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

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Key Points:

- Fairway dredging reduces the dynamics of channels and ecological valuable tidal flats.
- Further deepening of the navigation channel accelerates the adverse effects of dredging.
- Sea-level rise scenarios show potential improvement of channel dynamics and intertidal flat volumes.

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Abstract

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 time series of bathymetry of the Western Scheldt estuary (the Netherlands), morphodynamic model runs and physical scale-experiments to analyse the effects of dredging. All methods indicate that current 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 can be economically and ecologically better for the preservation of the multi-channel system. While future sea-level rise may revive the multi-channel system, further channel deepening will accelerate the adverse side effects.

1 Introduction

Estuaries worldwide are important centres of transportation and international 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 (De Vriend et al., 2011), e.g., Yangtze Estuary (Shanghai) (Chen et al., 2016), Western Scheldt (Antwerp) (Jeuken & Wang, 2010; Wang et al., 2015) and Elbe Estuary (Hamburg) (Kerner, 2007). The use of estuaries for shipping also poses considerable issues (Best, 2019). Dredging activities affect the hydrodynamics of estuaries. For example, tidal amplification (Temmerman et al., 2013; Zhu et al., 2014) increases circulation and increases the flood-dominance of the tidal asymmetry (Van Maren et al., 2015). 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 (Wang & Winterwerp, 2001; Monge-Ganuzas et al., 2013) or loss of ecologically valuable intertidal flats (Essink, 1999; Liria et al., 2009; De Vriend et al., 2011; Temmerman et al., 2013; Yuan & Zhu, 2015). 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 and sea-level rise.

The ecological quality of multi-channel systems is partly determined by the presence and characteristics of intertidal flats and channels (Toffolon & Crosato, 2007). Multi-channel systems often display a quasi-regular repetitive pattern that consists of mutually evasive meandering ebb channels and straight flood channels in the inner bends (Winterwerp et al., 2001). 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 (Toffolon & Crosato, 2007; Hibma et al., 2008; Swinkels et al., 2009). Winterwerp et al. (2001) schematised this system, present in the Western Scheldt, the Netherlands, into a chain of so-called macro-cells and meso-cells, based on morphological characteristics and tidally averaged sand transport. Each macro-cell consists of an ebb channel and a flood channel, displaying characteristic morphologic behaviour that is associated with net sediment exchange between the macro-cells. Smaller-scale connecting channels link the large ebb and flood channels in macro-cells, in some cases forming meso-cells. 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 (Van Veen, 1950). 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 (Swinkels et al., 2009). Shallowing of one of the main channels within the macro cells could destabilise the multi-channel system as like

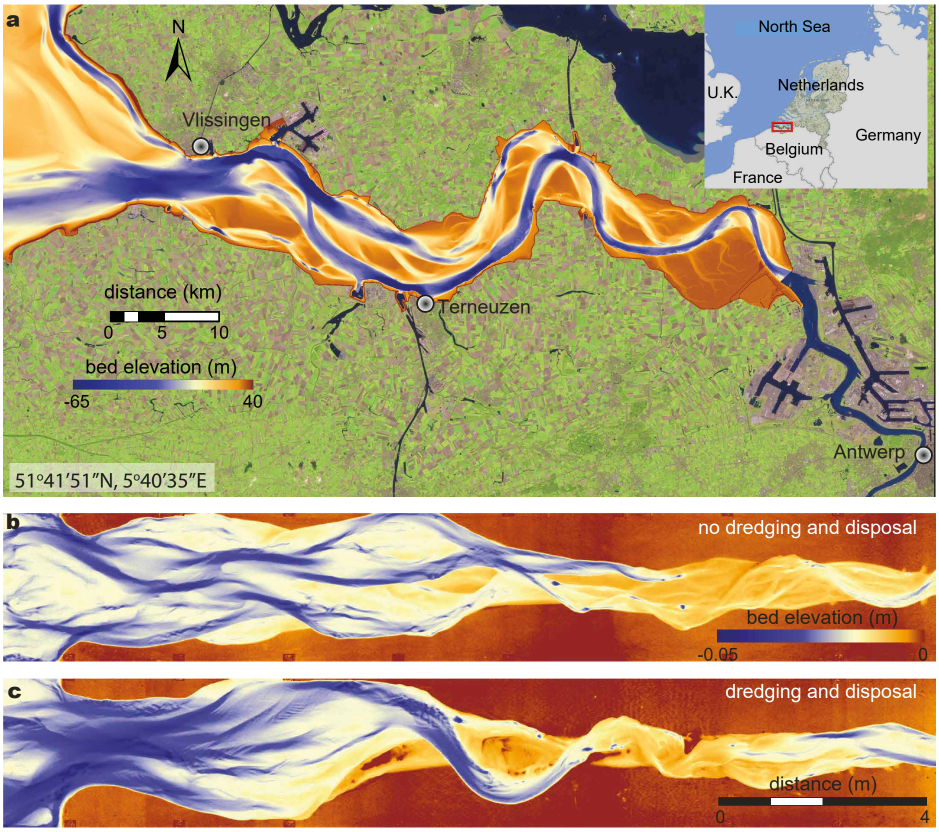

Figure 1. Bed elevation maps for the Western Scheldt and two flume experiments. a) 2014 bed elevation of the Western Scheldt. b) Final bed elevation for the control run after 13,000 tidal cycles. c) Final bed elevation after 13,000 tidal cycles for the experiment with dredging and disposal (DaD) occurring between 3,000-5,200 tidal cycles.

in a multichannel river with unstable bifurcations (Bolla Pittaluga et al., 2015), which also reduces the number of connecting channels over the intertidal flats (Jeuken & Wang, 2010).

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 (Murray et al., 2019). To improve biodiversity and increase tidal flat areas in estuaries it is becoming imperative to use nature-based solutions. Present dredging practices in the Western Scheldt estuary are based on a Long-Term Vision (LTV) program that forms a 'framework for sustainable management of the Scheldt estuary in a political context of Dutch-Flemish cooperation' (Depreiter et al., 2015), which includes an adaptive dredging and disposal strategy aiming to maintain the balance of the main ebb-and flood channels. Continuous monitoring of the Western Scheldt estuary since 1955 means that this system uniquely can provide insights into past responses of the multi-channel system to changes in dredging and disposal strategies. Urgent research questions related to dredging and disposal in large estuaries in general and the Western Scheldt in particular 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 (Church et al., 2013) on the morphological and ecological functioning of the estuary?

2 Methodology

We use three independent complementary methods. 1) Field data from the Western Scheldt was used to measure the morphological changes that occurred over time and literature/reports were used to connect these with changes in dredging and disposal strategy. 2) Numerical model scenarios allowed testing of the effects of disposal strategy and future changes in dredging regime and SLR scenarios. 3) 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. 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. See Supporting Information for an extensive description of the methods (Baar, De Smit, et al., 2018; Baar, Albernaz, et al., 2018; Dam, 2017; Depreiter et al., 2015; Edelsbrunner et al., 2001; Grasmeijer et al., 2013; Gruijters et al., 2004; Ikeda, 1982; Johnston Jr., 1981; Leuven et al., 2016; Leuven, De Haas, et al., 2018; Maximova, Ides, Vanlede, et al., 2009; Maximova, Ides, De Mulder, & Mostaert, 2009a, 2009b; MOW, 2013; Plancke et al., 2014; Robinson, 1960; Savenije, 2015; Schrijvershof & Vroom, 2016; Struiksma, 1985; Van der Spek, 1997; Van der Wal et al., 2010; Van Dijk et al., 2012, 2019, 2018; Van Veen, 1948; Vikolainen et al., 2014; Vroom et al., 2015).

To establish the development of the Western Scheldt and link this with dredging and disposal strategies and volumes (Supporting Figure S1a), 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 (Cleveringa, 2013). 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 'Vaklodingen' dataset was analysed for the long-term analysis. The estimated vertical accuracy of the dataset for practical use was determined at 10 cm (2σ), see Elias et al. (2016). 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 (Supporting Figure S8).

We modelled three scenarios of dredging and disposal strategies and compared the morphological development to a control run without dredging and disposal. The three scenarios are based on realistic recent and foreseen dredging and disposal locations and strategies in the Western Scheldt (see locations in Supporting Figure S3): i) 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; ii) a straightforward scenario with the distribution of the dredged sediment for 50% in the side channel and 50% in the scours of the main channel, as applied in the years before 2010; iii) a foreseen scenario with a sole distribution of the dredged sediment 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. There is only a small difference in the dredging volume between the three scenarios (Supporting Figure S1c). The maintained dredge depth was set to 14 m and thus controlled at 9 sill locations (see polygons in Supporting Figure S3). For further testing, 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 (Church et al., 2013; Van de Lageweg & Slangen, 2017). By using a wide range of values we implicitly study the sensitivity of the SLR predictions (Van de Lageweg & Slangen, 2017). Dredging volumes increased with dredging depth, while for SLR scenarios dredging volume slightly decreased (Supporting Figure S1d). Increasing SLR resulted in an increase in sediment import into the Western Scheldt, whereas the sediment import decreases with increasing dredging depth (see Supporting Table S1).

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 (Kleinhans, van der Vegt, et al., 2017), leading to autogenic development of estuarine morphodynamics (Leuven, Braat, et al., 2018; Braat et al., 2018). 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 (Kleinhans, van der Vegt, et al., 2017; Leuven, Braat, et al., 2018; Braat et al., 2018). 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 (Figures 1b-c and Supporting Movies 1 and 2). Both experiments consist of 13,000 tidal cycles, and dredging of the main channel took place between 3,000 and 6,000 tidal cycles.

We applied a novel, mathematically rigorous framework for extraction of multi-threaded channel networks from topographic surfaces (Kleinhans, Kreveld, et al., 2017). 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 Supporting Movies 3-5).

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 (see Supporting Figures S7c and f) (Graveland et al., 2005; Desjardins et al., 2012). 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 (Van der Wal et al., 2017). 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 (Desjardins et al., 2012). The bathymetric data provided by Rijkswaterstaat show 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 (Figure 2a and Supporting Figure S8), 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 (Wang et al., 2015; De Vet et al., 2017).

Numerical model runs with the current state of the Western Scheldt as initial condition demonstrate that after initial adaptation to the boundary conditions, the tidal flat volumes increase in the case with dredging (Figure 2b). Tidal flats become generally larger compared to the control run without dredging. The flume experiments also show that the tidal flats increase in volume (Figure 2c) and elevation over time whilst dredging and disposal is ongoing. This increases the total intertidal area and especially the total supratidal area (Supporting Figure S5). 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.

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 (Winterwerp et al., 2001). Field observations, model outcomes, and flume experiments show increasing differences in channel depth among the main, side and connecting channels in case of dredging (see also Supporting Figures 7a, b, d, and e). Field observations indicate 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 (Swinkels et al., 2009), respectively). The volume of disposal of dredged sediment in the side channels was reduced when it appeared that this tended to close them off (Swinkels et al., 2009; Jeuken & Wang, 2010). Despite this change in strategy, disposal of dredged sediment in the side channels has still led to shallowing of these channels since the 1980s (Roose et al., 2008), but was limited by the so-called East-West strategy from the 1990s (Figure 2d). 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 (Figure 2d). This development jeopardizes the multi-channel system and fails to improve the desired self-erosive capacity of the flow in the connecting channels (Roose et al., 2008).

The model runs and experiments demonstrate that dredging and disposal influences persist long after dredging has stopped. The elevation difference between main and side channel unnaturally increases in the control run (Figure 2e). Initially, the side channels become deeper but after adaptation of the model to the boundary conditions, the side channels silt up. The main channel becomes deeper for all runs. The variation in the depth distribution of the main channel increases for the control run (Supporting Figure S7). 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 the channel depth only varies slightly for the three channel scales in the control run. 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 (Figure 2f). These findings show that dredging leads to an unnatural imbalance among the main, side and connecting channels in a multi-channel system, and we expect that the consequences are irreversible within the human lifespan.

4 Decreasing channel dynamics and loss of connecting channels

Channels and intertidal flats form highly dynamic elements in natural estuaries (Hibma et al., 2004; Leuven, Braat, et al., 2018). The dynamics are determined by the displacement and migration of the channels that results in erosion and accretion of the intertidal flats (see Supporting Figure S6). Channels in the Western Scheldt migrate at different rates depending on channel scale, occupying a large portions of the estuary (Figure 3a). 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 (Figures 3a and b). However, dredging activity indirectly reduces the dynamics of side channels and connecting channels as showed by the decrease in the reworked area over time in the model runs, nearly independently of disposal strategy (Figure 3b). Actively disposing dredged sediment at the seaward side of intertidal flats was expected to increase dynamics of the connecting channels (Roose et al., 2008), but surprisingly the opposite was observed in the field, model and experiments. The decrease in side and connecting channel displacement due to dredging activities also reduced the migration rate of the main channel in the experiments by 10-25% (Figure 3c).

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

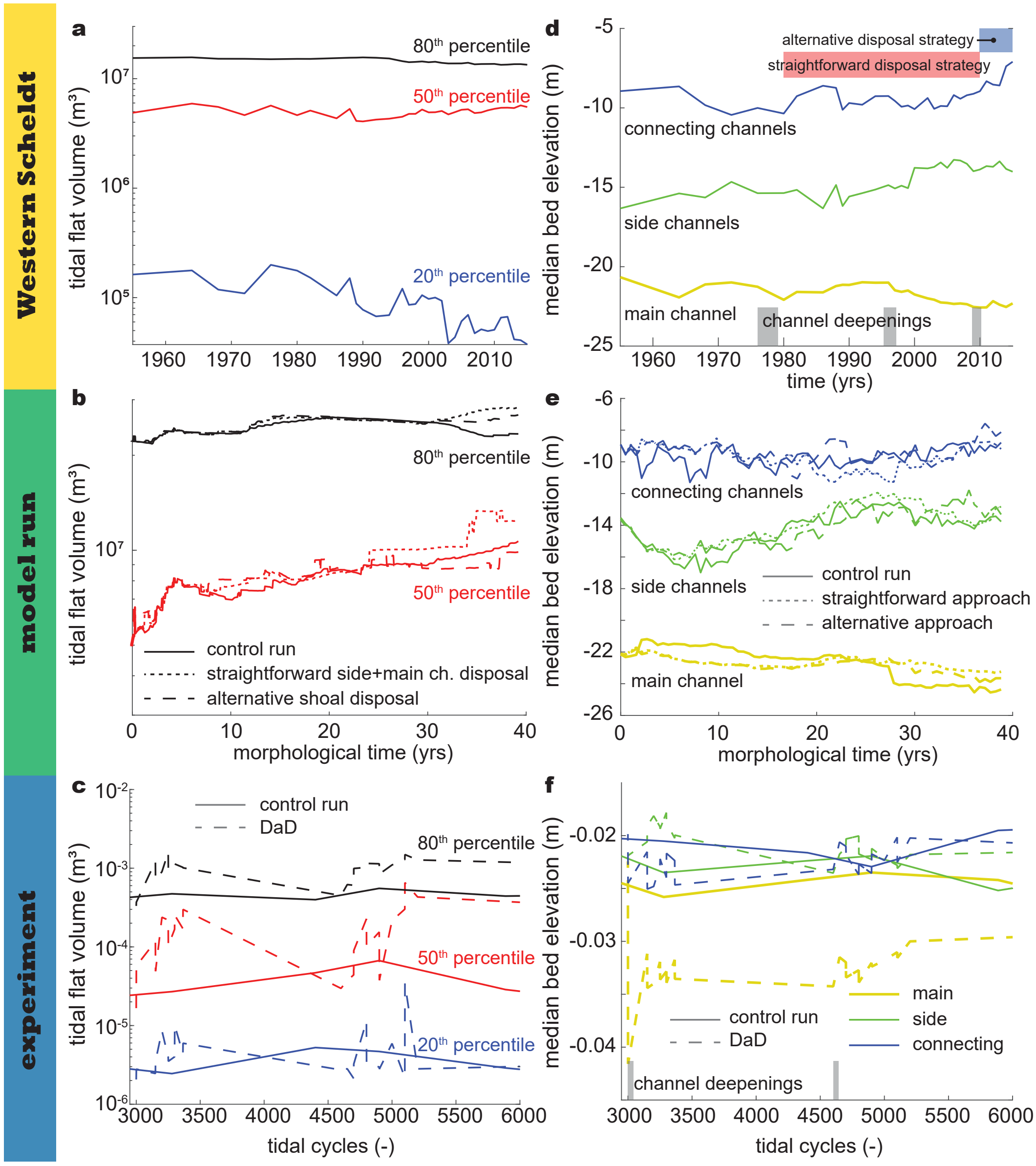

Figure 2. Increasing contrast between the deepening main channel and consolidating tidal flats shown by increasing tidal flat volumes, deepening main channels, and shallowing side and connecting channels. a) Tidal flat volume in the Western Scheldt since 1955. b) Tidal flat volume for three model runs. c) Tidal flat volume for two experiments. d) Median bed elevation for the main, side and connecting channels in the Western Scheldt. e) Median bed elevation of all three types of the channel for three model runs. f) Median bed elevation for all three types of the channel for the two experiments.

remained the same or slightly increased (Figure 3d). This observation is confirmed by the model simulations and experiments, which show a general decrease in the number of channels for the dredged scenarios compared to the control runs (Figures 3e-f). 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 (Van der Wal et al., 2017). A decrease in high-dynamic area is beneficial for habitats only if it is replaced by low-dynamic area, but in reality the tidal range increase in the Western Scheldt causes transformation of low-dynamic areas into high-dynamic areas, which is the opposite of the restoration target in the LTV program (Directie Zeeland; Ministerie van de Vlaamse Gemeenschap. Administratie Waterwegen en Zeewezen, 2001).

5 Effects of future pressures on the estuary

Since dredging began in the Western Scheldt at early 20^{th} century, the disposal strategy has evolved with the aim to counteract the adverse effects of dredging. The tidal flat disposal alternative shows, however, very little difference with a previous strategy (Figures 4a and b). For the near future, a new strategy was proposed to dispose dredged sediments in the deep scours of the main channel (Huisman et al., 2018). 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 (Figure 4a) and halts the increase in tidal flat volume (Figure 4b). The total scour volume of the Western Scheldt 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 (Huisman et al., 2018).

Increasing vessel draft (Rodrigue et al., 2017) brings management challenges for the Western Scheldt. 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 (Figure 4c). 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 (Figure 4d). 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 (Blott et al., 2006) 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 (Church et al., 2013). 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. The Western Scheldt is a flood-asymmetric estuary in which sediment is imported from the mouth (see Supporting Figure S2a). Depending on sediment availability, 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

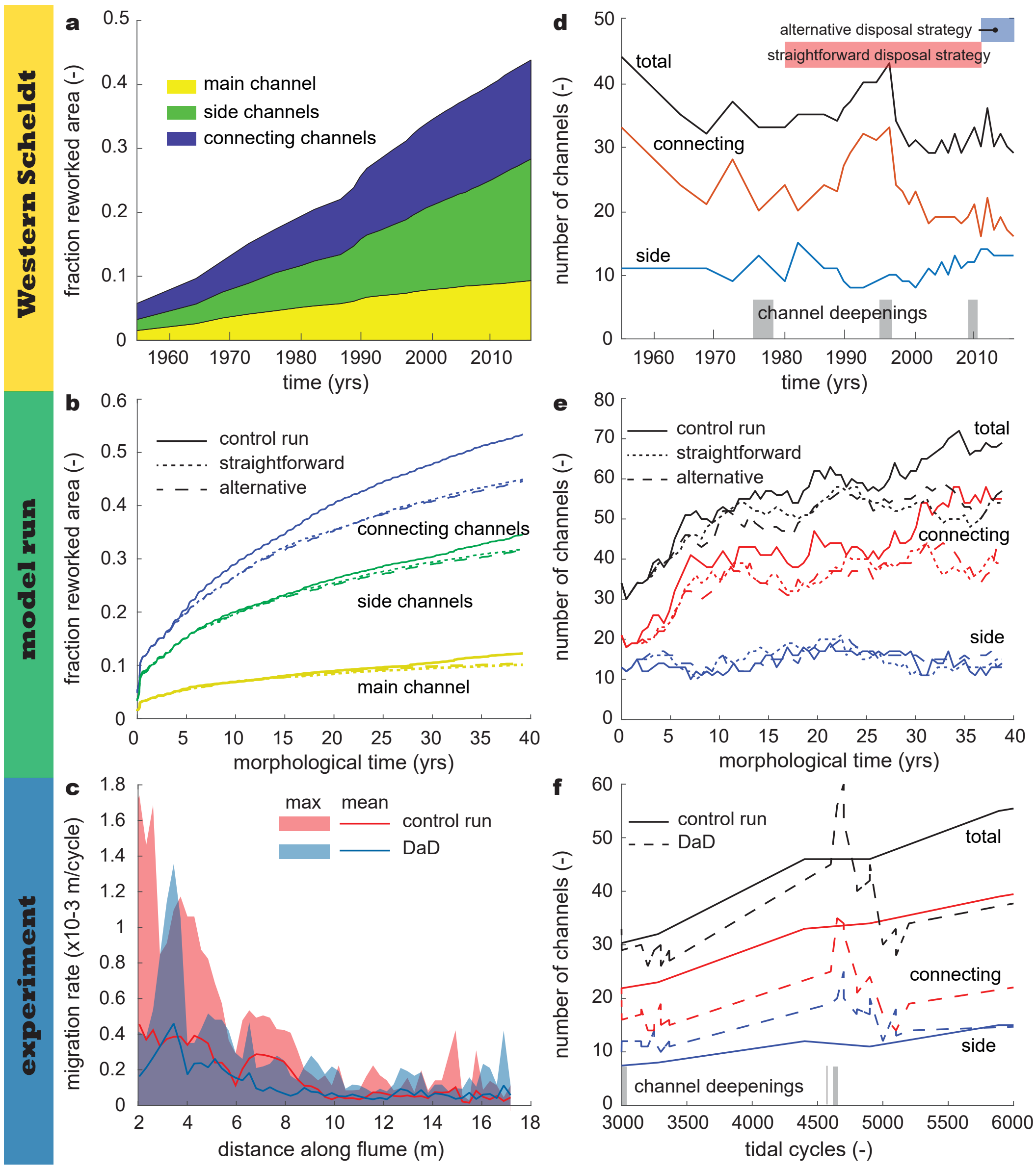

Figure 3. Channel activity and number of channels. a) Fraction of reworked area in the entire study area over the past 60 years by the main, side and connecting channels in the Western Scheldt. b) Fraction of reworked area by the three types of the channel for the three model runs. c) The migration rate of the main channel for the two experiments. d) The number of channels in the Western Scheldt since 1955. e) The number of channels for the three model runs. f) Number of channels for the two experiments.

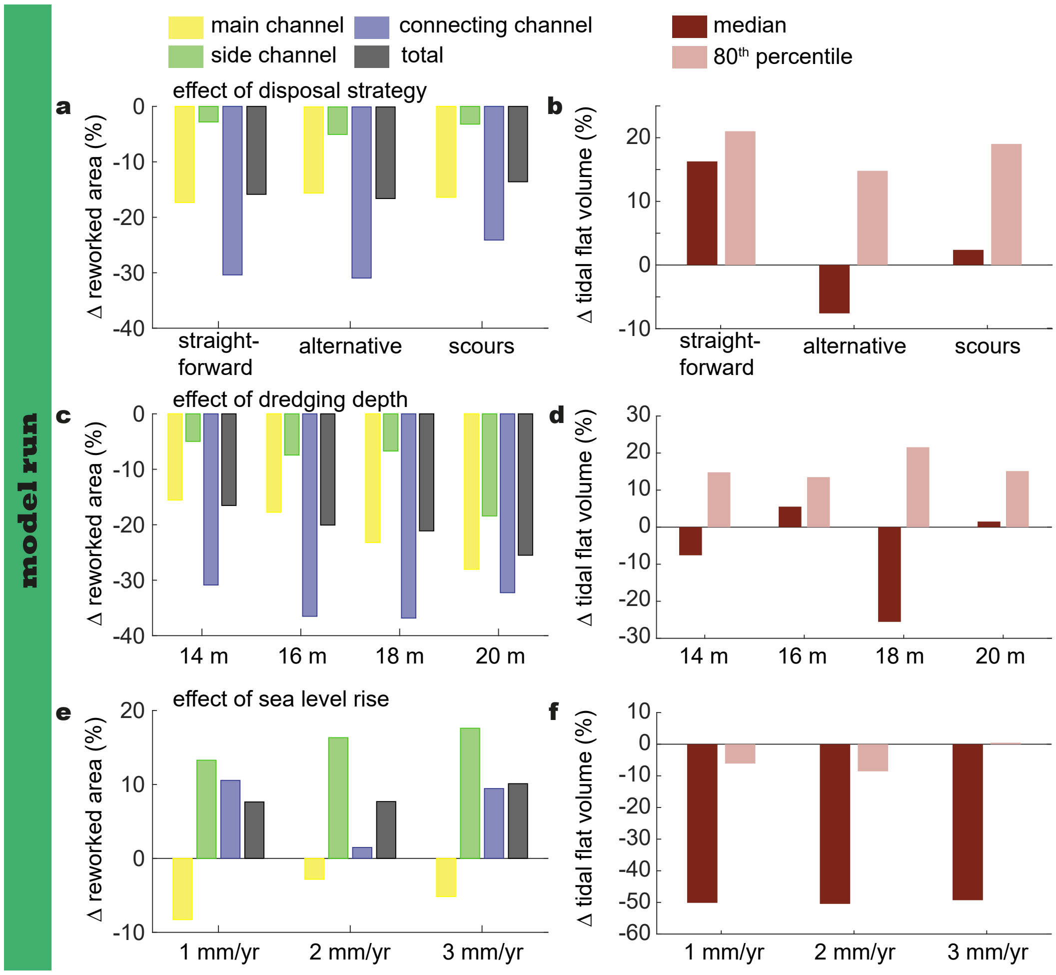

Figure 4. Effect of future scenarios on reworking by channels and tidal flat volume compared to the control run. a) Effect of disposal strategy on changes in the reworked area. b) Effect of disposal strategy on changes in tidal flat volume. c) Effect of dredging depth on changes in the reworked area. 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.

increase in dynamics in terms of the side and connecting channels, whilst the main channel becomes fixed even further (Figure 4e). Intertidal flat elevation increases with the sea-level rise in the model run whilst tidal flat volume decreases (Figure 4f).

6 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 (Boyd et al., 2000; Jensen & Mogensen, 2000; Wang et al., 2015). 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 (Huisman et al., 2018), but its effectiveness also depends on future threats such as increasing vessel draft and SLR. We would argue that further deepening of the Western Scheldt 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 the existence and persistence of the ecologically-important habitat, and the depth of side channels for navigability of smaller inland vessels (Nichols, 2018). Furthermore, dredging directly increases the tidal range resulting in higher flood risk, ebb-flood dominance alters, and peak velocity increases that complicates navigability (Liria et al., 2009; Colby et al., 2010). 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 (Kirwan et al., 2016).

From our field data, numerical modelling and laboratory experiments 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.

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References

Baar, A. W., Albernaz, M. B., Van Dijk, W. M., & Kleinhans, M. G. (2018). The influence of transverse slope effects on large scale morphology in morphodynamic models. In *Riverflow 2018* (Vol. 40). doi: 10.1051/e3sconf/20184004021

Baar, A. W., De Smit, J., Uijttewaal, W. S. J., & Kleinhans, M. G. (2018). Sediment transport of fine sand to fine gravel on transverse bed slopes in rotating annular flume experiments. *Water Resources Research*, *54*(1), 19–45. doi: 10.1002/2017WR020604

Best, J. (2019). Anthropogenic stresses on the world's big rivers. *Nature Geoscience*, *12*, 7–21. doi: 10.1038/s41561-018-0262-x

Blott, S. J., Pye, K., Van der Wal, D., & Neal, A. (2006). Long-term morphological change and its causes in the Mersey Estuary, NW England. *Geomorphology*, *81*(1–2), 185–206. doi: 10.1016/j.geomorph.2006.04.008

Bolla Pittaluga, M., Coco, G., & Kleinhans, M. G. (2015). A unified framework for stability of channel bifurcations in gravel and sand fluvial systems. *Geophysical Research Letters*, *42*(18), 7521–7536. doi: 10.1002/2015GL065175

Boyd, S. E., Rees, H. L., & Richardson, C. A. (2000). Nematodes as sensitive indicators of change at dredged material disposal sites. *Estuarine, Coastal and Shelf Science*, *51*, 805–819. doi: 10.1006/ecss.2000.0722

Braat, L., Leuven, J. R. F. W., Lokhorst, I. R., & Kleinhans, M. G. (2018). Effects of estuarine mudflat formation on tidal prism and large-scale morphology in experiments. *Earth Surface Processes and Landforms*. doi: 10.1002/esp.4504

Chen, Y., Dong, J., Xiao, X., Zhang, M., Tian, B., Zhou, Y., . . . Ma, Z. (2016). Land claim and loss of tidal flats in the Yangtze Estuary. *Scientific Reports*, *6*(1), 24018. doi: 10.1038/srep24018

Church, J. A., Clark, P. U., Cazenave, A., Gregory, J. M., Jevrejeva, S., Levermann, A., . . . Unnikrishman, A. S. (2013). Sea-level rise by 2100. *Science*, *342*(6165), 1445. doi: 10.1126/science.342.6165.1445-a

Cleveringa, J. (2013). *LTV - Veiligheid en Toegankelijkheid: Ontwikkeling mesoschaal Westerschelde (factsheets) (in Dutch)* (Tech. Rep.). International Mairne & Dredging Consultants, Deltares, Svašek Hydraulics BV and ARCADIS.

Colby, L. H., Maycock, S. D., Nelligan, F. A., Pocock, H. J., & Walker, D. J. (2010). An investigation into the effect of dredging on tidal asymmetry at the River Murray mouth. *Journal of Coastal Research*, *26*(5), 843–850. doi: 10.2112/08-1143.1

Dam, G. (2017). *Lange-termijn sedimentbalans Westerschelde (in Dutch)* (Tech. Rep.). SVASEK hydraulics.

Depreiter, D., Lanckriet, T., Van Holland, G., Vanlede, J., Beirinckx, K., & Maris, T. (2015). Mud disposal and suspended sediment concentration in the Lower Sea Scheldt - towards a hyperturbid system? In *E-proceedings of the 36th iahr world congress* (pp. 38–52). The Hague, the Netherlands.

Desjardins, P. R., Buatois, L. A., & Màngano, M. G. (2012). Chapter 18 - Tidal Flats and Subtidal Sand Bodies. In D. Knaust & R. G. Bromley (Eds.), *Trace fossils as indicators of sedimentary environments* (Vol. 64, p. 529 - 561). Elsevier. doi: 10.1016/B978-0-444-53813-0.00018-6

De Vet, P. L. M., Van Prooijen, B. C., & Wang, Z. B. (2017). The difference in morphological development between the intertidal flats of the Eastern and Western Scheldt. *Geomorphology*, *281*, 31–42. doi: 10.1016/j.geomorph.2016.12.031

De Vriend, H. J., Wang, Z. B., Ysebaert, T., Herman, P. M. J., & Ding, P. (2011). Ecomorphological problems in the Yangtze Estuary and the Western Scheldt. *Wetlands*, *31*, 1033–1042. doi: 10.1007/s13157-011-0239-7

Directie Zeeland; Ministerie van de Vlaamse Gemeenschap. Administratie Waterwegen en Zeewezen. (2001). *Langetermijnvisie Schelde-estuarium (in Dutch)* (Tech. Rep.). Middelburg, The Netherlands: Ministerie van de Vlaamse Gemeenschap. Departement Leefmilieu en Infrastructuur. Administratie Waterwegen en Zeewezen/Ministerie van Verkeer en Waterstaat. Directoraat-Generaal Rijkswaterstaat. Directie Zeeland. (86 pp.)

Edelsbrunner, H., Harer, J., & Zomorodian, A. (2001). Hierachical morse complexes for piecewise linear 2-manifolds. In *Proceedings of the seventeeth annual symposium on computational geometry* (pp. 70–79). New York, NY, USA: ACM. doi: 10.1145/378583.378626

Elias, E. P. L., Van der Spek, A. J. F., & Lazar, M. (2016). The 'Voordelta', the contiguous ebb-tidal deltas in the SW Netherlands: large-scale morphological changes and sediment budget 1965-2013; impacts of large-scale engineering. *Netherlands Journal of Geosciences*, *96*(3), 233–259. doi: 10.1017/njg.2016.37

Essink, K. (1999). Ecological effects of dumping of dredged sediments; options for management. *Journal of Coastal Conservation*, *5*(1), 69–80.

Grasmeijer, B., Dam, G., & Taal, M. (2013). *Actualisatierapport Delft3D Schelde-estuarium (in Dutch)* (Tech. Rep.). International Marine & Dredging Consultants.

Graveland, J., Van Eck, G. T. M., Kater, B. J., Liek, G. J., & van Maldegem, D. C. (2005). *Fysische en ecologische kennis en modellen voor de Westerschelde: wat is beleidsmatig nodig en wat is beschikbaar voor de m.e.r. Verruiming Vaargeul? (in*

Dutch) (Tech. Rep.). Middelburg: Rijkswaterstaat, Rijksinstituut voor Kust en Zee. (Rapport RIKZ/2005.018)

Gruijters, S. H. L. L., Schokker, J., & Veldkamp, J. G. (2004). *Kartering moeilijk erodeerbare lagen in het Schelde estuarium (in Dutch)* (rapport NITG No. 03213B1208). TNO.

Hibma, A., Schuttelaars, H. M., & De Vriend, H. J. (2004). Initial formation and long-term evolution of channel-shoal patterns. *Continental Shelf Research*, *24*(15), 1637–1650. doi: 10.1016/j.csr.2004.05.003

Hibma, A., Wang, Z. B., Stive, M. J. F., & De Vriend, H. J. (2008). Modelling impact of dredging and dumping in ebb-flood channel systems. *Transactions of Tianjin University*, *14*(4), 271–281.

Huisman, B., Schrijvershof, R., Lanckriet, T., & van der Werf, J. (2018). *Baggerdepositie in diepe geulen: strategie voor het plaasten van gebaggerd materiaal in de diepere getijdegeulen van de Westerschelde (in Dutch)* (Tech. Rep.). Deltares.

Ikeda, S. (1982). Lateral bed load transport on side slopes. *Journal of Hydraulics Division*, *108*(11), 1369–1373.

Jensen, A., & Mogensen, B. (2000). Effects, ecology and economy. In *Environmental aspects of dredging - guide no. 6* (p. 119).

Jeuken, M. C. J. L., & Wang, Z. B. (2010). Impact of dredging and dumping on the stability of ebb-flood channel systems. *Coastal Engineering*, *57*. doi: 10.1016/j.coastaleng.2009.12.004

Johnston Jr., S. A. (1981). Estuarine dredge and fill activities: a review of impacts. *Environmental Management*, *5*(5), 427–440. doi: 10.1007/BF01866820

Kerner, M. (2007). Effects of deepening the Elbe Estuary on sediment regimen and water quality. *Estuarine Coastal Shelf Science*, *75*(4), 492–500. doi: 10.1016/j.ecss.2007.05.033

Kirwan, M. L., Temmerman, S., Skeehan, E. E., Guntenspergen, G. R., & Fagherazzi, S. (2016). Overestimation of marsh vulnerability to sea level rise. *Nature Climage Change*, *6*, 253–260. doi: 10.1038/NCLIMATE2909

Kleinhans, M. G., Kreveld, M., Ophelders, T., Sinke, W., Speckmann, B., & Verbeek, K. (2017). Computing representative networks for braided rivers. In B. Aronov & M. J. Katz (Eds.), *33rd international symposium on computational geometry (socg 2017)* (Vol. 77, pp. 48:1–48:16). Schloss Dagstuhl–Leibniz-Zentrum fuer Informatik. doi: 10.4230/LIPIcs.SoCG.2017.48

Kleinhans, M. G., van der Vegt, J., Leuven, Braat, L., Markies, H., Simmelink, A., Roosendaal, C., ... van Maarseveen, M. (2017). Turning the tide: comparison of tidal flow by periodic sea level fluctuation and by periodic bed tilting in scaled landscape experiments of estuaries. *Earth Surface Dynamics*, *5*, 731–756. doi: 10.5194/esurf-5-731-2017

Leuven, J. R. F. W., Braat, L., van Dijk, W. M., De Haas, T., Van Onselen, E. P., Ruessink, B. G., & Kleinhans, M. G. (2018). Growing forced bars determine nonideal estuary planform. *Journal of Geophysical Research – Earth Surface*, *123*(11), 2971–2992. doi: 10.1029/2018JF004718

Leuven, J. R. F. W., De Haas, T., Braat, L., & Kleinhans, M. G. (2018). Topographic forcing of tidal sand bar patterns for irregular estuary planforms. *Earth Surface Processes and Landforms*, *43*(1), 172–186. doi: 10.1002/esp.4166

Leuven, J. R. F. W., Kleinhans, M. G., Weisscher, S. A. H., & Van der Vegt, M. (2016, October). Tidal sand bar dimensions and shapes in estuaries. *Earth Science Reviews*, *161*, 204–223. doi: 10.1016/j.earscirev.2016.08.004

Liria, P., Garel, E., & Uriarte, A. (2009). The effects of dredging operations on the hydrodynamics of an ebb tidal delta: Oka Estuary, northern Spain. *Continental Shelf Research*, *29*(16), 1983–1994.

Maximova, T., Ides, S., De Mulder, T., & Mostaert, F. (2009a). *LTV O & M thema Veiligheid - Deelproject 1: Verbetering hydrodynamisch NeVla model ten behoeve van scenario-analyse (in Dutch)* (WL rapporten No. 756_05). Antwerp, Belgium: Flanders Hydraulics Research & Deltares.

Maximova, T., Ides, S., De Mulder, T., & Mostaert, F. (2009b). *Verbetering randvoorwaardenmodel. Deelrapport 4: Extra aanpassingen Zeeschelde (in Dutch)* (WL rapporten No. 753_09). Antwerp, Belgium: Flanders Hydraulics Research.
Maximova, T., Ides, S., Vanlede, J., De Mulder, T., & Mostaert, F. (2009). *Verbetering 2D randvoorwaardenmodel. Deelrapport 3: kalibratie bovenlopen (in Dutch)* (WL rapporten No. 753_09). Antwerp, Belgium: Flanders Hydraulics Research.
Monge-Ganuzas, M., Cearreta, A., & Evans, G. (2013). Morphodynamic consequences of dredging and dumping activities along the Lower Oka estuary (Urdaibai Biosphere Reserve, southeastern Bay of Biscay, Spain). *Ocean & Coastal Management*, *77*, 40–49. doi: 10.1016/j.ocecoaman.2012.02.006
MOW. (2013). *Work package 5 'measures': dredging and diposal strategies* (Tech. Rep.). TIDE project.
Murray, N. J., Phinn, S. R., DeWitt, M., Ferrari, R., Johnston, R., Lyons, M. B., . . . Fuller, R. A. (2019). The global distribution and trajectory of tidal flats. *Nature*, *565*, 222–225. doi: 10.1038/s41586-018-0805-8
Nichols, M. M. (2018). Consequences of dredging. In B. Kjerfve (Ed.), *Hydrodynamics of estuaries: volume ii estuarine case studies.* CRC Press.
Plancke, Y., Beirinckx, K., Liek, G. J., Vos, G. R., & Schrijver, M. (2014). A new disposal straregy for the Western Scheldt, conciliating port accessibility and nature preservation. In *2nd pianc congress, 125th anniversary pianc - setting the course.* Liverpool, UK.
Robinson, A. H. W. (1960). Ebb-flood channel systems in sandy bays and estuaries. *Geography*, *45*(3), 183–199.
Rodrigue, J.-P., Comtois, C., & Slack, B. (2017). *The geography of transport systems.* London and New York: Routledge.
Roose, F., Plancke, Y., & Ides, S. (2008). A synthesis on the assessment of an alternative disposal strategy to serve sustainability in the Scheldt estuary. In *Ceda dredging days 2008: Dredging facing sustainability* (pp. 1–13). Antwerp (Belgium).
Savenije, H. H. (2015). Prediction in ungauged estuaries: an integrated theory. *Water Resources Research*, *51*(4), 2464–2476. doi: 10.1002/2015WR016936
Schrijvershof, R., & Vroom, J. (2016). *Effecten van realistische (extreme) stortstrategieën in de Westerschelde (in Dutch)* (Tech. Rep.). Deltares.
Struiksma, N. (1985). Prediction of 2-d bed topography in rivers. *J. of Hydraulic Engineering*, *111*(8), 1169–1182.
Swinkels, C. M., Jeuken, M. C. J. L., Wang, Z. B., & Nicholls, R. J. (2009). Presence of connecting channels in the Western Scheldt Estuary. *Journal of Coastal Research*, *253*, 627–640. doi: 10.2112/06-0719.1
Temmerman, S., Meire, P., Bouma, T. J., Herman, P. M. J., Ysebaert, T., & De Vriend, H. J. (2013). Ecosystem-based coastal defence in the face of global change. *Nature*, *504*, 79–83. doi: 10.1038/nature12859
Toffolon, M., & Crosato, A. (2007). Developing macroscale indicators for estuarine morphology: the case of the Scheldt estuary. *Journal of Coastal Research*, *23*(1), 195–212. doi: 10.2112/03-0133.1
Van de Lageweg, W. I., & Slangen, A. B. A. (2017). Predicting dynamic coastal delta change in response to sea-level rise. *Journal of Marine Science and Engineering*, *5*(2), 24. doi: 10.3390/jmse5020024
Van der Spek, A. J. F. (1997). Tidal asymmetry and long-term evolution of Holocene tidal basins in the Netherlands. *Marine Geology*, *141*(1–4), 71–90. doi: 10.1016/S0025-3227(97)00064-9
Van der Wal, D., Lambert, G. I., Ysebaert, T., Plancke, Y. M. G., & Herman, P. M. J. (2017). Hydrodynamic conditioning of diversity and functional traits in subtidal estuarine macrozoobenthic communities. *Estuarine, Coastal and Shelf Science*, *197*, 80–92. doi: 10.1016/j.ecss.2017.08.012
Van der Wal, D., Van Kessel, T., Eleveld, M. A., & Vanlede, J. (2010). Spatial heterogeneity in estuarine mud dynamics. *Ocean Dynamics*, *60*, 519–533. doi: 10.1007/s10236-010

-0271-9

Van Dijk, W. M., Hiatt, M., Van der Werf, J. J., & Kleinhans, M. G. (2019). Effects of shoal margin collapses on the morphodynamics of a sandy estuary. *Journal of Geophysical Research – Earth Surface*. doi: 10.1029/2018JF004763

Van Dijk, W. M., Mastbergen, D. R., Van de Ham, G. A., & Kleinhans, M. G. (2018). Location and probability of shoal margin collapses in a sandy estuary. *Earth Surface Processes and Landforms*, *43*(11), 2342–2357. doi: 10.1002/esp.4395

Van Dijk, W. M., Van de Lageweg, W. I., & Kleinhans, M. G. (2012). Experimental meandering river with chute cutoffs. *Journal of Geophysical Research*, *117*, F03023. doi: 10.1029/2011JF002314

Van Maren, D., Van Kessel, T., Cronin, K., & Sittoni, L. (2015). The impact of channel deepening and dredging on esuarine sediment concentration. *Continental Shelf Research*, *95*, 1–14. doi: 10.1016/j.csr.2014.12.010

Van Veen, J. (1948). Dredgers' work. In *Dredge drain reclaim* (pp. 60–104). Dordrecht, The Netherlands: Springer. doi: 10.1007/978-94-017-6236-6_2

Van Veen, J. (1950). Ebb and flood channel systems in the Netherlands tidal waters (in Dutch). *Journal of the Royal Dutch Geographical Society*, *67*, 303–325.

Vikolainen, V., Bressers, H., & Lulofs, K. (2014). A shift toward building with nature in the dredging and port development industries: managerial implications for project in or near Natura 2000 areas. *Environmental Management*, *54*(1), 3–13. doi: 10.1007/s00267-014-0285-z

Vroom, J., De Vet, P. L. M., & Van der Werf, J. J. (2015). *Validatie waterbeweging Delft3D NeVla model Westerscheldemonding (in Dutch)* (Tech. Rep.). Deltares.

Wang, Z. B., Maren, D. S. V., Ding, P. X., Yang, S. L., Prooijen, B. C. V., Vet, P. L. M. D., ... He, Q. (2015). Human impacts on morphodynamic thresholds in estuarine systems. *Continental Shelf Research*, *111*, 174 - 183. (Coastal Seas in a Changing World: Anthropogenic Impact and Environmental Responses) doi: https://doi.org/10.1016/j.csr.2015.08.009

Wang, Z. B., & Winterwerp, J. (2001). Impact of dredging and dumping on the stability of ebb-flood channel systems. In *Proceeding of the 2nd iahr symposium on river, coastal and estuarine morphodynamics* (pp. 515–524). Obihiro, Japan.

Winterwerp, J. C., Wang, Z. B., Stive, M. J. F., Arends, A., Jeuken, C., Kuijper, C., & Thoolen, P. M. (2001). A new morphological schematisation of the Western Scheldt Estuary, The Netherlands. In *Proceedings of the 2nd iahr symposium on river, coastal and estuarine morphodynamics* (Vol. 6, pp. 1–10).

Yuan, R., & Zhu, J. (2015). The effects of dredging on tidal range and saltwater intrusion in the Pearl River Estuary. *Journal of Coastal Research*, *31*(6), 1357–1362. doi: 10.2112/JCOASTRES-D-14-00224.1

Zhu, J., Weisberg, R., & Zheng, L. (2014). Influences of channel deepening and widening on the tidal and nontidal circulations of Tampa Bay. *Estuaries and Coasts*, *38*(1), 132–150.