River Flow 2020 – Uijttewaal et al (eds)
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The effects of dredging activities on the multi-channel network of the Western Scheldt

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ABSTRACT: Many shipping fairways need semi-continuous dredging to maintain access for ships to major ports, often located at river mouths, i.e. estuaries. One of the negative effects of dredging is the shift from a multi-channel system to a single-channel system. An increase in flow asymmetry between flood and ebb channels is regarded as undesirable for many user-functions, including ecological values. Our aim is to quantify how dredging and disposal affect the channel network composed of flood and ebb channels. Therefore, we analysed the bathymetry of the Western Scheldt (The Netherlands) since 1955 and used a Delft3D schematization of the Western Scheldt to isolate the effect of dredging and disposal strategies. We use a novel and mathematically rigorous network extraction method to characterise the channels in scale and topology. All model runs show that current dredging and disposal strategies are unsustainable for the multi-channel system because dredging (1) further disturbs the balance between high and lower bed levels of the flood and ebb channels and (2) increases bifurcation asymmetry, i.e. angles and elevation jumps. The model runs also suggest that disposal of dredged sediment in the scours of the main channel is economically feasible and contributes to the preservation of the multi-channel system. We argue that the disposal strategy of dredged material is as important as the dredging it-self in maintaining suitable conditions for the persistence of an ecologically valuable system.

1 INTRODUCTION

Estuaries worldwide are important centres of transportation and international commerce. Apart from conveying navigation to harbours, estuaries also provide other socio-economical functions like mining activities, flood conveyance and ecosystem services. These functions are enabled by the range of hydraulic and morphological properties that characterize estuaries. Main characteristics determining the functionality of an estuary are the river discharge, tidal prism, water level, flow speed, bed level and estuary width. The use of estuaries for shipping also poses considerable issues (Best et al., 2018), affecting the hydrodynamics and the long-term morphodynamics of the estuary.

The Western Scheldt estuary (Figure 1) is continuously dredged since the early 20th century with an increase in recent decades. Dredging is needed to maintain a minimum depth requirement for the shipping fairways so that large commercial vessels can access the port of Antwerp (Jeuken et al, 2010; De Vriend et al., 2011; Wang et al., 2015). Literature suggest that, dredging activities can cause a shift from a multi-channel system to a single channel (Wang et al., 2001) as well as

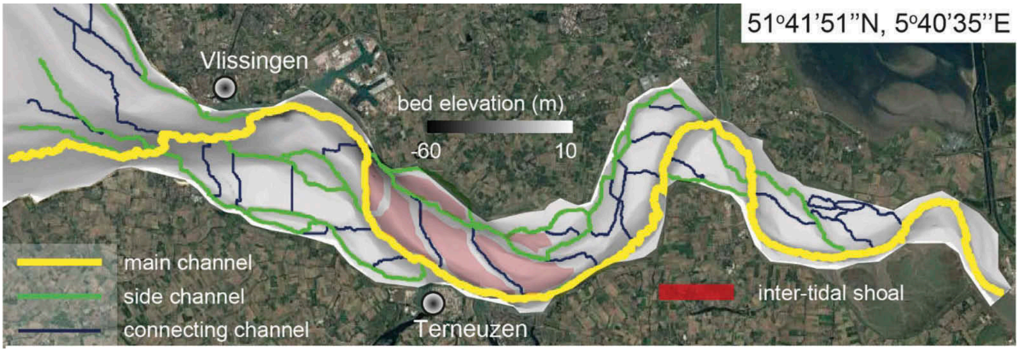

Figure 1. The Western Scheldt estuary and the identified network of channels and shoals by the method of Hiatt et al. (2019), distinguish main, side and connecting channels within the Western Scheldt estuary.

a loss of ecologically valuable intertidal flats (Essink et al., 1999; Temmerman et al., 2013). Yet, it remains undiscovered what the long-term effects of dredging and disposal strategies are on the sustainability of tidal flats and stability of the bifurcations within a multi-channel estuary.

For example, changes in the connecting channels affect the spatial extent of mudflats, tidal marshes and intertidal flat ecosystems. These provide ecologically valuable habitats. To improve ecological habitats and increase tidal flat areas in estuaries it is becoming imperative to use nature-based solutions, and therefore implement adaptive dredging and disposal strategies. Present dredging practices to sustain ecological habitats in the Western Scheldt estuary are based on a Long-Term Vision (LTV) (Depreiter et al., 2015). An adaptive dredging and disposal strategy is now in place, aiming to maintain and improve ecological values, by creating new habitat with dredged material and maintenance of ebb- and flood channels. The objective of this study is to use field observations and a morphodynamic model to quantify the degree to which the multi-channel system is sustained by current dredging and disposal practices and to infer implications for the future/other estuaries.

2 METHODS

We used two independent complementary methods: 1) Field data from the Western Scheldt was used to measure the morphological changes that occurred over time; and 2) Numerical model scenarios were used to isolate dredging effects and test different disposal strategies. For analysis of the bathymetry within both approaches, we employed a novel channel-network algorithm that extracts channel network topology scale-independently and objectively (Figure 1, see full explanation of the method Hiatt et al., 2019). The network was used to extract the characteristics of the multi-channel system, including channel depth distribution along the channel lines, channel migration, tidal flat volumes, and bifurcation asymmetry, i.e. the elevation difference and bifurcation angle between two channels.

2.1 *Field data*

To examine the development of the Western Scheldt and link this with dredging and disposal strategies and volumes, 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 several analogues to digital techniques. 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 used to establish the long-term development of the channel network of the

Western Scheldt. The estimated vertical accuracy of the dataset for practical use was determined at 10~cm (2σ).

2.2 *Model setup*

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 (Lesser et al., 2004). 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. 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 (Baar et al., 2019).

The Delft3D schematization was based on the optimised NeVla-Delft3D model for hydrodynamics (Vroom et al., 2015) and morphology (Schrijvershof et al., 2016) of the Scheldt estuary. We used a nested model from the NeVla-Delft3D model for reducing computational time (same model as in Van Dijk et al., 2019). 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. 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. 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 of the Western Scheldt.

2.3 *Model runs*

We performed three scenarios for 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 Figure 1): 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 main channel (scours), as proposed for future strategies.

3 RESULTS AND DISCUSSION

3.1 *Effect on intertidal flats*

The bathymetric field data of the Western Scheldt show that, as dredging volume increases, the median tidal flat volumes based on the area and elevation tends to increase due to amalgamation of shoals since 1990s (Figure 2), meaning an increase in intertidal area. This includes sub- and supratidal area, which is not equally valuable for all habitats. 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 (Figure 2c).

3.2 *Effect on channel depth*

Our field observations and numerical simulations show increasing differences in channel depth among the main, side and connecting channels (Figure 3). Field observations illustrate that, as

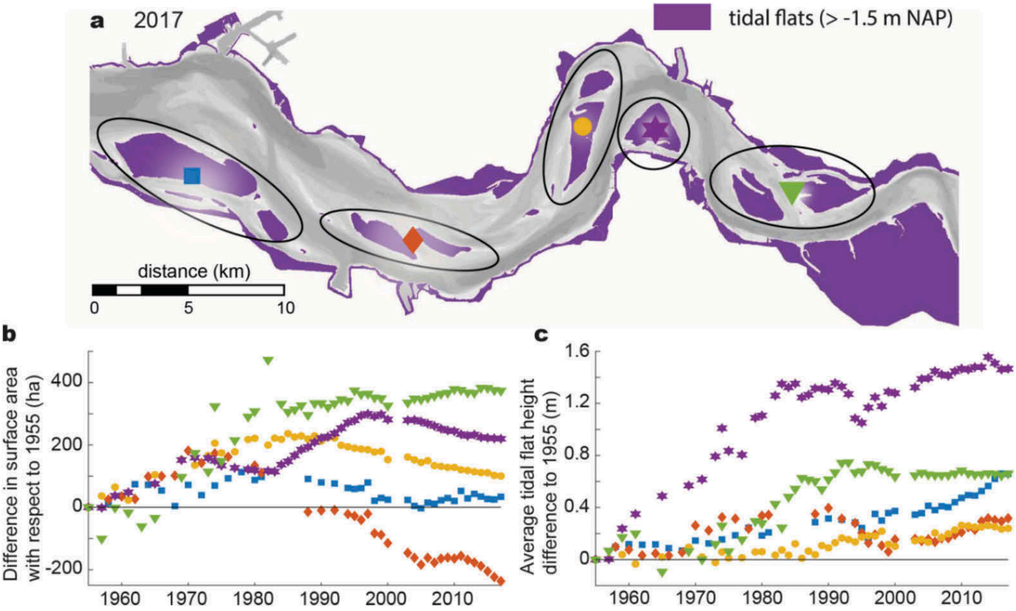

Figure 2. Shoal development in the Western Scheldt from 1955-2017. b) Shoal surface area difference with respect to 1955 shows a generally increase in tidal flat area. c) Average tidal flat height difference respect to 1955 shows an increase of all tidal flat locations.

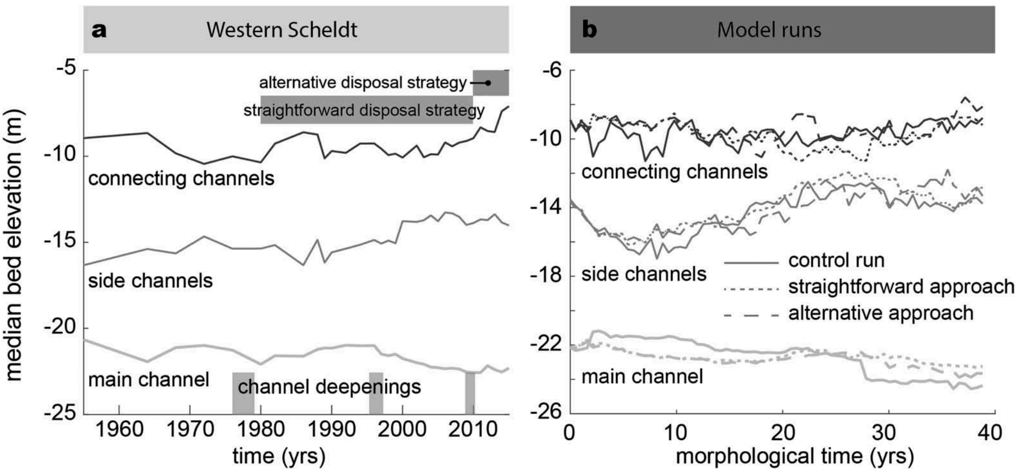

Figure 3. Increasing main channel depths due to dredging is counteracted by shallowing of the smaller side and connecting channels in the Western Scheldt (a), which trend continuous in all model runs (b).

expected, the main channel became deeper since dredging started. 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 et al., 2010). The conversion to an east-to-west strategy since the 1990 shows a stabilisation of the channel depth of the side channels (Figure 3a). The alternative tidal flat strategy, where a maximum of 20% of the dredged sediment was disposed on the downstream end of the intertidal flats, shows that between 2010-2015 the smaller extracted connecting channels continue become shallower (Figure 3a). This development impacts the multi-channel system and the alternative disposal strategy is unable to improve the desired self-erosive capacity of the flow (Roose et al., 2008). The model runs shows that for all runs that the main channel depth increases and that the side and connecting channels becomes shallower, even for the control run without dredging (Figure 3b). We suspect that the initial bed topography of the current situation is too much disturbed that the natural dynamics are not restored within the simulated morphological time.

3.3 *Effect on number of channels and channel dynamics.*

Water level differences between the ebb and flood channels drive the flow of water through the connecting channels. The connecting channels form a link between the large ebb and flood (main and side) channels. 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 (Figure 4a). A reduction in dynamics of the connecting channels is illustrated by a decreasing number of connecting channels since 1955, whilst the number of side channels remained the same or slightly increased (Figure 4a). 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.

The channel dynamics for the model simulations are quantified by the displacement and migration of the channels that results in erosion and accretion of the intertidal flats compared to the control run. Channels in the Western Scheldt migrate at different rates depending on channel scale, occupying a large portion of the estuary. The variation of the main channel location is limited laterally by geological constraints and embankments and is fixed in place by dredging. In contrast, the side and connecting channels are not fixed by dredging but may be by geological constraints and embankments. In a control run, the main channel can migrate, and this increases the reworked area. The model runs with dredging shows that the reworked area by the main channel decreases independent of disposal strategy (Figure 4b). This has less effect for the side channels that in all models almost evenly migrate. Because of the decrease in variation of the main channel due to dredging, the model also shows less reworked area for the determined connecting channels by the channel-network algorithm (Figure 4b). The dynamics of the connecting channels depends on the side and main channel, in which the main channel dynamics decreases for model runs with dredging. The least

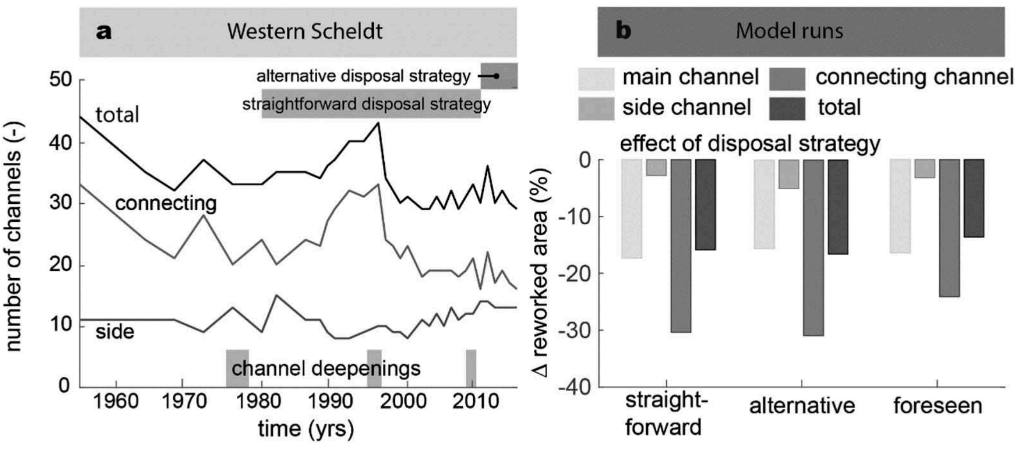

Figure 4. Reduction in channel dynamics and number of channels due to dredging and disposal. a) The number of channels in the Western Scheldt since 1955. b) The reduction in channel dynamics for different disposal strategies.

reduction in channel dynamics of the connecting channels is observed in the foreseen strategy, whereas for the alternative strategy dynamics decreases the most (Figure 4b).

3.4 *Effect on the bifurcation asymmetry*

Ebb and flood channels develop around sand bars forming multiple bifurcations in the Western Scheldt estuary. The order in channel scale means that branches at the bifurcations are asymmetric, which means there is an elevation jump between the channels. We automatic analysed bifurcation asymmetry by selecting stretches on the extracted channel network, representing the upstream channel and the two downstream branches. We observed that there generally is a larger elevation jump for the bifurcations of the smaller connecting channels than for the side channels. As the elevation jump increases, the bifurcation angle does not increase for the connecting channels. Basically, bifurcation theory argues that the asymmetry of bifurcations would lead to closure of the bifurcated channel unless a change in the other downstream channel opposes the increased gradient (Kleinhans et al., 2013; Bolla Pittaluga et al., 2015). This is however less the case for the connecting channels, which eventually would lead to closure according to river bifurcation theory. However, this is not the case for the Western Scheldt estuary where flow is in both directions.

Dredging and disposal affects the asymmetry and the stability of the bifurcations. Dredging of the main channels increases the elevation difference with the bifurcated channel. The few individual bifurcations that we analyzed did not show an increase in bifurcation asymmetry for the three dredging scenarios. Evaluation of the median normalized elevation jump, and normalized angle shows that side channel bifurcations are more symmetric during the simulation than initial. The analysis including the connecting channels show a more asymmetric behaviour. This is especially true for model run with the alternative disposal strategy, where elevation jump increases due to disposal at the tip of the shoals (Figure 5).

4 IMPLICATIONS

Extensive human intervention is common in many estuaries worldwide. The morphological and ecological functioning of estuaries are directly impacted by these. We argue that the disposal strategy of dredged material is as important as the dredging itself in maintaining suitable

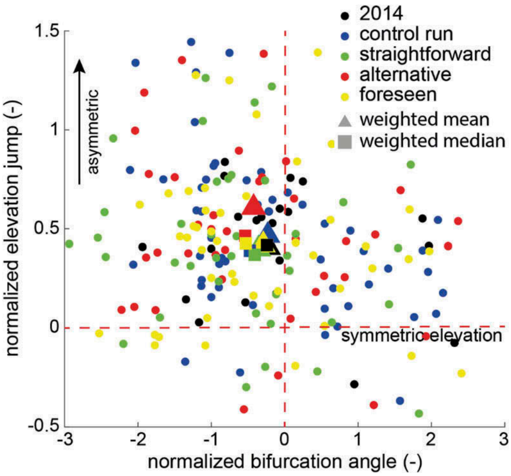

Figure 5. Normalized bifurcation angle plotted against normalized elevation jumps, shows a clear increase in asymmetry in the situation were dredged sediment is disposed on the tip of the shoals within the side channels.

conditions for the persistence of an ecologically valuable system. The development of natural habitats in estuaries partly depends on the total area of intertidal flats (Graveland et al., 2005). Particularly, the local physical conditions, i.e. low dynamic areas, are important for ecology in estuaries (Van der Wal et al., 2017, Brückner et al., 2019). Model simulations reveal that current dredging strategies are not suitable to sustain all ecosystem services, whereas current disposal strategies to counter adverse effects of dredging are hardly effective. A promising strategy could be the foreseen scour disposal strategy in which dredged sediment is disposed in the scours of the main channel (tested in more detail by Huisman et al., 2018), but its effectiveness also depends on future interventions such as further deepening and accelerated sea level rise and associated changes in tidal amplitude (e.g. Leuven et al., 2019). A decrease in channel dynamics and displacement contributes to destabilization of the multi-channel character, including intertidal flats and connecting channels, of the Western Scheldt. From the 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 limited or ineffective.

ACKNOWLEDGEMENTS

While working at Utrecht University WMvD, JRFWL were supported by the Dutch Technology Foundation TTW under project no STW-Vici-016.140.316/13710 (granted to MGK), which is part of the Netherlands Organisation for Scientic Research (NWO). We gratefully acknowledge Marco Schrijver and Gert-Jan Liek (Rijkswaterstaat Zee en Delta) for insightful discussions.

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