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Key Points:
- Human impacts on delta channels can be quantified using empirical relations between tidal prism and cross-section area in delta channels
- Establishing sediment budgets for delta channel networks requires data concerning both sand and mud, which are jointly subject to dredging
- Reduced sediment input to deltas may partially be compensated for by influx of marine sediment, which is a large source of uncertainty

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

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Anthropogenic Effects on the Contemporary Sediment Budget of the Lower Rhine-Meuse Delta Channel Network

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Abstract Deltas and estuaries worldwide face the challenge of capturing sufficient sediment to keep up with relative sea-level rise. Knowledge about sediment pathways and fluxes is crucial to combat adverse effects on channel morphology, for example, erosion which enhances bank collapse and increasing tidal penetration. Here, we construct sediment budgets which quantify annual changes for the urbanized Rhine-Meuse Delta of the Netherlands, a typical urban delta experiences changing fluvial and coastal fluxes of sediment, engineering works and dredging and dumping activities. The delta shows a negative sediment budget (more outgoing than incoming sediment) since the 1980s, due to anthropogenic intervention. Following a large offshore port expansion, dredging in ports and harbors in the region has doubled in the past 5 years, likely due to the induced change in net sediment fluxes. In addition, the deeper navigation channels, ports, and harbors are now trapping siltier sediment, changing the sediment composition in the mouth. The removal of sediment by dredging is adverse to the necessity for sediment in heavily eroding branches. To allow for sustainable sediment management in the future and to cope with sea-level rise, further measurements are required to properly quantify the amount of incoming sediment at the boundaries of the system and the internal mechanisms of transport. The varied response of the branches has important consequences for navigation, ecology and flood safety and management of the sediment in the system. These effects will be of pivotal importance in coming decades with similar implications for many urbanized deltas worldwide.

Plain Language Summary Deltas need sufficient sediment to grow with sea-level rise and counteract natural and human-induced subsidence. A sediment budget quantifies if a delta is net gaining sediment or if it is losing sediment over a long time period. The Rhine-Meuse Delta (RMD) has a negative budget: Its entire network of channels is losing sediment annually. The reason for this negative budget is the high amounts of sand and mud removed for navigation to inland ports and from harbors which are periodically dredged. As a result, some of the channels in the area degrade rapidly, which causes issues for river management and dynamics including water quality, flood safety, and ecology. Other deltas worldwide are managed similarly to the RMD and will therefore face the same sediment issues. A strategy is required to deal with channel degradation and find ways to maintain sediment in the system.

1. Introduction

Coastal regions and deltas are home to half of the world's population, and are locations for major ports and important global economic hotspots. These regions both record and are subject to, intense global natural and anthropogenic environmental change (Bianchi & Allison, 2009). They are also at the highest risk of climate change-induced sea-level rise (Giosan et al., 2014; Elliott et al., 2019). One of the key factors in determining if and how deltas will cope with sea-level rise is sediment management and in particular, actions that can increase sedimentation at desired locations (Tessler et al., 2015). To maintain their elevation in the face of sea-level rise, deltas need sufficient sediment (Giosan et al., 2014; Syvitski et al., 2009). A lack of sediment in a delta leads to a myriad of problems including channel deepening causing salinity intrusion (Eslami et al., 2019), increased flood risk from tidal penetration and surges and a loss of ecologically rich areas (Best, 2019).

Human interventions in rivers and deltas often cause a lack of sediment (Dunn et al., 2019; Kondolf et al., 2014; Leuven, Pierik, et al., 2019; J. Nienhuis et al., 2020). To quantify the amount of sediment lost or gained by deltas sediment budgets are often used (Tessler et al., 2018). Despite their relative simplicity, sediment budgets are still arguably the best way to encompass the recent sediment dynamics of a system on a timescale of decades, assuming the correct method is applied and there is both sufficient data coverage and accurate data available. Parsons (2012) and Frings and ten Brinke (2018) summarize the main reasons to continue to use sediment budgets for river and delta management. Anthropogenic alterations to delta systems mean that sediment availability and sediment supply in the can be not only out of balance, but also increasingly uncertain in the face of climate change as hydrodynamic boundary conditions continue to vary. Moreover, the importance of nature-based solutions for flood safety, healthy ecosystems as well as for navigation is increasingly recognized (Temmerman et al., 2013). In the Rhine-Meuse Delta (RMD), as in other heavily populated deltas, water safety policy had largely been focused on raising and maintaining dikes and other hard engineering methods that neglect the sediment dynamics of the region. Management of natural sediment materials and nature-based solutions are now often pursued to retain sediment in deltas at desired locations. However, to identify which sediment management strategies can be implemented and which will be most effective in solving the issues that the delta faces, it is crucial to understand (a) where sediment is currently removed, (b) the volumes of sediment that are removed (fluxes out), (c) where incoming sediment (fluxes in) can provide an opportunity to restore the natural sediment dynamics of the delta, (d) which channel reaches are eroding and which are showing net sedimentation, and (e) the influence of engineering measures and constructions (dikes, dams, storm surge barriers) on sediment dynamics.

Here, we use a sediment budget as a diagnostic instrument to assess and evaluate the main factors determining the changing sediment dynamics of the RMD. The RMD is an example of a heavily engineered system which historically and currently has led to issues with uneven erosion (which risks bank stability and infrastructure) and sedimentation (which increases dredging costs). As other deltas globally become more inhabited and engineered, the RMD serves as a key example for linking anthropogenic activities and the corresponding response of the deltas sediment budget and bed levels.

We focus on the urbanized RMD, which has undergone extensive human interventions of various kinds (see Table 1). As such it no longer resembles a classic delta or estuary system. Almost the entire area is embanked and used for anthropogenic benefit (housing, industry, shipping, etc.) with developments for navigation to the extensive Port of Rotterdam, and the closure of one of the two main estuaries in the 1971, to enhance flood safety, as part of the Delta Works engineering project commenced after the great flood of 1953. The flood safety of the ports and urban area, the fresh water supply and navigation have required embanking, channel narrowing, and large amounts of dredging all of which impact the sediment budget of the RMD.

As deltas worldwide are showing increasing human intervention (through dredging, channelization, damming, and other engineering), the case of the RMD provides an insightful example for what may happen to these increasingly urbanizing deltas worldwide in terms of degradation. Thus, the following research questions arise: What happens to sedimentation in urbanized deltas where dredging and engineering measures (e.g., dikes and storm surge barriers) are prominent and natural dynamics are disturbed? To what degree does local interference cause system-scale changes in morphological trends in the channel network on a timescale of decades? Is there sufficient sediment to cope with sea-level rise and where in the system should it be captured? How do the dynamics of the system influence sedimentation-erosion trends and how does that compare with empirical work for the system? To assess these questions, a sediment budget for 2000–2019 for the RMD is created and compared with previous budgets for the region. The main controls on the budget are identified and the RMD is compared with other deltas globally that are heading down the same sediment management route.

2. Material and Methods

2.1. The RMD

The RMD is located in the west of the Netherlands and is fed by the Maas river and several Rhine distributaries, namely the Waal and Lek rivers from upstream, whilst it discharges sediment and water at the coast at the Maasmond (Hoek van Holland) and at the Haringvliet sluices (see Figure 1). The lower Rhine-Meuse

Table 1
Main Anthropogenic Actions Undertaken in the Rhine-Meuse Delta Over Time Which Significantly Altered Discharge and Sediment Fluxes

Year(s)	Event	Description
1421	Saint Elisabeth Floods	Four subsequent inundations following poor dike maintenance and groundwater lowering create the Biesbosch wetland area, changing the course of the Maas and Waal rivers, diverting sediment, and discharge.
1851–1889	Groynes are built in the Rhine, Waal, and Lek	Multiple series of groyne construction are undertaken and hundreds of groynes are built.
1865–1877	Excavation of the Nieuwe Waterweg	This becomes the main passageway to the Port of Rotterdam connecting the port to the sea. It is subsequently deepened and widened several times.
1870	Nieuwe Merwede is created	It is created along the tidal creeks of the Biesbosch to divert water away from the Beneden Merwede and to stop upstream flooding due to siltation of the Biesbosch area.
1886	Splitting of the Waal and Maas	The mouth of the Maas is shifted to Amer and the Amer is normalized.
1904	Construction of the Bergsche Maas	The Bergsche Maas canal is cut to keep separate the flow of the Waal and Maas rivers to reduce flooding risk.
1919–1939	The Maas is embanked	This action causes bed degradation and channel deepening.
1954–1960	Botlek port constructed	Constructed to allow for more ships particularly the petrochemical industry.
1958–1964	Construction of the Europoort	Port constructed on the south bank of the Nieuwe Waterweg.
1962–1974	Hartelkanaal and Beerkanaal are dug	The Hartelkanaal and Beerkanaal are dug to allow access to the Europoort.
1960s	Construction of the Maasvlakte	The Maasvlakte harbor is constructed as part of the Deltaworks to increase shipping capacity. It was formed by rainbowing sediment which came from Limburg, Germany and Belgium.
1971	Closure of the Haringvliet	The Haringvliet branch of the RMD is closed by a large complex of sluices. Water and sediment no longer enter the system at this boundary, are only discharged.
1997	Opening of the Beerdams	Opening the dams allowed a direct connection of the Hartelkanaal and Beerkanaal with the North Sea
1997	Completion of the Maeslantkering	The Maeslantkering storm surge barrier is completed and is able to block of the landward section of the delta during storms.
2006–2015	Room for the River	Dike relocation, floodplain lowering, reducing groyne height and further actions are taken to improve flood protection.
2008–2015	Depoldering and channel diversions in the Biesbosch	As part of Room for the River, flood water, and suspended sediment are diverted to previously embanked, now lowered areas of the Biesbosch.
2008–2013	Maasvlakte 2 constructed	Sediment is deposited on the bottom of the North Sea to increase area of the Maasvlakte port

Table 1
Continued

Year(s)	Event	Description
2018	Haringvliet sluices open during high tide	By opening the sluices during high tide, the goal is to improve the nature in the area and allow fish migration
2018–2019	Deepening of the Nieuwe Waterweg	The Botlek and part of the Nieuwe Waterweg are deepened by 1.5 m to accommodate ships with a draft of 15 m

branches are a complex network of distributaries and a few cross-cutting channels that traverse the delta. These channels evolved mainly in the second half of the Holocene by natural avulsion (Pierik et al., 2018), but beach ridges caused a situation with two mouths only: The relatively deep Meuse (Maas) estuary close to present-day Rotterdam, and the relatively shallow Rhine (Rijn) estuary close to present-day Leiden. The fluvial-tidal transition is within the study area, and the tidal modulation of water levels in the rivers extends upstream of the study area. The Holocene development of the morphology and hydrodynamics of the RMD including the estimates of the initial boundary conditions of the region and history of the interactions with ecosystems and humans throughout the Holocene are described in de Haas et al. (2018).

Important aspects of human interference history include the embankment works in the late Middle Ages and the installation of groynes and bank protection along all branches, which led to narrowing and deepening for the purpose of safety and navigation (see Table 1) (P. H. Nienhuis, 2008). The embankment and bank protection works in the Rhine basin led to incision extending far upstream, that coarsened the bed of the Waal and Rhine into Germany. Furthermore, changes in the hinterland reduced the suspended wash material load (Frings et al., 2019). All of this reduced sediment transport into the delta (Frings et al., 2009, 2019).

Altogether, the RMD combines an extensive history of intervention at various scales that allow us to link the effects to the causes with confidence. To this end, we combine three methods, namely, the construction of a sediment budget on the basis of measured bed elevations in all branches, the data of fluxes of sediment, and analysis of deviations from typical relations between flow discharge or tidal volume and cross-sectional area for all channels in the network as an indication of morphological disequilibrium.

The hydrodynamic and tidal characteristics in the RMD network are the result of the interplay between river input from upstream, tidal conditions at sea that enter the system at the open mouth and the operation of the sluices on the former southern mouth (see map in Figure 1). Discharge from upstream is transported through three rivers: the Waal, Maas and Lek rivers, where the Waal conveys the largest part of the discharge (70%) and the Maas and Lek are equal in magnitude (14% and 16% respectively). The Lek and Maas are heavily regulated by a series of sluices and dams. The Lek is a minor distributary of the Rhine. Suspended sediment and bedload fluxes are largely proportional to discharge (see Figure 4) with the Waal discharging the greatest amount of sand and silt into the delta from upstream. The Maas imports more sediment than the Lek in terms of both suspended and bedload as seen in Figure 4. Discharge in the system is highly seasonal (also see the supporting information).

The downstream boundary of the RMD has undergone large changes in the past half century. The open estuary mouth, the Nieuwe Waterweg/Maasmond, has been deepened considerably, while the second estuary mouth, the Haringvliet, was closed in 1971, following which the tidal characteristics and discharge distribution of the RMD radically changed (Vellinga et al., 2014). Before closure, tides entered the system via the Maasmond and the Haringvliet and the connecting branches acted as a tidal divide, with relatively low flow velocities. After closure, the tide only entered via the Maasmond, decreasing the tidal range in the Haringvliet to 0.2–0.3 m (also see table in the supporting information). This new tidal range at Haringvliet is now smaller than the Maasmond causing water levels to be out of phase, that is, tidal propagation from Maasmond to Haringvliet takes roughly 6 h. As a result, the connecting and cross-cut branches have large water level gradients and carry a large amount of water (Vellinga et al., 2014). Strong estuarine circulation drives sediment import in the Maasmond area which causes a high import of both sand and silt.

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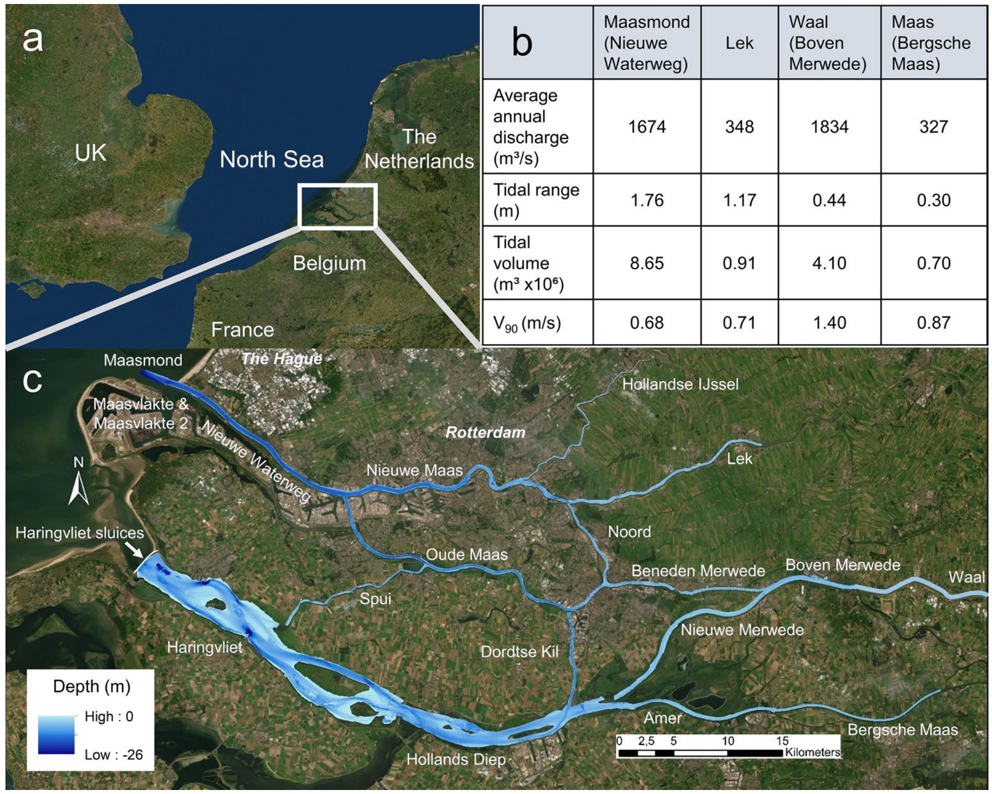

b	Maasmond (Nieuwe Waterweg)	Lek	Waal (Boven Merwede)	Maas (Bergsche Maas)
Average annual discharge (m^3/s)	1674	348	1834	327
Tidal range (m)	1.76	1.17	0.44	0.30
Tidal volume (m^3 x10^6)	8.65	0.91	4.10	0.70
V_{90} (m/s)	0.68	0.71	1.40	0.87

Figure 1. (a) The location of the Rhine-Meuse Delta, debouching into the Southern Bight of the North Sea on the west coast of the Netherlands. Note the Haringvliet branch is closed to the sea and maintained by sluices depending on the hydrodynamic conditions and thus its hydrodynamic parameters are not shown. (b) A table of the basic hydrodynamic boundary conditions (annual average discharge*, tidal range, tidal volume*, and 90th percentile flow velocity*) at the upstream and downstream boundaries of the study area. *Discharge, tidal volume and velocity data from 2013 run of 1D SOBEK-RE model. Tidal range data from measured water levels 2000–2019. (c) Map of the various branches of the Rhine-Meuse Delta and their elevation from the most recent bed level data (2019) for all years except Nieuwe Waterweg (2018) and Bergsche Maas (2015). Basemap courtesy of Esri.

The tidal volumes of the RMD (for definition and calculation, see supporting information) show a general decreasing trend from seaward to landward direction. There is only one main entrance point for the tides which is the Nieuwe Waterweg. In the Nieuwe Waterweg the tidal volume is 1.1×10^8 m^3, while it is a factor 20 smaller near the Haringvliet Sluices (where water is only exported). From the Nieuwe Waterweg the tides propagate to Nieuwe and Oude Maas, and from Oude Maas to the Merwedes and Hollands Diep branches (see Figure 2). Tides do not enter from Haringvliet Sluices, but tides do enter the Hollands Diep from Oude Maas via Dordtse Kil and Spui. These two cross-cut channels have therefore relatively high tidal volumes, in the order of 3.8×10^7 and 1.3×10^7 m^3, respectively (see Figure 2).

2.2. Sediment Budget Calculations

To create a sediment budget for the RMD, we make use of bed level data, dredging data and sediment transport data as far as available. We follow the same relation of Becker (2015) for each branch in the network:

$$\Delta_z = \Delta_{suspended} + \Delta_{bedload} - \Delta_{dredging} \tag{1}$$

where Δ_z is the bed level change (converted to Mt), $\Delta_{suspended}$ is the change in mass due to a gradient in suspended sediment transport between the upstream and downstream node of a channel (Mt), $\Delta_{bedload}$ is the change in mass due to a gradient in bedload transport and $\Delta_{dredging}$ is change in mass due to dredging or dumping activities within the channel (Mt). The overall bed level change is assumed to be equivalent to the net loss or gain of sediment within the river branches. Note that only changes within the branches are

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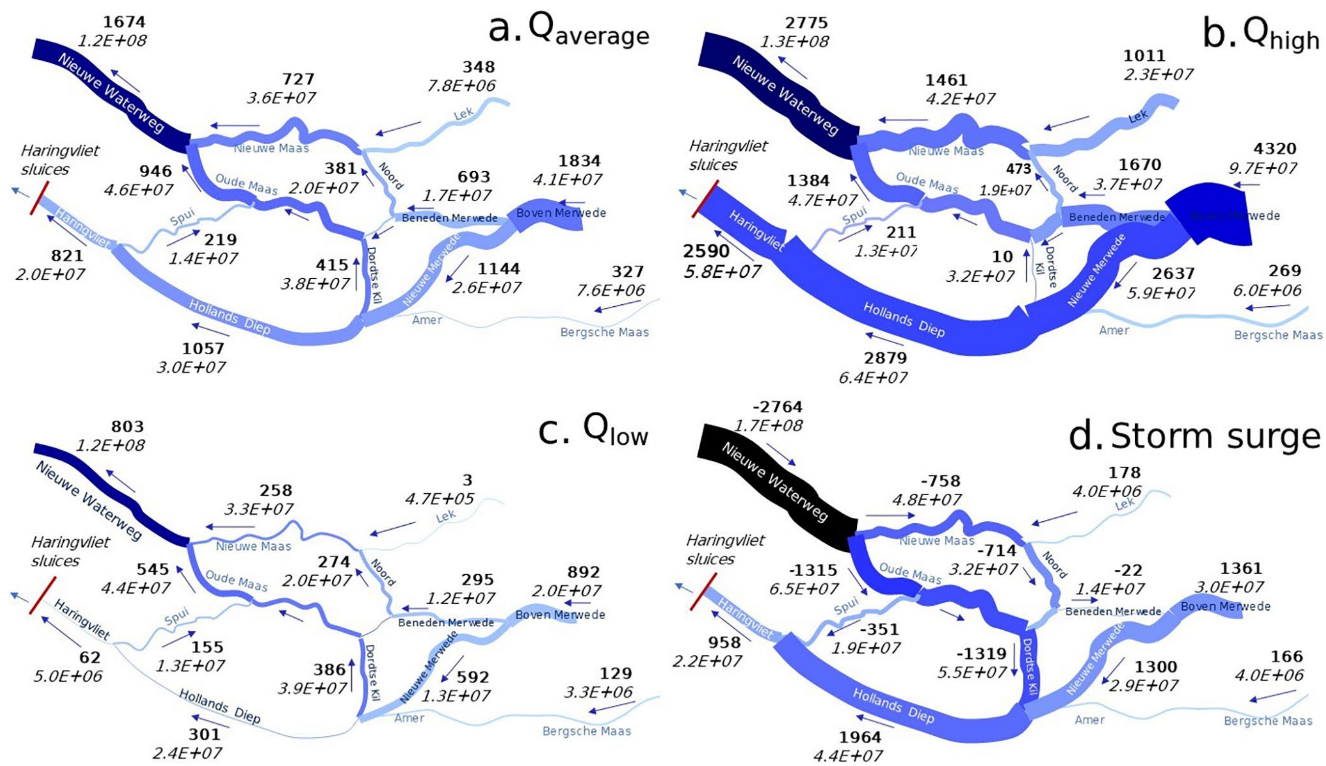

Figure 2. Discharge (m^3/s), in bold text, and tidal volumes (m^3), in italics, per branch for normal tidal conditions and (a) average, (b) high, (c) low river discharge, and for (d) a storm surge combined with a normal river discharge respectively. The width of the lines is proportional to the discharges, the darkness of the lines proportional to the tidal volumes. Arrows indicate the net flow direction. Values were extracted for two tidal cycles from the SOBEK run for 2013. The large variety between A and D indicates the various flow pathways for sediment in the Rhine-Meuse Delta.

included, that is, overbank sedimentation/floodplain sedimentation is neglected, as the floodplain surface area is small compared to the channel area in the RMD and sedimentation rates are negligible on the timescale considered here. This allows for creation of two estimates for the sediment budget, one solely from Δ_z and a second combining $\Delta_{dredging}$, $\Delta_{suspended}$, and $\Delta_{bedload}$.

In this paper, we analyze a very large dataset that was hitherto unpublished in international literature. For completeness, the supporting information provides details of all methods and sources, including data reports, and provides the main data used in the analyses.

2.2.1. Bed Elevation Differences

Single and multibeam bathymetric surveys carried out by the Rijkswaterstaat (national waterways authority) were converted to digital elevation models (DEMs) and used to calculate bed level trends for the branches of the RMD. To improve our estimates of average annual bed level, the data combines various intra-annual DEMs and weighted trends based on spatial coverage of the surveys (see supporting information for further explanation). Subsidence plays no significant role in the elevation of the RMD channels (as opposed to the land) and thus is neglected from our calculations.

2.3. Suspended and Bedload Fluxes

Suspended and bedload material enter the system from the Waal, Lek, and Maas. Although large amounts of suspended and bedload material are discharged via the main entrance channel in the Nieuwe Waterweg, an even larger amount of sediment is imported into the system via this entrance (Figure 4). Due to the closure of the Haringvliet, only suspended sediment is discharged through the Haringvliet sluices. This budget uses an average of all available suspended and bedload fluxes (as presented in mass units) from previous budgets (Becker, 2015; Frings et al., 2019; Snippen et al., 2005; van Dreumel, 1995) that make use of various methods to calculate and convert these fluxes which are detailed in the supporting information. The budget is highly sensitive to the values chosen at the boundaries and thus the range of values is also analyzed in detail in the supporting information. In particular the values of suspended and bedload flux at the coastal boundary have not been updated since the budgets of Snippen (2005) and van Dreumel (1995). The margin of error sums up to 2 Mt/a (Figure 4) which can easily change the budget from positive to negative. How the bedload and suspended load material distributes, settles and erodes in the complex channel network is reflected in bed level changes Δ_z over time. There is however, insufficient data available to determine how the bedload and suspended load is internally distributed over the branches of the RMD.

2.3.1. Dredging Volumes

Volumes of dredged material from the branches of the RMD are based on combined reports from the regional waterway management (Rijkswaterstaat West-Nederland-Zuid) and the Port of Rotterdam. Volumes of dredged material were converted to dry mass to allow for easy comparison with other components of the budget. This budget differs from previous budgets (Becker, 2015; Frings et al., 2019; Snippen et al., 2005; van Dreumel, 1995) as new composition data for the mouth area are included in the conversion of volume to mass due to a new measurement campaign undertaken by the Port of Rotterdam in 2018 and 2019 where samples of dredged material underwent grain size analysis (van Bruchem, 2018a, 2018b, 2019). This allowed for a more accurate conversion of dredging volumes to mass for the ports and harbors and for the Nieuwe Waterweg and Nieuwe Maas branches (the main navigation branches to the Ports of Rotterdam). The other branches in the system rely on the only other available composition data that dates from the 1980s (the same composition data used in previous budgets).

All dredged sediment that is not sold, is dumped off the coast (uncontaminated) and essentially fully removed from the area, or stored in a specially designated depot for contaminated material known as the "Slufter" (Kirichek et al., 2018). Most dredged material is therefore not returned to the system and thus the dumping component is negligible. The few planned and reported (by Rijkswaterstaat and Port of Rotterdam) disposal activities that took place in the branches were accounted for by removing this value from the dredging volume. Dredged volumes for the ports were also directly included in the sediment budget; a choice that is discussed later.

Figure 3 shows the total amount of dredging occurring in the RMD. This is a combination of the maintenance dredging, which is ongoing dredging to keep shipping fairways and ports open, and any capital dredging events, which are one-off events, channel deepening activities. Maintenance dredging volumes in the RMD are strongly controlled by hydrodynamic changes in the area and anthropogenic interference in the system. These complex interactions also cause shifts in required dredging volumes between the branches and the ports. The branches and ports have been maintained at the same dredge depth during the period of the sediment budget (no delta scale deepening has occurred) and so changes to the required dredging are a result of the changing sediment dynamics and not direct human intervention.

Two types of major engineering events occurred in the timeframe of this sediment budget that caused capital dredging or increased maintenance to occur in either the branches or the ports and harbors of the RMD. (a) The deepening of channels and ports, namely the Nieuwe Waterweg in 2012–2013 as part of the construction of the Maasvlakte 2 and in 2018–2019 for navigation purposes, and the deepening of the Botlek port entrance in 2014 for navigation. The dredging volumes for these activities are assimilated in to the dredging volumes per year for the area; and (b) The development of new port areas which require land building, namely the construction of the Maasvlakte 2 and new berths at the Maasvlakte. These large scale developments change the sediment dynamics and were found by the Port of Rotterdam to alter the amount of maintenance dredging required in the area by causing increased sedimentation locally (Leuven, Bart, et al., 2019).

2.4. Tidal Prism-Area Relations and Hydraulic Geometry Relations

To ascertain whether branches are close to their equilibrium bed level, whether they are too deep and have the tendency to accrete; or too shallow and have the tendency to erode, tidal prism-area (PA) relations are used. Tidal prism is the amount of water that flows in and out of an estuary with the flood and ebb of the tide: the volume of the incoming tide. While small deviations within a factor 2 can be attributed to empirical

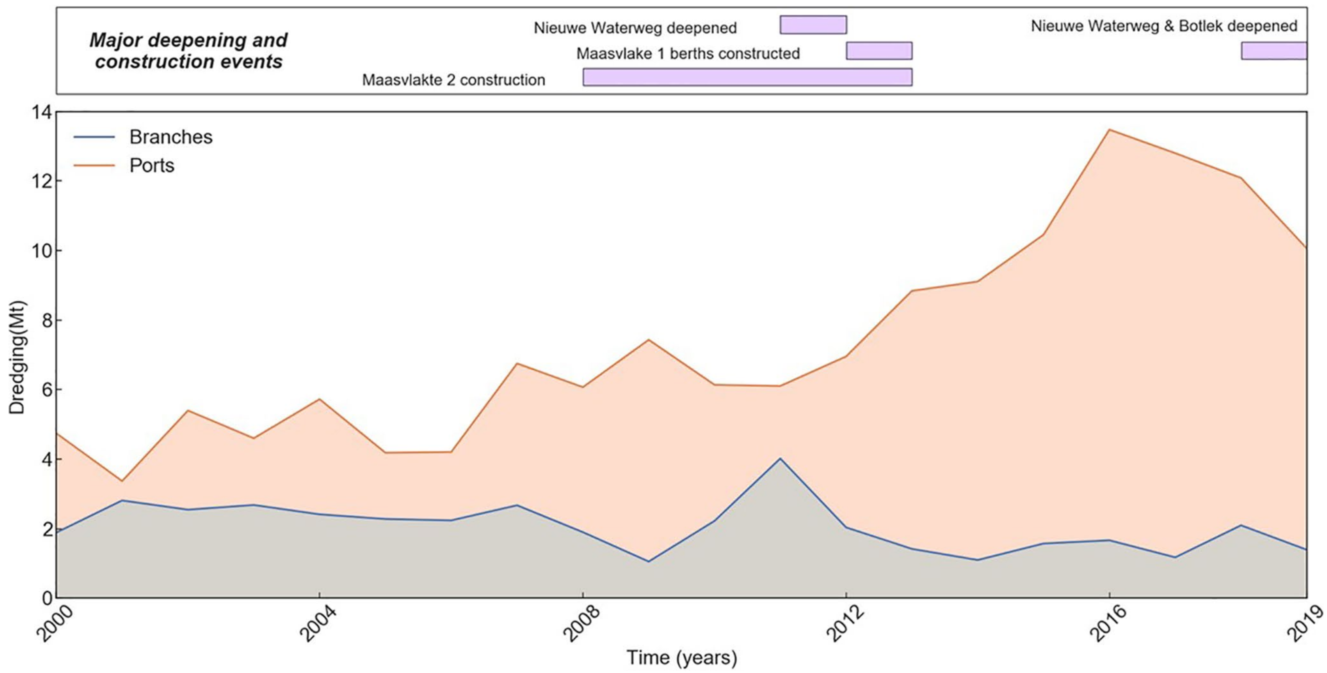

Figure 3. Total amount of dredging (Mt) in the branches and ports of the Rhine-Meuse Delta with a timeline of major engineering or construction works. Note that the volumes of dredging for the Nieuwe Waterweg and Botlek deepenings are both included in the branches portion of the dredging volumes as the Botlek deepening took place at the mouth of the harbor which is considered to be part of the branch.

uncertainty of these simple relations, large deviations between predicted and observed channel dimensions are the effect of disequilibrium. The PA relationships calculated in this report follow a derived equation from the original tidal PA relations of O'Brien (1931, 1969):

$$A_r = kP^{\alpha} \tag{2}$$

where A_r is the river cross-sectional area (m^2) and P is the tidal prism (m^3), α is a scaling coefficient and k is a constant which is dependent on α. If the tidal prism is large with respect to the flow cross-sectional area, the discharge passing through the cross section is high, generally resulting in erosion (high P/A). Conversely, sedimentation will occur if the tidal prism is low with respect to the flow cross-sectional area (low P/A), provided enough sediment is available for sedimentation.

For rivers without tides, a similar kind of relation exists between the width, depth and a formative flow discharge (usually bankful or mean annual flood): the hydraulic geometry relations for river channel dimensions and flow velocity (Leopold & Maddock, 1953). Here, we combine the relations for width and depth to obtain a "Q/A" relation between cross-sectional area A of a river and the flow discharge Q:

$$A_r = \alpha {Q_r}^{\beta} \tag{3}$$

where A_r is the cross-sectional area of the branch (m^2), $Q_r = uA_r$ is the discharge (m^3/s) where u is flow velocity, α is a constant multiplication factor and $\beta < 1$ to allow for the weak dependence of u on Q_r. We compare our data with the relations derived for the Jamuna (Marra et al., 2014) and Colombia (Klaassen et al. [1988] as cited in Kleinhans et al. [2012]) rivers; where α is equal to 4.2 (Colombia) and 3.7 (Jamuna) and β is equal to 0.85 (Jamuna) and 0.89 (Colombia). The resulting hydraulic geometry relations are similar to the PA relation.

Deviation of a river channel from a hydraulic geometry relation indicates its tendency to erode or aggrade. Here we use both relations with the expectation that tidally dominated channels will fit the PA relation better, whilst river-dominated channels will fit the QA relation. For channels that are in disequilibrium, neither relation will fit and thus we take this as an indication of disequilibrium sediment budget in those branches. The degree of disequilibrium is a qualitative indication of the timescale needed to adjust, as the

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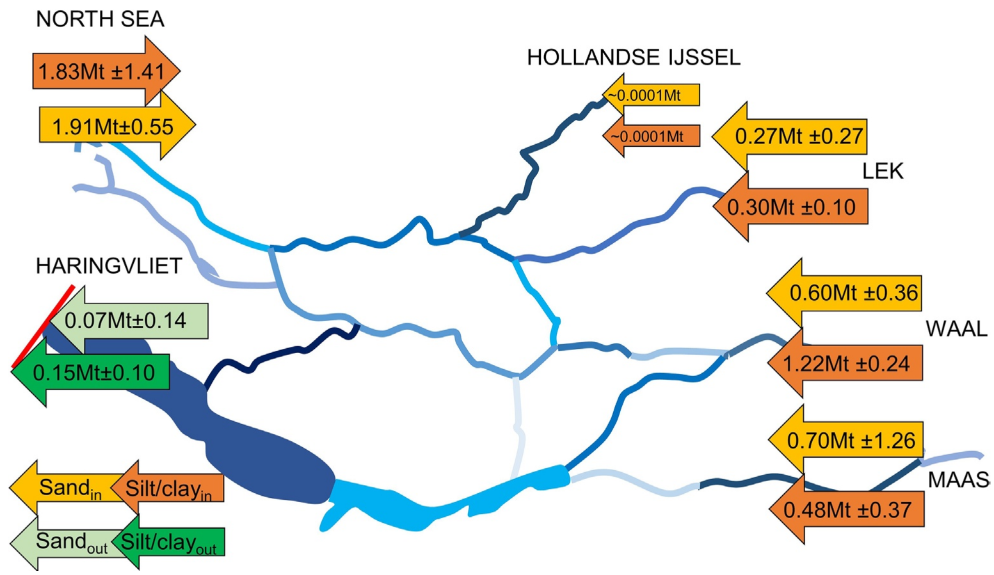

Figure 4. Annual average fluxes of suspended and bedload sediment in the RMD. Average of all published values of flux of suspended (silt/clay) and bedload (sand) sediment in Mt/year (average of the values reported by Becker [2015], Frings et al. [2019], Snippen et al. [2005], and van Dreumel [1995]) with error margins indicating the range of possible values as reported by these sources. At the North Sea boundary, these values represent the net flux of sediment.

adjustment rate in disequilibrium channels is mostly a function of sediment supply and human interference which require measurements as analyzed in this paper.

A SOBEK-RE model for the RMD was used to model the hydrodynamics of the area and to determine P, Q_r, and A_r. Full information about the hydrodynamics equations used and details of the model can be found in Kraaijeveld (2003). Water levels are calibrated using measured water levels at various measuring stations in the RMD and the model predicts water levels with an average deviation of <5 cm. The model also includes the steering of the Haringvliet sluices which is a key component for correct modelling of the flow distribution in this area. The model was run for the entire year of 2013 and we analyzed several time periods of different river discharge distribution and tidal volumes in the RMD. Discharge and velocity were extracted to calculate the volume of discharge (combined fluvial and tidal) passing through the cross-sectional area during four scenarios: (a) normal discharge, (b) high discharge, (c) low discharge, and (d) storm surge at the coastal boundary. Each period had a time duration of two tidal periods. Discharge was taken directly from the model and cross-sectional area was calculated following:

$$A_r = Q_r / u \tag{4}$$

where A_r is the cross-sectional area of the branch (m^2), $Q_r = uA_r$ is the discharge (m^3/s) and u is flow velocity. Flow velocity was also taken directly from the model.

3. Results

3.1. Fluxes of Suspended and Bedload Material

At the boundaries of the RMD, the average of all previously published values: Becker (2015), Frings et al. (2019), Snippen et al. (2005), and van Dreumel (1995) for suspended and bedload material entering and exiting the system are shown in Figure 4. Note there is a large range of values possible, particularly at the Maas boundary and the boundary with the North Sea due to differences in measurement method, calculation, and the use of these boundaries as closing terms in the various budgets (see supporting information for confidence and errors in these values).

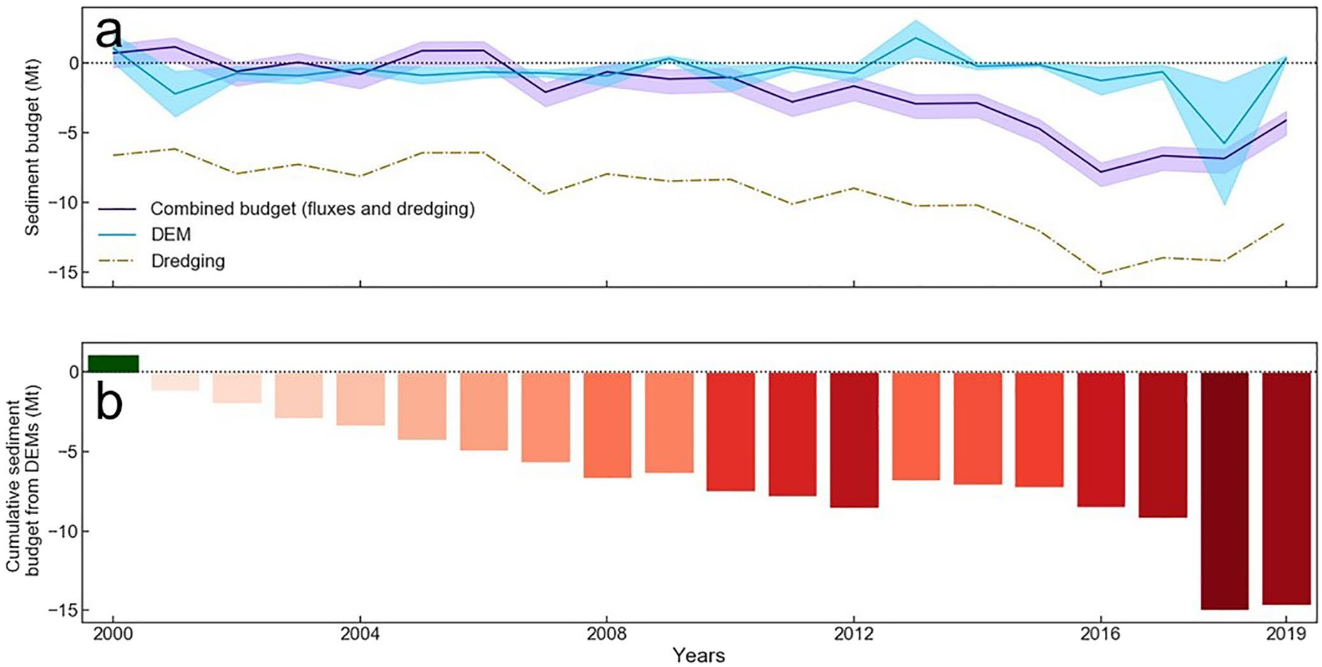

Figure 5. (a) Annual sediment budget as calculated by the following two methods: (1) Combined budget as described in Equations 1 and 2. DEM budget (Δ_z). Error margins are based on (1) the range of possible fluxes at the upstream and downstream boundaries (from Becker [2015], Frings et al. [2019], Snippen et al. [2005], van Dreumel [1995]) (note these values do not change yearly) and (2) the average percentage coverage of the DEMs as compared to the total area for the given year. Due to the constancy of the fluxes at the boundaries, only dredging (as indicated by the dashed line) changes the combined sediment budget values. (b) The cumulative sediment budget for the period as calculated from the DEM method.

3.2. A Negative Sediment Budget

Within the RMD system, the sediment budget shows a clear negative trend (Figure 5) in recent years linked to increased dredging of harbors areas in the mouth of the delta in recent years. This trend is true for both methods of calculation (sediment transport and bed level change) but with differing magnitudes. Differences in magnitude are largely linked to the uncertainties in incoming sediment fluxes. Note that no bed level data were available for the ports and harbors, which may account for part of the difference in magnitude between the two methods (i.e., only the difference in branches is calculated for the bed level method). Until 2012, it is observed that both methods show net results of the same order of magnitude, with the combined method showing a slightly positive budget and the DEM method showing a slightly negative budget. After the construction of the Maasvlakte II (offshore port), both methods strongly deviate. This is hypothesized to relate to increased dredging volumes caused by higher sediment import from sea triggered by the construction. However, as the influx at the sea is kept constant in the calculation of the combined budget (due to a lack of data), the magnitude of the negative budget calculated is larger than deemed to be correct. This stresses the need for continuous sediment measurements at the mouth.

There is, however, error associated with both methods due to the various inherent issues with the data as elaborated in the supporting information. Namely: (a) The quality of bed level data has inherent issues in collection, conversion and treatment to create an annual trend, and (b) The boundary flux data is outdated and shows a large range from various authors particularly at the seaward boundary, with annual changes unaccounted for due to a lack of data. Nevertheless, there is without doubt a sediment deficit in the region evidenced by both methods which is contributing to a large deficit over time.

The negative sediment budget as calculated by the DEM method does not affect all the branches evenly and clear differences are shown in Figure 6. The cumulative budgets (Figure 6a) clearly show that between 2000 and 2019 the biggest changes to bed level occurred in the Nieuwe Waterweg, Nieuwe Maas and Oude Maas (the northern branches of the system). The average dredged depth of the channels at the mouth (the Nieuwe Waterweg and Nieuwe Maas) have increased, which causes part of the negative trends in bed level

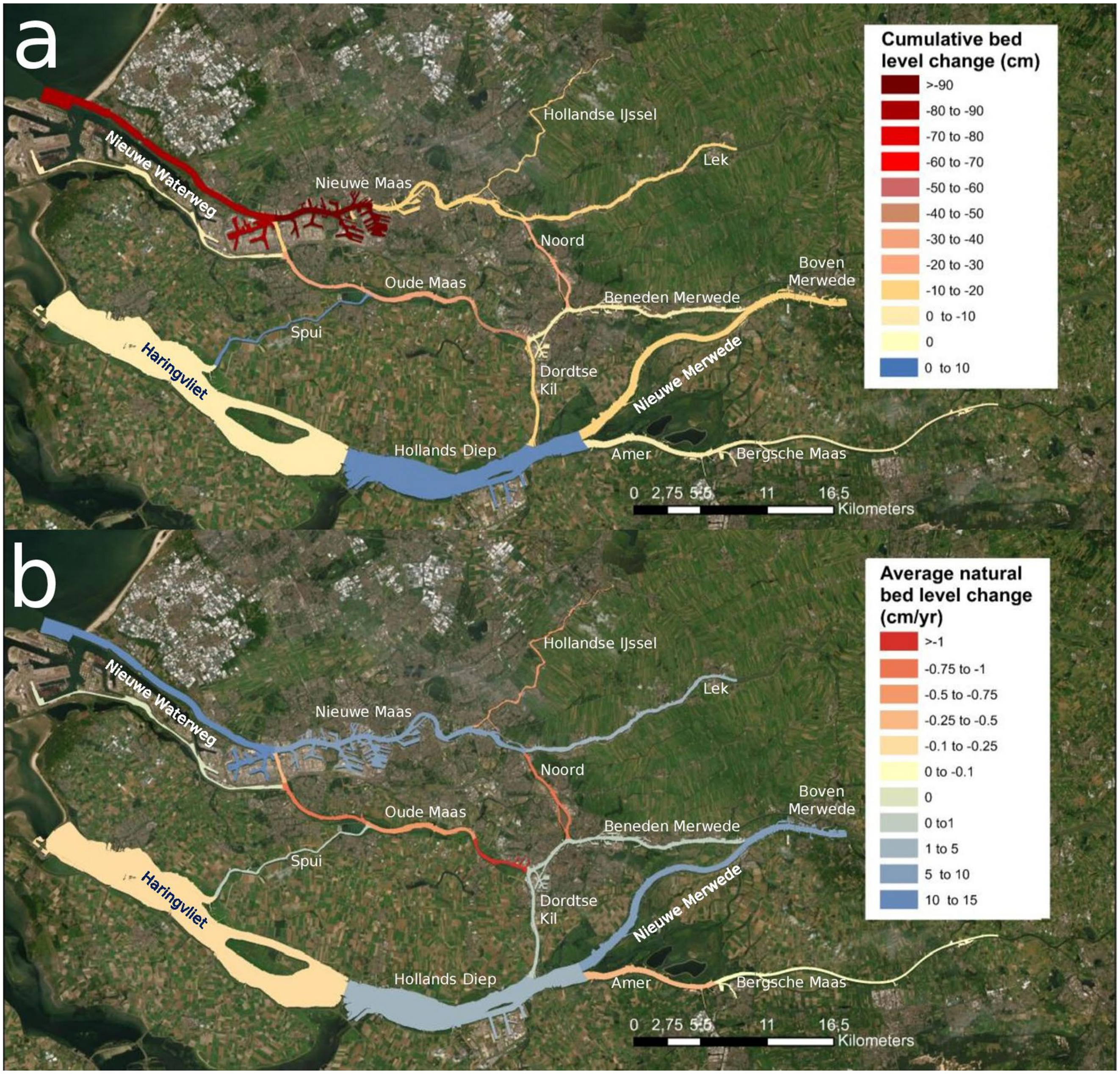

Figure 6. (a) The cumulative bed level change (cm) for each branch for 2000–2019. (b) The average "natural" bed level change (bed level change with the dredging term removed) per branch (in cm/yr) for 2000–2019.

in these branches. Thus the average bed level trend (where the impact of dredging is removed) presents a more accurate picture (Figure 6b). Bed level trends with the exclusion of dredging indicate that the northern branches (Nieuwe Waterweg, Nieuwe Maas, Lek), the Merwedes (Boven Merwede, Beneden Merwede) and the Hollands Diep are naturally aggrading. The Oude Maas, Noord, Hollandse IJssel, and Amer channels are naturally eroding whilst the remaining branches are in equilibrium with only minor annual fluctuations in bed level (Haringvliet, Spui, Dordtse Kil, Bergsche Maas, and Nieuwe Merwede). The Oude Maas is clearly a problem area as it shows extremely rapid erosion. There are many scours also developing in the Oude Maas branch which indicates the disequilibrium of the branch (Huismans et al., 2021).

This delta, despite having a wealth of data, illustrates that availability and quality of bed level data, transport measurements, and sediment composition all limit the quality of a sediment budget. A full overview of the potential sources of uncertainty and bias can be found in supporting information. To summarize, errors accumulate over the various stages of data collection and processing with inherent issues with bathymetric measurements, temporal issues (frequency of surveying), spatial issues (coverage of surveys), and post-processing issues determined by the method taken, all of which contribute to the uncertainty of the data. By including monthly surveys, the extreme variation calculated by using only one yearly averaged DEM are balanced out and a more accurate picture is given (see Figure 7). This is particularly significant in the northern branches (where many surveys are taken during the year which show large changes due to dredging) and the southern branches (where very few surveys are taken).

3.3. Deviations From Equilibrium Cross-Sectional Area Relations

The PA relations indicate whether each branch will erode or infill if there were no additional anthropogenic interference (in the absence of dredging activities) in the system, based on the dimensions of the branches and hydrodynamic conditions. The plotting locations of channels relative to the PA relations indicate that the southern branches (Haringvliet, Hollands Diep) and part of the Nieuwe Maas should be aggrading and the remaining northern branches (Nieuwe Maas, Nieuwe Waterweg, Oude Maas) and cross-cut channels (Dordtse Kil, Noord, Spui) should mainly be eroding (Figure 8a). When comparing this with the natural bed level changes (Figure 6b), the main outliers are the cross-cut channels, Dordtse Kil and Spui that are not eroding as severely as the PA suggests. According to the PA relation, the Nieuwe Waterweg should also be eroding, but, the natural bed level trends (without dredging) indicate a strong sedimentation trend. In the Nieuwe Waterweg, the tidal prism (P) has been increased as the channel was deepened and thus a larger cross-sectional area (A) is expected, but the cross-sectional area is not large enough to plot it in the sedimentation regime. However, the Nieuwe Waterweg shows a strong import of sediment from the North Sea and is subject to complex sediment transport processes, including those caused by tidal asymmetry and estuarine circulation, not all of which are captured in the PA relations. The strongly stratified conditions (due to poor mixing of fresh and salt water regions setting up complex density currents) are partial causes for this deviation, but further study is required to indicate what precisely the influence is.

Figure 8c indicates the relative impact of rivers and tides in the various branches by comparing the ratio of the mean velocity to 90th percentile velocity (velocity which is higher than 90% of recorded velocity measurements, taken to be the "highest" velocity during that tidal cycle). High ratios occur in a fluvial regime whilst low ratios occur in the tidal regime. The high ratio in the upper branches (Lek, Waal, Maas) indicates that river flow dominates in these branches and thus can be compared with the QA relation. As seen in Figure 8d, the river branches (Boven Merwede/Waal, Beneden Merwede, Nieuwe Merwede, Lek, Amer, Bergsche Maas) fall either below (eroding) or close to (at equilibrium) the QA relation. This differs slightly from the bed level trends, most notably for the Boven Merwede/Waal which according to the bed level trends, should be slightly aggrading but according to its hydraulic geometry should be slightly eroding. The Bergsche Maas and Amer branches also show slight erosion according to the natural bed level trends but should be aggrading according to their hydraulic geometry. The Hollandse IJssel branch is presently a tidal branch that receives no net discharge, but is controlled by the water taken in, or discharged from, the polders and thus is too heavily anthropogenically influenced in terms of discharge to accurately match either relation.

4. Discussion

4.1. Changes in Functioning and Sediment Budget of the RMD Mouth Area

Our analyses show that the RMD is currently losing sediment due to dredging activities. The large mouth and port area have lowered significantly in the past two decades, due to dredging activity, despite their natural tendency to aggrade sediment. Rather than trapping available sediment supplied from the boundaries, some branches are eroding due to changed hydrodynamics in the channel network, particularly the closure of the Haringvliet mouth. As a result, past and ongoing activities changed the character of the RMD from a net fluvial sediment trapping system (Pierik et al., 2017) to an estuarine system that increasingly traps fine sediment from the sea, as indicated by new sediment density data (this paper) and noted by Frings et al. (2019).

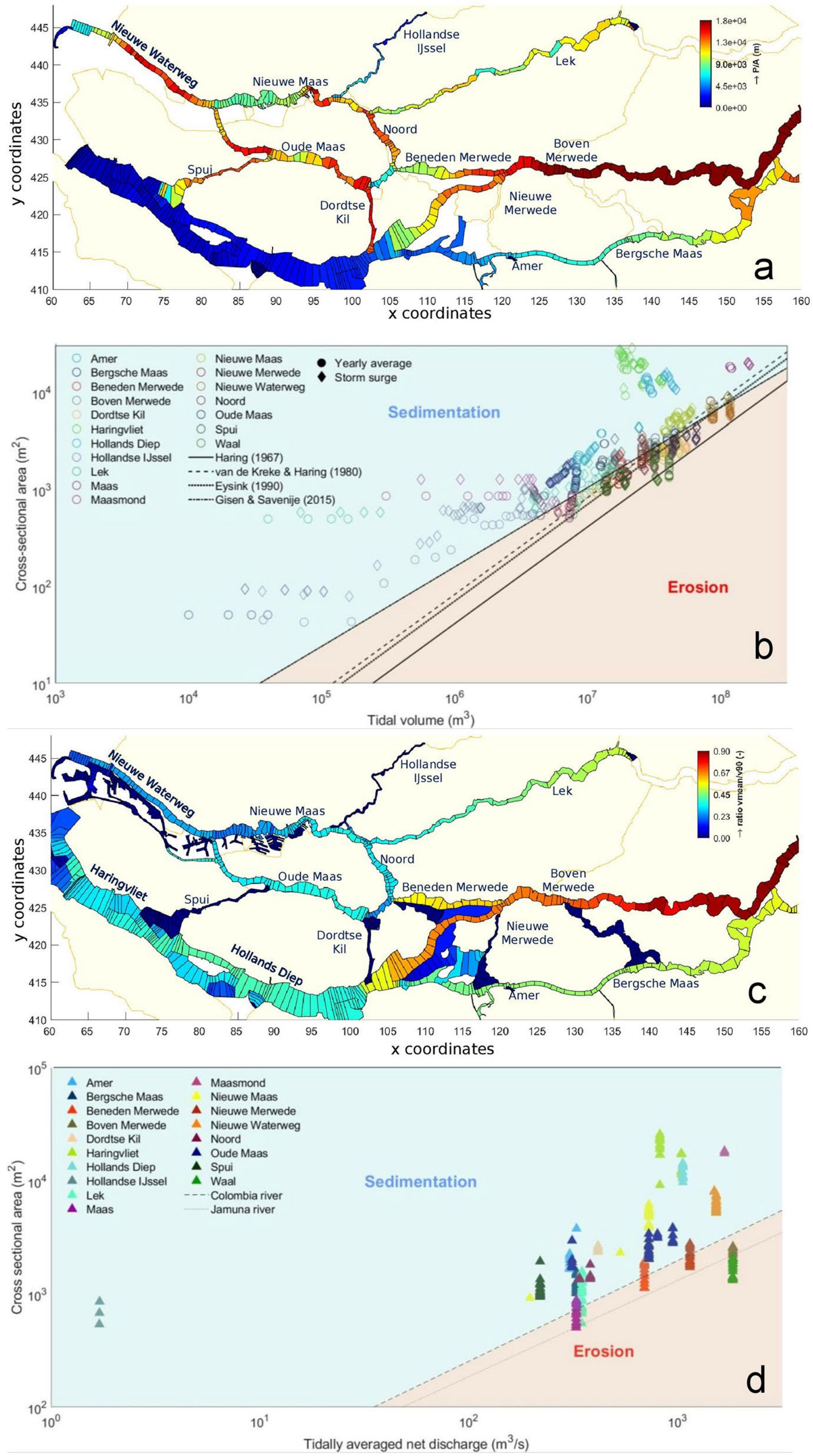

Figure 7. Cumulative bed level changes for (a) the northern branches, (b) the cross-cut branches, (c) the riverine branches and d. the southern branches of the RMD 2000–2019.

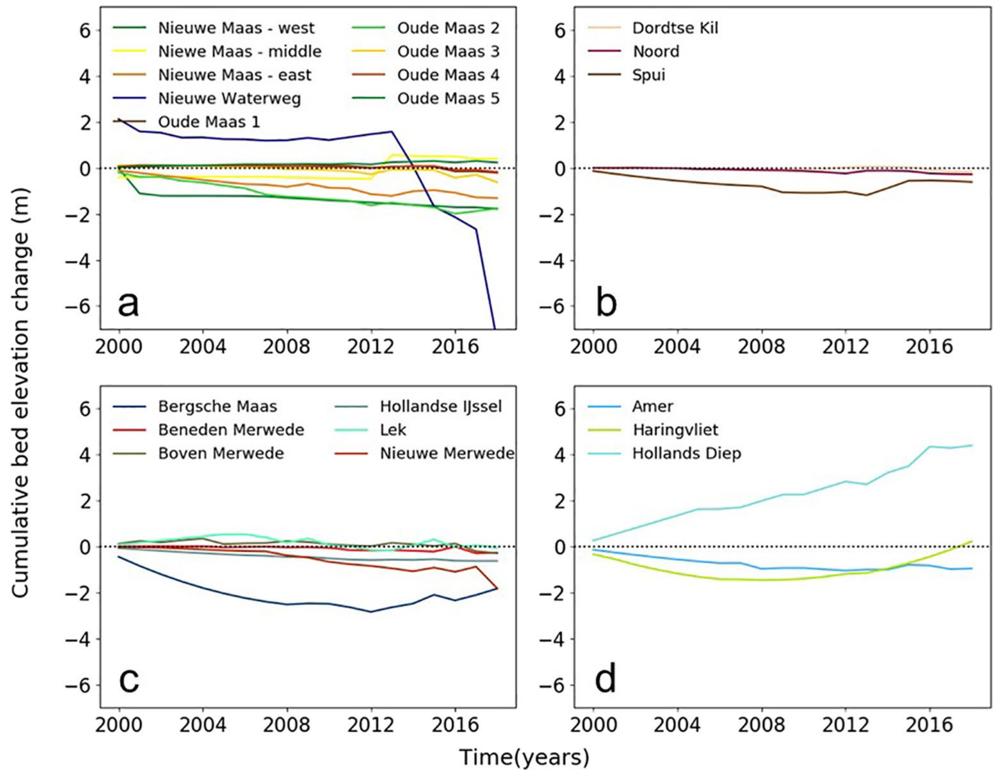

Figure 8. (a) Map showing the yearly averaged P/A from the SOBEK-RE model for 2013. (b) The P/A for the yearly average and storm surge conditions with relations from literature for the Netherlands (Eysink, 1990; Haring, 1967; van de Kreeke & Haring, 1980) and estuaries worldwide (Gisen & Savenije, 2015). (c) A map of the average flow velocity divided by the 90th percentile velocity (v90). (d) A comparison of the cross-sectional area versus discharge for the branches with the QA relation for rivers from literature (the Jamuna and Colombia). Note the Hollandse IJssel is not plotted due to its anthropogenically controlled discharge. The coordinate system used for maps (a) & (c) is the Dutch coordinate system (Rijks-Driehoek).

The sediment import at the coastal boundary is strongly dependent on the strength of estuarine circulation: the landward flow near the bed and seaward flow near the surface which is driven by density differences between fresh and seawater which is in turn dependent on river discharge, tidal amplitude and mean water depth. These complex processes are described by de Nijs and Pietrzak (2012); de Nijs et al. (2008, 2009) and collectively result at present in a net sediment import at the mouth. Complex tidally driven processes in river mouths are now often recognized globally as drivers of sediment circulation which make quantification of net coastal fluxes and their contribution to sediment budgets challenging (Eslami et al., 2019; Kappenberg et al., 1995; Nguyen et al., 2018). Deepened mouth areas in estuaries and delta will experience sea-level rise which will lead to further sediment import in the future. Indeed, deltas such as the Ems, Elbe, and Yangtze with dredged, deep mouths are showing enhanced sediment trapping, particularly of fine sediment (Dijkstra, Schuttelaars, Schramkowski, & Brouwer, 2019; Kerner, 2007; Luan et al., 2016; Van Maren et al., 2015). It could be argued that this natural trapping should counteract a negative sediment budget, however, the increased trapping is due to the overdeepening, and in the RMD all trapped sediment is continuously removed by maintenance dredging. This is a common trend in estuaries and deltas globally managed mainly for port accessibility (Hossain et al., 2004; Thomas et al., 2002).

There are system-wide effects on tidal dynamics and redistribution of sediment due to closure of one of the mouths by the Haringvliet sluices (1970s), leading to an erosive trend in the cross-cut channels (Huismans et al., 2021; Sloff et al., 2013). Blocking or controlling water through the use of dams and sluices generally leads to uneven sediment distribution and typically significant erosion of some channels in the system (Luan et al., 2016; Yang et al., 2007). There are indications that tidal channel bifurcations at which the branches are connected, can destabilize due to a perturbation, in this case a sluice, in only one of the channels (Buschman et al., 2010). While this "tidal floss" effect in crosscut channels connecting the two branches seems unique to the RMD, any other cause of redistribution of flow in the network would likewise cause significant erosion in some channels. The volume of sand involved in the cumulative bed lowering in the cross-cut channels is less than half of that removed by dredging in the mouth and port area. However, the erosive trend in the cross-cut channels is not caused by direct sediment removal but by the amplified tidal currents caused by permanent engineering measures that will continue in the foreseeable future. This gives rise to additional sediment which under normal conditions is deposited in the mouth area also.

These processes (closure of the Haringvliet, changing estuarine circulation, deep channels) have the tendency to drive additional sediment into the mouth region which consequently must be removed by dredging. Deep mouths of estuaries and deltas will struggle with this additional sediment in the future enhancing dredging intensity and costs.

4.1.1. Changes in Dredging Intensity

Here, we discuss the main trends and their causes in view of late Holocene evolution of the system and recent increases in human interference and speculate on likely future development.

Given the increased yearly dredging volume of 6 Mt in the ports and harbors, whilst the required depth remains constant, the input and composition of incoming sediment at the mouth are almost certainly changing. It is likely that several compound effects are responsible for the increase in maintenance dredging since 2012 (Figure 3). We can argue on the basis of timing that the main cause of changing sediment fluxes is the construction of the Maasvlakte 2, but the mechanism is not entirely clear. Predictions prior to construction indicated that there would be no impact of the Maasvlakte 2 on the large-scale mud or sand transport along the Dutch coast, but that local temporal effects close to the Maasvlakte 2 could be expected. These effects likely included changing estuarine circulation in the vicinity of the new port (due to changing presence, mixing and residence time of freshwater and saltwater) and changes in fine sediment deposition in the fairways and harbors (van Kruchten et al., 2008; van Ledden, 2005; Winterwerp, 2006). The permanence of this changed circulation is currently unknown and should be further investigated for better understanding of the sediment budget. This problem may also arise in other estuaries and deltas, particularly where offshore ports are rapidly being developed (Beresford et al., 2012; Jeevan et al., 2018; Pluijm, 2014).

Furthermore, local investigations into the increase in maintenance dredging volumes show that land reclamation during construction provided extra suspended sediment to the water system (de Bruijn, 2018). This relatively short response time (5–10 years) is expected for the RMD due to the fast conveyance of suspended sediment compared to bedload (Smit et al., 1997). Also other tidal systems in the Netherlands show rapid local hydrodynamic and morphodynamic response after the undertaking of large scale engineering works, (port and harbor construction, extensive dredging and more) as seen in the Wadden Sea (Gerritsen, 2000), Western Scheldt (Dijkstra, Schuttelaars, & Schramkowski, 2019), and Ems-Dollard systems (Talke & De Swart, 2006). Most recently, since 2019, the dredging volumes are decreasing again (see Figure 3) which may indicate that the extreme system response to construction is slowing down or perhaps stabilising. This could suggest that the temporary increase due to land reclamation works is superimposed on the increased estuarine circulation effects.

While much of the RMD has been urbanized, there are important ecosystems for which sediment supply is vital. For example, sufficient sediment in the RMD is required for the Biesbosch, one of the largest national parks in the Netherlands to maintain its ecosystem. During its formation, the Biesbosch area trapped the entire sediment load of the Rhine for nearly two centuries in the upstream part of the study area (Kleinhans et al., 2010). Presently, the Biesbosch hardly receives fluvial sediment (van der Deijl et al., 2019) that it crucially needs to prevent the system from drowning and to maintain its delicate ecosystem, which falls under European Natura2000 legislation. Systems like the Danube which have been making extensive efforts to restore its wetlands (Ebert et al., 2009) may transition towards the same ecosystem degradation if proposed urbanisation is pursued.

4.1.2. Possible System-Wide Effects of Local Change in the Mouth Area

More and finer sediment is now entering the system linked to changing hydrodynamics in the mouth area. The branches and eastern ports are experiencing increased silt and clay and less sand than reported by van

Dreumel (1995) as juxtaposed in the supporting information. This is likely attributed to a changing siltier upstream composition (despite upstream rivers delivering an overall load of less silt, the composition of upstream sediment is now dominated by silt and clay when compared with the 1980s) (Frings et al., 2019), but could also could stem from an increase in fine sediment import from the coast which over time is transported further into the system due to presence of long salt wedge and tidal penetration. As high volumes of sediment are either mined from, or relocated to, offshore locations in the North Sea, this changes the composition and amount of sediment transported along the coast and entering the RMD (van Ledden, 2005; Winterwerp, 2006).

The amount and composition of sediment entering the system at the mouth will be crucial for sustainable sediment management in the future, providing the system with an opportunity for land building or growth. This is particularly important as sea-levels continue to rise and that means these dynamics may be further altered. Many deltas are facing the issue of decreased sediment supply (Dunn et al., 2019) from upstream and channel sediment fining (Frings, 2008) to varying extents. Systems which show a clear sand and mud partitioning between channels and the floodplains or tidal flats (e.g., the Rhine, Mississippi, Pearl) and particularly those which rely solely on fine sediment to maintain their mouth area morphology will be more sensitive to changes than mixed composition estuaries with less distinctive suspended versus bedload sediment transport (e.g., the Yangtze and arctic systems), because the channel sediment and intermediate fractions provide a skeleton necessary for the mud to remain deposited. A trend of siltation in the RMD is detrimental for the capacity to cope with sea-level rise, for which sand as a stable material is needed as much as mud, which is no different from the global trend of increasing shortage of sand (Bendixen et al., 2019).

If the system continues to increase in silt and clay content, there will also be important future implications for shipping and major nature concerns such as the degradation and possible loss of Natura2000 areas (protected by the EU) which provide habitats and flood storage as already seen in other estuaries with high mud concentration (van Maren et al., 2016). This clearly indicates that not only process measurements are needed in the mouth but also sediment composition data. While advances in acoustic measurements have increased data quality considerably, continuation of labor-intensive, direct sediment sampling and analysis remains critical. This need for data is generally applicable to the mouths of estuaries worldwide, which will indicate and perhaps precede upstream, system-wide changes. This data is also crucially required to fully understand the sediment dynamics in relation to estuarine processes. Therefore, the mouths are the key locations to collect more measurements and data.

4.2. Comparison of Bed Level Trends and Deviation From the Prism Cross-Sectional Area Relations

The PA plots (Figure 8) were found to give an indication as to which branches have an overlarge cross-sectional area with reduced flow that will aggrade in case of sufficient sediment supply, and which branches have too small a cross-sectional area relative to the flow passing through and thus will have the tendency to erode if no poorly erodible layers limit the erosion. The data obtained from the PA relations generally match the patterns of the bed level trends seen in the RMD, with some minor deviations which are explained in the supporting information. This suggests that PA relations are effective in identifying large-scale trends of erosion or sedimentation for estuarine or delta branches despite their simplicity, except in the zone of estuarine circulation processes. Arguably, in systems with sparse data, PA relations are more cost-effective than multibeam data in identifying sedimentation and erosion trends in delta branches, as multibeam data is subject to various issues and the treatment of the data can easily change the erosion of sedimentation trend extracted (see the supporting information). PA relations can also be particularly effective in systems that have a lack of measurements or multibeam data but do have historic cross-sectional soundings. However, when the multibeam data can be both spatially and temporally of even higher quality than available in this paper, it can provide both more direct and more detailed quantification of the sediment budget and dynamics.

Combining three methods to analyze the sediment budget and sediment dynamics (bed level analysis, flux analysis, and PA-analysis), forms a powerful tool to unravel the causes of observed trends. The importance of seasonality was inferred from the PA relation analysis, which showed that for the tidal branches, for a single event, storm surge is a more important driver for erosion than high river discharge. Furthermore, the analysis of sediment fluxes in addition to sediment budgetting from bathymetry showed the relative importance of declining input at the boundaries, dredging and changed tidal flow patterns (as discussed before).

Temporal variability is not only caused by human interference but also by natural dynamics on the upstream and downstream boundaries of the system. Sediment delivery is driven by discharge and tides, both of which show strong seasonality, and the large deposition or erosion trends will be influenced by storm surges or high discharge, as explored for the RMD in the P/A analysis. However, the temporal scale of the available data (bed level, fluxes, dredging, etc.) does not allow for a detailed analysis of seasonality. For such an analysis, a much higher quantity and spatial extent of data is required, especially in the mouth area. To improve the sediment budget, as argued by Hoitink et al. (2020), it is key to improve our confidence in the fluxes, sources and sinks and our understanding of how these change over an annual cycle. This is particularly key in areas where episodic events such as seasonal monsoons (Clift, 2020), typhoons (Yang et al., 2019), hurricanes(Tweel & Turner, 2014) or other large scale seasonal events (Aalto et al., 2003) can contribute significantly to sediment budgets.

4.3. Comparisons With Deltas Worldwide and Implications

Human interference is systemic and has system-wide effect on channel networks and river mouths in deltas worldwide: The interference affects the upstream sediment supply, the downstream sediment flux, the erosion and aggradation in the channels and the condition of flood protection and floodplains. This is evidenced by the RMD case and is discussed for other systems below.

Large and deep estuaries may face sediment starvation and struggle to adapt to sea-level rise due to their sensitivity to changes in boundary conditions which translates into high sediment demand required for adaptation (Leuven, Pierik, et al., 2019). Most deltas are dominated by fluvial supply (J. Nienhuis et al., 2020). As shown by Dunn et al. (2019), most deltas worldwide will have a negative fluvial sediment budget in the future and thus all deltas need to consider sediment management strategies to counteract adverse effects. The urgency is also obvious from the fact that there is already a dearth of sand in many coastal systems (Bendixen et al., 2019). To identify the impact of sediment management strategies such as extensive dredging, which are likely projected paths for most deltas in the future, the RMD serves as a compelling case with causes, impacts, and effects that are likely to occur now or in the near future in other systems. As examples of deltas globally, we discuss the anthropogenic controls on sediment budgets and resulting issues in the Mekong, Pearl and Danube deltas. Whilst the deltas discussed above are vastly different in size, morphology, tidal and morphological characteristics, the common denominator is that the anthropogenic influence on sediment budgets is increasing and becoming the main controlling factor that determines the future sediment budget and indeed the fate of these deltas.

The channel morphology of the Mekong delta changes in the same fashion as the RMD in response to an anthropogenically controlled negative sediment budget, namely, uneven sediment distribution over its many branches which results in uneven bed level change and strong erosion in some channels (Schmitt et al., 2017; Eslami et al., 2019). Also like the RMD, future controls on the sediment budget of the Mekong delta, for example, changing sediment supply from upstream rivers and the coast are uncertain but projections indicate an increasingly negative budget (Allison et al., 2017; Jordan et al., 2019; Van Manh et al., 2015) that is primarily caused by human interference. What is notable is that despite different types of anthropogenic controls on the sediment budget (sand mining and upstream dams in the Mekong (Kondolf et al., 2018) juxtaposed with extensive dredging and closure of an estuary mouth in the RMD), the resulting effects on morphology are the same. In both the Mekong (Eslami et al., 2019) and Rhine (Frings et al., 2009), the upstream bed levels are degrading and so, more sediment will be required for management both in the delta and in the upper sections of the system. The negative sediment budget causes uneven bed degradation whereby the elevation differences between branches become more extreme and thus provides a challenge for sediment management. Both systems also suffer from bank instability and increased salinity intrusion due to channel deepening (Hackney et al., 2020; Jordan et al., 2019).

The sediment budget of the Pearl Delta is likewise dominated by human-induced changes that far outweigh the natural sediment supply (Ranasinghe et al., 2019). Arguably the Pearl delta is experiencing much more intense human interference than the RMD or indeed most deltas globally (Wu et al., 2018). As the Pearl Delta developed it became heavily embanked and fixed as land was reclaimed (Weng, 2007), in a similar manner as the RMD with the same concerns regarding the economy and shipping as the priority for sediment management (Wu et al., 2016). Despite the Pearl having a large upstream sediment delivery and showing net delta growth (Zhang et al., 2015), fluvial sediment delivery is predicted to decline rapidly. This decline is associated with several environmental issues in the delta linked to changing water transparency and chemistry. The system, like the RMD, experiences an uneven balance in fluxes of water and sediment which are also highly seasonal and will be further altered under climate change conditions (Hu et al., 2011). Sand excavation (like dredging in the RMD) is the primary cause of river bed degradation, outpacing subsidence and sea-level rise (Cai et al., 2019). Both systems also struggle with the challenge of maintenance of infrastructure, particularly dikes and underground tunnels and cables that must be safeguarded (Chan et al., 2021).

In the Pearl Delta rapid and extensive land reclamation is occurring simultaneously with the construction/operation of two large mega-dams upstream to result in decreased sediment supply (F. Liu et al., 2018). The resulting channel sediment deficit is currently and will in the future lead to large-scale coastal erosion and channel deepening (Ranasinghe et al., 2019). With numerous megacities and high rate of population and economic growth of this delta combined with high rates of subsidence of the Pearl mean there is an even higher priority in maintaining elevation through a positive sediment budget and addressing uneven sediment distribution (Yu et al., 2018). The Pearl Delta with its high population density and high levels of human interference (B. Liu et al., 2018) may represent a future state for the RMD as further urbanization continues in the delta as the Port of Rotterdam grows.

The Danube delta, like the RMD, has historic dikes and levees and a history of changing the length and width of branches for flood protection through dredging and canalisation (Giosan et al., 2013). Currently, the Danube delta shows a positive sediment budget controlled by sediment runoff in the branches (Mikhailova et al., 2019), although, if future planned anthropogenic activity occurs this will change (Tessler et al., 2018). The Danube has relatively low levels of urbanization but still experiences human intervention in the form of jetty construction, river intervention works and dredging and disposal activities which are decreasing the amount of sediment reaching the delta (Dan et al., 2009). Furthermore, several distributaries contain dams which control water and sediment flow upstream (Stagl & Hattermann, 2015). Projections indicate that in the coming century the Danube delta will have a negative sediment budget (Dunn et al., 2019). There is a strong economic interest in increasing the navigation capacity of the Danube (Habersack et al., 2016). Delta managers are already looking at what dredging and engineering measures are required to allow for increased navigation (Maslov, 2019) and the possible hydrodynamic and morphological implications of anthropogenic interference and in this process the RMD can serve as a useful example. The implications of altering channels for navigation on the sediment budget and sediment distribution are a key factor that must be considered to avoid the same negative effects as the RMD, which requires sediment management at the system scale.

5. Conclusion

Deltas need sediment to counteract subsidence, future sea-level rise and channel incision that destabilizes infrastructure. The constructed sediment budget of the heavily urbanized RMD for the past two decades shows that human activities control the sediment budget. Closure of one of the estuary mouths has led to an unbalanced tidal system that has caused branches to experience strong sedimentation and require high levels of dredging to maintain navigation. Meanwhile some branches are severely eroding, causing local scours which induce a potential risk for infrastructure. This is compounded by dredging and sand mining within the delta and the decline of upstream fluvial sediment supply, leading to a sediment budget that is negative. This is contradictory to the need for sediment for the severely eroding branches and the requirement of sediment to cope with sea-level rise in the delta. In addition, a change to siltier sediment is observed, which is disadvantageous for ecology and the ability of the system to cope with sea-level rise. Following a large harbor expansion in the mouth area, the dredging volumes in recent years have doubled, hinting at a changed sediment import from the mouth due to land reclamation activities and estuarine circulation.

As estuaries and deltas worldwide become more anthropogenically influenced, it is key to learn from the issues that have already arisen in the RMD. The example of the RMD shows responses of the system to interference that qualitatively generalize to other systems worldwide. The example also indicates that rather simple equilibrium relations between tidal prism and cross-sectional area can effectively indicate erosional and depositional tendencies of system branches. Meanwhile, a large measurement effort is required to more accurately quantify these trends, especially in the river mouth area where estuarine circulation processes muddle the net coastal sediment supply.

Data Availability Statement

All measurement data was made available by Rijkswaterstaat, Deltares and the Port of Rotterdam. All data or data sources used to conduct this research can be found in the supporting information table. Our words of gratitude for collecting and sharing this data go out to technical staff of Rijkswaterstaat and the Port of Rotterdam.

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