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

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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 12$^{\text{th}}$ and 13$^{\text{th}}$ 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 16$^{\text{th}}$ 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 15$^{\text{th}}$ 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 15$^{\text{th}}$ 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 19$^{\text{th}}$ 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).

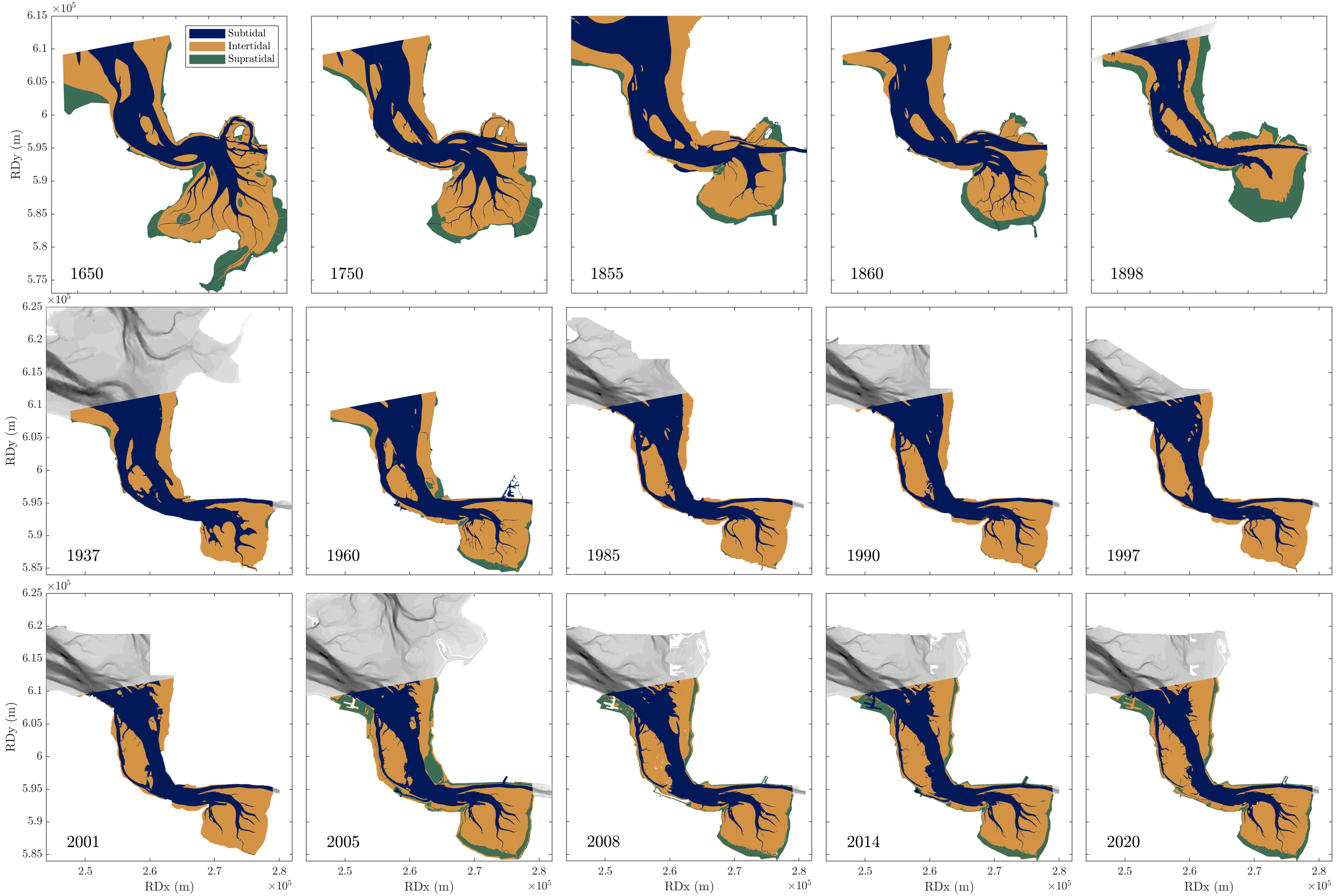

Figure S4. Tidal zones (subtidal, intertidal, supratidal) derived from the morphological reconstructions.

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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

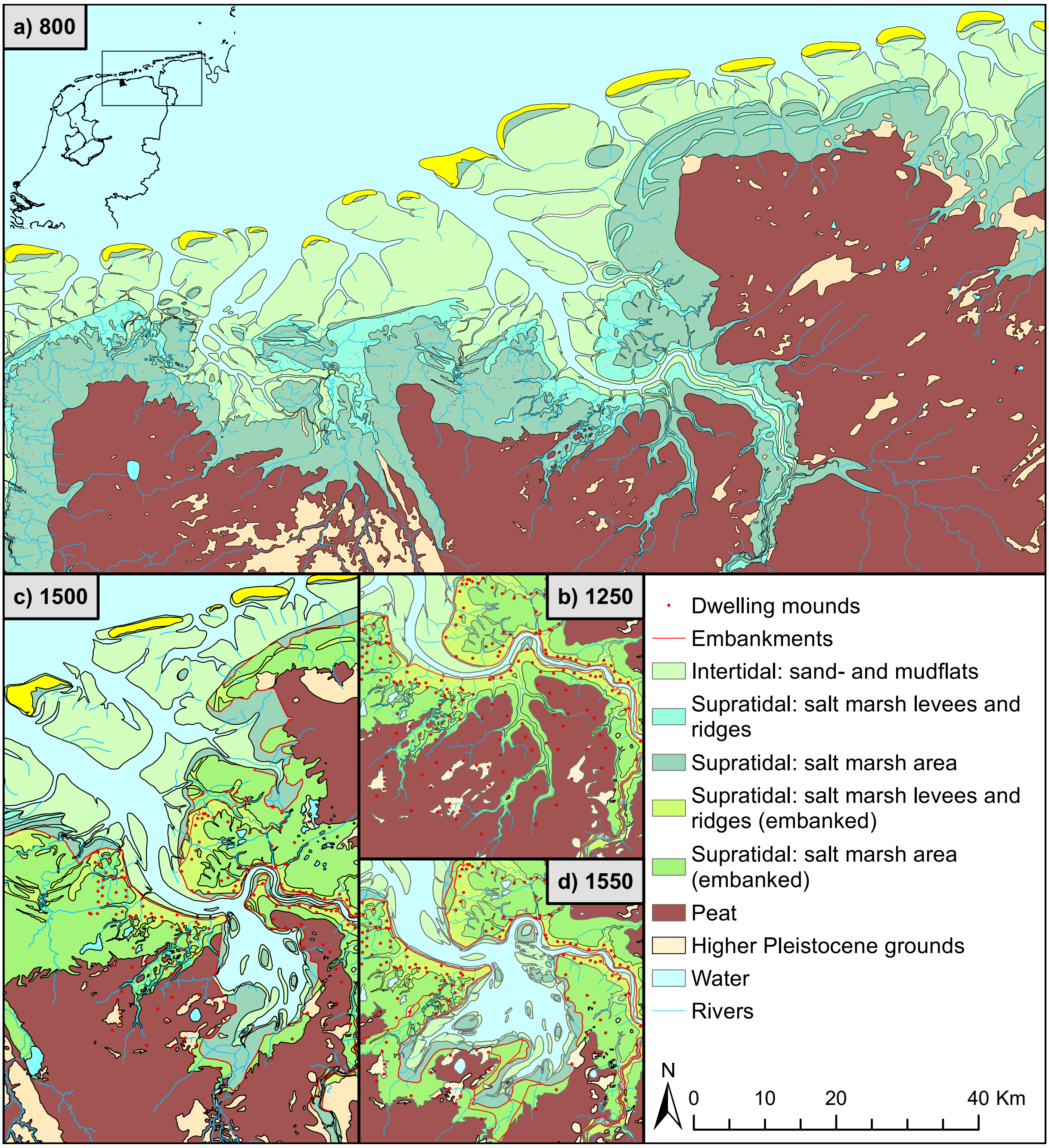

Figure S1. Palaeogeographic maps showing (a) the situation of the northeast Netherlands and northwest Germany around 800 A.D., and the situation for the Ems estuary around 1250 A.D. (b), 1500 A.D. (c), and 1550 A.D. (d) showing the formation of the storm-surge formed Ley bay and Dollard bay. Figure is 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."*

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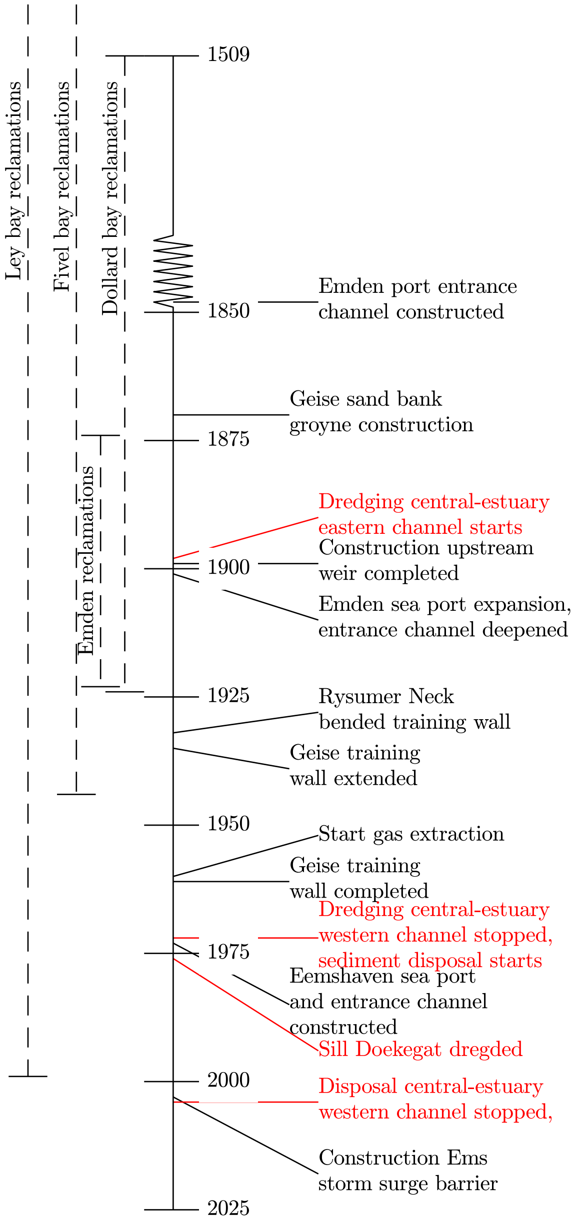

Figure S3. Time line of land reclamations, and most important dredging, disposal, and hydraulic re-alignment works in the Ems estuary.

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)

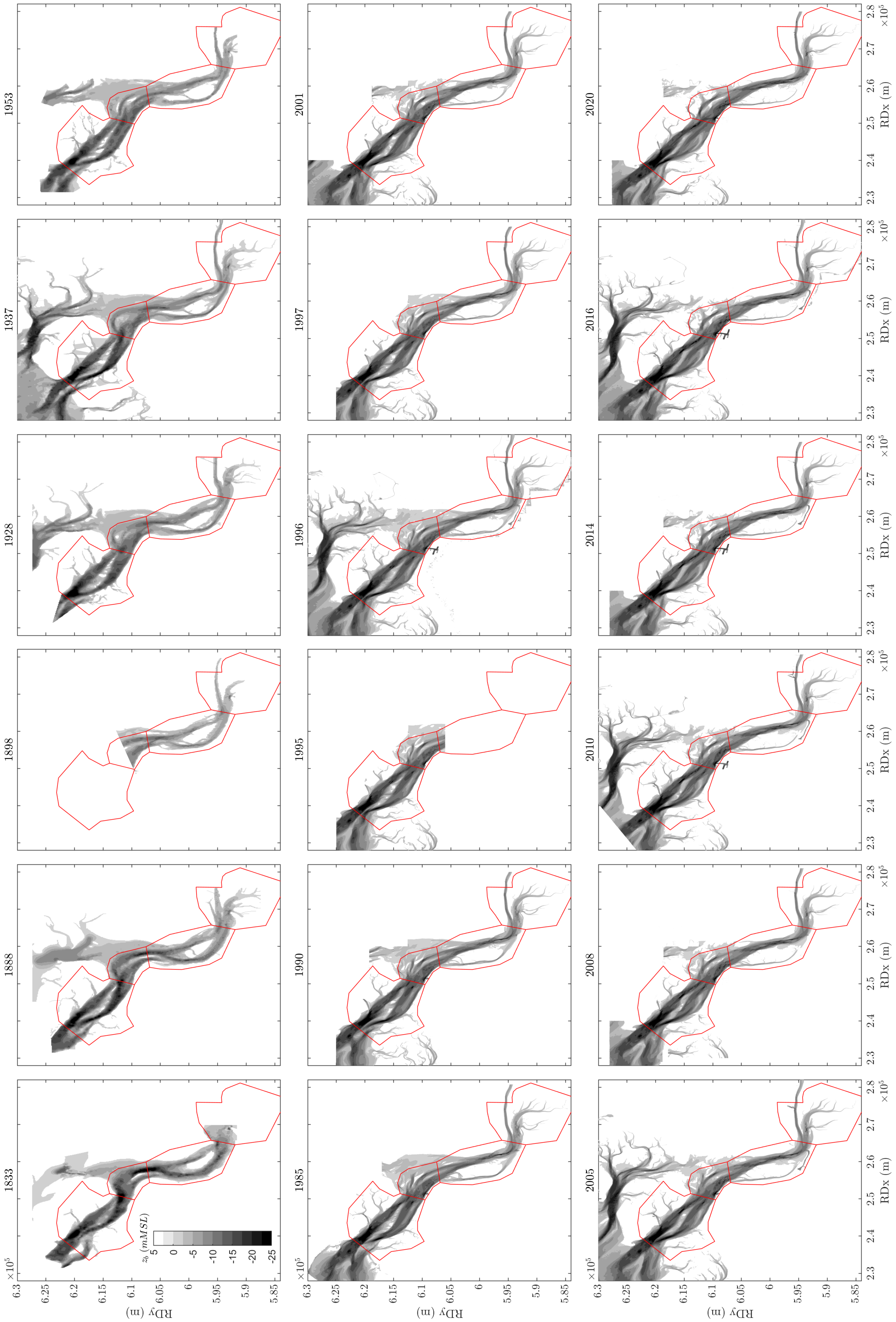

Figure S5. Subtidal bathymetries derived from the historical reconstructions.