Anthropogenic effects on the contemporary sediment budget of the lower Rhine-Meuse Delta channel network

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Key Points:

- The lower Rhine-Meuse Delta (RMD) has a negative sediment budget due to high amounts of dredging and sand mining
- In the future there will be a need for sediment to counteract erosion in several branches and to cope with future sea level rise
- The RMD exemplifies what happens to deltas with human interference and demonstrates the need for mitigation by sediment management

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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 are crucial to combat adverse effects on channel morphology, e.g. erosion which enhances risk of bank collapse and increasing tidal penetration. We constructed sediment budgets which quantify annual changes for the urbanized delta of the Netherlands affected by fluvial and coastal fluxes of sediment, engineering works and dredging and dumping activities. The Rhine-Meuse delta shows a negative sediment budget in recent decades due to anthropogenic intervention. Following a large offshore port expansion, dredging in ports and harbours in the region has doubled in the past five years, likely due to the induced change in net sediment fluxes. In addition, the deeper navigation channels, ports and harbours are trapping siltier sediment than before, changing sediment composition in the mouth. The removal of sediment from the system through 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 from the rivers and the seaward boundary and the mechanisms of transport which are key to solving the sediment issues in the delta. The varied response of the branches has important consequences for navigation, ecology and flood safety and management of the sediment in the system will be of pivotal importance in coming decades and for other deltas worldwide.

Plain Language Summary

Deltas need sufficient sediment to grow with sea level rise and counteract subsidence. A sediment budget calculates if a delta is net gaining sediment or if it is losing sediment over a long time period. The Rhine-Meuse Delta has a negative budget i.e. it is losing sediment. The reason for this negative budget is the high amounts of sand removed for navigation to inland ports and harbours which are periodically removed by dredging. As a result some of the channels in the area degrade rapidly which causes issues for river functions such as water quality, flood safety and ecology. Other deltas worldwide are similarly managed like the RMD and will therefore face the same sediment issues. As the RMD further develops, managers must think about a strategy to deal with bed degradation and find ways to maintain sediment in the system.

1 Introduction

Coastal regions and particularly deltas are home to half the world's population, acting as major ports and important global economic hotspots. These regions 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 urbanized 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 (Syvitski et al., 2009; Giosan et al., 2014). 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; Leuven, Pierik, et al., 2019; 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 Brinke (2018) summarize the main reasons to continue to use sediment budgets for river and delta management. Here we use it as a diagnostic instrument to assess and evaluate the main factors determining the changing sediment budget of the Rhine-Meuse Delta (RMD).

Here we focus on the urbanized Rhine-Meuse Delta (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 a focus on navigation to the extensive Port of Rotterdam, and closure of one of the two main estuaries in the 1971 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, closure of one mouth and large amounts of dredging all of which impact the sediment budget of the RMD.

Past changes mean that sediment availability and sediment supply in the RMD are 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 safety and healthy ecosystems as well as navigation are increasingly recognized (Temmerman et al., 2013). Previously, water safety policy had largely been focused on dike maintenance and dike raising and other hard engineering methods that neglect the sediment dynamics of the region. Management of natural sediment materials and dynamics are currently being tested to keep more sediment in the system at desired spots but 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 1) where sediment is currently removed, 2) the volumes of sediment that are removed (fluxes out) 3) where incoming sediment (fluxes in) can provide an opportunity to restore the natural sediment dynamics of the delta 4) which channel reaches are eroding and which are showing net sedimentation and 5) the influence of engineering measures and constructions (dikes, dams, storm surge barriers) on sediment dynamics.

As deltas worldwide are showing increasing human intervention, the case of the RMD is exemplary for what may happen to these increasingly urbanizing deltas worldwide in terms of sediment. 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? 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 who are heading down the same sediment management route.

2 Material and Methods

2.1 The Rhine-Meuse Delta

The RMD is located in the west of the Netherlands and is fed by several Rhine branches namely the Maas, 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 Fig. 1). The lower Rhine-Meuse branches are a complex network of distributaries and a few cross-cut channels which traverse the delta. The channels came about mainly in the second half of the Holocene by natural avulsion, 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 Lei-

den. 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 RMD in relation to the initial and boundary conditions of the region and the interactions with ecosystems and humans are described in de Haas et al. (2018).

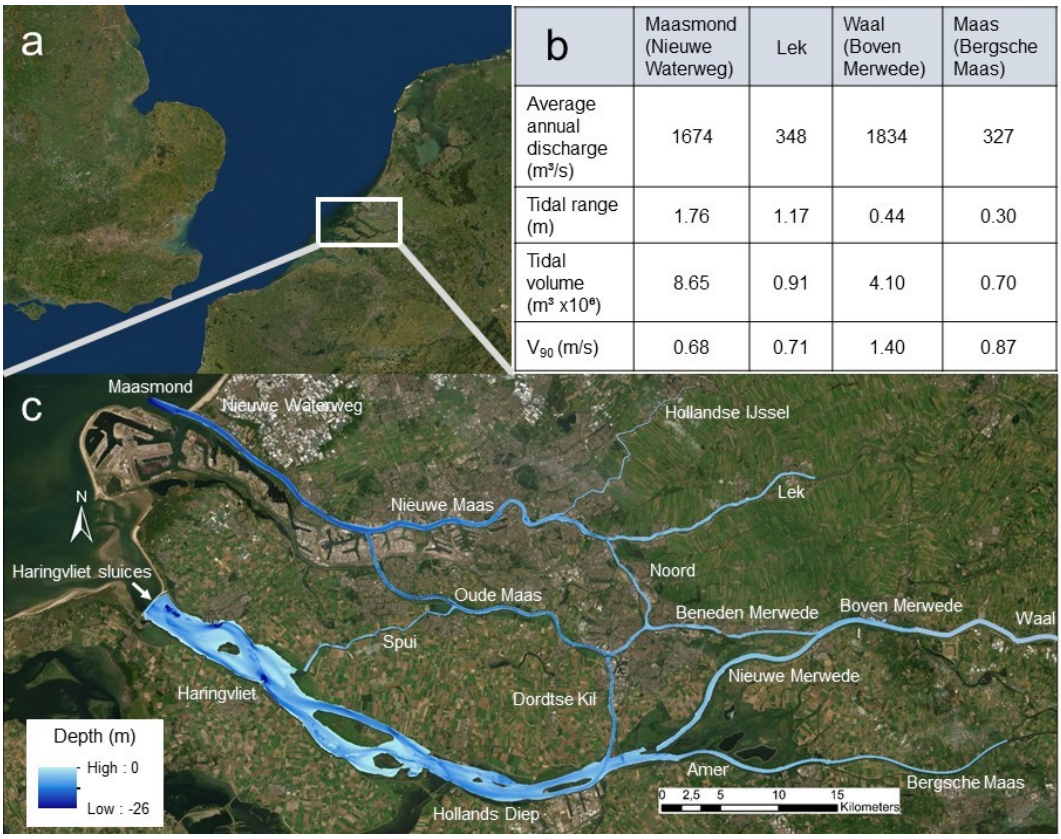
Important aspects of human interference history include the embankment works in the late Middle Ages and the installation of groynes and bank protection along all branches, which led to narrowing and deepening for the purpose of safety and navigation (see table 1). The embankment and bank protection works 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 a range and magnitude of human impacts 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 Fig. 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 former, minor distributary of the Rhine. Suspended sediment and bedload fluxes are largely proportional to discharge (see Fig. 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. Discharge in the system is highly seasonal (also see the supplementary information).

The downstream boundary of the RMD has undergone large changes in the past half century. The open estuary mouth, the Nieuwe Waterweg/Maasmond is the mouth of the Meuse river and has been deepened considerably, while the other estuary mouth, the Haringvliet, was closed in 1971, following which the tidal characteristics and discharge distribution of the RMD radically changed (N. Vellinga et al., 2014). Before closure, the tide 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, leading to a tidal range in the Haringvliet of 0.2-0.3m (also see supplementary table). This new tidal range at Haringvliet was now smaller than the Maasmond causing water levels which are out of phase i.e. tidal propagation from Maasmond to Haringvliet takes roughly 6 hours. As a result, the connecting and cross-cut branches have large water level gradients and carry a large amount of water.Strong estuarine circulation drives sediment import in the Maasmond area which causes a high import of both sand and silt.

The net discharge distribution over the branches is dependent on the tide, upstream river discharge and the related operation of the Haringvliet sluices. During average river discharge conditions 1686 m^3/s enters the system via the Waal (1443 m^3/s), Lek (159m^3/s) and Maas (92 m^3/s). The main route of water to the sea is first flowing southward via the Nieuwe Merwede to the Hollands Diep. From there most water flows back northward via the Dordtse Kil and Oude Maas, until it reaches the current main outlet at the Nieuwe Waterweg/Maasmond, through which a net discharge of 1395m^3/s debouches to sea. The remaining net discharge of 218 m^3/s debouches via the Haringvliet sluices, which are partially open during these average river discharge conditions. Note that the inflow and out-



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 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 RMD 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.

flow do not 100% match, the missing water is taken from the system for the polders and drinking water supply. The tidal volumes (for definition and calculation see appendix) show a general decreasing trend from sea to land and only one main entrance for the tides. In the Nieuwe Waterweg the tidal volume is 1.1 x10^8 m^3, while it is a factor 20 smaller near the Haringvliet Sluices (only export of water). From the Nieuwe Waterweg the tides propagate to Nieuwe and Oude Maas, and from Oude Maas to the Merwedes and Hollands Diep branches (see Fig. 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 x10^7 m^3 and 1.3 x10^7 m^3, respectively (see Fig. 2)

During low river discharges the Haringvliet sluices are completely closed, to ensure sufficient water flows through the Nieuwe Waterweg to counteract the salt intrusion. Though the main route of water to sea when the sluices are closed is similar to the average condition, discharge ratios over the branches are different. Tidal volumes are very similar to the average discharge conditions. Main differences are caused by the tidal volume which also accounts for river discharge, which is smaller in this case, and because tidal propagation is slightly affected by the smaller discharge.

During high river discharge, the Haringvliet sluices are fully open during low-tide (ebb phase only) and in this case water not only leaves via the Nieuwe Waterweg, but there is also a main route of water to sea from the Nieuwe Merwede to the Hollands Diep that leaves the system via the Haringvliet sluices. This changed pathway of river water also influences the tidal volumes in the southern branches, which become much larger because these branches carry much more river water at high river discharge. The tidal volumes in the northern and cross-cut branches are not as heavily affected.

In cases of storm surges, outflow can be temporarily hindered and in this case there can be a significant net inflow of water in the system during one or two tidal cycles. Discharge in all branches are strongly different in magnitude and can even change direction, particularly in the northern branches and cross cut channels. The tidal volumes are also very different in this case, and are sometimes 50 - 100 % larger than for the average discharge conditions. The strongest changes in both discharge and tidal volumes are observed in the cross-cut channel Dordtse Kil. When the storm surge at the North Sea boundary recedes, this extra water leaves the system again, giving rise to large outflows.

2.2 Making a sediment budget

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 (m), $\Delta_{suspended}$ is the bed level change due to a gradient in suspended sediment transport between the upstream and downstream node of a channel, $\Delta_{bedload}$ is the change in bed level due to a gradient in bedload transport and $\Delta_{dredging}$ is the bed level change due to dredging or dumping activities within the channel. As deltas are ultimately sediment traps, the overall bed level change is assumed to be equivalent to the net loss or gain of sediment within the river branches. 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. Fro completeness, the online supplement provides details of all methods and sources, including data reports, and provides the main data sued in the analyses.

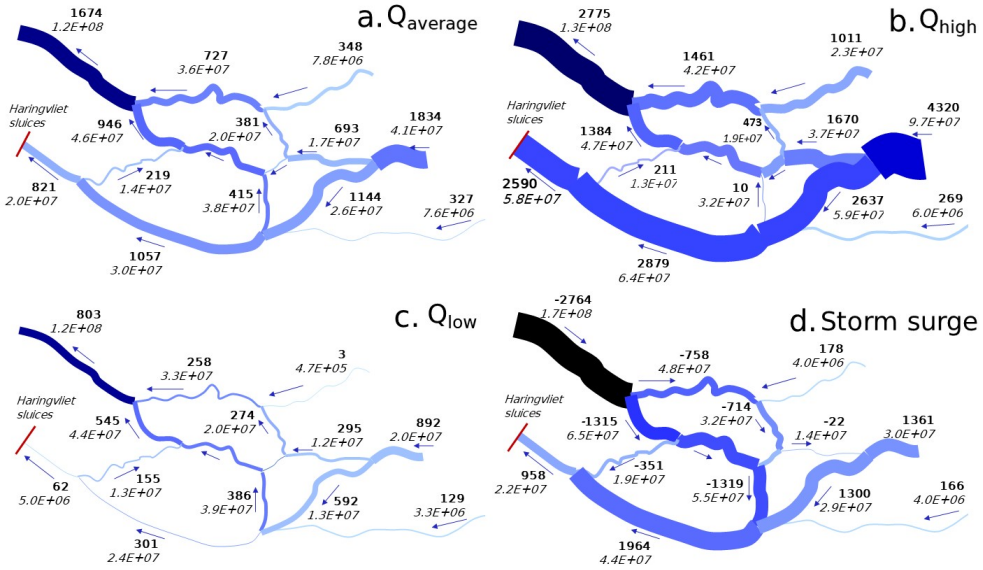


Figure 2. Discharge (m^3/s) and tidal volumes ($m/63$) per branch for normal tidal conditions and a. normal, b. high and c. low river discharge and for a d. storm surge combined with a normal river discharge respectively. The width of the lines are proportional to the discharges, the darkness of the 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. For clarity, the discharge values are in bold, and the tidal volumes are in italics.

2.2.1 Dredging volumes

Volumes of dredged material from the branches of the RMD used are combined reports from the regional waterway management (Rijkswaterstaat West-Nederlands-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 (van Dreumel, 1995; Snippen et al., 2005; Becker, 2015; Frings et al., 2019) as new composition data for the mouth area is 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 harbours and for the Nieuwe Waterweg and Nieuwe Maas branches. The other branches in the system rely on the only other available composition data which 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 "lost" 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 dumping 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 once-off events, here

channel deepening. 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.

Two kinds of major engineering events occurred in the timeframe of this sediment budget which caused capital dredging or increased maintenance to occur in either the branches or the ports and branches of the RMD. The first kind is 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 second kind is 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.

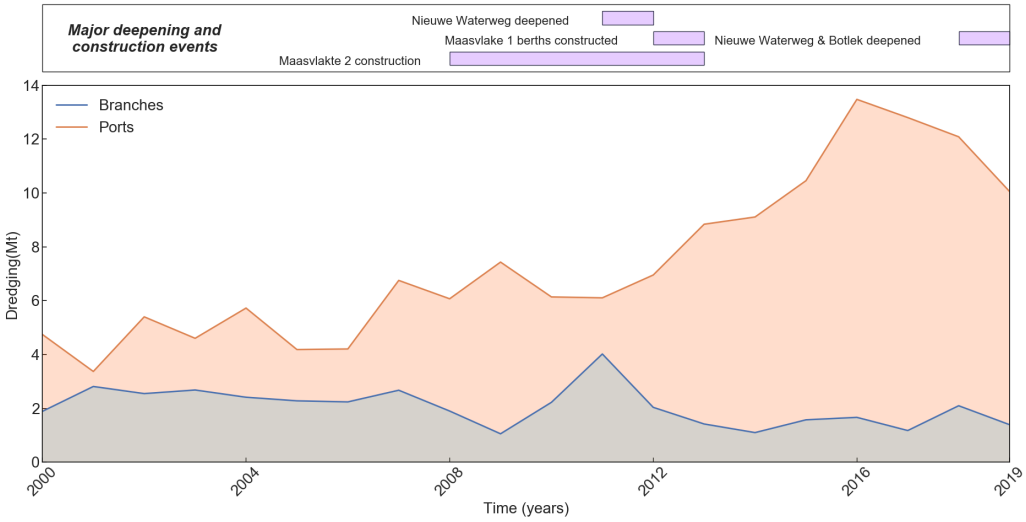


Figure 3. Total amount of dredging (Mt) in the branches and ports of the RMD with a timeline of major engineering or construction works. Note that the volumes of dredging for the Nieuwe Waterweg deepening and Botlek deepening are both included in the branches portion of the dredging volumes as the Botlek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

2.2.2 Bed elevation differences

Single and multibeam bathymetry surveys carried out by the Rijkswaterstaat (national waterways authority) are 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 supplementary information for further explanation).

2.3 Suspended and bedload fluxes

Suspended and bedload material enter the system from three major upstream rivers the Waal, Lek and Maas.Though large amounts of suspended and bedload material are

discharge via the main entrance channel in the Nieuwe Waterweg, an even larger amount of sediment is imported (see Fig. 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 from previous budgets (van Dreumel, 1995; Snippen et al., 2005; Becker, 2015; Frings et al., 2019) who make use of various methods to collect these fluxes. The budget is highly sensitive to the values chosen at the boundaries and thus the range of values is also analysed. In particular the values of suspended and bedload flux at the coastal boundary have not been updated since the budgets of van Dreumel (1995) and Snippen (2005). The margin of error sums to 2Mt (see Fig. 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 the bed level change Δ_z. There is however, not sufficient data available to determine how the bedload and suspended load is internally distributed.

2.4 Tidal Prism-Area (PA) relations and hydraulic geometry relations

To find out whether branches are close their equilibrium bed level, or whether they are too deep and have the tendency to sediment or too shallow and have the tendency to erode, tidal prism-area (PA) relations are used. The PA relationships calculated in this report follow a derived equation from the original tidal prism-area 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. Here 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.

A 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.

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. Discharge and velocity were extracted to calculate the volume of discharge (combined fluvial and tidal) passing through the cross-sectional area during four scenarios: (1) normal discharge, (2) high discharge, (3) low discharge and (4) storm surge at the coastal boundary. Details of the model and boundary conditions of the period selection are included in the supplement. The periods were all se-

lected from the 2013 run for the model as this year covered all conditions of interest. 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. Discharge and flow velocity were also determined from the model.

3 Results

3.1 Fluxes of suspended and bedload material

The average values (of van Dreumel (1995), Snippen et al. (2005), Becker (2015) and Frings et al. (2019)) for suspended and bedload material entering and exiting the system can be seen 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 using these boundaries as closing terms in the various budgets (see supplementary information for confidence and errors in these values).

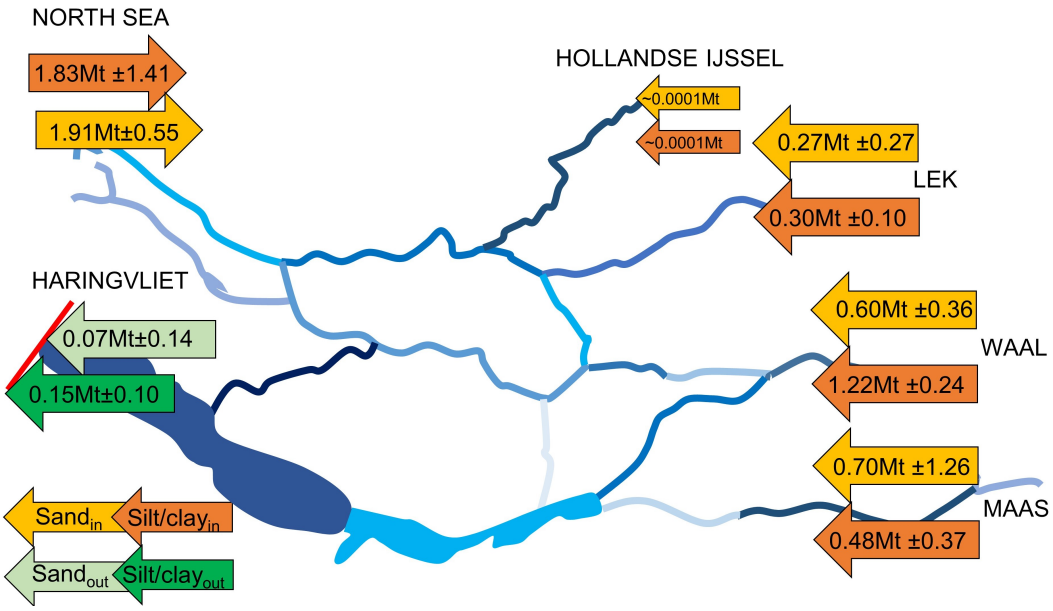


Figure 4. Annual average fluxes of suspended and bedload sediment in the RMD. Average flux of suspended (silt/clay) and bedload (sand) sediment in Mt/year from van Dreumel (1995), Snippen et al. (2005), Becker (2015) and Frings et al. (2019) with error margins indicating the range of possible values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

3.2 A negative sediment budget

The sediment budget shows a clear negative trend (Fig. 5) in recent years linked to increased dredging of harbours areas near the mouth in recent years. This trend is true for both methods of calculation (sediment transport and bed level change) but with differing magnitudes. Changes in magnitude are largely linked to the uncertainties in incoming sediment fluxes. Note that no bed level data was available for the ports and har-

bours, 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 a net results on 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 finalized 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. As however, the influx at the sea is kept constant in the calculation of the combined budget (due to a lack of data), there is a larger negative budget calculated than deemed to be correct. This further stresses the need for constant sediment measurements at the mouth.

There is however a large margin of error associated with both methods due to the various inherent issues with the data as elaborated in the supplement. Nevertheless, there is without doubt a sediment deficit in the region evidenced by both methods which is contributing to a large deficit over time.

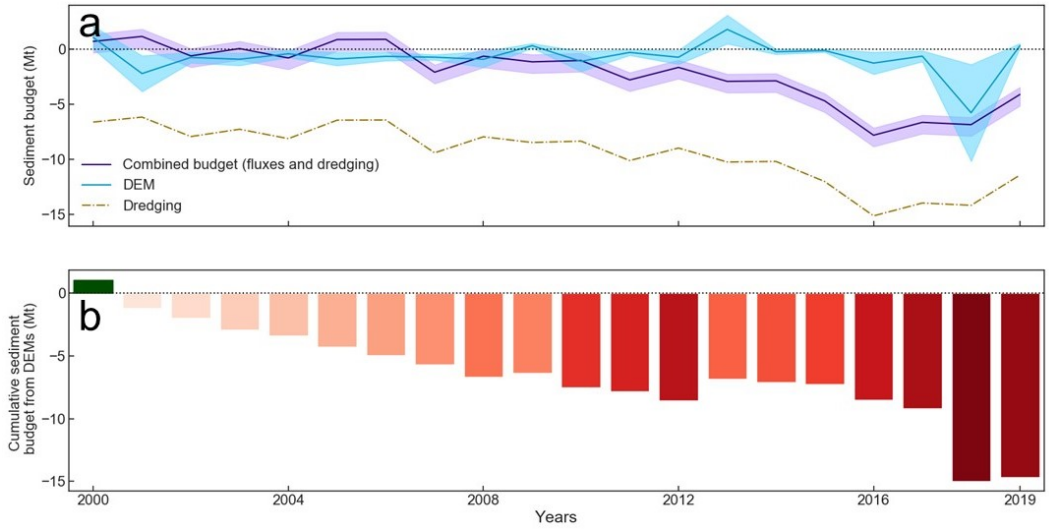


Figure 5. a. Annual sediment budget as calculated by the following two methods: 1. Combined budget as described in Equation1 and 2. DEM budget (Δ_z). Error margins are based on 1. the range of possible fluxes at the upstream and downstream boundaries (from van Dreumel (1995), Snippen et al. (2005), Becker (2015) and Frings et al. (2019) (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.

3.3 Bed level trends for individual branches

The negative sediment budget as calculated by the DEM method does not affect all the branches evenly and clear differences can be marked in Figure 6. The cumulative budgets (Fig. 6a) clearly show that between 2000-2019 the biggest changes to bed level occur in the Nieuwe Waterweg, Nieuwe Maas and Oude Maas. The average dredged depth of the channels at the mouth i.e. the Nieuwe Waterweg and Nieuwe Maas have increased, which causes part of the negative bed level trends in these branches. Thus the average "natural" bed level trend (where the impact of dredging is removed) presents

a more accurate picture (Fig. 6b). Note that for channels with harbours and ports, only the dredging volumes in the channels themselves and not the volumes of the ports and harbours are subtracted.

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 rather stable(Haringvliet, Spui, Dordtse Kil, Bergsche Maas and Nieuwe Merwede). The Oude Maas is a clear problem area as it shows extremely rapid erosion.

Previous work in the RMD indicated that two of the cross-cut channels, Spui and Dordtse Kil are undergoing severe erosion (Becker, 2015), which is not the case for the more recent bed level data. Older bed level data indicated that both Spui and Dordtse Kil branches were strongly eroding due to the changing tidal propogation patterns associated with the closure of the Haringvliet. However the latest bed level indicates that this erosive trend is slowing down and the branches are now reaching some form of "equilibrium". We propose several compound reasons for this. The Spui contains several sharp bends and thus contains both strong erosive pits and sills which cause extreme local variations in bed level data. Recently several of these pits are filling in, or erosion is halted, whilst sills are continuing to grow and so the trend is showing a neutral bed level trend. The southern part of the Dordtse Kil has a strongly varying bed with migrating bed forms which similar to Spui can cause false trends in the bed level data as some bed forms are removed by dredging, thus timing of surveying becomes crucial. The Dordtse Kil also has significant local changes such as dredging events and added sediment which is used to reinforce banks which can skew the trends devrived from the bed level data. Another factor that is important is the presence of hard layers in these branches which are limiting changes, we propose that in recent years the pits, holes and deeper parts of these branches are reaching hard layers or are reaching an equilibrium depth and are thus no longer eroding as quickly as before. Scours can reach an equilibrium depth if their surrounding bed level remains the same which is occurring in these branches. In the Oude Maas several scours are present, but the negative erosive bed level trend continues due to the formation of new scours and degradation of the surrounding bed level (which is a clay layer). A further possibility is that the channels are reaching an equilibrium depth, deeper channels with lower flow velocities no longer show severe erosion. This may not be reflected in the PA relations because this change has only occurred recently and the bed level data in the 1D model has not been sufficiently updated.

A further outlier is the Haringvliet. Previous budgets indicate that the Haringvliet is sedimenting, which is expected as this former estuary is now almost a dead end in the channel network. Unfortunately, there is a lack of data for the Haringvliet with the only additional data for this budget being a full survey in 2013 and partial surveys in 2018. Thus this trend is not well qualified and the bed level trends in the Haringvliet should be further investigated based on more complete bed level surveys.

3.4 Deviations from equilibrium cross-sectional area relations

The PA relations indicate whether each branch will erode or sediment if there were no anthropogenic interference in the system, based on the dimensions of the branches and hydrodynamic conditions. The plotting positions of channels relative to the PA relations indicate that in the absence of dredging activity, situation the southern branches (Haringvliet, Hollands Diep) and part of the Nieuwe Maas would be sedimenting and the remaining northern branches (Nieuwe Maas, Nieuwe Waterweg, Oude Maas) and cross-cut channels (Dordtse Kil, Noord, Spui) would mainly erode (Fig. 7a). When comparing this with the natural bed level changes (Fig. 6b) the main outliers are the cross-cut channels, Dordtse Kil and Spui which are not eroding as severely as the P/A suggests.

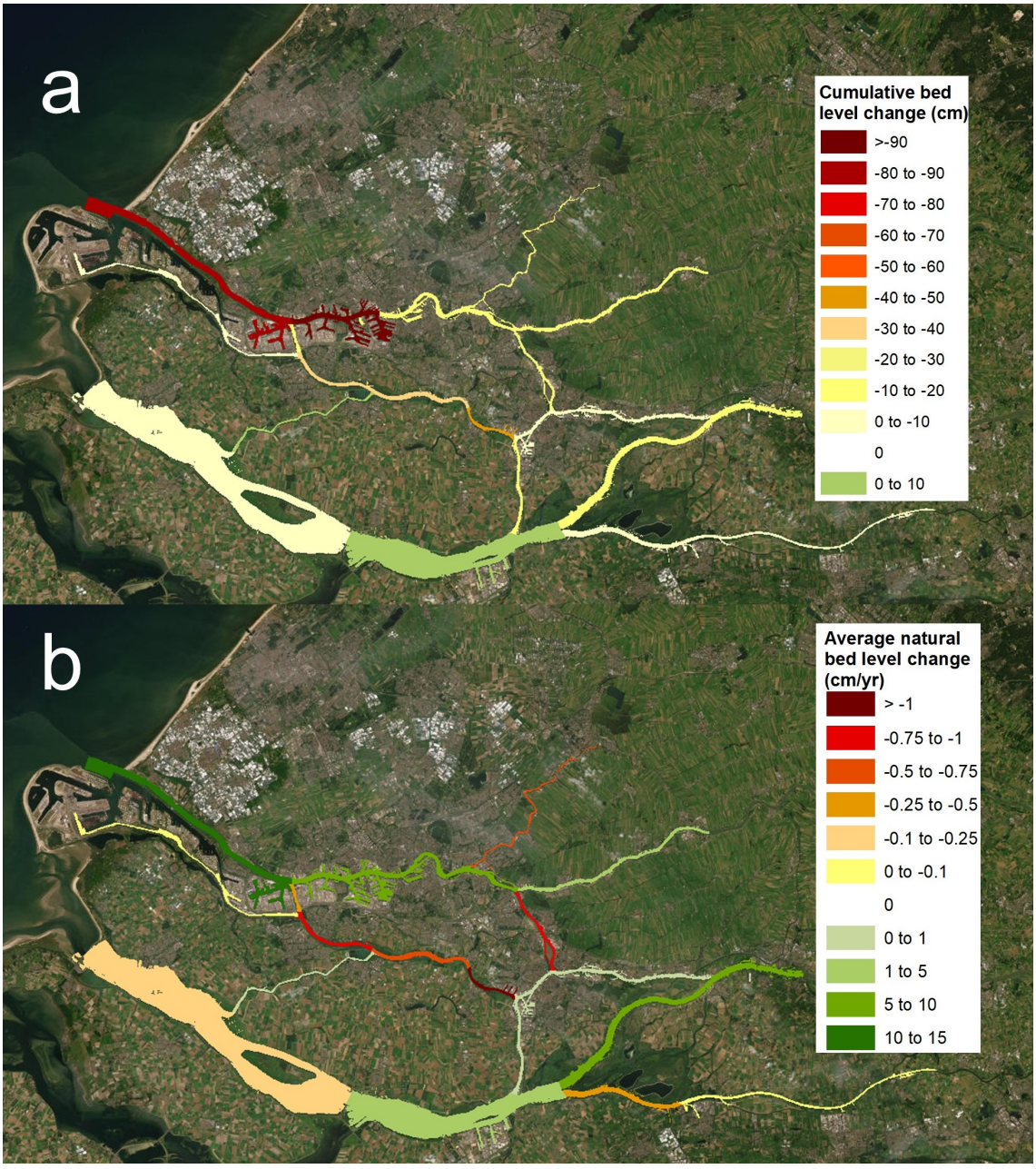


Figure 6. a.The cumulative bed level change (cm) for each branch for 2000-2019. b. The average natural bed level change (without the dredging term) per branch (in cm/yr) for 2000-2019.

According to the PA relation, the Nieuwe Waterweg should also be eroding or near equilibrium, however the natural bed level trends (without dredging) indicate a strong sedimentation trend. In the Nieuwe Waterweg tidal prism (P) has been increased as the channel was deepened and thus we now expect to see a larger cross-sectional area (A), however the cross-sectional area is not large enough to place it in the sedimentation regime. The Nieuwe Waterweg has 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 can be captured in the PA relations. The

strongly stratified conditions are in part responsible for this deviation, but further study is required to indicate what precisely the influence is.

Figure 7c indicates the relative impact of the rivers and tides in the various branches by comparing the ratio of the mean velocity to 90th percentile velocity. The high ratio in the upper branches (Lek, Waal, Maas) indicates that river flow dominates in these branches. Thus, these riverine branches are compared with the QA relation

As seen in Figure 7d, 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 sedimenting but according to its hydraulic geometry should be eroding. The Bergsche Maas and Amer branches are also showing slight erosion according to the natural bed level trends but should be sedimenting according to their hydraulic geometry. The Hollandse IJssel branch is at present 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 mouth area

Regardless of future sea level rise, our analyses show that the Rhine-Meuse Delta is currently losing sediment due to dredging activities, while some branches erode due to changed hydrodynamics in the channel network. Especially the large mouth and port area have lowered significantly in the past two decades while they would naturally gain sediment in the absence of dredging. Past and ongoing activities changed the character of the RMD from a net fluvial sediment trapping system to an estuarine system that increasingly traps sediment from the sea. The sediment import at the coastal boundary is strongly dependent on the strength of estuarine circulation i.e. the landward flow near the bed and seaward flow near the surface which is driven by densitiy differences between fresh and seawater which is in turn dependent on river discharge, tidal amplitude and mean water depth. These complex processes as described by de Nijs et al. (2008, 2009); de Nijs and Pietrzak (2012) are currently resulting in sediment import at the mouth. The deep mouth area combined with sea level rise will lead to further sediment import in the future. This natural trapping opposes the interference but the trapped sediment is continuously removed by maintenance dredging.

As a result of reduced import of sand and increased trapping of mud, sediment is fining in the mouth area. Moreover, there are system-wide effects on tidal dynamics and redistribution of sediment due to closure of one of the mouths by a dam, in particular leading to an erosive trend in the cross-cut channels. The cumulative bed lowering in the cross-cut channels and the volume of sediment removed 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 which will continue in the foreseeable future. Below we discuss the main trends and their causes in view of late Holocene development of the system and recent increases in human interference and look forward to likely future development. The sensitivity of the conclusions to the uncertainties in the data is briefly discussed. The main insights are then compared with, and generalized to other urbanized deltas in the world.

4.1.1 Changes in dredging intensity and in sediment composition

Given the increased yearly dredging volume of 6 Mt in the ports and harbours, whilst their required dredge 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 (Fig. 3) . We argue on the basis of timing, that the main cause of changing sediment fluxes is the construction of the Maasvlakte 2. The focus of Environmental Impact Assessment reports prior to, during and after construction of the Maasvlakte 2 are the impact of construction on large scale sediment transport along the Dutch coast, the influence on ecology (Heinis et al., 2005; Borst et al., 2013) and the impact of the construction on sand removal from the North Sea (van Kruchten et al., 2008). 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 harbours (van Ledden, 2005; Winterwerp, 2006; van Kruchten et al., 2008).

However, the volumes of maintenance dredging far outweigh the expected change to sedimentation rates in the ports and harbours and moreover the continued need for increased dredging in the ports and harbours was not predicted. Local investigations into the increase in maintenance dredging volumes conclude that there has been local changes in sedimentation patterns in the ports and harbours due to the development of the Maasvlakte 2 and in particular that land reclamation during construction provided extra suspended sediment to the water system (de Bruijn, 2018). Thus it is likely that increased dredging is a consequence of the systems response of changing sediment fluxes as a result of the construction of the Maasvlakte 2.Most recently, the maintenance dredging volumes are decreasing again (see Fig. 3) indicating that the extreme system response to construction is slowing down or perhaps stabilising.

Another key factor which creates peaks in both branch and port dredging volumes is channel deepening events. In the case of the RMD, the Nieuwe Waterweg branch represents the largest fraction of branch maintenance dredging volumes. As described in Figure 6 the Nieuwe Waterweg is naturally gaining sediment which is continuously removed to allow navigation to the inland ports of the RMD. The Nieuwe Waterweg underwent two significant channel deepening events in 2012-2013 as part of the development of the Maasvlakte 2 and in 2018-2019 to create a deeper navigable depth for shipping. As seen in Figure 3 maintenance dredging of branches decreases following the 2012-2013 event and since 2018 (on year before the end point of this budget). Since 2018, the maintenance dredging volumes are decreasing in both the Nieuwe Waterweg and in the ports and harbours (Leuven, Bart, et al., 2019). Thus in the long term, the channel deepening events reduce required maintenance dredging, however the system response to these events takes time to stabilize in terms of sediment circulation and sediment dynamics.

It is also conceivable that the ports are now more efficient at trapping sediment than previously as they became deeper, particularly during high river discharge due to salinity-induced density currents (de Nijs et al., 2009; de Nijs & Pietrzak, 2012). For example the Botlek harbour has 100% trapping efficiency (de Nijs et al., 2009). Harbour basins in tidal dominated regions typically receive high volumes of silty and clayey material through suspended sediment transport and less amounts of sand due to the lower energy waters in harbours compared to channels. In the RMD a combination of complex hydrodynamics create an estuarine turbidity maximum (ETM) meaning that the ports and harbours have a strong tendency to siltate (de Nijs et al., 2008). This is reflected in the increasing silt content in the ports and harbours as noted in this budget. The provenance of this material is not explored in this budget but in general the sediments in the western port areas are marine in origin whilst the eastern ports (around Rotterdam city) are in-

fluenced by fluvial sediments (Verlaan & Spanhoff, 2000; T. Vellinga & Eisma, 2005). Meanwhile, the sediment deposited in the branches e.g. the Nieuwe Waterweg and Nieuwe Maas are fluvial in origin (de Nijs & Pietrzak, 2012). This further indicates the need to understand how much of which type of sediment is coming in at the mouth of the RMD and where it is being deposited.

4.1.2 Possible causes of local change in the mouth area and system-wide effects

Possibly, more sediment is now entering the system linked to changing hydrodynamics in the mouth area. 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 could be crucial for sustainable sediment management in the future, providing the system with an opportunity for land building or growth, particularly as sea levels continue to rise and these dynamics may be further altered. To fully understand the sediment dynamics in relation to estuarine processes at the mouth, more measurements and data are required. The branches and eastern ports are experiencing increase silt and clay and less sand than reported by van Dreumel (1995). This is likely attributed to a relatively increased silt import from upstream but could also could stem from an increase in fine sediment import from the coast which reaches further into the system with a long salt wedge.

The composition of the material in question is an important consideration in particular for dredging as it determines not only the type and cost of dredging but also where the dredging material can be used, relocated or disposed of. A trend of silting up 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 (van Maren et al., 2016). This clearly indicates that not only process measurements are needed in the mouth but also sediment composition data of the branches of the RMD must be updated. While advances in acoustic measurements have increased data quality considerably, continuation of labour-intensive, direct sediment sampling and analysis remains critical.

4.2 Comparison of bed level trends and deviation from equilibrium relations for the cross-sectional area

The P/A plots (Fig. 7) give an indication of which branches have an overlarge cross-sectional area with reduced flow which will have the tendency to 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.

The Haringvliet and Hollandsch Diep are firmly located in the sedimentation regime. Due to closure of the mouth, flow velocities in these branches has greatly reduced, inducing a sedimentation front which started in the Hollandch Diep and is migrating westwards.

The Oude Maas and Noord are eroding due to the increased tidal currents following the closure of the Haringvliet mouth, which is in line with the predictions from the PA relations. Like the Oude Maas and Noord, the cross-cut channels of Dordtse Kil and Spui also eroded heavily following the closure of the Haringvliet, as predicted. However, the erosion in these branches has slowed down since 2012, which is likely linked to poorly

erodible substrates which have recently begun to limit bed level erosion, in combination with some deeper sandy parts that have reached equilibrium (Leuven, Bart, et al., 2019). If these layers were to break open, the erosion rates would once more increase severely as is locally already happening in the Oude Maas(Huismans et al., 2016).

The Nieuwe Maas shows a spread of data in both the erosion and sedimentation regime, which is due to strong local variations in cross-sectional area and related P/A-values (Fig. 7A), which indicates erosion in the western part and sedimentation in the eastern part. Over the full branch this averages out to sedimentation, which is in line with the derived natural bed level trends (Fig. 6B). For all the tidal branches, most erosion takes place during storm conditions (diamond points in Fig. 7b), which is different than for river-dominated branches which typically have most erosion during high river discharge.

The upstream tidal river branches can be compared with the trend of the hydraulic geometry relations valid for rivers. Most of the branches lie to the sedimentation side of the relations. This is as expected because the anthropogenic deepening of the rivers has lowered their flow velocity. The downstream estuarine branches all have larger cross-sectional areas than expected from the net discharge, in part because tidal currents contributed to their formation, in part because they were deepened and, for the Haringvliet and Hollandse IJssel because sluices control the discharge. On the other hand, the upstream Boven Merwede and Waal show a tendency to erode in comparison with the hydraulic geometry relations. This fits with the observed response of the channel to extensive human intervention such as narrowing and the construction of extensive groynes. The upstream branches have eroded over the past century due to decreased upstream sediment supply and upstream armouring, and the deepening caused by the narrowing and the erosion increased the bed shear stress (Frings et al., 2009). The bed load sediment is mainly captured in the Beneden Merwede (Frings & Kleinhans, 2008), where is it removed from the system by dredging. In terms of volume this is a minor loss to the RMD, but it is the only source of medium and coarse sand.

4.3 The need for sediment budgets of sufficient quality

This RMD, despite the 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 supplementary information. By including monthly surveys the extreme trends calculated by using only one yearly averaged DEM are balanced out and a more accurate picture is given (see Figure 8). In addition, upon combining three methods to analyze the sediment budget and sediment dynamics (bed level analysis, flux analysis and PA-analysis), the causes of the observed trends became clear. 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 relative importance of the declining input at the boundaries, dredging and changed tidal flow patterns.

A factor absent from both this and previous sediment budgets is an interannual perspective and the importance of seasonality. Sediment delivery is driven by discharge and tides both of which show strong seasonality. Moreover, many of the large deposition or erosion trends can be due to specific events e.g. storm surges or high discharge as indicated 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 the seasonality. For this to be possible, a much higher quantity and spatial extent of data is urgently required, especially in the mouth area. To improve the sediment budget, as elucidated 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.

The large bed level changes in the period considered here, especially following the construction of the Maasvlakte 2, have altered sediment dynamics in the RMD leading to a strong increase in sedimentation in the port area and a doubling of the dredging volumes. The sediment budget furthermore stresses that more sediment is taken out than sedimentation is occurring, resulting in a negative sediment budget. This is converse to what is required, as the central branches of the system are starved of sediment and degrade (triggered by the altered hydrodynamics due to the closure of the Haringvliet) and the future need for sediment to cope with sea level rise. Since the most recent sediment budget was created (2012), we see a further shift in the system, whereby more sediment has to be removed through dredging and a change in the composition of this sediment in the mouth area. Given that upstream the bed levels of the Rhine are degrading (Frings et al., 2009) quantifying the coastal flux is crucial. Given the large increase in dredging numbers since construction of Maasvlakte 2, sediment import from the coastal boundary has likely changed drastically, but the lack of flux measurements to confirm this make the coastal boundary a key weakness in the current and previous budgets.

While much of the study area 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 budget 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) which it crucially needs to prevent the system from drowning and to maintain its delicate ecosystem, which falls under Natura2000 legislation.

The striking observations for the RMD are the high levels of dredging and sand mining which are causing the ever increasing negative budget.

The RMD is a rapidly expanding urban area with infrastructure, particularly dikes and underground tunnels and cables that must be safeguarded. Changes in the hydrodynamics in response to closure of one of the estuary branches and resulting bed level trends can cause instability of dikes and exposure of these tunnels and cables. In particular in the cross-cut channels of the RMD where there are hardly erodible layers where, if these hard layers break and runaway erosion ensues, infrastructure is at risk. Disruption to the sediment budget by intensive dredging may aggravate these trends. Even without the sea level rise expected in the future, the erosional drivers in the delta already exceed the sediment supply from the upstream and seaward boundaries by an order of magnitude . Moreover, changing upstream discharge, seasonality of discharge and tides, and salinity intrusion may provide further challenges in the future.

4.4 Comparison with, and implications for deltas globally

A recent model study suggests that large and deep estuarine systems may face sediment starvation and will 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 by definition dominated by fluvial supply. 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. Deltas globally including the Mekong, Pearl and Danube

deltas are already facing similar challenges and are also experiencing sediment budgets which are anthropogenically controlled (Syvitski & Saito, 2007; Giosan et al., 2013; Zhang et al., 2015; Li et al., 2017).

The morphology of the Mekong delta reacts in the same fashion to an anthropogenically controlled negative sediment budget as the RMD, namely, uneven sediment distribution 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 e.g. changing sediment supply from upstream rivers and the coast are uncertain but projections indicate an increasingly negative budget (Van Manh et al., 2015; Allison et al., 2017; Dunn et al., 2019) 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. A negative sediment budget causes uneven bed degradation and thus provides a challenge for sediment management.

The sediment budget of the Pearl Delta is dominated by human actions which far outweigh the effect of the natural sediment supply and arguably the delta has and is experiencing human interference that far outweighs that of the RMD or indeed most deltas globally. Despite the Pearl having a large upstream sediment delivery and showing net growth (Zhang et al., 2015), this is predicted to change in the future as the sediment flux to the deltas has declined since the 1980s (Dai et al., 2008)with further rapid decline of sediment expected. This decline in sediment is associated with several environmental issues in the delta linked to changing water transparency and chemistry In the Pearl Delta rapid and extensive land reclamation is occurring and this is combined with two large mega dams upstream to result in decreased sediment supply. Projections for the Pearl indicate that the natural rate of sedimentation cannot compensate for the extreme predicted anthropogenic influence on the sediment budget which will cause sediment deficit leading to large scale coastal and channel erosion (Ranasinghe et al., 2019). As the Pearl developed it became heavily embanked and fixed in the same manner as the RMD with the same concerns regarding the economy and shipping as the priority for sediment management. It too sees 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). 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. The Pearl Delta with high population and high levels of human interference may represent a future state for the RMD as further urbanization continues in the delta as the Port of Rotterdam continues to grow.

The Danube delta, like the RMD, has historic dikes and and levees and a history of changing the length and width of branches for flood protection through dredging and canalisation. Currently the Danube delta shows a positive sediment budget controlled by sediment runoff in the branches (Mikhailova et al., 2019), however if future planned anthropogenic activity occurs this will change. 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). 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). The Danube is already looking at what dredging and engineering measures are required to allow for increased navigation (Maslov, 2019) and the possible hydrological and morphological implications of anthropogenic interference and in this process the RMD can serve as a useful example. The implications of alter-

ing 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.

Whilst the deltas discussed above are vastly different in size, morphology, tidal and morphological characteristics, what is clear is that 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.

5 Conclusion

Urbanized deltas need sediment to counteract subsidence, future sea level rise and channel incision that destabilizes infrastructure. The constructed sediment budget of the Rhine-Meuse Delta 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 which has caused branches that experience strong sedimentation and require high levels of dredging to maintain navigation. Meanwhile some branches that 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 anticipated 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 in sediment composition is observed, with a change to siltier sediment, which is disadvantageous for ecology and the 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. Further measurements are required to properly quantify the sediment import at this seaward boundary. As estuaries and deltas worldwide become more anthropogenically influenced, it is key to learn from the issues that have arisen in the Rhine-Meuse Delta. The response of the system to interference such as dredging, port construction and closure of major river branches on the system has amplified unwanted trends. These negative effects include risks to flood and channel bank safety, threats to habitat quality, and the elimination of the natural means to mitigate negative trends through sediment management.

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References

Allison, M. A., Nittrouer, C. A., Ogston, A. S., Mullarney, J. C., & Nguyen, T. T. (2017). Sedimentation and survival of the mekong delta: A case study of decreased sediment supply and accelerating rates of relative sea level rise. *Oceanography*, *30*(3), 98–109.

Becker, A. (2015). Sediment in (be)weging. *Deltares 1208925-000*.

Bendixen, M., Best, J., Hackney, C., & Iversen, L. L. (2019). *Time is running out*

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	Sint Elizabeth Flood*	Four subsequent inundations create the Biesbosch wetland nature 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 stop siltation of the delta.
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 in the Nieuwe Waterweg to expand the Botlek.
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 harbour 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 arm of the RMD is closed and becomes a large complex of sluices. Water and sediment no longer enter the system at this boundary 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	Dyke 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 areas of the Biesbosch.
2008-2013	Maasvlakte 2 constructed	Sediment is at the bottom of the North Sea to increase area of the Maasvlakte port
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 metres to accommodate ships with a draft of 15m

*Not anthropogenic but had major influence on the system

for sand. Nature Publishing Group.

Best, J. (2019). Anthropogenic stresses on the worlds big rivers. *Nature Geoscience*, *12*(1), 7–21.

Bianchi, T. S., & Allison, M. A. (2009). Large-river delta-front estuaries as natural recorders of global environmental change. *Proceedings of the National Academy of Sciences*, *106*(20), 8085–8092.

Borst, W., Vellinga, T., & Van-Tongeren, O. (2013). The Monitoring Programme for the Maasvlakte 2 Construction at the Port of Rotterdam Part II. *Terra-Aqua*(130).

Dai, S., Yang, S., & Cai, A. (2008). Impacts of dams on the sediment flux of the pearl river, southern china. *Catena*, *76*(1), 36–43.

Dan, S., Stive, M. J., Walstra, D.-J. R., & Panin, N. (2009). Wave climate, coastal sediment budget and shoreline changes for the danube delta. *Marine Geology*, *262*(1-4), 39–49.

de Bruijn, L. (2018). *Maintenance dredging in the Port of Rotterdam: A research to the increase in maintenance dredging volume at Port of Rotterdam* (Master's Thesis). TU Delft.

de Haas, T., Pierik, H., Van der Spek, A., Cohen, K., Van Maanen, B., & Kleinhans, M. (2018). Holocene evolution of tidal systems in the netherlands: Effects of rivers, coastal boundary conditions, eco-engineering species, inherited relief and human interference. *Earth-Science Reviews*, *177*, 139–163.

de Nijs, M. A., & Pietrzak, J. D. (2012). Saltwater intrusion and ETM dynamics in a tidally-energetic stratified estuary. *Ocean Modelling*, *49*, 60–85.

de Nijs, M. A., Winterwerp, J. C., & Pietrzak, J. D. (2008). SPM variations in a harbour basin. In *Proceedings in Marine Science* (Vol. 9, pp. 357–378). Elsevier.

de Nijs, M. A., Winterwerp, J. C., & Pietrzak, J. D. (2009). On harbour siltation in the fresh-salt water mixing region. *Continental Shelf Research*, *29*(1), 175–193.

Dunn, F. E., Darby, S. E., Nicholls, R. J., Cohen, S., Zarfl, C., & Fekete, B. M. (2019). Projections of declining fluvial sediment delivery to major deltas worldwide in response to climate change and anthropogenic stress. *Environmental Research Letters*, *14*(8), 084034.

Elliott, M., Day, J. W., Ramachandran, R., & Wolanski, E. (2019). A synthesis: what is the future for coasts, estuaries, deltas and other transitional habitats in 2050 and beyond? In *Coasts and estuaries* (pp. 1–28). Elsevier.

Eslami, S., Hoekstra, P., Trung, N. N., Kantoush, S. A., Van Binh, D., Quang, T. T., & van der Vegt, M. (2019). Tidal amplification and salt intrusion in the Mekong Delta driven by anthropogenic sediment starvation. *Scientific Reports*, *9*(1), 1–10.

Eysink, W. (1990). Morphologic Response of Tidal Basins to Changes: The Dutch Coast: Paper no. 8. In *Coastal engineering 1990* (pp. 1948–1961).

Frings, R., Berbee, B. M., Erkens, G., Kleinhans, M. G., & Gouw, M. J. (2009). Human-induced changes in bed shear stress and bed grain size in the River Waal (The Netherlands) during the past 900 years. *Earth Surface Processes and Landforms*, *34*(4), 503–514.

Frings, R., & Brinke, W. B. M. T. (2018). Ten reasons to set up sediment budgets for river management. *International Journal of River Basin Management*, *16*(1), 35-40. Retrieved from `https://doi.org/10.1080/15715124.2017.1345916` doi: 10.1080/15715124.2017.1345916

Frings, R., Hillebrand, G., Gehres, N., Banhold, K., Schriever, S., & Hoffmann, T. (2019). From source to mouth: Basin-scale morphodynamics of the rhine river. *Earth-Science Reviews*. doi: 10.1016/j.earscirev.2019.04.002

Frings, R., & Kleinhans, M. G. (2008). Complex variations in sediment transport at three large river bifurcations during discharge waves in the river Rhine. *Sed-*

imentology, *55*(5), 1145–1171.

Giosan, L., Constantinescu, S., Filip, F., & Deng, B. (2013). Maintenance of large deltas through channelization: Nature vs. humans in the danube delta. *Anthropocene*, *1*, 35–45.

Giosan, L., Syvitski, J., Constantinescu, S., & Day, J. (2014, 12). Climate change: Protect the world's deltas. *Nature*, *516*, 31-3. doi: 10.1038/516031a

Gisen, J. I. A., & Savenije, H. H. (2015). Estimating bankfull discharge and depth in ungauged estuaries. *Water Resources Research*, *51*(4), 2298–2316.

Habersack, H., Hein, T., Stanica, A., Liska, I., Mair, R., Jäger, E., ... Bradley, C. (2016). Challenges of river basin management: current status of, and prospects for, the River Danube from a river engineering perspective. *Science of the Total Environment*, *543*, 828–845.

Haring, J. (1967). De verhouding van getijvolume en doorstroomprofiel in de Zeegaten Haringvliet, Brouwershavense Gat, Oosterschelde en de Mond van de Rotterdamse Waterweg uit alle beschikbare waarnemingen. *Nummer 40, Driemaandelijks Bericht Deltawerken en note K271 Rijkswaterstaat*.

Heinis, F., Van der Vegte, J., De Vlas, J., Van Ledden, M., & Jager, Z. (2005). *Impact of Maasvlakte 2 on the Wadden Sea and North Sea coastal zone-effects in the context of the Birds and Habitats Directives.* Consortium 3—MV2, client: Port of Rotterdam and RWS/RIKZ 2005.

Hoitink, A., Nittrouer, J., Passalacqua, P., Shaw, J., Langendoen, E., Huismans, Y., & van Maren, D. (2020). Resilience of river deltas in the Anthropocene. *Journal of Geophysical Research: Earth Surface*, *125*(3), e2019JF005201.

Hu, J., Li, S., & Geng, B. (2011). Modeling the mass flux budgets of water and suspended sediments for the river network and estuary in the Pearl River Delta, China. *Journal of Marine Systems*, *88*(2), 252–266.

Huismans, Y., van Velzen, G., OMahoney, T., Hoffmans, G., & Wiersma, A. (2016). Scour hole development in river beds with mixed sand-clay-peat stratigraphy.

Kirichek, A., Rutgers, R., Wensween, M., & Van Hassent, A. (2018). Sediment managment in the port of rotterdam. In *Book of abstracts* (Vol. 10).

Klaassen, G., Vermeer, K., & Uddin, N. (1988). Sedimentological processes in the Jamuna (Lower Brahmaputra) river, Bangladesh. In *Proceedings of the International Conference onFluvial Hydraulics* (pp. 381–394).

Kleinhans, M. G., De Haas, T., Lavooi, E., & Makaske, B. (2012). Evaluating competing hypotheses for the origin and dynamics of river anastomosis. *Earth Surface Processes and Landforms*, *37*(12), 1337–1351.

Kleinhans, M. G., Weerts, H. J., & Cohen, K. M. (2010). Avulsion in action: Reconstruction and modelling sedimentation pace and upstream flood water levels following a medieval tidal-river diversion catastrophe (biesbosch, the netherlands, 14211750ad). *Geomorphology*, *118*(1), 65 - 79. Retrieved from `http://www.sciencedirect.com/science/article/pii/S0169555X0900525X` doi: https://doi.org/10.1016/j.geomorph.2009.12.009

Kondolf, G. M., Schmitt, R. J., Carling, P., Darby, S., Arias, M., Bizzi, S., ... Wild, T. (2018). Changing sediment budget of the Mekong: Cumulative threats and management strategies for a large river basin. *Science of The Total Environment*, *625*, 114 - 134. Retrieved from `http://www.sciencedirect.com/science/article/pii/S0048969717334198` doi: https://doi.org/10.1016/j.scitotenv.2017.11.361

Leopold, L. B., & Maddock, T. (1953). *The hydraulic geometry of stream channels and some physiographic implications* (Vol. 252). US Government Printing Office.

Leuven, J., Bart, K., Stuij, S., Busnelli, M., van der Zee, P., & van Zanten, M. (2019). Monitoring Verdieping Nieuwe Waterweg, Chapter: Morphology. *RoyalHaskoningDHV iReport commisioned by the Port of Rotterdam. Available upon request.*.

Leuven, J., Pierik, H. J., van der Vegt, M., Bouma, T. J., & Kleinhans, M. G. (2019). Sea-level-rise-induced threats depend on the size of tide-influenced estuaries worldwide. *Nature Climate Change*, *9*(12), 986–992.

Li, X., Liu, J. P., Saito, Y., & Nguyen, V. L. (2017). Recent evolution of the mekong delta and the impacts of dams. *Earth-Science Reviews*, *175*, 1–17.

Marra, W. A., Kleinhans, M. G., & Addink, E. A. (2014). Network concepts to describe channel importance and change in multichannel systems: test results for the Jamuna River, Bangladesh. *Earth Surface Processes and Landforms*, *39*(6), 766–778.

Maslov, Y. (2019). Transformational aspects of the European Union strategy for the Danube Region. *Baltic Journal of Economic Studies*, *5*(3), 108–115.

Mikhailova, M., Kravtsova, V., & Morozov, V. (2019). Long-term variations of Danube Delta coastline. *Water Resources*, *46*(5), 659–669.

Nienhuis, J., Ashton, A., Edmonds, D., Hoitink, A., Kettner, A., Rowland, J., & Törnqvist, T. (2020). Global-scale human impact on delta morphology has led to net land area gain. *Nature*, *577*(7791), 514–518.

O'Brien, M. P. (1931). Estuary tidal prisms related to entrance areas. *Civil Engineering*.

O'Brien, M. P. (1969). Equilibrium flow areas of inlets on sandy coasts. *Journal of the Waterways and Harbors Division*, *95*(1), 43–52.

Parsons, A. J. (2012). How useful are catchment sediment budgets? *Progress in Physical Geography: Earth and Environment*, *36*(1), 60-71. Retrieved from `https://doi.org/10.1177/0309133311424591` doi: 10.1177/0309133311424591

Ranasinghe, R., Wu, C. S., Conallin, J., Duong, T. M., & Anthony, E. J. (2019). Disentangling the relative impacts of climate change and human activities on fluvial sediment supply to the coast by the worlds large rivers: Pearl River Basin, China. *Scientific Reports*, *9*(1), 1–10.

Schmitt, R., Rubin, Z., & Kondolf, G. (2017). Losing ground-scenarios of land loss as consequence of shifting sediment budgets in the mekong delta. *Geomorphology*, *294*, 58–69.

Snippen, E., Fioole, A., Geelen, H., Kamsteeg, A., Van Spijk, A., & Visser, T. (2005). Sediment in (be) wegingsedimentbalans Rijn-Maasmonding periode 1990–2000. *Rapport Rijkswaterstaat RIZA, afdeling WRE*.

Syvitski, J. P., Kettner, A. J., Overeem, I., Hutton, E. W., Hannon, M. T., Brakenridge, G. R., ... others (2009). Sinking deltas due to human activities. *Nature Geoscience*, *2*(10), 681–686.

Syvitski, J. P., & Saito, Y. (2007). Morphodynamics of deltas under the influence of humans. *Global and Planetary Change*, *57*(3-4), 261–282.

Temmerman, S., Meire, P., Bouma, T. J., Herman, P. M., Ysebaert, T., & De Vriend, H. J. (2013). Ecosystem-based coastal defence in the face of global change. *Nature*, *504*(7478), 79–83.

Tessler, Z. D., Vörösmarty, C. J., Grossberg, M., Gladkova, I., Aizenman, H., Syvitski, J., & Foufoula-Georgiou, E. (2015). Profiling risk and sustainability in coastal deltas of the world. *Science*, *349*(6248), 638–643.

Tessler, Z. D., Vörösmarty, C. J., Overeem, I., & Syvitski, J. P. (2018). A model of water and sediment balance as determinants of relative sea level rise in contemporary and future deltas. *Geomorphology*, *305*, 209–220.

van Dreumel, P. (1995). Slib- en zandbeweging in het noordelijk Deltabekken in de periode 1982-1992. *Afdeling Watersysteemkennis Rotterdam 11*.

van Bruchem, R. (2018a). Monstercampagne Rotterdam 2018. *HaskoningDHV Nederland B.V*, *BF5370*.

van Bruchem, R. (2018b). Monstercampagne Rotterdam 2018: addendum 2019. *HaskoningDHV Nederland B.V*, *BF5370*.

van Bruchem, R. (2019). Monstercampagne Rotterdam 2019. *HaskoningDHV Nederland B.V*, *BF5370-106*.

van de Kreeke, J., & Haring, J. (1980). Stability of estuary mouths in the Rhine-Meuse Delta. In *Coastal engineering 1980* (pp. 2627–2639).

van der Deijl, E. C., van der Perk, M., & Middelkoop, H. (2019). Pathways of water and sediment in the Biesbosch freshwater tidal wetland. *Wetlands*, *39*(1), 197–215.

van Kruchten, Y., Vellinga, T., & Heinis, F. (2008). A probabilistic analysis of the ecological effects of sand mining for Maasvlakte 2. *Delft University of Technology, Delft*.

van Ledden, M. (2005). Effects of Maasvlakte 2 on the Wadden Sea and the North Sea coastal zone - Track 1 detailed modelling research. *9R2847.A0*.

Van Manh, N., Dung, N. V., Hung, N. N., Kummu, M., Merz, B., & Apel, H. (2015). Future sediment dynamics in the mekong delta floodplains: Impacts of hydropower development, climate change and sea level rise. *Global and Planetary Change*, *127*, 22–33.

van Maren, D., Oost, A., Wang, Z., & Vos, P. (2016). The effect of land reclamations and sediment extraction on the suspended sediment concentration in the Ems estuary. *Marine Geology*, *376*, 147-157.

Vellinga, N., Hoitink, A., van der Vegt, M., Zhang, W., & Hoekstra, P. (2014). Human impacts on tides overwhelm the effect of sea level rise on extreme water levels in the Rhine–Meuse delta. *Coastal engineering*, *90*, 40–50.

Vellinga, T., & Eisma, M. (2005). Management of contaminated dredged material in the Port of Rotterdam. In *Managing European Coasts* (pp. 315–322). Springer.

Verlaan, P., & Spanhoff, R. (2000). Massive sedimentation events at the mouth of the Rotterdam waterway. *Journal of Coastal Research*, 458–469.

Winterwerp, J. (2006). Fluxes of fine sediment along the Dutch coast and the impact of Maasvlakte 2: a system description. *Deltares Z4046*.

Zhang, W., Xu, Y., Hoitink, A., Sassi, M., Zheng, J., Chen, X., & Zhang, C. (2015). Morphological change in the Pearl River Delta, China. *Marine Geology*, *363*, 202–219.

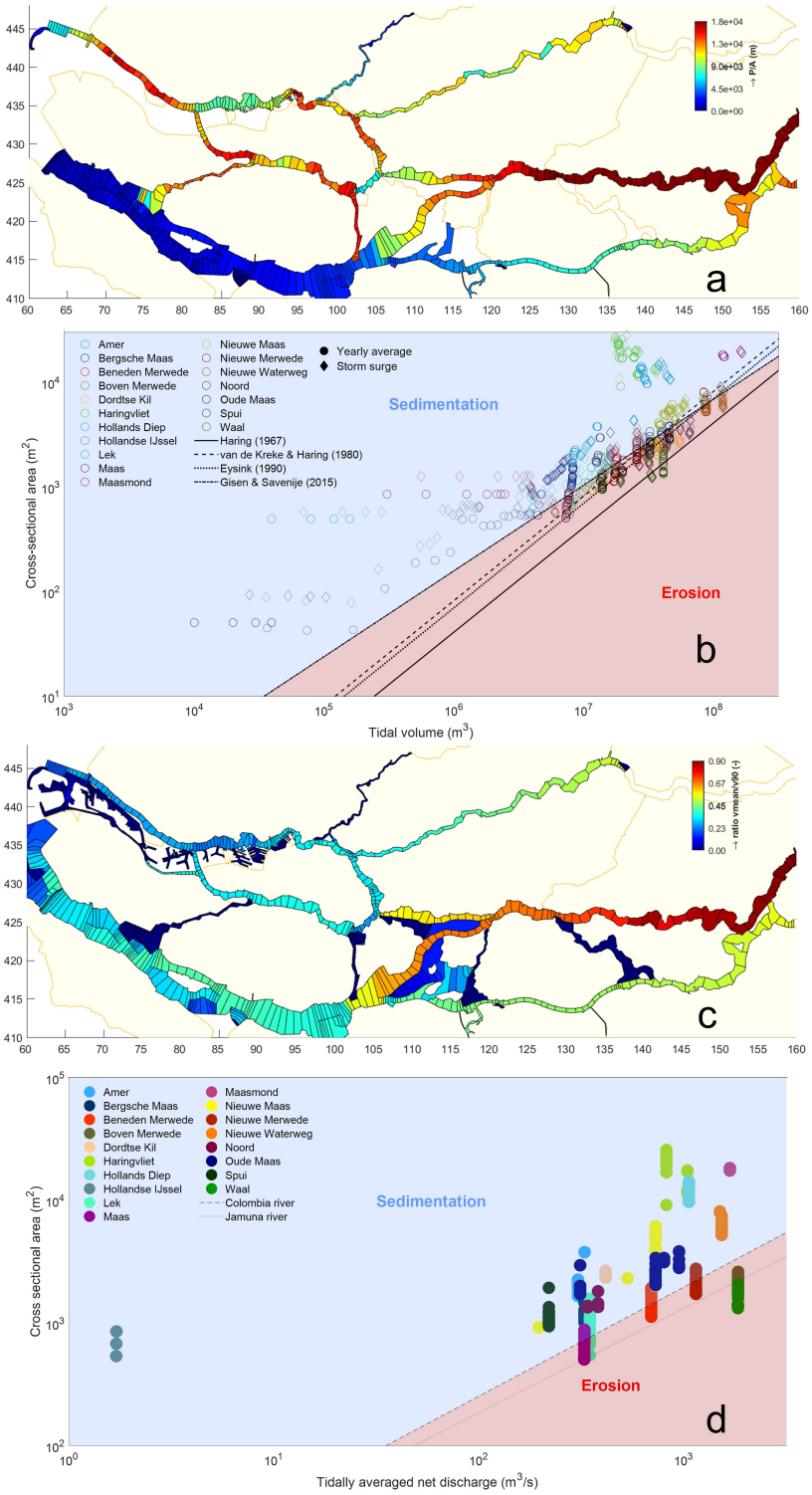


Figure 7. a.Map showing the yearly averaged P/A from the SOBEK-RE model for 2013. b. The P/A for the yearly average and storm surge conditions with relations from literature for the Netherlands (Haring, 1967; van de Kreeke & Haring, 1980; Eysink, 1990) and estuaries worldwide (Gisen & Savenije, 2015) 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.6

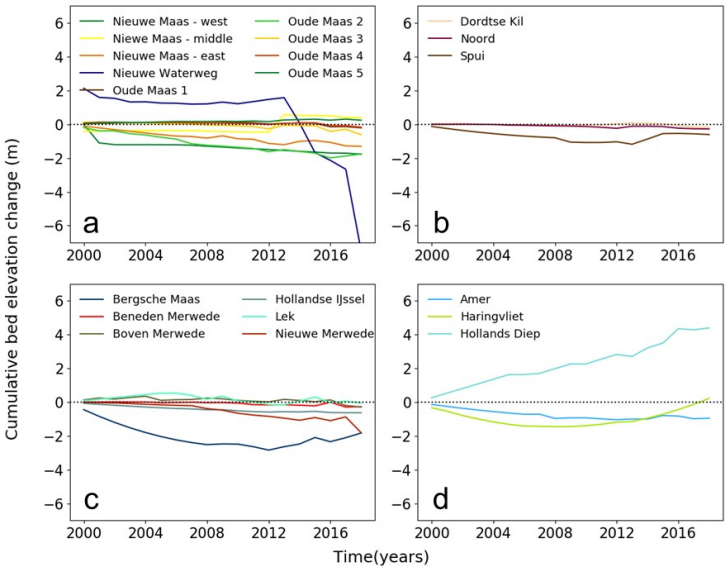


Figure 8. Cumulative bed level changes for a. the northern branches, b. the cross-cut branches, c. the riverine branches and d. the southern branches of the RMD 2000-2019

Figure 1.

a

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 ($m^3 \times 10^6$)	8.65	0.91	4.10	0.70
V_{90} (m/s)	0.68	0.71	1.40	0.87

Figure 1b.

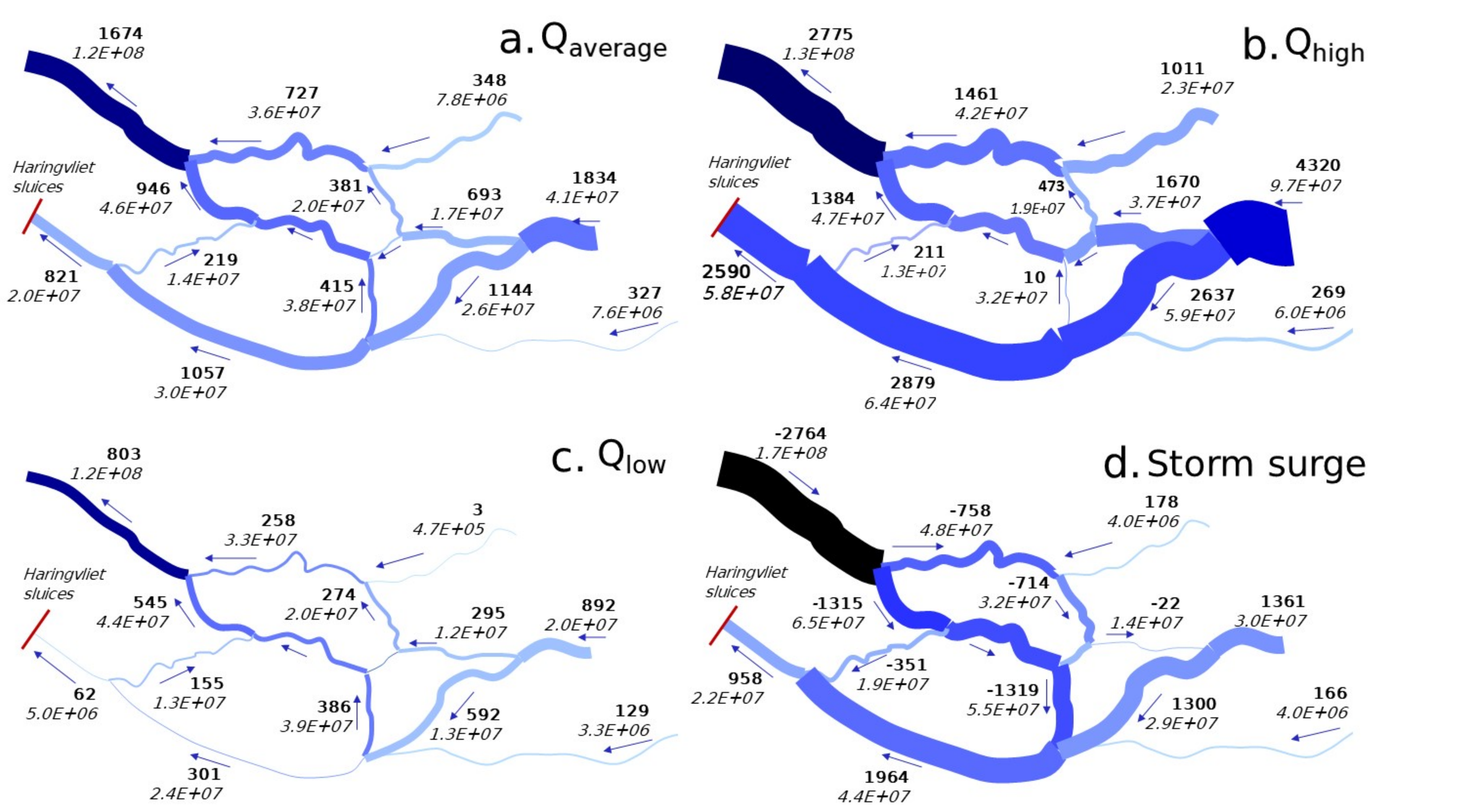

a. Q average
1674
1.2E+08
727
3.6E+07
348
7.8E+06
Haringvliet
sluices
946
4.6E+07
381
2.0E+07
693
1.7E+07
1834
4.1E+07
219
1.4E+07
821
2.0E+07
415
3.8E+07
1144
2.6E+07
327
7.6E+06
1057
3.0E+07
b. Q high
2775
1.3E+08
1461
4.2E+07
1011
2.3E+07
Haringvliet
sluices
1384
4.7E+07
473
1.9E+07
1670
3.7E+07
4320
9.7E+07
211
1.3E+07
2590
5.8E+07
10
3.2E+07
2637
5.9E+07
269
6.0E+06
2879
6.4E+07
c. Q low
803
1.2E+08
258
3.3E+07
3
4.7E+05
Haringvliet
sluices
545
4.4E+07
274
2.0E+07
295
1.2E+07
892
2.0E+07
155
1.3E+07
62
5.0E+06
386
3.9E+07
592
1.3E+07
129
3.3E+06
301
2.4E+07
d. Storm surge
-2764
1.7E+08
-758
4.8E+07
178
4.0E+06
Haringvliet
sluices
-714
3.2E+07
-1315
6.5E+07
-22
1.4E+07
1361
3.0E+07
-351
1.9E+07
958
2.2E+07
-1319
5.5E+07
1300
2.9E+07
166
4.0E+06
1964
4.4E+07

Figure 2.

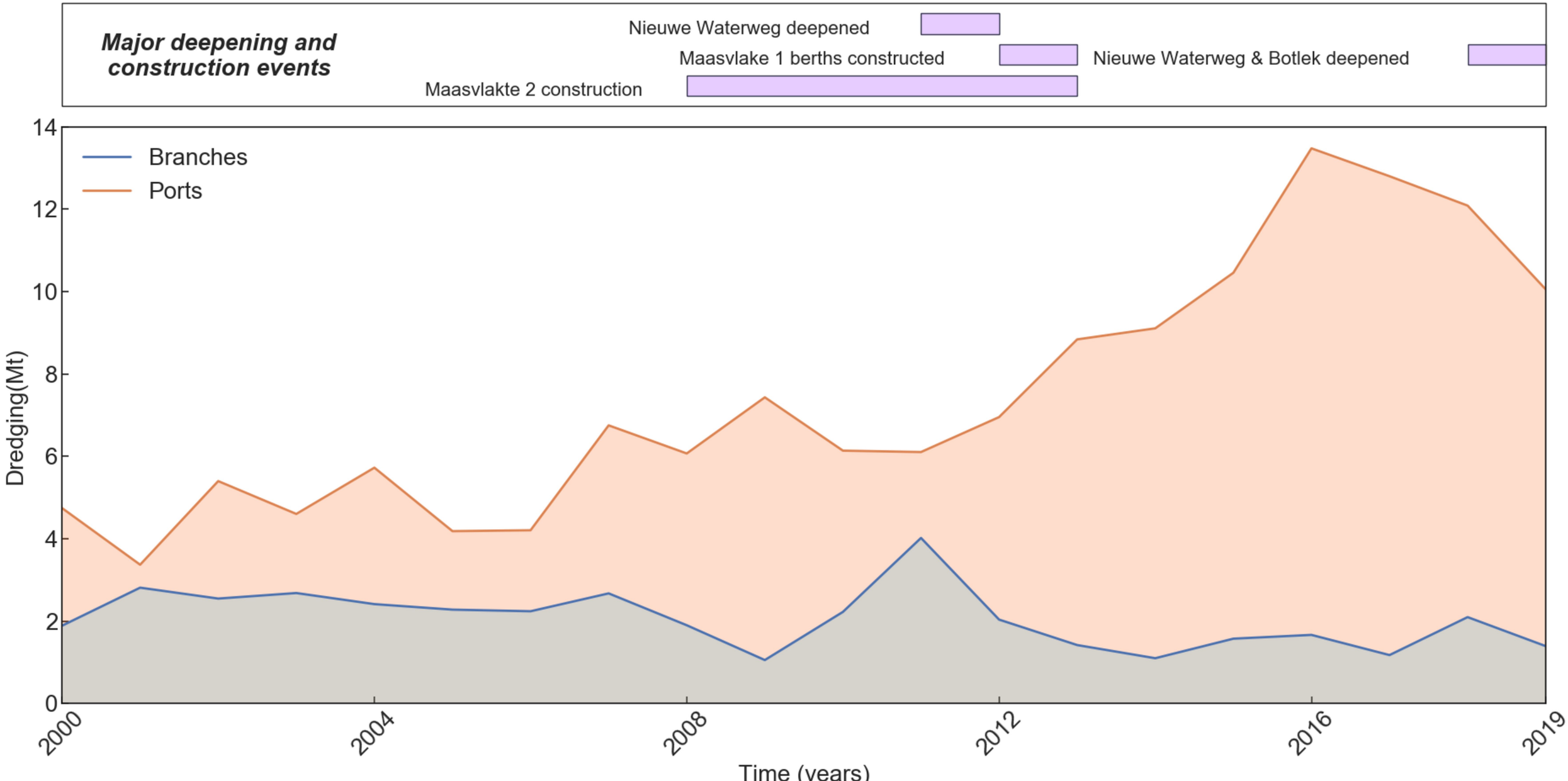

Major deepening and construction events
Nieuwe Waterweg deepened
Maasvlake 1 berths constructed
Nieuwe Waterweg & Botlek deepened
Maasvlakte 2 construction
Branches
Ports
Dredging(Mt)
0
2
4
6
8
10
12
14
2000
2004
2008
2012
2016
2019
Time (years)

Figure 3.

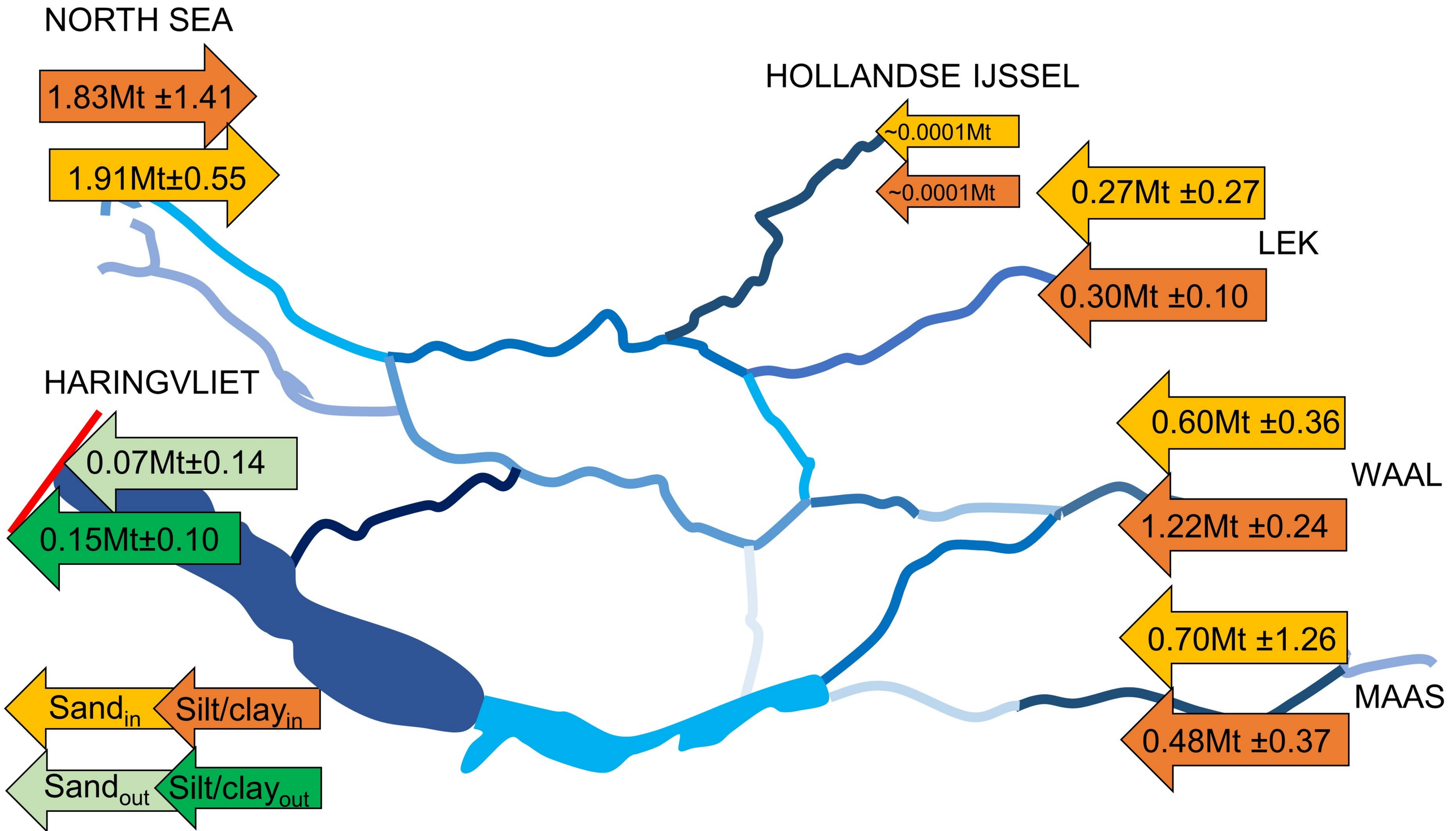

NORTH SEA
1.83Mt ±1.41
1.91Mt±0.55
HOLLANDSE IJSSEL
~0.0001Mt
~0.0001Mt
0.27Mt ±0.27
LEK
0.30Mt ±0.10
HARINGVLIET
0.07Mt±0.14
0.15Mt±0.10
0.60Mt ±0.36
WAAL
1.22Mt ±0.24
0.70Mt ±1.26
MAAS
0.48Mt ±0.37
Sand$_{in}$
Silt/clay$_{in}$
Sand$_{out}$
Silt/clay$_{out}$

Figure 4.

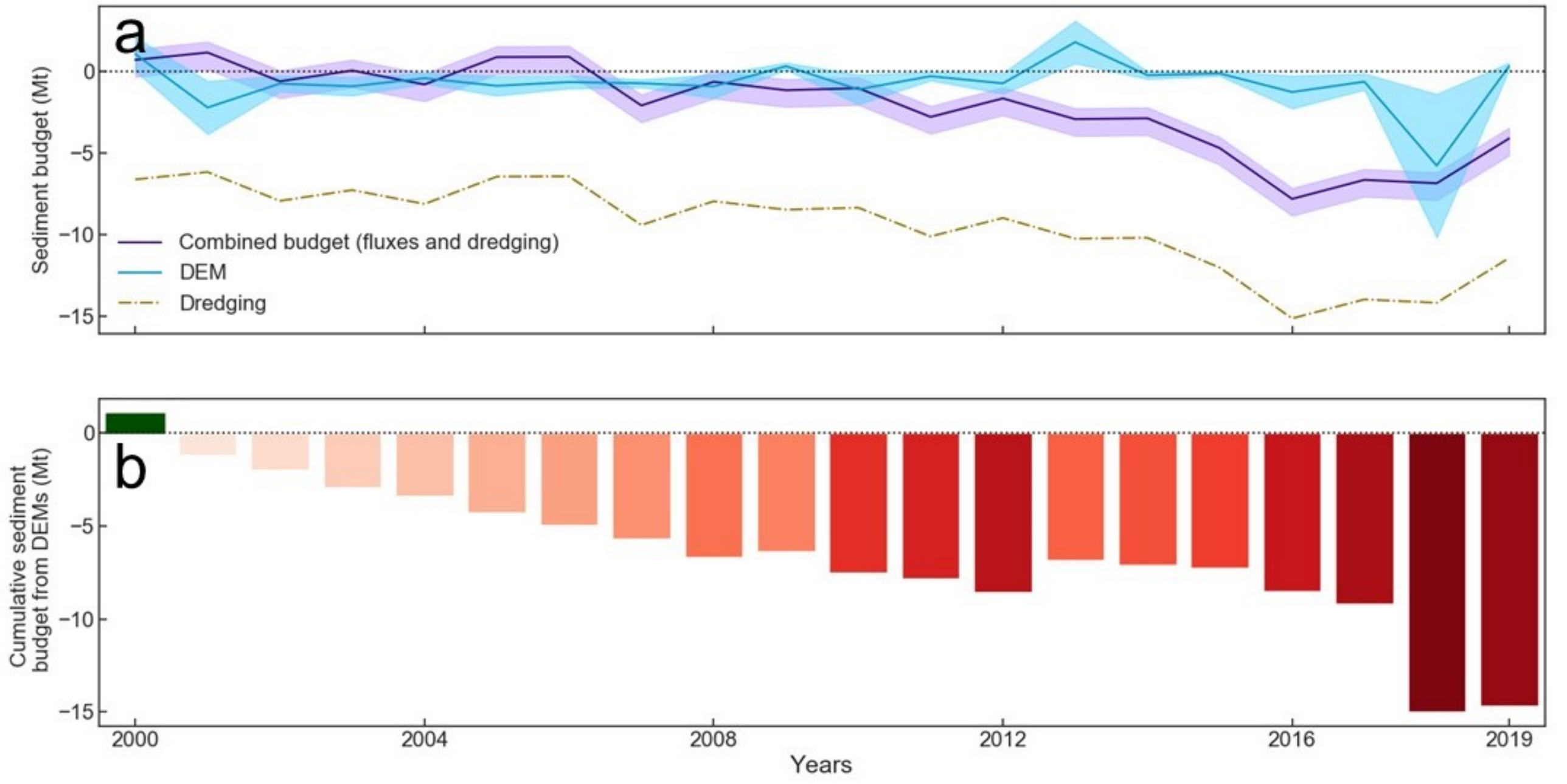

a
Sediment budget (Mt)
0
−5
−10
−15
Combined budget (fluxes and dredging)
DEM
Dredging
b
Cumulative sediment budget from DEMs (Mt)
0
−5
−10
−15
2000
2004
2008
2012
2016
2019
Years

Figure 5.

a

Cumulative bed level change (cm)

- >-90
- -80 to -90
- -70 to -80
- -60 to -70
- -50 to -60
- -40 to -50
- -30 to -40
- -20 to -30
- -10 to -20
- 0 to -10
- 0
- 0 to 10

b

Average natural bed level change (cm/yr)

- > -1
- -0.75 to -1
- -0.5 to -0.75
- -0.25 to -0.5
- -0.1 to -0.25
- 0 to -0.1
- 0
- 0 to 1
- 1 to 5
- 5 to 10
- 10 to 15

Figure 6.

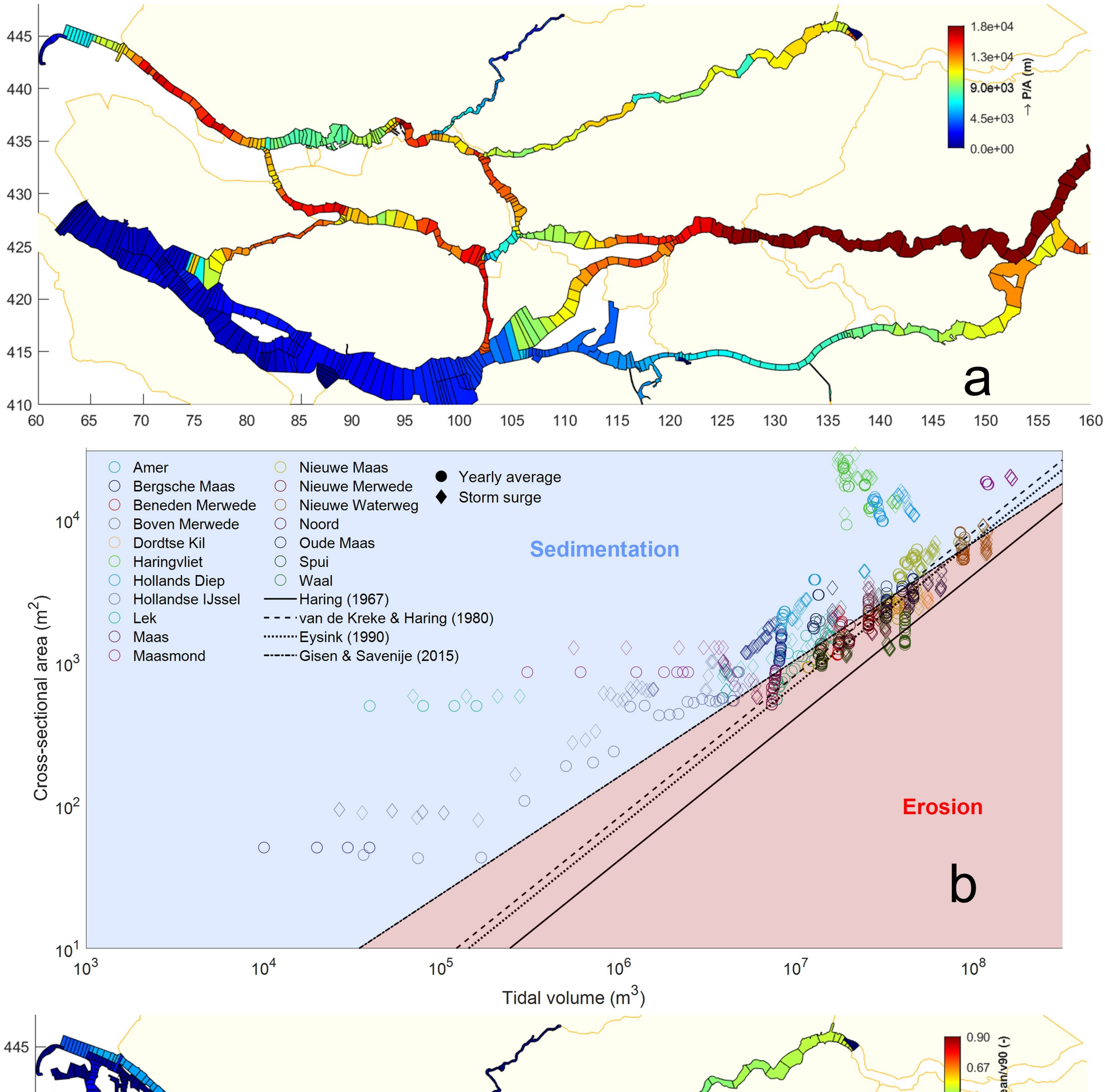
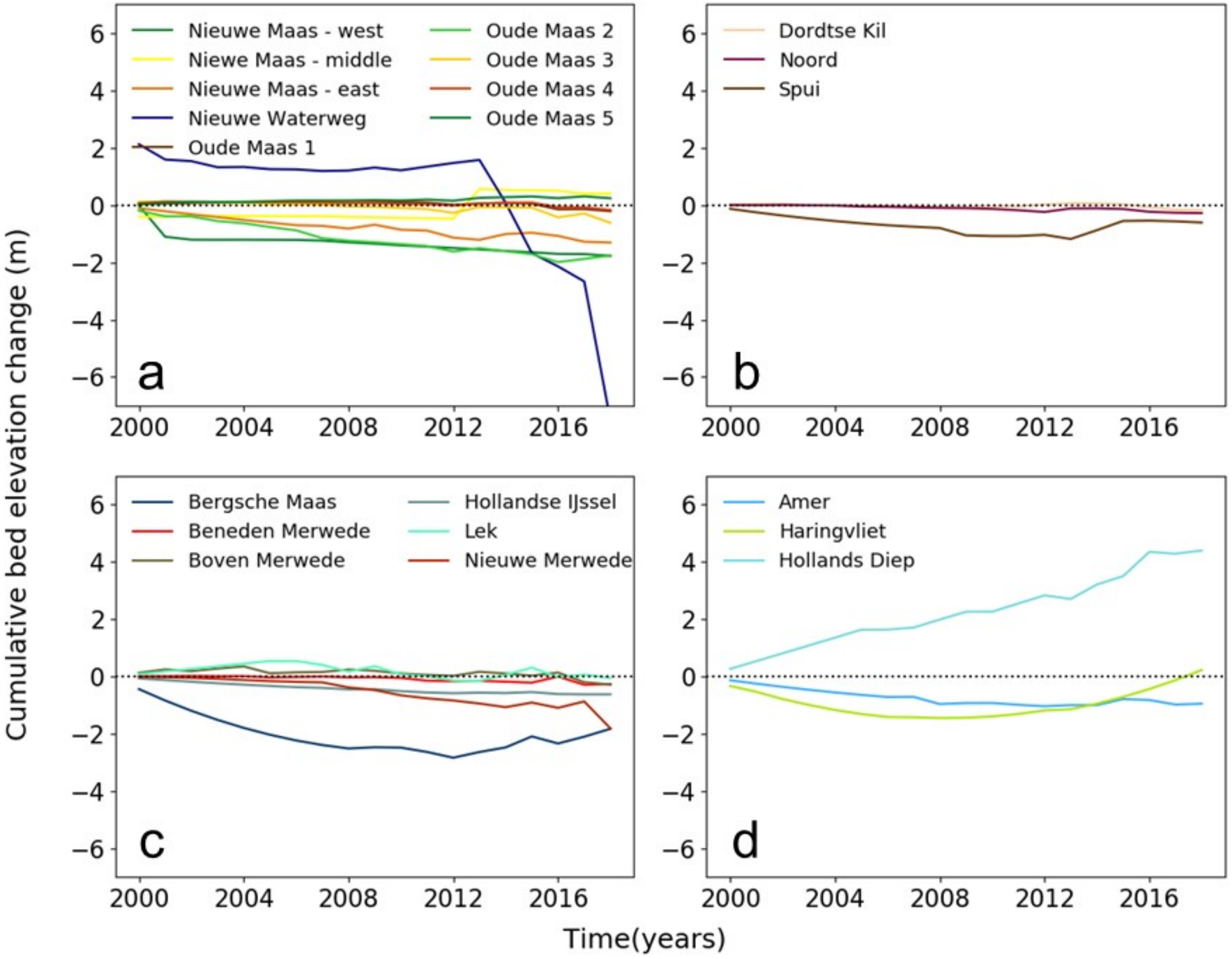

a
1.8e+04
1.3e+04
9.0e+03
4.5e+03
0.0e+00
→ P/A (m)
b
Amer
Bergsche Maas
Beneden Merwede
Boven Merwede
Dordtse Kil
Haringvliet
Hollands Diep
Hollandse IJssel
Lek
Maas
Maasmond
Nieuwe Maas
Nieuwe Merwede
Nieuwe Waterweg
Noord
Oude Maas
Spui
Waal
Yearly average
Storm surge
Haring (1967)
van de Kreke & Haring (1980)
Eysink (1990)
Gisen & Savenije (2015)
Sedimentation
Erosion
Cross-sectional area (m2)
Tidal volume (m3)
c
0.90
0.67
0.45
0.23
0.00
→ ratio vmean/v90 (-)
d
Colombia river
Jamuna river
Cross sectional area (m2)
Tidally averaged net discharge (m3/s)

Figure 7.


Cumulative bed elevation change (m)
Time(years)
a
b
c
d
Nieuwe Maas - west
Niewe Maas - middle
Nieuwe Maas - east
Nieuwe Waterweg
Oude Maas 1
Oude Maas 2
Oude Maas 3
Oude Maas 4
Oude Maas 5
Dordtse Kil
Noord
Spui
Bergsche Maas
Beneden Merwede
Boven Merwede
Hollandse IJssel
Lek
Nieuwe Merwede
Amer
Haringvliet
Hollands Diep
6
4
2
0
−2
−4
−6
2000
2004
2008
2012
2016