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Climate change and human influences on sediment fluxes and the sediment budget of an urban delta: the example of the lower Rhine–Meuse delta distributary network

J.R. Cox, F.E. Dunn, J.H. Nienhuis, M. van der Perk, and M.G. Kleinhans

Abstract: Deltas require sufficient sediment to maintain their land area and elevation in the face of relative sea-level rise. Understanding sediment budgets can help in managing and assessing delta resilience under future conditions. Here, we make a sediment budget for the distributary channel network of the Rhine–Meuse delta (RMD), the Netherlands, home to the Port of Rotterdam. We predict the future budget and distribution of suspended sediment to indicate the possible future state of the delta in 2050 and 2085. The influence of climate and anthropogenic effects on the fluvial and coastal boundaries was calculated for climate change scenarios, and the effects of future dredging on the budget were related to port development and accommodation of larger ships in inland ports. Suspended sediment rating curves and a 1D flow model were used to estimate the distribution of suspended sediment and projected erosion and sedimentation trends for branches. We forecast a negative sediment budget (net annual loss of sediment) for the delta as a whole, varying from −8 to −16 Mt/year in 2050 and −11 to −25 Mt/year by 2085, depending on the climate scenario and accumulated error. This sediment is unfavourably distributed: most will accrete in the northern part of the system and must consequently be removed by dredging for navigation. Meanwhile, vulnerable intertidal ecosystems will receive insufficient sediment to keep up with sea-level rise, and some channels will erode, endangering bank protection. Despite increased coastal import of sediment by estuarine processes and increased river sediment supply, extensive dredging for port development will cause a sediment deficit in the future.

Key words: sediment, climate change, deltas, dredging, bed level, sediment budget.

1. Introduction

Deltas are hotspots of trade, population, agriculture, and economic growth, hosting the world's largest urban areas while also being rapidly expanding centres of environmental risk (Tessler et al. 2015). Delta populations face numerous natural and anthropogenic challenges (Syvitski 2008; Nienhuis et al. 2020). Subsidence (Keogh and Törnqvist 2019; Shirzaei et al. 2020) and sea-level rise (Ericson et al. 2006) threaten to drown deltas,

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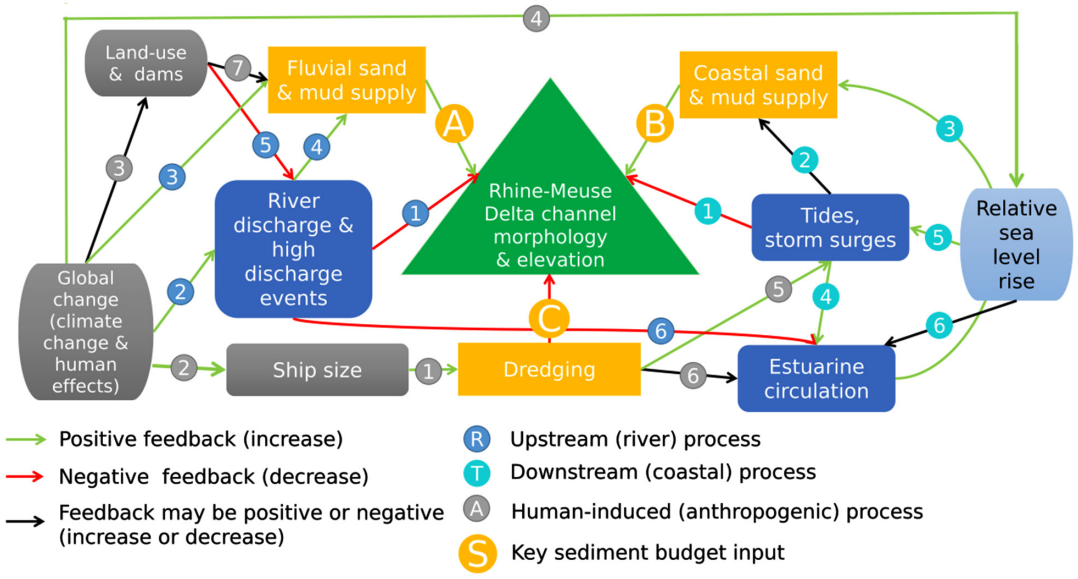
Fig. 1. Processes affecting and driving the channel elevation and morphology of urban deltas, where A, B, and C are the main components of the sediment budget (Q_{rivers}, Q_{coast}, and $Q_{dredging}$, respectively). Details of the river processes are outline in Table 1, coastal processes in Table 2, and anthropogenic processes in Table 3.



but these threats can, in principle, be offset by sediment supply. Most sediment supplied to deltas is fine-grained and transported in suspension from upstream rivers (van der Vegt et al. 2016) or enters the delta via the river mouth through waves and tides.

Climate-induced changes to river discharge resulting from altered land use, glacier behaviour, precipitation, seasonality, and basin temperature can increase or decrease sediment delivery (Dunn et al. 2019). Dam building (Syvitski and Kettner 2011), dredging (Rovira et al. 2014), and river engineering measures, such as diversions and canal construction (Ericson et al. 2006), can trap sediment and lower sediment delivery to deltas (see Fig. 1; Table 1). Insufficient sediment supply can result in scour holes and channel bed erosion (which places infrastructure at risk), ecosystem loss, bank instability, and land loss.

Sea-level rise further threatens estuaries and deltas, not only increasing the risk of drowning and losing elevation but also altering hydrodynamics. Changes to tidal dynamics influence, in particular, the transport and circulation of sediment that enters deltas and estuaries from the seaward boundary (see Fig. 1). Sea-level rise alters tidal amplitude by altering amphidromic points (tidal nodes), and it is the distance between an estuary or delta mouth and these amphidromic points which controls tidal amplitude (Pickering et al. 2017). How tidally dominated systems will react to this change in terms of their morphology is determined by their dimensions, size and, crucially, sediment supply (see Fig. 1; Table 1). In the case of systems with large estuaries such as the Rhine–Meuse delta (RMD), which are likely to undergo decreased tidal amplification, a lack of sufficient sediment will threaten the survival of intertidal areas (Leuven et al. 2019).

Deltas generally consist of a complex distributary network of channels that distribute discharge and sediment across the delta. The distribution of sediment across the delta is often not monitored or investigated, but quantitative insight into sediment transport or sediment fluxes in distributary channels is essential to assess the effects of changes in upstream and downstream boundary conditions. Such assessments are vital for appropriate and effective river management in deltas, which concern the sediment as much as the

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Table 1. Upstream (river) processes affecting the channel network and sediment budget.

Process number*	Corresponding process	Reference(s)
1	River discharge increases channel size and reduces delta growth	n/a
2	Climate change increases fluvial discharge and causes more frequent high discharge events	KNMI 2015; Hoegh-Guldberg et al. 2019
3	Climate change increases fluvial supply of mud and sand	Dunn et al. 2019
4	River discharge provides fluvial sand and mud, high discharge events provide high concentrations of sediment episodically	n/a
5	Dams decrease sediment and water discharge upstream and land-use change can introduce additional sediment to the system	Dunn et al. 2019
6	River floods reduce estuarine circulation	n/a

*Process numbers are marked with blue circles in Fig. 1.

Table 2. Downstream (coastal) processes affecting the channel network and sediment budget.

Process number*	Corresponding process	Reference(s)
1	Tides and storm surges erode delta channels	Oppenheimer et al. 2019
2	Tides and storm surges provide sediment and export sediment	n/a
3	Estuarine circulation leads to more coastal sediment supply	n/a
4	Tides increase estuarine circulation	n/a
5	Sea-level rise alters tidal amphidromic points and changes tidal range and amplitude	Pickering et al. 2017
6	Sea-level rise alters estuarine circulation, salinity and density currents	Bindoff et al. 2019

*Process numbers are marked with turquoise circles in Fig. 1.

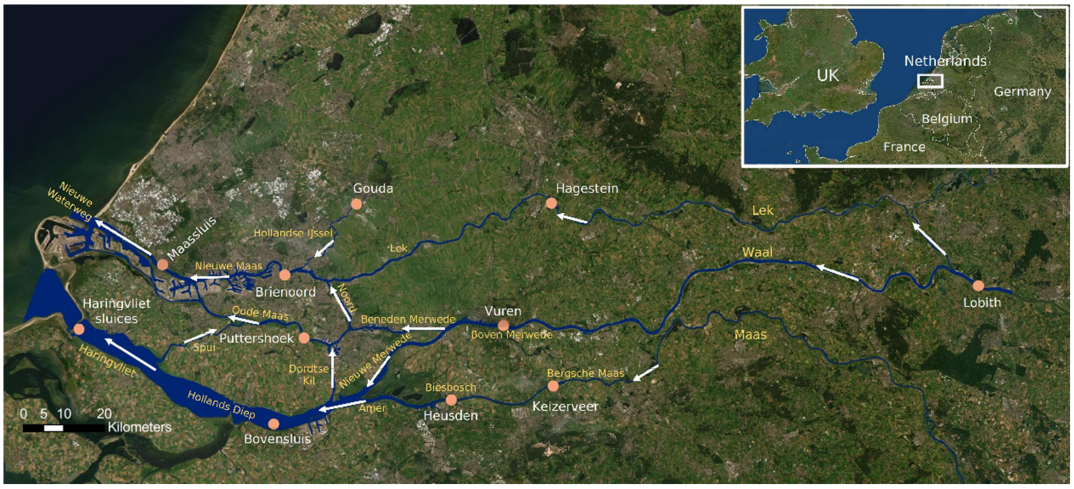
Table 3. Human-induced (anthropogenic) processes affecting the channel network and sediment budget.

Process number*	Corresponding process	Reference(s)
1	Growing ship size increases dredging volumes to ensure navigation depths	Merk et al. 2015
2	Global growth of population and economy increases demand for resources via shipping industry	Assumption in this paper
3	Global change drives land-use change and dam construction or removal	Lehner et al. 2011*b*
4	Global change exacerbates climate change and causes sea-level rise	Oppenheimer et al. 2019
5	Channel deepening leads to stronger tidal influence	van Rijn et al. 2018
6	Channel deepening alters estuarine circulation	van Rijn and Grasmeijer 2018
7	Land-use change can increase or decrease sediment supply, while dam construction decreases fluvial sediment supply	Dunn et al. 2019

*Process numbers are marked with grey circles in Fig. 1.

water. It is widely recognised that many deltas worldwide have modified fluvial sediment supply and are at risk of drowning under sea-level rise and subsidence (Ericson et al. 2006; Schmidt 2015; Dunn et al. 2019). However, the changes made to channels and the effects of channel deepening on the functioning of deltas are understudied. However, these changes are increasingly relevant for deltas where sand mining occurs in the channels (C. Wu et al. 2016; Hackney et al. 2020) and for urbanised deltas with ports that need fairway (shipping channel) maintenance and channel deepening for increasingly larger ships (see Fig. 1; Table 3). Here, we study the future sediment budget of a heavily influenced delta

Fig. 2. The distributary network of the Rhine–Meuse delta (RMD), including the names of branches and the location of long-term suspended sediment measuring stations. Arrows indicate annual net water flow direction. At the Nieuwe Waterweg, net flow under average conditions is out to sea. Map created using ArcGIS® software by Esri; SSC measuring station locations and multibeam data from RWS. Basemap courtesy of Esri (ESRI 2021).



with a large port as an example of human-induced effects on deltas: the Rhine–Meuse delta (RMD) in the Netherlands.

While many deltas and estuaries worldwide experience strong human influence, this particular system has both a large seaport and high population density that drive changes. Therefore, the projected trends of this research, which juxtapose natural and human-induced sediment displacement, hint at "worse case" future scenarios for other rapidly developing systems. The RMD is a heavily anthropogenically influenced estuary with a sediment budget and channels that respond quickly and significantly to the many ongoing hydrodynamic and morphological interventions of the region (Cox et al. 2021). One key process is the impact of navigation dredging, which is growing in urbanised deltas worldwide to accommodate larger ships (Carse and Lewis 2020). Responses to ongoing anthropogenic changes in urbanising deltas are challenging to capture in global models and predictors of future delta change (Nienhuis et al. 2020). Figure 1 indicates the complexity of both the natural and anthropogenic processes affecting the boundary conditions of urban deltas, their channel networks, and the sediment budget. Thus, a detailed study is required to identify future challenges in terms of sediment. The RMD also provides a valuable example for other deltas globally that are experiencing rapid human intervention and alterations in terms of their sediment budget.

Here, we aim to quantify future sediment flux projections for the distributary channel network of the RMD, located in the west of the Netherlands (see Fig. 2). We assessed future sediment flux changes from upstream (delta apex) and downstream (river mouth) sources, as well as changes between individual branches. Upstream sediment was calculated using the BQART model for delta sediment delivery, while downstream fluxes were calculated using simple equations to estimate additional sediment import due to sea-level rise. We compared direct anthropogenic drivers (dredging) to climate-change driven sediment flux changes, with implications for channel bed dynamics.

The climate change processes included in this analysis are as follows: (*i*) sea-level rise at the seaward boundary, (*ii*) basin temperature change, and (*iii*) glacier cover change at the upstream (fluvial) boundary. These were modelled for a variety of climate scenarios for

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the basin. Dredging is statistically predicted from past dredging information and a new relation that incorporates ship size and its influence on delta channel depths. Meanwhile, the distribution of sediment over the bifurcations of the region is used to indicate the future distribution and response of channel beds to this sediment distribution.

2. The Rhine–Meuse delta

The lower RMD is a mixed wave-tide-dominated delta (Nienhuis et al. 2020). The fluvially dominated apex of the delta is commonly identified as being located near the German–Dutch border (Lobith) on the Rhine River. After the border, the river divides into the Waal and Nederrijn at the Pannerdsche Kop. The Nederrijn becomes known as the Lek after it passes through Culemborg. The Meuse River comes from the south of the Netherlands, and at Nijmegen begins to run parallel to the Waal to the west. At the coastal boundary, only one branch of the delta remains open to the influence of the sea and tides, the Nieuwe Waterweg, located at Hoek van Holland (Maassluis). The Haringvliet branch is closed off from the sea, and both discharge and sediment flux to the sea are controlled by a large system of sluices known as the Haringvlietsluizen. Since 2018, the Haringsvlietsluizen are opened during flood tide to restore the upstream migration of fish species into the Rhine River. However, this has a limited effect on the influx of seawater and sediment into the Haringvliet branch.

Net annual discharge at Lobith is 2198 m^3/s, and at the Nieuwe Waterweg, it is 1520 m^3/s with discharges in other branches ranging from 200 to 1200 m^3/s. Typical flow velocities in the mouth (Nieuwe Waterweg) are 1 m/s, with other branches ranging from 0.1 to 1 m/s. The tidal range in the mouth is 1.5 m/s. There is net sediment import due to the strong estuarine circulation and tidal asymmetry, which drives sediment transport in the mouth region. The discharge distribution and direction of flow is determined by the tides, magnitude of the upstream riverine discharge, and the operation of the Haringvlietsluizen. The main route of upstream discharge to the sea is via the Boven Merwede and Nieuwe Merwede to the Hollands Diep, after which it is redirected back to the north via the Dordtse Kil and Oude Maas, then 1395 m^3/s debouches to sea. We refer to Cox et al. (2021) and references therein for a more detailed description of the hydrodynamics of the region.

From upstream, the delta receives ~1.6 ± 1.8 Mt/year sand (34% from the Maas and 66% from the Rhine) and ~2 ± 0.7 Mt/year silt/clay (24% from the Maas and 76% from the Rhine). From the coastal boundary, the delta receives ~1.96 ± 0.6 Mt/years and ~1.8 ± 1.4 Mt/year silt/clay, leading to a total sediment influx of ~7.3 Mt/year (Cox et al.2021). However, at present, intensive dredging significantly outweighs this flux, and leads to a net sediment budget which is negative, on average −5 to −7 Mt/year in 2019, according to Cox et al. (2021), while the average sediment budget for the period 2000–2019 was −2 Mt/year. Previous budgets for the region have shown a negative sediment budget since the 1980s ranging from −0.5 to −2.5 Mt/year. Earlier sediment budgets, prior to the closure of the Haringvliet, were no longer comparable, as the sediment transport significantly shifted after their construction.

It is important to note the large difference in magnitude between the dredging flux and the import of sediment at the mouth, which indicates the disequilibrium of the system. As elucidated by Cox et al. (2021), disequilibrium exists regardless of the high uncertainty regarding the current sediment import from the North Sea, the value of which, despite efforts from various authors, has not been improved since the 1990s (van Dreumel 1995; Becker 2015; Frings et al. 2019). The error of this value is estimated to be 15%–30% (van Dreumel 1995), and most previous sediment budgets use this flux as a closing term (hence the large margin of error). Upstream riverine fluxes and the discharge at the Haringvlietsluizen are periodically updated with measured sediment concentrations;

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however, large uncertainty still remains with the transport and flux of sand, particularly in the Maas, owing to a lack of bedload measurements or updated composition data for the upstream branches.

The RMD has experienced long-term anthropogenic interventions and natural changes that have affected its sediment delivery and distribution. In the upstream (non-Dutch) part of the basin, several dams have been constructed that have trapped sediment. They were built from the early 1800s to the 1970s to divert and control discharge, and they trap gravel and sand in the upstream part of the system (Frings et al. 2014). There are also two large dams (Rio (Schweich) and Sorpeberg–Glinge (Ermecketal)) planned in the German part of the basin to add to the existing 46 reservoirs with volumes over 10 Mm^3 (Zarfl et al. 2015). We refer to Frings et al. (2019) for an overview of dams and embankments in the German part of the Rhine.

Changes in the delta include extensive land reclamation, embankments, deepening of channels, and development of new channels, all of which have implications for the sediment distribution and morphodynamics of the RMD (Cox et al. 2021). The delta is almost entirely embanked and channels are maintained at specific depths by dredging; thus, the course and dimensions of the branches are relatively fixed.

The Port of Rotterdam is located in the RMD. It is a network of several inland ports and harbours, and a large offshore port which combined has made the area Europe's largest seaport. As of 2018, the port provides 6.2% of the gross domestic product (GDP) of the Netherlands, and its contribution to GDP is rising, doubling in value between 2011 and 2018 (Kuipers 2018). Ships entering and navigating in the Port of Rotterdam's channels, including at the mouth (Nieuwe Waterweg), require channels to have a nautically guaranteed depth. Dredging in the delta is closely related to this standard. The nautically guaranteed depth of the Nieuwe Waterweg has increased over time as commercial container ships have expanded in berth and depth. This has also led to increased volumes of the required dredging in the ports (Cox et al. 2021). Dredging can lead to enhanced sediment concentrations in channels (van Rijn et al. 2018), despite the primary goal of dredging being the removal of sediment.

Maasvlakte 2, a new offshore port, enhances marine sediment transport into the Nieuwe Waterweg (van Ledden 2005; Winterwerp 2006; van Kruchten et al. 2008), meaning that intensive dredging is required to keep the channel network and port areas of the RMD navigable. Dredging removes large quantities of sediment and, crucially, nearly all the sediment that is imported from the sea (Cox et al. 2021). This sediment is then sold, dumped off the coast if uncontaminated, or stored in a specially designated depot for contaminated material (locally known as the Slufter) and therefore lost from the area (Kirichek et al. 2018).

2.1. Sediment distribution within the Rhine–Meuse delta

There are many bifurcations in the RMD, resulting in complex flow and sediment transport patterns (Vellinga et al. 2014). Extensive work has been done on the division of flow and sediment upstream in the fluvial part of the delta, particularly at the major bifurcations of the Rhine and Waal (Kleinhans 1996; Kleinhans et al. 2007; Frings and Kleinhans 2008). These studies show that the majority of suspended Rhine sediment flows into the Waal (~1.2 Mt/year) compared to the Lek (~0.5 Mt/year).

The discharge distribution and sediment transport among downstream bifurcations are less well understood. As indicated by Cox et al. (2021), the central and crosscut channels of the RMD are tidally influenced and experience flow reversal and density-driven flows, leading to complex flow and sediment transport. No field-validated sediment transport model has been developed yet for the region to improve understanding of the complex flow structures and patterns of the RMD.

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Furthermore, human actions have directly affected sediment distribution within the delta through dredging. The southern branches of the system have experienced sedimentation since the closure of the Haringvliet river mouth in 1970. The tidal cross-cut channels, in particular the Oude Maas, have eroded due to a lack of sediment (Huismans et al. 2020; Cox et al. 2021).

2.2. Future changes to the Rhine–Meuse delta sediment fluxes

Further changes linked to both climate change and the ever-expanding needs of the population (in terms of the efficiency and capacity of the port) will continue to place pressure on the RMD. With sea levels predicted to rise globally for nearly all deltas, the RMD is no exception (Oppenheimer et al. 2019; van den Hurk et al. 2014). Sea-level rise alters the hydrodynamics and sediment fluxes at the river mouth (Leuven et al. 2019). It expands the accommodation space and, hence, the estuarine tidal prism, which can increase flood dominance and marine sediment import into the delta (Friedrichs et al. 1990). However, this also depends on the estuarine geometry (Friedrichs et al. 1990; Leuven et al. 2019). Sea-level rise also alters the distributary network further upstream (Jerolmack 2009). However, because marine sediment import is limited by the dredging operations of the Port of Rotterdam, the natural mechanisms of sedimentation from sea-level rise may be limited in the RMD. This can make fluvial sediment from upstream increasingly important in the future sediment budget of the RMD.

Sediment supply to the RMD may change as upstream basin conditions react to climate change and human impacts. Global modelling studies indicate a decrease in fluvial sediment supply for the RMD, not unlike many other deltas globally (Dunn et al. 2019). Changes in sediment fluxes from upstream, sea-level rise, and port development are likely to have significant effects that extend into the distributary network. In this study, we quantify these effects.

We expect that in the future, as in the past, major changes in the RMD will be driven by socioeconomic factors such as population growth and demand for goods. We include socioeconomic growth in the RMD in two ways: directly in the upstream sediment model (where it is assumed there is no influential change over this century) and indirectly in the projected dredging depths and volumes for the region which are directly linked to the economic development of the port (and therefore to increased population and resource demand). Furthermore, we include the effects of climate change in the projections for fluvial sediment, in the discharge projections for the upstream boundary and on sediment supply at the coast by inducing sea-level rise at the coastal boundary.

2.3. Influence of high discharge events

Pulse sediment events (high river floods or storm surges) also typically play a large role in the transport and distribution of sediment into the system. These events also contribute to the erosion and sedimentation of the channels. Storm surges (short-lived extreme water levels) arriving from the North Sea are predicted to increase (Schrum et al. 2016). These storms affect erosion and sedimentation processes, particularly in intertidal wetlands and marshes (Bakker et al. 2016). Moreover, these events can provide large amounts of sediment in the system, change sediment transport systems, and, consequently, where erosion and deposition occur. Storm surges change the flow direction and distribution in the RMD, reducing the outflow of riverine sediment at the mouth and increasing the duration of high water levels in the system (Zhong et al. 2014), which may play a role in altering erosion and sedimentation trends. Similarly, peak flows in rivers are projected to increase (Quante and Colijn 2016). This will contribute to higher amounts of sediment episodically, particularly to the southern branches that may be key to sustaining the elevation of intertidal areas in

these branches. Thus, we also quantify the influence of high discharge events on the future sediment budget of the RMD.

3. Methods

3.1. Making a delta sediment budget

We created an annual sediment budget of the suspended sediment flux of the RMD, following Becker (2015) and Cox et al. (2021):

$$(1) \quad Q_{SB} = Q_{rivers} + Q_{coast} - Q_{dredging}$$

where Q_{SB} (Mt/year) is the calculated sediment budget, Q_{rivers} (Mt/year) is the suspended sediment flux from the upstream rivers, Q_{coast} (Mt/year) is the flux of suspended sediment from the coast, where a positive flux is directed upstream into the river, and $Q_{dredging}$ (Mt/year) is the amount of dredged material removed from both the channels and ports of the RMD. A notable difference between the calculation methods of Becker (2015) and Cox et al. (2021) is the unit used in the budgets, in which the latter advocates the use of dry mass of sediment, which we adhere to in this study, while the former uses the volume of sediment. This method has already been applied to the RMD for the past 20 years, as outlined in Cox et al. (2021), and has built on previous budgets for the region since the 1980s. This formulation is adapted to include climate change effects and future dredging trends, as outlined below.

3.2. Climate predictions

We followed a set of climate scenarios for projections of future river and coastal suspended sediment flux. For future river discharge, we followed the Royal Netherlands Meteorological Institute (KNMI) predictions for 2050 and 2085, known as the KNMI'14 predictions (van den Hurk et al. 2014). These predictions include four major scenarios that are modelled for 2050 and 2085. They are based on EC-Earth-RACMO2, a 12 km resolution regional climate model that is used to project global data to small areas such as the Netherlands (Sperna Weiland et al. 2015). The transition from EC-Earth-RACMO2 and the link between the KNMI'14 scenarios and CMIP5/IPCC scenarios are outlined in Lenderink et al. (2014). The four scenarios are summarized in Table 4.

Furthermore, specific predictions were made for the hydrological conditions in the Rhine and Meuse rivers for these scenarios (Sperna Weiland et al. 2015) using measured rainfall and discharge data to predict the typical and extreme (flood) conditions in the rivers, specifically considering Lobith and Borgharen for the Rhine and Meuse and making use of the extensive data collected at these points. These climate scenarios, resulting discharge predictions, and related sea-level rise for the RMD are shown in Fig. 3. Similarly, sea-level rise rates as recorded for the past and projected for the future from the KNMI'14 scenarios were used.

3.3. Estimating the fluvial sediment flux—BQART

Several processes alter fluvial sediment flux in the system (see Fig. 1). Most of these processes can be captured using the BQART equation. The BQART sediment flux equation (Syvitski and Milliman 2007) was used to calculate the change in suspended sediment flux from upstream rivers over time given scenarios for independent variables. The fluvial sediment delivery was modelled at Lobith and Borgharen for the Rhine and Meuse rivers, respectively, as these are where the rivers enter the delta area and where discharge projections exist (van den Hurk et al. 2014; Sperna Weiland et al. 2015). The BQART equation was chosen because it incorporates both future climatic changes and future anthropogenic changes in the basin. This equation determines the flux in suspended sediment by

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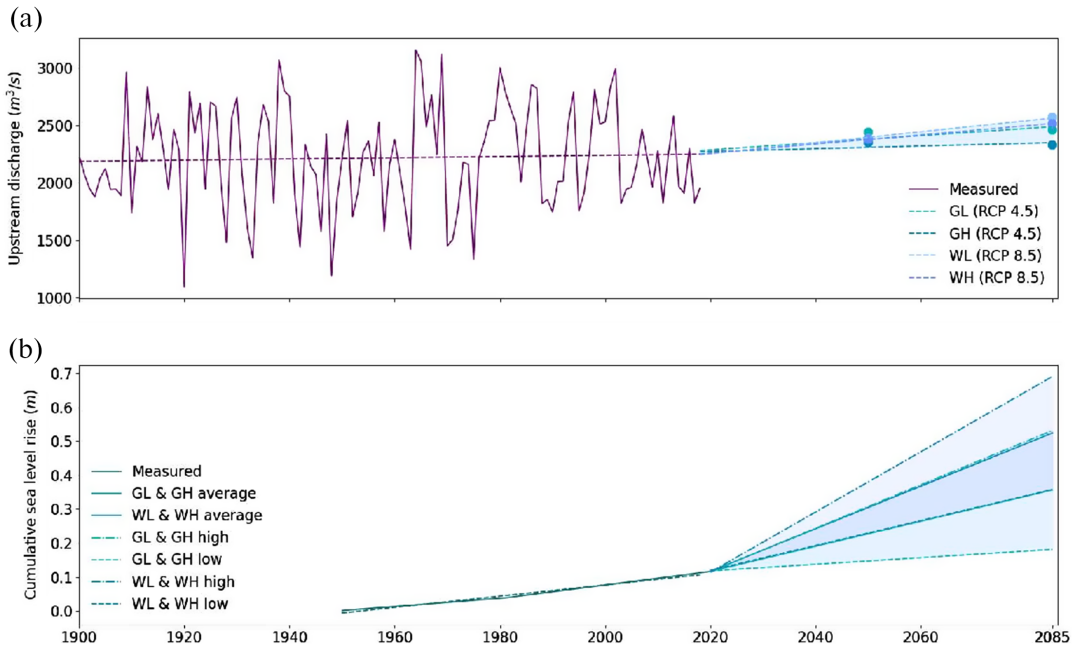
Table 4. Conditions associated with the scenarios of the KNMI'14 future climate predictions (van den Hurk et al. 2014; KNMI 2015).

Scenario	Temperature increase (°C) 2050	Temperature increase (°C) 2085	Sea-level rise rate (mm/year) 2050	Sea-level rise rate (mm/year) 2085	Notes
GL	1	1.5	1–5.5	1–7.5	Wet spring and dry summer in reference period, reverse in future
GH	1	1.5	1–5.5	1–7.5	Cold and wet summer in reference period, warm and dry in future
WL	2	3.5	3.5–7.5	4–10.5	Wet spring and dry summer in reference period, reverse in future
WH	2	3.5	3.5–7.5	4–10.5	Cold and wet summer in reference period, warm and dry in future

Fig. 3. Historical and predicted discharge and sea-level rise rate of the Rhine–Meuse delta (RMD). Upstream changes to river discharge are modelled at Lobith and sea-level rise at the coastal boundary (KNMI 2015).



incorporating a catchment factor ("B"), discharge ("Q"), drainage basin area ("A"), basin relief ("R"), and basin temperature ("T"). The catchment factor further incorporates reservoirs, glacier erosion, lithology, and soil erosion. The BQART equation has been extensively documented and validated elsewhere (Syvitski Milliman 2007); therefore, we only detail the input data used for the RMD scenario projections. Existing water discharge projections for the Rhine and Meuse basins (van den Hurk et al. 2014; Sperna Weiland et al. 2015) were used to drive the model, which also requires other temporally variable inputs and constants. Those that were assumed constant for this research were basin area (160 800 km^2), maximum relief (4274 km), lithology factor (set as 2, indicating erodible basin lithology,

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Syvitski and Milliman (2007)), glacier cover (338 km^2, RGI (2017)), and anthropogenic factor (calibrated to 0.2, indicating a densely populated, highly developed basin).

The basin temperature and reservoir trapping efficiency were used to construct the future scenarios, and so were time-varying. Temperature projections were taken from the previously discussed climate projections (Table 4) for consistency, as they were also used to produce the discharge input (van den Hurk et al. 2014; Sperna Weiland et al. 2015). Existing reservoir data were obtained from the GRanD database (Lehner et al. 2011*a*, 2011*b*), and information on planned dams was obtained from Zarfl et al. (2015). It is assumed that all existing dams are maintained, and none are removed before 2085. The four climate scenarios were run, including future dam construction, resulting in eight scenarios for each of the two time slices (2050 and 2085).

The model was run for current conditions and compared with the total riverine flux of Cox et al. (2021) and showed an error margin of 0.5 Mt. The reported riverine flux of Cox et al. (2021) of 3.7 Mt/year was an average of previous sediment budgets for the region, including the data and error margins of van Dreumel (1995), Snippen et al. (2005), Becker (2015), and Frings et al. (2019). The BQART model was also validated against previously measured and estimated values: 3.15 Mt/year for 1975–1991 (Asselman et al. 2003), 3.4 Mt/year for 1970–2000 (Erkens et al. 2006), and compare favourably with the values from BQART of 3.56 Mt/year for the 1990s and 3.85 Mt/year for the 2000s.

While the anthropogenic factor could be made part of scenario construction, in this modelling, it was kept constant as a result of lessons learned from previous modelling of sediment delivery to the RMD (Dunn et al. 2019). The previous work was global in scope, so global datasets were used and globally consistent assumptions were made, but when focusing on individual river basins, more nuances can be introduced. In this case, it was found that the timing of socioeconomic changes (increases in wealth and population) in the Rhine River Basin, which would cause decreases in sediment delivery in the model, were inaccurately represented by the global data and assumptions. Socioeconomic changes were assumed to occur later than in reality, so decreases in sediment delivery to the RMD were modelled to occur in the 21st century, although they had already been observed in the 20th century. These assumptions have been corrected in this current work, so the model was set up assuming that socioeconomic transitions leading to lower fluvial sediment fluxes have already occurred and will remain in their current state until at least 2085, considering the current heavily populated and modified state of the watershed with little possibility for change.

The method used in this study is a local improvement on that presented by Dunn et al. (2019). The latter used the hydrogeomorphic model WBMsed, incorporating BQART, and presented results showing a decrease in sediment delivery to the RMD across the 21st century for all climate and socioeconomic scenarios considered. The results of the current study instead showed increases in the sediment flux for some modelled scenarios. The sediment delivery from the Meuse increased under every scenario for each time slice due to increases in temperature and water discharge. The sediment flux from the Rhine increased under every scenario for each time slice for the same reasons as the Meuse, assuming that no new dams are constructed in the basin before 2085. However, if it is assumed that the two large planned dams (Rio (Schweich) and Sorpeberg–Glinge (Ermecketal)) are constructed before 2050, then sediment delivery only increases by 2085 under the more extreme climate change scenarios (as defined in Table 4).

3.4 Coastal sediment import

We estimated the net coastal sediment flux (Q_{coast}) from the coast into the Nieuwe Waterweg (Fig. 1) as the sum of two components:

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(2) $Q_{coast} = Q_{base} + Q_{slr}$

The first component, Q_{base}(Mt/year), represents the net sediment flux, independent of sea-level rise. We estimate Q_{base} as the difference between the observed modern sediment flux Q_{coast} (1.8 Mt/year, Cox et al. (2021)) and our estimated present-day Q_{slr} (0.96 Mt/year, see Eq. 3). Q_{base} is 0.87 Mt/year and remains unchanged over time—an assumption we resort to because of the limited observational data.

The second component, Q_{slr} (Mt/year), represents the additional sediment flux from sea-level rise. Similar to the infilling of artificially deepened/dredged channels, we assume sea-level rise-induced channel deepening will lead to marine sediment import through estuarine processes. Furthermore, in keeping with our simplified, long-term approach, we assume sufficient marine sediment availability, such that the magnitude of sea-level rise induced import will scale with the channel surface area and the sea-level rise rate. We estimate Q_{slr} as

(3) $Q_{slr} = \rho_s \cdot A \cdot r_{slr}$

where ρ_s is the bulk sediment density (here 1.6 t/m^3), A is the channel surface area, including its connected floodplains (m^2), and r_{slr} is the sea-level rise rate in m/year. Dry bulk density is commonly used in the RMD to convert to mass units (Cox et al. 2021) because of a lack of wet density data, which is a more accurate unit.

This estimate assumes linearity in the estuarine processes and might underpredict or overpredict the true sediment flux at the river mouth resulting from sea-level rise, depending on estuary shape, upstream freshwater discharge, and coastal sediment availability (Friedrichs et al. 1990). More detailed formulations are difficult to verify from existing observations at the Nieuwe Waterweg, which include coastal sediment import from anthropogenic and natural factors. Our estimate for A is based on the total distributary channel width (~2 km) and the onlap distance of the aggradation of the RMD (~150 km) (Blum and Törnqvist 2000). Sea-level rise projections for 2050 and 2085 are from the KNMI'14 projections, as detailed in Table 4.

3.5. Dredging component

We employed two methods to calculate future dredging volumes for the RMD. The first was a simple linear forecast based on dredging volumes from the past 37 years (1982–2019) to calculate $Q_{dredging}$. The reported dredging volumes for the channels and ports of the RMD were recorded by regional waterway management (Rijkswaterstaat West–Nederland–Zuid) and the Port of Rotterdam. This first relation assumes continued and expanded use of the offshore port Maasvlakte 2 to accommodate growing container ships.

The second method was a forecast derived by linking the changing ship size with the changes to the channels and dredging in the Rotterdam port area (see Fig. 4). This relationship assumes that the inland channel and port network will continue to accommodate increasingly larger container ships. As the ship draft increases, a deeper navigational channel (the Nieuwe Waterweg) and deeper inland ports are required. These deeper channels and harbours are more efficient at trapping sediment and have recently required increased dredging (de Nijs et al. 2009; de Nijs and Pietrzak 2012; Cox et al. 2021). We predicted dredging volumes based on the observed relationship between the ship draft, the Nieuwe Waterweg navigational channel depth, and concurrent dredging volumes:

(4) $h_{NWG} = -0.06^{*}d_{ships} + 109$

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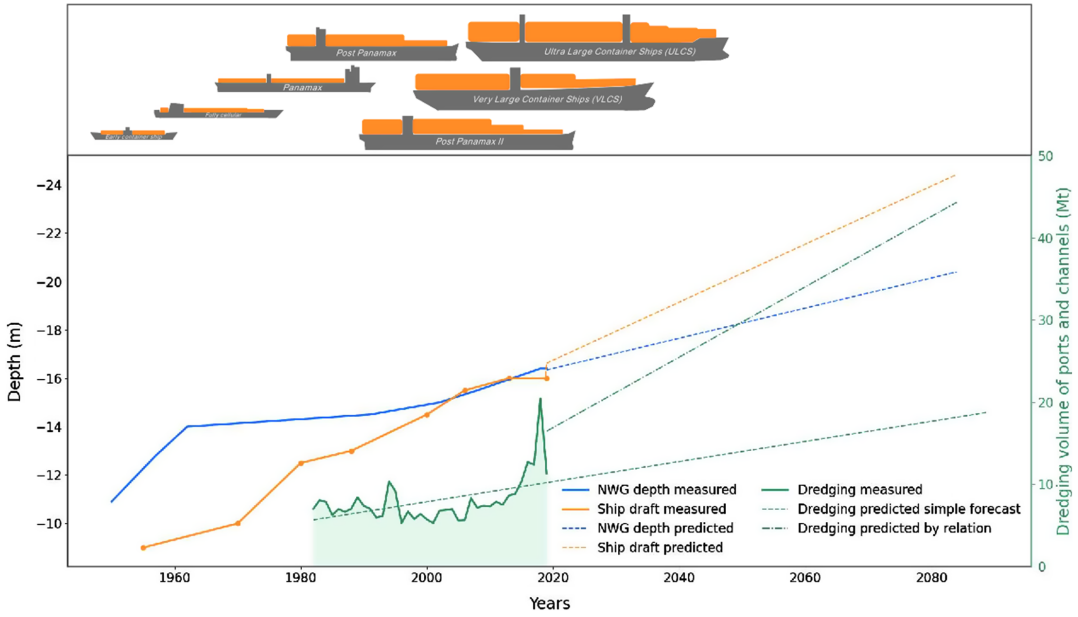
Fig. 4. The relationship between ship size and draft, the depth of the navigational channel in the Rhine–Meuse delta (RMD), and the dredging volumes for the region. The measured ship draft is the maximum ship draft (m) of the largest commercial container ship at that point in time.The names of those ship types are represented as graphics (scaled relative to each other) in the panel. The dashed lines represent the simple linear forecast for all three components, whilst the dot–dash line represents the dredging component as calculated using Eqs. 4 and 5.



and for the dredging volume:

(5) $$Q_{\text{dredging}} = -0.12^{*}h_{\text{NWG}} + 226$$

where h_{NWG} is the nautically guaranteed depth of the Nieuwe Waterweg channel (m), d_{ships} is the draft (m) of the largest class of ships, and Q_{dredging} is the volume of material dredged from the RMD (Mt/year). These empirical equations should be applied with caution, and not beyond the reasonable bounds of the ship size. The range of error for this derived value is ±23%, which is the cumulative root-mean-square error of the linear interpolations.

We retrieved the maximum ship draft (m) of the largest commercial container ships over time from Rodrigue (2020). The change in maximum ship depth represented here is for container ships only (as these are the primary types of ships entering the ports and harbours of Rotterdam). The relationship shown here seems physically unrealistic (Fig. 4): the Nieuwe Waterweg is not always deep enough to allow passage of the largest ships, as increased use of a new port offshore (Maasvlakte 2) has reduced the need for ships to enter the main navigational channels. However, if ships continue to get larger, Maasvlakte 2 may also require deepening (the current depth is 20 m and ships of a draft of up to 17.4 m can be accommodated). Similarly, we did not include any geological or other constraints that could provide a barrier to further deepening. We assume that the Nieuwe Waterweg will not be widened, as it has not been widened since it was dug in 1872, and the ship width would have to increase significantly for any widening to occur.

We used both methods 1 (linear extrapolation) and 2 (relationship between ship draft, navigational depth, and dredging volume) to predict a dredging component for the future

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sediment budget. A major assumption in the calculation of this budget is that the stakeholder priorities remain the same and the current sediment management strategies continue, that is, dredging to maintain navigability remains the key management focus. At present, small pilot activities are being undertaken to sustainably manage sediment in the system. However, we assume that the current strategy for dredged material persists and the material is essentially completely removed from the system, as has been the case for the past 30 years (Cox et al. 2021). For the purposes of this study, we also assume that no large-scale engineering measures that drastically affect the delta system, such as the Maasvlakte 2 or sand engine projects, will be undertaken. No such projects have currently been designed or planned, but if large-scale changes would occur that drastically affect the channel network (width, depth, flow direction, discharge, velocity, salt wedge) the sediment budgets and distribution would also be altered.

Dredging data and sediment fluxes were converted from volume to weight using the density data for the given branches. We assumed that the density of the sediment in the different branches remained constant in the future. However, as pointed out by Cox et al. (2021), the density of sediment, particularly in the mouth region, is changing, which cannot be accounted for in this budget. We also assumed that all material removed by dredging is settled suspended sediment. This is a reasonable assumption for the downstream part of the system where the majority of dredging occurs, as recent surveys of the dredging spoils indicate that the material is largely mud, silt, or fine-grained sand (van Bruchem 2018*a*, 2018*b*, 2019). In the upstream branches, sand and bedload transport can be significant, but these branches only contribute a very small amount to the overall dredging in the system. Updated density information about the upstream riverine branches was not available, and thus, the data of van Dreumel (1995) is used for conversion.

3.6. Available suspended sediment and discharge data

We analysed the suspended sediment concentration (SSC) and discharge data to investigate the partitioning of sediment between the RMD distributary channels. The SSC data used are available from the Rijkswaterstaat (RWS) Service Desk (WaterInfo) for the years 2000–2018. Measurements were obtained by the RWS following two methods. The primary method was the collection of in-situ samples, 1 m above the bed. The second method determined the SSC from residual acoustic Doppler current profiler (ADCP) measurements from permanently fixed ADCPs on buoys or other stationary objects. We included sampling stations with a monthly measurement frequency or greater, resulting in 11 stations (Fig. 2).

We used a 1D SOBEK-RE model (more information about the model can be found in Kraaijeveld (2003) and Cox et al. (2021)) to extract water discharge for 2000–2018 at the SSC measurement station locations. The seasonality and interannual variations in discharge were also explored using this discharge data.

3.7. Calculating annual fluxes and erosion and sedimentation patterns per branch

The annual sediment flux at each measuring station was calculated as the arithmetic mean of the instantaneous sediment fluxes (calculated as the product of SSC and Q) at the time of SSC measurement:

$$Q_{\text{branch}} = D\overline{Q_{\text{water}}\text{SSC}} \quad (6)$$

where $D = 31\,557\,600$ s/year is the duration of the year in seconds, Q_{branch} is the annual sediment flux (Mt/year), Q_{water} is the water discharge at the time of suspended sediment measurement (m^3/s), and SSC is the measured sediment concentration in dry weight per

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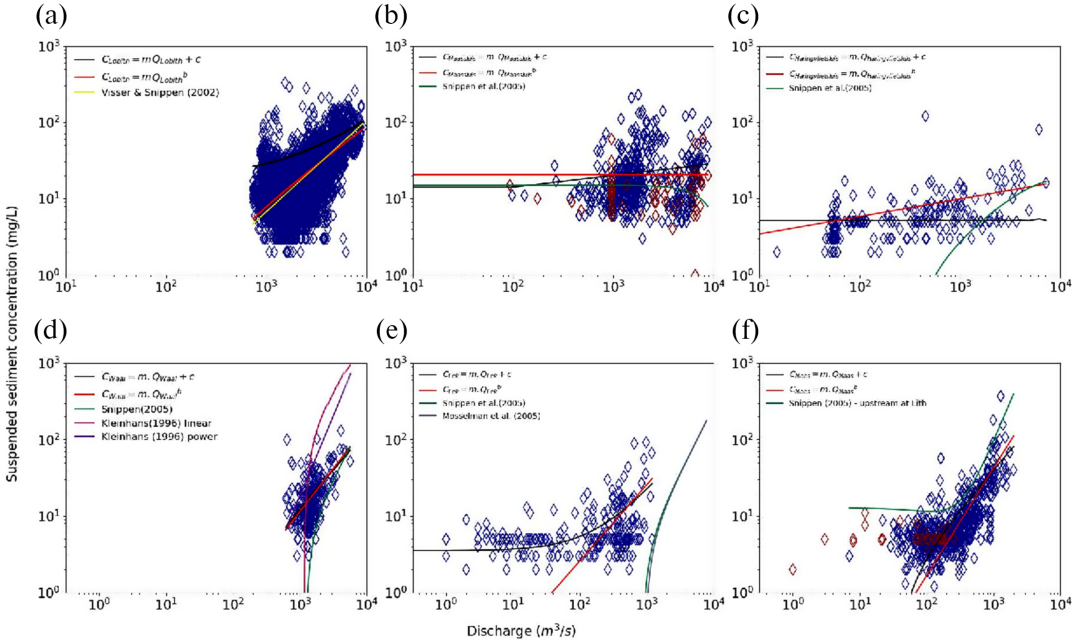
Fig. 5. Suspended sediment concentration relations for (*a*) Lobith (the delta apex), (*b*) Maasluis (the downstream boundary), (*c*) the Haringvliet sluices where sediment is discharge, (*d*) the Waal, (*e*) Lek, and (*f*) Maas upstream rivers. Positive discharge values are marked by blue diamonds and negative discharge values by red diamonds. The linear relationship (black line), power relationship (red line), and previously derived relationships from literature (various colours of lines, plot dependent) are also marked.



unit volume (Mt/m^3). Note that Q_{branch} for the Rhine and Q_{branch} for the Meuse together equals Q_{rivers}.

Furthermore, we assumed a simple linear increase of suspended sediment with discharge for the SSC measuring stations of the RMD and used these locations as "tie points" for the future state of the system. The relationship between discharge and suspended sediment is complex with various relations to describe this process, known as QS relations that have often been historically applied to the riverine and coastal boundaries in the RMD (Kleinhans 1996; Middelkoop et al. 2010). Becker (2015) investigated the historical QS relationships for the upstream rivers of the RMD (the Waal, Maas, and Lek) and identified the best relationship for 2000–2012. We also investigated the various relationships in our timeframe and outline any differences. The known relationships for the various stations are outlined in Table S1[1].

As seen in Fig. 5, for the most recent data from 2000 to 2018, the linear relationship holds well for the boundary stations where linear interpolation was undertaken. This also applies to intermediary stations (Fig. S1[1]). Moreover, previously derived relationships (1980s–2000 data) for the branches mostly remain accurate, with the exception of the Lek. There is high variability present in the QS measurements due to their random sampling periods, under a wide range of discharge conditions. In this analysis, however, only yearly averaged values are used to minimize the effect of this variability. Therefore, there is high confidence in

[1]Supplementary data are available with the article at https://doi.org/10.1139/anc-2021-0003.

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these relations to predict the future SSC at these measuring stations with known future discharge scenarios in the branches.

Sediment flux partitioning at channel bifurcations was calculated assuming that the sediment was well mixed and followed the annual average discharge distribution. We selected the average flow discharge from 2013 from the model to indicate the flow direction and distribution. The net sediment flux differences between stations were used to close the balance by assuming erosion (net increase of sediment from one point to the next — sediment had to be entrained) or sedimentation (net decrease in sediment from one point to the next — sediment had to be deposited).

Annual bed level trends were predicted by

$$\frac{dz}{dt} = \frac{Q_{\text{branch}_{\text{in}}} - Q_{\text{branch}_{\text{out}}}}{A_{\text{branch}} \cdot \rho_{\text{branch}}} \quad (7)$$

where $\frac{dz}{dt}$ is the annual change in bed level (m/year), $Q_{\text{branch}_{\text{in}}}$ and $Q_{\text{branch}_{\text{out}}}$ are the sediment flux into and out of a branch, respectively (Mt/year). $\rho_{\text{s,branch}}$ (Mt/m^3) is the dry bulk density of the sediment for each branch (see Eq. 3), and A_{branch} (m^2) is the surface area of the branch or section of that branch.

We compared estimated bed-level trends with measured bed-level data from 2000 to 2018 (multibeam bathymetry surveys carried out by the Rijkswaterstaat which were converted to digital elevation models) (Cox et al. 2021) to indicate reliability and to isolate the effects of suspended sediment on the bed-level trends.

Future predictions for sediment fluxes assume that the flow directions and discharge distributions remain the same. The increased discharge for the Rhine and Meuse follows van den Hurk et al. (2014) and is imposed at the boundaries. We further assume that sediment concentrations will remain the same, that is, the increase in discharge at the measurement station location corresponds linearly to an increase in suspended sediment at that point. A comparison with the discharge–sediment flux relations previously recorded for the RMD shows that this is a reasonable assumption. Furthermore, we do not predict or analyse how the changes to discharge and sea-level rise will change the hydrodynamic circulation of the system in terms of salt intrusion, density currents, changing tidal range, or otherwise. We assume that under average "normal" discharge conditions, the flow direction and distribution of discharge over bifurcations and confluences will remain the same.

3.7.1. Contribution of high discharge events

The contribution of high discharge events to the annual totals (as calculated by Eq. 6) was also analysed. The fractional contribution of the 90th percentile discharge events to the annual sediment flux was calculated as follows:

$$C_{90} = \frac{Q_{\text{branch}_{90}}}{Q_{\text{branch}}} \quad (8)$$

where C_{90} is the fractional contribution of the ≥90th percentile discharge events to the total annual sediment flux, $Q_{\text{branch}_{90}}$ is the sediment flux (Mt/year) corresponding to the ≥90th percentile discharge, and Q_{branch} is the annual sediment flux (Mt/year), where the 90th percentile discharge is calculated over all 20 years of data. These 90th percentile high discharge ranges incorporate both high upstream discharge (river flooding) and high coastal discharge (coastal flooding from storm events), as the model does not distinguish the two types of discharge. The contribution of the high discharge events was assessed for each SSC measurement station.

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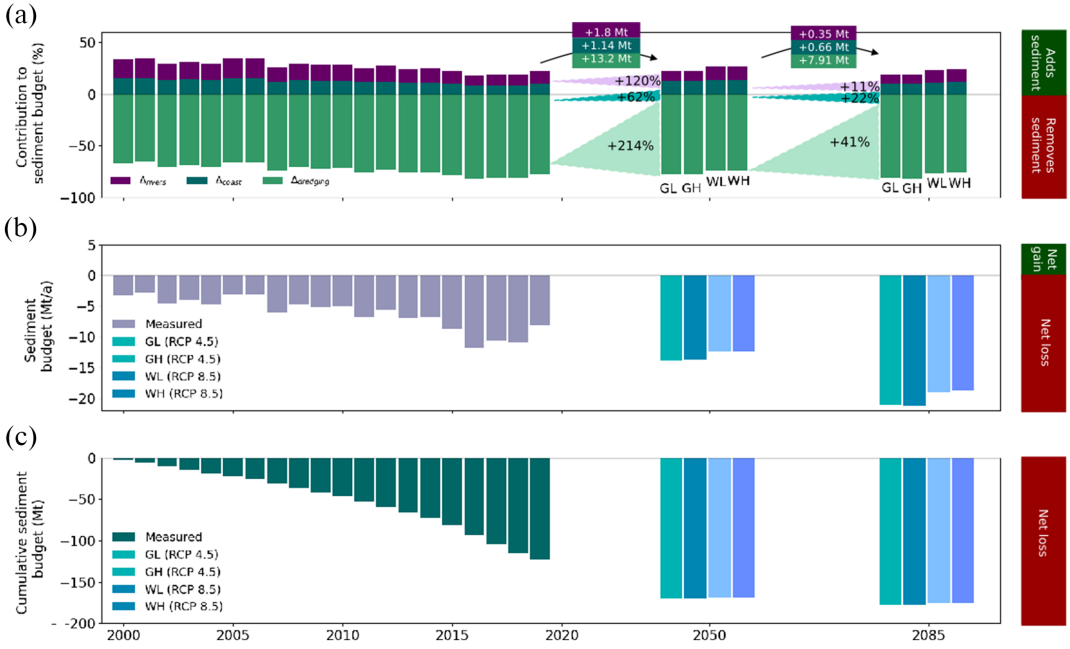
Fig. 6. (*a*) The relative contribution of the three components of Eq. 1 at present and predicted future changes, where the boxes indicate the change in budget (Mt/year) and shaded areas and percentages indicate the relative increase in magnitude of each component. (*b*) The calculated sediment budget for the various climate scenarios. (*c*) The cumulative sediment budget for the various climate scenarios. These climate scenarios for the upstream boundary include the predicted dam construction.



3.7.2. Overbank sedimentation

We accounted for the effect of floodplain sedimentation on the mass balance of the Waal and Lek branches. Overbank sedimentation will increase as the winter Rhine discharge is predicted to increase, causing more frequent inundation (Middelkoop et al. 2010). Following Middelkoop et al. (2010), we assumed that at present, 6% of the incoming sediment in the Waal and 4% in the Lek is lost to overbank sedimentation. Predictions for 2050 indicate that overbank sedimentation will increase to 9.2% and 6.2% of the annual fluxes in the Waal and Lek, respectively (Middelkoop et al. 2010). We also used these fractions for our 2085 calculations because of the lack of more recent predictions for the Lek (between the Pannerdense Kop and Hagestein) and Waal (between the Pannerdense Kop and Vuren). Other downstream branches are assumed to have negligible overbank sedimentation due to their narrow floodplains, heavy embanking, and dampened water level fluctuations.

4. Results

4.1. Predicted sediment budget

As indicated in Fig. 6*a*, both river and coastal inputs will increase significantly by 2050, but will decrease by 2085. Similarly, the dredging component drastically increases by 2050 but slows down by 2085. For all scenarios there is projected to be a negative sediment budget (Fig. 6*b*) in 2050 and 2085 with different ranges of possible values from −12 ± 3.7 Mt/year in 2050 to −18 ± 7.5 Mt/year in 2085. These results include dam construction. If the dams were not included, the riverine flux would contribute an additional 1–1.3 Mt/year for the various scenarios, which is minor relative to the scale of the budget.

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The average for the past 20 years was calculated as −6 ± 0.57 Mt/year. The primary reason for this negative sediment budget is the high dredging component, which matches the contributions of the various components for the present. The high range of values for the predicted scenarios is due to the large differences between the simple dredging relation and the newly derived relation. In Fig. 6, we use the average of both dredging relations, although it is worth noting that if the ship size and dredge depth increase as predicted, then the budget will be significantly more negative. Despite a large potential increase in coastal flux and riverine sediment (Fig. 6), dredging in the delta is predicted to outweigh both of these components. The magnitude of the negative budget strongly depends on dredging activities in the area and if adaptations are made in the system to allow for increased ship size.

Margins of error in all three components accumulate on average to ±8 Mt/year for 2050 and ±4 Mt/year for 2085. These are the combined accumulated errors from all three components: (*i*) variation of climate scenarios in BQART, (*ii*) variation due to different sealevel rise rates, and (*iii*) cumulative root-mean-square error of the dredging interpolations, where they contribute 12%–28%, 7%–11%, and 65%–77% of the cumulative error, respectively. The range of BQART values comes from the future scenarios employed, constructed from four climate projections. The range of sea-level rise rates and resulting variation of coastal flux values come from the KNMI'14 scenarios, where the upper and lower bounds of rates were used to give a range of Q_{slr} and thus range of coastal import values for the future states reported. The largest uncertainty comes from the dredging component, which is strongly dependent on the choices of basin managers and the potential accommodation of larger ships, as discussed in Section 5.2.2. Indeed, yearly variations in dredging can be several megatons, as shown in Fig. 4, making the uncertainty in this component relatively high, depsite a wealth of recorded dredging information.

4.2. Sediment distribution and concentrations

As shown in Fig. 7, the increased fluxes of riverine sediment will lead to increased sediment deposition in many branches in the future. The majority of additional coastal sediment will end up in the Nieuwe Waterweg and Nieuwe Maas channels and, under the current system of management, will therefore have to be dredged and removed from the system entirely.

A large proportion of the increased riverine flux (~54% in 2050 and ~49% in 2085) is projected to be deposited in the Lek and Waal (Boven Merwede) channels, which are currently infrequently dredged. However, the active bedload processes in these branches may prevent that from occurring. These channels are still frequently used for shipping as they provide routes to the Amsterdam–Rhine canal and other important inland waterways. The additional sediment is also notably fed into the Biesbosch wetlands and may provide an opportunity for the system to counteract sea-level rise.

Most branches will remain relatively stable in terms of bed level, with some notable exceptions being increased bed level in the mouth and upper river branches and erosion in the Oude Maas branch. It is worth noting that Fig. 8 indicates changes in the absence of dredging activity.

Despite the overall increase in sedimentation and bed levels, the southern branches (Haringvliet and Hollands Diep) that crucially need sediment to sustain wetlands receive negligible sediment relative to their area, as reflected in the bed-level trends. Similarly, the cross-cut tidal branches such as the Oude Maas will continue to erode with extreme erosion predicted in parts of the branch. This uneven distribution will therefore continue to create challenges in the management of the RMD.

Fig. 7. Comparison of (*a*) the actual measured bed-level change in the Rhine–Meuse delta (RMD) (2000–2018 cumulative), (*b*) cumulative bed-level change due to dredging (2000–2018), (*c*) predicted bed-level change due to changes in suspended sediment fluxes and mass balance (2000–2018 cumulative), (*d*) predicted cumulative bed-level change due to the contribution of suspended sediment (2018–205), (*e*) predicted cumulative bed-level change due to the contribution of suspended sediment (2018–2085) with modelled sediment fluxes imposed at the boundaries. Map created using ArcGIS® software by Esri, and multibeam data from RWS. Basemap courtesy of Esri (ESRI 2021).

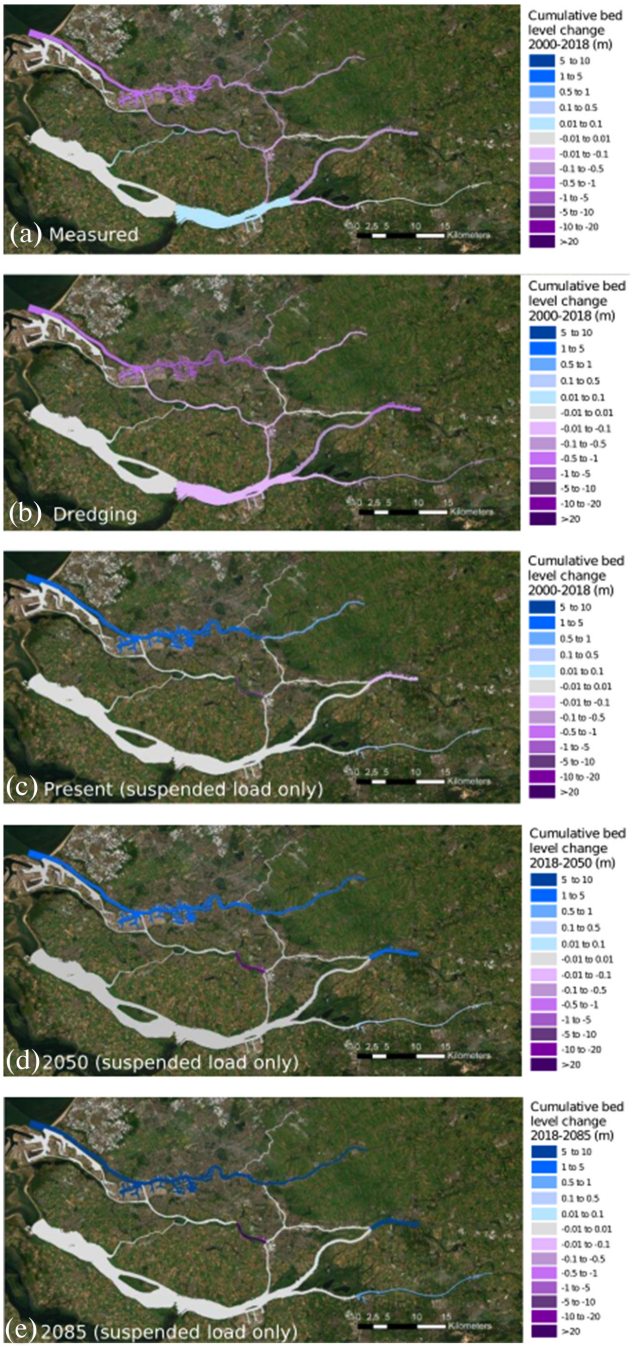

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Fig. 8. Comparison of (*a*) the distribution of suspended sediment fluxes at present (annual average flux 2000–2018), indicating measuring stations, measured and modelled sediment fluxes, and consequent erosion and sedimentation, (*b*) the predicted suspended sediment distribution in 2050 with modelled sediment fluxes imposed at the boundaries and bifurcations using QS for the measuring stations, and (*c*) the predicted suspended sediment distribution in 2085 with modelled sediment fluxes imposed at the boundaries and bifurcations using QS for the measuring stations. All units are in Mt/year.

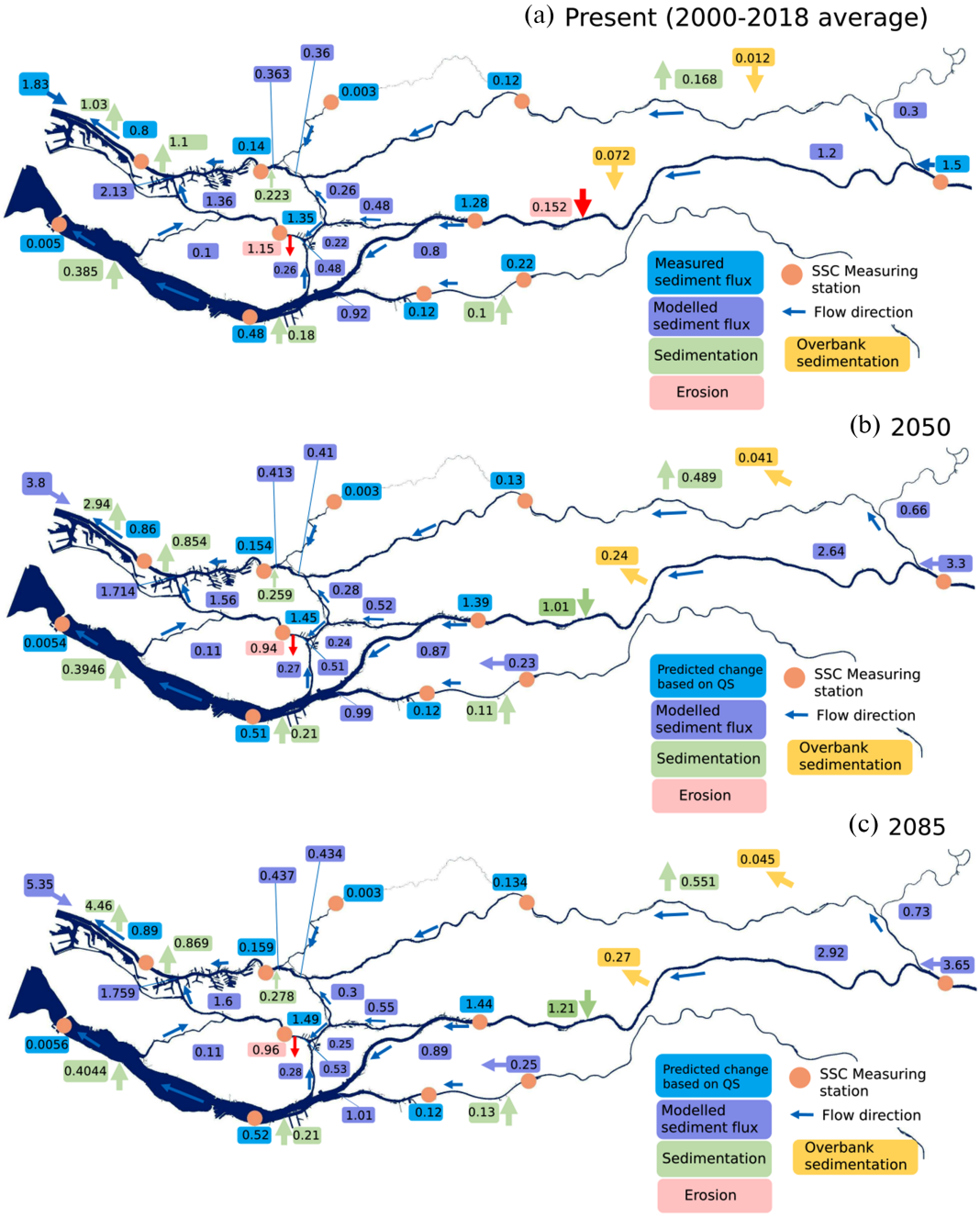

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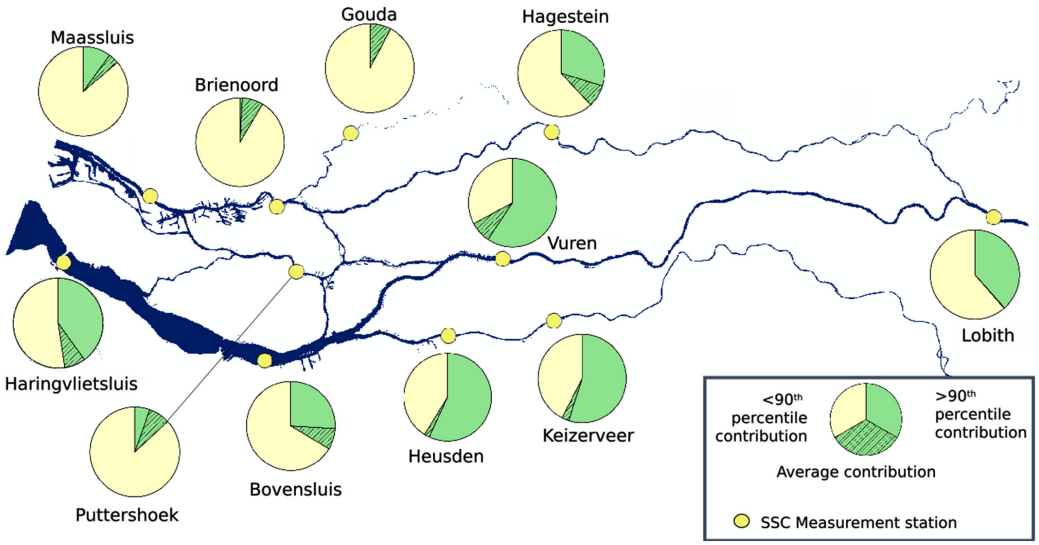
Fig. 9. Contribution of fluxes carried during ≥90th percentile (high) discharge events to the annual average flux for each SSC measurement station (average 2000–2018). Where yellow slices mark the contribution of sediment fluxes carried during 0–90th percentile discharge events to the annual average flux, green slices mark the contribution of sediment fluxes carried ≥90th percentile discharge events to the annual average flux, and the overlain hashed area indicates the average contribution of each measured flux to the annual average sediment flux, which varies depending on data density from 0.2% to 8.3%.



4.2.1. Relative contribution of high discharge events to annual averages

Figure 9 shows the contribution of high discharge events to the annual average fluxes. For most branches, the contribution is quite significant (10%–20% of the annual flux). In the upstream riverine stations Lobith, Hagestein (Lek), Vuren (Waal), and Keizerveer (Maas), the contribution can be extremely significant (40%–60%). It is notable that in the southern branches, the contribution of high discharge events contributes more sediment to the annual sediment flux than that of the northern and middle branches. More extensive data are required for many of the stations to accurately assess the contribution of discharge ranges to annual fluxes. Currently, SSC data do not encompass sufficient ranges of discharge to accurately and confidently predict the ranges and events for future climate scenarios.

5. Discussion

5.1. Why does dredging outweigh natural sediment fluxes?

The mouth of the RMD is at a clear disequilibrium between the coastal import and the amount of ongoing dredging. It may seem counter-intuitive that the amount of dredging occurring in the delta outweighs the sediment delivery to the distributary network. However, there are several reasons for this difference. The primary reason is the uneven distribution of sediment within the system, which causes significant volumes of sediment to end up in the mouth area. The management system for maintaining the navigation depth of the channels then removes this sediment. The dominant flow direction of the system (see Fig. 2) under normal conditions drives sediment from the upstream rivers into the Nieuwe Maas and Nieuwe Waterweg, and the continuous removal of that sediment leaves other channels sediment-starved and eroding.

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This is compounded by several other minor effects. First, the dredging component forecast includes capital dredging events (not only maintenance dredging to keep channels at depth, but also sediment removed in once-off events to deepen channels). We predict that these will continue to play a role in the RMD but can also cause significant yearly increases in dredging volumes in the channel network. Second, the erosion of material from channel beds is likely to contribute additional sediment that is not captured in the budget. For example, the Oude Maas channel degrades several centimetres per year, and it is likely that this sediment becomes entrained and is transported within the channel network. It is likely that this additional sediment accretes in the Nieuwe Waterweg and surrounding ports, owing to the dominant flow direction (see Fig. 2) and high trapping efficiency in the mouth area (de Nijs et al. 2009; De Nijs and Pietrzak 2012). The frequency of bed-level measurements (monthly to yearly) and scattered spatial coverage are not accurate enough to measure the exact volume of sediment entrained by erosion annually but may account for part of this "additional" sediment that is dredged annually in the mouth.

Third, as previously noted, the coastal flux has not been accurately updated since the 1990s and may be significantly higher than estimated. However, even an error of up to 100% would still not outweigh the dredging volume in the region. Finally, although most maintenance dredging takes place close to the river mouth, where the suspended load is more significant than the bedload, it does not necessarily correlate perfectly with marine sediment import. Furthermore, as discussed below, the influence of seasonality and high discharge events are not captured in annual averages; however, storm surges and high discharge events can cause high influxes of sediment that are also removed by dredging.

It is worth noting that a minor increase in dredging (or yearly fluctuations) will not change this trend. Currently, dredging is 30% greater than incoming fluxes (Cox et al. 2021), and in the future, it will be 180%–300% larger than the incoming fluxes. Thus, a stark decrease in dredging would need to occur for the sediment budget to become positive.

5.2. Future changes and uncertainties of boundary conditions

The fluvial sediment projections were modelled with BQART, an equation designed for basin-scale long-term usage, and so, are ideal for this research. However, it is a simple equation and there are aspects that could be improved in the future. First, although the glacier extent in the basin is small and therefore has minimal impact on the sediment fluxes, it would be ideal if the assumption of a constant glacial area was updated to take into account changing glacier behaviour due to climate change. While smaller glaciers would reduce sediment flux under the current BQART assumptions, it is possible that as glaciers shrink, they could deliver increased water and sediment discharge to the fluvial system (Lane et al. 2017). These processes would be interesting and important for the exploration of systems with large current glaciers.

While scenarios with and without planned reservoir construction were considered, the discharge projections used were the same for each set of scenarios, that is, the planned reservoirs were assumed to have no impact on the discharge. Unfortunately, it is very difficult to determine the effect of an as-yet non-existent dam on a river, considering that dam management can play a significant part in its ultimate impact. An additional topic for future work concerns the assumptions in the model around reservoir trapping, which is currently a simple relationship; however, as stated, it can be greatly affected by management. It is currently unfeasible to include this type of water engineering management at the basin scale, considering both model complexity and data availability. While the anthropogenic factor was tailored to this research (see Methods), it is still a proxy for anthropogenic actions that have a direct impact on fluvial sediment but are difficult to assess at the basin scale, such as agricultural practices and fluvial engineering. For future development of

more complex, spatially explicit implementations of BQART, a promising area of research is to represent these anthropogenic activities directly rather than by proxy, which would avoid the issues with assumptions of human behaviour under certain levels of socioeconomic development at a global scale.

5.2.1. Complex processes at the mouth and uncertainty in the coastal import

We acknowledge that our linear relationship for sea sediment import is an oversimplification of a complex set of processes. For example, it does not take into account tidal asymmetry in the North Sea, which could prove important in sediment delivery in the future, as it has done in the past (van der Molen et al. 2001; Haas et al. 2019), which may enhance sand export (Jiang et al. 2020). Moreover, the region of freshwater influence, salt wedge, and density currents also impact sediment transport in the mouth, making it difficult to quantify accurately.

The ongoing complex processes at the mouth limit our confidence in our relationships for the import and distribution of sediment at the coastal boundary. Quantifying the flux of sediment coming from the North Sea has historically been a challenge in creating sediment budgets for the region, as most budgets rely on outdated data and there is a lack of newer information, particularly since large-scale engineering measures such as the Maasvlakte 2 have been undertaken (van Dreumel 1995; Snippen et al. 2005; Becker 2015; Frings et al. 2019; Cox et al. 2021). The SSC measurements taken at the Maassluis while providing some insight are currently too infrequently recorded to improve our understanding, and a large margin of error is reported. Tidal processes, a pervasive salt wedge, density currents, waves created by ships, and complex water chemistry have consistently made the suspended sediment in the mouth area challenging to quantify (de Nijs et al. 2008, 2009; de Nijs and Pietrzak 2012), and a relationship linked to hydrodynamic change is difficult to quantify. Although improvements are being made with mounted ADCP measurements, our understanding of the 3D profile of sediment and sediment transport in the mouth remains limited. A more accurate and detailed time series of SSC measurements at varying depths and locations (accounting for varying densities and currents) is required to improve this element of the sediment budget.

Deepened systems such as the RMD distributary channel network tend to have increased tidal penetration (Quante and Colijin 2016), which increases with sea-level rise, giving rise to a larger salt wedge in the RMD in the future (Huismans et al. 2018). The salinity of the North Sea will decrease in the future (due to freshening associated with additional freshwater input) (Schrum et al. 2016), which in turn will alter the density-driven salinity currents in the mouth and will impact the suspended sediment concentrations even further in the future, making 3D profiles of SSC more important for accurate quantification. The amount of suspended sediment in the mouth area is closely linked to the tidal excursions of the salt wedge and the estuary turbidity maximum (de Nijs and Pietrzak 2011; de Nijs et al. 2011), and we did not include changes to any of these processes in our study. Thus, the uncertainty in the coastal flux remains high as these complex processes continue to interact and affect sediment concentrations and circulation in the mouth region.

The feedback mechanism between enhanced sediment import at the coastal boundary and the shallowing and deepening of channels is a further question. Channels will have an increased water depth due to sea-level rise due to estuarine circulation, but there are points where channel inlets are so deep that the bed shear stress in flood is smaller and sand import will decline. However, without a functioning model for the region and further data on mud and sand transport, we cannot quantify these feedback mechanisms, which may alter sediment transport patterns at the coastal boundary and indeed in the channel network.

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Changes in the North Sea circulation, temperature, waves, tides, wind patterns, and salinity, which together with alongshore currents drive sediment transport along the Dutch coast and into the RMD, are not included in this study. This points to the need for a hydrodynamic and morphological model in this region to more accurately account for sediment import in the future and at present. Moreover, field measurements are required to validate such a model.

5.2.2. The future of dredging and ship growth

While we assume no limitations to the possible channel dredge depth, in reality, the channel depth is limited by subsurface geology. The presence of non-erodible clay layers can limit the depth of the channels in the RMD and contribute to differential erosion and deposition rates within channels (Sloff et al. 2013). Similarly, the requirements to preserve sufficient sediment above the extensive cable networks laid underneath the channels may limit the dredge depth (Haasnoot et al. 2018). These processes are difficult to quantify and thus are neglected in our study, but could be important limiting factors for the future of dredging in the RMD.

It is speculated that ship size cannot continue to grow at current rates and that an increase in ship size will not bring any further additional benefit or significantly reduce transport costs (Lian et al. 2019; Malchow 2017). Despite this, ports and harbours require joint operational decisions to be made or to decide to limit ship size for themselves, which puts them at a market disadvantage (Malchow 2017). It should be noted that there seem to be few benefits to increasing ship size further, recent trends suggest that there is no slowing down of ship size increase. Indeed, there has been a sharp increase in ship size in recent years (Lian et al. 2019). Gomez Paz et al. (2015) identified that ship growth (and consequently navigation dredging) in the coming 20 years will be limited mainly by the straits and channels used for sea transport with responding changes in port and ship infrastructure as growth-limiting factors. Physical alterations to ports are not only limited to an increase in depth, but as ships grow larger, they also become longer and wider which demands longer and stronger quays, wider access channels, and in estuary ports, wider rivers are necessary (Merk 2018). Changing innovations in ship dimensions (e.g. wider but shallower ships) may still demand changes to the RMD channels, which are difficult to predict.

Dredging deeper channels and ports to accommodate growing ships is not unique to the RMD. Indeed, ports located in deltas and estuaries worldwide, including in the USA (Carse and Lewis 2020; Shepsis et al. 2001), South America (Guerrero et al. 2013), Asia (Z. Wu et al. 2014, 2016; Jarriel et al. 2020), Australia (Sampson et al. 2014), Africa (Nabee and Walters 2018), and Europe (Grossmann 2008; van Maren et al. 2015; Gasparotti et al. 2016) periodically or continuously remove sediment to compete with each other economically and to provide goods to growing populations. Recently, innovative solutions have been explored to address this issue, including under-keel clearance modelling (Mortensen et al. 2017), improvements to engines and engine efficiency (Merk et al. 2015), and an increased focus on adaptive port planning (Taneja et al. 2010). However, the future of global port development and its relationship with growing ship size is still unclear and depends on many factors, including technological development, city development, available sea space, port relocation, and climate change (Becker et al. 2013; Schipper et al. 2017; Merk 2018; Harlambides 2019; Yap and Loh 2019). These changes directly impact sediment budgets in urban estuaries, as shown in Fig. 6, which can significantly outweigh the natural fluxes in deltas. One key factor is that the Suez Canal is often identified as a key limiting factor, as it is a bottleneck in the connection between Asia and Europe with many commercial container ships designed with the Suez Canal specifically in mind (Malchow 2017; Park and Suh 2019).

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As the water depth in the major navigation channels increases with sealevel rise, this affects the navigation depth. Haasnoot et al. (2018) predicted that sealevel rise will increase water depth in channels as sedimentation will not occur quickly enough, thereby creating the required water depth for navigation with less dredging. The interaction of the deposition and dredging processes should be studied to investigate whether an equilibrium dredge depth can be achieved to minimise cost and optimise dredging in the RMD. An equilibrium dredge depth may not, however, be possible if ships continue to grow at the current rate, for the Port of Rotterdam to remain competitive.

5.3. Uncertainty of fluxes, distribution, and sedimentation and erosion trends

The morphological effects of climate change due to altered high and low discharge will cancel each other out in the future (Haasnoot et al. 2018). Therefore, changes in the morphology, sedimentation, and erosion patterns of the branches will be strongly controlled by sediment supply and circulation in the RMD. As described by Kleinhans (1996), Visser and Snippen (2002), Mosselman et al. (2005), Snippen et al. (2005), and Becker (2015), the relationship between suspended sediment and discharge in the RMD is complex, and more data are required both spatially and temporally to improve our confidence in the QS relations for this budget. Moreover, as shown in the high discharge analysis, episodic fluxes are key for future management of the delta, and an investigation into the influence on bed level would require more frequent bed-level and SSC measurements. Surveys that can encompass a full range of hydrodynamic conditions, such as Xie et al. (2017, 2018), would be particularly beneficial to indicate the influence of these events on the morphodynamics of the system.

A further concern is the simplified pattern of the discharge and suspended sediment flow through the system. However, as sea levels rise, the tendency for suspended sediment is to follow the discharge distribution more directly at bifurcations (Kleinhans et al. 2008, 2013), which increases our confidence in these estimates for the future.

The bed-level trends calculated are derived from suspended load only, but in some of the southern branches in particular, bedload can contribute significantly to sedimentation and erosion (Becker 2015; Frings et al. 2019). We calculated these maps (Fig. 2) in the absence of dredging. However, in reality, the northern branches will never experience cumulative sedimentation, as they will be dredged for navigation, and the interaction of these processes and effects through time are not accounted for.

The predicted level trends calculated for the present primarily differ from the measured bed-level data for the tidal cross-cut channels. There is a distinct lack of measurement data available in these channels (see the distribution of stations in Fig. 2). Therefore, our projections do not show any changes, as we assume that all sediment is transported until the next measurement point. These branches contain large scours, which are currently slowed by the presence of hard layers, which cause bed level differences (Cox et al. 2021). The erosion trends are largely caused by increased tidal currents in these branches, as the tides are now out of phase following the closure of the Haringvliet mouth and not directly by sediment starvation.

5.4. Negative effects of a negative sediment budget

Sufficient SSC is key for intertidal areas to keep up with sea-level rise, with marshes with a low tidal range and low SSC (<20 mg/L), similar to those of the RMD which are most at risk of submergence (Kirwan et al. 2010; Quante and Colijn 2016). As sea levels rise, an increased amount of sediment will be required to offset the drowning of the delta. Several factors control sediment deposition in tidal wetlands in the face of sea-level rise, including suspended sediment load and flooding frequency, depth, and duration (Asselman and Middelkoop 1998; Middelkoop and van der Perk 1998; Temmerman et al. 2003; Schuerch et al. 2013; Noe et al. 2016). To continue to grow, the Biesbosch wetlands need sufficient supplies of

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sediment and water (van der Deijl et al. 2017). Extensive measures have been taken in the Biesbosch (by depoldering and diversion of water and sediment) to counteract future sea-level rise, and it can currently compensate for rates of sea-level rise and subsidence (van der Deijl et al. 2018). In fact, the Biesbosch currently has a positive sediment budget (van der Deijl et al. 2017), and according to our future budgets, riverine sediment will continue to feed this region sufficiently. However, the seasonality of discharge will play an important role with longer periods of low discharge and more frequent high discharge events (van den Hurk et al. 2014; Sperna Weiland et al. 2015), which are not always beneficial for sediment deposition in the Biesbosch (van der Deijl et al. 2017). As noted in Fig. 9, the extremely high importance of high discharge events to annual sediment fluxes indicates that these events are key to understanding how the Biesbosch will develop in the future.

Balancing stakeholder needs is not unique to the RMD; indeed, many systems struggle with maintaining nature areas while also providing housing, navigation, and economic growth (Loucks 2019). The current benefits of the sediment management system and negative sediment budget are the free navigation of goods, allowing the Port of Rotterdam to remain competitive and highly efficient. It is possible that negative effects such as the loss of ecosystems and damage to infrastructure can even be financially offset by the high profits of the port (Kuipers 2018). Thus, the benefits and consequences of such a negative sediment budget in the future must be carefully considered by system managers and will likely be determined by their choices and preferences. However, as deltas, the RMD included, move towards nature-based solutions and Room for the River projects (Temmerman et al. 2013; van Wesenbeeck et al. 2014; van der Deijl et al. 2018), the ability of the RMD to adapt is currently limited by its hard engineering and sediment management structure.

Sustainable reuse of sediment to target sediment-starved areas is becoming increasingly common in deltas globally (Frihy et al. 2016; De Vincenzo et al. 2019; Baptist et al. 2019). However, in the RMD, the sediment that is dredged is either dumped off the coast (if uncontaminated), sold to the market (mostly sandy sediment), or stored in a depot known as the "Slufter" (if contaminated). This provides a possible solution for the negative sediment budget, that is, to retain the dredged material within the system.

It is not only that the sediment budget is negative but that the distribution is extremely unfavourable. The current circulation system ensures that the mouth region and northern upstream branches will see a positive sediment budget (net gaining sediment), while the central and southern branches will experience a negative sediment budget (net loss of sediment), meaning that the negative sediment budget does not affect all parts of the system equally.

5.5. Application to other deltas

The various kinds of human influence on the sediment budget of the RMD delta are valid and applicable to other deltas worldwide. In many urban deltas, channels are dredged for both navigation and sand mining (Bendixen et al. 2019; C. Wu et al. 2016; Hackney et al. 2020), which directly removes sediment from the system. As a result, tidal penetration and estuarine circulation may increase with channel depth, and sediment transport patterns are altered. In the case of the RMD, which debouches into a shallow, sediment-rich sea, this leads to an increase in coastal sediment import, but whether this occurs in other deltas depends strongly on offshore bathymetry and sedimentology. The upstream boundary conditions were changed by human interference. In many deltas, sediment delivery is reduced due to dams that trap sediment and changes in land use, including measures to avoid land degradation and hillslope erosion. In the case of the RMD, this has led to increased trapping of sediment in the floodplains that have been lowered to reduce flood risk (Middelkoop and van der Perk 1998, 2010). The change in upstream sediment import

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is crucial for determining delta sediment budgets, as outlined in Dunn et al. (2019). However, changes to the upstream and downstream boundary conditions (which supply sediment) are considerably outweighed by anthropogenic activities (which remove sediment) in most urban deltas. As navigation dredging increases in ports globally, driven by increasing ship size, similar effects are observed in the channel networks and sediment budgets of urban deltas. That is, a negative sediment budget (net annual sediment loss) and an uneven distribution of the remaining sediment among delta channel networks. The associated negative consequences are bed erosion can cause damage to infrastructure (pipes and cables) and increase the risk of failure of many flood and bank protection measures. Furthermore, the lack of sediment input induces uneven deepening in channels, depending on their sediment dynamics and proximity to sediment-delivering boundaries. The uncertainty of coastal sediment import, due to climate change or other factors, will also determine the sediment budget of deltas in the future.

6. Conclusion

The Rhine–Meuse delta will continue to have a negative sediment budget in the future, with the degree of negativity dependent on climate scenario and including uncertainty in the budget. The primary cause of this annual sediment loss is the immense dredging that occurs in this region. As the Port of Rotterdam continues to develop and accommodate larger ships, the influence of dredging dominates the sediment budget. The distribution of sediment in the system is uneven and unfavourable. Branches in the southern part of the delta, which are ecosystemrich, will receive insufficient sediment to maintain their elevation in the future. The middle part of the delta lacks sediment, which is urgently needed to counteract extensive bed erosion, scours, and bank instability. Meanwhile, it is inconvenient for the northern navigational branches to trap the majority of incoming sediment, which under the current policy must then be dredged to allow passage into inland ports. The RMD is heavily urbanised; thus, extensive flood safety infrastructure, underground wires, and tunnels must be preserved, and protection requires sufficient sediment. However, high discharge events (storms and river floods) can provide high amounts of sediment annually and may prove key in providing the required sediment episodically.

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