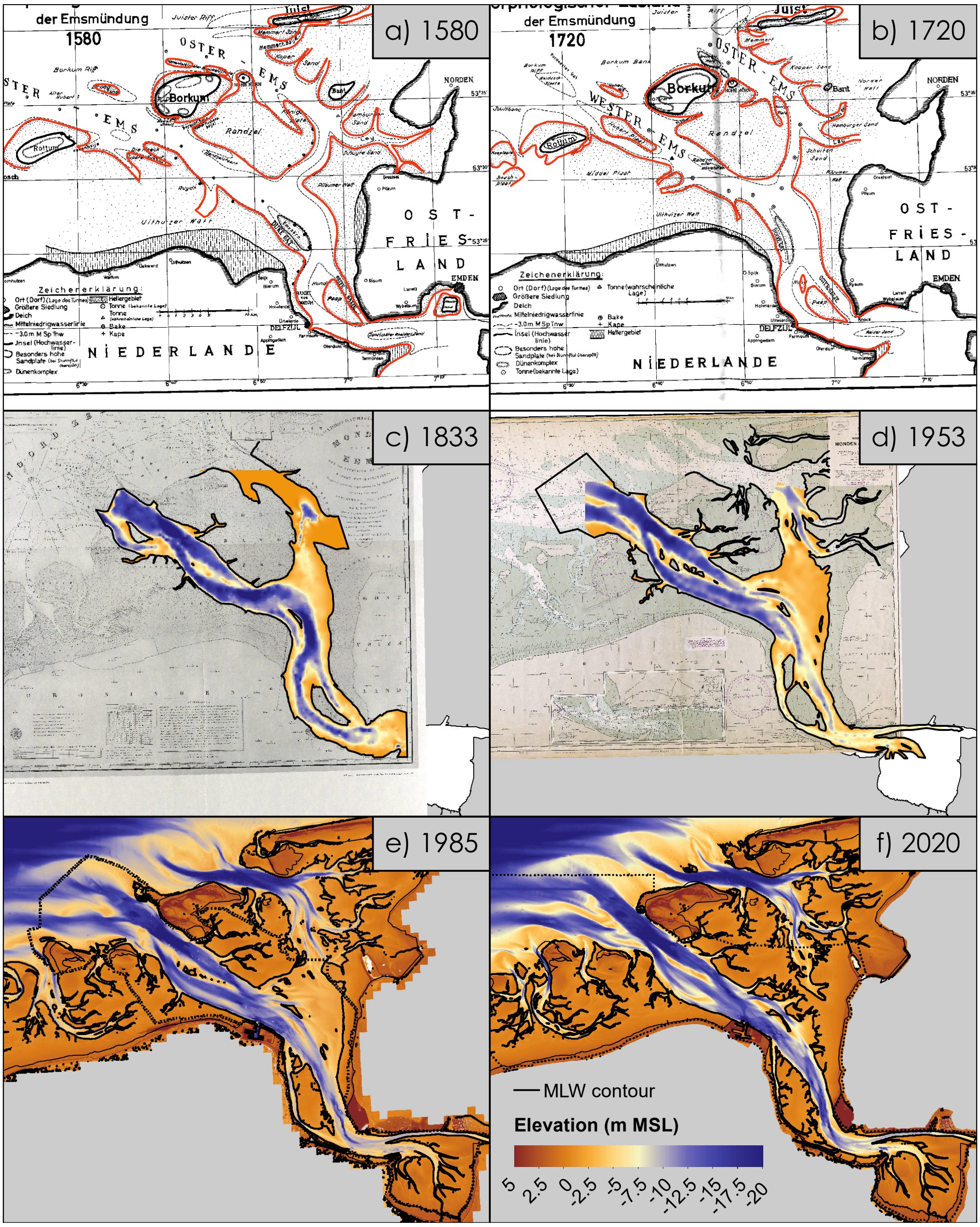


Figure 3. Centennial morphological evolution of the Ems estuary, based on: historical reconstructions of Lang (1954) (a, b); reconstructed subtidal bathymetry from H. J. Pierik et al. (2022); H. Pierik (2019) (c, d); and compiled datasets of echo sounding observations from the years 1985 and 1996 (e) 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 datasets.

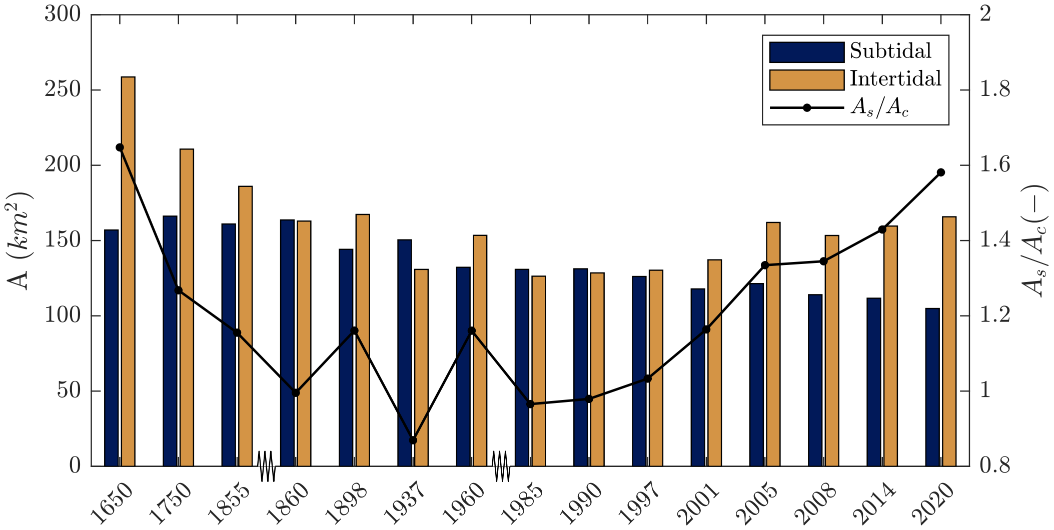


Figure 4. Subtidal and intertidal surface area (A) and subtidal to intertidal surface area ratio (A_s/A_c) in the estuarine zone, excluding the mouth zone (see Figure 1 for the demarcation of the estuarine zone). The zigzags on the x-axis indicate a time-scaling discontinuity.

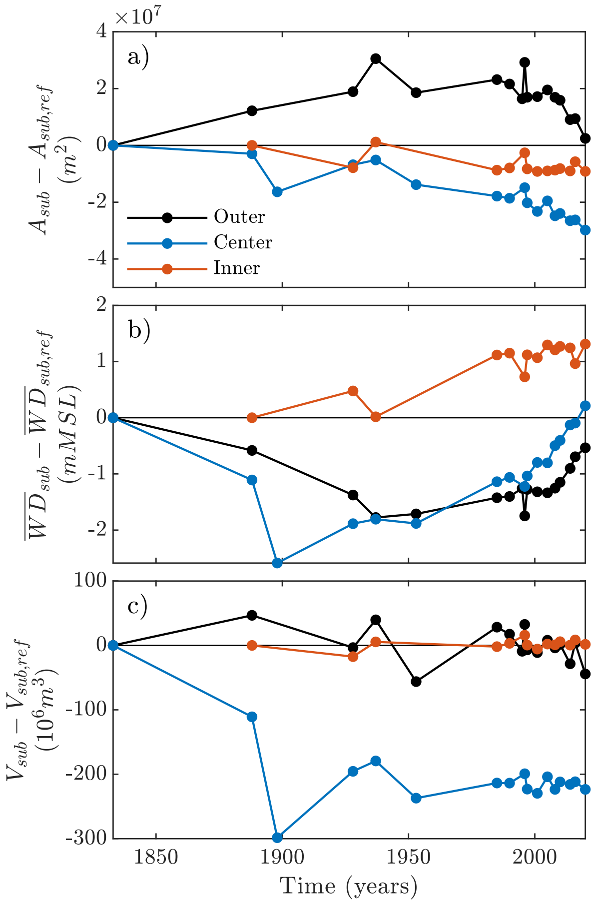


Figure 5. Relative change of the subtidal (below Mean Low Water) area A_{sub} (a), mean water depth $\overline{WD}_{sub}$ (b, with negative values implying shallower channels) and volume V_{sub}(c) with respect to the same properties derived from the first available subtidal bathymetry (1833 or 1888),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

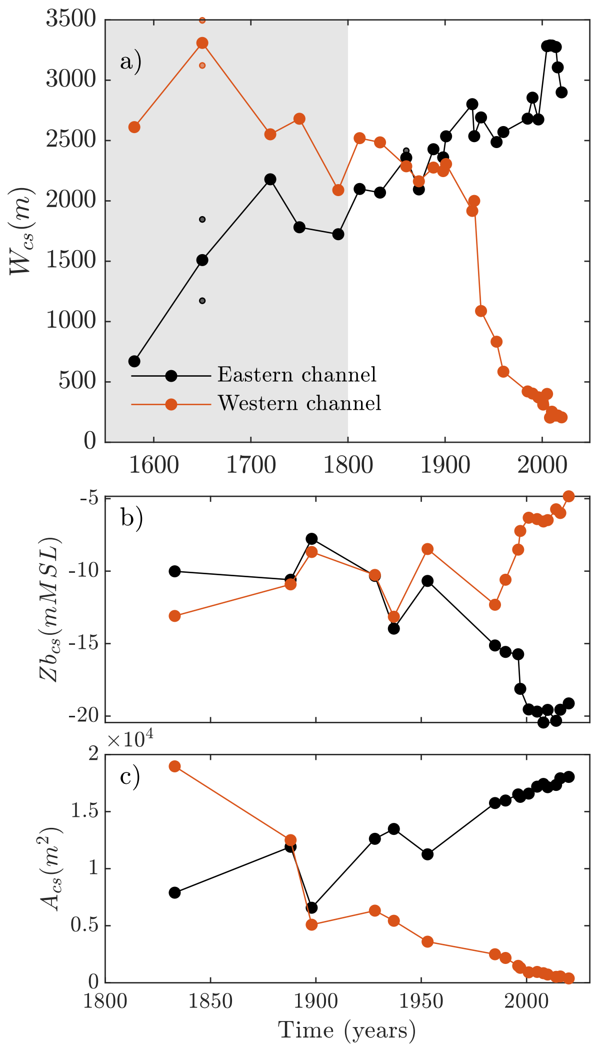


Figure 6. Channel width W_{cs} (a), deepest point Zb_{cs} (b), and cross-sectional volume V_{cs} (c) along the cross-section A-A' in Figure 1. Note that the channel geometry metrics are shown for time periods with data availability, leading to a longer time span in panel a (indicated by a gray patch)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

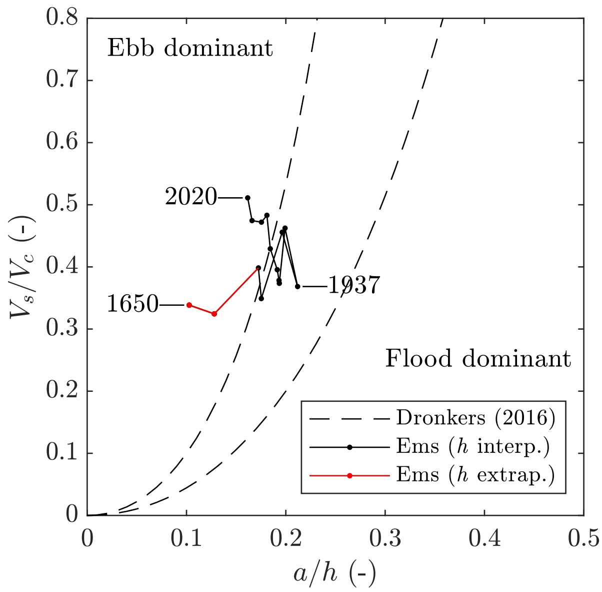


Figure 7. Tidal asymmetry based on the stability diagram in Zhou et al. (2018). For the Ems estuary data, V_s/V_c is derived by applying equations 1 and 2 on the surface areas from the morphological reconstructions, the tidal amplitude a is assumed constant at 1.2 m, and the mean water depth h is derived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

Table 1. Overview of the type and sources of the geospatial datasets 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 (100x100)	Nautical chart Dutch dep. of defense	H. J. Pierik et al. (2022); H. Pierik (2019)
1855	MLW, MHW and supratidal contours	Hist. reconstruction (Stratingh & 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 (100x100)	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 (20x20)	Nautical charts Ems Mündung (1:50000) & Die Ems Von Delfzijl Bis Pogum (1:25000) von Reichs Marine Amt	This article
1901	MLW contours	Hist. reconstruction Gerritsen (1952)	This article
1928	Gridded (100x100)	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 (5x5)	Depth soundings (German marine, RWS, Waterway agency Emden & Meppen)	Herrling and Niemeyer (2008)
1953	Gridded (100x100)	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 (20x20)	Echo soundings	Rijkswaterstaat
1990	Gridded (20x20)	Echo soundings	Rijkswaterstaat
1996	Gridded (10x10)	Echo soundings	Sievers et al. (2021)
1997	Gridded (20x20)	Echo soundings	Rijkswaterstaat
2001	Gridded (20x20)	Echo soundings	Rijkswaterstaat
2005	Gridded (20x20)	Echo soundings	Rijkswaterstaat
2008	Gridded (20x20)	Echo soundings	Rijkswaterstaat
2010	Gridded (25x25)	Echo soundings	WSA Emden
2014	Gridded (20x20)	Echo soundings	Rijkswaterstaat
2016	Gridded (10x10)	Echo soundings	Sievers et al. (2021)
2020	Gridded (20x20)	Echo soundings	Rijkswaterstaat

Open Research Section

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 25 m resolution provided by Copernicus (EU-DEM - version 1.1, Apr. 2016; `https://doi.org/10.5270/ESA-c5d3d65`), subaqueous bathymetry of the North Sea at ≈90 m resolution provided by the European Marine Observation and Data Network (EMODnet - `https://emodnet.ec.europa.eu/en/bathymetry`) and the coastal bathymetry which was requested through the servicedesk data of Rijkswaterstaat (`https://www.rijkswaterstaat.nl/formulieren/contactformulier-servicedesk-data`).

The main sources for the reconstruction of the land reclamation history are geospatial datasets with the location of historical embankments (`https://geoportaal.provinciegroningen.nl/portal/apps/experiencebuilder/experience/?id=9e93c75c4e5e47a584829e1deb0ad5f6`) and the National Historical Culture registry (`https://nationaalgeoregister.nl/geonetwork/srv/dut/catalog.search#/metadata/9a9cef3a-2dfc-4aa8-b248-f73f4064d7ad`). 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 (Lang, 1954; Gerritsen, 1952) and the 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. The gridded (subtidal) bathymetry datasets are available through the references included in Table 1 and therefore not included in Schrijvershof (2024).

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 datasets 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.

References

Alebregtse, N. C. (2015). *Modeling the Hydrodynamics in Tidal Networks* (Unpublished doctoral dissertation). Utrecht University, Utrecht. (ISBN: 9789462992597)

Allersma, E. (1992). *Studie inrichting Oostelijk deel Westerschelde. Analyse van het fysische systeem* (Tech. Rep.).

Allersma, E. (1994). *Geulen in estuaria: 1-D modellering van evenwijdige geulen* (Tech. Rep. No. H1828). Retrieved 2024-04-04, from `https://repository.tudelft.nl/islandora/object/uuid%3A3afdbae5-f4cc-4ad3-a5f2-2445a7e696dc` (Publisher: Deltares (WL))

Arcadis. (2011, December). *Afleidingen Hydromorfologie Rijkswateren* (Tech. Rep.). Author. Retrieved from `https://www.helpdeskwater.nl/publish/pages/130334/rapport_hydromorfologie_rijkswateren_23-12-2011.pdf`

Auerbach, L. W., Goodbred, S. L., Mondal, D. R., Wilson, C. A., Ahmed, K. R., Roy, K., ... Ackerly, B. A. (2015). Flood risk of natural and embanked landscapes on the Ganges-Brahmaputra tidal delta plain. *Nature Climate Change*, *5*(2), 153–157. doi: 10.1038/nclimate2472

Bain, R. L., Hale, R. P., & Goodbred, S. L. (2019). Flow Reorganization in an Anthropogenically Modified Tidal Channel Network: An Example From the Southwestern Ganges-Brahmaputra-Meghna Delta. *Journal of Geophysical Research: Earth Surface*, *124*(8), 2141–2159. doi: 10.1029/2018JF004996

Bao, S., Zhang, W., Qin, J., Zheng, J., Lv, H., Feng, X., ... Hoitink, A. J. F. (2022). Peak Water Level Response to Channel Deepening Depends on Interaction Between Tides and the River Flow. *Journal of Geophysical Research: Oceans*, *127*(4), e2021JC017625. Retrieved 2024-03-04, from `https://onlinelibrary.wiley.com/doi/abs/10.1029/2021JC017625` (_eprint: https://onlinelibrary.wiley.com/doi/pdf/10.1029/2021JC017625) doi: 10.1029/2021JC017625

Beets, D. J., van der Valk, L., & Stive, M. J. F. (1992, January). Holocene evolution of the coast of Holland. *Marine Geology*, *103*(1), 423–443. Retrieved 2024-02-28, from https://www.sciencedirect.com/science/article/pii/002532279290030L doi: 10.1016/0025-3227(92)90030-L

Behre, K.-E. (1999, January). Die Veränderung der niedersächischen Küstenlinien in den letzten 3000 Jahren und ihre Ursachen. *Probleme der Küstenforschung im südlichen Nordseegebiet*, *26*, 9–33.

Borchert, S. M., Osland, M. J., Enwright, N. M., & Griffith, K. T. (2018). Coastal wetland adaptation to sea level rise: Quantifying potential for landward migration and coastal squeeze. *Journal of Applied Ecology*, *55*(6), 2876–2887. Retrieved 2024-03-28, from https://onlinelibrary.wiley.com/doi/abs/10.1111/1365-2664.13169 (_eprint: https://onlinelibrary.wiley.com/doi/pdf/10.1111/1365-2664.13169) doi: 10.1111/1365-2664.13169

Braat, L., Van Kessel, T., Leuven, J. R., & Kleinhans, M. G. (2017). Effects of mud supply on large-scale estuary morphology and development over centuries to millennia. *Earth Surface Dynamics*, *5*(4), 617–652. doi: 10.5194/esurf-5-617-2017

Chen, L., Zhou, Z., Xu, F., Jimenez, M., Tao, J., & Zhang, C. (2020, January). Simulating the impacts of land reclamation and de-reclamation on the morphodynamics of tidal networks. *Anthropocene Coasts*, *3*(1), 30–42. Retrieved 2023-08-17, from https://cdnsciencepub.com/doi/full/10.1139/anc-2019-0010 (Publisher: NRC Research Press) doi: 10.1139/anc-2019-0010

Coco, G., Zhou, Z., van Maanen, B., Olabarrieta, M., Tinoco, R., & Townend, I. (2013). Morphodynamics of tidal networks: Advances and challenges. *Marine Geology*, *346*, 1–16. Retrieved from http://dx.doi.org/10.1016/j.margeo.2013.08.005 (Publisher: Elsevier B.V.) doi: 10.1016/j.margeo.2013.08.005

Cox, T., Maris, T., De Vleeschauwer, P., De Mulder, T., Soetaert, K., & Meire, P. (2006, November). Flood control areas as an opportunity to restore estuarine habitat. *Ecological Engineering*, *28*(1), 55–63. Retrieved 2024-03-04, from https://www.sciencedirect.com/science/article/pii/S0925857406000735 doi: 10.1016/j.ecoleng.2006.04.001

Dai, Z., Fagherazzi, S., Mei, X., Chen, J., & Meng, Y. (2016). Linking the infilling of the North Branch in the Changjiang (Yangtze) estuary to anthropogenic activities from 1958 to 2013. *Marine Geology*, *379*, 1–12. doi: 10.1016/j.margeo.2016.05.006

de Haas, T., Pierik, H. J., van der Spek, A. J., Cohen, K. M., van Maanen, B., & Kleinhans, M. G. (2018). Holocene evolution of tidal systems in The Netherlands: Effects of rivers, coastal boundary conditions, eco-engineering species, inherited relief and human interference. *Earth-Science Reviews*, *177*(October 2017), 139–163. Retrieved from https://doi.org/10.1016/j.earscirev.2017.10.006 (Publisher: Elsevier) doi: 10.1016/j.earscirev.2017.10.006

De Jong, J. (2006). *Habitat Maps Ems Estuary and Historical Habitat Change* (HARBASINS report). Assen: Ecca advies.

Donatelli, C., Ganju, N. K., Zhang, X., Fagherazzi, S., & Leonardi, N. (2018). Salt Marsh Loss Affects Tides and the Sediment Budget in Shallow Bays. *Journal of Geophysical Research: Earth Surface*, *123*(10), 2647–2662. Retrieved 2023-07-31, from https://onlinelibrary.wiley.com/doi/abs/10.1029/2018JF004617 (_eprint: https://onlinelibrary.wiley.com/doi/pdf/10.1029/2018JF004617) doi: 10.1029/2018JF004617

Dronkers, J. (1986). Tidal asymmetry and estuarine morphology. *Netherlands Journal of Sea Research*, *20*(2-3), 117–131. doi: 10.1016/0077-7579(86)90036-0

Dronkers, J. (2016). *Dynamics of Coastal Systems.* WORLD SCIENTIFIC. Retrieved from https://www.worldscientific.com/doi/abs/10.1142/9818 doi: 10.1142/9818

D'Alpaos, A., Lanzoni, S., Marani, M., & Rinaldo, A. (2010, January). On the tidal prism—Channel area relations. *Journal of Geophysical Research*, *115*. doi: 10.1029/2008JF001243

Fortunato, A. B., & Oliveira, A. (2005). Influence of Intertidal Flats on Tidal Asymmetry. *Journal of Coastal Research*, *215*(215), 1062–1067. doi: 10.2112/03-0089.1

Friedrichs, C. T. (2010). *Barotropic tides in channelized estuaries.* (Publication Title: Contemporary Issues in Estuarine Physics Issue: January 2010) doi: 10.1017/CBO9780511676567.004

Friedrichs, C. T., & Aubrey, D. G. (1988). Nonlinear tidal distortion in shallow well-mixed estuaries. *Estuarine, Coastal and Shelf Science*, *30*(3), 321–322. (ISBN: 0272-7714) doi: 10.1016/0272-7714(90)90054-U

Gerritsen, F. (1952). *Historical and hydrographical investigations in the Ems estuary* (Tech. Rep.). Hoorn: Ministry of Public Works. Retrieved from https://open.rws.nl/open-overheid/onderzoeksrapporten/@91330/historisch-hydrografisch-onderzoek-eems/

Groen, P. (1967). On the residual transport of suspended matter by an alternating tidal current. *Netherlands Journal of Sea Research*, *3*(4), 564–574. doi: 10.1016/0077-7579(67)90004-X

Guo, L., Xie, W., Xu, F., Wang, X., Zhu, C., Meng, Y., ... He, Q. (2022). A historical review of sediment export–import shift in the North Branch of Changjiang Estuary. *Earth Surface Processes and Landforms*, *47*(1), 5–16. doi: 10.1002/esp.5084

Guo, L., Zhu, C., Xu, F., Xie, W., van der Wegen, M., Townend, I., ... He, Q. (2022). Reclamation of Tidal Flats Within Tidal Basins Alters Centennial Morphodynamic Adaptation to Sea-Level Rise. *Journal of Geophysical Research: Earth Surface*, *127*(6), 1–24. doi: 10.1029/2021jf006556

Herrling, G., & Niemeyer, H. D. (2007). Long-term Spatial Development of Habitats in the Ems-Dollard Estuary.

Herrling, G., & Niemeyer, H. D. (2008). Reconstruction of the historical tidal regime of the Ems-Dollard estuary prior to significant human changes by applying mathematical modeling.

Hiatt, M., & Passalacqua, P. (2015). Hydrological connectivity in river deltas: The first-order importance of channel-island exchange. *ater Resources Research*, *51*, 2264–2282. doi: 10.1111/j.1752-1688.1969.tb04897.x

Hibma, A., Schuttelaars, H. M., & De Vriend, H. J. (2004). Initial formation and long-term evolution of channel-shoal patterns. *Continental Shelf Research*, *24*(15), 1637–1650. doi: 10.1016/j.csr.2004.05.003

Hibma, a., Stive, M., & Wang, Z. (2004, October). Estuarine morphodynamics. *Coastal Engineering*, *51*(8-9), 765–778. Retrieved 2015-01-14, from http://linkinghub.elsevier.com/retrieve/pii/S037838390400081X doi: 10.1016/j.coastaleng.2004.07.008

Hoitink, A. J., Nittrouer, J. A., Passalacqua, P., Shaw, J. B., Langendoen, E. J., Huismans, Y., & van Maren, D. S. (2020). Resilience of River Deltas in the Anthropocene. *Journal of Geophysical Research: Earth Surface*, *125*(3), 1–24. doi: 10.1029/2019JF005201

Homeier, H. (1962). *Historisches Kartenwerk 1:50 000 der niedersächsischen Küste* (Tech. Rep.).

Homeier, H., Siebert, E., & Kramer, J. (1969). *Der Gestaltwandel der ostfriesischen Küste im Laufe der Jahrhunderte: ein Jahrtausend ostfriesischer Deichgeschichte. Entwicklung des Deichwesens vom Mittelalter bis zur Gegenwart.* Deichamt Krummhörn. (Google-Books-ID: w6ikPQAACAAJ)

Jarrett, J. (1976). Tidal prism-inlet area relationships General investigation of tidal inlets. (3).

Jeuken, M. C., & Wang, Z. B. (2010). Impact of dredging and dumping on the stability of ebb-flood channel systems. *Coastal Engineering*, *57*(6), 553–566. Retrieved from http://dx.doi.org/10.1016/j.coastaleng.2009.12.004 (Publisher: Elsevier B.V.) doi: 10.1016/j.coastaleng.2009.12.004

Kleinhans, M. G., Roelofs, L., Weisscher, S. A. H., Lokhorst, I. R., & Braat, L. (2022). Estuarine morphodynamics and development modified by floodplain formation. , 367–381. Retrieved from https://doi.org/10.5194/esurf-2021-75

Knottnerus, O. S. (2013a). Dollardgeschiedenis(sen) - Mythe en realiteit. In: K. Essink (Red.), Stormvloed 1509 - Geschiedenis van de Dollard. In (pp. 95–116). Groningen: Stichting Verdronken Geschiedenis.

Knottnerus, O. S. (2013b, January). Reclamations and submerged lands in the Ems River Estuary (900–1500). In *Landscapes or seascapes? The history of the coastal environment in the North Sea area reconsidered.* (pp. 241–266). CORN Publication Series. doi: 10.1484/M.CORN.1.101555

Lang, A. W. (1954). *Untersuchung zum Gestaltungswandel des Emsmündungstrichters* (Tech. Rep.).

Leuven, J. R., & Kleinhans, M. G. (2019). Incipient Tidal Bar and Sill Formation. *Journal of Geophysical Research: Earth Surface*, *124*(7), 1762–1781. doi: 10.1029/2018JF004953

Liu, J., Dietz, T., Carpenter, S. R., Alberti, M., Folke, C., Moran, E., ... Taylor, W. W. (2007, September). Complexity of Coupled Human and Natural Systems. *Science*, *317*(5844), 1513–1516. Retrieved 2023-10-23, from https://www.science.org/doi/10.1126/science.1144004 (Publisher: American Association for the Advancement of Science) doi: 10.1126/science.1144004

Monge-Ganuzas, M., Cearreta, A., & Evans, G. (2013, June). Morphodynamic consequences of dredging and dumping activities along the lower Oka estuary (Urdaibai Biosphere Reserve, southeastern Bay of Biscay, Spain). *Ocean & Coastal Management*, *77*, 40–49. Retrieved 2023-10-12, from https://www.sciencedirect.com/science/article/pii/S0964569112000270 doi: 10.1016/j.ocecoaman.2012.02.006

O'Brien, & P., M. (1931). Estuary tidal prisms related to entrance areas. *Civil Engineering*. Retrieved 2020-10-21, from http://ci.nii.ac.jp/naid/10016529954/en/

Olds, A., Nagelkerken, I., Huijbers, C., Gilby, B., Pittman, S., & Schlacher, T. (2017). Connectivity in coastal seascapes. In *Seascape Ecology* (pp. pp. 261–292). John Wiley & Sons Ltd.

Pierik, H. (2019). *GIS dataset historical bathymetry and resistant layers in the Ems-Dollard estuary.* DANS. Retrieved from https://easy.dans.knaw.nl/ui/datasets/id/easy-dataset:118303/tab/1 (Place: Utrecht) doi: 10.17026/dans-x8w-wzsj

Pierik, H. J., Leuven, J. R. F. W., Busschers, F. S., Hijma, M., & Kleinhans, M. G. (2022). Depth-limiting resistant layers restrict dimensions and positions of estuarine channels and bars. *Depositional Record*(February), 1–20. doi: 10.1002/dep2.184

Ralston, D. K., Talke, S., Geyer, W. R., Al-Zubaidi, H. A. M., & Sommerfield, C. K. (2019). Bigger Tides, Less Flooding: Effects of Dredging on Barotropic Dynamics in a Highly Modified Estuary. *Journal of Geophysical Research: Oceans*, *124*(1), 196–211. Retrieved 2024-03-06, from https://onlinelibrary.wiley.com/doi/abs/10.1029/2018JC014313 (_eprint: https://onlinelibrary.wiley.com/doi/pdf/10.1029/2018JC014313) doi: 10.1029/2018JC014313

Ridderinkhof, W., de Swart, H. E., van der Vegt, M., Alebregtse, N. C., & Hoekstra,

P. (2014). Geometry of tidal inlet systems: A key factor for the net sediment transport in tidal inlets W. *Journal of Geophysical Research: Oceans*(119), 3868–3882. Retrieved from http://onlinelibrary.wiley.com/doi/10.1002/jgrc.20353/abstract doi: 10.1002/2014JC010226.Received

Schrijvershof, R. (2024, April). *Geospatial datasets of land reclamation and morphological reconstructions of the Ems estuary since the 16th century.* [object Object]. Retrieved 2024-04-09, from https://data.4tu.nl/datasets/78ac0cf9-e9f7-47c7-8c4e-93f7fb2c633e/1 doi: 10.4121/78AC0CF9-E9F7-47C7-8C4E-93F7FB2C633E.V1

Siemes, R. W. A., Duong, T. M., Willemsen, P. W. J. M., Borsje, B. W., & Hulscher, S. J. M. H. (2023, November). Morphological Response of a Highly Engineered Estuary to Altering Channel Depth and Restoring Wetlands. *Journal of Marine Science and Engineering*, *11*(11), 2150. Retrieved 2024-03-06, from https://www.mdpi.com/2077-1312/11/11/2150 (Number: 11 Publisher: Multidisciplinary Digital Publishing Institute) doi: 10.3390/jmse11112150

Sievers, J., Milbradt, P., Ihde, R., Valerius, J., Hagen, R., & Plüß, A. (2021, August). An integrated marine data collection for the German Bight – Part 1: Subaqueous geomorphology and surface sedimentology (1996–2016). *Earth System Science Data*, *13*(8), 4053–4065. Retrieved 2023-06-08, from https://essd.copernicus.org/articles/13/4053/2021/ (Publisher: Copernicus GmbH) doi: 10.5194/essd-13-4053-2021

Speer, P. E., & Aubrey, D. G. (1985). A Study of Non-linear Tidal Propagation in Shallow Inlet/Estuarine Systems Part II: Theory". *Estuarine, Coastal and Shelf Science*, *21*(5691), 207–224.

Stive, M. J. F., & Wang, Z. B. (2003, January). Chapter 13 Morphodynamic modeling of tidal basins and coastal inlets. In V. C. Lakhan (Ed.), *Elsevier Oceanography Series* (Vol. 67, pp. 367–392). Elsevier. Retrieved 2024-04-02, from https://www.sciencedirect.com/science/article/pii/S0422989403801307 doi: 10.1016/S0422-9894(03)80130-7

Stratingh, G. A., & Venema, G. A. (1855). *De Dollard of Geschied,- Aardrijks- en Natuurkundige Beschrijving van dezen Boezem der Eems.* Winschoten.

Talke, S. A., & Jay, D. A. (2020). Changing Tides: The Role of Natural and Anthropogenic Factors. *Annual Review of Marine Science*, *12*(1), 121–151. Retrieved 2023-04-24, from https://doi.org/10.1146/annurev-marine-010419-010727 (_eprint: https://doi.org/10.1146/annurev-marine-010419-010727) doi: 10.1146/annurev-marine-010419-010727

Van de Kreeke, J., & Robaczewska, K. (1993). Tide-induced residual transport of coarse sediment; Application to the EMS estuary. *Netherlands Journal of Sea Research*, *31*(3), 209–220. doi: 10.1016/0077-7579(93)90022-K

van der Molen, J., & de Swart, H. E. (2001). Holocene tidal conditions and tide-induced sand transport in the southern North Sea. *Journal of Geophysical Research: Oceans*, *106*(C5), 9339–9362. Retrieved 2024-03-07, from https://onlinelibrary.wiley.com/doi/abs/10.1029/2000JC000488 (_eprint: https://onlinelibrary.wiley.com/doi/pdf/10.1029/2000JC000488) doi: 10.1029/2000JC000488

van der Spek, A. J. (1994). *Large-scale evolution of holocene tidal basins in the Netherlands.*

Van Der Wegen, M. (2013). Numerical modeling of the impact of sea level rise on tidal basin morphodynamics. *Journal of Geophysical Research: Earth Surface*, *118*(2), 447–460. doi: 10.1002/jgrf.20034

van der Wegen, M., Wang, Z. B., Savenije, H. H. G., & Roelvink, J. A. (2008). Long-term morphodynamic evolution and energy dissipation in a coastal plain, tidal embayment. *Journal of Geophysical Research: Earth Surface*, *113*(F3). Retrieved 2024-03-28, from https://

onlinelibrary.wiley.com/doi/abs/10.1029/2007JF000898 (_eprint: https://onlinelibrary.wiley.com/doi/pdf/10.1029/2007JF000898) doi: 10.1029/2007JF000898

van Dijk, W. M., Cox, J. R., Leuven, J. R., Cleveringa, J., Taal, M., Hiatt, M. R., . . . Kleinhans, M. G. (2021). The vulnerability of tidal flats and multi-channel estuaries to dredging and disposal. *Anthropocene Coasts*, *4*(1), 36–60. doi: 10.1139/anc-2020-0006

van Maren, D. S., Beemster, J., Wang, Z., Khan, Z. H., Schrijvershof, R., & Hoitink, A. (2023). Tidal Amplification and River Capture in Response to Asynchronous Land Reclamation in the Ganges-Brahmaputra Delta. *Catena*, *220*(PA), 106651. Retrieved from https://doi.org/10.1016/j.catena.2022.106651 (Publisher: Elsevier B.V.) doi: 10.2139/ssrn.4064791

van Maren, D. S., Colina Alonso, A., Engels, A., Vandenbruwaene, W., de Vet, P. L. M., Vroom, J., & Wang, Z. B. (2023). Adaptation timescales of estuarine systems to human interventions. *Frontiers in Earth Science*, *11*. Retrieved 2023-05-16, from https://www.frontiersin.org/articles/10.3389/feart.2023.1111530

Van Maren, D. S., Oost, A. P., Wang, Z. B., & Vos, P. C. (2016). The effect of land reclamations and sediment extraction on the suspended sediment concentration in the Ems Estuary. *Marine Geology*, *376*, 147–157. Retrieved from http://dx.doi.org/10.1016/j.margeo.2016.03.007 (Publisher: The Authors) doi: 10.1016/j.margeo.2016.03.007

Van Maren, D. S., van Kessel, T., Cronin, K., & Sittoni, L. (2015). The impact of channel deepening and dredging on estuarine sediment concentration. *Continental Shelf Research*, *95*, 1–14. Retrieved from http://dx.doi.org/10.1016/j.csr.2014.12.010 (Publisher: Elsevier) doi: 10.1016/j.csr.2014.12.010

Van Maren, D. S., Winterwerp, J. C., & Vroom, J. (2015). Fine sediment transport into the hyper-turbid lower Ems River: the role of channel deepening and sediment-induced drag reduction. *Ocean Dynamics*, *65*(4), 589–605. (ISBN: 1023601508) doi: 10.1007/s10236-015-0821-2

Van Veen, J. (1950). Eb- en Vloedschaar Systemen in de Nederlandse Getijwateren. *Journal of the Royal Dutch Geographical Society*, *67*(November), 303–325.

Van Veen, J., van der Spek, A. J. F., Stive, M. J. F., & Zitman, T. (2005). Ebb and Flood Channel Systems in the Netherlands Tidal Waters. *Journal of Coastal Research*, *216*(November), 1107–1120. doi: 10.2112/04-0394.1

Vellinga, N. E., Hoitink, A. J., van der Vegt, M., Zhang, W., & Hoekstra, P. (2014). Human impacts on tides overwhelm the effect of sea level rise on extreme water levels in the Rhine-Meuse delta. *Coastal Engineering*, *90*, 40–50. Retrieved from http://dx.doi.org/10.1016/j.coastaleng.2014.04.005 (Publisher: Elsevier B.V.) doi: 10.1016/j.coastaleng.2014.04.005

Voorsmit, O. V. (2006, April). *Het meergeulenstelsel van de Westerschelde en de relatie met de functies van de Langetermijnvisie : een kritische analyse van het beleidsuitgangspunt 'Instandhouding van het meergeulenstelsel van de Westerschelde'* [info:eu-repo/semantics/masterThesis]. Retrieved 2024-04-02, from https://essay.utwente.nl/56958/ (Publisher: University of Twente)

Vos, P., Van der Meulen, M., Weerts, H., & Bazelmans, J. (2020). *Atlas of the Holocene Netherlands: Landscape and Habitation since the Last Ice Age.* doi: 10.5117/9789463724432

Vos, P., & van Kesteren, W. (2000, September). The long-term evolution of intertidal mudflats in the northern Netherlands during the Holocene; natural and anthropogenic processes. *Continental Shelf Research*, *20*, 1687–1710. doi: 10.1016/S0278-4343(00)00043-1

Vos, P. C., & Knol, E. (2013). De ontstaansgeschiedenis van het Dollardlandschap; natuurlijke en antropogene processen. In: K. Essink (Red.), Stormvloed 1509 -

Geschiedenis van de Dollard. Groningen: Stichting Verdronken Geschiedenis.

Vos, P. C., & Knol, E. (2015). Holocene landscape reconstruction of the Wadden Sea area between Marsdiep and Weser. *Geologie en Mijnbouw/Netherlands Journal of Geosciences*, *94*(2), 157–183. doi: 10.1017/njg.2015.4

Wang, Z., Jeuken, C., & Vriend, H. d. (1999). *Tidal asymmetry and residual sediment transport in estuaries* (Tech. Rep.). WL | Delft hydraulics. (Issue: November)

Wang, Z. B., Van Maren, D. S., Ding, P. X., Yang, S. L., Van Prooijen, B. C., De Vet, P. L., ... He, Q. (2015). Human impacts on morphodynamic thresholds in estuarine systems. *Continental Shelf Research*, *111*, 174–183. doi: 10.1016/j.csr.2015.08.009

Wang, Z. B., & Winterwerp, H. (2001, September). Impact of Dredging and Dumping on the Stability of Ebb-Flood Channel Systems..

Weisscher, S. A., Baar, A. W., van Belzen, J., Bouma, T. J., & Kleinhans, M. G. (2022). Transitional polders along estuaries: Driving land-level rise and reducing flood propagation. *Nature-Based Solutions*, *2*(June), 100022. Retrieved from `https://doi.org/10.1016/j.nbsj.2022.100022` (Publisher: Elsevier Inc.) doi: 10.1016/j.nbsj.2022.100022

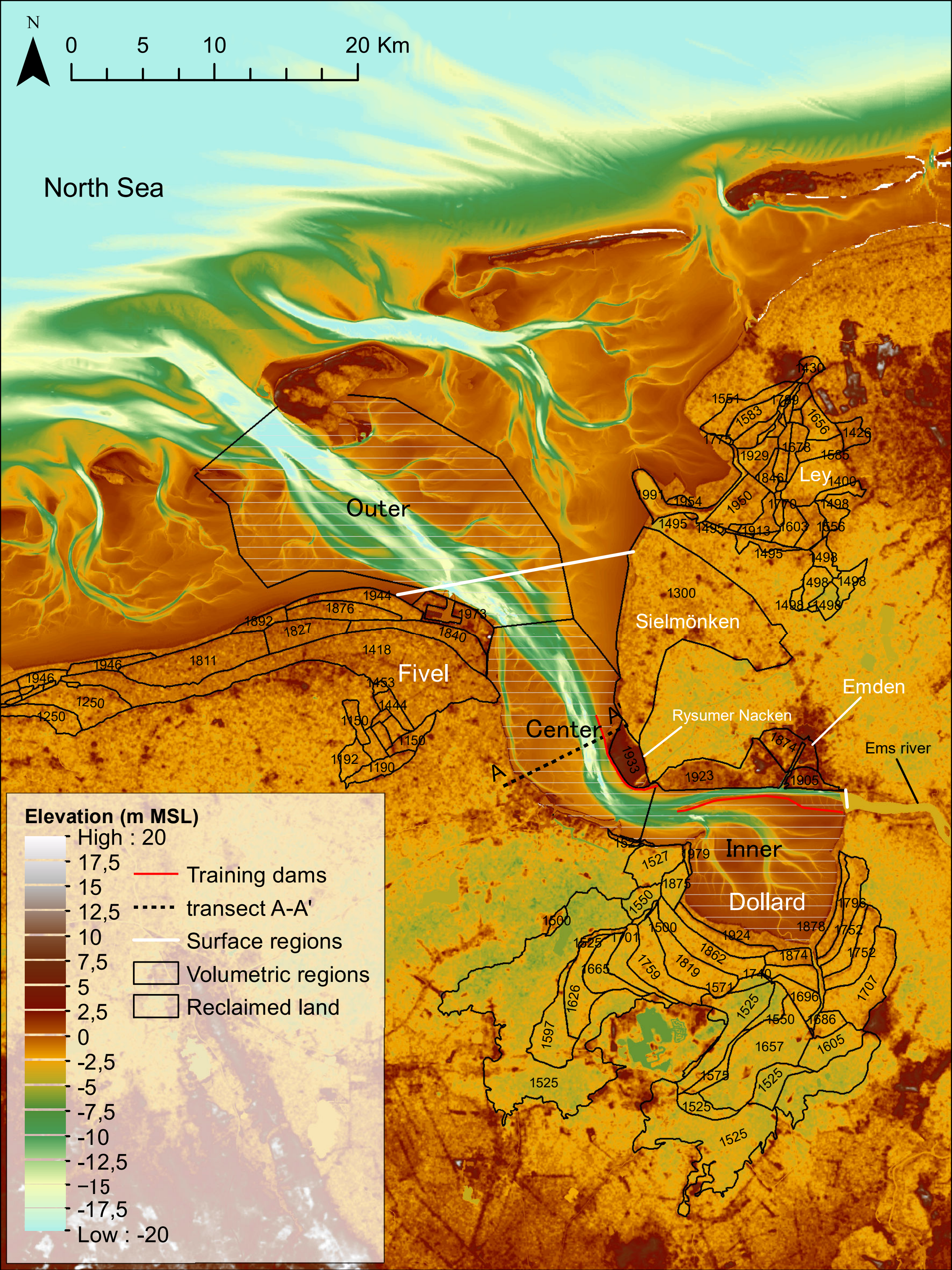
Wilson, C., Goodbred, S., Small, C., Gilligan, J., Sams, S., Mallick, B., & Hale, R. (2017). Widespread infilling of tidal channels and navigable waterways in the human-modified tidal deltaplain of southwest Bangladesh. *Elementa*, *5*. doi: 10.1525/elementa.263

Winterwerp, J. C., Wang, Z. B., Van Braeckel, A., Van Holland, G., & Kösters, F. (2013). Man-induced regime shifts in small estuaries - II: A comparison of rivers. *Ocean Dynamics*, *63*(11-12), 1293–1306. doi: 10.1007/s10236-013-0663-8

Zhou, Z., Coco, G., Townend, I., Gong, Z., Wang, Z., & Zhang, C. (2018). On the stability relationships between tidal asymmetry and morphologies of tidal basins and estuaries. *Earth Surface Processes and Landforms*, *43*(9). doi: 10.1002/esp.4366

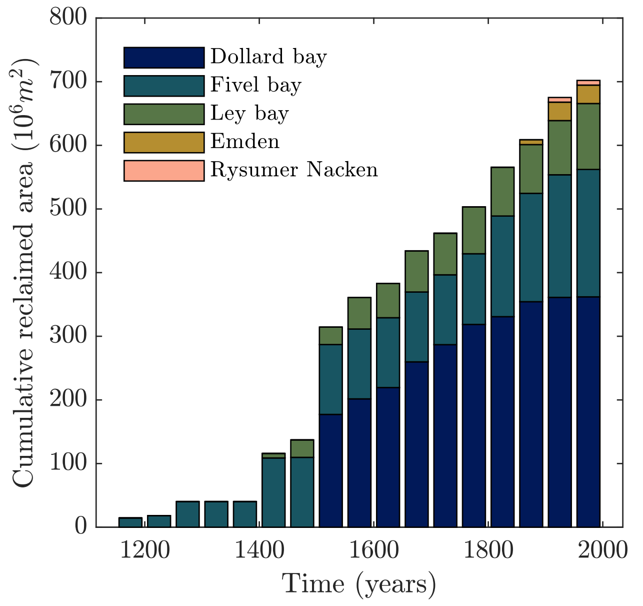
Zhu, C., Guo, L., van Maren, D. S., Tian, B., Wang, X., He, Q., & Wang, Z. B. (2019). Decadal morphological evolution of the mouth zone of the Yangtze Estuary in response to human interventions. *Earth Surface Processes and Landforms*, *44*(12), 2319–2332. Retrieved 2023-10-12, from `https://onlinelibrary.wiley.com/doi/abs/10.1002/esp.4647` (_eprint: https://onlinelibrary.wiley.com/doi/pdf/10.1002/esp.4647) doi: 10.1002/esp.4647

Figure 01.



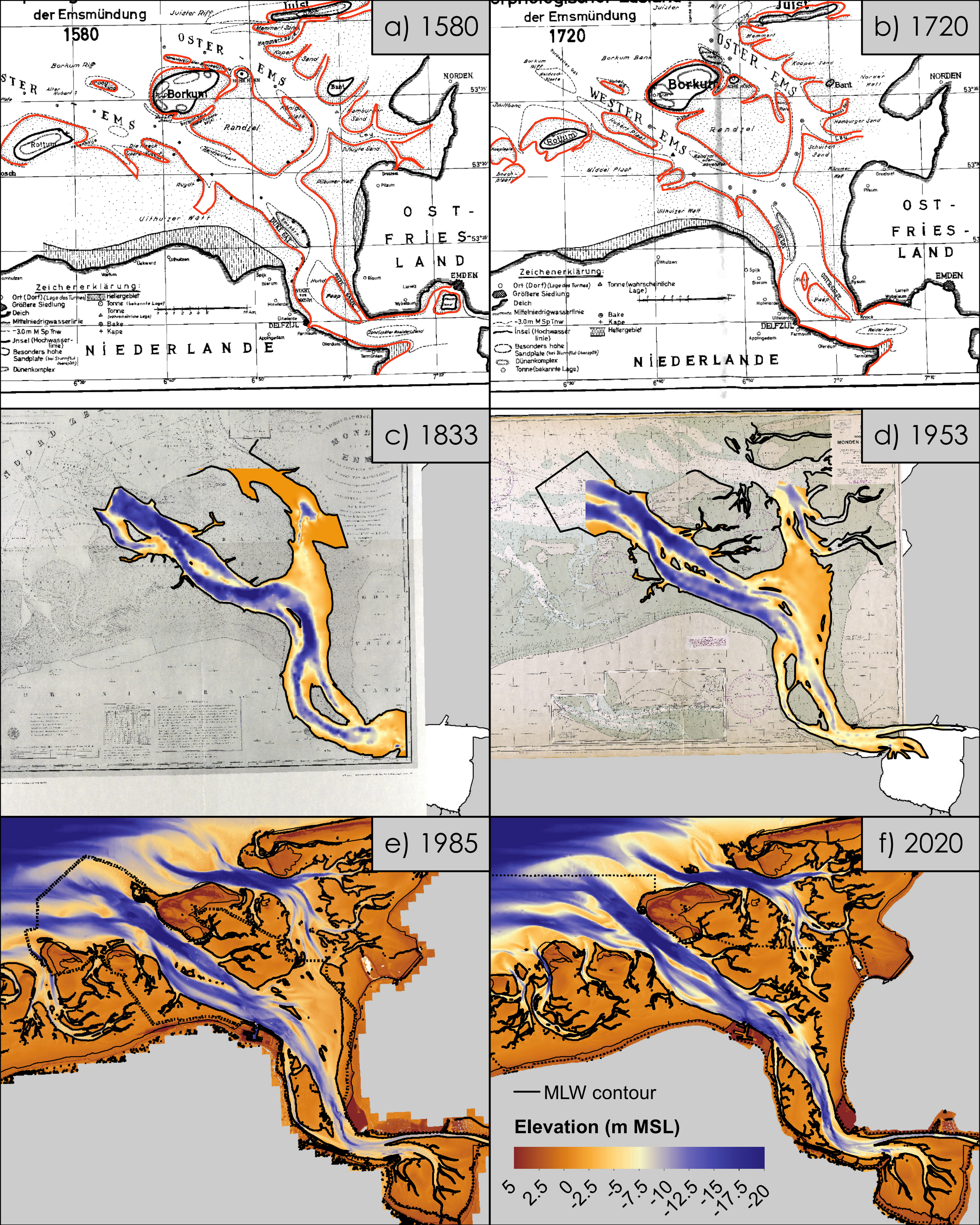
N
0
5
10
20 Km
North Sea
Outer
Fivel
Center
Sielmönken
Ley
Inner
Dollard
Rysumer Nacken
Emden
Ems river
A
A'
Elevation (m MSL)
High : 20
17,5
15
12,5
10
7,5
5
2,5
0
-2,5
-5
-7,5
-10
-12,5
−15
-17,5
Low : -20
Training dams
transect A-A'
Surface regions
Volumetric regions
Reclaimed land

Figure 02.



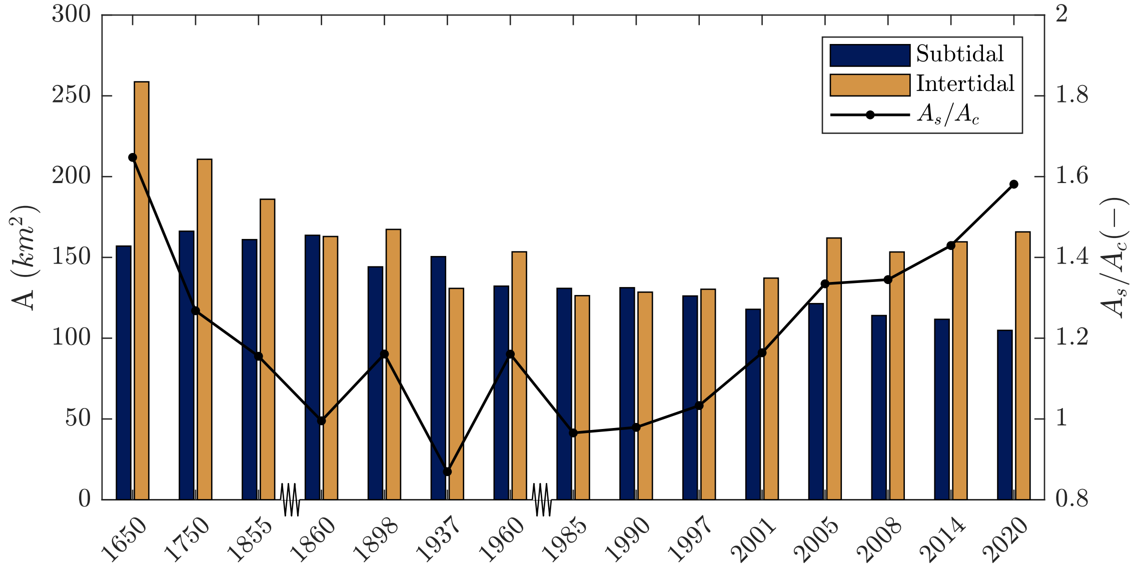
Dollard bay
Fivel bay
Ley bay
Emden
Rysumer Nacken
Cumulative reclaimed area ($10^6 m^2$)
Time (years)
0
100
200
300
400
500
600
700
800
1200
1400
1600
1800
2000

Figure 03.



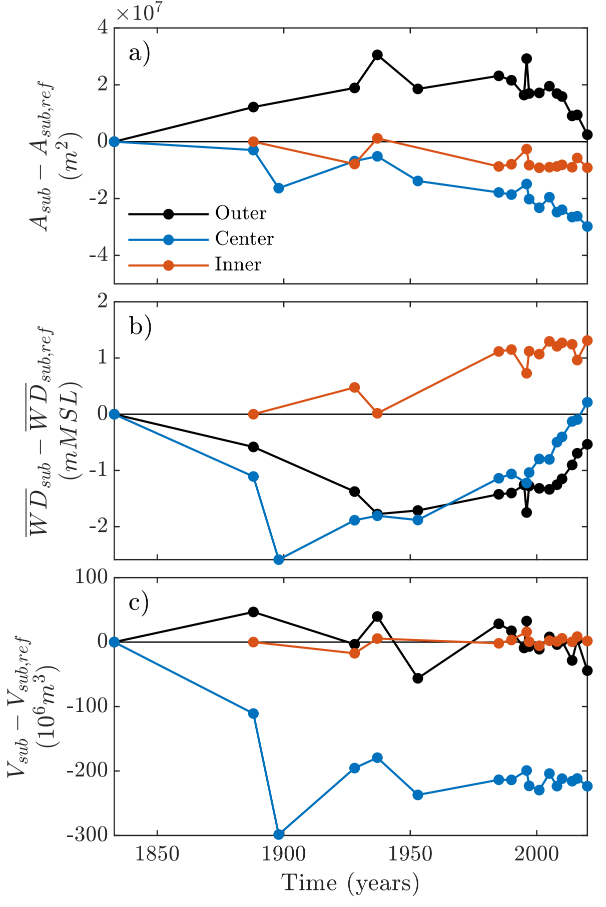
a) 1580
b) 1720
c) 1833
d) 1953
e) 1985
f) 2020
der Emsmündung
1580
1720
Borkum
Rottum
Juist
NORDEN
OST-FRIESLAND
EMDEN
DELFZIJL
NIEDERLANDE
Zeichenerklärung:
MLW contour
Elevation (m MSL)
5
2.5
0
-2.5
-5
-7.5
-10
-12.5
-15
-17.5
-20

Figure 04.



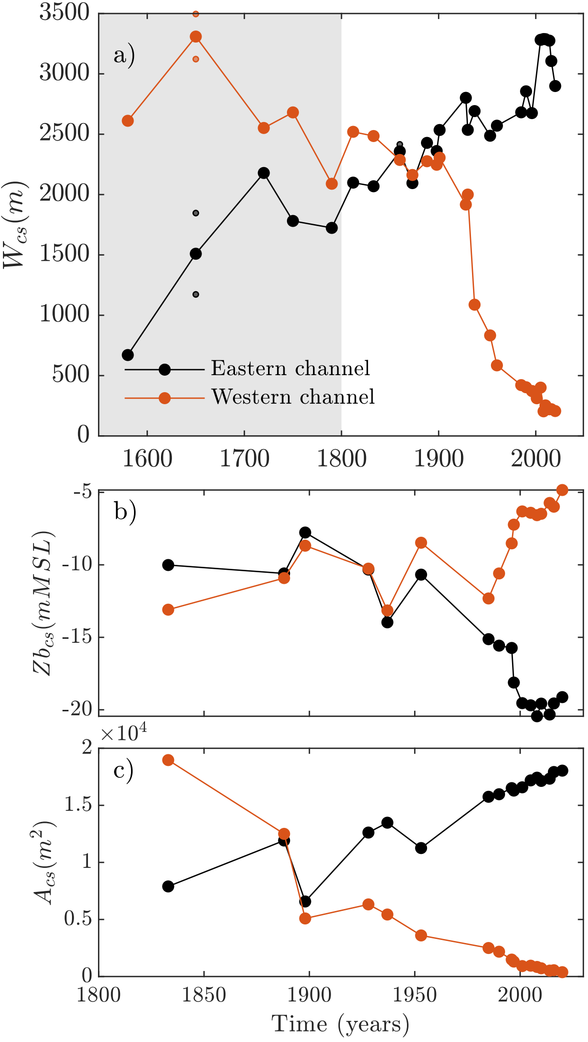
Subtidal
Intertidal
A_s/A_c
A (km^2)
$A_s/A_c(-)$
300
250
200
150
100
50
0
2
1.8
1.6
1.4
1.2
1
0.8
1650
1750
1855
1860
1898
1937
1960
1985
1990
1997
2001
2005
2008
2014
2020

Figure 05.



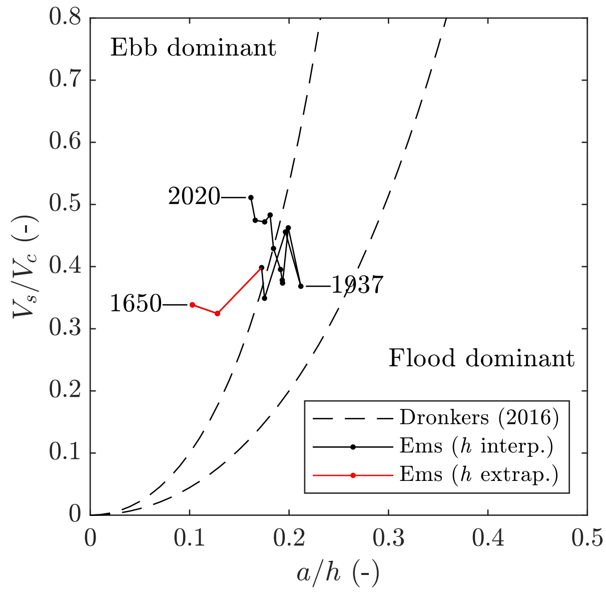
$\times 10^7$
a)
$A_{sub} - A_{sub,ref}$ (m^2)
Outer
Center
Inner
b)
$\overline{WD}_{sub} - \overline{WD}_{sub,ref}$ $(mMSL)$
c)
$V_{sub} - V_{sub,ref}$ $(10^6 m^3)$
Time (years)

Figure 06.



a)
b)
c)
$W_{cs}(m)$
$Zb_{cs}(mMSL)$
$A_{cs}(m^2)$
$\times 10^4$
Eastern channel
Western channel
Time (years)
3500
3000
2500
2000
1500
1000
500
0
1600
1700
1800
1900
2000
-5
-10
-15
-20
2
1.5
1
0.5
0
1800
1850
1900
1950
2000

Figure 07.



Ebb dominant
Flood dominant
2020
1937
1650
Dronkers (2016)
Ems (h interp.)
Ems (h extrap.)
V_s/V_c (-)
a/h (-)
0
0.1
0.2
0.3
0.4
0.5
0.6
0.7
0.8
0
0.1
0.2
0.3
0.4
0.5

Land Reclamation Controls on Multi-Centennial Estuarine Evolution

R.A. Schrijvershof[1,2], D.S. van Maren[2,3], M. van der Wegen[2,4], A.J.F. Hoitink[1]

[1]Wageningen University & Research, Environmental Sciences Group, Wageningen, The Netherlands
[2]Deltares, Delft, The Netherlands
[3]Delft University of Technology, Faculty of Civil Engineering and Geosciences, The Netherlands
[4]IHE-Delft Institute for Water Education, Delft, The Netherlands

Key Points:

- Land reclamation in the Ems estuary has led to 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 predict the evolutionary trajectory of real-world estuaries responding to land reclamation

Corresponding author: R.A. Schrijvershof, `reinier.schrijvershof@wur.nl`,`reinier.schrijvershof@deltares.nl`

Abstract

Land reclamations influence the morphodynamic evolution of estuaries and tidal basins, because 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) add a morphodynamic adaptation timescale to a system that may still adapt as the result of land reclamations. 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 20$^{\text{th}}$-century intensification of channel dredging and re-alignment works accelerated rather than cause this development. The centennial-scale observations suggest that estuarine systems responding to land reclamations follow the evolutionary trajectory predicted by tidal asymmetry-based stability theory as they move towards a new equilibrium configuration with modified tidal flats and channels. Existing estuarine equilibrium theory, however, fails in linking multichannel stability to the loss of intertidal area, emphasizing the need for additional research.

Plain Language Summary

Reclaiming land along the margins of estuaries and tidal basins leads to loss of intertidal areas. The response of the remaining underwater landscape to the loss of intertidal areas takes decades to centuries. This impacts 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 beginning of the 16$^{\text{th}}$ century, when 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. Further research should address the link between changes in intertidal areas and channel dynamics because we currently lack such a comprehensive understanding. This hampers our ability to predict the effects of future anticipated tidal flat changes, as a result of, for example, sea level rise or tidal flat restoration works.

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 provided by estuarine morphology because the channel-flat pattern and geometry (hypsometry) determine hydrological connectivity (Hiatt & Passalacqua, 2015), ecological connectivity (Olds et al., 2017), and influences future morphodynamic evolution because of the link with tidal asymmetry and residual sediment transport (Dronkers, 1986; Z. 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 pressure requires grasping the complex interaction between the tidal channels and the adjacent intertidal areas (Z. B. Wang et al., 2015; Hoitink et al., 2020).

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 (A. Hibma et al., 2004; van der Wegen et al., 2008; Braat et al., 2017; Leuven & Kleinhans, 2019). Important hydrodynamic mechanisms linked to the tidal flats are the temporal storage of mass and dissipation of momentum (Friedrichs & Aubrey, 1988; Alebregtse, 2015; 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 versus export) and steer the morphodynamic evolution of an estuary or tidal basin (Van Der Wegen, 2013; Guo, Zhu, et al., 2022; Chen et al., 2020).

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 basins' geometry (i.e.; depth, width, length) is essentially changed (Talke & Jay, 2020). Tidal flat loss reduces the embayments' 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).

The morphodynamic response to large-scale interventions, such as tidal flat reclamation is, however, often slow and manifests itself on longer time-scales (Guo, Zhu, et al., 2022). 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). Various concurrent human interventions (reclamation, deepening, construction of hydraulic works) may impact a system. It is difficult to isolate the impact of a single intervention because each intervention adds a morphodynamic adaptation timescale to a system that may still adapt as the result of previous interventions. As a result, multiple interventions may interactively impact the system within the morphodynamic adaptation time, possibly exacerbating or accelerating the system's response to the principle intervention (Z. B. Wang et al., 2015).

Land reclamation and channel deepening may influence system-scale sediment budgets (Guo, Xie, et al., 2022; Donatelli et al., 2018), initiate a transition to hyper-concentrated flow conditions (Winterwerp et al., 2013; Van Maren, Winterwerp, & Vroom, 2015; Van Maren et al., 2016), and influence channel migration and avulsion (Dai et al., 2016). In the Ganges-Brahmaputra-Meghna (GBM) mega delta, for example, large-scale land reclamation (>5000 km^2) in the 60's and 70's of the 20$^{\text{th}}$ 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). Such 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 (Liu et al., 2007; Coco et al., 2013). The observed and widely varying impact of land reclamation can not be predicted on the basis of estuarine equilibrium theory. To date, it remains unclear to what extent these developments are driven by land reclamations or other human interference. Based on long-term observations that span the time of morphological adaptation to tidal flat reclamations, here we explore if the evolution of real-world tidal systems agrees with the theoretical frameworks describing the evolutionary trajectory towards 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, 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 16$^{\text{th}}$ century. This was followed by fairway re-alignment, deepening, and maintenance dredging since the 20$^{\text{th}}$ 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 20$^{\text{th}}$ century (Gerritsen, 1952), which is still poorly understood. Two hypotheses exist explaining these channel pattern changes: (1) channel system instability due to fairway deepening and related sediment disposal (Van Veen et al., 2005; Van Veen, 1950), and (2) 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).

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 datasets with the location of historical embankments[1] and the National Historical Culture registry[2]. 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 palaeogeographical reconstructions (P. C. Vos & Knol, 2015, 2013) were used to detail the maximum extent of storm-surge-formed bays, to include the oldest (poorly-documented)

[1] `https://geoportaal.provinciegroningen.nl/portal/apps/experiencebuilder/experience/?id=9e93c75c4e5e47a584829e1deb0ad5f6`

[2] `https://nationaalgeoregister.nl/geonetwork/srv/dut/catalog.search#/metadata/9a9cef3a-2dfc-4aa8-b248-f73f4064d7ad`

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)[3]. 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 intense anthropogenic interventions since the 16^{th} century. A unique long-term record of geospatial datasets is compiled that almost completely covers this time-period (Table 1). The datasets were collected from published literature (Lang, 1954; Homeier, 1962; Gerritsen, 1952; Stratingh & Venema, 1855), published data sources (H. Pierik, 2019; Sievers et al., 2021), or collected from national archives, and were provided in digitized format (Herrling & Niemeyer, 2007, 2008; De Jong, 2006) or, otherwise, digitized using GIS software. The recent gridded topo-bathymetrical datasets (1985-2020) are publicly available at Rijkswaterstaat[4] and WSA Emden[5]. The datasets can be divided in three categories: (1) historical reconstructions of channel and tidal flat planform, based on a large variety of written and illustrated sources, but interpreted and compiled in the 20^{th} century, (2) digitized nautical charts originally collected in hydrographic surveys for military and water way organizations, and (3) recent (1937, 1985-2020) full coverage digital elevation models (DEM) collected through (echo) sounding observations. All geospatial datasets were provided or converted in a digitized format (Table 1) and published with this paper (Schrijvershof, 2024). The three types of datasets 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 (NAP +1.30 NAP), following Arcadis (2011). The spatial extent of the geospatial datasets varies and do not all cover the full extent of the estuary. Datasets with incomplete coverage are not used for all analyses. The accuracy and precision of the geospatial information are lower for older datasets than for more recent datasets. The historical reconstructions of pre-19^{th}-century morphology (made in the 20^{th} 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 datasets.

We identify and quantify the main morphological changes in the estuary over the past 500 years. Subtidal surface area (A_c) and intertidal surface area (A_s) 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 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

[3] https://www.nlwkn.niedersachsen.de/startseite/hochwasser_kustenschutz/kustenschutz/ausgewahlte_projekte/kustenschutz_projekt_leybucht/kuestenschutz-projekt-leybucht-43552.html

[4] https://www.rijkswaterstaat.nl/formulieren/contactformulier-servicedesk-data

[5] https://www.wsa-ems-nordsee.wsv.de/Webs/WSA/Ems-Nordsee/DE/00_Startseite/startseite_node.html

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 interactions 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 of the Ems estuary region (Section 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 (Section S1.2 in Supporting Information S1). The 20th-century human-landscape interactions, particularly relevant for the recent observed morphological developments, include channel dredging, port construction, and channel-realignments. An overview of these anthropogenic works is presented in Section S1.3 in Supporting Information S1.

3 Results

3.1 Land reclamation reconstruction

In the Ems estuary region land reclamation works started probably in the 11th century (Homeier et al., 1969; Behre, 1999). 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 untill 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 towards the river (Figure 1), after it lost its access due to a meander bend cut-off (see Section 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[6], was followed-up by landfill deposits on the sheltered tidal flats with dredged material[7].

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

[6] `https://delibra.bg.polsl.pl/Content/22564/heft53_54.pdf`
[7] `https://de.wikipedia.org/wiki/Rysumer_Nacken`

km^2 per century since the Dollard reclamations started in the beginning of the 16$^{\text{th}}$ century. The extent of the Ems estuary was largest after the formation of Dollard Bay in 1509 ($\approx$1750 km^2) and decreased due to the land reclamation works to a present-day size of $\approx$1200 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

Channel-flat configuration

The 16$^{\text{th}}$-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 16$^{\text{th}}$ 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. In the 16$^{\text{th}}$-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 18$^{\text{th}}$ 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 19$^{\text{th}}$ 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 16$^{\text{th}}$ century into a tidal divide in the 18$^{\text{th}}$ century to beginning of the 19$^{\text{th}}$ century (see Figure 3b, c). The main tidal channels are filling in with sediments in the 20$^{\text{th}}$ 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 21$^{\text{th}}$ 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 20$^{\text{th}}$ 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 areas occupied by tidal channels (A_c) and tidal flats (A_s). Up to the end of the 19$^{\text{th}}$ century, A_s decreased (Figure 4), which is a result of land reclamation in Dollard Bay (Figure S4 in Supporting Information S1). Since the beginning of the 20$^{\text{th}}$ 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_c 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 20$^{\text{th}}$ century), and the central-estuary channel transition from a double to single channel system. The estuary-scale A_s/A_c ratio decreases up to the beginning of the 20th century, and since then increases again (Figure 4). The decrease in A_s/A_c is mostly attributed to a loss in A_s (due to land reclamations works) whereas the increase in A_s/A_c is mostly attributed to a loss of subtidal area A_c (resulting from subtidal infilling).

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 (Figure 5a and Figure 4). 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 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 of 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 along-shore (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).

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 (Speer & Aubrey, 1985; Friedrichs & Aubrey, 1988), 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 (van der Spek, 1994; de Haas et al., 2018). Despite the abundant sediment supply, the Ems Estuary required centuries to adapt to human interventions.

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 (Ralston et al., 2019; Bao et al., 2022; Siemes et al., 2023), maintenance dredging and disposal (Vellinga et al., 2014; Jeuken & Wang, 2010; van Dijk et al., 2021), 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-19$^{\text{th}}$-century land reclamation may still impact the present-day morphodynamic evolution, which needs to be taken into account when differentiating between natural controls and recent human modifications (Monge-Ganuzas et al., 2013; Dai et al., 2016; Zhu et al., 2019). The morphodynamic impact of future newly proposed interventions (e.g., Cox et al., 2006; Weisscher et al., 2022) should carefully embed the lagging effects of a still adapting morphology.

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_s/A_c. Land reclamations resulted in a decrease in A_s/A_c over several 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_s/V_c) (e.g., Friedrichs & Aubrey, 1988; Z. Wang et al., 1999; Dronkers, 2016). 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 (for example, 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:

$$V_s = 2a(S_{HW} - S_{LW}) \tag{1}$$

$$V_c = h(S_{LW}) \tag{2}$$

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 ($S_{HW} = A_s + A_c$). 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 19$^{\text{th}}$ 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 20$^{\text{th}}$ century, the system evolved towards a more flood dominant regime (increasing a/h), but became more ebb dominant since then (decreasing a/h and increasing V_s/V_c). 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 towards 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.

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, towards 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 16$^{\text{th}}$ century (Figure 3) untill 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 16$^{\text{th}}$ century, the loss of the characteristic multichannel pattern is not caused by channel re-alignment and dredging works in the 19$^{\text{th}}$ and 20$^{\text{th}}$ centuries (Van Veen, 1950; Van Veen et al., 2005). The past decadal developments of channel geometry do show a clear signature of dredging activity (Figure 5, Figure 6) but these changes are superimposed on the long-term system-scale response to the loss of intertidal areas (Figure 4, Figure 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). 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) (O'Brien & P., 1931; Jarrett, 1976). 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 (a. 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 19^{th} 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). 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 a contemporary challenge that is crucial in making future predictions for estuarine morphology.

5 Conclusion

The land reclamation history and the morphodynamic evolution of the Ems estuary were reconstructed since the beginning of 16^{th} 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 20^{th} 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 towards 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 estuarine systems follow the evolutionary trajectory predicted by tidal asymmetry-based stability theory as they move toward a new equilibrium configuration with modified tidal flats and channels. The channel pattern transition - from a multichannel single channel system - is found to be related to the changes in tidal prism and the width to depth ratio of the estuary.

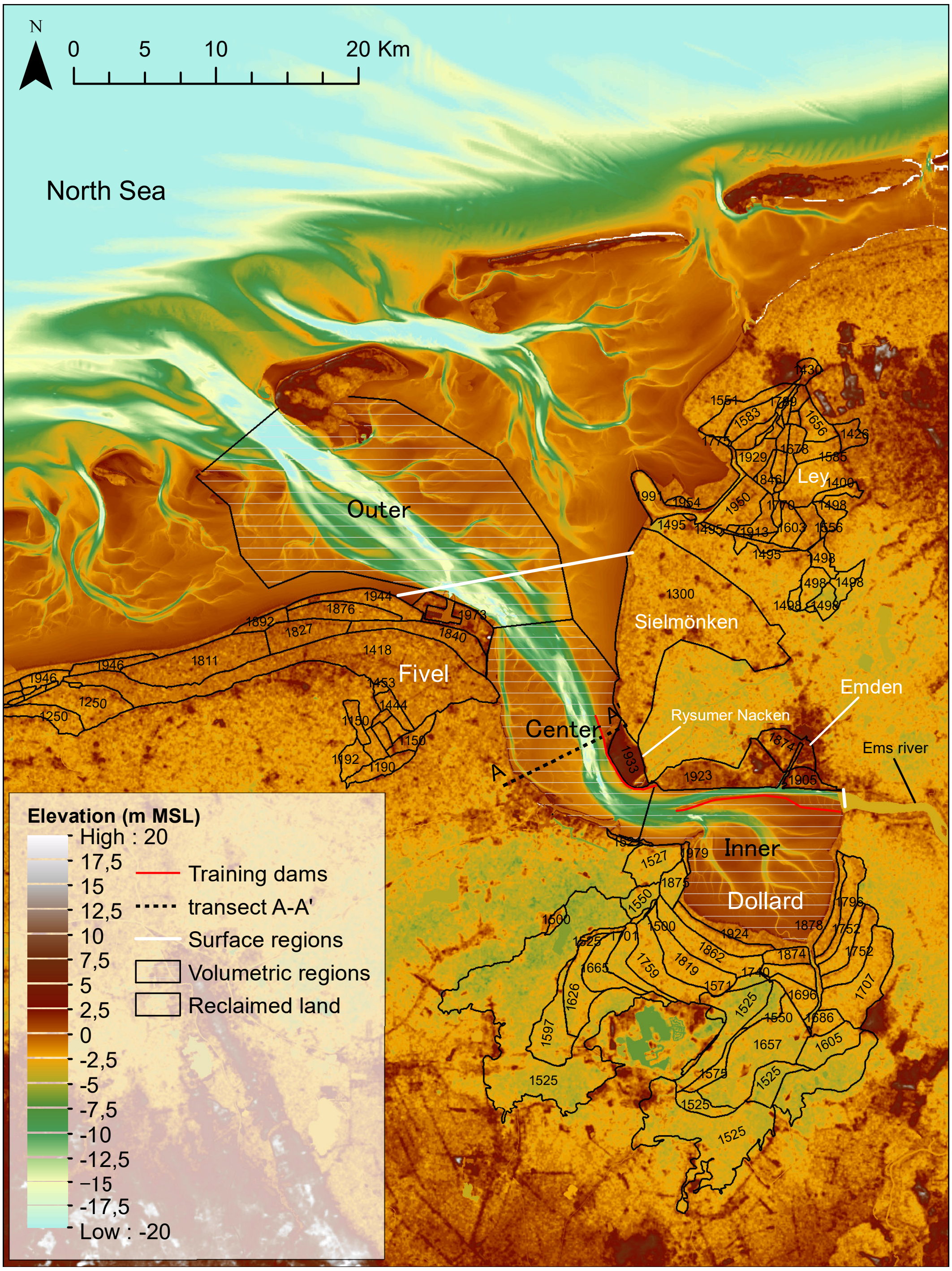


Figure 1. Land surface reclaimed in the region of the Ems estuary, with the year of completion indicated in the reclaimed area. The background color-scale visualizes the present-day topo-bathymetric Digital Elevation Model, compiled from multiple sources (see Open Research section, Section 5)

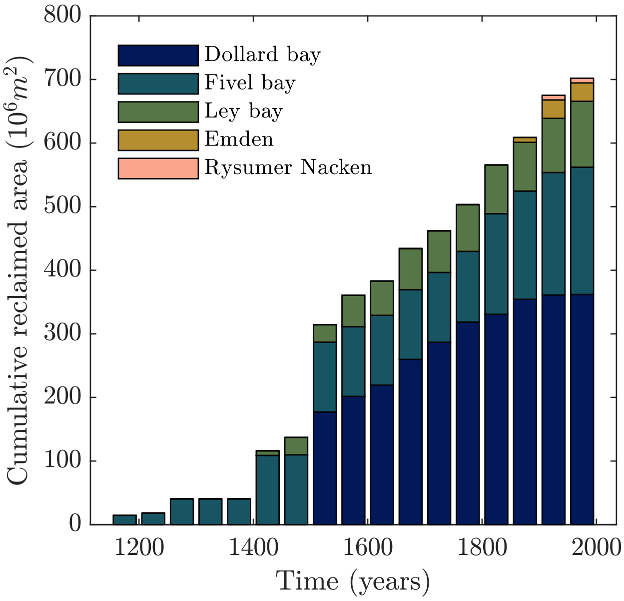


Figure 2. Cumulative area reclaimed since the 12$^{\text{th}}$ century, summed over half-century periods and subdivided for each defined land reclamation region.

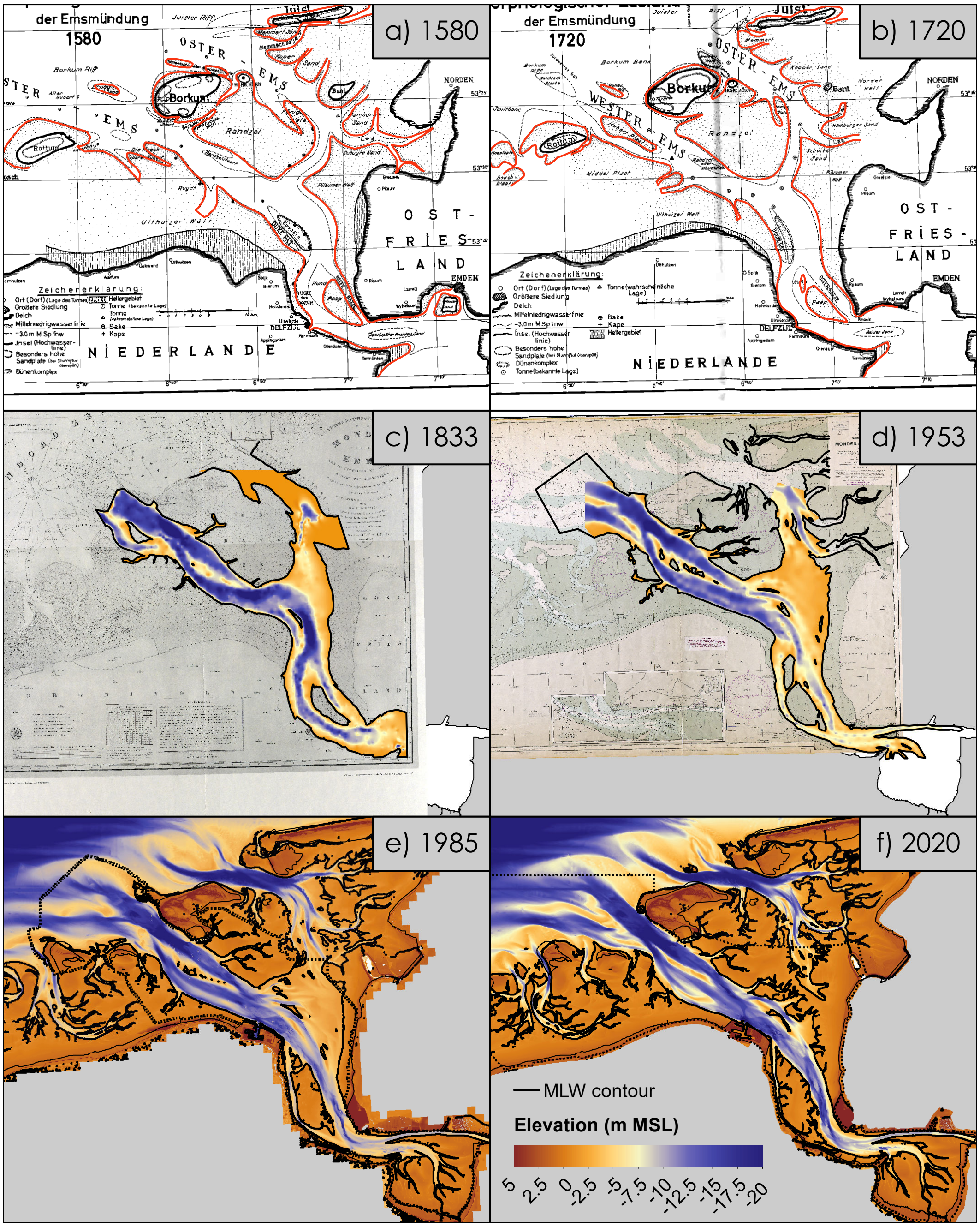


Figure 3. Centennial morphological evolution of the Ems estuary, based on: historical reconstructions of Lang (1954) (a, b); reconstructed subtidal bathymetry from H. J. Pierik et al. (2022); H. Pierik (2019) (c, d); and compiled datasets of echo sounding observations from the years 1985 and 1996 (e) 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 datasets.

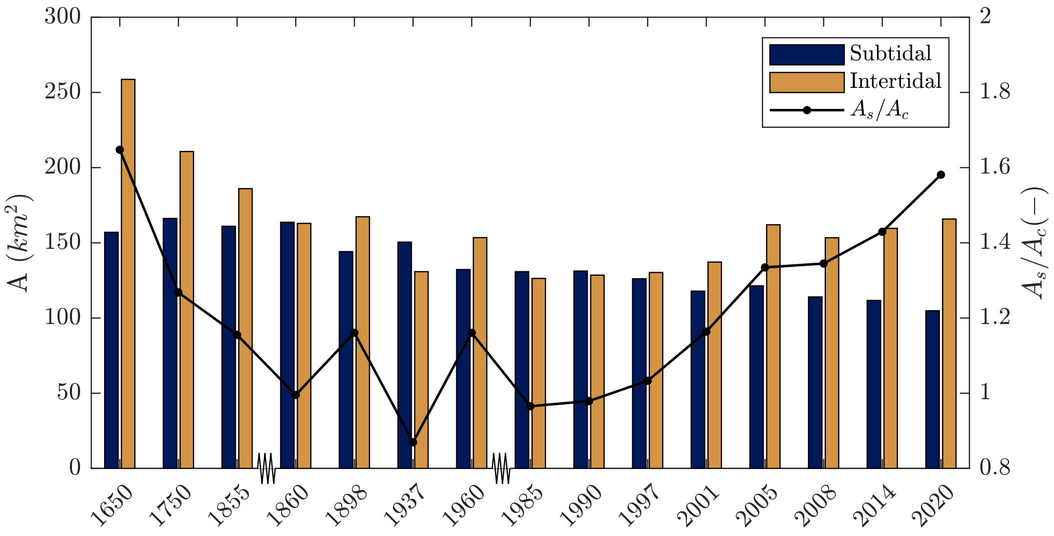


Figure 4. Subtidal and intertidal surface area (A) and subtidal to intertidal surface area ratio (A_s/A_c) in the estuarine zone, excluding the mouth zone (see Figure 1 for the demarcation of the estuarine zone). The zigzags on the x-axis indicate a time-scaling discontinuity.

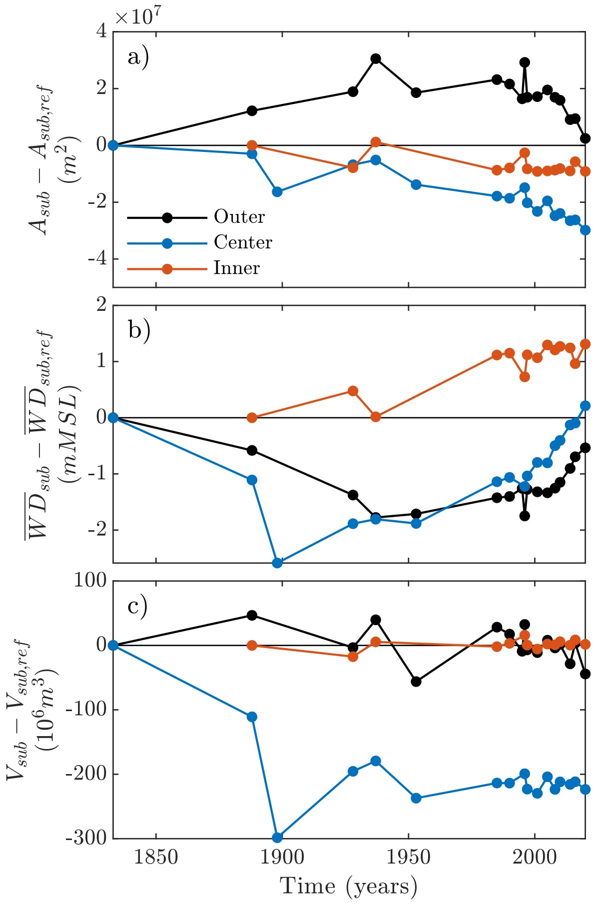


Figure 5. Relative change of the subtidal (below Mean Low Water) area A_{sub} (a), mean water depth $\overline{WD}_{sub}$ (b, with negative values implying shallower channels) and volume V_{sub}(c) with respect to the same properties derived from the first available subtidal bathymetry (1833 or 1888),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

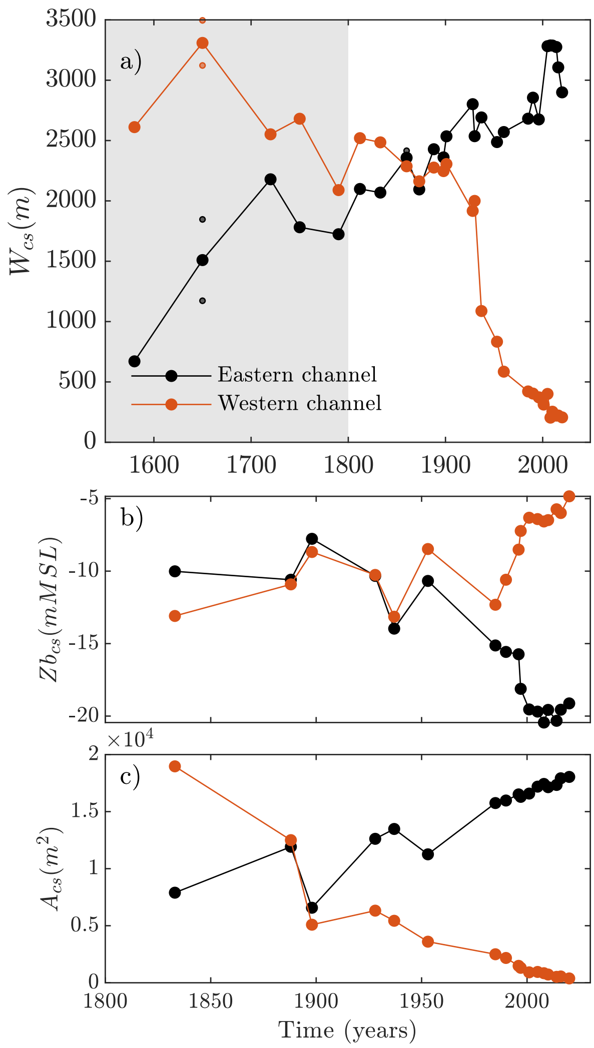


Figure 6. Channel width W_{cs} (a), deepest point Zb_{cs} (b), and cross-sectional volume V_{cs} (c) along the cross-section A-A' in Figure 1. Note that the channel geometry metrics are shown for time periods with data availability, leading to a longer time span in panel a (indicated by a gray patch)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

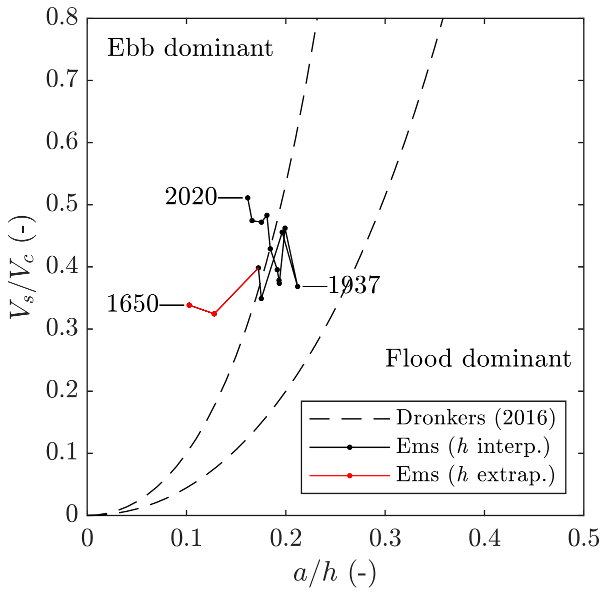


Figure 7. Tidal asymmetry based on the stability diagram in Zhou et al. (2018). For the Ems estuary data, V_s/V_c is derived by applying equations 1 and 2 on the surface areas from the morphological reconstructions, the tidal amplitude a is assumed constant at 1.2 m, and the mean water depth h is derived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

Table 1. Overview of the type and sources of the geospatial datasets 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 (100x100)	Nautical chart Dutch dep. of defense	H. J. Pierik et al. (2022); H. Pierik (2019)
1855	MLW, MHW and supratidal contours	Hist. reconstruction (Stratingh & 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 (100x100)	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 (20x20)	Nautical charts Ems Mündung (1:50000) & Die Ems Von Delfzijl Bis Pogum (1:25000) von Reichs Marine Amt	This article
1901	MLW contours	Hist. reconstruction Gerritsen (1952)	This article
1928	Gridded (100x100)	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 (5x5)	Depth soundings (German marine, RWS, Waterway agency Emden & Meppen)	Herrling and Niemeyer (2008)
1953	Gridded (100x100)	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 (20x20)	Echo soundings	Rijkswaterstaat
1990	Gridded (20x20)	Echo soundings	Rijkswaterstaat
1996	Gridded (10x10)	Echo soundings	Sievers et al. (2021)
1997	Gridded (20x20)	Echo soundings	Rijkswaterstaat
2001	Gridded (20x20)	Echo soundings	Rijkswaterstaat
2005	Gridded (20x20)	Echo soundings	Rijkswaterstaat
2008	Gridded (20x20)	Echo soundings	Rijkswaterstaat
2010	Gridded (25x25)	Echo soundings	WSA Emden
2014	Gridded (20x20)	Echo soundings	Rijkswaterstaat
2016	Gridded (10x10)	Echo soundings	Sievers et al. (2021)
2020	Gridded (20x20)	Echo soundings	Rijkswaterstaat

Open Research Section

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 25 m resolution provided by Copernicus (EU-DEM - version 1.1, Apr. 2016; `https://doi.org/10.5270/ESA-c5d3d65`), subaqueous bathymetry of the North Sea at ≈90 m resolution provided by the European Marine Observation and Data Network (EMODnet - `https://emodnet.ec.europa.eu/en/bathymetry`) and the coastal bathymetry which was requested through the servicedesk data of Rijkswaterstaat (`https://www.rijkswaterstaat.nl/formulieren/contactformulier-servicedesk-data`).

The main sources for the reconstruction of the land reclamation history are geospatial datasets with the location of historical embankments (`https://geoportaal.provinciegroningen.nl/portal/apps/experiencebuilder/experience/?id=9e93c75c4e5e47a584829e1deb0ad5f6`) and the National Historical Culture registry (`https://nationaalgeoregister.nl/geonetwork/srv/dut/catalog.search#/metadata/9a9cef3a-2dfc-4aa8-b248-f73f4064d7ad`). 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 (Lang, 1954; Gerritsen, 1952) and the 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. The gridded (subtidal) bathymetry datasets are available through the references included in Table 1 and therefore not included in Schrijvershof (2024).

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 datasets 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.

References

Alebregtse, N. C. (2015). *Modeling the Hydrodynamics in Tidal Networks* (Unpublished doctoral dissertation). Utrecht University, Utrecht. (ISBN: 9789462992597)

Allersma, E. (1992). *Studie inrichting Oostelijk deel Westerschelde. Analyse van het fysische systeem* (Tech. Rep.).

Allersma, E. (1994). *Geulen in estuaria: 1-D modellering van evenwijdige geulen* (Tech. Rep. No. H1828). Retrieved 2024-04-04, from `https://repository.tudelft.nl/islandora/object/uuid%3A3afdbae5-f4cc-4ad3-a5f2-2445a7e696dc` (Publisher: Deltares (WL))

Arcadis. (2011, December). *Afleidingen Hydromorfologie Rijkswateren* (Tech. Rep.). Author. Retrieved from `https://www.helpdeskwater.nl/publish/pages/130334/rapport_hydromorfologie_rijkswateren_23-12-2011.pdf`

Auerbach, L. W., Goodbred, S. L., Mondal, D. R., Wilson, C. A., Ahmed, K. R., Roy, K., ... Ackerly, B. A. (2015). Flood risk of natural and embanked landscapes on the Ganges-Brahmaputra tidal delta plain. *Nature Climate Change*, *5*(2), 153–157. doi: 10.1038/nclimate2472

Bain, R. L., Hale, R. P., & Goodbred, S. L. (2019). Flow Reorganization in an Anthropogenically Modified Tidal Channel Network: An Example From the Southwestern Ganges-Brahmaputra-Meghna Delta. *Journal of Geophysical Research: Earth Surface*, *124*(8), 2141–2159. doi: 10.1029/2018JF004996

Bao, S., Zhang, W., Qin, J., Zheng, J., Lv, H., Feng, X., ... Hoitink, A. J. F. (2022). Peak Water Level Response to Channel Deepening Depends on Interaction Between Tides and the River Flow. *Journal of Geophysical Research: Oceans*, *127*(4), e2021JC017625. Retrieved 2024-03-04, from `https://onlinelibrary.wiley.com/doi/abs/10.1029/2021JC017625` (_eprint: https://onlinelibrary.wiley.com/doi/pdf/10.1029/2021JC017625)

doi: 10.1029/2021JC017625
Beets, D. J., van der Valk, L., & Stive, M. J. F. (1992, January). Holocene evolution of the coast of Holland. *Marine Geology*, *103*(1), 423–443. Retrieved 2024-02-28, from https://www.sciencedirect.com/science/article/pii/002532279290030L doi: 10.1016/0025-3227(92)90030-L
Behre, K.-E. (1999, January). Die Veränderung der niedersächischen Küstenlinien in den letzten 3000 Jahren und ihre Ursachen. *Probleme der Küstenforschung im südlichen Nordseegebiet*, *26*, 9–33.
Borchert, S. M., Osland, M. J., Enwright, N. M., & Griffith, K. T. (2018). Coastal wetland adaptation to sea level rise: Quantifying potential for landward migration and coastal squeeze. *Journal of Applied Ecology*, *55*(6), 2876–2887. Retrieved 2024-03-28, from https://onlinelibrary.wiley.com/doi/abs/10.1111/1365-2664.13169 (_eprint: https://onlinelibrary.wiley.com/doi/pdf/10.1111/1365-2664.13169) doi: 10.1111/1365-2664.13169
Braat, L., Van Kessel, T., Leuven, J. R., & Kleinhans, M. G. (2017). Effects of mud supply on large-scale estuary morphology and development over centuries to millennia. *Earth Surface Dynamics*, *5*(4), 617–652. doi: 10.5194/esurf-5-617-2017
Chen, L., Zhou, Z., Xu, F., Jimenez, M., Tao, J., & Zhang, C. (2020, January). Simulating the impacts of land reclamation and de-reclamation on the morphodynamics of tidal networks. *Anthropocene Coasts*, *3*(1), 30–42. Retrieved 2023-08-17, from https://cdnsciencepub.com/doi/full/10.1139/anc-2019-0010 (Publisher: NRC Research Press) doi: 10.1139/anc-2019-0010
Coco, G., Zhou, Z., van Maanen, B., Olabarrieta, M., Tinoco, R., & Townend, I. (2013). Morphodynamics of tidal networks: Advances and challenges. *Marine Geology*, *346*, 1–16. Retrieved from http://dx.doi.org/10.1016/j.margeo.2013.08.005 (Publisher: Elsevier B.V.) doi: 10.1016/j.margeo.2013.08.005
Cox, T., Maris, T., De Vleeschauwer, P., De Mulder, T., Soetaert, K., & Meire, P. (2006, November). Flood control areas as an opportunity to restore estuarine habitat. *Ecological Engineering*, *28*(1), 55–63. Retrieved 2024-03-04, from https://www.sciencedirect.com/science/article/pii/S0925857406000735 doi: 10.1016/j.ecoleng.2006.04.001
Dai, Z., Fagherazzi, S., Mei, X., Chen, J., & Meng, Y. (2016). Linking the infilling of the North Branch in the Changjiang (Yangtze) estuary to anthropogenic activities from 1958 to 2013. *Marine Geology*, *379*, 1–12. doi: 10.1016/j.margeo.2016.05.006
de Haas, T., Pierik, H. J., van der Spek, A. J., Cohen, K. M., van Maanen, B., & Kleinhans, M. G. (2018). Holocene evolution of tidal systems in The Netherlands: Effects of rivers, coastal boundary conditions, eco-engineering species, inherited relief and human interference. *Earth-Science Reviews*, *177*(October 2017), 139–163. Retrieved from https://doi.org/10.1016/j.earscirev.2017.10.006 (Publisher: Elsevier) doi: 10.1016/j.earscirev.2017.10.006
De Jong, J. (2006). *Habitat Maps Ems Estuary and Historical Habitat Change* (HARBASINS report). Assen: Ecca advies.
Donatelli, C., Ganju, N. K., Zhang, X., Fagherazzi, S., & Leonardi, N. (2018). Salt Marsh Loss Affects Tides and the Sediment Budget in Shallow Bays. *Journal of Geophysical Research: Earth Surface*, *123*(10), 2647–2662. Retrieved 2023-07-31, from https://onlinelibrary.wiley.com/doi/abs/10.1029/2018JF004617 (_eprint: https://onlinelibrary.wiley.com/doi/pdf/10.1029/2018JF004617) doi: 10.1029/2018JF004617
Dronkers, J. (1986). Tidal asymmetry and estuarine morphology. *Netherlands Journal of Sea Research*, *20*(2-3), 117–131. doi: 10.1016/0077-7579(86)90036-0
Dronkers, J. (2016). *Dynamics of Coastal Systems*. WORLD SCIENTIFIC. Re-

trieved from https://www.worldscientific.com/doi/abs/10.1142/9818 doi: 10.1142/9818

D'Alpaos, A., Lanzoni, S., Marani, M., & Rinaldo, A. (2010, January). On the tidal prism—Channel area relations. *Journal of Geophysical Research*, *115*. doi: 10.1029/2008JF001243

Fortunato, A. B., & Oliveira, A. (2005). Influence of Intertidal Flats on Tidal Asymmetry. *Journal of Coastal Research*, *215*(215), 1062–1067. doi: 10.2112/03-0089.1

Friedrichs, C. T. (2010). *Barotropic tides in channelized estuaries.* (Publication Title: Contemporary Issues in Estuarine Physics Issue: January 2010) doi: 10.1017/CBO9780511676567.004

Friedrichs, C. T., & Aubrey, D. G. (1988). Nonlinear tidal distortion in shallow well-mixed estuaries. *Estuarine, Coastal and Shelf Science*, *30*(3), 321–322. (ISBN: 0272-7714) doi: 10.1016/0272-7714(90)90054-U

Gerritsen, F. (1952). *Historical and hydrographical investigations in the Ems estuary* (Tech. Rep.). Hoorn: Ministry of Public Works. Retrieved from https://open.rws.nl/open-overheid/onderzoeksrapporten/@91330/historisch-hydrografisch-onderzoek-eems/

Groen, P. (1967). On the residual transport of suspended matter by an alternating tidal current. *Netherlands Journal of Sea Research*, *3*(4), 564–574. doi: 10.1016/0077-7579(67)90004-X

Guo, L., Xie, W., Xu, F., Wang, X., Zhu, C., Meng, Y., ... He, Q. (2022). A historical review of sediment export–import shift in the North Branch of Changjiang Estuary. *Earth Surface Processes and Landforms*, *47*(1), 5–16. doi: 10.1002/esp.5084

Guo, L., Zhu, C., Xu, F., Xie, W., van der Wegen, M., Townend, I., ... He, Q. (2022). Reclamation of Tidal Flats Within Tidal Basins Alters Centennial Morphodynamic Adaptation to Sea-Level Rise. *Journal of Geophysical Research: Earth Surface*, *127*(6), 1–24. doi: 10.1029/2021jf006556

Herrling, G., & Niemeyer, H. D. (2007). Long-term Spatial Development of Habitats in the Ems-Dollard Estuary.

Herrling, G., & Niemeyer, H. D. (2008). Reconstruction of the historical tidal regime of the Ems-Dollard estuary prior to significant human changes by applying mathematical modeling.

Hiatt, M., & Passalacqua, P. (2015). Hydrological connectivity in river deltas: The first-order importance of channel-island exchange. *ater Resources Research*, *51*, 2264–2282. doi: 10.1111/j.1752-1688.1969.tb04897.x

Hibma, A., Schuttelaars, H. M., & De Vriend, H. J. (2004). Initial formation and long-term evolution of channel-shoal patterns. *Continental Shelf Research*, *24*(15), 1637–1650. doi: 10.1016/j.csr.2004.05.003

Hibma, a., Stive, M., & Wang, Z. (2004, October). Estuarine morphodynamics. *Coastal Engineering*, *51*(8-9), 765–778. Retrieved 2015-01-14, from http://linkinghub.elsevier.com/retrieve/pii/S037838390400081X doi: 10.1016/j.coastaleng.2004.07.008

Hoitink, A. J., Nittrouer, J. A., Passalacqua, P., Shaw, J. B., Langendoen, E. J., Huismans, Y., & van Maren, D. S. (2020). Resilience of River Deltas in the Anthropocene. *Journal of Geophysical Research: Earth Surface*, *125*(3), 1–24. doi: 10.1029/2019JF005201

Homeier, H. (1962). *Historisches Kartenwerk 1:50 000 der niedersächsischen Küste* (Tech. Rep.).

Homeier, H., Siebert, E., & Kramer, J. (1969). *Der Gestaltwandel der ostfriesischen Küste im Laufe der Jahrhunderte: ein Jahrtausend ostfriesischer Deichgeschichte. Entwicklung des Deichwesens vom Mittelalter bis zur Gegenwart.* Deichamt Krummhörn. (Google-Books-ID: w6ikPQAACAAJ)

Jarrett, J. (1976). Tidal prism-inlet area relationships General investigation of tidal inlets. (3).

Jeuken, M. C., & Wang, Z. B. (2010). Impact of dredging and dumping on the stability of ebb-flood channel systems. *Coastal Engineering*, *57*(6), 553–566. Retrieved from http://dx.doi.org/10.1016/j.coastaleng.2009.12.004 (Publisher: Elsevier B.V.) doi: 10.1016/j.coastaleng.2009.12.004

Kleinhans, M. G., Roelofs, L., Weisscher, S. A. H., Lokhorst, I. R., & Braat, L. (2022). Estuarine morphodynamics and development modified by floodplain formation. , 367–381. Retrieved from https://doi.org/10.5194/esurf-2021-75

Knottnerus, O. S. (2013a). Dollardgeschiedenis(sen) - Mythe en realiteit. In: K. Essink (Red.), Stormvloed 1509 - Geschiedenis van de Dollard. In (pp. 95–116). Groningen: Stichting Verdronken Geschiedenis.

Knottnerus, O. S. (2013b, January). Reclamations and submerged lands in the Ems River Estuary (900–1500). In *Landscapes or seascapes? The history of the coastal environment in the North Sea area reconsidered.* (pp. 241–266). CORN Publication Series. doi: 10.1484/M.CORN.1.101555

Lang, A. W. (1954). *Untersuchung zum Gestaltungswandel des Emsmündungstrichters* (Tech. Rep.).

Leuven, J. R., & Kleinhans, M. G. (2019). Incipient Tidal Bar and Sill Formation. *Journal of Geophysical Research: Earth Surface*, *124*(7), 1762–1781. doi: 10.1029/2018JF004953

Liu, J., Dietz, T., Carpenter, S. R., Alberti, M., Folke, C., Moran, E., … Taylor, W. W. (2007, September). Complexity of Coupled Human and Natural Systems. *Science*, *317*(5844), 1513–1516. Retrieved 2023-10-23, from https://www.science.org/doi/10.1126/science.1144004 (Publisher: American Association for the Advancement of Science) doi: 10.1126/science.1144004

Monge-Ganuzas, M., Cearreta, A., & Evans, G. (2013, June). Morphodynamic consequences of dredging and dumping activities along the lower Oka estuary (Urdaibai Biosphere Reserve, southeastern Bay of Biscay, Spain). *Ocean & Coastal Management*, *77*, 40–49. Retrieved 2023-10-12, from https://www.sciencedirect.com/science/article/pii/S0964569112000270 doi: 10.1016/j.ocecoaman.2012.02.006

O'Brien, & P., M. (1931). Estuary tidal prisms related to entrance areas. *Civil Engineering*. Retrieved 2020-10-21, from http://ci.nii.ac.jp/naid/10016529954/en/

Olds, A., Nagelkerken, I., Huijbers, C., Gilby, B., Pittman, S., & Schlacher, T. (2017). Connectivity in coastal seascapes. In *Seascape Ecology* (pp. pp. 261–292). John Wiley & Sons Ltd.

Pierik, H. (2019). *GIS dataset historical bathymetry and resistant layers in the Ems-Dollard estuary.* DANS. Retrieved from https://easy.dans.knaw.nl/ui/datasets/id/easy-dataset:118303/tab/1 (Place: Utrecht) doi: 10.17026/dans-x8w-wzsj

Pierik, H. J., Leuven, J. R. F. W., Busschers, F. S., Hijma, M., & Kleinhans, M. G. (2022). Depth-limiting resistant layers restrict dimensions and positions of estuarine channels and bars. *Depositional Record*(February), 1–20. doi: 10.1002/dep2.184

Ralston, D. K., Talke, S., Geyer, W. R., Al-Zubaidi, H. A. M., & Sommerfield, C. K. (2019). Bigger Tides, Less Flooding: Effects of Dredging on Barotropic Dynamics in a Highly Modified Estuary. *Journal of Geophysical Research: Oceans*, *124*(1), 196–211. Retrieved 2024-03-06, from https://onlinelibrary.wiley.com/doi/abs/10.1029/2018JC014313 (_eprint: https://onlinelibrary.wiley.com/doi/pdf/10.1029/2018JC014313) doi: 10.1029/2018JC014313

Ridderinkhof, W., de Swart, H. E., van der Vegt, M., Alebregtse, N. C., & Hoekstra,

P. (2014). Geometry of tidal inlet systems: A key factor for the net sediment transport in tidal inlets W. *Journal of Geophysical Research: Oceans*(119), 3868–3882. Retrieved from http://onlinelibrary.wiley.com/doi/10.1002/jgrc.20353/abstract doi: 10.1002/2014JC010226.Received

Schrijvershof, R. (2024, April). *Geospatial datasets of land reclamation and morphological reconstructions of the Ems estuary since the 16th century.* [object Object]. Retrieved 2024-04-09, from https://data.4tu.nl/datasets/78ac0cf9-e9f7-47c7-8c4e-93f7fb2c633e/1 doi: 10.4121/78AC0CF9-E9F7-47C7-8C4E-93F7FB2C633E.V1

Siemes, R. W. A., Duong, T. M., Willemsen, P. W. J. M., Borsje, B. W., & Hulscher, S. J. M. H. (2023, November). Morphological Response of a Highly Engineered Estuary to Altering Channel Depth and Restoring Wetlands. *Journal of Marine Science and Engineering*, *11*(11), 2150. Retrieved 2024-03-06, from https://www.mdpi.com/2077-1312/11/11/2150 (Number: 11 Publisher: Multidisciplinary Digital Publishing Institute) doi: 10.3390/jmse11112150

Sievers, J., Milbradt, P., Ihde, R., Valerius, J., Hagen, R., & Plüß, A. (2021, August). An integrated marine data collection for the German Bight – Part 1: Subaqueous geomorphology and surface sedimentology (1996–2016). *Earth System Science Data*, *13*(8), 4053–4065. Retrieved 2023-06-08, from https://essd.copernicus.org/articles/13/4053/2021/ (Publisher: Copernicus GmbH) doi: 10.5194/essd-13-4053-2021

Speer, P. E., & Aubrey, D. G. (1985). A Study of Non-linear Tidal Propagation in Shallow Inlet/Estuarine Systems Part II: Theory". *Estuarine, Coastal and Shelf Science*, *21*(5691), 207–224.

Stive, M. J. F., & Wang, Z. B. (2003, January). Chapter 13 Morphodynamic modeling of tidal basins and coastal inlets. In V. C. Lakhan (Ed.), *Elsevier Oceanography Series* (Vol. 67, pp. 367–392). Elsevier. Retrieved 2024-04-02, from https://www.sciencedirect.com/science/article/pii/S0422989403801307 doi: 10.1016/S0422-9894(03)80130-7

Stratingh, G. A., & Venema, G. A. (1855). *De Dollard of Geschied,- Aardrijks- en Natuurkundige Beschrijving van dezen Boezem der Eems.* Winschoten.

Talke, S. A., & Jay, D. A. (2020). Changing Tides: The Role of Natural and Anthropogenic Factors. *Annual Review of Marine Science*, *12*(1), 121–151. Retrieved 2023-04-24, from https://doi.org/10.1146/annurev-marine-010419-010727 (_eprint: https://doi.org/10.1146/annurev-marine-010419-010727) doi: 10.1146/annurev-marine-010419-010727

Van de Kreeke, J., & Robaczewska, K. (1993). Tide-induced residual transport of coarse sediment; Application to the EMS estuary. *Netherlands Journal of Sea Research*, *31*(3), 209–220. doi: 10.1016/0077-7579(93)90022-K

van der Molen, J., & de Swart, H. E. (2001). Holocene tidal conditions and tide-induced sand transport in the southern North Sea. *Journal of Geophysical Research: Oceans*, *106*(C5), 9339–9362. Retrieved 2024-03-07, from https://onlinelibrary.wiley.com/doi/abs/10.1029/2000JC000488 (_eprint: https://onlinelibrary.wiley.com/doi/pdf/10.1029/2000JC000488) doi: 10.1029/2000JC000488

van der Spek, A. J. (1994). *Large-scale evolution of holocene tidal basins in the Netherlands.*

Van Der Wegen, M. (2013). Numerical modeling of the impact of sea level rise on tidal basin morphodynamics. *Journal of Geophysical Research: Earth Surface*, *118*(2), 447–460. doi: 10.1002/jgrf.20034

van der Wegen, M., Wang, Z. B., Savenije, H. H. G., & Roelvink, J. A. (2008). Long-term morphodynamic evolution and energy dissipation in a coastal plain, tidal embayment. *Journal of Geophysical Research: Earth Surface*, *113*(F3). Retrieved 2024-03-28, from https://

onlinelibrary.wiley.com/doi/abs/10.1029/2007JF000898 (_eprint: https://onlinelibrary.wiley.com/doi/pdf/10.1029/2007JF000898) doi: 10.1029/2007JF000898

van Dijk, W. M., Cox, J. R., Leuven, J. R., Cleveringa, J., Taal, M., Hiatt, M. R., ... Kleinhans, M. G. (2021). The vulnerability of tidal flats and multi-channel estuaries to dredging and disposal. *Anthropocene Coasts*, *4*(1), 36–60. doi: 10.1139/anc-2020-0006

van Maren, D. S., Beemster, J., Wang, Z., Khan, Z. H., Schrijvershof, R., & Hoitink, A. (2023). Tidal Amplification and River Capture in Response to Asynchronous Land Reclamation in the Ganges-Brahmaputra Delta. *Catena*, *220*(PA), 106651. Retrieved from https://doi.org/10.1016/j.catena.2022.106651 (Publisher: Elsevier B.V.) doi: 10.2139/ssrn.4064791

van Maren, D. S., Colina Alonso, A., Engels, A., Vandenbruwaene, W., de Vet, P. L. M., Vroom, J., & Wang, Z. B. (2023). Adaptation timescales of estuarine systems to human interventions. *Frontiers in Earth Science*, *11*. Retrieved 2023-05-16, from https://www.frontiersin.org/articles/10.3389/feart.2023.1111530

Van Maren, D. S., Oost, A. P., Wang, Z. B., & Vos, P. C. (2016). The effect of land reclamations and sediment extraction on the suspended sediment concentration in the Ems Estuary. *Marine Geology*, *376*, 147–157. Retrieved from http://dx.doi.org/10.1016/j.margeo.2016.03.007 (Publisher: The Authors) doi: 10.1016/j.margeo.2016.03.007

Van Maren, D. S., van Kessel, T., Cronin, K., & Sittoni, L. (2015). The impact of channel deepening and dredging on estuarine sediment concentration. *Continental Shelf Research*, *95*, 1–14. Retrieved from http://dx.doi.org/10.1016/j.csr.2014.12.010 (Publisher: Elsevier) doi: 10.1016/j.csr.2014.12.010

Van Maren, D. S., Winterwerp, J. C., & Vroom, J. (2015). Fine sediment transport into the hyper-turbid lower Ems River: the role of channel deepening and sediment-induced drag reduction. *Ocean Dynamics*, *65*(4), 589–605. (ISBN: 1023601508) doi: 10.1007/s10236-015-0821-2

Van Veen, J. (1950). Eb- en Vloedschaar Systemen in de Nederlandse Getijwateren. *Journal of the Royal Dutch Geographical Society*, *67*(November), 303–325.

Van Veen, J., van der Spek, A. J. F., Stive, M. J. F., & Zitman, T. (2005). Ebb and Flood Channel Systems in the Netherlands Tidal Waters. *Journal of Coastal Research*, *216*(November), 1107–1120. doi: 10.2112/04-0394.1

Vellinga, N. E., Hoitink, A. J., van der Vegt, M., Zhang, W., & Hoekstra, P. (2014). Human impacts on tides overwhelm the effect of sea level rise on extreme water levels in the Rhine-Meuse delta. *Coastal Engineering*, *90*, 40–50. Retrieved from http://dx.doi.org/10.1016/j.coastaleng.2014.04.005 (Publisher: Elsevier B.V.) doi: 10.1016/j.coastaleng.2014.04.005

Voorsmit, O. V. (2006, April). *Het meergeulenstelsel van de Westerschelde en de relatie met de functies van de Langetermijnvisie : een kritische analyse van het beleidsuitgangspunt 'Instandhouding van het meergeulenstelsel van de Westerschelde'* [info:eu-repo/semantics/masterThesis]. Retrieved 2024-04-02, from https://essay.utwente.nl/56958/ (Publisher: University of Twente)

Vos, P., Van der Meulen, M., Weerts, H., & Bazelmans, J. (2020). *Atlas of the Holocene Netherlands: Landscape and Habitation since the Last Ice Age.* doi: 10.5117/9789463724432

Vos, P., & van Kesteren, W. (2000, September). The long-term evolution of intertidal mudflats in the northern Netherlands during the Holocene; natural and anthropogenic processes. *Continental Shelf Research*, *20*, 1687–1710. doi: 10.1016/S0278-4343(00)00043-1

Vos, P. C., & Knol, E. (2013). De ontstaansgeschiedenis van het Dollardlandschap; natuurlijke en antropogene processen. In: K. Essink (Red.), Stormvloed 1509 -

Geschiedenis van de Dollard. Groningen: Stichting Verdronken Geschiedenis.

Vos, P. C., & Knol, E. (2015). Holocene landscape reconstruction of the Wadden Sea area between Marsdiep and Weser. *Geologie en Mijnbouw/Netherlands Journal of Geosciences*, *94*(2), 157–183. doi: 10.1017/njg.2015.4

Wang, Z., Jeuken, C., & Vriend, H. d. (1999). *Tidal asymmetry and residual sediment transport in estuaries* (Tech. Rep.). WL | Delft hydraulics. (Issue: November)

Wang, Z. B., Van Maren, D. S., Ding, P. X., Yang, S. L., Van Prooijen, B. C., De Vet, P. L., ... He, Q. (2015). Human impacts on morphodynamic thresholds in estuarine systems. *Continental Shelf Research*, *111*, 174–183. doi: 10.1016/j.csr.2015.08.009

Wang, Z. B., & Winterwerp, H. (2001, September). Impact of Dredging and Dumping on the Stability of Ebb-Flood Channel Systems..

Weisscher, S. A., Baar, A. W., van Belzen, J., Bouma, T. J., & Kleinhans, M. G. (2022). Transitional polders along estuaries: Driving land-level rise and reducing flood propagation. *Nature-Based Solutions*, *2*(June), 100022. Retrieved from `https://doi.org/10.1016/j.nbsj.2022.100022` (Publisher: Elsevier Inc.) doi: 10.1016/j.nbsj.2022.100022

Wilson, C., Goodbred, S., Small, C., Gilligan, J., Sams, S., Mallick, B., & Hale, R. (2017). Widespread infilling of tidal channels and navigable waterways in the human-modified tidal deltaplain of southwest Bangladesh. *Elementa*, *5*. doi: 10.1525/elementa.263

Winterwerp, J. C., Wang, Z. B., Van Braeckel, A., Van Holland, G., & Kösters, F. (2013). Man-induced regime shifts in small estuaries - II: A comparison of rivers. *Ocean Dynamics*, *63*(11-12), 1293–1306. doi: 10.1007/s10236-013-0663-8

Zhou, Z., Coco, G., Townend, I., Gong, Z., Wang, Z., & Zhang, C. (2018). On the stability relationships between tidal asymmetry and morphologies of tidal basins and estuaries. *Earth Surface Processes and Landforms*, *43*(9). doi: 10.1002/esp.4366

Zhu, C., Guo, L., van Maren, D. S., Tian, B., Wang, X., He, Q., & Wang, Z. B. (2019). Decadal morphological evolution of the mouth zone of the Yangtze Estuary in response to human interventions. *Earth Surface Processes and Landforms*, *44*(12), 2319–2332. Retrieved 2023-10-12, from `https://onlinelibrary.wiley.com/doi/abs/10.1002/esp.4647` (_eprint: https://onlinelibrary.wiley.com/doi/pdf/10.1002/esp.4647) doi: 10.1002/esp.4647

Supporting Information for "Land reclamation controls on multi-centennial evolution of the Ems Estuary"

R.A. Schrijvershof[1,2], D.S. van Maren[2,3], M. van der Wegen[2,4], A.J.F. Hoitink[1]

[1]Wageningen University & Research, Environmental Sciences Group, Wageningen, The Netherlands

[2]Deltares, Delft, The Netherlands

[3]Delft University of Technology, Faculty of Civil Engineering and Geosciences, The Netherlands

[4]IHE-Delft Institute for Water Education, Delft, The Netherlands

Contents of this file

1. Text S1: Contextual background information on the historic landscape developments

2. Text S2: The most important human-landscape interactions in the 19th and 20th centuries (besides land reclamations).

3. Figure S1: Palaeogeographical reconstructions of the Ems estuary, showing the formation of storm-surge formed embayments

4. Figure S2: Historical map "Submerged lands of the Dollard" (Hendricus Teysinga, 1735)

5. Figure S3: Time-line of land reclamations and most important dredging, disposal, and hydraulic re-alignment works

6. Figure S4: Tidal zones derived from the morphological reconstructions

7. Figure S5: Subtidal bathymetries derived from the historical reconstructions

8. Table S1: Major anthropogenic interventions in the Ems estuary

Introduction

This supplement outlines contextual background information on the historal landscape development in the Ems estuary, and the most important human-landscape elements besides the land reclamations.

1. Text S1: Historical landscape setting

1.1. Palaeogeography

The Ems estuary is a meso-tidal system located on the border between the Netherlands and Germany and part of the larger Wadden Sea tidal lagoon. The present-day geomorphological setting of the estuary is largely inherited from the Early to Mid-Holocene development of the Wadden Sea region, after which it transformed into a marine environment under a fast-rising sealevel (van der Spek, 1994; de Haas et al., 2018). After the Last Glacial Period (the Weichselian), lower-lying Pleistocene valley systems drowned under the rapidly rising sealevel (van der Spek, 1994). The first Holocene tidal basins and estuaries developed by channel erosion of the Pleistocene substrate and became progressively deeper because of sealevel rise. These tidal systems required sediments to keep pace with sealevel rise, resulting in erosion of the adjacent coastline and the North Sea. Early Holocene sealevel rise rates exceeded sediment availability and as a result the Wadden islands, tidal basins, and estuaries migrated landwards (van der Spek, 1994). The sealevel rise rate decreased between 7000 Before Present (B.P.) - 5500 B.P. to 0.15 m/century (Meijles et al., 2018), and the Early Holocene tidal basins started to fill in with deltaic sediments.

The tidal channels silted up, salt marshes formed along the coastline, and the drainage of the back-barrier basin deteriorated, creating favorable conditions for the formation and expansion of peatlands (Figure S1a). Between 5000 B.P. and 4250 B.P., sediment supply to the basins exceeded sealevel rise rate (Cleveringa, 2000), leading to a transition from coastline transgression to regression. Salt marshes along the coastal margins did not expand further seaward because of the stable sealevel and became more vulnerable to erosion during storm surges. From 2500 B.P. till present the sea regularly flooded the coastal peat area in the back-barrier basin, often following the paths of existing drainage systems (van der Spek, 1994). Erosion of the back-barrier peat bogs led to expansion of the tidal embayments and increasing tidal channels and inlet size. Eventually, the regular flooding led to more efficient natural drainage of the peatlands, strengthening oxidation and therefore subsidence. Clay deposited on the peatlands during subsequent storm surge induced flooding, increasing the sediment load on the peatlands, exacerbating the subsidence process (known as auto-compaction). From the Late Iron age (400 - 800 AD) onwards, however, human involvement dominated the landscape development by artificially draining the margins of the coastal peatlandscape.

1.2. Formation of storm surge basins

Early habitation in the Ems estuary region concentrated on high grounds of natural levees and sand ridges around 100 A.D (Anno Domini). The regularly flooding landscapes were settled by constructing dwelling mounds (Figure S1b). The peatlands surrounding the settlements were fertile grounds, but needed artificial drainage for agriculture. Oxidation of the peat, and peat extraction, led to subsidence and land surface heights lowered below the high water storm surge level. The first artificial levees (embankments) were therefore constructed in the 12th and 13th century at the border of the salt marshes and the peatlands (Figure S1b). The protected lands provided a safe and productive area, allowing the region to flourish and population density to increase. Extreme high water levels in the estuary, however, increased because storm surge waves were less effectively attenuated over the (partly) embanked tidal marshes while the embanked land progressively lowered because of subsidence. This created a vulnerable situation for the low lying peatlands protected by basic earthen embankments.

The Ley bay (Figure S1c) probably resulted from a storm surge breach on December 26, 838 A.D[1]. Its largest extent, however, was reached after two storm surges in the years 1374 and 1376 (Homeier, 1962)[2,3]. Formation of the Dollard bay (referring it's name to 'Dolle aarde', Dutch for 'mad lands') has been clouded with mythical anecdotes, that have persisted for many centuries (Knottnerus, 2013). Historical geographical maps of the Dollard expansion often date the storm-surge flooding disaster to the year 1277 (Figure S2). The date originates from a 16th century missal that assigns the storm surge breach to a divine vengeance for the victims' sinning and contentiousness, in which 33 villages were swept away in the disaster (Knottnerus, 2013). Palaeogeographic reconstructions, however, indicate that the first large breaches occurred in the 15th century and were mainly a consequence of landscape developments (P. C. Vos & Knol, 2013) and negligence of the land owners in maintenance of the embankments (Knottnerus, 2013). The Eastern part of the Dollard basin formed in the 15th century (Figure S1c). After the Second Cosmas and Damianus storm surge on 26 September 1509 formed the western inlet, the Dollard bay reached its largest extent (Figure S1d).

The shape of the newly formed Dollard bay reflects the position of former Pleistocene valley systems, which were filled with peat in the early Holocene (P. C. Vos & Knol, 2013). A secondary, adverse, effect of the formation of the Dollard bay was a redistribution of the tidal prism at the river-estuary transition. The channel along the port city of Emden (located at a meander bend of the Ems river; Figure S2), started to degenerate leading to an obstruction of the harbors entrance. In an effort to guide the tidal and river flow towards the channel near Emden, a 4.5 kilometer long stockage (a barrier from upright wooden posts) was constructed: the Nesserlander head[4] (1585 - 1616). These water works can be considered as one of the first large engineering works in the Ems estuary. The flow-diverting stockage failed eventually because maintenance was costly and abandoned in 1631. The main tidal flow from the Ems Estuary was now towards the Dollard bay rather than the upper Ems Estuary, and carried sediments that led to rapid sedimentation in the embayment and development of tidal (fringing) flats.

2. Text S2: Human-landscape interaction

2.1. Channel re-alignment and dredging

Human interference in the Ems estuary intensified in the second half of the 19$^{\text{th}}$ century as the expansion of seaports led to more extensive fairway requirements to accommodate increasing ship traffic and size. Navigation benefits from deep, well-accessible, and well-connected fairways to facilitate the shortest travel route from port to outer sea. In this context several fairway re-alignment works have been implemented and channel deepening and associated maintenance dredging is performed on a regular basis.

A large shoal, called Geise shoal, separates Dollard Bay from the main tidal channel connected to the Ems river (see Figure 1 in the paper). Hydraulic construction works consisting of groynes and longitudinal training walls were built on the tidal flats flanking the fairway to concentrate tidal and river flow and to prevent navigational-hindering lateral flow (Figure S3). A secondary effect of the construction of the channel re-alignment works on the Geise shoal is a redirection of tidal flows in to Dollard Bay, towards an east-west orientation. As a result, the western Dollard Bay channels decreased in size (Gerritsen, 1955). In 1933 a bended longitudinal training wall was completed at the southern side of the eastern central-estuary channel (Figure S3); the Rysumer Nacken training wall (Figure 1 in the main text). The purpose of the training wall was to guide the tidal flow through the main tidal channel, instead of over the tidal flats as flood chutes. As a result of this dam the fairway deepened and stabilized.

The fairway re-alignment works were combined with regularly executed maintenance dredging to maintain fairway depths, specifically at channel bifurcations/confluences where sediment transport diverges and sills are formed. Dredging started probably in the late 19th century (Figure S3). Dredging volumes, however, increased substantially in the 1960s through the 1980s to an averaged $10 * 10^6$ ton/year (Van Maren et al., 2016), because of increasing ship traffic and size requiring progressively deeper access channels (Essink et al., 1992). The main dredged material disposal sites are the Dollard entrance channel (up to approximately 2010), the central-estuary western channel up to 1973 (Figure S3), a channel in the western Ems inlet, and the connection between the eastern tidal inlet and main estuary (Boon et al., 2002).

The most recent major flow-regulating construction in the Ems estuary was the the Ems storm surge barrier completed in 2003. The barrier closes during storm surges to prevent flooding of the lands surrounding the Ems river and is also used approximately twice a year to increase navigational draft for cruise ships build upstream (Talke & de Swart, 2006) by storing water. In the near future, the storm surge barrier will be used additionally to regulate tidal flow into the Ems river with the purpose of controlling fine sediment import (Oberrecht & Wurpts, 2014).

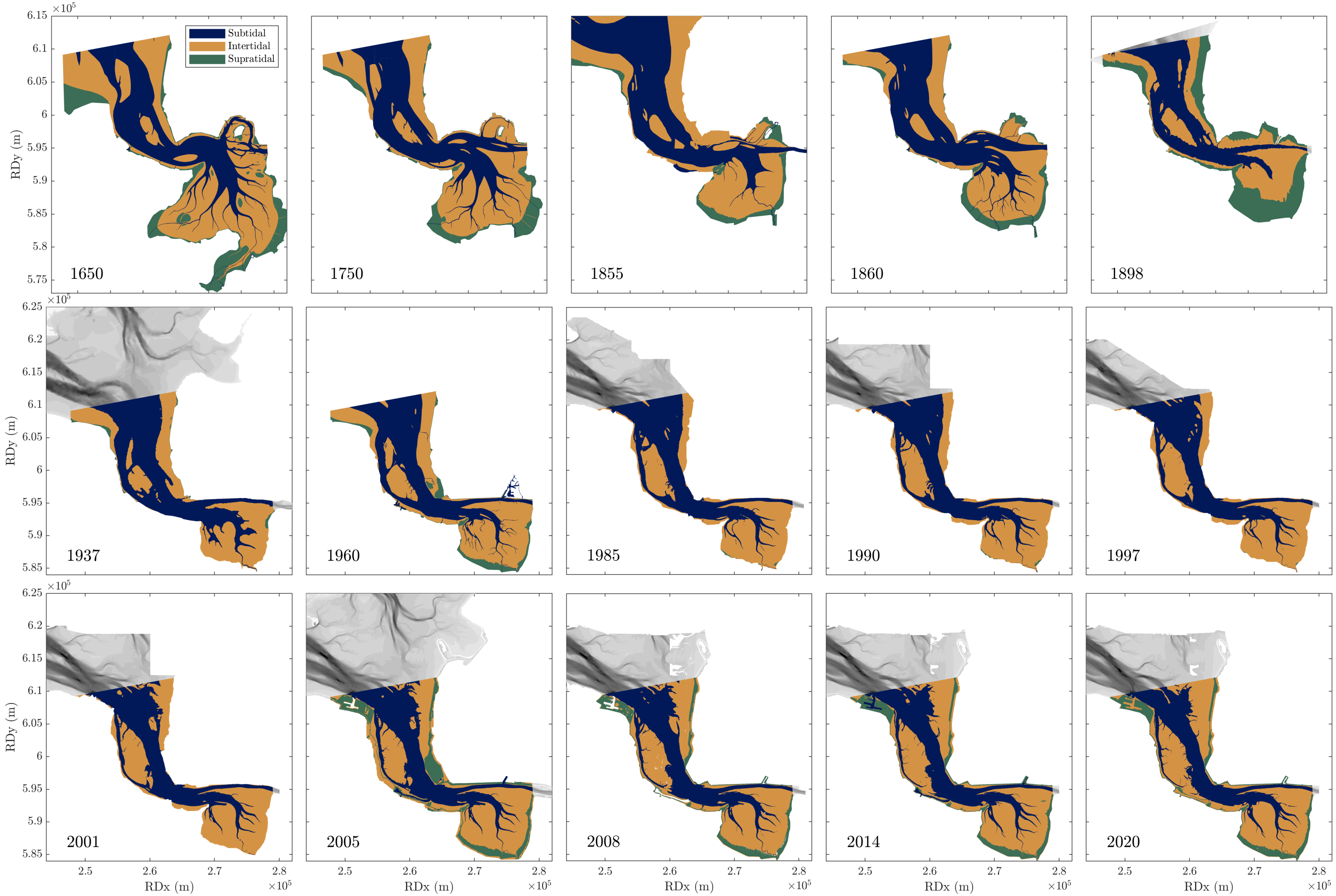


Figure S4. Tidal zones (subtidal, intertidal, supratidal) derived from the morphological reconstructions.

References

Boon, J., Dardengo, L., & Kernkamp, H. (2002). *Alternative Dumping Sites in the Ems Dollard Estuary* (Tech. Rep. No. Z3328). Delft: Delft Hydraulics. Retrieved 2024-02-26, from https://www.google.com/search?q=Boon%2C+J.+G.%2C+L.+Dardengo%2C+et+al.+(2002).+Alternative+Dumping+Sites+in+the+Ems+Dollard+Estuary%2C+Delft+Hydraulics.&rlz=1C1GCEA_enNL915NL915&oq=Boon%2C+J.+G.%2C+L.+Dardengo%2C+et+al.+(2002).+Alternative+Dumping+Sites+in+the+Ems+Dollard+Estuary%2C+Delft+Hydraulics.&gs_lcrp=EgZjaHJvbWUyBggAEEUYOdIBBzIyMmowajmoAgCwAgA&sourceid=chrome&ie=UTF-8

Cleveringa, J. (2000). *Reconstruction and modelling of holocene coastal evolution of the western Netherlands* (No. 200). Utrecht: Univ.

de Haas, T., Pierik, H. J., van der Spek, A. J., Cohen, K. M., van Maanen, B., & Kleinhans, M. G. (2018). Holocene evolution of tidal systems in The Netherlands: Effects of rivers, coastal boundary conditions, eco-engineering species, inherited relief and human interference. *Earth-Science Reviews*, *177*(October 2017), 139–163. Retrieved from https://doi.org/10.1016/j.earscirev.2017.10.006 (Publisher: Elsevier) doi: 10.1016/j.earscirev.2017.10.006

Essink, K., Steyaert, F. H. I. M., Mulder, H. P. J., De Jonge, V. N., Van Heuvel, T., & van den Bergs, J. (1992). Effects of dredging activities in the Ems estuary and Dutch Wadden Sea. *Publication Series. Netherlands Institute for Sea Research (NIOZ)*. Retrieved 2024-02-23, from https://www.vliz.be/nl/imis?module=ref&refid=53571&printversion=1&dropIMIStitle=1

Gerritsen, F. (1955). *Enige opmerkingen over de ontwikkeling van de Dollart* (Tech.

Rep.).

Homeier, H. (1962). *Historisches Kartenwerk 1:50 000 der niedersächsischen Küste* (Tech. Rep.).

Knottnerus, O. S. (2013). Dollardgeschiedenis(sen) - Mythe en realiteit. In: K. Essink (Red.), Stormvloed 1509 - Geschiedenis van de Dollard. In (pp. 95–116). Groningen: Stichting Verdronken Geschiedenis.

Meijles, E. W., Kiden, P., Streurman, H.-J., van der Plicht, J., Vos, P. C., Gehrels, W. R., & Kopp, R. E. (2018, November). Holocene relative mean sea-level changes in the Wadden Sea area, northern Netherlands. *Journal of Quaternary Science*, *33*(8), 905–923. Retrieved 2023-03-09, from `https://onlinelibrary.wiley.com/doi/10.1002/jqs.3068` doi: 10.1002/jqs.3068

Oberrecht, D., & Wurpts, A. (2014, January). Impact of controlled tidal barrier operation on tidal dynamics in the Ems estuary. *Kuste*, 427–433.

Talke, S. A., & de Swart, H. E. (2006). *Hydrodynamics and Morphology in the Ems/Dollard Estuary: Review of Models, Measurements, Scientific Literature, and the Effects of Changing Conditions* (Tech. Rep.). Utrecht: Institute for Marine and Atmospheric Research Utrecht (IMAU).

van der Spek, A. J. (1994). *Large-scale evolution of holocene tidal basins in the Netherlands.*

Van Maren, D. S., Oost, A. P., Wang, Z. B., & Vos, P. C. (2016). The effect of land reclamations and sediment extraction on the suspended sediment concentration in the Ems Estuary. *Marine Geology*, *376*, 147–157. Retrieved from `http://dx.doi.org/10.1016/j.margeo.2016.03.007` (Publisher: The Authors) doi: 10.1016/

j.margeo.2016.03.007

Vos, P., Van der Meulen, M., Weerts, H., & Bazelmans, J. (2020). *Atlas of the Holocene Netherlands: Landscape and Habitation since the Last Ice Age.* doi: 10.5117/9789463724432

Vos, P. C., & Knol, E. (2013). De ontstaansgeschiedenis van het Dollardlandschap; natuurlijke en antropogene processen. In: K. Essink (Red.), Stormvloed 1509 - Geschiedenis van de Dollard. Groningen: Stichting Verdronken Geschiedenis.

Vos, P. C., & Knol, E. (2015). Holocene landscape reconstruction of the Wadden Sea area between Marsdiep and Weser. *Geologie en Mijnbouw/Netherlands Journal of Geosciences*, *94*(2), 157–183. doi: 10.1017/njg.2015.4

Notes

1. https://de.wikipedia.org/wiki/Leybucht
2. https://www.nlwkn.niedersachsen.de/startseite/hochwasser_kustenschutz/kustenschutz/ausgewahlte_projekte/kustenschutz_projekt_leybucht/kuestenschutz-projekt-leybucht-43552.html
3. http://www.michaeltillheinze.de/f_k1989/f_k890223.htm#1
4. https://nl.wikipedia.org/wiki/Nesserlander_Hoofd

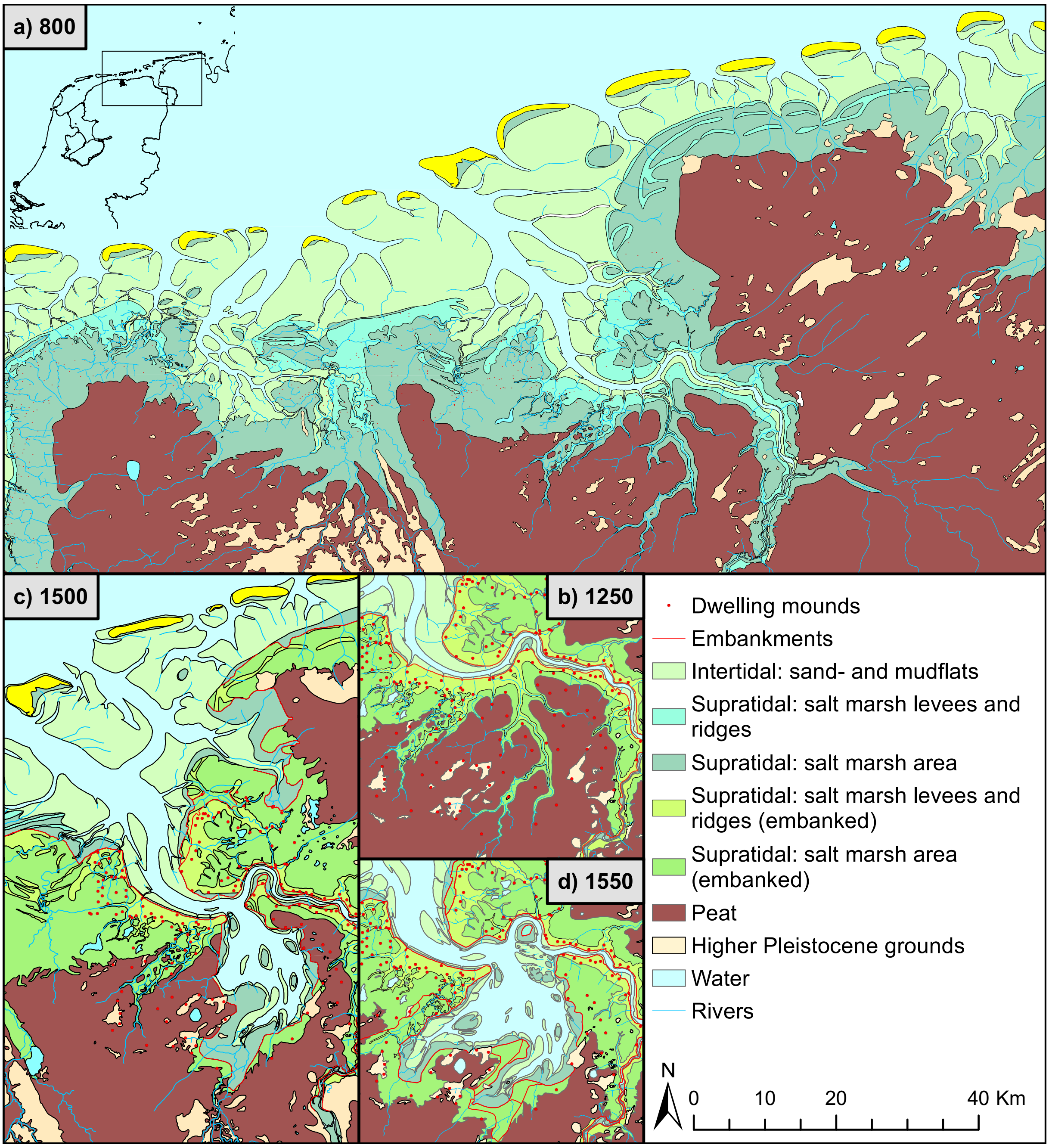


Figure S1. Palaeogeographic maps showing (a) the situation of the northeast Netherlands and northwest Germany around 800 A.D., and the situation for the Ems estuary around 1250 A.D. (b), 1500 A.D. (c), and 1550 A.D. (d) showing the formation of the storm-surge formed Ley bay and Dollard bay. Figure is produced with data from P. Vos et al. (2020) and P. C. Vos and Knol (2015, 2013).

Figure S2. "Submerged lands of the Dollard" (Hendricus Teysinga, 1735). The maps shows the extent of the Dollard Bay and the towns lost in the storm surge. The map subscription, written in Old Dutch and, wrongfully, dating the event to the year 1277 (see main text), translates:*"The 25 December 1277 storm surge flooding submerged and destroyed 33 villages, including thousands of inhabitants and livestock. The flooding disaster, likewise the previous flood [13 January 1277], repeated three quarters of a year later and created a breach at the village Jansum to create the Dollard expansion. The cause of the disaster can be found in quarrel: the villagers living near the dyke were unable to restore the dyke and those living at a distance felt irresponsible."*

.

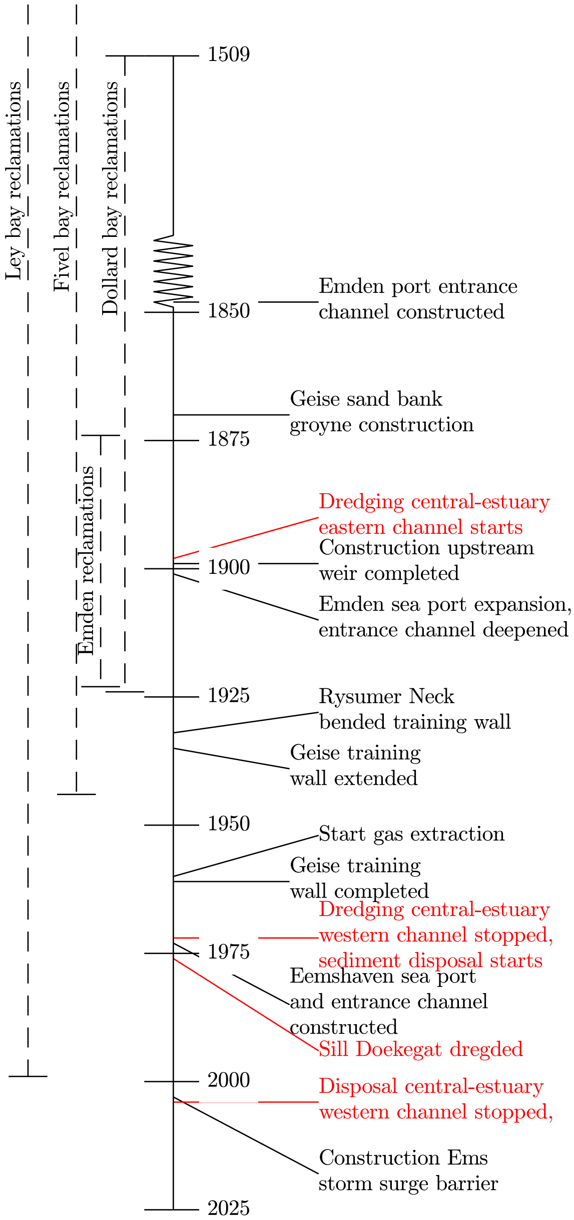


Figure S3. Time line of land reclamations, and most important dredging, disposal, and hydraulic re-alignment works in the Ems estuary.

Table S1. Major anthropogenic interventions in the Ems estuary.

Start	End	Intervention
12^{th} century	13^{th} century	Embankment of Ems river and Ems estuary
11^{th} century	13^{th} century	Sielmönken bay reclamations
1190	1944	Fivel bay reclamations
1400	1999	Ley bay reclamations
1509	1924	Dollard bay reclamations
1583	1631	Construction and operation of Nesserlander head
1860		Start canalization Lower Ems river
1870	1871	Construction of rubble mounted groynes on the Geise Sand bank
1897	1899	Construction first weir at Herbrum
1898		Start dredging *Oost Friesche Gaatje*
1899		Tidal barrier upper Ems river (at Herbrum)
1907		Sluice Nieuwe Statenzijl constructed
1912	1924	Land reclamations Emden
1911	1929	
		Lower Ems maintenance depth at 5 m
		Upper Ems maintenance depth at 4.0 - 5.0 m
1930	1935	Extension Geise training dam
1932		Construction bended training wall at Rysumer Nacken
1932	1939	Lower Ems maintenance depth at 5.5 m
1958	1961	Construction Geiseleit training wall
1959		Construction Harbor at Leer (Lower Ems river)
1960		Extraction gas from Groningen field starts
1961	1962	Narrowing river bed between Herbrum and Papenburg
1960	1964	Land reclamation Rysumer Nacken
	1969	Closure Lauwerszee
	1972	
		Reconstruction of Delfzijl harbor entrance channel
		Dredging at Bocht van Watum is stopped
1970	1973	Construction Seaport Eemshaven
	1985	Lower Ems maintenance depth at 5.7 m
	1991	New sluice and watergate at Nieuwe Statenzijl
	1992	Lower Ems maintenance depth at 6.5 - 6.8 m
	1994	Lower Ems maintenance depth at 7.3 m
2002	2003	Storm surge barrier Gandersum (Emssperrwerk)

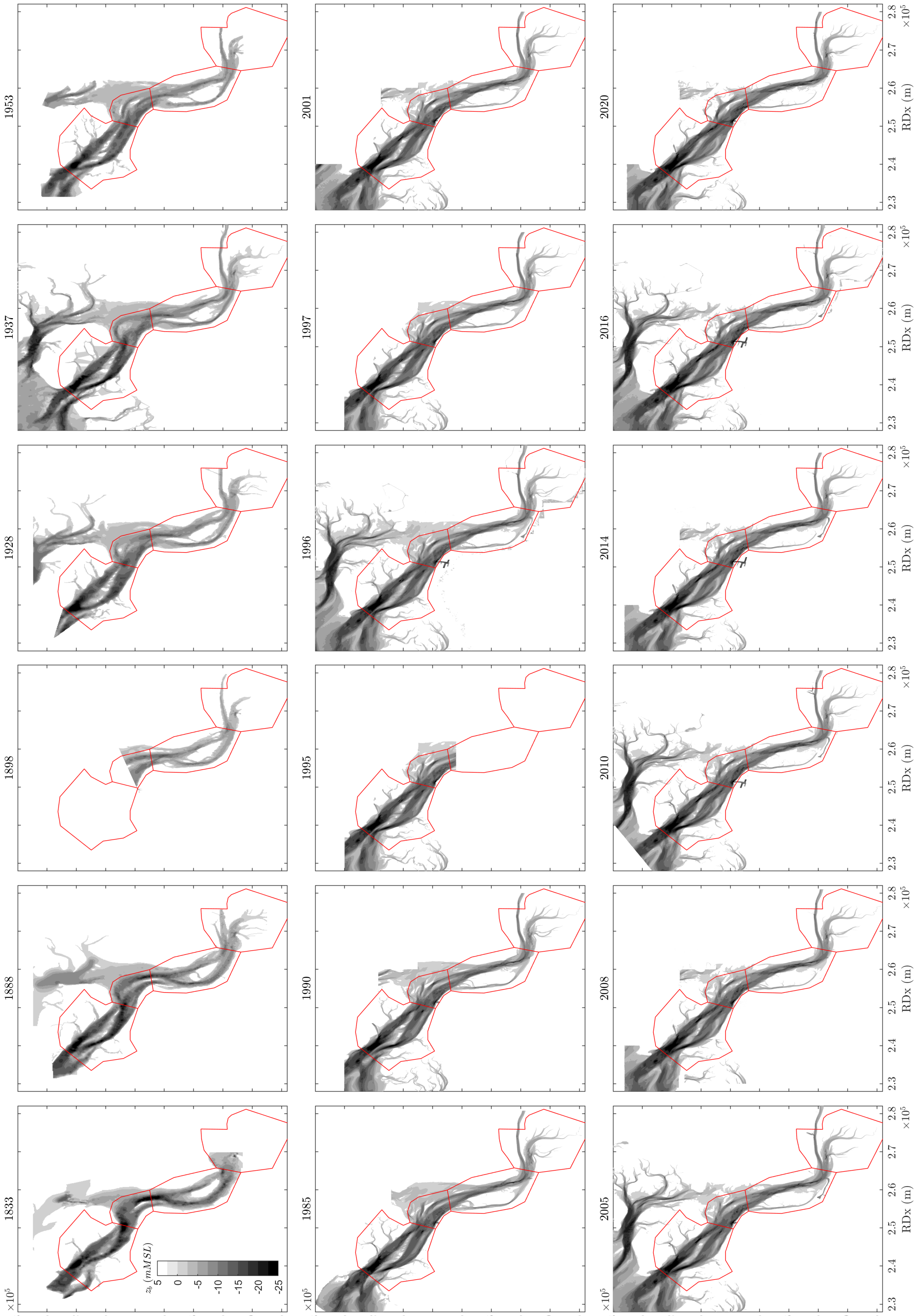


Figure S5. Subtidal bathymetries derived from the historical reconstructions.

Wageningen University & Research
Droevendaalsesteeg 3
6708 PB, Wageningen
The Netherlands
reinier.schrijvershof@wur.nl

April 13, 2024

Dr. K.K. Caylor
Editor-in-chief
Earth's Future

Dear Dr. K.K. Caylor

I am pleased to submit a research article entitled '**Land Reclamation Controls on Multi-Centennial Estuarine Evolution**' by Reinier Schrijvershof, Bas van Maren, Mick van der Wegen, and Ton Hoitink. Intertidal areas are wetlands that alternate between being flooded by tides and a state of exposure. The submitted manuscript reports a study that investigates the impact of reclaiming intertidal areas on estuarine landscape development. Relatively little is known about land reclamation effects on estuary evolution, because observations taken in recent history display the effect of multiple natural and human-induced controls. Human-forced changes in intertidal areas potentially impact coastal evolution for centuries, and few studies have addressed this multi-centennial evolution.

We address this knowledge gap by focusing on the reclamation of intertidal embayments along the Ems estuary, which were mostly formed during storm surges in the 16th century. We use historical maps to build an open access digital dataset that covers the complete adaptation period since that time, and show that the present-day morphology is still adapting to the large-scale and continued land reclamation works over the past centuries.

We believe the manuscript is of interest to readers in the journal *Earth's Future*, because it emphasizes that future morphological developments of our coastal systems (estuaries and tidal basins) will still inherit the lagged effects of Medieval land reclamations. This bears relevance for coastal management, because additional interventions will cumulatively impact estuarine systems that are still adapting to past interventions.

The manuscript is original and is not under consideration for publication elsewhere. Furthermore, there are no conflicts of interest to disclose. If the manuscript is considered appropriate for the journal, we suggest the following reviewers:

Dr. Zeng Zhou (zeng.zhou@hhu.edu.cn)

Dr. Leicheng Guo (lcguo@sklec.ecnu.edu.cn)

Dr. Chris Paolo (cpaola@umn.edu)

Dr. Alvise Finotello (alvise.finotello@unipd.it)

Thank you for considering our manuscript for publication in Earth's Future.

Sincerely,

R.A. Schrijvershof, MSc.