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Sediment deficit and morphological change of the Rhine–Meuse river mouth attributed to multi-millennial anthropogenic impacts

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ABSTRACT

Many delta systems worldwide are becoming increasingly urbanized following a variety of processes, including land reclamation, embanking, major engineering and port constructions, dredging and more. Here, we trace the development of one system, the Rhine–Meuse delta in the Netherlands (RMD) from two natural estuaries (the RME fed by the Rhine river and the HVL fed by the Meuse river) to a densely urbanized delta and the effect human activities have had on its morphology through time. Estuary outlines determined from palaeogeographical and old maps and tidal range at the estuary mouth were used to reconstruct basic estuary parameters. Depth distribution was predicted with a morphological tool. We have determined that the northern estuary, where port activities dominate, shows a stepwise deepening due to dredging for navigation. The southern port shows stepwise shallowing as humans closed off this branch from tidal action. Both estuaries show narrowing and loss of intertidal width over the past five centuries. The total loss of water volume has been -5.5 $m^3 \times 10^9$ since 1500 AD coinciding with major human intervention in the system, driven by the rapid economic boom during the mid 16th century. This has led to a reduction of intertidal areas and floodplains and long-term sediment shortage resulting in a myriad of problems, including increased flood risk, threats to bank protection and infrastructure and loss of nature areas. These problems will be exacerbated in coming centuries by predicted sea-level rise. Other urban deltas, unrestricted by engineering and dredging innovations which took place more gradually in earlier centuries, are now undergoing rapid changes in mere decades, changes which took hundreds of years in the RMD. Future predictions indicate that by 2050 the RMD will experience the highest loss of sediment in the 3500 year history of the system, despite these changes only occurring vertically (deepening) and not laterally (narrowing or embanking). This shows an urgent need to reconsider sediment management and spatial planning of port expansion in urbanized systems and the fate of such systems under climate change and rising sea-levels.

1. Introduction

Humans interact with river deltas in several ways to influence their development. In particular, many deltas are becoming heavily urbanized (Loucks, 2019) i.e. their surrounding plains are converted and developed for cities, ports and industry, meanwhile, they are also home to extensive populations resulting in significant altering of the natural functioning of the delta. The rate and extent of urbanization in deltas varied, with interventions ranging in scale, both temporal and spatial, but the overall long-term impact is to set up a new type of river delta: the urban delta. The Rhine–Meuse delta in the Netherlands has uniquely recorded human interventions in the delta area since the Roman period (Vos, 2015; Pierik et al., 2018). It is also commonly identified as the prime example of a new urban delta equilibrium or "end-state" for other deltas, an example often followed by deltas which are rapidly urbanizing e.g. the Yangtze and Pearl deltas. In this study, we aim to use the Rhine–Meuse as a case study to indicate how human interventions can influence the delta landscape and set up a new urban delta equilibrium, and identify how these rates of change compare with other modern global delta systems. This research assesses the interactions between human activities and natural estuarine landscapes, to indicate how their rates of change compare with natural changes and how major anthropogenic processes can determine

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estuary development in terms of shape, width and sediment budget. For the first time, estuary depth and shape can be reconstructed at a multi-millennial time scale, a study which can be extended to other similar systems, to identify how hydrodynamics and morphology have developed, and indicate future effects of large-scale engineering or other human interventions on estuarine and delta morphology.

The Rhine and Meuse rivers have shaped the landscape of the Netherlands since their formation millions of years ago (Erkens, 2009; Hijma et al., 2009). The Holocene Rhine and Meuse rivers have formed two large estuaries on the Dutch coast which have been used for navigation, trade and have driven urban and economic development of the Netherlands. The study area is outlined in Fig. 1 and both estuaries together will henceforth be called the Rhine–Meuse Delta (RMD). The two estuaries are the Rhine estuary to the north (henceforth RME) and the Meuse estuary in the south (henceforth HVL, named for the previously open estuary boundary, the Haringvliet). Initially, both estuaries were formed through a combination of natural processes including sea-level rise (SLR), deposition of sediment and peat and the interaction of rivers, waves and tides (Erkens, 2009; Hijma et al., 2009). However, as early as Roman times, the estuaries became affected by human interference through land reclamation, deforestation and changing depth of channels for navigation (Berendsen and Stouthamer, 2002; Pierik et al., 2018), altering the landscape radically.

Natural estuaries may form in a converging funnel shape (Savenije, 2015; Dronkers, 2017), often forming multichannel systems with several intertidal areas both within their channels (shoals and bars) and adjacent to their channels (marshes, mudflats etc.), which are highly dynamic (Leuven et al., 2018a, 2019). Increasingly however, as systems become more urbanized, they tend towards narrower single channel systems, with fixed banks, deep channels for navigation and less intertidal area due to embanking and reclamation (Monge-Ganuzas et al., 2013; van Dijk et al., 2021). This trend is experienced by many estuaries globally, largely driven by port development and economic growth as outlined in Cox et al. (2021a). The RMD is unique as it has an excellent record of both human interventions through time and data concerning the rivers and estuaries. Here we analyse the RMD to derive insights which apply to other systems globally that are trending towards rapid urbanization e.g. the Pearl and Yangtze in SE Asia.

Natural systems tend to import high volumes of sand, if available, building complex patterns of shoals and channels, where channels migrate rapidly and change their course and depth in response to changing conditions (Jeuken and Wang, 2010; van Dijk et al., 2021). Urban systems are now commonly losing sediment annually due to dredging of fine sediment (upstream sand is removed by mining or trapped by upstream dams) which was trapped in deep navigation channels (van Maren et al., 2015; Frings et al., 2019; Bendixen et al., 2019; Nienhuis et al., 2020).

The RMD currently has a negative sediment budget: it loses 2 Mt annually from its area (Cox et al., 2021b) and is predicted to lose much more sediment in the future if the current management practices continue (Cox et al., 2021a). But how did the sediment budget become negative? What developments in the estuary led to the current shape and sediment transport patterns? Have recent interventions been more severe than past interventions in changing the RMD? These questions will be assessed by creating a long-term sediment budget of the RMD area.

Human settlement causes a variety of changes to estuaries. Firstly, the reclamation of land through poldering and embanking to accommodate the development of urban centres removing river floodplains, shoals, islands and in general decreasing estuary width. This is particularly the case in the Netherlands as embankments, dikes and land reclamation dominate the RMD as “dredge, drain, reclaim” is a motto of the Dutch (van Veen, 1962). Secondly, the growing navigation and trade associated with human settlements, require the control of estuary depth to accommodate the increased size of ships, which leads to dredging of channels. The control of water for freshwater supply, flood control and navigation are also achieved through major hydraulic constructions (dams, groynes, barriers, canals). The importance of these different causes of changing estuary shape through time needs to be assessed.

The RMD has an excellent record of such human interventions through time, with maps and government documents dating back to the 16th century and written records since 800AD. This allows for clear construction of timelines of major human activities, allowing us to link these changes with estuary development with high confidence. It provides us not only with a reconstruction of how the RMD has changed in terms of both hydrodynamics and morphodynamics, but also can provide a blueprint and predicted pattern of change for other global estuaries which are currently undergoing the same rapid alterations.

We make use of palaeogeographical and old maps with a bathymetry estimation tool (hereafter “hypsometry tool”) that predicts sub-aqueous morphology from estuary outline and boundary conditions to trace back the influence of human interventions on the dimensions and shape of the RMD, focusing on changes to estuary width, depth, volume and intertidal area and compare the current rate of change with the past to identify how the RMD became so sediment starved. We also compare this rate of change with other major systems worldwide.

2. Study area: known development of the Rhine-Meuse estuary

The river courses and estuary positions have changed several times in recent millennia in the dynamic Rhine–Meuse delta under decelerating sea-level rise. Whilst human habitation has been present in the study area during most the Holocene, it only started affecting estuary evolution significantly from the Roman period onwards (Moree et al., 2018; Pierik, 2021). Here we present the major activities that prior to and during the timeframe of this sediment budget were relevant in shaping the RME and HVL estuaries. The RME (northern estuary see Fig. 1) was already present during the Middle Holocene, HVL (southern estuary, see Fig. 1) only formed after AD 800. We highlight the major activities which influenced: (1) estuary shape, (2) estuary depth, (3) urban or port development and thus dredging in the area, (4) hydrodynamics, including flow distribution and flow velocities. The development is divided into 4 sections: (A) Geological history, (B) Early Human Influences, (C) City and Port Development and (D) Recent Growth. An overview of all the major changes during these periods can be seen in Fig. 3 with accompanying images in Fig. 2. Lastly, we discuss the rise of mechanic dredging and growth of ships and the influence on the RMD.

2.1. Geological history, early human influences, city and port development and recent growth

A full and detailed overview of the history of the RMD can be found in the Supplementary text and accompanying tables. Here, we summarize this detailed history. In the beginning of the Holocene (around 9500 BC), most of the study area was positioned in the Rhine–Meuse valley, a ~30 km wide valley, sloping from 15 m in the east to 20 m in the western part of the study area (Hijma et al., 2009; Hijma and Cohen, 2011). Around 6500 BC, sea-level was still around -18 m below its current level (Hijma and Cohen, 2019), but the coastline already reached its current position. As a result, the westernmost part of the study area started to transform into a freshwater tidal landscape. Around 5400 BC, the Rhine river shifted north, forming a new estuary outside the study area (see Fig. 2a), leaving the Meuse as the only large river in the study area for several millennia (Stouthamer and Berendsen, 2001; Cohen et al., 2012). The tidal range at the mouth stabilized (around 5000 BC van der Molen and De Swart (2001) and Hijma and Cohen (2010)) and the coastline closed and this meant sedimentation started to keep up with decelerating sea-level rise (Beets et al., 1992; Hijma and Cohen, 2011).

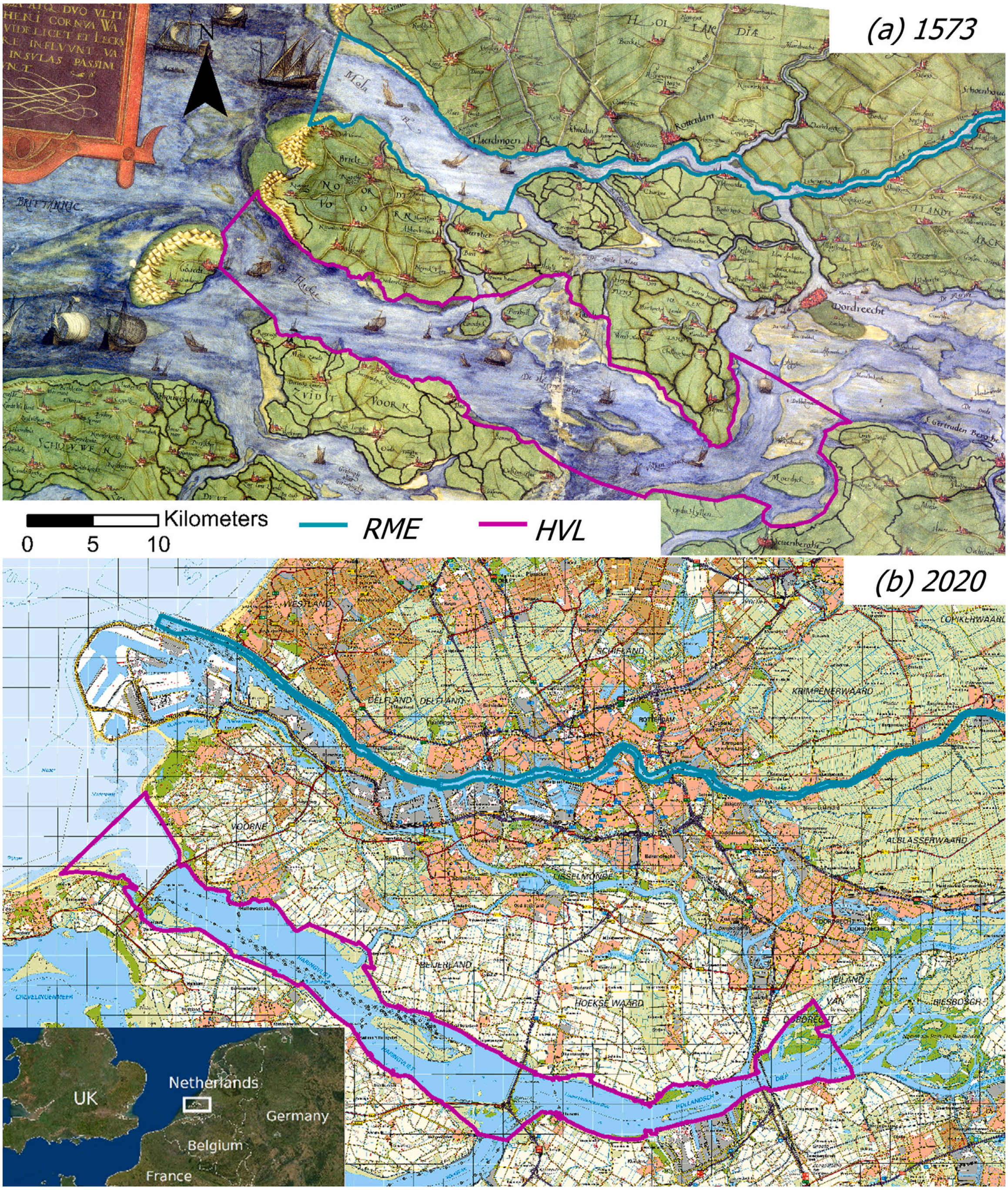

Fig. 1. The RMD in (a) 1573 (b) 2020 where the northern estuary (RME) is marked in blue and the southern estuary (HVL) is marked in purple. Map (a) was supplied by the Utrecht University Map Library. Map (b) is the Top 250 map for the Netherlands with an inset of the location of the RMD in western Europe. Full details of these maps can be found in the Supplementary Material.

Around 1500 BC the RME estuary was positioned in coastal peatlands and obtained a nearly funnel-shaped planform (see maps in Supplementary Material). It predominantly received discharge from the river Meuse (Cohen et al., 2012; Vos et al., 2020). Compared to earlier periods, the geomorphological setting and boundary conditions were much more stable and we therefore start our analysis for the Meuse estuary (RME) at this timestep. Around 250 BC, the estuary expanded creating intertidal areas in former peat areas and forming the Gantel branch (see maps in Supplementary Material), Vos et al. (2017), also evidence of major flooding events were found from that period (Vos and Eijskoot, 2015). This is linked to the upstream avulsion of several Rhine branches, that increased total discharge of the RME estuary (Vos et al., 2017; Pierik et al., 2018).

The arrival of the Romans in the RME region around 12 BC stimulated the beginning of extensive human habitation (Nienhuis, 2008). The number of settlements around the estuary strongly increased (van Dinter, 2013), reclamation infrastructures were built (Ter Brugge et al., 2002; de Kort and Raczynski-Henk, 2014). Meanwhile, avulsions (Hollandse IJssel, Lek and Waal respectively - Cohen et al. (2012), Pierik et al. (2018)) gradually routed more water from the river Rhine to the current RME estuary. As a result, the northern Old Rhine branch had become very small by 700 AD (van Dinter et al., 2017; de Haas et al., 2019) and the RME estuary received nearly all river Rhine discharge.

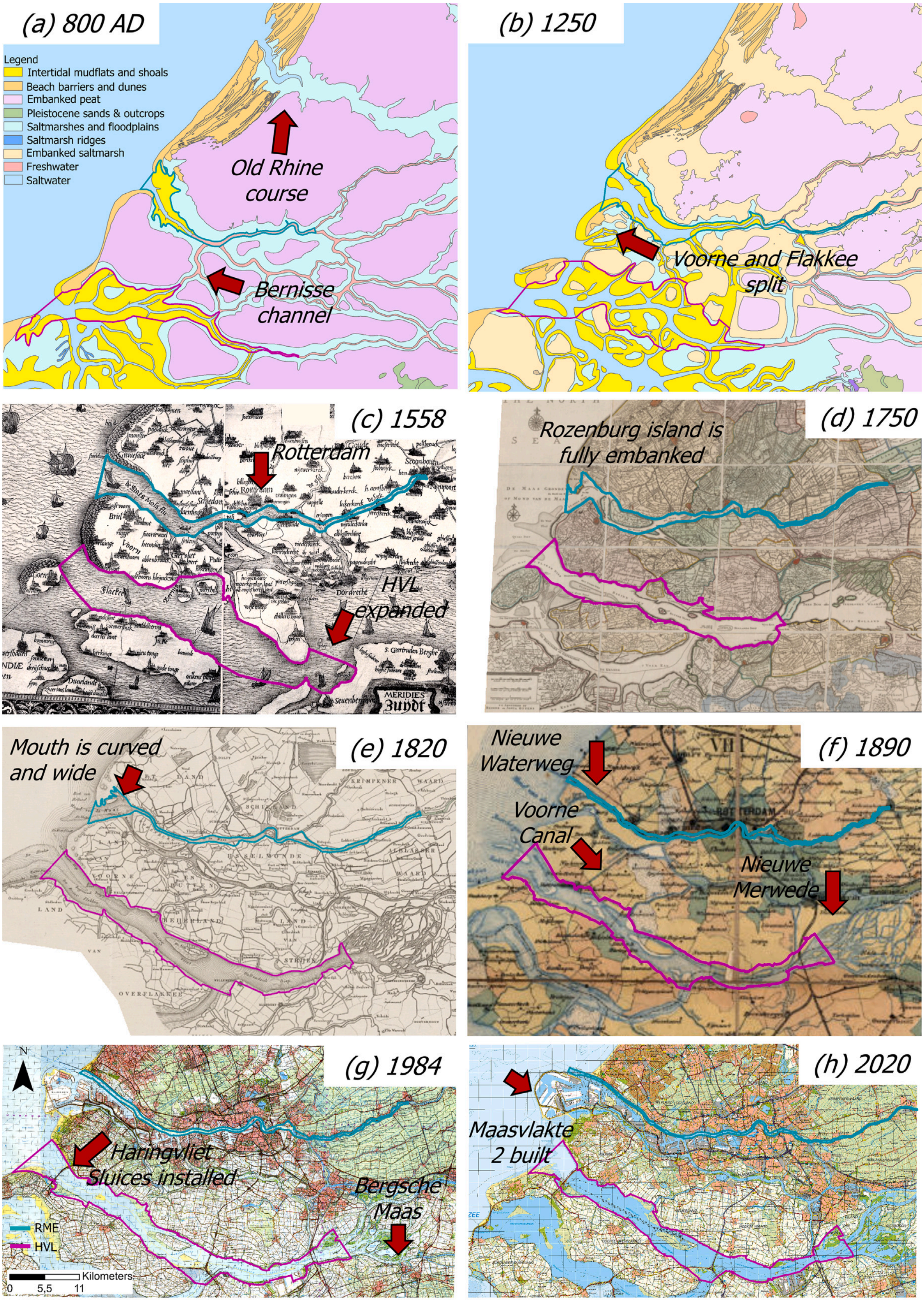

Fig. 2. The RMD in (a) 800 AD (b) 1250, (c) 1558, (d) 1750, (e) 1820, (f) 1890, (e) 1984, (f) 2020. Maps a–b modified from Vos et al. (2020), maps (c–e, g) from Utrecht University Map Library, map (f) from Topo NL, and map (i) from Top 250 (PDOK, 2021).

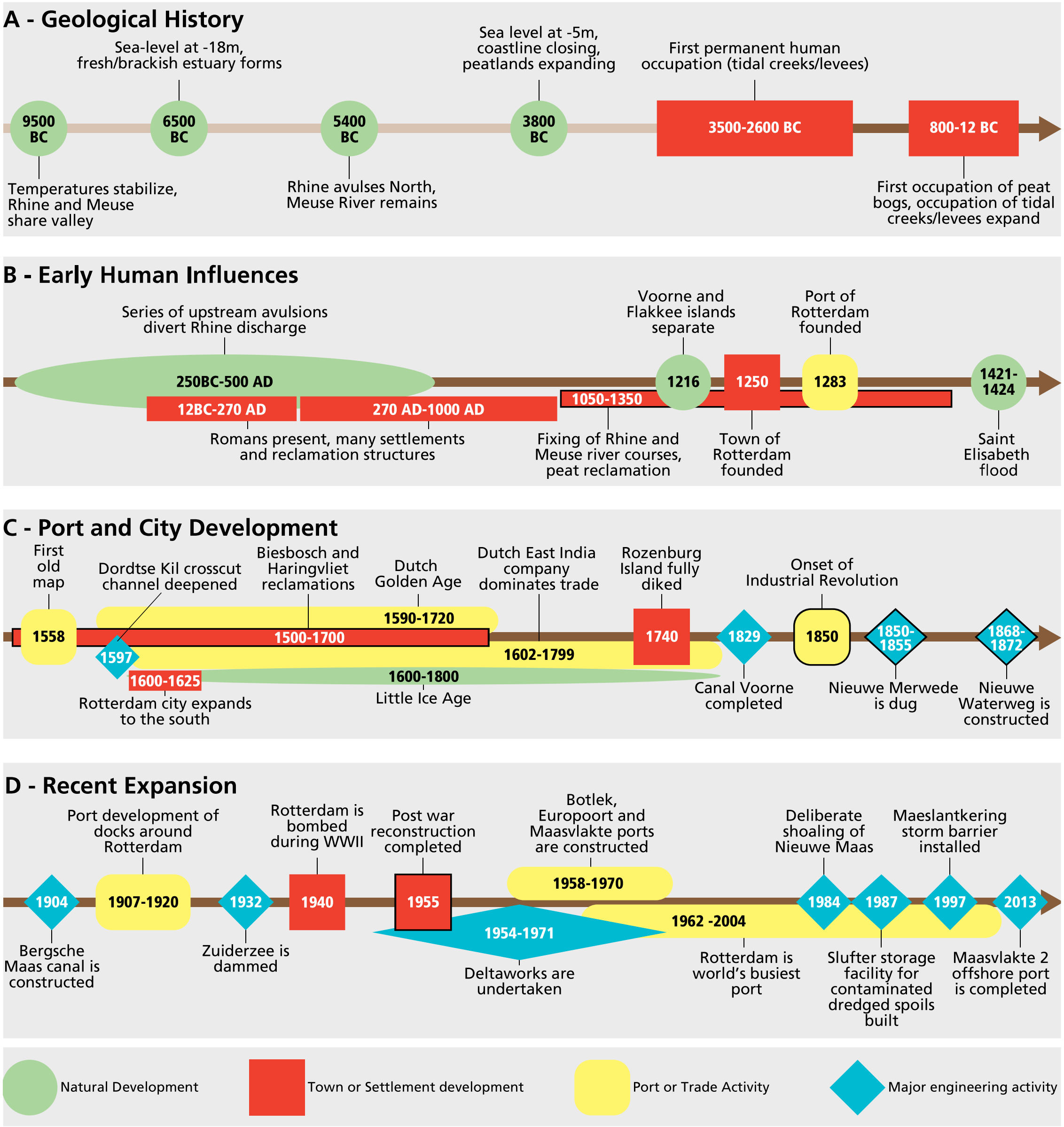

Fig. 3. Timelines of major events that occurred in the 4 periods of the budget: (A) Geological History, (B) Early Human Influence, (C) Port and City Development and (D) Recent Expansion, where colour and shape indicates the type of activity. Activities on the light brown line in part A are prior to the sediment budget but provide important geological context.

In terms of the southern estuary, the HVL, a very small tidal inlet already existed in Roman times (Vos and David Zeiler, 2008). It was located in a wide peatland and had not yet become connected to the Rhine and Meuse rivers. This inlet expanded gradually, and by around 800 AD, it became connected (see Fig. 2a) to the RME estuary (Vos, 2015; Pierik et al., 2017). By 800 AD, the HVL estuary received river discharge and this is the start point for our analysis of the HVL.

From 1050–1350, large scale reclamation and embankment in the area started. The courses of the rivers Rhine and Meuse were constrained through embankments, their floodplains were reclaimed, and avulsions could no longer occur (Hesselink et al., 2003). This resulted in an increased sediment transport capacity and increased sedimentation between the dykes, while in the embanked area sedimentation stopped (Hesselink et al., 2003; Middelkoop, 1997). Further embankment was undertaken when imported sediments from the coast had shallowed the channels and tidal flats to a level so new embankment was possible. An important event occurred in 1216, when a large storm surge event attacked the coast breaking through the dunes and dividing the land mass of Voorne and Flakee forming the current path for the Haringvliet and Hollands Diep channels (Elias et al., 2017; van der Spek and Elias, 2021).

Urban development started in the 13th century when the Rotterdam city and harbours were founded (van de Ven, 2003; Abrahamse et al., 2016; Moree et al., 2018). A series of modest floods, the Saint Elisabeth floods, caused several periodic inundations (1421–1424) that led to formation of the Biesbosch intertidal freshwater wetlands (Zonneveld, 1960; Gottschalk, 1971; Kleinhans et al., 2010). This flood had major subsequent effects for channel patterns and discharge distribution in the lower RMD (see Nieuwe Merwede in Supplementary Material tables). Following the large-scale redistribution of Rhine discharge from a northern branch to the Merwede (de Haas et al., 2019), a large portion of the combined Rhine–Meuse discharge was from then on routed via the expanded HVL (see Fig. 2c). The flooding immediately caused this area to become an expanse of water that was re-embanked in several phases in the following centuries.

Starting in the mid 16th century, the first accurate maps of the study area began to appear, coinciding with the Dutch Golden Age during which exploration and seafaring became synonymous with the Netherlands. This led to several expansions of Rotterdam city and port (Rutte and Abrahamse, 2016) including: the fixing of several river banks at Rotterdam city and further west, the development of many polders and clearing the river bed for shipping using new dredging technology (Krabbelaars or scratchers) which operated on wind power to remove sandbanks (van Veen, 1962). In the 16th century several mid channel bars were embanked (e.g. Rozenburg - Moree et al. (2018)), also a large spit evolved at the entrance of the estuary (van Staalduinen, 1979; van der Spek and Elias, 2021) and nautical charts indicate silting up since the 16th century (Hofland, 1986a,b). This period also saw digging of several canals including Voorne (significantly shortening the distance from Rotterdam to the sea), the Nieuwe Merwede (which decreased flow in the Waal), and the most famous, the Nieuwe Waterweg (the current route to the network of the Port of Rotterdam).

The 20th and early 21st century have been characterized by several major engineering works, which altered the hydrodynamics and consequently the morphology of the study area. This coincides with rapid urbanization since the industrial revolution, including transforming the estuary to an industrial harbour at an unprecedented scale. The Dutch Deltaworks were undertaken: a series of large-scale engineering projects to protect the region from floods. In the RMD, this meant 3 important constructions by the during the 1950s-1970s: (1) the Haringvlietsluis was installed, blocking the southern estuary (HVL) from any tidal influence and controlling discharge, (2) a flood barrier was installed on the Hollandse IJssel controlling the discharge of this branch entering the northern estuary (RME) and (3) the Volkerak dam was installed, allowing separation of the discharge of the southern estuary (HVL) from the Eastern Scheldt estuary which lies to the south of the study area.

Following a rapid post war reconstruction, Rotterdam became the world's busiest port in 1962 and held this title until 2004, when it was overtaken by Singapore and later Shanghai (on the Yangtze river). By 1997, the last of the Deltaworks was completed in the RMD: the installation of the Maeslantkering, a storm surge barrier in the northern estuary (RME) which could be closed under storm conditions. By 2013, to accommodate the growing ships, a large offshore port, the Maasvlakte 2 was built using sand from the North Sea and changed the circulation of water and sediment in the estuary mouth, also providing a boost to port traffic.

2.2. The rise of mechanic dredging and growth of ships

In the earliest centuries, it is difficult to identify detailed information about dredging (locations, methods, volumes etc.) and in particular, which methods were applied to which parts of the RMD. However, several technologies were developed in the Netherlands and would have been available to undertake dredging, which we outline below.

Before 1500, dredging in the rivers and ports was done solely by hand, using old nets by either removing small amounts of sand or mud, or by agitating the bed and allowing sediment to be removed by the tides. Dredging in the RME and HVL between 1500 and 1900 was limited by the available technology. The first Dutch dredger was the Zeeuwse Krabbelaar, a type of scraper or "hedgehog" dredger (see Fig. 4). It was a ship which had a bed leveller, that was capable of maintaining ports at a given depth by removing sandbanks and shoals.

By the 16th century, dredging machines such as mills and dredgers specifically made for mud began to be patented in the Netherlands. These mud mills were run by either horses or manpower and they were mostly built in Amsterdam and shipped throughout Europe, but these mud mills were not suitable for sea dredging which was needed at Rotterdam (van Veen, 1962). Dredging changed dramatically in the RMD in 1867 when the first steam bucket dredgers were applied the Netherlands. This type of dredging was fast and decreased the amount of intensive labour required for dredging, also making it considerably cheaper. 15 of these steam dredgers were used to cut the Nieuwe Waterweg in 1872 (van Veen, 1962).

In 1960, the type of modern dredgers in use today known as trailer suction hopper dredgers were developed and first used in the RMD in 1962. Since the 1950s, global container ship size (see Fig. 4) has controlled the required dredging depth and volumes in both estuaries, and consequently larger and more efficient dredging boats have been developed which can remove all types of sediment.

3. Material and methods

3.1. Hypsometry tool for equilibrium morphology of estuaries

To assess the change of sediment volume through time, estimates of historic bathymetries must be calculated and compared. Such data is not available on long-term geological and historic timescales, so here we employ relations between estuary planform shape (Leuven et al., 2018b), which is available on maps, and boundary conditions, which are reasonably well known for the RMD (de Haas et al., 2019) to reconstruct morphology for the past. We reconstructed former estuarine morphology with a hypsometry tool that estimates morphology based on the along-estuary width profile, tidal range at the seaward mouth of the estuary and river discharge. This hypsometry tool has previously been applied to estimate the effects of SLR for 36 estuaries globally (Leuven et al., 2019). A full overview of how the hypsometry tool works can be found in Leuven et al. (2018b).

The hypsometry tool calculates hypsometry (elevation and depth) using empirical relationships for estuary morphology, which assume that the morphology is in equilibrium with the hydrodynamics, and sufficient sediment is available to reach that equilibrium. The relations in the hypsometry tool were based on tidal and morphological principles and have been calibrated and validated on data of other estuaries (Leuven et al., 2018b). The hypsometry tool is applied in this study to palaeogeographical and old maps of the Netherlands to determine estuary morphology through time. The hypsometry tool is an open source Python tool, which uses Excel inputs for each given timestep allowing input of specific conditions for each timestep.

The hypsometry tool estimates the tidal prism at the mouth based on surface area and tidal range. The tidal prism is used to estimate the maximum and average depth at the mouth from a classic stability relation (Jarrett, 1976; Eysink, 1991; Gisen and Savenije, 2015). Similarly, a hydraulic geometry relation is applied at the landward boundary to obtain depth from river discharge. Together, these boundary conditions result in a maximum depth profile along the channel. This simplified approach to estimating tidal prism neglects the amplification and damping of the tide as well as changes in the character of wave (standing versus propagating character). This means that for damping tidal conditions we might overestimate the tidal prism, while for amplifying conditions we might underestimate the tidal prism by 10%–40%. However, this simplification has a limited effect on the results in this study. If we overestimate tidal prism, it also means that we overestimate depth.

To assess the uncertainty arising from mispredictions in tidal prisms, the predicted depths at the mouth were compared with geological cross-sections that show the base of the channel belt (i.e. the maximal depth at some point in time). Historic maps are more accurate, because they incorporate measurements at the estuary mouth. Therefore, we decided to estimate maximum depth at the mouth for the period before 1820 based on the hypsometry tool output, and use the measured depth at the mouth from 1820 onward (see Supplemental Information and references therein).

As elucidated in Leuven et al. (2018b), the distribution of bed levels per cross-section (the hypsometry) depends on the ratio between the local width and the width as expected from a fitted converging shape (e.g. ideal shape). The hypsometry tool estimates hypsometry to be convex with a wide zone of intertidal area at locations where the

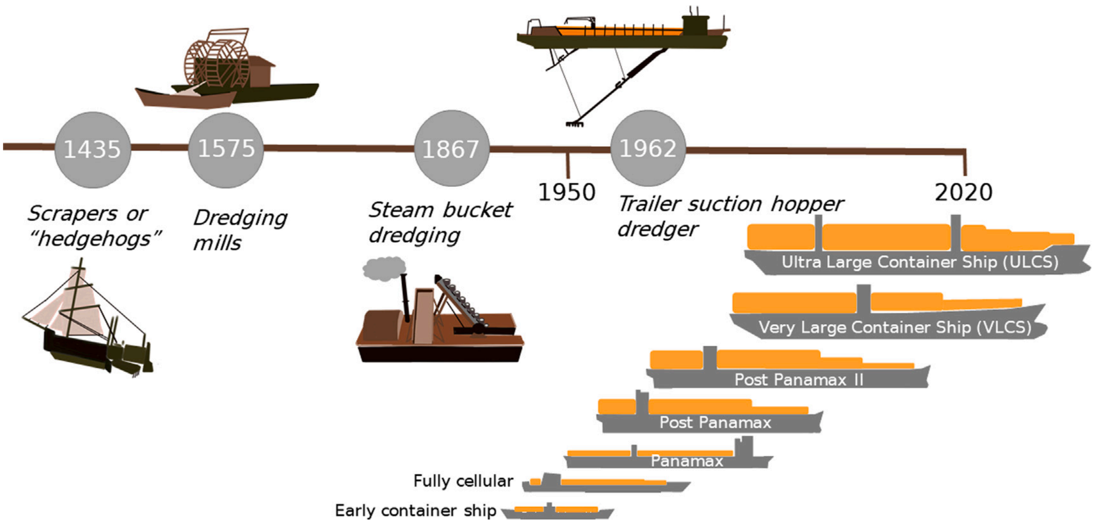

Fig. 4. Timeline of major dredging developments with graphics of how the machinery looked, and change in container ship size over time (which determines the depth required for channels in the RMD).

estuary is wide relative to the fitted convergent channel; however, a more concave hypsometry with narrow stretches of intertidal area is expected at locations where the estuary width is close to the ideal width profile.

There are two crucial inputs: estuary width profiles and tidal amplitude at the mouth. There are also several optional inputs which can improve the outputs of the hypsometry tool including: upstream discharge, depth at the estuary mouth and width of the river at the tidal limit.

3.1.1. Maps

For the hypsometric calculations, estuary extent for various timesteps needed to be established. Thus, a series of maps were used to demarcate these estuary extents through time. Both palaeogeographical reconstructions and old maps were used in this process. The palaeogeographical maps were adjusted from Vos et al. (2020). These maps originally part of the *Atlas van Nederland in Het Holoceen* were developed and subsequently updated using new insights and data, mainly based on detailed observations on archaeological excavation sites. The map series extends back as far as 9000 BC but we begin with the map of 1500 BC, because boundary conditions were relatively stable and the estuary reach a near funnel shaped planform (see section geological setting).

In the 1550s, the first reliable and topographically accurate regional maps began to emerge for the Netherlands. The Utrecht University Library (https://www.uu.nl/en/georeferencing) has made extensive efforts to georeference these types of old maps, and thus hundreds of maps were available to choose from for the period of 1500–1870. Maps were chosen on the basis of: extent (that covered the study area in full), accuracy (in consultation with map experts) and to give a variety of different map makers (to test the validity and sensitivity of the hypsometry tool). Since 1870, the TopoNL maps for the Netherlands were available in ARCGIS online. TopoNL are map sheets for the Netherlands which aim to combine all available open Geodata sources. They are created and maintained by ESRI (2021). For a full overview of more map information, including links to upload these maps to GIS, please see the Supplementary Material.

Combined these three data sources led to a total of 38 timesteps at varying intervals for the analysis. The hypsometry tool was then applied to all maps.

3.1.2. Map accuracy and uncertainty

With regard to old maps, we distinguish three types of accuracy, following from Blakemore et al. (1980):

1. chronometric accuracy, 2. geometric accuracy, 3. topographic accuracy.

The chronometric accuracy can also be referred to as dating accuracy. The question is to what extent the map reflects the situation at the time it was made or was dated by the map maker. Secondly, the geometrical accuracy is about the difference between points on the map and reality. This accuracy concerns the extent to which map elements are depicted true to distance, area and angle. Thirdly and finally, there is topographical accuracy. This can be defined as the quality and quantity of the topographical elements on the map. This involves the selection made by the map maker from the total of elements in the terrain. It is clear that topographic accuracy is to a large extent the result of the influence of the mapping target on the quantitative composition of the elements on an old map. The qualitative composition of these elements, determined by the mapping goal, is also strongly related to chronometric and geometric accuracy. The purpose of the old map therefore has a major influence on all three aspects of accuracy, which are therefore interrelated.

All three types of accuracy are estimated in the Supplemental information. For our purposes, the chronometric accuracy is of minimal importance (as timesteps are mostly 10 years or larger). Topographic accuracy is generally high for the selected maps. Fig. 5 indicates where the estuary outlines used in this study are relative to each other in space. Geometric accuracy is estimated for each map and included in Fig. 8

The palaeogeographical maps are manually drawn, based on geological, geomorphological information, supplemented with dating evidence (e.g. archaeological finds, radiocarbon dates, relative dating) (Vos, 2015; Pierik and Cohen, 2020). The extent of geological units in the substrate (e.g. peat, saltmarsh clays) were generally accurately mapped (geometric accuracy), where they were well-preserved. Following the mapping stage, dating these geological units is a next step to place these elements on the map with the accurate timestep (chronometric accuracy). This is often supported by evidence from well-studied local case studies ('key sites' - Vos (2015)).

For this study, the spatial extent of tidal channels and flats is more relevant than their exact ages. Best preservation of old landscapes is on the northern shore of the Meuse where there is high data density and many old tidal channels of flats often are still visible in the landscape. Reconstructions of the estuary extent in locations which have undergone large scale erosion (e.g. Haringvliet channel) or have undergone large-scale urban development (Rotterdam Harbour) are less accurate due to bad preservation and lower data-densities. Phasing and timing of initial drowning of peatlands (around HVL in 800 AD) have high uncertainty, while final phases of embankment are generally most accurate.

A detailed overview of the map information and an estimation of all three types of accuracy can be found in the Supplementary Material.

3.2. *Crucial inputs*

3.2.1. *Width profiles*

The RMD study area was split into two estuaries following the original two open mouths to the sea: 1. The Rhine-estuary hereafter: RME and 2. The Meuse Estuary hereafter: HVL. The Rhine estuary is taken to be the northern estuary which follows the course of the modern Lek ending at the North Sea at Maassluis. The Meuse estuary is taken to be the southern estuary which follows the course of the Waal and Maas ending in the North Sea at the Haringvlietsluizen (see 2).

The estuary outline was determined manually, creating shapefiles in ARCGIS Pro. The outline includes all intertidal areas e.g. bars, shoals and fringing marshes, mudflats etc. All supratidal areas excluded from analysis where possible to avoid overestimating the width of the intertidal zone (the hypsometry tool predicts intertidal and subtidal area only).

Due to differences in maps, and differences in the estuary course through time the outlines do not always span the exact same length, however efforts were made to correct for this by using the same markers for estuary extent and comparing maps to these modern day markers. In the case of the RME, the dunes along the coast mark the coastal extent, while the city of Schoonhoven marks the upstream extent. The landward boundary marks the end of tidal influence and is the city is also easily identifiable on old maps. In the case of the Haringvliet the crest of Goeree island marks the coastal extent while the junction of the Hollands Diep and the Amer/Nieuwe Merwede rivers east of the city of Klundert marks the upstream extent. This extent was chosen to keep the geometry of the southern estuary simplified and similarly, the city of Klundert is easily identifiable on old maps. In early timesteps, where upstream bifurcations and avulsions are present, we follow the course of the major feeding river (the Meuse or Rhine respectively).

The centreline of each shapefile was then determined using the *Polygon to Centreline* tool. This was manually adjusted for any errors. Then the *Generate Transects Along Line* tool was used to create width profiles at regular intervals (clipped to the estuary extent). These profiles were created every kilometre along the estuary and exported to a .csv for use in the hypsometry tool.

3.2.2. *Tidal range and sea-level rise*

Since 6500 calendar years before present, the tidal amplitude and range at the mouths of the RME and HVL have been approximately constant. Thus, we take the value of 1.5 m for tidal range as given in de Haas et al. (2019), and improved values for 2010 and 2020 using measured data as in Cox et al. (2021b). Since the 1970s, the HVL has been closed to the tides and discharge is regulated, thus the tidal range is decreased to 0.36 m after the construction of the Haringvliet sluices (Cox et al., 2021b).

Over the last 3500 years, sea level rise was 1–2 m (Hijma and Cohen, 2019), with rates below 2 mm/yr. No evidence of major fluctuations have been found. Its effect on coastal morphology is likely negligible compared to human impact (Vos, 2015) and it is not included in this study.

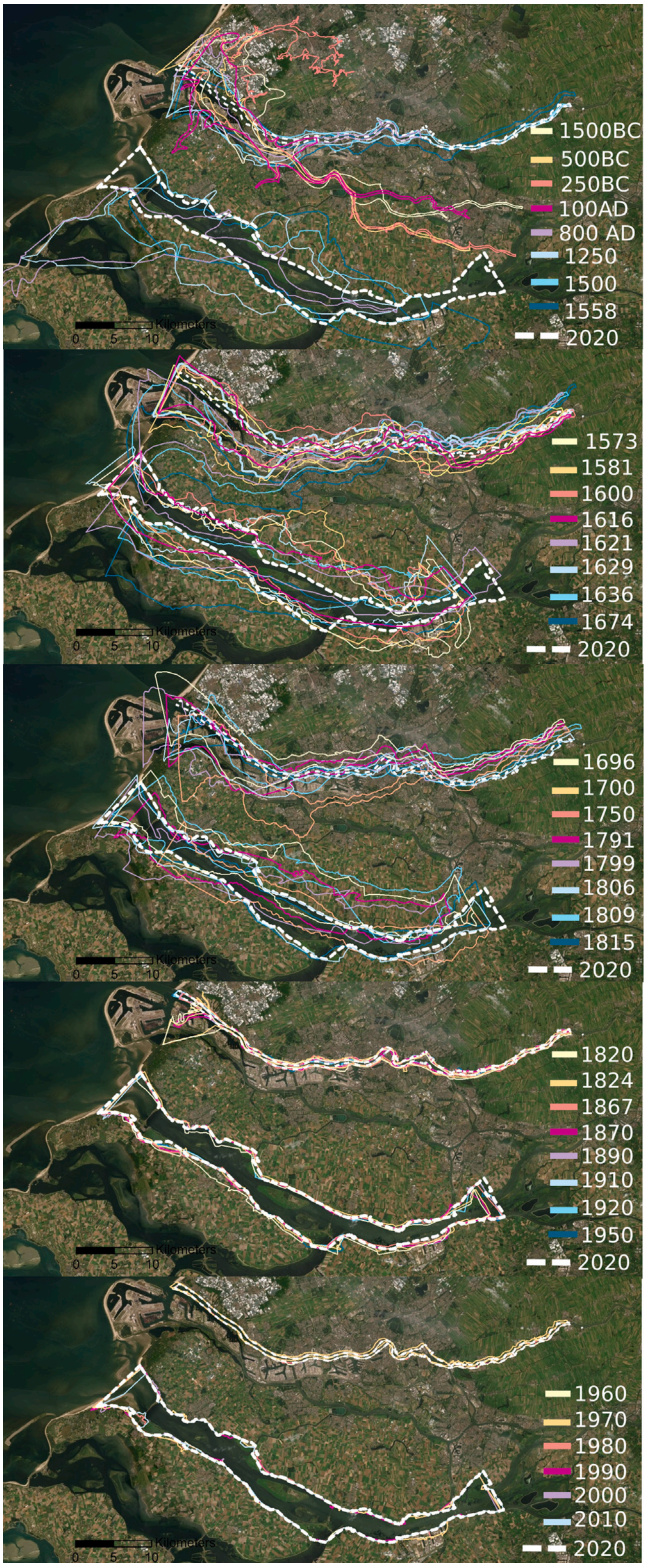

Fig. 5. Indication of evolution of estuary outlines over time, where each estuary is represented.
Source: Background map from ESRI (2021).

3.3. *Optional inputs*

Upstream Discharge: Both estuaries (RME and HVL) have received varying river discharge from both the Meuse and Rhine rivers in the study period. Based on avulsion history (Berendsen and Stouthamer,

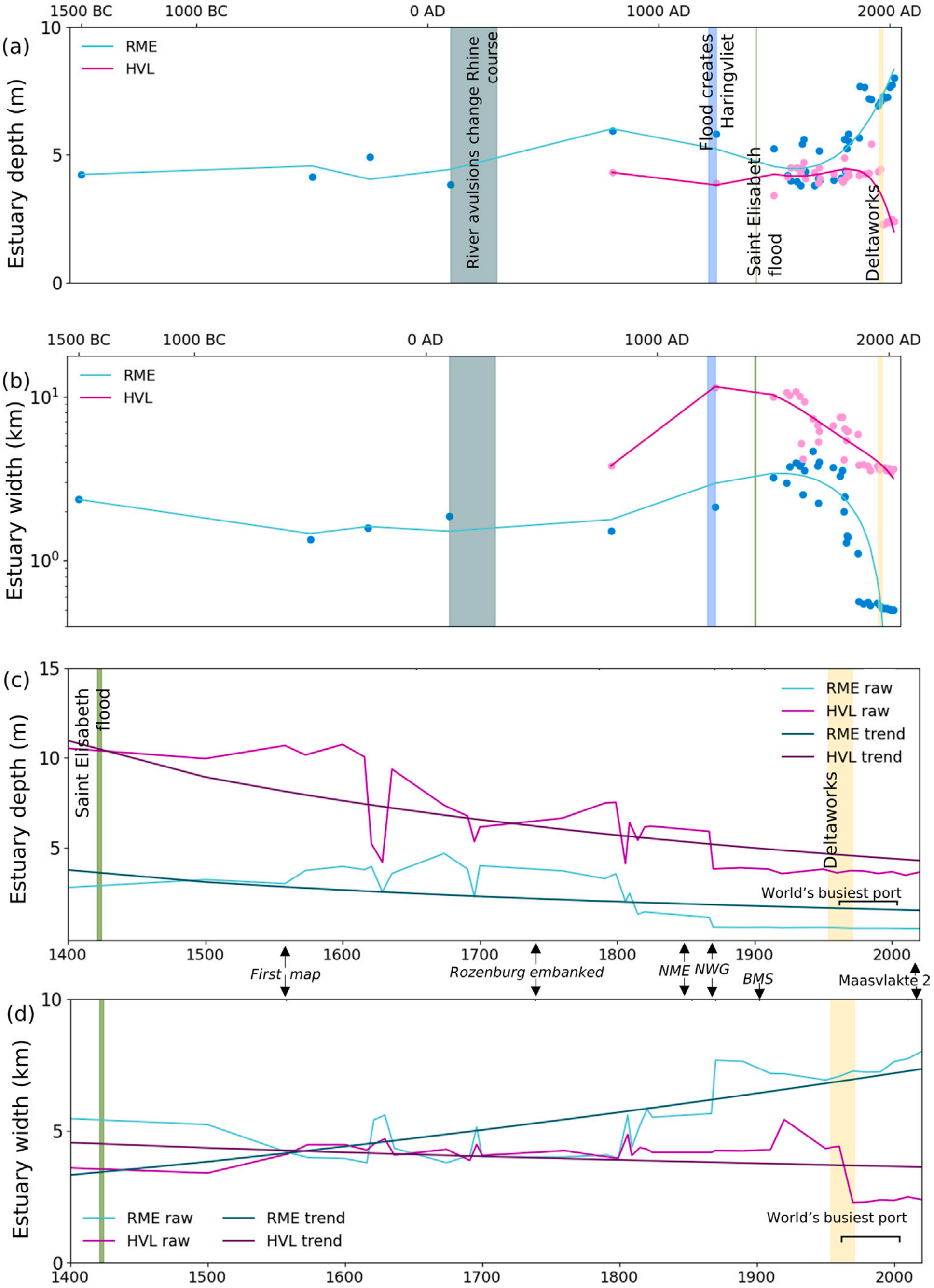

Fig. 6. Average estuary depth and width for the RME and HVL through time, where (a) depth change over total budget, (b) width change over the total budget, (c) depth change since 1400 and (d) width change since 1400. Major events which altered width or depth marked (NWG = Nieuwe Waterweg canal dug, NME = Nieuwe Merwede canal dug, BMS = Bergsche Maas canal dug).

2000; van Dinter et al., 2017; de Haas et al., 2019), we estimated the total discharge for both estuaries in their early phases. We assume that when entering the Netherlands, the Rhine and Meuse had a constant mean annual discharge of ~2000 m^3/s and ~200 m^3/s respectively. Before 250 BC RME received full Meuse and only modest Rhine input (the main path of discharge was through the Old Rhine, north of the study area — see Fig. 2a). Gradually, more Rhine water was routed towards the RME until around 500 AD (the formation of the Waal was last major avulsion). Around 800 AD the HVL formed, taking over some of this combined Rhine and Meuse discharge, the portion of which increased after the Saint Elisabeth flood in the 14th century.

The discharge through the RME and HVL is then assumed to be constant until the 1970s (Haringvliet branch is closed off) after which the measured average discharge of the Lek (RME) and Hollands Diep (HVL) are used from Cox et al. (2021b).

Depth at the mouth: The depths of the estuary mouths are included from the 1860s. Prior to the 1860s, the hypsometry tool auto generates estuary depth at each estuary mouth. For the validation of the channel depth at the mouth for the earliest time periods, geological cross sections are used that show the base of the Meuse channel belt which we identify as the maximum possible channel depth (van Staalduinen, 1979; Koeman et al., 2016; Huismans et al., 2021; TNO-GSN, 2021).

For the RME estuary, the maximum depth at the mouth reconstructed from the hypsometry tool is −7 to −12 m. Absolute maximum channel depth is estimated at −24 m from inland cross sections (Koeman et al., 2016), but with limiting erosion-resistant layers estimates at −18 m (Huismans et al., 2021). However, estimates from van Staalduinen (1979) and TNO-GSN (2021) estimate the depth at the mouth to be closer to −10 to −17 m and −5 to −9 m respectively in the late Medieval period (1250–1500) which is in line with the estimates from the hypsometry tool.

For the HVL, less data is available and so geological reconstructions are limited. However, cross sections at the Haringvlietdam indicate a maximum depth of −20 to −33 m for the late Medieval period (TNO-GSN, 2021). Meanwhile, the hypsometry tool predicts a maximum depth of −10 to −15 m, perhaps shallower than reality.

The presence of erosion-resistant layers which limit vertical erosion are in reality, a major control on depth in the RMD, particularly in the RME estuary (Huismans et al., 2021). However, the hypsometry tool does not account for the possible presence of these layers through time.

For 1860–2000 estimates of depth at the mouth for both the RME and HVL from literature are used (Paalvast, 2014; van de Ven, 2008; van der Spek and Elias, 2021), which are detailed in the Supplementary Material. For the 2000s onwards, the actual measured depth at mouth from multibeam bathymetric surveys are used (Cox et al., 2021b).

Width of the river at the tidal limit: This was determined manually for each timestep for each estuary using the ruler tool in ArcGIS.

3.4. From reconstructed estuary volumes to a sediment budget

We define estuary volume as the total water volume in the estuary under mean sea-level conditions (including all interconnected channels and bars, see estuary outlines in Fig. 5).

Estuary volume change for each estuary was calculated using the reconstructed hypsometry from the hypsometry tool. At a regular interval (1 km) cross sections of the estuary are calculated by the hypsometry tool. These were used to calculate the estuary volume at each cross section (channels and bars) and multiplied by the interval to interpolate the volume between the cross sections and give total estuary volume below mean sea-level.

We identify that a change in estuary water volume is indicative of gain or loss of sediment, through either sedimentation (water volume loss, sediment gain) and erosion (water volume gain, sediment loss) in the estuary, removal of sediment via dredging (volume gain) or embanking which leads to exclusion of certain areas (volume loss). This gain or loss was quantified by estimating mass change and subsequently the sediment budget of the estuary. This allows us to quantify the importance of the various losses and gains through time.

For comparison to present-day sediment budgets, sediment mass rather than sediment volume change is needed. To convert the volume change to mass change for comparison with other sediment budgets, estuary volume change was multiplied by sediment density. The density of sediment is assumed to be constant through time. The average sediment density from Cox et al. (2021b) are used for the branches that make up the estuaries, i.e. an average sediment density for the Haringvliet, Hollands Diep and Amer branches for HVL (558 kg/m^3) and an average sediment density of the Lek, Nieuwe Maas and Nieuwe Waterweg for the RME estuary (984 kg/m^3). However, we acknowledge that sediment composition has changed rapidly in the past 50 years and it is conceivable that similar variation may have taken place earlier, however, we cannot quantify this change.

4. Results

4.1. General estuary development

The clear decrease in estuary width of both estuaries is evident in Fig. 1. Particularly in the RME, the estuary mouth in particularly has narrowed significantly, with original intertidal shoals and islands now completely embanked. Initially the RME formed as a classic trumpet shaped estuary, which widened as Rhine discharge became redirected into its channels. After embanking, it became gradually narrower as ports and harbours grew into the estuary and the new channels were constructed to control flow and navigation.

The HVL initially formed as tidal inlet, and following storm surges and redirecting of Meuse discharge, by 1500 it was a wide tidal estuary. The area was embanked over time, following the Saint Elisabeth flood, slowly narrowing the estuary, reclaiming islands and in particular narrowing the middle and eastern parts of the estuary. This area however, still contains some fringing salt marshes and the large intertidal shoal of Tiengemeten. The was largely stable in area from 1700 onwards, until the closure of the estuary from the tides in 1970. This then led to a significant shallowing of the estuary.

4.2. Estuary depth

Before large scale human interventions in the region, both the RME and HVL show only minor fluctuations in average depth (see Fig. 6). Despite significant changes to discharge conveyance and avulsing channels during this period, the average depth of both estuaries only varied by less than 1.5 m. However, average depths in the mouth areas varied more significantly. For the RME from −3 m to −11 m and for the HVL from −3 m to −9 m.

Following major human interventions beginning around 1500, the RME shows a stepwise increase in depth trend, as the estuary is dredged and deepened for navigation. This reflects 2 processes: (1) the forcing of flow into narrower channels which causes erosion and deepening and (2) manual deepening events through dredging.

Meanwhile, the HVL shows a stepwise shallowing, particularly following the implementation of the Deltaworks and Haringvliet sluices which sealed the HVL arm off from tidal influence. The biggest deepening in the RME coincides with the cutting of the Nieuwe Merwede and Nieuwe Waterweg channels in 1855 and 1873 respectively.

4.3. Total estuary width

Initially, both estuaries grew in width as they formed and developed. This is particularly significant for the HVL where human peatland reclamation in the Middle Ages, led to a rapid widening. Both estuaries show an exponential decrease in width over time (see Fig. 6 since 1500). Figs. 1 and 2 indicate that for the RME nearly all of this narrowing has occurred in the mouth and in the section of the estuary between Rotterdam city and the sea, for the HVL, most changes were further inland, near the Biesbosch area. Human intervention led to large scale embanking and reclamation of most intertidal areas of both estuaries and the rapid narrowing of channels over time. Both have maintained their average width since around 1900, however, several harbours have been built adjacent to the estuary. Meanwhile, as seen in Fig. 6, their depths are continuing to change. The width of the estuary is unlikely to change in the future unless dikes are removed or moved. However, the depth trend of the RMD in particular is likely to continue in the future due to accommodation of larger container ships (Cox et al., 2021a).

4.4. Intertidal width

Both the RME and HVL have suffered a loss of intertidal area (Fig. 7) over time as human actions converted the land use of these areas to housing, farms and urban centres. While the RME was still developing, it initially was losing intertidal width (when it received just Meuse discharge). However, following the influx of Rhine discharge there was a rapid gain in intertidal width until around 1000 AD when the area became embanked. Meanwhile, the HVL, has shown a nearly constant decrease in intertidal width since its formation.

Fig. 7 indicates that both the RME and HVL had “tipping points” in their loss of intertidal area relative to the total estuary area. In the case of the RME, by the 1860s, the intertidal width of the estuary was at an all time high, but following the cutting of the Nieuwe Waterweg,

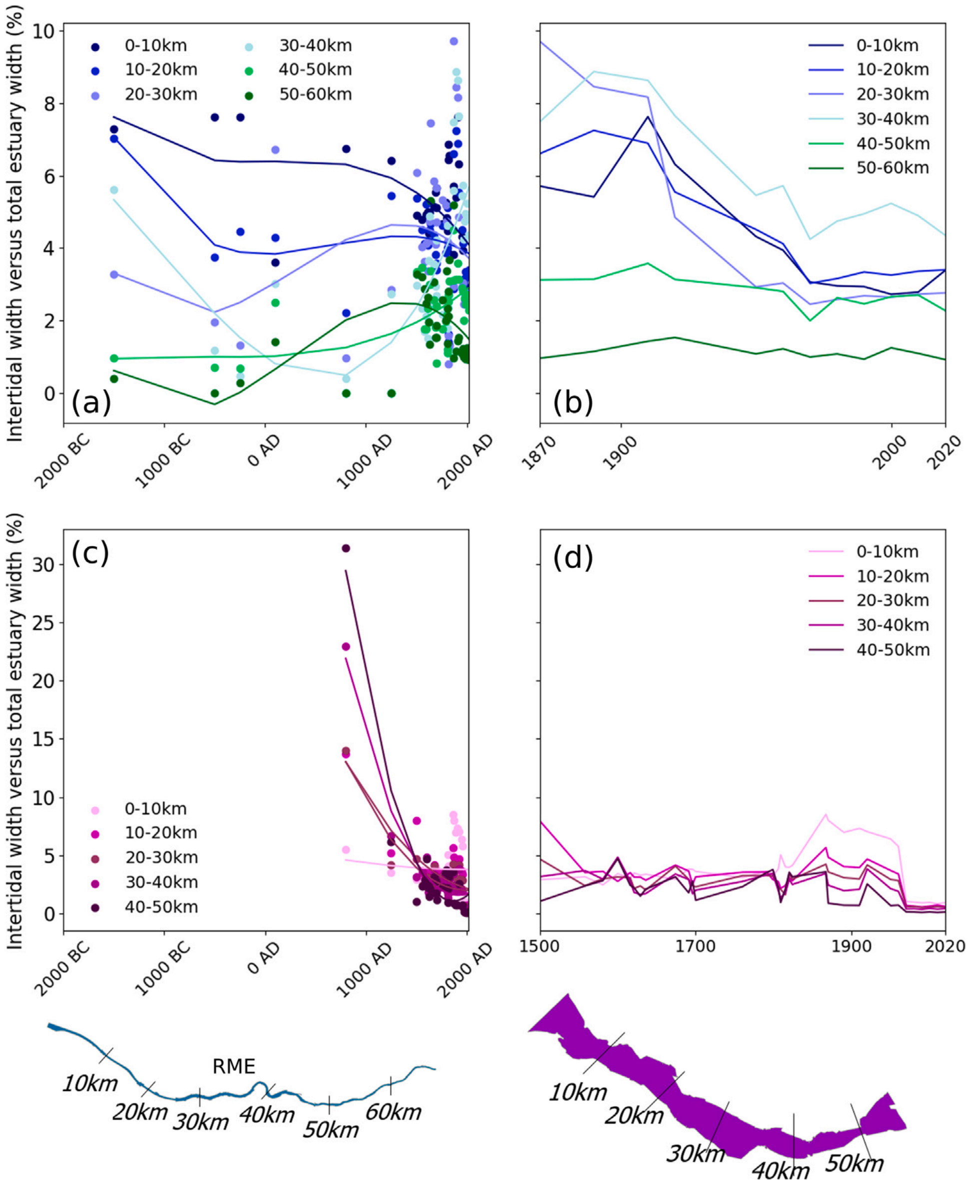

Fig. 7. Intertidal width as percentage of total estuary width for the RME and HVL where (a) is the development of the intertidal width of the RME from 1500 BC to 2020, (b) is the development of the intertidal width of the RME from 1870 (when the Nieuwe Waterweg was dug) until 2020, (c) is the development of the intertidal width of the HVL from 800 AD to 2020 and (d) is development of the intertidal width of the HVL from 1500 to 2020, outlines indicating the kilometre stretches analysed are indicated below the figure for each estuary.

most intertidal areas in the mouth were lost and the rest of the estuary shows a similar trend.

Fig. 7 also indicates that the construction of the Deltaworks in the HVL led to a decrease in the intertidal area width in the system. The control of the Haringvliet sluices has shrunk these intertidal areas in the south significantly. It is important to note that the hypsometry tool recreates the change in tidal range caused by the sluices as an instantaneous change in the estuary, when in reality, the changes were stepwise.

4.5. Estuary volume loss

Fig. 8 shows the cumulative estuary volume change for both the RME and HVL through time. Both estuaries initially gained water volume. In particular, the HVL continued to expand until around 1600 when it became embanked. Both estuaries showed a significant decrease in water volume from 1600–1900 and a period of stabilization since 1900.

A comparison of the recent timestep (2010) as calculated by the tool, with recent bathymetry (from 2013–2019, as determined by data availability and coverage) indicates that in general the tool underestimates the volume of the RME (by ~20%) and overestimates the volume of the HVL (by ~37%). These variations in recent timesteps are likely due dredging causing deviation from normal tidal-prism cross sectional area relationships (as indicated in Cox et al. (2021b)) for the RME. For the HVL overestimation is likely due to the closure of the HVL in the 1970s which has been causing sedimentation in this area (the pace of which would not necessarily be accurately predicted by this simple hypsometry tool).

As evidenced in Table 1, in the early phases of human intervention, the estuary was expanding and gaining volume, which we equate to a loss of sediment volume. These new tidal areas replaced existing peat areas. More tidal sediment was required to fully replace this peat which is a large portion of the loss of sediment. Accompanying significant human intervention from 1500–1900 the estuary rapidly lost water volume and “gained” sediment volume. Subsequently, in the most

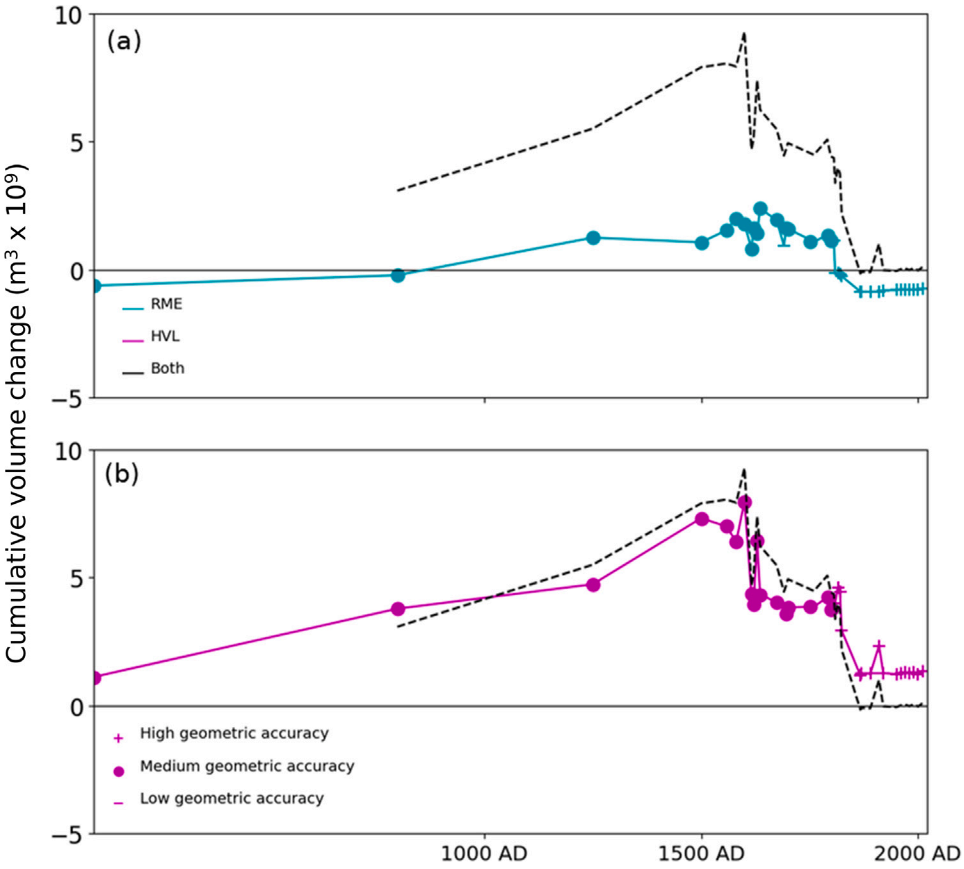

Fig. 8. Volume change of (a) the RME (b) the HVL, with combined volume change marked by black dashed line. The associated geometric error for each map is indicated by marker.

recent periods and future predictions, the estuary is gaining volume and there is permanent loss of material through dredging.

4.6. Sediment budget past, present and future

In total, −5.5 $m^3 \times 10^9$ of estuary water volume has been lost since 1500 through a combination of human activities including embanking, cutting of new canals and dredging. This "loss" of volume is essentially equivalent to either land gain (through embanking) or complete removal of sediment from the system due to dredging.

Comparing the sediment budgets of Cox et al. (2021b) and Cox et al. (2021a) we see that the period of 1500–1900 shows the only period with a positive sediment budget for the RMD. This "gain" of sediment is not due to an increased flux of sediment into the system during this period or rapid sedimentation/infilling of channels. It is actually due in large part to the permanent storage of sediment through extensive embanking which actually means less sediment can be entrained in the estuary in the long-term. During this time period, embanking of floodplains, narrowing of existing channels and cutting new channels were dominant in this time period, causing loss of estuary water volume.

Surprisingly, both estuaries show a relatively fixed estuary volume since the 1920s. Possible reasons for recent stagnation (1900–2020) in estuary volume: (1) the fixing of estuary shape and width by 1900 (see Fig. 5); (2) lower rates of embanking and reclamation and; (3) the focus on flood safety measures which did not radically alter estuary volume. However this stagnation is not represented in calculated sediment budgets as channel depth varies due to dredging 1.

Since the 1970s, dredging has been the main process controlling the sediment budget and estuary volume, which causes a net annual loss of sediment from the RMD and this trend is predicted to be even more extreme in the future as channel depths and thus amount of dredging are controlled by global container ship size (see Fig. 4 and Cox et al. (2021a) for the development in size). Dredged material in the past was removed and sold, or placed on land to aid building. Similarly, in the current situation, dredged material is placed in the North Sea and thus the sediment is permanently lost (Cox et al., 2021a).

5. Discussion

Our results indicate that the sediment budget of the Rhine–Meuse budget has become negative due to human intervention. In the following section we discuss which estuary developments have changed estuary shape (width and depth) through time and the long-term effect this has had on sediment transport patterns and resulting sediment budget. We reflect on one key period: 16 000–1890 which was instrumental in setting up the current estuary shape. This is followed by a juxtaposition of the sediment budgets calculated with the sediment budgets for and human activities undertaken in different estuaries and deltas (both those with similar boundary conditions and those with similar degrees of urban/human activity). Finally, we reflect on future challenges for urban deltas (such as the RMD) which have, or are following a similar development and the effects of new estuary/delta geometry on flood safety and how this may interact with SLR in the future.

5.1. Which major events altered the RMD? Creating a negative sediment budget

In the early history (pre-1050) of the RMD, changes in both were due to mostly natural processes including sea-level rise, sea ingressions, floods, storms and switching discharge distribution through avulsions.

Table 1
Comparison of sediment budgets through time.

Budget	Timespan	Average annual sediment budget (Mt/a)	Source	Comments
Present	2000–2018	−2	Cox et al. (2021b)	Volume gain, sediment loss
Future	2018–2085	−12 to −18	Cox et al. (2021a)	Volume gain, sediment loss
Geological[a]	1500 BC–250 BC	−1.90	This paper	Volume gain, sediment loss
Early human	250 BC–1500 AD	−2.86	This paper	Volume gain, sediment loss
City and port development	1500–1900	10.3	This paper	Volume loss, sediment gain
Recent growth	1900–2020	−1.2	This paper	Volume gain, sediment loss

[a] RME only, HVL had not yet formed.

Both estuaries widened and expanded in water volume, but stayed relatively constant in depth. Intertidal areas were free to expand and flood and storm waters flowed unobstructed into adjacent peat swamps and flood plains.

We identify four major human activities which significantly influenced the width, depth and volume of the HVL and RME estuaries since 1050. Firstly, from 1050–1350 when the courses of the Rhine and Meuse rivers became fixed and significant human habitation led to large scale peat reclamation. This set up the modern setting of these estuaries and essentially ensured that neither the RME or upstream HVL could ever widen significantly in subsequent years (though storms and floods in the lower HVL did alter width in later centuries). This also meant that sediment was no longer "freely" available from the banks of the estuary, and the major sediment sources were now solely the upstream riverine sediment delivery and coastal sediment flux.

Secondly, the extensive reclamation of land from 1500–1700 in the HVL decreased estuary volume, with significant land gain through changing the land use of intertidal areas. This permanently constrained the width and water volume of the HVL estuary.

Thirdly, the digging of canals from 1850–1890 altered discharge distribution and with this, major dredging activities were begun. Finally, the rapid post war reconstruction (1955) and the importance of Rotterdam as the world's busiest port from 1962–2004 set up a system of sediment management where channels were regularly deepened by dredging.

This meant that by 1900, the estuary was annually losing sediment, a trend that has become more serious and significant in recent decades (see Table 1).

5.2. What happened from 1600–1890? Setting up a new shape and equilibrium

During the 17th-20th centuries, both estuaries significantly decreased in water volume below mean sea-level. There were several reasons for this change. The RME development was closely intertwined with the development of the ports and harbours of Rotterdam which enhanced reclamation of land, fixing of banks and deepening of channels (by the forcing of flow into narrower channels and manual deepening events by dredging). Meanwhile, the Haringvliet, following the Saint Elisabeth floods was stepwise embanked and reclaimed during this period.

One major change was the development of dredging technologies during this period. Between 1600–1850 dredging mills were the primary method of removing sediment. These mud mills were operated by either horse or manpower (Dekkers et al., 2011). Despite this available technology, records from the 16th and 17th centuries indicate that the estuary and harbours were actually silting up, causing issues to navigation, with several small dams being built in the harbours (Hazewinkel, 1940). But beginning in the 18th century, dredging became the primary method of removing sediment from the area.

Despite the fact that slavery officially did not exist in the Dutch republic, slaves were regularly shipped in and out of Rotterdam port during the Dutch Golden Age (van Welie, 2008; Antunes and Ribeiro da Silva, 2018) and this slave labour contributed to its trade and economic importance globally. The manual work of dredging and shipbuilding often required thousands of labourers who migrated to this centre of economic importance. As around 50% of Rotterdam's population during this period were living on or below the poverty line, cheap labour was easily available for these manual dredging tasks, specifically to operate mud mills (Noordegraaf and van Zanden, 1995; Prak and Maarten, 2005).

Intertwined with this mass increase in labour, was the large increase in population related to the economic boom in the region. Coastal provinces, and Rotterdam in particular experienced a doubling of population from 1600–1850 as migrants flocked to this centre of trade (Paping, 2014). As the population grew, more land was required for large agricultural areas and existing polders to create farms and provide food for the growing population which was driving port growth and economic growth.

It is worth noting that there is not constant population and economic growth from 1600 to 1890, but between 1700 and 1850 there was a stagnation in both population growth and economic growth (Rutte and Abrahamse, 2016), and this stagnation is reflected in Fig. 6d where the period from 1700–1800 shows a constant width as there is reduced land reclamation during this period.

By 1850, with the onset of the Industrial Revolution, the estuaries began to once more experience rapid changes. After 1860, steam and suction dredgers decreased the need for manual labour, and made the dredging process significantly quicker and increased the possibilities for bigger and deeper channels and significantly reduced dredging costs (van Veen, 1962). These type of boats were used for the cutting of the major canals (the Nieuwe Merwede and Nieuwe Waterweg).

One further explanation is that not all the maps used from this period are geodetically not as accurate as the more recent maps of the study area. The accuracy of the maps is indicated in Fig. 8. In particular, the way the maps were made and the goal behind each map determines how accurately waterways were marked and therefore the accuracy of the width profiles used in this study. The Supplementary Material provides more information on map scale and the goals of individual mapmakers with an indication of accuracy and reliability.

5.3. Does this sediment loss deviate from global trends?

In general, most urban deltas are experiencing negative sediment budgets (Giosan et al., 2014). Sediment in estuaries and deltas globally is commonly decreased due to dam building (Nienhuis and van de Wal, 2021), sand-mining (Bendixen et al., 2019) and dredging (Cox et al., 2021b). The general loss of sediment from river channels, estuaries and deltas has multiple morphological effects. Firstly, a lack of sediment can cause river-bed scouring (Bendixen et al., 2019; Huismans et al., 2021). Secondly, a lack of sediment puts infrastructure (in, under and adjacent to channels) embankments at risk (Bendixen et al., 2019; Cox et al., 2021a; Hackney et al., 2020). Thirdly, sediment is required to maintain delta elevation under sea-level rise conditions to stop drowning (Cox et al., 2022; Nienhuis and van de Wal, 2021). However, as is increasingly identified, sediment supply from rivers is decreasing (Dunn et al., 2019) and river delta land loss is predicted to be exceptional in river deltas in the coming century (Nienhuis and van de Wal, 2021).

Here we compare our results to two groups of estuaries/deltas: (1) systems of similar size and similar boundary conditions to the RMD and

(2) systems undergoing similar rates of urbanization to the RMD. See also Table 2.

Systems with similar scale and boundary conditions to the Rhine–Meuse include the Ems-Dollard (Netherlands–Germany), Loire (France) and Seine (France) estuaries. These all have port networks and have all undergone similar types of human intervention over time with varying effects.

As documented in Pierik et al. (2022), the shape of the Ems-Dollard estuary has been also been strongly influenced by human interference for several centuries, with a total volume loss (due to infilling) of 3.5 $m^3 \times 10^9$ since 1800 (see also Table 2). However, several human activities have enlarged the estuary volume especially dredging (19th century-present). Regular channel deepening and dredging are still ongoing, particularly over the last 50 years as ports have developed and grown. The estuary was also embanked around the extensively like the RMD (16th to 19th century) constraining changes to a largely vertical direction. As in the RMD, intertidal area was also significantly decreased due to human interventions (van Maren et al., 2015).

The Loire also has a similar long-term history of human interventions due to its port and the need to facilitate navigation. It also now suffers from decreased sediment supply and bed degradation. At the mouth of the estuary, the Saint-Nazaire port drove extensive human intervention in the late 19th century. Interventions included: groyne construction, cutting off channels, main channel narrowing, dredging and reclamation of intertidal areas (Briere et al., 2012a). In general, this has led to bed degradation, with a channel that annually deepens (Dronkers, 2017), tidal amplification and increased tidal penetration and loss of intertidal areas (Briere et al., 2012b). This pattern is similar to the RMD, with extensive urbanization and port development driving long-term estuary dynamics.

The Seine estuary, home to the port of Le Havre, has also undergone significant morphological changes driven by navigation and port development. Particularly from 1960–2010, there were extensive anthropogenic interventions including a deepening and narrowing of the lower estuary, diking of the main channel and a large port extension from 1995–2005 (Grasso and Le Hir, 2019). This corresponds to the opening of the present day navigation channel, which due to intensive dredging doubled the depth of the channel (Lesourd et al., 2001). As in all above examples, this led to a large decrease in intertidal area and a deeper narrower estuary configuration. The upper channel experienced infilling, while the downstream part of the system experienced shoal erosion and scouring (Lesourd et al., 2001), which are also demonstrated in the RMD. There has been an overall decrease in sediment volume of 53% since the 19th century (Lesourd et al., 2001).

The Ems, Loire, and Seine estuaries have all become hyper-turbid in response to these anthropogenically influenced changes to estuary planform, a further challenge for ecology and navigation which is not currently experienced in the RMD. However, none of the above examples have ports as large and influential as the Port of Rotterdam or urban centres, or population densities as exceptional as the RMD. Despite showing similar effects due to human intervention, they are not as heavily urbanized or influenced by large-scale engineering as the RMD, thus we look to more extreme examples.

Despite a great variation in formation, geological setting and boundary conditions, the mega-deltas of Asia are displaying similar rates of urbanization and growth to the RMD. Changes in the estuary are also driven by similar motivations. The Yangtze delta, home to the port of Shanghai, currently the world's busiest port, is losing 346 Mt/yr according to recent estimates (Guo et al., 2021), and the RMD is currently only losing 0.5% of that in terms of total sediment mass. However, when comparing this to the area of the delta (Table 2), the Yangtze loss is a mere 12.5% of the rate of loss of the RMD. Despite their differences in sediment budget magnitude, the development of the Yangtze in recent decades shows similar patterns to the RMD. Human interventions, such as dam building, land reclamation and embanking have transformed the system from a once growing delta to an area which suffers extreme sediment loss (Yang et al., 2015, 2018; Yuan et al., 2020).

Just like the RMD, the initial influence of human activities was to increase suspended sediment delivery through cultivation and deforestation (Saito et al., 2001), and as early as 1291, Shanghai officially became a port city (Johnson, 1995; Wasserstrom, 2008). During this early stage, trade developed slowly, but during the 19th century Shanghai port increased in importance globally, particularly after 1843 when the British named it a "treaty port" opening it to foreign trade (Wasserstrom, 2008; Nield, 2015).

As the port developed, land use and urbanization were extensive, particularly from 1978 onwards, following economic reform (Yue et al., 2014). This was accompanied by engineering interventions in the basin including the building of the Three Gorges Dam (which significantly decreased upstream fluvial sediment delivery), several channel deepening events in the estuary mouth and a channel maintenance project. This recent project is so large-scale that it is likened to the Dutch Deltaworks (Dai et al., 2013). Most of these projects took place later than in the RME, from the 1960s onwards and at a far more rapid rate than the RME due to improved engineering when the interventions took place (Guo et al., 2021). One could argue that the processes that happened over hundreds of years in the RMD, happened in a mere 150 years in the Yangtze area contributing to an accelerated sediment loss. The current loss is estimated at ~100–346 Mt/yr (Wang et al., 2007; Guo et al., 2021).

Other systems that are becoming urbanized are indicating similar rates of sediment loss including the Mississippi, Mekong and Pearl River deltas with losses of ~1400 Mt/yr (Blum and Roberts, 2009), ~1310 Mt/yr (Schmitt et al., 2017) and ~5.46 Mt/yr (Zhang et al., 2012) respectively. Table 2 indicates how the budgets in this paper compare to these global deltas. Whilst it is clear that major deltas vary in their magnitude of sediment loss, the RMD has been suffering long-term sediment deprivation with an increase in magnitude in recent years. Moreover, it is important to note that delta and estuary response to human interventions is highly dependent on: scale, sediment availability and fluxes, and geological setting. These case-study specific constraints should be investigated per system.

5.3.1. Validity of the hypsometry tool and application to other systems

Historic bathymetries are often not available, especially not on long-term geological and historic timescales. Therefore, the hypsometry tool relies on assumptions we can make based on estuary planform shape, which is available from maps, and boundary conditions, which are reasonably well known for the RMD (de Haas et al., 2019) to reconstruct morphology for the past. Application and thus the results of this hypsometry tool to other delta or estuary systems, is limited by one main factor: data availability (accurate maps or aerial photographs to trace estuary planform through time and past boundary conditions data).

As shown in Leuven et al. (2018b), the hypsometry tool has been applied to a range of different estuaries with different geological and boundary conditions (36 in total). These validity tests also incorporated dredged and urbanized systems. In general, the hypsometry tool works well for most systems, with median and minimum bed elevations generally within a factor 2 of the measured values from bathymetry (see Figure 7 in Leuven et al. (2018b)).

Since the hypsometry tool estimates morphodynamic equilibrium, it is not directly suitable for estuaries with high anthropogenic impact. However, in cases with high anthropogenic impact, it is possible to set the depth at the mouth and/or upstream river to known values, which significantly improves the prediction. By specifying depth at the mouth of the estuary (constraining the hypsometry tool using measured data and geological estimates (see Methods)), we can improve the accuracy of the model. As elucidated in Pierik et al. (2022), many estuaries have erosion resistant layers which limit depth. Incorporating this

Table 2

Comparison of sediment budgets with current sediment budgets for other estuaries and river deltas globally.

Delta/budget	Timespan	Average sediment budget ($Mt/km^2/yr$)	Source
RMD Present	2000–2018	-7.9×10^5	Cox et al. (2021b)
RMD Future	2018–2085	-4.7 to -7.1×10^4	Cox et al. (2021a)
RMD Geological[a]	1500 BC–250 BC	-7.7×10^5	This paper
RMD Early human	250 BC–1500 AD	-1.1×10^4	This paper
RMD City & port development	1500–1900	4.1×10^4	This paper
RMD Recent growth	1900–2020	-4.7×10^5	This paper
Ems	1800–2010	1.1×10^{-1}	Pierik et al. (2022)
Mekong	2016–2100	-3.2×10^2	Schmitt et al. (2017)
Mississippi	2020 prediction	-1.5×10^2	Blum and Roberts (2009)
Pearl	2000s	-1.2×10^5	Zhang et al. (2012)
Seine	2006–2014	6.8×10^{-2}	Schulz et al. (2018)
Yangtze	2000s	-1×10^3	Wang et al. (2007)

[a] RME only, HVL had not yet formed.

information into the hypsometry tool can therefore help with validation and improve accuracy when applying this analysis to other systems.

To make connections to specific human interventions and extend the data to a multi-millennial scale, the accuracy is highly dependent on how well recorded interventions are (timing, scale etc.) and the availability of data at a good enough temporal resolution to compare morphology before and after individual events. The RMD has uniquely undergone both extremely constant, but also very well recorded, human interventions over the past millennia. Many systems have not undergone such intensive engineering or sediment management activities, nor has extensive data on the estuary/delta area been collected and recorded, the Netherlands tends to be unique in that respect. We identify, however, that while extensive human impact in the RMD occurred over several centuries, similar trends in land-use change, embankment and channel deepening and widening are now happening at a decadal scale in many rapidly developing estuaries and deltas (e.g. the Yangtze). Therefore, extensive long-term data or records of human intervention may not be required to perform a comparable analysis for an estuary with that is currently undergoing a recent but similar degree of urbanization.

Furthermore, there are almost certainly local specific climate events (e.g. storms, floods), or other natural factors (e.g changing sediment supply, changes to hydrodynamics through time) that interact with the results and patterns reported here, which cannot be disentangled. However, we assume these are negligible relative to the scale of human interventions assessed in this study with large known reported events (e.g. the Saint Elisabeth floods) assessed throughout.

5.4. Future challenges for urbanized deltas

Table 2 demonstrates that many deltas globally are losing sediment. Many of these deltas are experiencing change rapidly (in 100 or 200 years) whilst human interventions occurred over nearly 1000 years in the RMD. Nonetheless, common issues arise when a negative sediment budget occurs in these urban deltas. These include: threats to infrastructure and flood safety measures, loss of valuable intertidal areas and risks of bank instability (Cox et al., 2021a).

As deltas are shifting into the urban sphere, they reach a new quasi-equilibrium, with deep channels, minimal intertidal areas and fixed shape due to embanking and reclamation of land. The RMD is a classic example of this trend, as shown by the stasis of estuary width reached by 1900. However, as SLR threatens deltas globally, this quasi-equilibrium is disrupted. Intertidal areas, which can provide flood storage and help to offset some of the negative effects of sea-level rise, are minimal or absent in these types of system. Those that still remain risk drowning (Costanza et al., 1997; Yuan and Zhu, 2015). Meanwhile, flood risk in the delta increases (Nicholls and Cazenave, 2010) and navigability of channels can be reduced (Mao et al., 2004).

In the RMD, recent estimates indicate that SLR will be double previous estimates used to construct flood protection measures and estimate future changes in the system (KNMI, 2021). Risks due to SLR faced by these deltas are also dependent on the basic shape and hypsometry of estuaries, with large deep systems (like the RMD and Yangtze) primarily threatened due to sediment starvation and loss of intertidal area (Leuven et al., 2019). Different deltas and their wetlands will respond to SLR differently, depending on their riverine sediment supply and other factors (such as subsidence, land use change etc.) with some systems e.g. the Yangtze having greater ability and more time to adapt to these changes (Yang et al., 2021). But could the hypsometry model provide more insight into possible future morphology of estuaries and deltas under SLR conditions?

To use the hypsometry tool to predict future changes, two main types of data are required for any scenario: a prediction of changes to tidal amplitude at the mouth and, for anthropogenically altered systems, a prediction of future depth of the estuary at the mouth. SLR is predicted to increase tidal prism, consequently promoting incision and expansion of channel cross sections and naturally deepening tidal channels (Hijma and Cohen, 2011; Leuven et al., 2019; Stefanon et al., 2012). Estimation of tidal response to sea-level rise is system specific, but predictions have been made for several estuaries using modelling (Du et al., 2018), empirical relations (Leuven et al., 2019) and predictions based on measured data (Idier et al., 2019). Several systems have locally specific predictions for how tidal characteristics will change due to SLR (Harker et al., 2019; Hong et al., 2020; Lodder et al., 2019; Nhan, 2016) including the RMD (Vellinga et al., 2014).

As previously mentioned, depth at the mouth is particularly important to improve accuracy of the hypsometry tool in anthropogenically altered systems. Changes to depth in dredged or altered systems are difficult to predict with any accuracy for the future. Although, Cox et al. (2021a) have made strides to provide estimates for the possible future depth of the RMD (assuming current practice whereby channel depth is determined solely by shipping and navigation concerns), the actual channel depths in the future will be determined by choices made by river and estuary managers to balance conflicting functions. In natural systems, however, the tool does not require such a depth prediction to provide information about how channel depth will change under SLR conditions.

In systems where channels are unconstrained and there is sufficient sediment, SLR can in theory re-naturalize estuaries and reverse human impacts (similar to the expansion phase of the RMD — see Table 1). But, in the RMD and many other systems, lateral constraints mean that channels will struggle to accommodate additional water and in general, the addition of SLR will manifest as channel bed and bank erosion. Thus, solutions are urgently required which can harness the power of SLR to restore natural processes. However, with current management of deltas and demand of their populations, the possibility to return to the pre-human, natural delta system is difficult to accomplish. Flood risk and retaining new urban land functions tend to be prioritized. However, possibilities are rapidly developing to "re-nature" and use nature based solutions to attempt to offset these negative effects (Cox et al., 2022; Temmerman et al., 2013). These projects provide opportunities to shift estuaries back to a more natural shape, but the current rate of implementation of these projects will need to be rapid to offset the long history of changes to aid adaptation in the RMD. These projects also require available land, and therefore the reversal of the extensive embankments that occurred in the 1600–1900s in the RMD.

5.5. Effects of estuary narrowing on flood safety and capability to grow with sea-level rise

The RMD is now heavily embanked and diked with narrow floodplains due to the activities from 1500–1900. By gradually reducing floodplains and intertidal areas, the RMD lost not only valuable nature areas (Raffaelli et al., 1996) but also an important tool in combating flood safety and sea-level rise (Kiedrzyńska et al., 2015). Removal of these areas and long-term alterations to sediment transport regimes has changed the delta area from a once laterally expanding area, that could use its natural sediment banks to grow with sea-level rise, to a system which is annually losing sediment, the crucial building block for deltas to combat sea-level rise (Vörösmarty et al., 2009; Nienhuis and van de Wal, 2021).

Increasingly, systems are searching for opportunities to restore ecosystems to provide a sustainable solution to climate concerns, in particular, sea-level rise (Temmerman et al., 2013; Vuik et al., 2019) including the Netherlands where working with nature is increasingly recognized as the future of estuary and delta management (van Koningsveld et al., 2008; van Loon-Steensma, 2015). However, a glance at the most recent map for the area (Fig. 1b) the huge degree of urbanization is immediately clear. Land-use is completely dominated by housing, ports and urban centres. This makes managed realignment (Esteves, 2014) or creation of new nature areas not only costly, but increasingly challenging with political, legal and stakeholder management ramifications (Cox et al., 2022). However, as the cost of reinforcing dikes to provide flood safety globally is estimated to be billions (Hinkel et al., 2014), and with the Netherlands having the highest density of dikes in the world (O'Dell et al., 2021), questions are being asked about the long-term future of these narrow diked systems (de Graaf et al., 2009; Baptist et al., 2019). Re-widening the estuary through creation or restoration of intertidal or floodplain areas, and halting/reducing channel deepening and dredging may still provide the best long-term solution, i.e. to revert to the natural pre-human state of the RMD.

6. Conclusions

The Rhine–Meuse delta has been affected by human interventions for over more than 2000 years. These changes include: poldering, embanking, channel deepening, construction of dams, cutting of canals and new channels and urban development. These changes have led to a narrowing of the estuaries by 85% (RME) and 65% (HVL) since 1600. In the case of the RME, the use of the estuary for navigation led to fixing of the estuary, construction of channels, increased discharge and high levels of dredging. In the HVL, the system was systematically embanked following the Saint Elisabeth floods to reclaim land causing narrowing, and later shallowing. The systems have been deepened by 94% (RME) and shallowed by 45% (HVL) since 1600. There was also a loss of 33% (RME) and 79% (HVL) intertidal width since 1600, which decreased tidal flood storage and habitats. Prior to 1500, as the estuaries developed, human interference in the landscape determined avulsion paths and created new channels, but ultimately, these activities led to a net gain in estuary water volume until the channels of the Rhine and Meuse rivers were constrained and final embankments of the tidal area took place, around 1350.

Major changes in both estuaries occurred between 1600–1700 and 1850–1900 when Rotterdam held a seat of great importance in global trade. The need for quick shipping routes led to rapid narrowing and deepening of existing channels (by dredging and forcing discharge into narrower channels) and construction of new channels, creating and fixing the current channel network of the RME estuary. Meanwhile, the HVL estuary was periodically embanked to gain land and subsequently sealed off from the sea. In total, $-5.5\ \mathrm{m}^3 \times 10^9$ of estuary volume has been lost since 1500 either by dredging (primarily in the northern port estuary, the RME) or through land gain (primarily in the southern estuary, the HVL). The system has continued to urbanize and lose volume leading to a negative sediment budget (annual sediment loss) since 1900. Recent predictions for the sediment budget of the RMD indicate that in the next 50 years the most rapid rate of sediment loss ever experienced by the system will be reached. Other delta systems are showing similar sediment loss, at an even quicker rate than the RMD. Solutions are rapidly needed, particularly with the additional threat of sea-level rise to combat these negative sediment budgets, to reduce flood risk, protect infrastructure and maintain biodiversity-rich intertidal areas.

Declaration of competing interest

The authors declare that they have no known competing financial interests or personal relationships that could have appeared to influence the work reported in this paper.

Data availability

All data or links to data can be found in the Supplementary Information.

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Appendix A. Supplementary data

Supplementary material related to this article can be found online at https://doi.org/10.1016/j.csr.2022.104766.

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