The vulnerability of tidal flats and multi-channel estuaries to dredging and disposal

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Shipping fairways in estuaries are continuously dredged to maintain access for large vessels to major ports. However, several estuaries worldwide show adverse side effects to dredging activities, including a shift from multi-channel systems to single-channel systems and the loss of ecologically valuable intertidal flats. We used a physical scale-experiments, field assessment of the Western Scheldt estuary (the Netherlands) and morphodynamic model runs to analyse the effects of dredging and future scenarios. All methods indicate that dredging and disposal strategies are in the long run unfavourable because dredging increases the imbalance between shallow and deeper parts of the estuary, causing a loss of valuable connecting channels and fixation of the tidal flats and main channel positions. Changing the disposal

strategy towards main channel scour disposal can be economically and ecologically better for the preservation of the multi-channel system. Further channel deepening will accelerate the adverse side effects, whereas future sea-level rise may revive the multi-channel system.

1 Introduction

River mouths, or estuaries, are important centres of global transportation and commerce. Most estuaries are continuously dredged since the early 20^{th} century with an acceleration of activity in recent decades. Continuous dredging is needed to maintain a minimum depth requirement for the shipping fairways so that large commercial vessels can access major ports[1], e.g., Yangtze Estuary (Shanghai)[2], Western Scheldt (Antwerp)[3,4] and Elbe Estuary (Hamburg)[5]. The use of estuaries for shipping also poses considerable issues[6]. Dredging smooths the estuary as obstruction, e.g. shoals, bars and sills are removed[7], which affect smaller channels and bars that are important for seabed animals, fish and birds. The hydrodynamic effects of dredging consists of tidal amplification[8,9] that increases circulation and increases the flood-dominance of the tidal asymmetry[10]. It is site-specific which hydrodynamic processes dominate and how these affect sediment transport and morphodynamics of the system. Moreover, dredging activities are thought to cause a shift from a multi-channel system to a single-channel[11,12] or loss of ecologically valuable intertidal flats[1,8,13–16]. Yet, it remains undiscovered what the long-term effects of the current dredging and disposal strategies have on the sustainability of tidal flats and multi-channel estuaries, and what the response will be from future stresses such as increasing minimum channel depth for shipping and sea-level rise.

The ecological quality of multi-channel systems is partly determined by the presence and characteristics of intertidal flats and channels[17]. Multi-channel systems often display a quasi-regular repetitive pattern that consists of meandering ebb-dominated channels and straight flood-dominated channels in the inner bends[18,19]. The difference in meander action between ebb and flood channels, and the opposite direction of residual sand fluxes in these channels lead to the formation of intertidal flats, which are dissected by connecting channels[17,18,20,21]. Estuaries consists of an ebb-dominated channel and a flood-dominated channel, displaying characteristic morphologic behaviour that is associated with net sediment exchange between channel junctions. Besides the ecological value of the multi-channel system, there are more reasons that advocate sustaining the multi-channel system, namely:

- side channel shallowing reduces the navigability of smaller inland vessels [4],
- main channel deepening increases tidal range and flood risk [14],
- increased peak velocity in deepened main channel affects navigability [7,22],
- channel deepening threatens bank stability, and tidal flat stability and salt-marsh stability [14,23,24],
- large morphological changes alter ebb-flood dominance, including duration and asymmetry [22], potentially affecting mud and sand budgets.

Changes in the connecting channels affect the spatial extent of mudflats, tidal marshes and intertidal flat ecosystems that provide important services, such as storm protection, shoreline stabilization, and food production, which support the livelihoods of millions of people worldwide[25].

To improve biodiversity and increase tidal flat areas in estuaries it is becoming imperative to use nature-based solutions. Urgent research questions related to dredging and disposal in large estuaries in general are: (1) To what degree can the multi-channel system be sustained/ improved by current dredging and disposal practices? (2) What are the effects of further main channel deepening on the morphology of the multi-channel system? (3) What will be the effect of predicted sea-level rise[26] on the morphological and ecological functioning of the estuary? By a combination of scale experiments in the laboratory where the effect of dredging was isolated and data assessment from the Western Scheldt (the Netherlands) for real scale practice, we show how dredging changes the natural development of estuaries. We applied a numerical model to quantify how disposal strategy can limit adverse side effects, and how future scenarios, such as increasing shipping draft and sea level rise, will affect the estuary morphodynamics and the habitat suitability.

2 Experimental development of a multi-channel estuary

A new experiment in the Metronome[27] with dredging and disposal was conducted in otherwise the same conditions as an undredged control experiment that shows three phases of development[21]. First, alternate bars, i.e. shoals, develop during widening of the estuary. The initial alternate bars grow and bound a meandering channel, comparable to alternate bars in rivers[28–30]. As soon as the bars exceed a width-to-length ratio of approximately 1/7, the flood flow cuts barb channels, described as a one-ended channel that partly crosscuts a bar[31,32], into the alternate bars. The seaward barb channels progressively cut through the alternate bars, while the bended channels expands laterally, forming an estuary planform. This estuary shape follows a Van Veen[33] like structure with mutually evasive ebb- and flood-dominated channels, and is similar to the Western Scheldt.

Second, mid-channel bars formed that are large enough to divert the flow, accelerate outer-bend erosion, and form major bifurcations and confluences seaward and landward of the mid-channel bars. A quasi-periodic estuary planform forms, where at the confluence locations the estuary width remains generally narrow and dynamic channels and bars only occur within a small stretch of the estuary width. Around this phase dredging was started in the new experiment presented here (Figure 1 top panel). This required the cutting of an initial shipping fairway after 3000 cycles, or single main channel, which connected ebb and flood channels to follow the naturally deepest course.

In the third phase, further extension of the outer bends makes the mid-channel bar favourable for a short cut during both the ebb and flood flows. New barb channels formed on the mid-channel bars, which cross cut the bar forming a new main channel in the middle of the estuary (Figure 1 left panel 4401-5887 tidal cycles). In case of dredging, the meander bend and accompanying disposal of dredged sediment on the shoal in the middle of the flume makes the meander stable and only migrates in lateral direction. Because of the higher shoal the water level does not exceed shoal elevation and no new barb channels formed (Figure 1 right panel 4600-5200 tidal cycles). After the final maintenance dredging event (5200 tidal cycles) the estuary was allowed to evolve further for 8000 cycles until it reached termination at 13,000 tidal cycles. The lateral migration of the bend in the middle of the flume continuous even when dredging stopped, whereas seawards mid-channel bars are cross cut. Eventually, a dynamic equilibrium at the bar-confluence scale is reached, in which sediment from bars and banks is reworked into new bars within the estuary. In both experiments, with and without dredging, the quasi-periodic planform deviates from the ideal estuary shape[34], which describes estuaries as perfectly converging channels, at the end of the experiments[21] (Figure 1 bottom). In general, the experiments confirm that the shoal elevation and sizes increases, whereas channel dynamics decreases due to dredging and disposal.

The Supporting Movies 1 and 2 presents the development of the two experiments observed from the overhead cameras.

3 Increasing dominance of the main channel and intertidal flats

The development of natural habitats in estuaries is partly determined by the cumulative area of intertidal flats[35,36]. Particularly, the local physical conditions, i.e. low dynamic areas, are highly important for ecology in estuaries with a complex spatial configuration of tidal flats, shoals and channels[16]. Tidal flats with elevation above high-tide level are referred to as supratidal and those with an elevation below low-tide level are classified as subtidal[36]. Analogue flume experiments of a multi-channel estuaries show that the tidal flats increase in volume (Fig. 2a), by the increase of area size as well as elevation, whilst dredging and disposal is ongoing. This increases the total intertidal area and especially the total supratidal area (Fig. 1). Tidal flats that were frequently used as disposal locations increased in volume and elevation, causing an increase in elevation difference with the deeper dredged main channel.

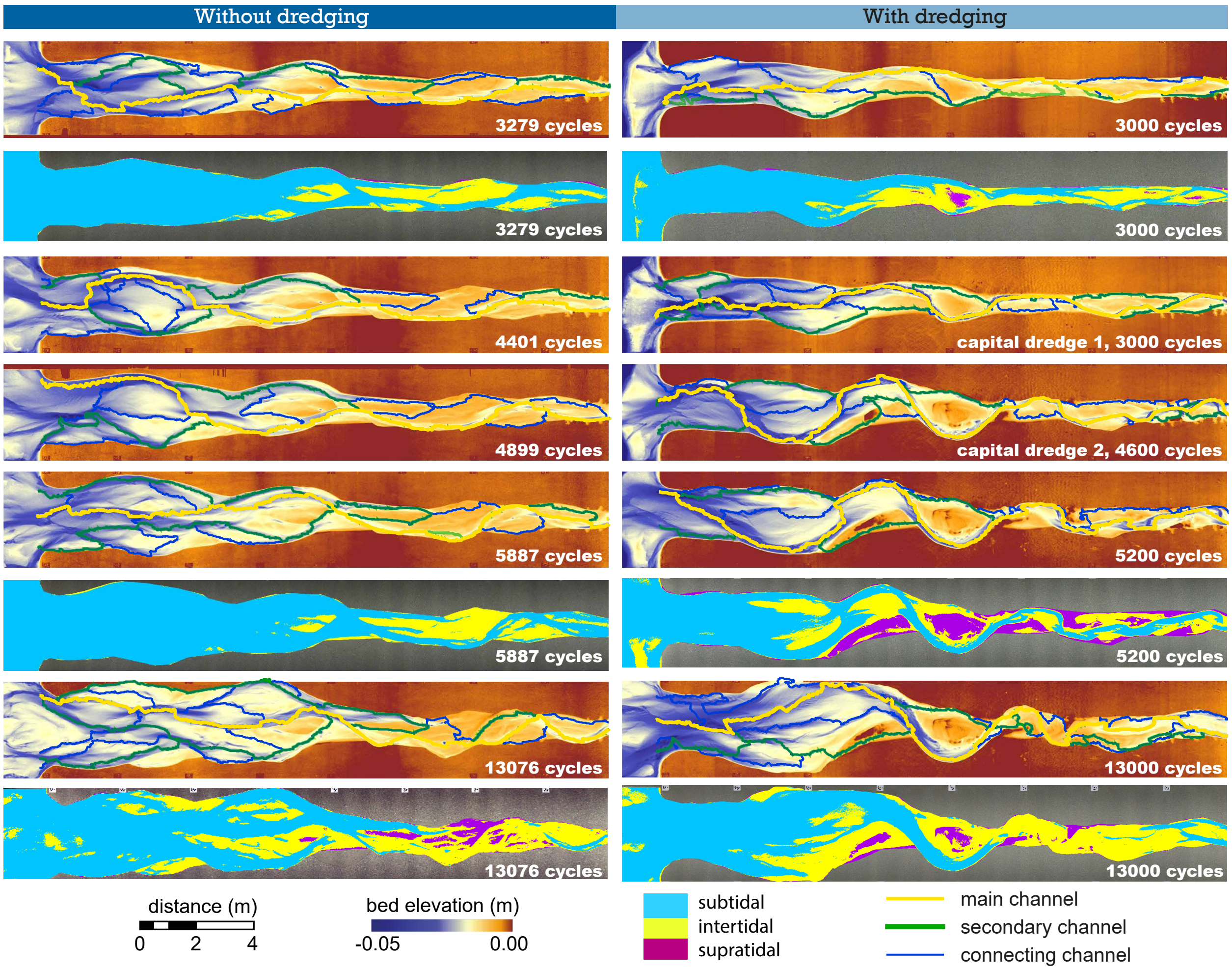

Figure 1: Estuary evolution of the experiment without (left panels) and with dredging (right panels) overlain by the extracted channel network illustrated by bed elevation maps. The sub-, inter- and supratidal area are based on water level measurements.

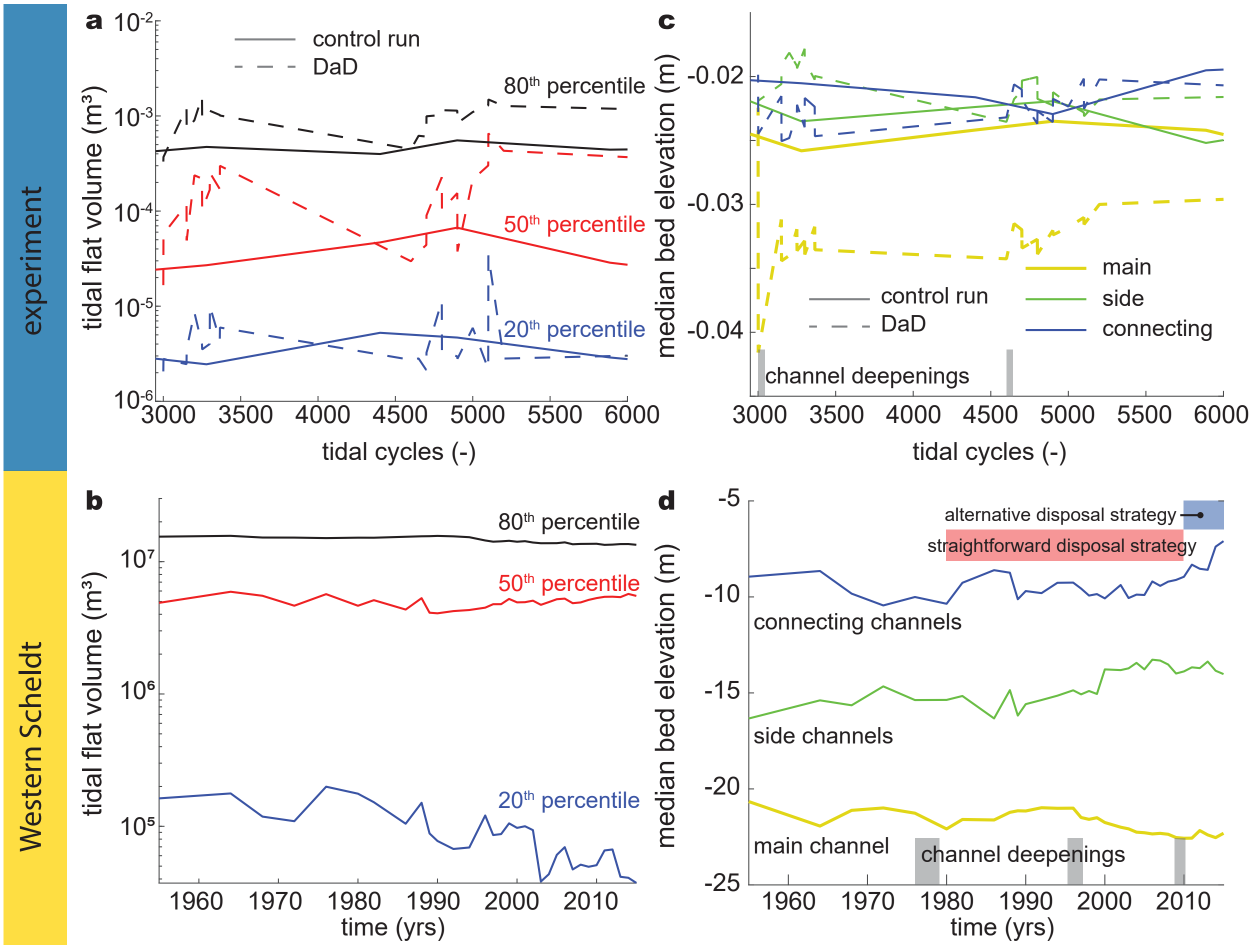

Figure 2: Increasing contrast between the deepening main channel and consolidating tidal flats shown by increasing tidal flat volumes, deepening main channels, and shallowing side and connecting channels. a) Tidal flat volume for two experiments. b) Tidal flat volume in the Western Scheldt since 1955. c) Median bed elevation for all three types of the channel for the two experiments. d) Median bed elevation for the main, side and connecting channels in the Western Scheldt. In a and b the percentiles are taken from the distribution of all tidal flat areas encompassed by the channel network, where the 80^{th} percentile represents the larger more significant tidal flats.

The bathymetric field data of the heavily dredged Western Scheldt confirms that, as dredging volume increases, the median tidal flat volumes calculated from area and elevation tends to increase due to consolidation of shoals since 1990s (Figs. 2b and 3), meaning an increase in intertidal area. The tidal flat elevation above mean sea level (0 m NAP, Amsterdam Ordnance Datum) has increased by half a meter since 1955 and slowed down in the last decade[4,37].

Important criteria for the maintenance of a multi-channel system are the channel width-to-depth ratio and flow velocity of the ebb- and flood-dominated channels[19]. Shallowing of one of the main (ebb or flood) channels could destabilise the multi-channel system as like in a multichannel river with unstable bifurcations[38], which also reduces the number of connecting channels over the intertidal flats[3]. Flume experiments and field observations show increasing differences in channel depth among the main, side and connecting channels in case of dredging (see also Supplementary Figs. 3a, b, d, and e). Dredging deepens one of the channels and causes the secondary channels to become shallower (Fig. 2c).

The flume experiments demonstrate that bed elevation for the main channel becomes significantly deeper than the side and connecting channels in case of dredging, whereas without interference, ebb-and flood dominated channels form that are equal in size in the flume experiments (Fig. 2c). This suggests that, in a natural multi-channel system, all channel scales are equally important, and the imbalance in bed elevation is a direct effect of dredging. The difference in channel depth persists long after dredging was terminated in the experiment. These findings show that dredging leads to an unnatural imbalance among the main, side and connecting channels in

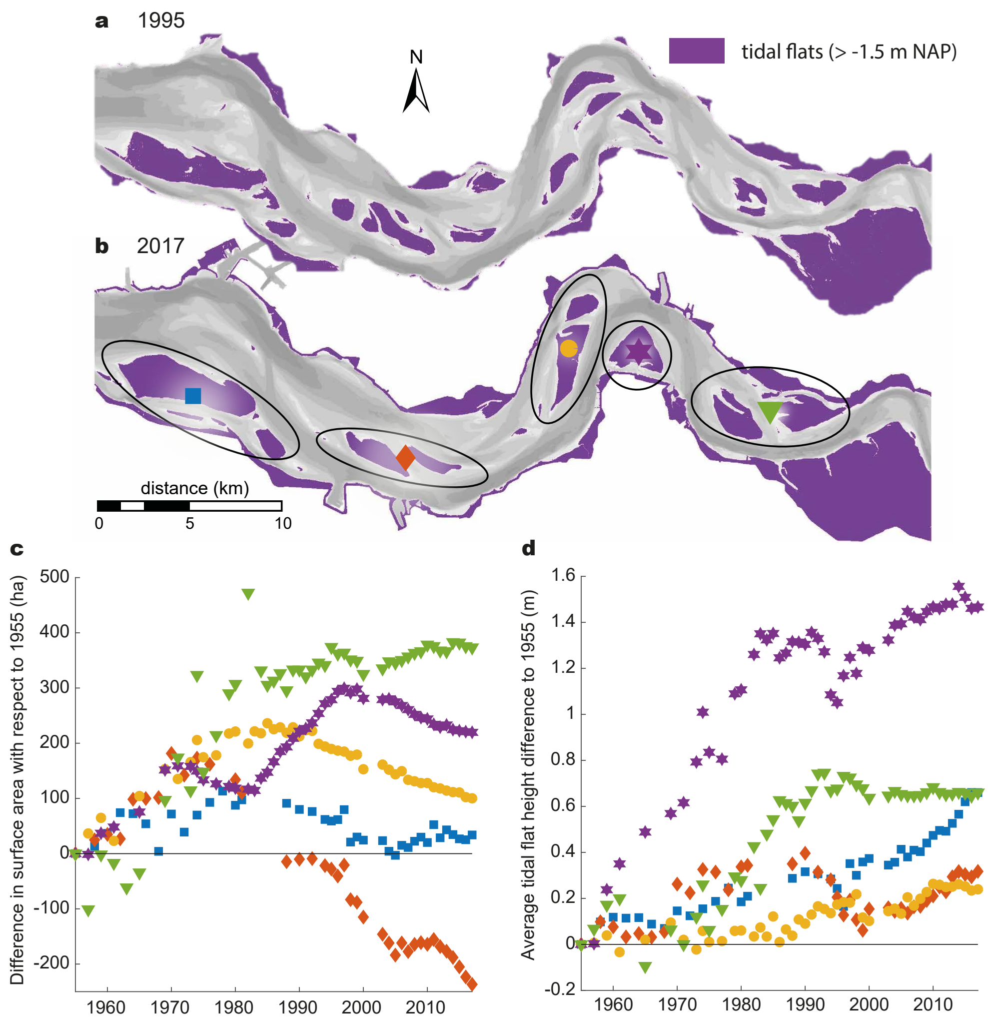

Figure 3: Shoal development in the Western Scheldt from 1955-2017. a-b) Ongoing consolidation of tidal flats, from fragmented shoal complexes (a) to 2-3 large tidal flats per meso-cell (b). c) Shoal surface area difference with respect to 1955 shows a generally increase in tidal flat area. d) Average tidal flat height difference respect to 1955 shows an increase of all tidal flat locations.

a multi-channel system, and we expect that the consequences are irreversible within the human lifespan.

Field observations confirm that, since dredging started, the main channel became deeper, as expected, especially following major main channel deepening events (the 1970s, 1997-98 and 2010-11, to the tidal-free water depths of 9.5 m, 11.6 m, and 14.5 m[39], respectively). The volume of disposal of dredged sediment in the side channels was reduced when it appeared that this tended to close them off[3,39]. The conversion to an alternative tidal flat disposal strategy, where 20% of the dredged sediment was disposed on the downstream end of the intertidal flats, resulted in stabilisation of the channel depth of the side channels. However, our analysis shows that in the last 5 years the smaller-scale connecting channels continue to silt up (Fig. 2d). This development jeopardizes the multi-channel system and fails to improve the desired self-erosive capacity of the flow in the connecting channels [40].

4 Decreasing channel dynamics and loss of connecting channels

Channels and intertidal flats form highly dynamic elements in natural estuaries[21,41]. The dynamics are determined by the displacement and migration of the channels that results in erosion and accretion of the intertidal flats (see Supplementary Fig. 2). The flume experiments show that because of the decrease in channel displacement and fixation of the main channel by the dredging activity, the channel mainly migrates laterally. As result, the meander bend increases in amplitude and sinuosity (Fig. 6b). Stabilization of the meander bend reduced the migration rate of the main channel in the experiments by 10-25% (Fig. 4a). Channels in the Western Scheldt migrate at different rates depending on channel scale, occupying a large portions of the estuary (Fig. 4b). The variation of the main channel location is limited laterally by geological constraints and man-made structures and is fixed in place by dredging. In contrast, the side and connecting channels are largely free to migrate.

Actively disposing dredged sediment at the seaward side of intertidal flats was expected to increase dynamics of the connecting channels[40], but surprisingly the opposite was observed in the field and experiments. Smaller-scale connecting channels link the large ebb and flood channels. These smaller channels often display a quasi-cyclic morphologic behaviour, characterised by processes of channel origination, migration, and degeneration at a timescale of years to decades[18,42]. Water level differences between the ebb and flood channels drives the flow of water through these connecting channels and the connecting channels form where the difference in water levels is the largest, typically in shoal areas at the landward end of the flood channel[39]. The large reduction in dynamics of the connecting channels is demonstrated by the decreasing number of connecting channels since 1955, whilst the number of side channels remained the same or slightly increased (Fig. 4d).

This observation is confirmed by the flume experiments, which show a general decrease in the number of channels for the dredged scenarios compared to the control runs (Fig. 4c). This is again especially true for the number of connecting channels, which reduces by almost 50% during dredging and remains 10-20% lower for the period after termination of dredging. This is a problem, because low-dynamic areas were in the past characterised by substantial reworking of their muddy sediment by migration of the connecting channels. Mud-rich areas are desirable for establishment of valuable habitats [16]. A decrease in high-dynamic area is beneficial for habitats only if it is

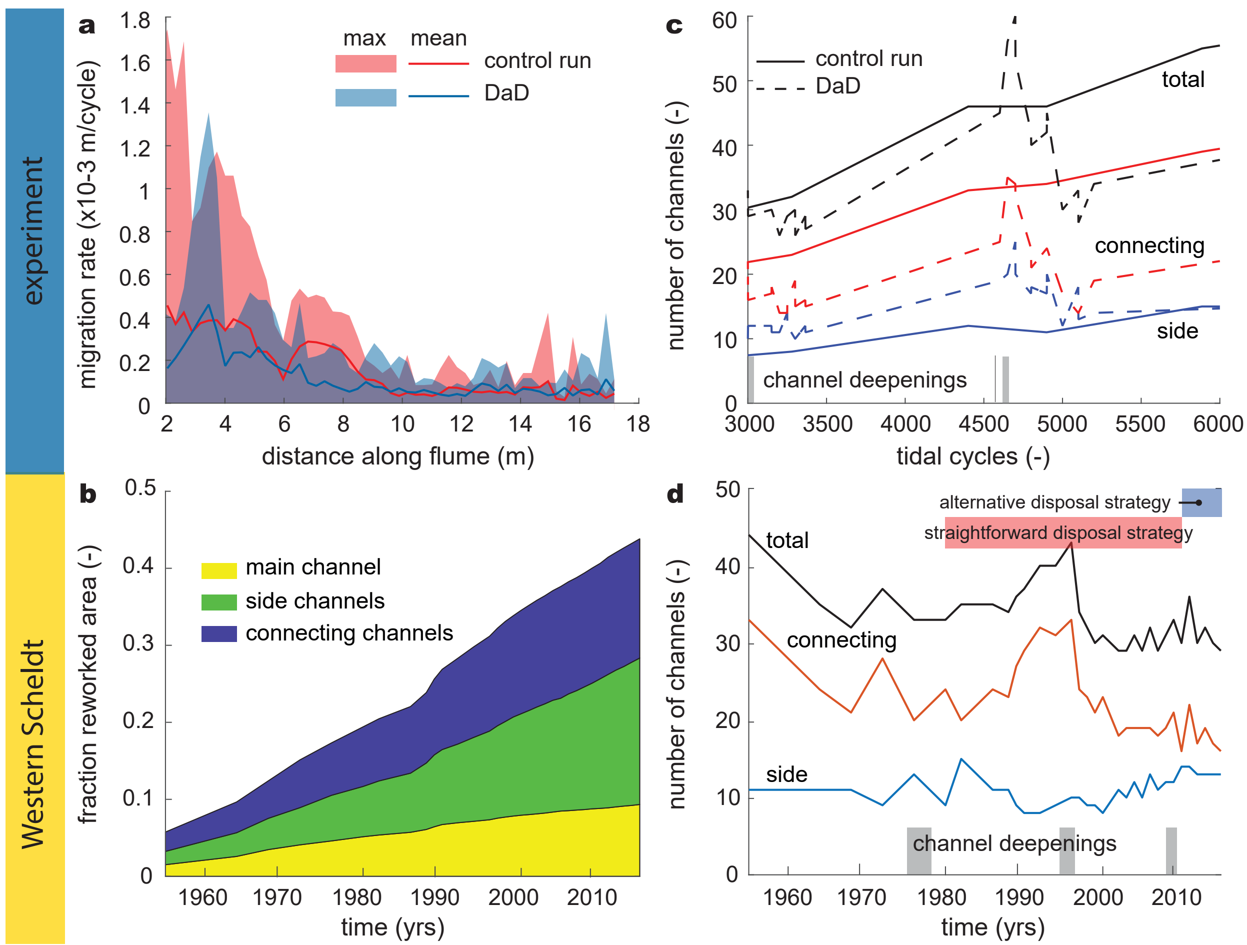

Figure 4: Channel activity and number of channels. a) The migration rate of the main channel for the two experiments. b) Fraction of reworked area in the entire study area over the past 60 years by the main, side and connecting channels in the Western Scheldt. c) The number of channels for the two experiments. d) The number of channels in the Western Scheldt since 1955.

replaced by low-dynamic area, but in reality the tidal range increase causes transformation of low-dynamic areas into high-dynamic areas, which is the opposite of the restoration targets[43].

5 Effects of future pressures on the estuary

The numerical modelling are complementary to the flume experiments and are a valuable tool to explorer the effect of future pressures on the estuary development. Since dredging began at early 20^{th} century, the disposal strategy has evolved with the aim to counteract the adverse effects of dredging. Model result for an alternative tidal flat disposal shows, however, very little difference with a previous straightforward strategy (Fig. 5a, b). For the near future, a new strategy was proposed to dispose dredged sediments in the deep scours of the main channel[44]. Our model simulations, with a foreseen approach of dredged sediment disposal solely in scours of the main channel, indicate that this reduces the adverse effect of decreasing channel dynamics (Fig. 5a) and halts the increase in tidal flat volume (Fig. 5b). In case of the Western Scheldt, the total scour volume available for disposal is $1.7{\cdot}10^9$ m^3 assuming the current tidal-free navigation depth of 14.5 m. This means that with a disposal rate of $10{\cdot}10^6$ m^3 it will take at least 100 years to fill the deep scours, assuming that it is not transported out. This promising disposal strategy should therefore be tested in reality[44].

Increasing vessel draft[45] brings management challenges. Increasing the minimum main channel depth in the model simulation shows decreasing dynamics of the main channel, whereas there appears to be a minimum in connecting channel dynamics (Fig. 5c). While channel dynamics decrease with dredging depth, there is no systematic increase in tidal flat volume with dredging depth. The tidal flat volume is annually 10-25% higher for 16-20 m water depth, respectively (Fig. 5d). We argue that further deepening of the shipping fairway for short-term economic purposes should be carefully evaluated against long-term ecological value, as a further decrease in channel dynamics will directly affect intertidal flat dimensions and therefore valuable habitat area as shown by past developments in the Western Scheldt and by scenarios in the numerical modelling and experiments.

Future threats from sea-level rise (SLR) are expected in estuarine systems[46] and should be a key issue in future assessments for understanding the dynamic response of channel-shoal interactions in estuaries. Here, we systematically evaluate the response of the estuary to various SLR scenarios based on the Intergovernmental Panel on Climate Change Fifth Assessment Report[26]. We expect that SLR has less effect on the channel-shoal interactions compared to the deepening of the shipping fairway because the rates are small compared to the draft depth rate of 140 mm/yr for the container-vessels. For this case study of a flood-asymmetric estuary, in which sediment is imported from the mouth (see Supplementary Fig. 4b), the development depends on sediment availability at the seaward side. We expect that sea-level rise will transport additional sediment into the estuary. The model simulations showed a doubling of coastal sediment input for the lower bound of SLR, up to 150% increase for the upper bound of SLR, based on bed elevation differences after 40 yrs morphological development. The actual import will partly depend on ebb delta dynamics, alongshore drift and sediment availability, which are not considered in the present model runs. The model scenarios show that limited future sea-level rise will cause a valuable increase in dynamics in terms of the side and connecting channels, whilst the main channel becomes fixed even further (Fig. 5e). Intertidal flat elevation increases with the sea-level rise in the model run whilst tidal flat volume decreases (Fig. 5f).

6 Discussion and Conclusions

Extensive human intervention is common in many estuaries worldwide. The morphology of estuaries including location and presence of bars and shoals, amount of intertidal flats, number of channels and side channels are directly impacted by these human interventions. We argue that the disposal strategy of dredged material is as important as the dredging itself in maintaining suitable conditions for the persistence of an ecologically valuable multi-channel system[4,47,48]. Model simulations reveal that current dredging strategies are not sustainable and current disposal strategies to counter adverse effects are hardly effective. The experiments suggest that channel-shoal interactions in anthropogenically altered estuaries are affected for a much longer time-span than the period of dredging.

A promising strategy could be the scour disposal strategy in which dredged sediment is disposed of in the scours of the main channel[44], but its effectiveness also depends on future threats such as increasing vessel draft and SLR. We would argue that further deepening of the should be carefully considered against adverse effects. In view of future SLR the sediment must be kept in the system rather than mined or disposed. A further decrease in channel dynamics and displacement directly destabilise the valuable multi-channel system, including intertidal flats that determines

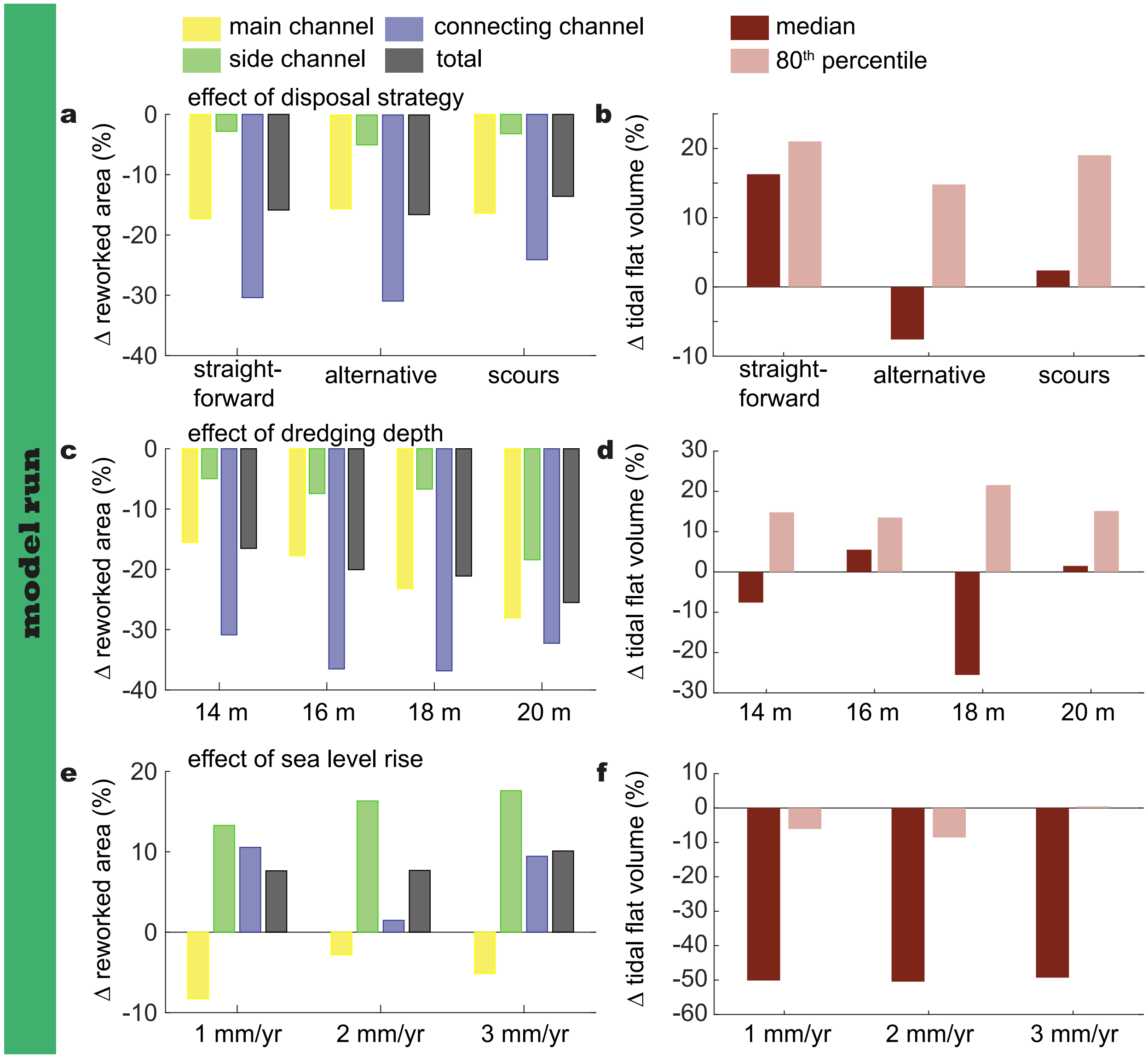

Figure 5: Effect of future scenarios on channel dynamics (reworked area) and ecological valuable waterline length (intertidal flat volume) compared to the control run. a) Effect of disposal strategy on changes in the reworked area. b) Effect of disposal strategy on changes in tidal flat volume. c) Effect of dredging depth on changes in the reworked area. d) Effect of dredging depth on changes in tidal flat volume. e) Effect of sea-level rise on changes in the reworked area. f) Effect of sea-level rise on changes in tidal flat volume.

the existence and persistence of the ecologically-important habitat, and the depth of side channels for navigability of smaller inland vessels[7]. Furthermore, dredging directly increases the tidal range resulting in higher flood risk, ebb-flood dominance alters, and peak velocity increases that complicates navigability [14,22]. The increase in channel dynamics associated with SLR provides an opportunity to restore ecologically valuable areas, by increasing intertidal flats and the number of connecting channels that flow through and feed these systems, while biophysical feedback processes may adapt to the SLR[49].

From our laboratory experiments, field data and numerical model study we conclude that fairway dredging mainly determines the dynamics of channels and ecological valuable tidal flats, while the disposal strategy aiming to reduce these adverse effects is ineffective. Further deepening of the navigation channel accelerates the adverse effects of dredging, whereas sea-level rise scenarios show potential improvement of channel dynamics and intertidal flat volumes.

7 Experimental Procedure

We use three independent complementary methods. 1) In physical scale-experiments, the long-term development and resilience of an estuary with dredging and disposal was compared with a reference experiment without interventions. 2) Field data from the well-monitored Western Scheldt was used as a case to measure the morphological changes that occurred over time of an actual dredged estuary. Literature/reports were used to connect morphological changes to changes in dredging and disposal strategy. 3) Numerical model scenarios allowed testing of the effects of disposal strategy and future changes in dredging regime and SLR scenarios. For all three approaches, we employ, a novel channel-network algorithm that scale-independently and objectively extracts channel network topology. The network is then used to determine the channel depth distribution, channel migration, and the tidal flat volumes.

Physical scale-experiments Experiments with and without dredging and disposal were conducted in a periodically tilting flume, the Metronome. The flume is 20 m long and 3 m wide and had a sandy bed of 7 cm thick. Periodic tilting of the flume enables sediment transport during both ebb and flood phase[27], leading to autogenic development of estuarine morphodynamics[21,50]. A single tidal cycle spans 40 seconds and had a maximum tilting gradient of 0.008 m/m. Further information on scaling is reported in earlier papers[21,27,50]. Changes of the experiment were recorded by time-lapse overhead imagery and DEMs are constructed with the structure-for-motion software, AGISOFT Photoscan (version 1.2.6.2038). The DEMs were used to calculate dredging and disposal volumes and their locations. The development of the experiment with dredging was compared to a control run without dredging (Figs. 6a-b and Supplementary Videos 1 and 2).

The experiment started with a narrow initial converging channel in the middle of the sand-bed. Boundaries are erodible, and continuous erosion and deposition led to the development of a self-formed estuary before dredging and disposal were started at 3000 tidal cycles (Fig. 1). The self-formed estuary consisted of a multi-channel system with ebb and flood channels as well as tidal flats and an irregular shape, similar to the same morphological properties as the control run[21]. After 3000 cycles, an initial 'shipping fairway' was cut along the deepest natural course of the

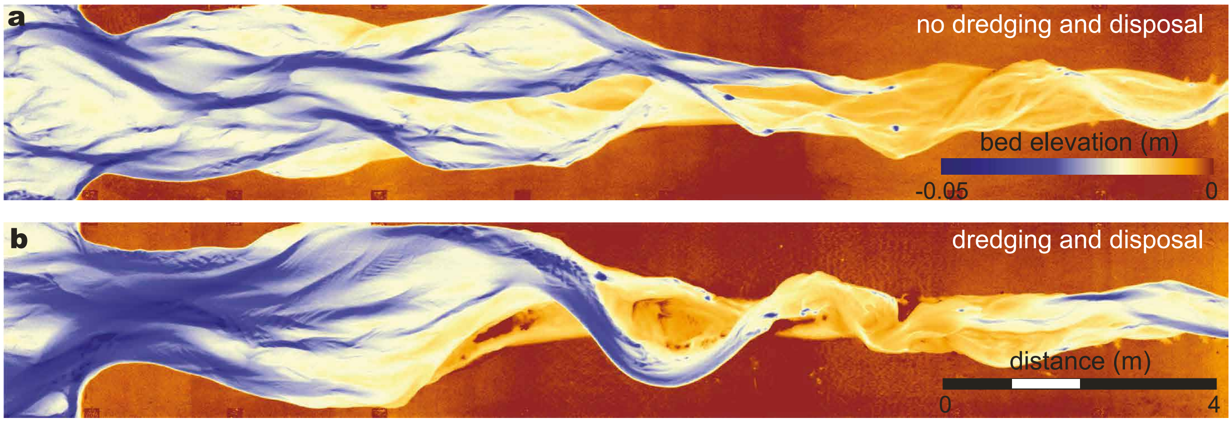

Figure 6: Bed elevation maps for the two flume experiments. a) Final bed elevation for the control run after 13,000 tidal cycles. b) Final bed elevation after 13,000 tidal cycles for the experiment with dredging and disposal (DaD) occurring between 3,000-5,200 tidal cycles.

estuary, which linked both ebb and flood channels when necessary (capital dredging). The shipping fairway was lowered by about 1/5 of the original depth using a palette knife and removal of sediment by hand. The minimum depth requirement for the dredging was set to 3.5 cm for the first capital dredge, whereas for the second capital dredge, which was necessary because of the continuous rapid expansion of the estuary, the minimum depth requirement was set to 3 cm. Maintenance dredging then took place every 50-100 cycles to remove material which made the channel ‘unnavigable’, in other words when the water depth was below the minimum depth requirement. The width of the dredged main channel was proportional to the width of the estuary in the same ratios as for the field example, the Western Scheldt. For the landward end, this was approximately 10% of the estuary width, 15% moving into the middle reaches of the estuary and at the seaward end up to 20% of estuary width. Sediment from the first capital dredge was removed from the system entirely, while sediment removed later during maintenance dredging was redistributed on the seaward side of tidal flats, at the entrance of side channels, and in the scours of the main channel (depth $>$ 4 cm). The disposal location was dependent solely on proximity to the dredge site. Dredging volumes varied along the estuary, with an increased volume in the middle section (Supplementary Fig. 5a). After the final maintenance dredging event (5200 tidal cycles) the estuary was allowed to evolve further for 8000 cycles until it reached termination at 13,000 tidal cycles.

Field data The Western Scheldt Estuary is a well-monitored estuary in the southwestern part of the Netherlands and refers to the seaward section of the tide-dominated Scheldt estuary. To establish the development of the Western Scheldt and link this with dredging and disposal strategies and volumes (Supplementary Fig. 5b), bathymetry data, so called 'Vaklodingen', are used that are acquired for the period 1955-2015 by Rijkswaterstaat. This dataset consists of single beam measurements at 100-200 m transects. Positioning and height measurements were done with a number of analogue to digital techniques[51]. Since 2001, the dry parts of the estuaries have been measured with the LiDar technique that provides full coverage with a resolution of 1-5 m. The estimated vertical accuracy of the dataset for practical use was determined at 10 cm (2σ), see Elias and others[52]. The bathymetry data of the Western Scheldt are used for the network extraction, which we used to calculate channel dynamics, depth, and tidal flat volumes. Additionally, we determined the intertidal flat elevation and area by comparing bed elevation distributions of the tidal flats over time (Supplementary Fig. 3).While field experiments and monitoring provided valuable insights, the lack of control inhibits the clear conclusions possible with controlled scenario modelling introduced below.

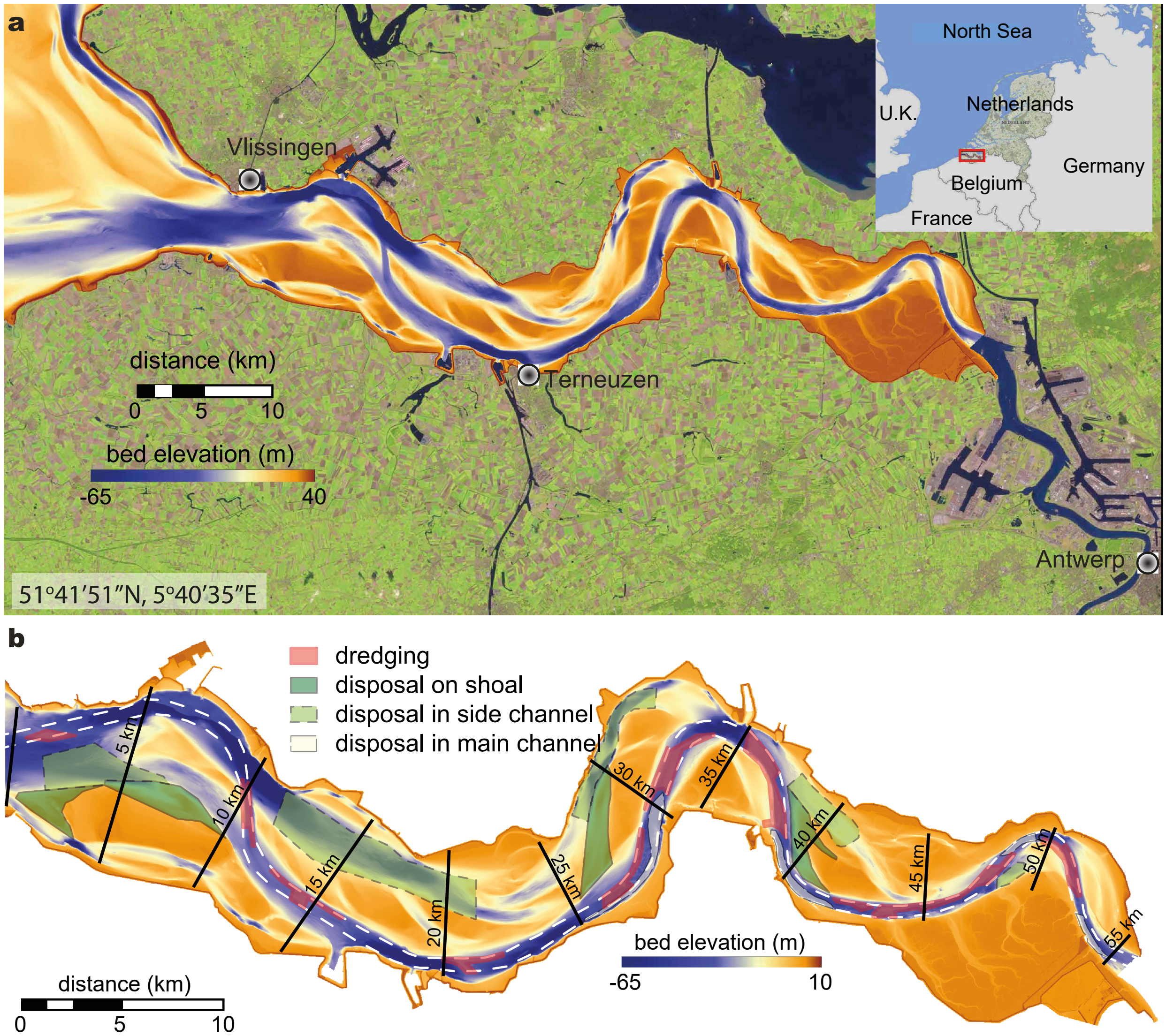

Figure 7: a) a) 2014 bed elevation of the Western Scheldt. b) Dredging and disposal locations for the model runs plotted as polygons on top of the bed elevation map of 2015. The disposal strategy varies and uses all three types of disposal locations (alternative shoal disposal), only two types (straightforward side and main channel disposal) or only 1 type (foreseen scour disposal). The white dashed line represents the shipping fairway and red polygons are dredging locations.

The Western Scheldt is an estuary that has undergone human interference since the 14^{th} century, which reduced its lateral expansion capacity. At the beginning of the 20^{th} century small-scale sand mining, dredging and disposal became the foci of human activity which has intensified since the 1970s (Supplementary Fig. 5b). The Western Scheldt has undergone three major deepening events (in the 1970s, 1990s and 2010s) as well as annual maintenance dredging activities to allow access to the port of Antwerp[53]. Disposal locations are chosen such that costs, efforts and hindering the shipping are minimised and thus selected in the vicinity of dredging locations[54]. The "flexible disposal" approach for the Western Scheldt includes monitoring and adjustment when necessary. In the last decade, the dredging and disposal strategy has changed in 2010 from straightforward disposal in the side channels and deeper parts of the main channel to an alternative approach in which sediment is disposed near eroded intertidal flats. This approach allows slow movement of material towards the flats with the aim of enhancing subtidal and intertidal habitats[1] and decreasing disposal intensity in the side channels that began to close off[40]. The intention was to maintain and preserve the equilibrium of the multi-channel system of the Western Scheldt, attain maximum ecological gain on the edges of inter-tidal flats and preserve the ecologically valuable habitats of the Western Scheldt[1,55–58].

Numerical model In this study, we used a Delft3D model that simulates fluid flow and morphological changes over time and has been validated and applied previously for rivers, estuaries, and tidal basins[24,59,60]. Our runs were computed using depth-averaged, nonlinear, shallow-water equations, wherein the effect of helical flow driven by flow curvature on bed shear-stress direction was parametrized[60]. The associated transverse bed slope effect is defined as sediment on a slope transverse to the main flow direction that is deflected downslope due to gravity. When a secondary current is present, e.g., in bends, the inward and upslope directed shear stress drags particles upslope. We applied the method of Bagnold, and we set the tuning parameter for the transverse bedload transport, α_{bn} to 30, so that realistic dimensions of bed slopes for long-term simulations were maintained[24,61].

The Delft3D schematization was based on the optimised NeVla-Delft3D model for hydrodynamics[62] and morphology[63] of the Scheldt estuary. We used a nested model from the NeVla-Delft3D model for reducing computational time[24]. The nested model consists of a curvilinear grid with various grid sizes and we validated the nested model to the original calibrated NeVla-Delft3D model (Supplementary Fig. 1). The boundaries of the nested model include a water level fluctuation due to tides at the seaward boundary and a current at the landward boundary. Sediment fraction was uniform with a median grain-size of 200 μm, comparable to field observations[24]. For simplification of the boundary conditions, these were selected from a single spring-neap tide cycle of January 2013 (about 14 days) and repeated for a 2 year period. We speed up the bed adjustments by multiplying the morphological change during hydrodynamics timesteps by a factor of 20 (M). In some places the thickness of the bed is limited by underlying non-erodible layers from Holocene and Tertiary deposits [64,65]. Sediment transport at the boundaries is in an equilibrium state with the flow and is unlimited, leading to deviations of the sediment balance in the model compared to the observations (see Supplementary Fig. 4c and Supplementary Table 2). For reduction of the computational time, several processes are excluded, including wind (direction and magnitude) and salinity, as these effects are negligible for the large-scale morphological development.

Numerically it is not practically possible to apply a flexible approach in which yearly the disposal locations are shifted. Instead, we isolated the effects of three fixed strategies on the long-term development that represent real-case approaches. These approaches include i) a straightforward approach were dredged sediment is disposed equally between the main and side channel; ii) an alternative scenario, as applied from 2010 and onwards, in which dredged sediment is distributed for 20% on the tidal flats, 38% in the side channels and 42% in the scours of the main channel; and iii) a foreseen approach were solely sediment is disposed in the scours of the main channel, as proposed for future strategies. In order to limit the number of variation between the three scenarios, we did not adjust the disposal polygons for the third scenario. This was for clarity. For simplification, the dredged sediment was not distributed in the nearest disposal polygon as done in reality. Here, the dredged sediment is distributed over all polygons according to the percentage given above. The maintained dredge depth was set to 14 m and thus controlled at 9 sill locations (see polygons in Fig. 7).

The dredging and disposal locations for the three strategies are given in Figure 7 and are fixed for the entire duration of the model simulation. Eventually, we expect that disposal locations in the Western Scheldt will be re-used and the flexible approach merely delays the unwanted shift from a multi-channel system towards a single-channel system. For further testing of future scenarios, we performed some additional runs for the first scenario with increasing maintenance depth of 16, 18 and 20 m. Additionally, we ran the model with three scenarios of sea-level rise (1, 2 and 3 mm/yr) to test the effectiveness of dredging against future sea-level rise scenarios[26,66]. By using a wide range of values we implicitly study the sensitivity of the SLR predictions[66]. Dredging volumes increased with dredging depth, while for SLR scenarios dredging volume slightly decreased (Supplementary Fig. 5d). Increasing SLR resulted in an increase in sediment import into the model domain, whereas the sediment import decreases with increasing dredging depth (see Supplementary Table 2).

Network tool We applied a novel, mathematically rigorous framework for extraction of multi-threaded channel networks from topographic surfaces[67]. In contrast to previous methods, this framework automatically captures network topology with channel bifurcations, confluences and channels of various sizes. Specifically, this method is scale-independent and uses only bed elevation as input, so it works independently from water elevation. For the analysis in this paper, we used a variation of the original framework, which makes channel recognition more locally than the original algorithm. This local approach results more stable attribution of channel size, which is hence better suited for the analysis of channel networks, with a range of channel sizes that evolve over time (see Supplementary Videos 3-5).

The underlying algorithm computes the Morse-Smale complex (MSC) of the terrain[67,68], a topological complex that describes the structural elements of the terrain. The MSC contains the local minima, maxima and saddle points (points that are a local minimum in one direction and a local maximum in the other), along with steepest-descent paths (called MS-edges) from each saddle point towards a minimum. These MS-edges partition the terrain into pieces (called MS-cells), each representing a local maximum with the descending area around it. The algorithm proceeds by merging insignificant MS-cells together to form larger, significant cells, each representing a tidal flat/ shoal in the channel network. The remaining MS-edges around those cells then form the channels. Whether a cell is significant or not is determined by the volume of sediment contained in the cell: we keep merging cells until the volume in each cell is larger than some fixed threshold δ. This implies that channels are separated by at least volume δ, which is morphologically meaningful, because this volume is related to the morphological work required to cut shoals and merge channels. By running the method for different threshold values δ, we obtain networks with more and fewer paths, from which main, side, and connecting channels can be extracted. The main channel is the path with a maximum value for δ as there are no tidal flats enclosed. Side channels are the channels that are connected to the main channel at both ends, and connecting channels are the channels that connect the side with the main channel. Starting with a low threshold δ, and then gradually increase δ, channels disappear from the network one by one. We annotate each channel in the network by the highest threshold value δ for which that channel still appears in the network. That is, the threshold value for a channel represents the volume of the smaller of the two tidal flats next to it.

To compute statistics on the tidal flat volumes, we used the channel network for a fixed threshold value δ of 100,000 m^3. The tidal flat volume was calculated by the summation of the bed elevation above the median bed elevation along the estuary. The median bed elevation was determined by the same method as Leuven and others[69]. Firstly, a centreline was defined as the mean location line between the boundaries of the estuary. Secondly, the centreline was smoothed and resampled at an interval of 200 m. At all resampled points, a cross-section was constructed with a 20 m transverse grid spacing, perpendicular to the centreline and within the boundaries of the estuary. Then, the median bed elevation was determined for each cross-section, and a linear regression was fitted to the median bed elevation along the estuary channel. Elevation above the regression line was included for the tidal flat volume within the channel network. Afterwards, the 20^{th}, 50^{th} and 80^{th} percentile were calculated as representations of channels, intermediate and high bed elevations.

Data & Software Availability

The Delft3D model software is open source, and the code is available from the Deltares website (https://oss.deltares.nl/web/delft3d). All field data from Rijkswaterstaat are publicly available from a variety of web portals or via the service desk (https://www.rijkswaterstaat.nl/zakelijk/open-data).

Supplemental Information Description

The supplemental information includes model calibration and validation (Text S1), extended description of the data and network analysis (Text S2), and analysis of dredging volumes and sediment budgets for the experiments, field and numerical modelling (Text S3). Five figures are included that support the Text S1 to S3. Furthermore, two movies show the experimental development of a dredged and non-dredged system and three movies show the changes in extracted channel network over time for the model simulations (disposal strategy, fairway depth and sea-level rise).

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Author Contributions

W.M.D managed the numerical model simulations. J.R.C. and J.R.F.W.L conducted the physical scale-experiments. J.C. and M.T. contributed to background information and data of the Western Scheldt. M.R.H, W.S., K.V. and B.S. developed and tested the network extraction tool. W.M.D., J.R.C., J.R.F.W.L and M.G.K. provided critical result interpretation. W.M.D. wrote the initial draft of the paper, with substantial contributions from all authors. B.S. led network extraction research and M.G.K. led modelling and experimental research.

Declaration of Interest

The authors declare no competing interests.

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