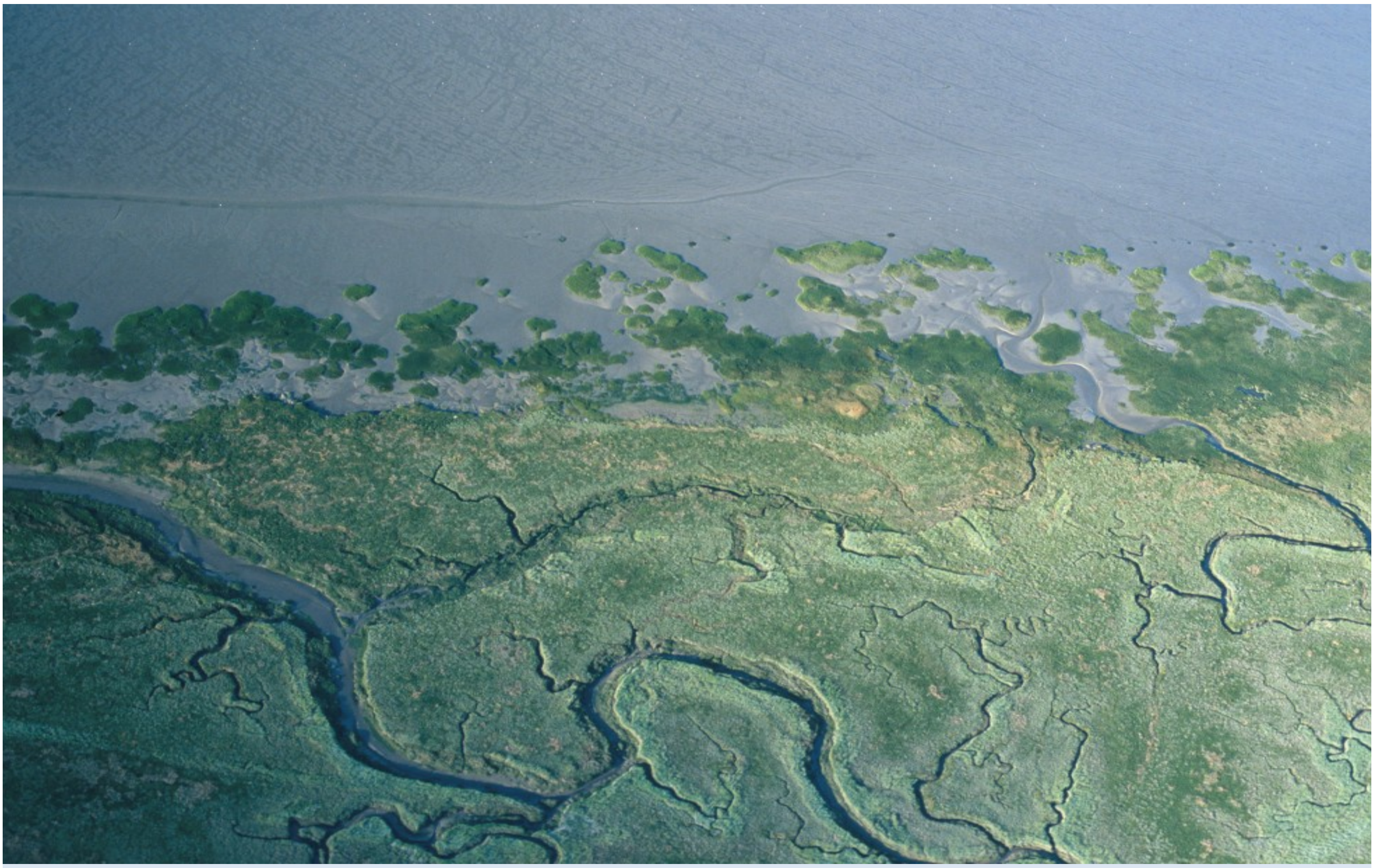

Characterization of the impact of dredging and disposal on the channel network of the Western Scheldt estuary

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Abbreviations

DEM	Digital Elevation Model
HW	High Water
HWS	Higher Water Slack
LW	Low Water
LWS	Low Water Slack
SLR	Sea level rise

Definitions

Main channel	The largest channel in size, length and flow concentration *(Dutch 'Hoofdgeul')*
Side channel	Channel that branches off and flows along the main channel *(Dutch 'Zijgeul')*
Chute channel	Shallow, short channel that cuts through banks in between main and side channels *(Dutch 'Kortsluitgeul')* (also: Connecting channel)
Scour	Deep section in the channel caused by erosion
Shoal	Sand bar separating channels
Thalweg	Lowest elevation pathway along the channel length
Saddle point	Point in the channel network that is a local minimum in one direction, and a local maximum in the other direction
Lowest path	Lowest elevation pathway or highest depth pathway in a channel network
Flow path	Highest velocity pathway in a channel network

Abstract

In recent history, the Western Scheldt estuary has been influenced by regular dredging and disposal operations performed to facilitate shipping. The exact response of the estuary to different dredging and disposal protocols is still not fully understood, while dredging and disposal is known to have an extensive range of effects that, in the case of the Western Scheldt, can threaten the multichannel system and ecosystem service functioning. The aim of this study is to assess the long term effects of three different dredging and disposal protocols on the tidal flow conditions and network complexity of the flow patterns in the Western Scheldt estuary. These effects and their morphologic impacts are examined and differentiated at a channel scale with the use of novel flow field based networks, and are compared to bathymetry based networks. After modelling the three dredging and disposal scenarios over 40-year periods, this study finds: a) a roughly 20% decrease in the number of active chute channels for all dredging and disposal strategies, with disposal in the main channel scours resulting in the highest mean number of active channels; b) a decrease in the area that is ebb asymmetric with disposal in the main channel scours and an increase with flexible disposal and disposal in the side channels and main channel scours. Until now, research has predominantly found a tendency towards ebb asymmetry with dredging and disposal which can increase erosion rates; and c) the strongest decrease in tidal flow conditions takes place in side channels and in the eastern part of the estuary, which can lead to increased sedimentation at those locations. Overall, disposal in the main channel scours seems to have a lower negative effect on the flow network complexity and tidal dominance in the estuary on the long term. The assessment is based on flow field networks, which on the whole, provide a good method to analyze tidal flow dynamics. The results in this study highlight the significance of the disposal strategy for future estuary management in the Western Scheldt and demonstrate that flow field based networks allow for efficient analysis of tidal flow dynamics at a channel scale.

Samenvatting

Baggeren en het storten van baggerspecie vormt al decennialang een belangrijk onderdeel van het beheer van de Westerschelde. Voor de regio een noodzakelijk goed om het doorvaren van de steeds groter wordende schepen mogelijk te maken. Daar zit een keerzijde aan, baggeren en storten kan, afhankelijk van de strategie, grote invloed uitoefenen op de stroomdynamiek en morfologische ontwikkeling van de Westerschelde. Dit onderzoek heeft door middel van geulnetwerken op basis van stroomvelden, uitgezocht wat de invloed is van drie verschillende bagger en stort strategieën op de complexiteit van het netwerk, de stroom patronen en de getijde invloed. Het gebruik van geulnetwerken gebaseerd op stromingsvelden is nieuw en zorgt ervoor dat de veranderingen in stromingsdynamiek per geul geanalyseerd kunnen worden, dit wordt gerelateerd aan de verandering in morfologie. De resultaten van het onderzoek zijn dat er, na een implementatie periode van 40 gemodelleerde jaren,: a) een vermindering van ongeveer 20% plaats heeft gevonden van het aantal actieve kortsluitgeulen met alle drie de strategieën, maar dat storten alleen in de hoofdgeul gemiddeld tot het grootste aantal geulen leidt; b) een afname is in eb asymmetrie wanneer er alleen in de hoofdgeul gestort wordt, terwijl er een toename is in eb asymmetrie met flexibel storten en storten in de zijgeulen en de hoofdgeul. Tot nu toe, werd er hoofdzakelijk een toenemende eb asymmetrie geconstateerd met baggeren en storten, wat betekent dat er meer sediment zeewaarts wordt getransporteerd; en c) een grotere afname is in de gemiddelde stroomsnelheid in de zijgeulen en in het oostelijke deel van de Westerschelde, wat kan leiden tot meer sedimentatie aldaar. Concluderend, het alleen storten in de hoofdgeul vermindert het negatieve effect van baggeren en storten op de netwerk complexiteit en de getijde dominantie op de lange termijn. De resultaten laten zien hoe belangrijk de stort strategie is en dat geulnetwerken gebaseerd op stromingsvelden een efficiënte methode is voor de analyse van de getijde dynamiek in geulen.

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1. Introduction

The Western Scheldt estuary is characterised by a valuable multichannel system, containing a multitude of side and chute channels. At the same time, the estuary provides many important ecosystem services, one of which is the provision of navigation routes to the ports of Antwerp, Gent, Terneuzen and Vlissingen (Jeuken & Wang, 2010). In order to keep these routes navigable, continuous dredging and disposal operations take place. The dredging and disposal of the dredged sediment changes the morphology and tidal flow conditions in the estuary, affecting the multichannel system (Jeuken & Wang, 2010). Changes in tidal flow conditions and tidal asymmetry affect the sediment transport and therefore the multichannel system on a long timescale. In the past, disposal strategies such as disposal in side channels have been shown to negatively impact the multichannel system (Roose et al, 2008; Wang & Winterwerp, 2001; van der Wal et al., 2011). While a different strategy is being implemented currently – flexible disposal – there is still concern that dredging and disposing is strongly affecting the estuary and the multichannel system it contains.

One of the effects is that dredging and disposal lowers the ecological productivity and biodiversity of the estuary, by reducing the intertidal area and number of chute or connecting channels (Jeuken & Wang, 2010; Swinkels et al., 2009). The intertidal area that the multichannel system of the Western Scheldt provides, offers valuable habitat for a diverse range of flora & fauna (Swinkels et al., 2009). However, dredging and disposal increases the elevation of intertidal shoals and decreases the elevation of shallow water areas (Jeuken & Wang, 2010). Initially, accumulation of sand on intertidal shoals increases the total amount of intertidal area, but in the long term the intertidal area is reduced, as it converts to supratidal area (Cox, 2018). Eventually, large scale dredging and disposal can result in the transition from a multiple channel system into a single channel system, reducing the complexity and dynamics of the system (Hibma et al., 2008). These changes in morphology and the reduction in complexity of the multichannel system also reduce the ecological value of the estuary (Thoolen & Fokkink, 1997; de Vet et al., 2017).

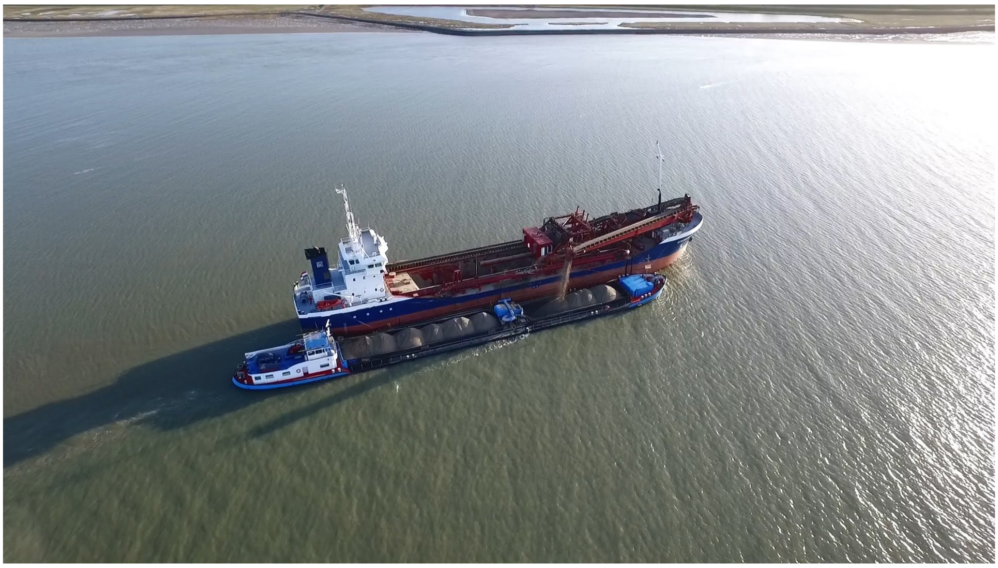


Figure 1. Dredging ship in the Western Scheldt (Breskens, 2015).

A multichannel estuary, such as the Western Scheldt, is often characterized by high dynamics and is ever changing (Marra et al., 2014). Different to braiding rivers, multichannel estuaries are formed by the interplay between the tidal, wave and river influence. The formation of new channels takes place by bifurcation or avulsions and eventually the channels can disappear by infilling or shift through erosion and deposition (Kleinhans et al., 2013). In the Western Scheldt, channel migration and formation have been limited by hard structures, but also by dredging and disposal (van Dijk et al., 2019b). If the dynamics in a system decrease, the system can shift to a new equilibrium with fewer channels. This is an undesirable development for the Western Scheldt estuary, as the objective of current management is to maintain the system as it is at present, preserving the current values and services (Jeuken & Wang, 2010; Depreiter et al., 2012). The pressing question is: how can we prevent the shift of the Western Scheldt estuary to a less dynamic system? Part of the Long Term Vision for the Western Scheldt is the conservation of the multichannel system by maintaining morphological sustainability (Roose et al., 2008). To achieve this, it is essential to understand and limit the negative consequences of different dredging and disposal strategies on the Western Scheldt over long time spans.

The main issue is that the exact response of the Western Scheldt to different dredging and disposal strategies is not fully understood, especially at a channel scale. As the effects of different dredging and disposal protocols vary strongly between the main, side and chute channels, these scales should ideally be examined separately. This study examines the long-term effects of dredging and disposal with the use of a Channel Network Extraction Tool, making it possible to distinguish the effects on different channel scales. A channel network describes the channel pathways in the river system and indicates the different channel scales. In the networks, channels are divided into three scales; the main channel, the side channels and the chute channels. The main ebb channel has a large proportion of the total flow, it is used for shipping and dredged intensively (Dam et al., 2015). The side channels branch off the main channel and flow alongside this channel. The chute channels are shallow & short channels that link the main and side channels by cutting through the sub- and intertidal areas in between these channels (Swinkels et al., 2009).

While networks are commonly generated using bathymetry or imagery as input (Hiatt et al., 2019), this study tests the novel approach of using flow fields as input for the generation of channel networks. Flow field based networks are used to assess the tidal flow conditions at each channel scale, as well as looking at the network complexity of the flow patterns. The network complexity depends on the number of channels in the network at different scales. This study uses the number of channels and number of active channels as metrics to describe network complexity. The number of channels describes the channels present in the morphology of the estuary, while the number of active channels describes the channels through which flow is occurring at a given moment. The number of active channels indicates the complexity of the flow patterns and the flow network derived from this. As mentioned before, decrease in network complexity of the multichannel system is undesirable, as this means a decrease in the ecological value of the estuary and affects the ecosystem services the Western Scheldt offers (de Vet et al., 2017).

The primary aim of this study is to provide insight into the long term effects of three dredging and disposal protocols on the flow network complexity and tidal flow conditions in the Western Scheldt estuary. The effects are compared to the morphologic impact and differentiated at a channel scale; to do this, channel networks based on bathymetry and flow fields are used. To this end, a secondary aim of this study is to compare the novel use of flow fields to bathymetry as inputs for generating channel networks using the Network Tool. The most significant finding of this study pertains to which of the examined dredging and disposal strategies has the least negative impact on the Western Scheldt estuary. The findings of this paper could aid decision-makers tasked with the creation of the dredging and disposal protocol for the estuary.

2. Literature review

This chapter provides the necessary information on the network terminology used in this study, to give an understanding of channel networks that form an essential part of the methodology in this study. It also highlights the mechanisms involving tidal asymmetry and dominance and their influence on the sediment transport. This is important as the tidal flow conditions and tidal asymmetry are examined later in this study. The chapter also explores the morphology, hydrodynamics and sediment transport patterns in the Western Scheldt, as well as the effects of dredging and disposal operations have had on this estuary. The information acquired in the literature study is used to form a base from which the research questions and hypotheses are developed.

2.1. Network terminology

In a broad sense, a network is a mathematical representation of a set of objects and connections among those objects (Hiatt et al., 2019). A channel network represents the channels in the river system and the points at which the channels merge and branch off. There are many rivers that transport all water and sediment through a single channel, like meandering rivers, but there are also more complex river systems that are made up of many different channels of various scales (Limaye, 2013). In general, there are multichannel networks that are convergent and channel networks that are divergent (Limaye, 2013). An example of convergent channel networks is a tributary stream network, where channels merge. In divergent systems channels frequently bifurcate and also confluence, as in braided rivers, deltas and estuaries (Hiatt et al., 2019). In these systems, flow often does not only follow the direction of the steepest descent. This study focuses on the Western Scheldt, an example of an estuarine multichannel system.

The type and formation of the channel system depends on the local conditions. Important factors are the sediment composition (Braat et al., 2017), the vegetation (Bij de Vaate, 2018) and the division between the tidal, wave and river influence. Multichannel systems form where there is a large supply of non-cohesive bed material and a high stream power (Braat et al., 2017; Kleinhans & van den Berg et al., 2011). Multichannel systems are dynamic and change over a range of time and spatial scales, resulting in a complex environment. Estuarine multichannel systems are shaped through competition between tidally and fluvial-driven transport and sediment composition (Hiatt et al., 2019).

In multichannel systems channels are separated by sub- and intertidal shoals of various scales (Jeuken & Wang, 2010). The positions of these bars are ever changing as the channels, especially chute channels, migrate and rework the shoals (Jeuken & Wang, 2010). The system also contains channels of various sizes and lengths. The channel with the largest proportion of the total flow is the main channel in the channel network, in the Western Scheldt the main ebb channel (Dam et al., 2015). The side channels are shallower than the main channel and branch off and flow alongside the main channel. Then lastly, there is a large number of chute channels or connecting channels, these channels link the main and side channels by cutting through the shallow sub- and intertidal areas in between (Swinkels, et al., 2009). The chute channels have the shallowest depth of all three channel categories and are formed by water level differences between the main and side channels (Swinkels et al., 2009).

Channels can be depicted in the network by the channel centerline or the thalweg (Smart, 1972). The channel centerline simply follows the middle of the channel over its length. The thalweg, nowadays more commonly used, represents the path with the lowest elevation along the channel length. The latter pathway is used in the channel networks based on bathymetry in this study. The most common input for channel networks are bathymetry and imagery (Hiatt et al., 2019). In addition to bathymetry, this study tests the novel approach of using flow fields as input. The use of this input is elaborated in the methodology, the effects of using this input on the resulting network is examined as part of the results of this study. When analyzing a multichannel network, a threshold can be used for the channels to limit the amount of detail in the channel network (Smart, 1972). This threshold can be based on a minimum discharge, a minimum depth, or, as is the case in the Network Extraction Tool, a minimum difference between channels.

Channel networks can be used to establish the network complexity and to derive the conditions within channels in terms of depth, flow velocity and water level. The network complexity depends on the number of channels in the network at different scales. An often-used metric to describe the complexity is the Braiding Index, which describes the number of channels per cross-section, averaged for the entire study area (Marra et al., 2014). The number of channels at each scale or the sum of all scales can also be used to describe network complexity. The number of channels describes the channels present in the morphology of the estuary, while the number of active channels describes the channels through which flow is occurring at a given moment. The latter is derived from the flow field based network and is a measure for the complexity of the flow network.

2.2. Tidal asymmetry and dominance

Dredging and disposal affects tidal flows and can change the division of flood and ebb asymmetry in the estuary (Bolle et al., 2010). This study looks at the changes in tidal asymmetry and its consequences on sediment transport with different dredging and disposal protocols. In this section, the concepts of tidal asymmetry and tidal dominance are described, which are referred to throughout the thesis.

The channel network of an estuary is strongly influenced by the interaction between tidal and fluvial sediment transport and the sediment composition in the estuary. Small differences between ebb and flood tidal velocities can strongly affect the sediment transport and estuary development (Brown & Davies, 2010). Within channels and estuaries there is both an ebb and a flood flow occurring; the residual of the opposing ebb and flood flow is what characterises the channel. If, for example, the flood tide has the highest tidal velocity, the channel is flood asymmetric. In this sense, flood asymmetry is used to describe a situation where the peak flood velocities are higher than the peak ebb velocities. Conversely, the channel or estuary as a whole can be ebb asymmetric.

The tidal dominance can be determined by combination of peak tidal ebb and flood velocity and tidal period between flow reversal. For instance, when the ebb tide has both a longer duration and magnitude of the tidal velocity, the estuary is ebb dominated and sediment will be transported out of the estuary (Brown & Davies, 2010). The opposite also holds for flood dominance. To characterize the dominant direction of net sediment transport there are two ratios; the peak velocity ratio and the tidal duration ratio (Brown & Davies, 2010). The former will be explained in more detail in the methodology section.

When an estuary is flood asymmetric it does not always function as a sediment sink, there can still be ebb dominant net transport. This happens when the ebb flow is enhanced by channel constraints, which often occurs in estuaries with a dynamic channel-sandflat system (Brown & Davies, 2010). If the ebb flow is enhanced, the ebb duration is longer than the flood duration, resulting in ebb directed sediment transport. The estuary under these conditions is a sediment source, even though there is flood asymmetry (Brown & Davies, 2010). Tidal asymmetry therefore only indicates, but does not give conclusive evidence of the direction of the net sediment transport. To establish this, it needs to be combined with the tidal duration, as this can be used to calculate the actual volume of sediment transported during the tidal flow. While the tidal duration is not examined in this study, Brown & Davies (2010) conclude that bottom friction promotes longer tidal flood duration, while build-up of sandflats promotes tidal ebb duration.

2.3. The Western Scheldt Estuary

The Western Scheldt estuary is located in the southwest of the Netherlands and north of Belgium (figure 2). The Dutch part of the Scheldt estuary, which is the focus area of this study, is 60 km long (figure 2; rectangular box). The Belgian part is 100 km long and much narrower (de Vriend et al., 2011). The Western Scheldt estuary was chosen due to the high availability of data on the dredging and disposal strategies (used as input for the Delft3D model), and the existence of the high resolution NeVla-model. The Western Scheldt has been, and continuous to be, heavily influenced by humans, just like numerous other estuaries around the world. This threatens the ecological values and biodiversity of the estuary. Examining different dredging and disposal strategies, to choose the least impactful strategy for this estuary, can help reduce the negative impact of humans on this system.

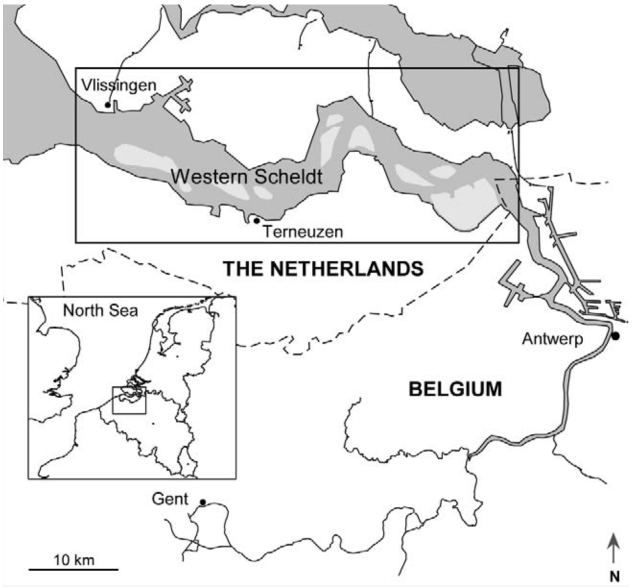


Figure 2. The Western Scheldt estuary (Modified from Swinkels et al., 2009).

2.3.1. Morphological setting

The Western Scheldt is a tide dominated, well-mixed estuary covering an area of approximately 300 km^2 (Swinkels et al., 2009). The estuary can be characterized as a multi-channel system, meaning that it consists of a main and side channel separated by subtidal and intertidal shoals, linked by connecting or chute channels (van den Berg et al., 1996; Jeuken & Wang, 2010; figure 3). The estuary shows a repetitive pattern of mutually evasive meandering ebb channels and straight flood channels (Wang et al., 2015). Bars can be found seaward of the ebb channels and landward of the flood channels (Bolle et al., 2010). The funnel shaped estuary is 6 km wide at its mouth reducing to a width of 100 m near the tidal limit 160 km upstream (Swinkels et al., 2009). The width-averaged depth decreases from 15 m at Vlissingen to only 3 m near Gent (Bolle et al., 2010). Since mid-20th century there has been an overall change in morphology with the irregular distribution of intertidal flats with branching channels and shallow areas transforming into smoother tidal flats between the main ebb and flood channels (Cleveringa & Taal, 2015). A general steepening of the bathymetry has been taking place since 1955, indicated by the increased area of intertidal shoals and decreased sub-tidal area (Bolle et al., 2010). These intertidal areas have also been increasing in elevation (Cleveringa, 2013).

2.3.2. Sediment transport and budget

The sediment in the estuary consists mainly of sand, with some mud present in intertidal areas (de Vriend et al., 2011). Sediment import is twice the amount required to balance SLR, which is the result of closure of the Zuiderzee and Lauwerszee (Wang et al., 2015). This excess of sediment has contributed to the formation of the characteristic multichannel system of the Western Scheldt (Cox, 2018). At present, the sediment balance in the Western Scheldt is strongly influenced by sand mining, and the import and export of sediment at the mouth of the estuary, the fluvial sediment input being negligible (Wang et al., 2015). The import of sediment is similar to the amount removed by sand mining (Wang et al., 2015). Since 1990 the mouth of the Western Scheldt estuary began to export sediment rather than import it, this is thought to be related to exceeding a critical threshold depth of the estuary (Bolle et al., 2010; Wang et al., 2015).

The highest amount of sand transport takes place in the main ebb and flood channels (Bolle et al., 2010). Based on the sediment circulation, the Western Scheldt can be divided into a chain of six morphological macro-cells (figure 3). A macro-cell consists of a shallow area fully enclosed by the main channels (Winterwerp et al., 2001). The sediment circulation within the cell is caused by flow asymmetry. Due to the difference in flow asymmetry, the main ebb channel has the tendency to silt up due to dredging, while the main flood channels have eroded (Jeuken, 2000).

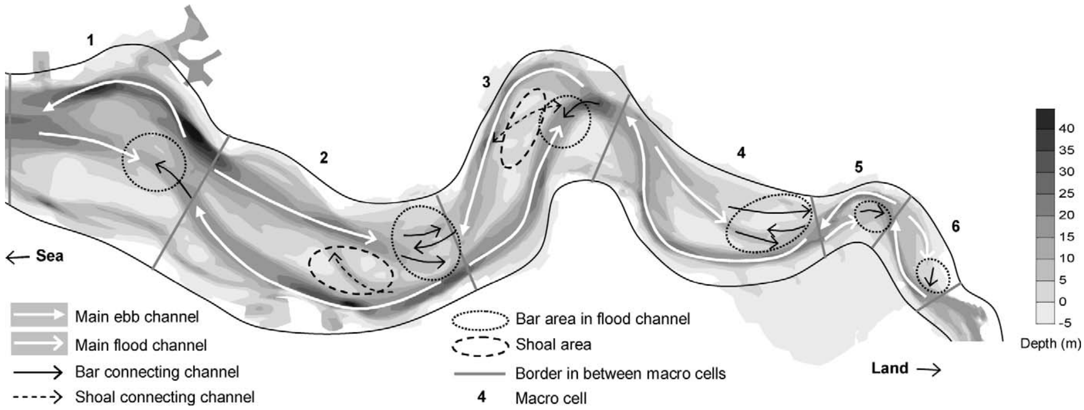


Figure 3. Channel types and bar areas in the macro-cells in the Western Scheldt with underlay of the 2002 bathymetry (Swinkels et al., 2009).

2.3.3. Hydrodynamics and tidal influence

The tide in the Western Scheldt is dominantly semi-diurnal (Bolle et al., 2010). The neap-spring tidal cycle is 14.8 days (van Rijn, 2010). The estuary consists of a dominant and meandering ebb channel and straight flood channels that cross-cut these meanders (van den Berg et al., 1996). This pattern is the result of flow divergence from the flood channels onto the shallower shoals (van den Berg et al., 1996). Flood channels in the Western Scheldt are shallow, while the ebb channels are deeper (Swinkels et al., 2009). A difference that is enhanced by dredging and disposal. The tidal wave is amplified as it travels up the estuary with the tidal range varying from 3.8 m to 5.2 m 80 km upstream (Swinkels et al., 2009). The tidal wave has a period of 12 hours and 25 minutes in most places of the estuary (van Rijn, 2010). The mean river discharge of the Scheldt River is approximately 120 m^3/s, which is less than 1% of the tidal prism of about $2x10^9$ m^3 (Bolle et al., 2010; Swinkels et al., 2009; de Vriend et al., 2011). Thus, the river influence is weak and the fluvial sediment input is small (Swinkels et al., 2009; de Vriend et al., 2011).

The maximum depth-averaged current velocities in the channels are between 1-1.5 m/s (Bolle et al., 2010). The asymmetry of the vertical and horizontal tides changed measurably between 1970 and 2002 (Bolle et al., 2010). The largest change took place in the eastern part of the Western Scheldt, these changes were accompanied by a deepening of the flood and ebb channels due to the dredging (Bolle et al., 2010). The morphologic evolution of connecting channels is primarily driven by differences in tidal wave propagation along two neighbouring main channels (Swinkels et al., 2009). Centrifugal and Coriolis forces are relatively constant over time & do not cause significant water level differences (Swinkels et al., 2009).

2.3.4. A history of dredging and disposal

Dredging operations started around 1920 to provide an access route to the various ports along the estuary (Swinkels et al., 2009). The changes in bathymetry since 1970 are in most cases due to the dredging, disposal and sand mining that took place throughout the estuary (Bolle et al., 2010). The disposal of sediment led to a reduction in channel depth and can induce erosion in the opposite channel, while the dredging and sand mining caused a deepening of the bathymetry. During the 1970s the channels were deepened from 12 m to 14.5 m, which increased to 16 m around 1997 (de Vriend et al., 2011). In 2010 channels were deepened with an additional 1.2 m (de Vet et al., 2017). The most commonly dredged areas in the channels are the sills (Cox, 2018). These are shallow areas at the transition between channel bends or crossings (Cox, 2018). Especially in the eastern part of the estuary there are a number of heavily dredged sills (Swinkels et al., 2009). In volume, the amount of sediment displaced by dredging and disposal has increased from 0.5 Mm^3/year in 1950 to over 15 Mm^3/year in 1975 (Wang & Winterwerp, 2001).

Over time ebb channels have been deepened in particular, as these are generally designated for navigation due to flow concentration in these channels (Dam et al., 2015). Disposal locations of the dredged sediment from these ebb channels have changed over time. At first, the sediment was generally disposed of in shallow side or flood channels close to the dredging sites, in order to not remove it from the system entirely (Swinkels et al., 2009; Wang & Winterwerp, 2001; Mow, 2013). In the 90's the East-West strategy was developed, where the dredged material from the east was disposed of in the west. The idea was that the sediment disposed in the west would remobilize and spread more evenly within the system (Mow, 2013).

In 2010 flexible disposal was implemented as a way to preserve the multichannel system of the Western Scheldt, improve the ecological quality of the estuary and preserve the ecosystem services the Western Scheldt offers (Depreiter et al., 2012). In practice this means that sediment is disposed of in scours in the main channel on subtidal shoals, besides the disposal in side channels (Depreiter et al., 2012; van der Wal et al., 2011). One of the main concerns is that intensive & prolonged dredging and disposal can destabilize the multi-channel system, resulting in a single channel system (Wang & Winterwerp, 2001). This would take place when the threshold of around 10% of the total transport capacity of a macro cell in the estuary is exceeded (Wang & Winterwerp, 2001). Implementation of the flexible disposal strategy has as one of its main goals to prevent this transition. Still, there is concern regarding the sustainability of the current dredging strategy (van Dijk et al., 2019b).

2.3.5. Impacts of dredging and disposal

Overall, dredging and disposal operations have had extensive effects on the estuary, varying from small scale and short-term effects to planform scale and long-term effects (Cox, 2018). Many of these effects are part of feedback mechanisms, which are not always fully understood. For example, changes in morphology due to dredging and disposal affect the hydrodynamics, which alters the sediment transport patterns. This forms a dynamic feedback mechanism, as it in turn shapes the morphology of the estuary. One of these changes in morphology is the deepening of the main channels caused by dredging and shallowing of the locations where the sediment is disposed of (van Dijk et al., 2019b). Depending on the dredging and disposal strategy, this can result in a loss of shallow water areas, an increase in elevation of intertidal shoals and a reduction of chute channels (Jeuken & Wang, 2010; Swinkels et al., 2009). Analysis of the bathymetries between 1955 and 2015 indicates a deepening of the main channel, especially the outer bends, infilling of the side channels and accumulation of sediment of the shoals (Cox, 2018). Especially shoals seaward tended to grow, while those landward tended to erode (Cox, 2018).

In areas where a high amount of sediment is dredged and little is disposed of, sedimentation is high and the transport occurs towards these areas (Bolle et al., 2010). As a result, the sediment budget per macro-cell has been changed significantly by dredging and disposal, with the outer and inner cells experiencing erosion, while the middle cells area experiencing an increase in sediment import (Wang et al., 2002). Until recently the dredged material was disposed of in or at the entrance of side channels, but calculations from a stability analysis showed that this practice can destabilize the multi-channel estuarine system (Wang & Winterwerp, 2001; van der Wal et al., 2011). The threshold for this is 10% of the total transport capacity of a macro cell in the estuary (Wang & Winterwerp, 2001). An experiment by van der Wal et al. (2011) showed that disposal of sand seawards of eroding tidal flats helps maintain the multi-channel system, although they were not able to prove that this measure can add ecologically productive shallow water habitat. Still, the measure did achieve morphological success by increasing the area of shallow subtidal and intertidal area.

Besides deepening, dredging also smoothens the bathymetry, which causes a reduction of friction and in turn results in a higher velocity of tidal propagation (Nichols, 2018). As only the main ebb channel is being dredged in the Western Scheldt (Dam et al., 2015), the bottom friction in this channel is decreasing. On the other hand, friction in the side channels could be increasing, as these channels experience infilling when used for disposal (Cox, 2018). This could result in a higher tidal propagation in the main channel and a lower propagation in the side and chute channels (Nichols, 2018). Besides affecting tidal propagation, dredging can also amplify the tidal wave and alter the tidal asymmetry (Bolle et al., 2010). Dredging alters the tidal duration, tidal asymmetry and peak discharges in the estuary (Nichols, 2018). Especially the dredging of the sills at the end of ebb and flood channels changes the flow dynamics within these channels (Bolle et al., 2010; Swinkels et al., 2009). Small changes in the tidal flows can alter the sediment transport and in turn the morphology (Brown & Davies, 2010).

Over time, dredging and disposal can reduce the number of chute channels in the estuary (Swinkels et al., 2009). The temporal evolution of chute channels is primarily driven net water level differences, caused by differences in tidal wave propagation along the main channel and principal side channel (van den Berg et al., 1996; Swinkels et al., 2009). However, the change in tidal wave propagation with dredging and disposal is decreasing the difference in net water level between neighbouring channels (Swinkels et al., 2009). The linear relation between connecting channel dimensions and net water level differences suggests that the chute channel dimensions will decrease as a consequence (Swinkels et al., 2009). This correlation would mean that dredging operations could significantly affect evolution of chute channels by altering the depth ratio between the two main channels and inducing a decline in size or reduction in number of chute channels (Swinkels et al., 2009).

3. Research Questions and Development of Hypotheses

Currently, there is a relatively good understanding of the short term effects of dredging and disposal strategies, but less is known about the long term effects, especially regarding newer strategies such as flexible disposal and main channel scour disposal. Additionally, more is known about the long term effects of dredging and disposal on morphology than on flow dynamics. Up until now, no comparison has been done of the impacts of of different dredging and disposal strategies on flow dynamics, which is closely related to the impacts on morphology. This study aims to fill these knowledge gaps, by looking at the effects of each dredging and disposal strategy over 40 morphologic years and focusing on tidal flow dynamics and the network complexity of the flow patterns with each scenario.

In this chapter, the present research questions and hypotheses are developed based on the literature review, additionally the reasoning behind each hypothesis is explained. The primary aim of this study is to analyze and compare the long term impacts of three different dredging and disposal strategies on the flow network complexity and tidal flow conditions in the Western Scheldt estuary. The secondary aim of this study is to qualitatively compare how using flow fields versus bathymetry as inputs to the Network Tool changes the output channel networks. To achieve these aims, the research addresses three questions related to the impacts of different dredging and disposal strategies and one initial question to explore the novel methodology used in this study.

The first question examines the novel approach of producing channel networks with a flow field as input. It compares the flow field based channel networks to the more common bathymetry based networks, to understand the differences and similarities between them. Secondly, the change complexity of the flow network with each of the dredging and disposal strategies is assessed, as literature study indicated that a decrease in network complexity due to dredging and disposal was a major concern for the Western Scheldt. Third, an analysis of the tidal flow conditions, including the changes in average flow and flow patterns at different channel scales, is done. Lastly, data on peak flows, water levels and tidal range is combined to provide an assessment of the change in tidal dominance and asymmetry.

Q1) What is the effect of using flow fields versus bathymetry as input on the resulting channel networks?

The bathymetry based channel network describes all the channels present in the estuary, while the flow field based network gives the channels through which flow is occurring at that moment. Thus, the number of channels through which flow is occurring should be equal or lower to the number of channels present in the estuary. The hypothesis tested is: **The active channel number in the flow field based network is lower than the channel number in the bathymetry based network (Hypothesis 1).** Confirmation of this hypothesis indicates that flow field based channel networks are realistic.

Besides this, the length of the model run can influence the number of channels in the estuary. If this is the case, the channel number at the end can be much higher than the channel number at the beginning. This development is not necessarily realistic, therefore the second hypothesis examines what the difference at the beginning and end of the model run is to establish whether this model error is occurring. The hypothesis is: **The channel numbers after 40 morphologic years are of similar magnitude to the channel numbers at 0 morphologic years (Hypothesis 2).**

Channels in the flow field based networks shift over short timescales, while channels in bathymetry based networks are more static, only changing with morphologic change. The amount of shifting in both networks and the drivers behind the main channel shifting in the flow field based networks are examined as part of this section. The main channel shifting could be influenced by the velocity of the flood or ebb flow, with higher velocities resulting in larger amounts of main channel shifting. Then, **the degree of main channel shifting is significantly higher during flood than during ebb (Hypothesis 3).** In addition, a large tidal amplitude and thus a larger amount of water flowing through the estuary at higher velocities, could be a driver behind the main channel shifting in the network. Hypothesis 4 examines whether this is the case or not, by establishing whether **the degree of main channel shifting is correlated with the tidal range (Hypothesis 4).**

In addition to comparing the main channel shifting, the main channel velocity in both networks is compared too. It is expected that the flow velocity is higher in the flow field based networks, as the channel lines describe the highest velocity pathways. However, this hypothesis checks whether the flow velocity in the main channel in the bathymetry based channel network is equal to the flow field based channel network at locations where the main channel does not shift much. The hypothesis is that **the main channel velocity using bathymetry based networks is equal to the main channel velocity using flow field based networks when there is a low amount of main channel shifting in the flow field based networks (Hypothesis 5)**. At locations with high amount of main channel shifting in the flow field based networks, it is expected that the flow velocity is underestimated by the bathymetry based network.

Q2) What is the effect of dredging and disposal strategies on the complexity of the multichannel system of the Western Scheldt?

The active channel number in the flow field based networks are highly variable as a result of the tidal dynamics in the estuary. This hypothesis examines the influence of the water level on the active channel number, by establishing whether **the number of active side and chute channels is correlated with the tidally generated water level fluctuations (Hypothesis 6).**

A high active chute channels number can be an indicator of a complex and dynamic system. On the other hand, a decrease in the mean active channel number indicates a decrease in network complexity and a less dynamic system. A similar argument can be made for the number of side channels. Therefore, the following hypotheses are tested: **the mean number of active chute channels is reduced as a result of dredging and disposal (Hypothesis 7) & the mean number of active side channels is reduced as a result of dredging and disposal (Hypothesis 8).** Previous research found that especially the number of chute channels is affected by dredging, by reducing the water level differences between the channels (Swinkels et al., 2009). These hypotheses test whether this decrease in the active channel number occurs with each of the dredging and disposal protocols.

Besides a decrease in the active channel number, the variability in active channel number can also be a valuable indicator to establish whether there is a change in dynamics in the system. If this is the case, then **there is a lower range in the number of active channels with dredging and disposal (Hypothesis 9).** A lower range indicates less variability, thus would indicate a less dynamic system. However, the range gives no indication on the network complexity of the estuary, as it does not show the actual channel numbers.

Q3) What is the effect of the dredging and disposal protocols on the flow conditions in channels at different scales?

Dredging of the main channel is reduces bottom friction and increases the ease with which water flows through the channel (Nichols, 2018). Therefore, **dredging and disposal increases the average flow velocity in and along the length of the main channel (Hypothesis 10).** On the other hand, in areas where a high amount of sediment is dredged and little is disposed, sedimentation is high and the transport occurs towards these areas (Bolle et al., 2010). This could also be the case in the main channel, perhaps causing a decrease in flow velocity in parts of the main channel where high sedimentation is occurring.

At the same time, dredging and disposal causes infilling of the side channels, especially when used for disposal (Cox, 2018). Sedimentation can increase bottom friction (Nichols, 2018). Therefore, the expectation is that: **disposal in side channels decreases the average flow velocity (Hypothesis 11).** The chute channels could also be experiencing a reduction in flow velocity, possibly also by increased sedimentation or by a reduction in the net water levels reducing the flow gradient, but so far research has focused on the changes in the number of chute channels. So in this study, it is tested whether **dredging and disposal reduces the average flow velocity in the chute channels (Hypothesis 12).**

Q4) What is the effect of different dredging and disposal strategies on the tidal dominance of the estuary?

Dredging and disposal changes the peak flows, tidal propagation, tidal duration and tidal asymmetry (Nichols, 2018; Bolle et al., 2010). The tidal flows and changes therein affect the sediment transport processes (Brown & Davies, 2010). Therefore, this question looks at the changes in tidal flows and their meaning for sediment transport. It examines the peak flood velocity and the peak ebb velocity, throughout the estuary, but also at a channel scale. It examines whether **there is spatial variation in the effect of dredging and disposal on the average peak ebb and flood velocity (Hypothesis 13).** It also looks at the change in magnitude of the peak velocities at each channel scale with dredging and disposal, to establish whether **there is channel scale variation in the effect of dredging and disposal on the average peak ebb and flood velocity (Hypothesis 14).** Moreover, if **the difference in peak ebb and flood velocity between the main channel, versus side and chute channels increases (Hypothesis 15),** this could indicate changes in tidal wave propagation.

Earlier studies already established that the tidal wave is amplified in the Western Scheldt (Savenije, 2006) and that there is an increase in tidal range with dredging (Cox, 2018). If the tidal range increases in the upstream direction, then the tidal wave is amplified (Savenije, 2006). This study examines the change in tidal amplification with each of the three strategies or whether there is a strategy that has a lesser effect than the other scenarios. The hypothesis is that **dredging and disposal amplifies the tidal wave in the main channel with each of the dredging and disposal strategies (Hypothesis 16).**

Previous research has established a tendency towards ebb asymmetry in the Western Scheldt with channel deepening (Bolle et al., 2010), as well as in a scaled dredging and disposal experiment (Cox, 2018). This study examines whether this is the case with each of the three strategies or whether there is a strategy that has a lesser effect than the other scenarios. The corresponding hypothesis is: **there is an increase in ebb asymmetry and decrease in flood asymmetry with each of the dredging and disposal strategies (Hypothesis 17).**

4. Methodology

This chapter provides a description of the scenarios in Delft3D that were used to model the flow fields and bathymetry. By modelling the four scenarios in Delft3D over a long timescale, the long term impact of each dredging and disposal scenario can be quantified. The modelled data is used as input for the Network Extraction Tool, which generate channel networks using both bathymetry and flow fields. The channel networks make it possible to analyze the effects of dredging and disposal at a channel scale and are also used to compare the tidal flow dynamics to the elevation based channel network. The workings of the Network Tool and the implications of using different inputs are discussed to explain the meaning of different channel networks. After the channel network generation, analysis is done for different metrics to test each of the hypotheses. The metrics are used to assess the change in tidal flow dynamics and to compare the three dredging and disposal protocols. The last section describes which metrics are used and for which purpose, and explains how each metric is calculated.

4.1. Data collection

In order to assess the impact of dredging and disposal operations this study uses three different dredging and disposal protocols (table 1; figure 4). The study uses and compares channel networks for each scenario after 40 morphologic implementation years, as well as the network at 0 morphologic years, which forms the starting of all scenarios. With this approach the effects of each dredging and disposal protocol can be distinguished, but it also makes it possible to look at the impact of long term implementation for each scenario. The scenarios were all modelled in Delft3D for the 40-year period. Scenario A is the baseline or control run, no dredging or disposal takes place in this scenario. Scenario B includes disposal on shoals, in the side channels and in the main channel scours. Scours are deeper sections in the channel caused by erosion. Shoals are sand bars in between channels. Scenario B is equal to the currently implemented flexible disposal. Scenario B includes disposal in the side channels and the main channel scours. Scenario D only includes disposal in the main channel scours. Besides the locations of disposal differing between the scenarios (table 1; figure 4b), the volume of dredged and disposed material also differs per scenario (Figure 4a).

Scenario \ Disposal locations	Shoals	Side channels	Main channel scours
A			
B			
C			
D			

Table 1. The four scenarios with the different disposal locations used per scenario.

4.1.1. Scenario A: Baseline

Scenario A is used as the baseline to which the other scenarios are compared. In this scenario no dredging or disposal takes place over the course of 40 years. This situation is not an entirely realistic scenario, as dredging will always continue in order to keep the estuary accessible for shipping. As the economic importance of the shipping industry is too high to stop dredging altogether. As the Western Scheldt estuary has been influenced by humans for centuries, this scenario still does not represent a natural state of an estuary. Still, sediment transport patterns – sedimentation and erosion – have not been altered for a period of 40 years, resulting in a relatively unrestricted channel migration during this period.

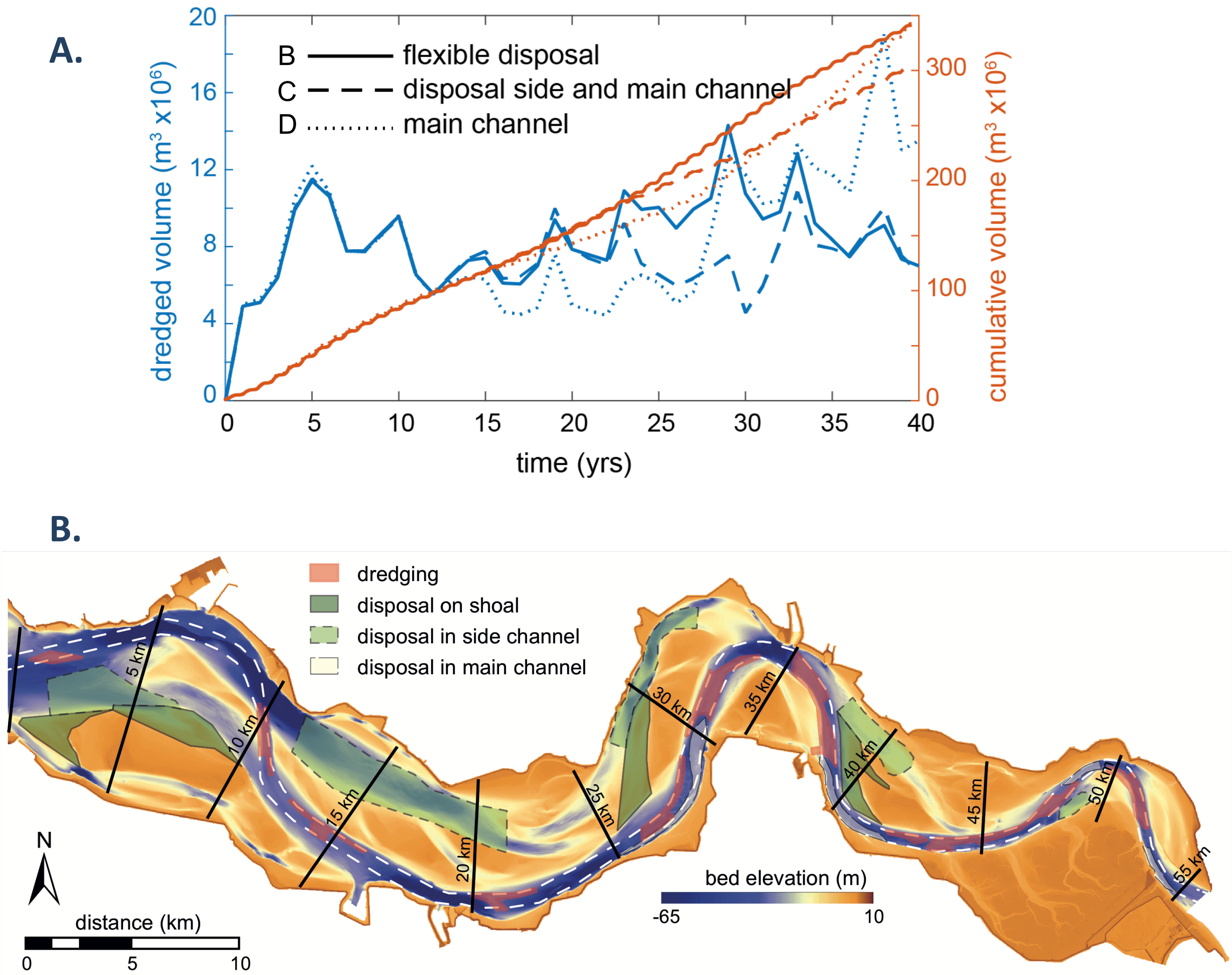


Figure 4. (A) The volume (left axis) and cumulative volume (right axis) of sediment dredged per scenario over the course of the 40-year model runs from 2015 to 2055 (Adapted from van Dijk et al., 2019b). (B) The locations that are dredged in the main channel in each of the scenarios & the locations used for disposal. In scenario B all three disposal locations are used, scenario C uses the main and side disposal locations and scenario D only uses disposal locations in the main channel (Figure from van Dijk et al., 2019b).

4.1.2. Scenario B: Flexible disposal

Disposal in side channels, on shoals and in main channel scours

Flexible disposal is a strategy currently implemented in the Western Scheldt. The aim of this strategy is to create ecologically valuable habitat & preserve the multichannel system, while at the same time facilitating shipping (Depreiter et al., 2012). The exact locations used for disposal in reality and the amount that is disposed can differ to a degree, as the flexibility means the disposal locations can be changed based on monitoring. Still, Scenario B is a good approximation of the current protocol. It is the most extensive dredging and disposal protocol, with the largest volume of dredged sediment almost all years and steepest increase in cumulative volume (figure 4a). Disposal takes place in side channels, on shoals and in the scours of the main channel (figure 4b). Scenario B is the only scenario in which disposal on shoals takes place, which is done in an attempt to increase the elevation of the shoals and thus increase the size of the intertidal area (de Vriend et al., 2011). By increasing the intertidal area, the ecological value of the estuary is increased, although the effectiveness of this remains uncertain (van der Wal et al., 2011). The disposal of sediment seawards of eroding tidal flats has been proven to help maintain the multi-channel system (van der Wal et al., 2011).

4.1.3. Scenario C: Disposal in side channels and main channel scours

In this scenario the sediment is disposed of in the side channels and in the scours of main channels (figure 4b). Scenario C has a lower cumulative volume of dredged sediment after the 40-year period than the other two scenarios (figure 4a). Disposal in side channels – often done at the entry point of these channels due to practical reasons – can cause a strong reduction of flow velocity in these channels and result in infilling of the side channel (Swinkels et al., 2009; van der Wal et al., 2011). The idea behind it was that the sediment in the side channels would be redistributed in such a way that would keep the main and side and chute channels in balance (Taal, 2012). Disposal in side channels was the main disposal protocol before the implementation of the flexible disposal strategy in 2010 (Roose et al., 2008).

4.1.4. Scenario D: Disposal in main channel scours

In Scenario D disposal only takes place in the scours of the main channel (figure 4b). The cumulative amount of dredged sediment is lower than the other two protocols between 15 and 30 years, but at the end of the scenario run has the same cumulative volume as scenario B (figure 4a). Scours are deep sections in the channel, formed in locations with increased sediment erosion. While disposal only in the main channel is thought to have a lower impact, the disposed sediment in the scours is easily entrained and removed again. After entrainment, it is deposited in locations with lower flow velocity, possibly again requiring dredging. So while this is a strategy with a possible lower impact, high frequency dredging (maintenance dredging) would still be required. Large amounts of sediment disposed of in one concentrated location in a small scour seems to be the most stable and least likely to mobilize, but further research is needed to prove whether this effect is significant (Depreiter et al., 2012; Cox, 2018). On the other hand, in theory, this strategy would ideally affect the evolution of the channels less and would lower the loss in ecological value.

4.1.1. Bathymetry Data: Digital Elevation Model

The DEM (Digital Elevation Model) of the Western Scheldt was generated by Rijkswaterstaat; the Ministry of Water & Infrastructure, and is publicly available. The DEM of 2015 was used as input for the initial Delft3D model runs. As such all scenarios have the same starting point, but the bathymetries of 2055 used to generate the flow fields significantly differ per scenario. The resolution of the initial DEM is 20 meters and the study area includes the entire Dutch part of the estuary.

4.1.2. Delft3D Modelling

Delft3D is a numerical, depth-averaged model that simulates hydrodynamic processes, sediment transport and morphological change (Deltares, 2014). The model solves equations for 3-dimensional unsteady flow and transport phenomena derived from the Navier-Stokes equations for incompressible free surface flow (Deltares, 2014). In this study, the runs were computed using a 2D-depth averaged, nonlinear, shallow water equations (van Dijk et al., 2019b). A nested model (same as van Dijk et al., 2019a) of the NeVla-Delft3D model is used in this study to distinguish the effects of dredging and disposal on the flow dynamics of the Western Scheldt. The nested model has a curvilinear grid, which is converted to a Cartesian grid for analysis. At the boundaries, fluvial discharge (landwards) and tidal influence through water level variations (seaward) is prescribed. The tidal flow boundary conditions incorporate the spring and neap tidal cycle.

The model runs for this study produce four series of flow fields based on the bathymetry of each scenario after 40 years of morphological development (for bathymetry per scenario, see Appendix A.1.). The flow fields were run for a period of a month, including two spring-neap tidal cycles, with an interval of 10 minutes. As a result, a comparison of the flow fields from each scenario provides an assessment of the long-term impact of the three different dredging and disposal protocols examined here. This impact can be differentiated from the development the estuary would go through without dredging and disposal operations with the use of the baseline scenario.

4.2. The Network Tool

Analysis with the Network Extraction Tool was done for the final bathymetry and a series of flow fields that were modelled using the final bathymetry for each scenario. Channel networks provide the opportunity to differentiate the impact per channel scale. In this case, the channels in the networks are subdivided into three scales: the main channel, the side channels and the chute channels. Below the workings of the Network Tool are explained, as well as the use of different inputs, followed by a description of the process to generate channel networks.

4.2.1. Theoretical background

Creating channel networks in systems that frequently bifurcate, such as the Western Scheldt estuary, has long been a challenge. In multichannel estuaries like the Western Scheldt, channels both split and merge and the flow does not only go in the direction of the steepest descent. The Network tool, first introduced by Kleinhans et al. (2017), effectively generates channel networks in both multi- and single channel systems based on DEM's and imagery. Whereas most fluvial network analysis tools follow the most descending pathway, as long as no bars are encountered, this tool computes the lowest path from source to sink, even if the topography is not only descending (Vlaming, 2018). In this study the tool will be applied for the first time to flow fields, as well as water level grids. More information on these applications is given in the sections below.

The network is constructed by calculating lowest paths or flow paths through the input grid. This is the lowest elevation in a DEM or bathymetry, but the highest velocity in a flow field. The paths are calculated with the use of a descending quasi Morse-Smale complex (Kleinhans et al., 2017). This complex describes the structural elements of the grid, such as local maxima, minima and saddle points (Kleinhans et al., 2017; Hiatt et al., 2019). Saddle points are the local minimum in one direction, while being the local maximum in the other. The path that goes from a saddle point to local minima is called a Morse-Smale edge and describes the lowest path.

As a measure of difference between the channels a function is used, which describes a volume based on the input variable that is separating the channels. The volume is calculated using the highest saddle point on the path that is being connected to another path (van Dijk et al., 2019b). The current version of the Network Tool sums the volumes of each individual path, while a previous version of the Network tool used by Hiatt et al. (2019) summed the volumes of several independent paths. The tool calculates unidirectional flow based only on the input variable with no underlying hydrologic principles (Kleinhans et al., 2017; Vlaming, 2018). Therefore, the lowest paths - the lines that represent the channels - do not necessarily correspond to the fluid flow direction.

4.2.2. Application to bathymetry, flow fields and water levels

Up until now, the Network tool has been used to represent topology and geometry in channel systems. By using flow fields as input, the channel network is created based on solely the flow dynamics and not the topology of the system. A similar argument can be made for the water level channel networks. To generate realistic channel networks a threshold scale value can be set for the function that describes the difference between the channels, which has until now been named the 'sand function'. The threshold scale indicates the minimum amount of volume of the input variable that is separating the channels. Lowering the threshold value would result in more paths being sufficiently different; the total channel number would increase.

When using bathymetry as input, the threshold scale indicates a volume of sediment, which is a representation of the amount of work required to cut through the bar and merge the channels (van Dijk et al., 2019b). For the bathymetry based networks of the Western Scheldt estuary, the threshold was set to 10.000 m^3 of sand. For the flow field based networks, the sand function takes on a different meaning. It describes the volume of flow or discharge between flow paths. The threshold scale for the flow field networks was lowered as the magnitude of the bathymetry levels is higher than the magnitude of the flow velocities. A threshold of 1000 m^3/s of water was chosen as the minimum amount of water separating two high velocity paths.

The lowest paths from source to sink that are calculated by the Network Tool are termed flow paths in this study, when used in relation to flow field based networks. The lowest path follows the lowest elevation (or highest depth) in the bathymetry, while the flow path indicates the highest velocity in a flow field. The Network Tool follows the highest velocity path by converting the positive flow field values to negative values of the same magnitude. The flow field based network describes all high velocity flow paths, which represent the active channels in the estuary; the channels through which flow is occurring at a certain point in time. The flow fields do not provide information on the direction of flow, and under the influence of the tide the channel flow could be going in multiple directions at the same time. The bathymetry based network displays all channels present in the estuary based on the elevation. The channel network line in the bathymetry based network is equal to the river thalweg, which is defined as the deepest part of a continuous channel. This is not usually the channel centerline, but has a more sinuous shape as it follows the deeper pools in the outer bends.

The use of water levels as input was only briefly examined. While low water level networks generate networks similar to bathymetry, as higher water levels occur in the channels, water levels at HW (high water), do not generate realistic networks due to the flatness of the water surface in this particular estuary. A significant difference is that the topographic and velocity networks describe the path along which the water is expected to accumulate. However, when using water levels, the network describes the path were the water is the highest, but there will be no flow towards that point, but rather the water will flow away from the high water point to a low water point. The lack of information on flow direction and the exclusion of any fluid flow principles make the information that can be acquired from the water level networks questionable. As such, these were not analysed, but it should be noted that the Network Tool can be applied to water level grids.

Overall, the Network Tool provides a good method to generate flow networks, making it possible to efficiently analyze tidal flow dynamics at a channel scale. Using flow fields as input results in highly variable channel networks that follow the variability in flow patterns. As such, flow field based channel networks are useful for analyzing short term variations in flow dynamics.

4.2.3. Channel Network generation

The Network tool was used to generate flow field based channel networks for the four scenarios used in this study, as well as for a series of flow field based networks of the present day Western Scheldt. In addition, bathymetry based networks were generated for 2015 and for each of the scenarios in 2055. The flow field based networks series were for the duration of seven days in which 13 tidal cycles took place (figure 6). Close to half of one full neap-spring tidal cycle of 14.8 days (van Rijn, 2010).

Before network generation with the Network Tool the data is pre-processed in Matlab (2017a), by resampling the data to a Cartesian grid with grid cells of 50 by 50 m and converting to text files used as input. The data is masked by a boundary of the Western Scheldt. After this, the input files are run through the Network Tool in a batch file to make the operation more efficient. The output of the Network Tool is post-processed. At this stage the threshold scale is set. During post-processing the channels are divided into three scales, namely the main channel, the side channels and the cute channels. The values of the variable used as input are retrieved for each channel path and saved for later analysis. Post-processing also filters and visualizes the data, saving the channel networks as images and always creating a Matlab (2017a) structure in which multiple variables are saved for later analysis. This includes the channel scales, the coordinates, and the depth, velocity or water level values along the channel lines. The output of the Network Tool as used in this study – visualized below – consists of a main channel (yellow), side channels (orange) and chute channels (blue) (figure 5).

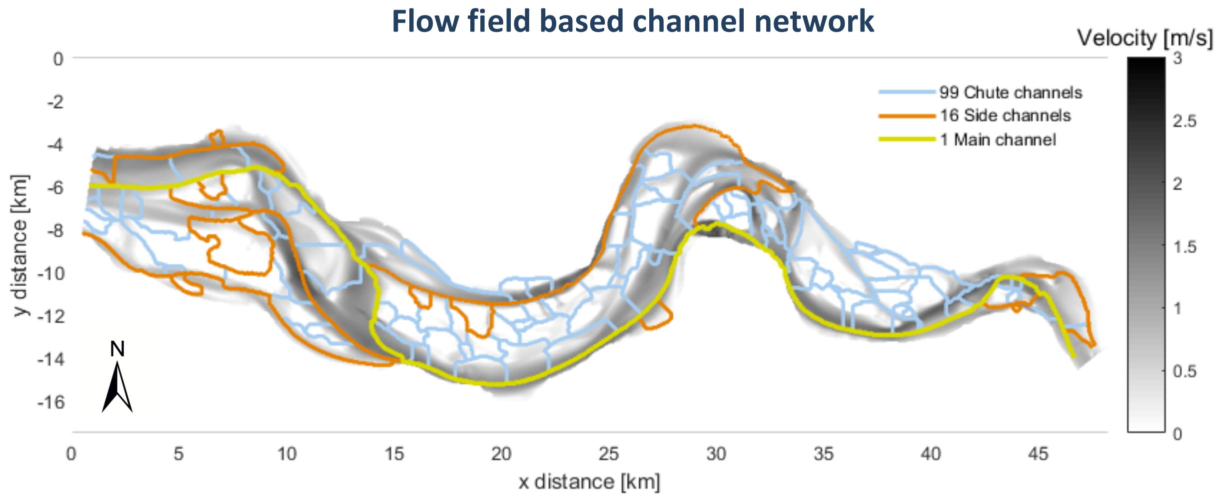


Figure 5. Flow field based channel network of scenario A (2055) generated with the Network Tool. The channels are divided into three channel scales: the main channel (yellow), the side channels (orange) and the chute channels (blue).

4.3. Data analysis: Metrics

With the use of these networks, different metrics are calculated and analysed to answer the research questions. For each channel in the network, the magnitude of a given variable can be retrieved, per cell and time step. As such the channel networks are a tool for targeted data collection. At the same time the channel number per channel scale in the network is an important variable as well. Below, the use of each variable is explained.

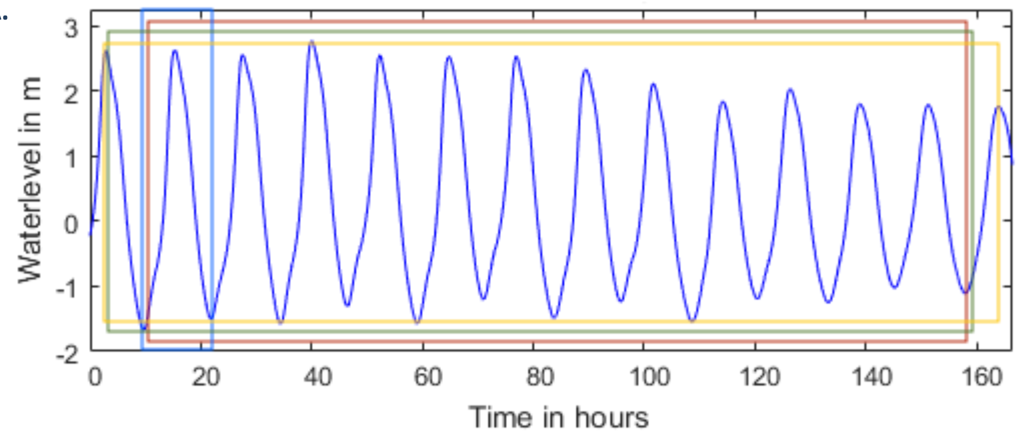
For comparison of the flow field and bathymetry based networks (Q1) the channel number, the flow velocity in the main channel and the main channel variability is used. To describe the network complexity (Q2) the active channel number is used, both the average and change over time are examined. For the analysis of the flow conditions at a channel scale (Q3), the average flow velocity is used. To examine the tidal dominance (Q4), the peak ebb and flood velocity, the peak velocity ratio and the tidal range along the main channel are used. The peak velocity ratio indicates the tidal asymmetry in the estuary.

Question one uses bathymetry based networks, as well as flow field based networks, both for scenario A only. For questions two to four only flow field based channel networks are analysed, for each scenario. Not all metrics were analysed for the same time period. Figure 6 shows the total time length for which flow field based channel networks were generated, but the analysis of metric does not necessarily account for the entire time period, so the time periods for each metric are defined in their respective sections. The estuary was divided into three shares to look at the peak velocity and the peak flow ratio, as the peak velocity moments shift along the estuary with the movement of the tidal wave (figure 7).

The analysis of the variables was done in Matlab (2017a). Multiple comparison tests were done for the number of active channels, the flow velocity and the peak flow velocity at each channel scale, the flood and ebb asymmetric area established with the peak velocity ratio and the tidal range in the main channel. A multiple comparison test determines which scenarios are significantly different from one another and which are not. This provides more information than an analysis of variance, which tests the means of several groups for the hypothesis whether they are all equal, against the hypothesis that they are not equal. A multiple comparison graph displays the means and their confidence interval, which describes the standard error around the mean.

The tidal cycles

A.



B.

	Box	Time period	Metric
Period 1		165 hours	Mean active channel number
			Mean flow velocity per channel scale
			Tidal range along main channel
Period 2		157 hours	Peak flow velocity
			Peak velocity ratio
Period 3		150 hours	Main channel variability
Period 4		12.5 hours	Flow velocity along main channel
			Active channel number pattern

Figure 6. (A) The tidal cycles for which channel networks were generated at 10 minute intervals and (B) the time periods used for analysis of the metrics.

4.3.1. (Active) Channel number

The number of channels in a channel network is a similar measure to the Braiding Index of the estuary. The number of channels is a measure of network complexity summing all channels in the estuary or all channels of a certain scale. This while the total braiding index is the number of channels per cross-section, averaged for the entire study area (Marra, et al., 2014). The channel number in a flow field based network represents the number of active channels, as these networks indicate the channels through which flow is taking place during that time step. The channel number in a bathymetry based network describes all channels present in the estuary.

It should be noted that the absolute channel number is highly influenced by the value of the threshold scale and thus is not necessarily an accurate representation of number of channels in reality. Changes of channel numbers over time provide important information on either morphologic change or changes in flow dynamics. The channel scales analyzed for channel number are the side channels and chute channels, since there is always one main channel. The second tidal cycle (figure

6: period 4) was used for analysis of the active channel number pattern, which is similar for each tidal cycle. Period 2 was used for calculation of the average channel number per scale (figure 6: period 1).

4.3.2. Main channel variability

The main channel changes position in the estuary over time. The main channel variability is calculated by averaging the movement (m) along the y-axis over the length of the x-axis per tidal cycle. The average of this movement is compared to the amplitude of the tidal cycle. For analysis of the main channel variability 12 tidal cycles (figure 6; period 3) were analysed with varying tidal ranges and the main channel movement was averaged per tidal cycle. The average movement per flood and ebb tide is also calculated and tested for significant difference in means using a Student T-test.

4.3.3. Flow Velocity

The flow velocity in the channels is retrieved from the modelled flow fields per channel cell. This results in flow velocity profiles for each individual channel from which the average velocity per channel or channel group can be calculated. For comparison of the main channel velocity between the bathymetry based network and the flow field based network, period 4 in figure 6 was analysed. The average velocities per channel group were calculated for the period 1, to test whether there was a consistent difference between the scenarios (figure 6).

4.3.4. Peak Flow Velocity

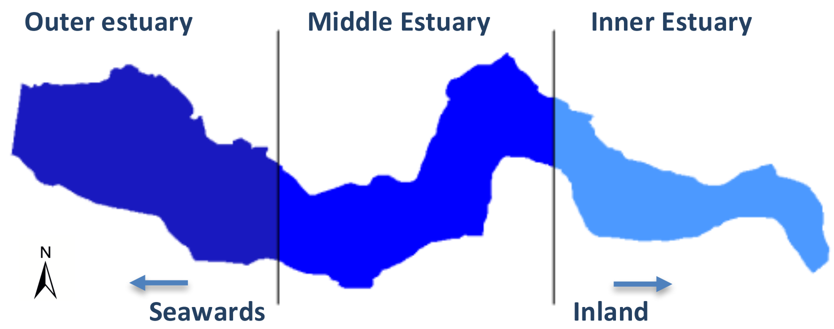


Figure 7. The three shares into which the Western Scheldt estuary was divided for analysis of the peak velocity

The flow velocity does not include a directional component; as such the peak velocity moments were established with the use of the water levels (see Appendix B.3). There is a phase lag ϕ between the peak velocity and high and low water, meaning that the peak velocity moment takes place before the HW and LW (low water). The phase lag is the result of the estuary induced tidal deformation. In alluvial estuaries this phase lag ϕ has a magnitude between 0 and $\pi/2$ (Savenije, 2006). The phase lag ϕ in the Western Scheldt was set to 60 minutes based on van der Spek (1997) and was assumed to be constant throughout the length of the estuary studied here. This assumption is a simplification of the actual situation and could be improved for future research, by implementing a phase lag gradient that increases with distance inland (Hibma et al., 2003). In addition, the phase lag ϕ between the peak ebb velocity and LW could be increased, to a magnitude larger than the phase lag ϕ between the peak flood velocity and HW (Dam et al., 2015).

Due to the length of the Western Scheldt the moments of HW and LW vary in time over the length of the estuary. Therefore, the moments of HW and LW per third of the estuary were used (figure 7). The corresponding thirds of the velocity grids were merged to create the peak flow grids. For these merged peak flow grids new channel networks were generated. These networks were used for analysis of the peak flow velocity and ratio per channel group and the process was repeated for all 13 peak ebb and 13 peak flood moments (figure 6; period 2). The relative range between the mean peak flow velocity in the main channel versus the side channels as well as the main channel versus the chute channels were used as indicator for the tidal wave propagation speed. This was done with the assumption that the tidal wave propagation speed is higher when the channel scale has a higher mean peak velocity.

4.3.5. Peak velocity ratio

The peak velocity ratio is calculated per cell based on the approach in Brown & Davies (2010). The peak velocity ratio is based on the ratio between the peak flood velocity and the peak ebb velocity. As it is calculated per cell of equal sizing throughout the grid, the ratios are not width averaged in this study. There is however a threshold velocity for incipient motion set for the peak ebb velocities. During low water, the ebb peak velocity can be low on drying shoals where there is a low amount of sediment transport (Brown & Davies, 2010). As these values would result in very large velocity ratio values, a threshold ebb peak velocity is set to avoid this bias towards larger values. More information on the peak velocity ratio can be found in Brown & Davies (2010).

The threshold velocity for incipient motion was calculated per grid cell. It was based on a D50 of 200 micrometer or 0.0002 m in the Western Scheldt estuary and the depth (d) of the bathymetry (van Dijk et al., 2019a). The approximation formula was used to obtain the threshold values (van Rijn, 2007). The use of the peak ebb threshold can increase the average peak ebb velocities in the channels. The magnitude of this effect was briefly checked to ascertain the soundness of the peak ebb threshold, as it is only supposed to adjust for low values on or near shoals (Appendix C.1.). There is no change in the main channel peak velocity, as the threshold only corrects for low peak velocity values. The threshold does influence the side and chute channel velocity somewhat, but only slightly; it increases the average between 0.03 m/s to 0.9 m/s (Appendix C.1.). The increase of the chute channel velocity is to be expected as these often flow through or over shoals. Based on this outcome, the threshold velocity for incipient motion seems to be functioning well. For analysis of the peak velocities itself, the velocities without threshold correction were used.

Peak velocity ratio

Ratio (-) = $\frac{\hat{U}f}{\hat{U}e}$ with $\hat{U}_e = U_{cr,\,motion}$ when $\hat{U}_e < U_{cr,\,motion}$ (Brown & Davies, 2010)

Approximation formula

$U_{cr,\,motion}$ (m/s) = $0.19\,(D50)^{0.1} \log \frac{12d}{6d50}$ for $0.0001 < D50 < 0.0005$ m (van Rijn, 2007)

$\hat{U}_f$	Peak flood velocity (m/s)
$\hat{U}_e$	Peak ebb velocity (m/s)
$U_{cr,\,motion}$	Threshold velocity for sediment movement (m/s)
D50	Median grainsize (m)
d	Depth of the bathymetry (m)

4.3.6. Tidal range along the main channel

The average tidal range is calculated by calculating the maximum and minimum water levels along the main channel over the course of period 1 (figure 6). An increasing tidal range indicates amplification of the tidal wave, while a decreasing tidal range indicates damping of the tidal wave. This depends largely on the convergence length and geometry of the estuary (Savenije, 2006).

5. Results

5.1. Examination of the flow field based networks

This chapter explores the effects of using flow fields as input on the channel network. Here, I verify the use of flow fields as input for channel network generation and highlight the main differences between channel networks based on bathymetry and those based on flow fields, by comparing the two inputs.

5.1.1. Channel network comparison

Flow field based networks versus bathymetry based networks
Hypothesis 1: The active channel number in the flow field based network is lower than the channel number in the bathymetry based network.

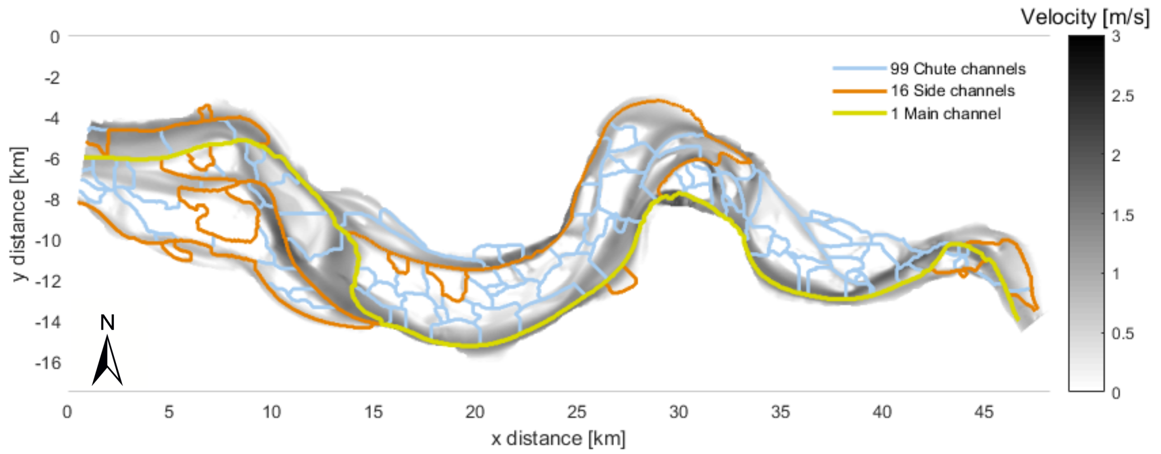
The spatial distribution of channels in the flow field based networks and the bathymetry based networks differ from one other, but in general, the number of active channels in the flow field based networks seems to correspond with the number of channels in the bathymetry based networks. The first point means that the highest velocity paths in the flow field based networks do not consistently align with the lowest elevation paths in the bathymetry based networks, which indicates that flow is taking place not only along the lowest elevation pathways (figure 8).

The second point is important because, realistically, there should not be more channels in the flow field based network, as high velocity flow should not occur through more channels than are present in the bathymetry based network. Since, as noted before, the flow field based channel network indicate the number of active channels e.g. all paths along which flow is occurring. While the bathymetry based channel network indicates the number of channels present in the estuary based on elevation. Occasionally, however, the total number of active channels in the flow field based network is higher than the total number of channels in the bathymetry based network. This indicates again, that flow is not only taking place along the lowest elevation pathways.

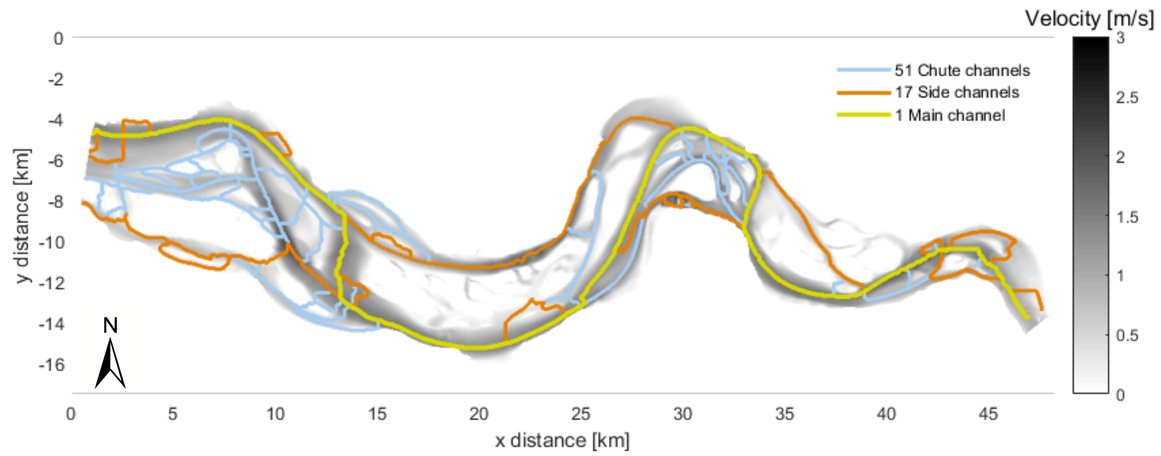
This difference is especially pronounced at high tide and this appears to be the result of the flow field based network having a higher number of chute channels and a lower number of side channels. At low tide, the number of active channels is lower due to the lower water level; there are less channels through which flow is occurring (figure 8). This effect is especially strong on the shallow chute channels. At high tide, there is flow taking place through many more of the chute channels in the network. The underlying bathymetry, on which the flow fields are modelled is the same in both instances.

In order to generate flow field based networks with active channel numbers that are in line with the bathymetry based networks the threshold scale for flow field networks is lowered by tenfold the flow field networks. If this is not done, the number of active channels in the flow field network is unrealistically high.

A. High tide network (40 years: Scenario A)



B. Low tide network (40 years: Scenario A)



C. Network based on Bathymetry (40 years: Scenario A)

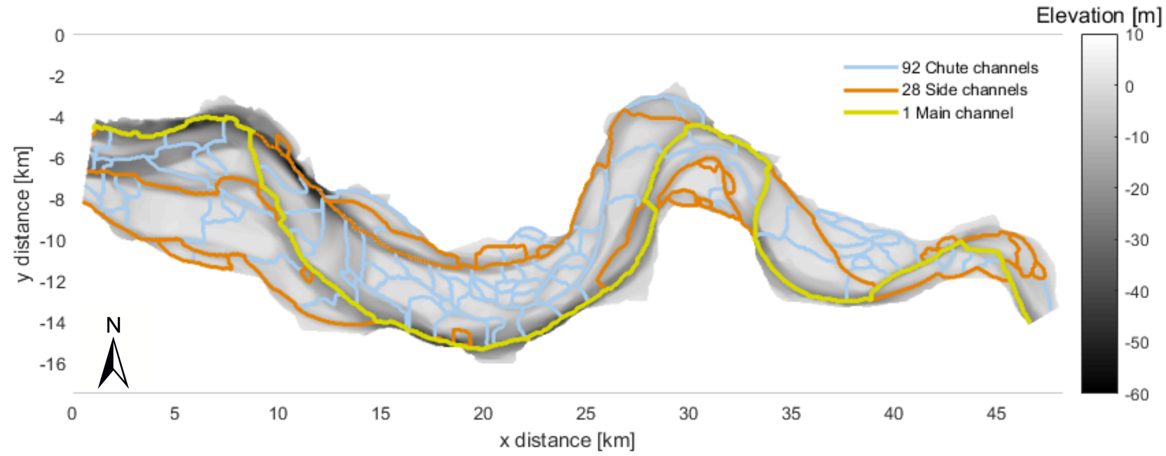
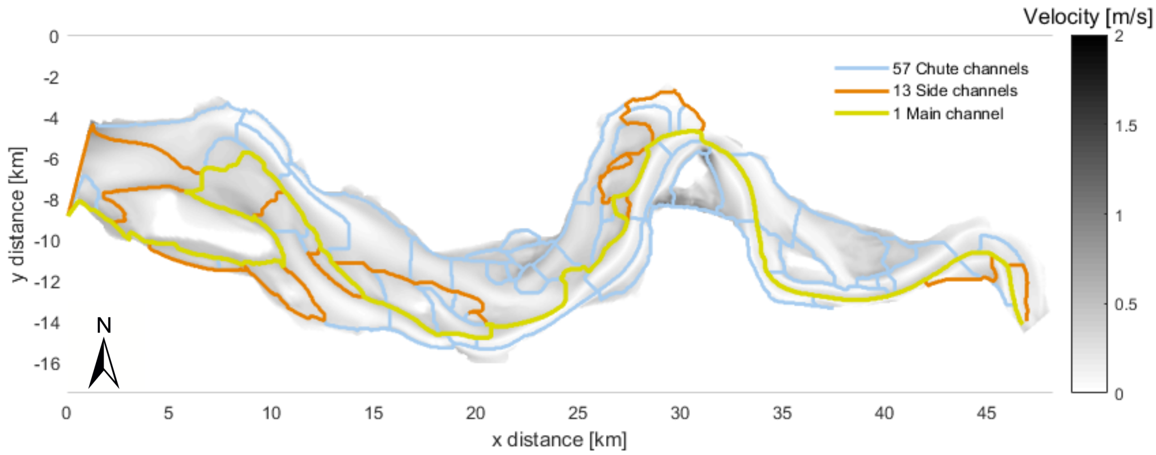


Figure 8. (A) The high tide and (B) low tide flow field based channel network in the Western Scheldt after 40 morphologic years for scenario A. (C) The bathymetry based channel network in the Western Scheldt modelled for scenario A after 40 morphologic years.

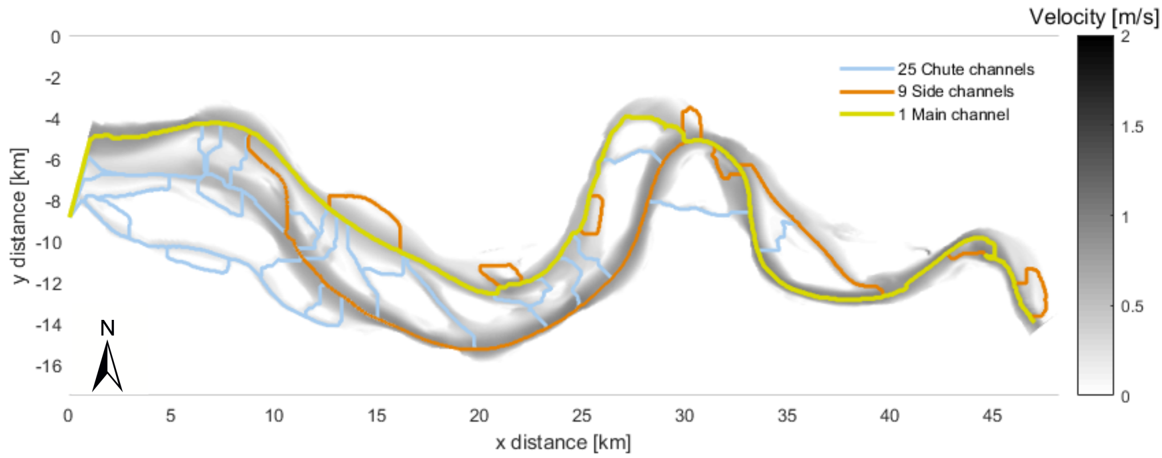
Comparison of final networks versus start networks

Hypothesis 2: The channel numbers after 40 morphologic years are of similar magnitude to the channel numbers at 0 morphologic years.

A. High tide network (0 years)



B. Low tide network (0 years)



C. Network based on Bathymetry (0 years)

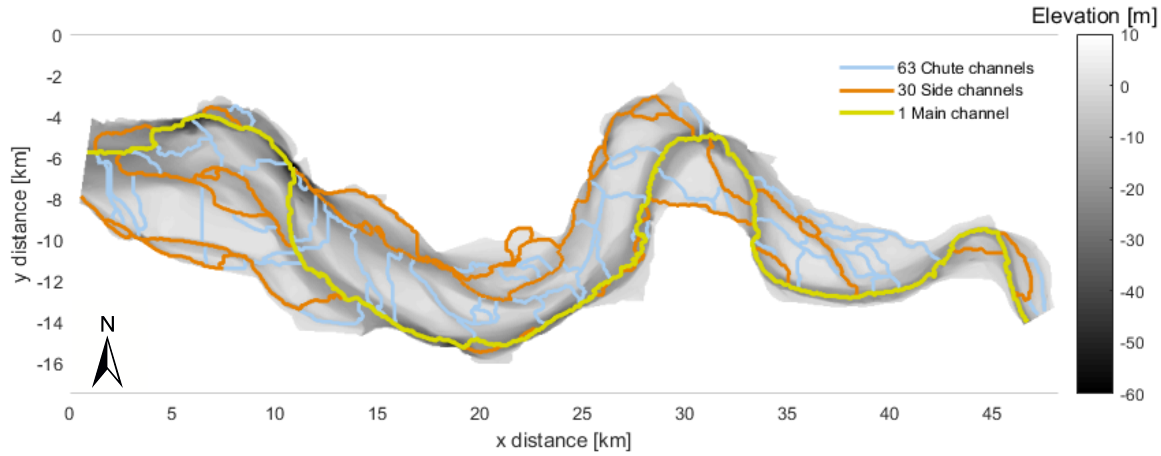


Figure 9. (A) The high tide and (B) low tide flow field based channel network in the Western Scheldt at 0 morphologic years. (C) The bathymetry based channel network in the Western Scheldt at 0 morphologic years. This bathymetry forms the starting point of each of the scenario runs.

The channel networks after 40 morphologic years have a higher number of chute channels than networks at 0 morphologic years for both of the network types, with the same threshold scale used at 0 and 40 years (figure 8 & 9). The number of side channels is less affected. On average, there are 52 channels in total in the flow field based networks after 0 morphologic years, of which 37 are chute channels and 14 are side channels. After 40 morphologic years (i.e. at the end of the model run), there is a mean of 89 channels in total, of which 70 are chute channels and 18 are side channels. This is an increase in the number of channels by 37 (71%), of which the largest share is chute channels (from 37 to 70, an 89% increase). A similar trend can be seen in the bathymetry based networks, where there is a 29% increase in the total channel number, from 94 channels to 121 channels and an increase of 46% (from 63 to 92) for the chute channels.

These increases are surprisingly high and are a result of the length of time of the model run in Delft3D. While the increase is not realistic, the scenario comparison done in the following chapters only looks at the final networks after the 40-year period, which are all affected by this increasing chute channel number, tied to the time length of the model run.

5.1.2. Variability of the flow field networks

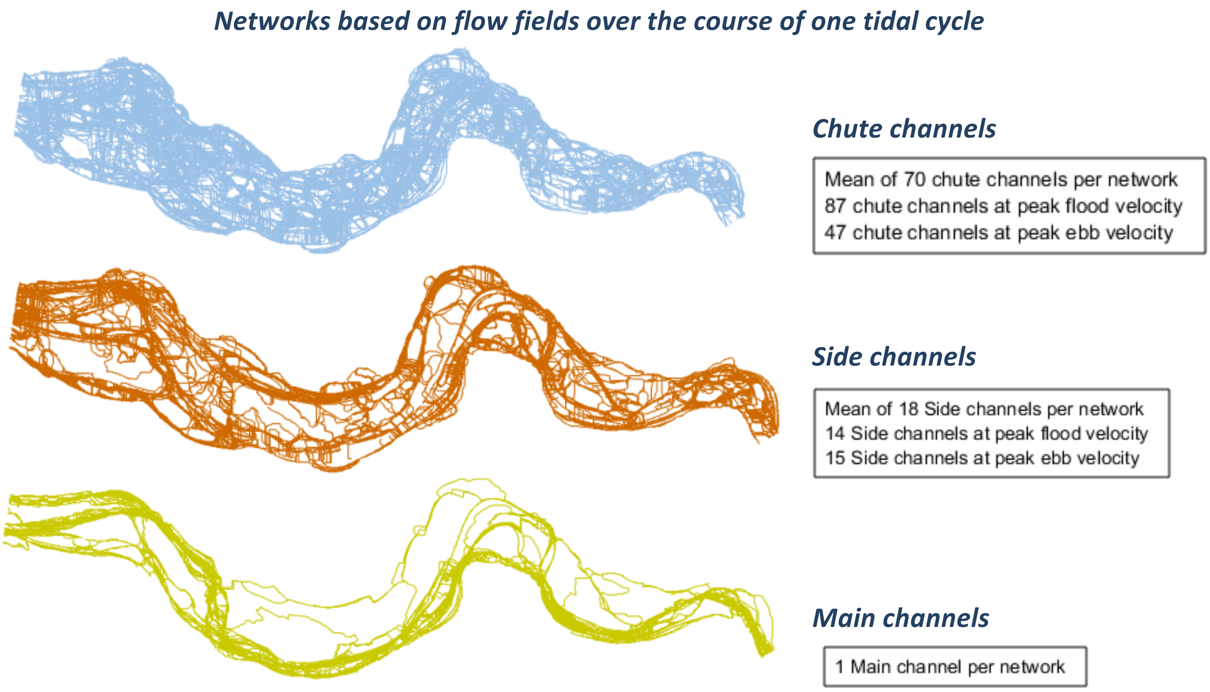


Figure 10. All networks over one tidal cycle (12.5 hours). These figures show that the flow field based networks are highly variable and change on a short time scale. After only one tidal cycle the chute channels have covered almost the entire surface of the estuary. This is less so for the side channels and the main channels, but still all channel groups cover a larger surface area compared to the bathymetry based networks taken over any given time period.

Over the timespan of a tidal cycle, the flow field based channel networks are highly variable, both in channel location and active channel numbers (figure 10). The amount of movement of the three different channel classes in the flow field based networks and the area they cover in the estuary after a week is much larger compared to the bathymetry based network. To put it in perspective, the bathymetry based network only changes every 24 hours in the model runs; this makes sense as it indicates the amount of morphological change in the estuary, which changes on a longer timescale than flow field patterns. On the other hand, the flow patterns change with the tide and thus vary at a shorter timescale.

The large number of active chute channels and the large area covered by these channels after one tidal cycle gives rise to the question of whether all these channels are indeed best defined as chute channels (figure 10). In the flow field based networks, there are a high number of active chute channels at high tide compared to low tide. It is important to remember that all these active channels are modelled on the same bathymetry & that the surface area covered by the chute channels based on elevation is much lower. Most of the active chute channels in the flow field based networks are likely not fully formed chute channels in the bathymetry based network. The active chute channels in the flow field based networks indicate all chute channel-like flows in the estuary, but these do not only occur through channel shaped chutes in the morphology. It is likely that only the 'prevalent' active chute channel flows in the flow field based networks result in actual chute channels in the topography, by cutting through the banks and forming a channel.

All channels in the network change position over time. For the chute and side channels it would be difficult to perform a precise comparison between the same channel at different times, as the channels change position and can shift from being active to non-active, thus disappearing from the channel network. Therefore, the network variability demonstrated in the following section is based on the main channel only.

Main channel variability

Hypothesis 3: The degree of main channel shifting is significantly higher during flood than during ebb.
Hypothesis 4: The degree of main channel shifting is correlated with the tidal range.

The main channel shifts position over time (figure 11); on average, the channel shifts 542.95m per grid cell every 10 minutes. Moreover, there is a significantly (P=0.0007 with a Student T-test) larger average amount of shifting during flood (609.6m) than during ebb (472.2m), which means that hypothesis 3 is accepted. The shifting of the main channel flow path takes place due to the changing flow velocities with the tide (figure 11), which follows the highest velocity pathways. The higher average amount of shifting of the main channel during flood than during ebb could be due to the higher water levels at high tide, resulting in larger amounts of shifting of the high velocity flow path. If this is the case, large tidal ranges, characterized by high water levels at high tide and a large volume of water flowing into the estuary, could be correlated with more shifting of the main channel.

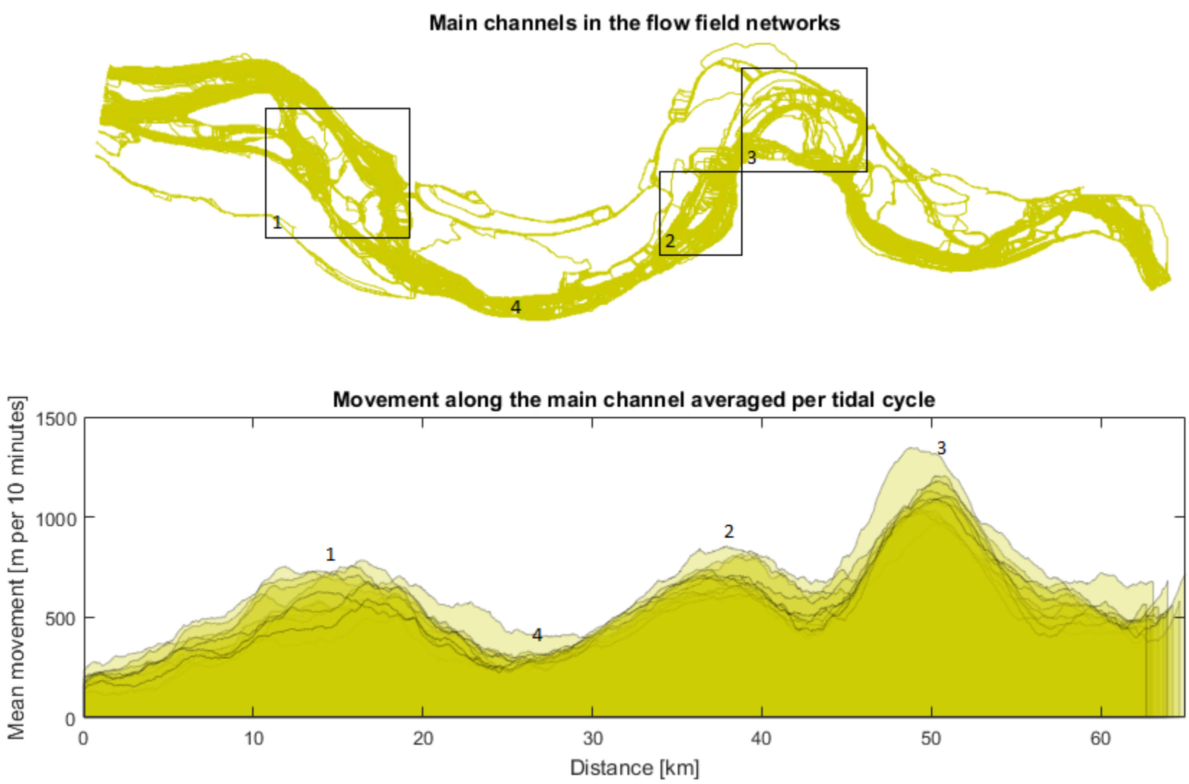


Figure 11. (A) All main channels in the networks over 165 hours (13 tidal cycles). The estuary length is 46 km. The number 4 indicates a location with one dominant flow path, which is referred to below. (B) The average distance the main channel moves every 10 minutes (averaged per tidal cycle). The average main channel length varies between 63 and 65 km. The boxes display the approximate locations along the main channel with the highest amounts of shifting.

The amount of shifting varies along the main channel (figure 11b). The locations where the largest amounts of shifting take place are related to the locations in the estuary where there are two flow paths between which the channel alternates. The shifting of the main channel is measured along the x-axis of the grid, so it does not follow the lateral curvature of the Western Scheldt. This amplifies the apparent shifting of the main channel at locations where the main channel flows at a greater angle to the x-axis. Figure 11a shows all main channels over the course of a week. The main channel always starts at the inland side & ends at the outer side of the estuary, but the length of the channel varies depending on its flow path. Throughout each modelled tidal cycle, the average length of the main channel varies between 62.7 and 65.2 km (figure 11b).

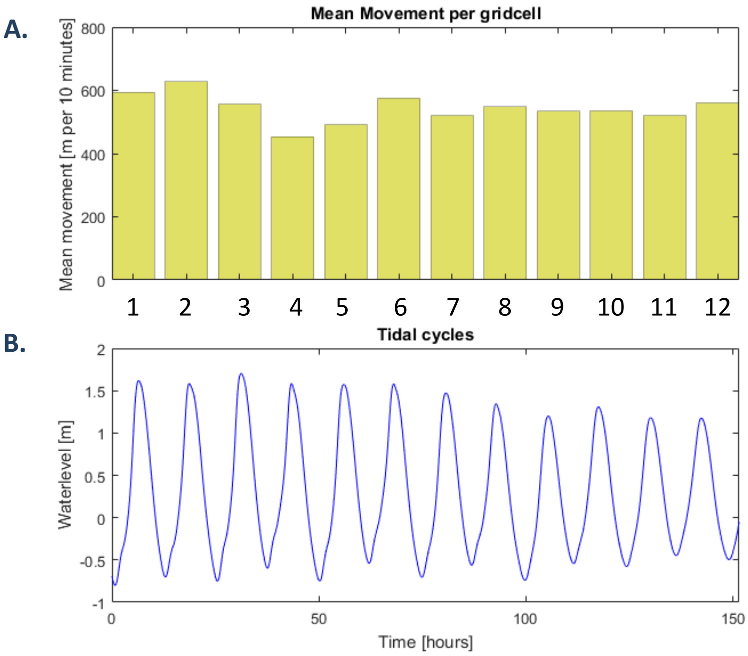


Figure 12. (A) The mean distance a grid cell of the main channel shifts per 10 minutes - averaged per tidal cycle number 1 to 12, corresponding with the tidal cycles in figure 12B. (B). The tidal cycles for which the mean grid cell shift of the main channel was calculated to examine if large tidal ranges correspond with high mean shifting of the main channel.

While the channel network is tidally dependent due to the tide's influence on flow patterns, the conclusion is that the magnitude of the tidal range does not influence the amount of shifting of the main channel per grid cell (figure 12), demonstrated by the poor fit between average main channel shifting and tidal range (figure 13). Hypothesis 4 is therefore rejected.

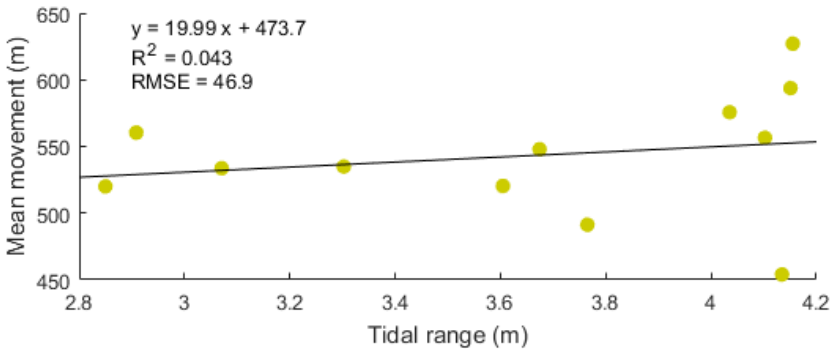


Figure 13. The linear fit for the tidal range (x) and the mean movement (y) with the quality of the fit based on the R^2 and the RMSE.

5.1.3. Comparison of the main channel velocity

Hypothesis 5: The main channel velocity using bathymetry based networks is equal to the main channel velocity using flow field based networks when there is a low amount of main channel shifting in the flow field based networks.

When analyzing channel velocity over short timescales, flow field based networks would provide a more accurate description of the velocity than when using bathymetry based networks. This is because bathymetry based networks significantly underestimate the flow velocity along the main channel (figure 14; P=0 with Student T-test); the mean velocity is similar only when the main channel has one dominant flow pathway in the flow field based networks (figure 11: location 4). This is the case from the 23rd to 38th kilometer along the main channel (figure 14).

While the maxima velocities correspond for part of the main channel, the minima are always lower. It was expected that the flow velocity is higher in the flow field based networks, as the channel lines describe the highest velocity pathways. The bathymetry based networks are determined based on the morphology; they do not follow the highest flow path, resulting in an overrepresentation of low values, especially where the main channels in the flow field based networks frequently shift.

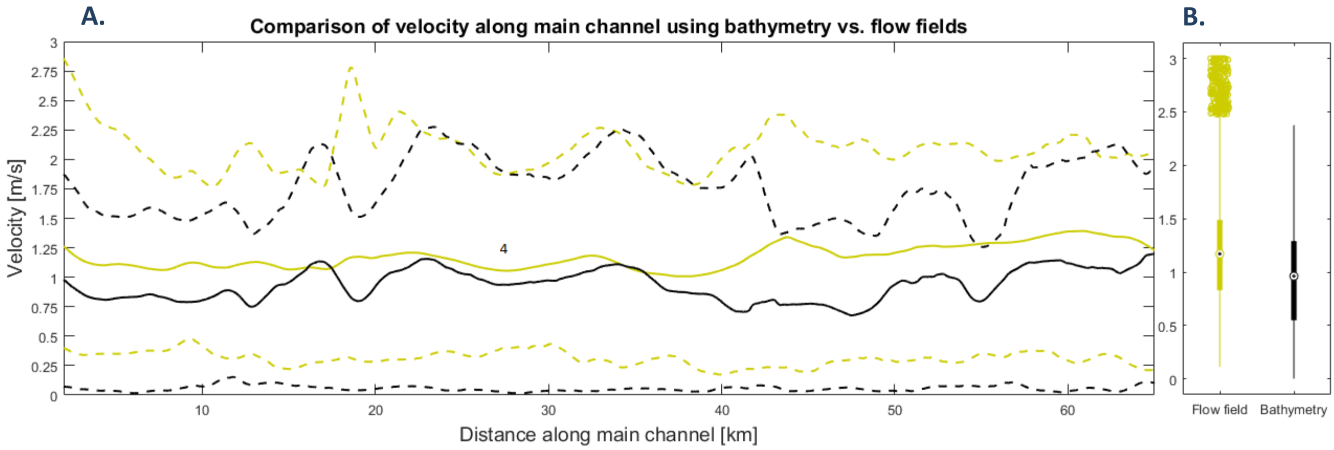


Figure 14. (A) The average velocity in the main channel over the course of one tidal cycle (12.5 hours) using flow field based networks (yellow) versus bathymetry based networks (black). The bathymetry based networks consistently underestimate the flow velocity along the main channel, especially the lower values. The velocity profiles were smoothed using a weighted average filter. (B) Boxplot of the main channel velocity.

Conclusions

- The flow field based networks have similar total active channel numbers relative to the bathymetry based networks when the threshold scale for flow field networks is lowered at least by tenfold, but the channel locations in both network types do not precisely match. This means that high velocity flow paths are not exclusively occurring along the lowest elevation paths.
- Channel networks based on temporally long Delft3D model run results have a higher numbers of chute channels than the starting point networks, but side channels numbers are not affected by the time length of the model run.
- Using flow fields as input results in highly variable channel networks that follow the variability in flow patterns. This makes flow field based channel networks useful for analyzing short term variations in flow patterns. Especially since the flow velocity in the main channel is underestimated when using bathymetry based channel networks (particularly at locations where there is more than one preferential flow pathway).
- The movement of the main channel is influenced by the tide, with a higher amount of movement during flood than ebb; however, the tidal range is not correlated with shifting of the main channel. As a result of the channel shifting – at all channel scales and over the same time span, flow field based networks cover a larger area of the estuary than bathymetry based networks.

5.2. The effect of dredging and disposal on the complexity of the channel system

One of the major concerns for the Western Scheldt is that dredging and disposal decreases the complexity of the multi-channel system. A decrease in complexity occurs when there are fewer channels, especially fewer chute channels, but also fewer side channels. This chapter aims to answer the question whether there is a dredging and disposal protocol that reduces the complexity less than others. The number of active channels in the flow field based networks indicates the number of pathways along which flow is occurring at that time step, not the number of channels present based on the elevation.

5.2.1. The variability of active channels with the tide

Hypothesis 6: The number of active side and chute channels is strongly dependent on the tidally generated water level fluctuations.

The main driver behind the number of active chute channels is the tidal cycle, whereas with the number of active side channels has a much lower correlation with the tidal cycle (figure 15, figure 16). On average, around 80% of the variation in the number of active chute channels is explained by water level fluctuations versus only 30% of the variation in the number of active side channels (figure 16, table 2). This is caused by the lack of flow occurring through shallow chute channels at LW, while at HW there are many chute channel flows present in the network (figure 15). On the other hand, most side channels are present both at HW and LW, perhaps because these channels are deeper and flow is therefore still occurring at LW.

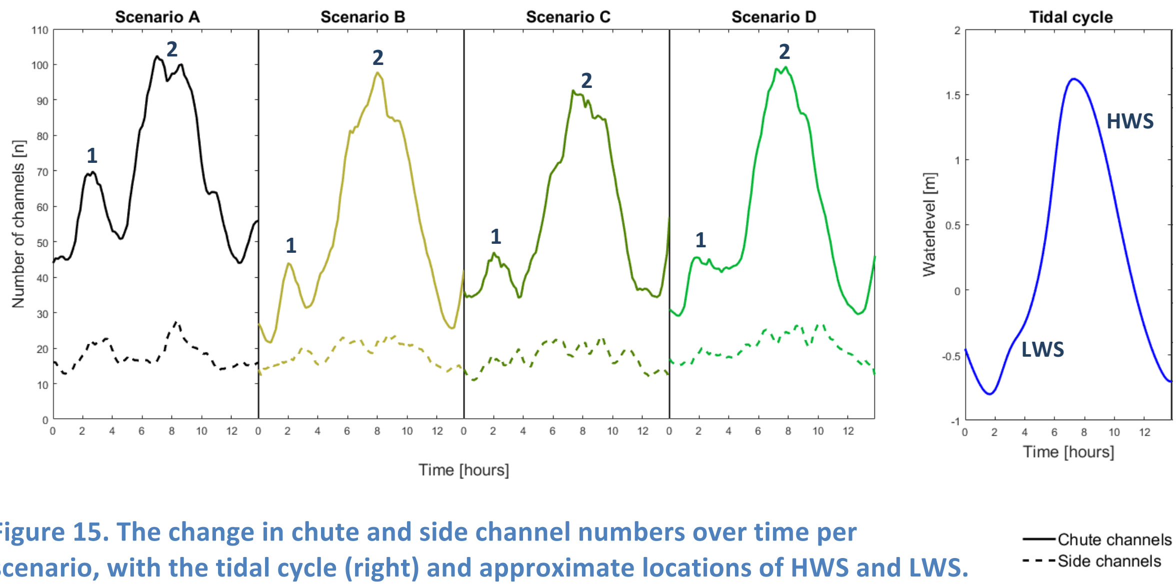


Figure 15. The change in chute and side channel numbers over time per scenario, with the tidal cycle (right) and approximate locations of HWS and LWS.

The correlation between the number of active channels and water level increases with dredging and disposal for both the side and the chute channels (table 2), but there is a decrease in the secondary peak in active channel numbers around the moment of LWS (figure 15: location 1). For all dredging and disposal scenarios there is an increase in the correlation value with increasing water level, especially for scenario B and D (table 2). At the same time, the number of both chute and side channels in scenario A show two peaks in active channel number - around HW and LW, though the peak at LW is lower - while in the dredging and disposal scenarios the secondary peak (figure 15; location 1) diminishes and the main peak increases (figure 15; location 2). These two peaks for scenario A are also visible in figure 16 for the chute channels, where at both high and low water levels there is a higher amount of active chute channels. This secondary peak (figure 15; location 1) seems to occur around the moment of LWS (low water slack), a short period during which there is no flow, right before the reversal of the tidal flow direction. The magnitude of this peak - and perhaps the influence of the LWS on the active channel number - becomes smaller in the dredging and disposal scenarios.

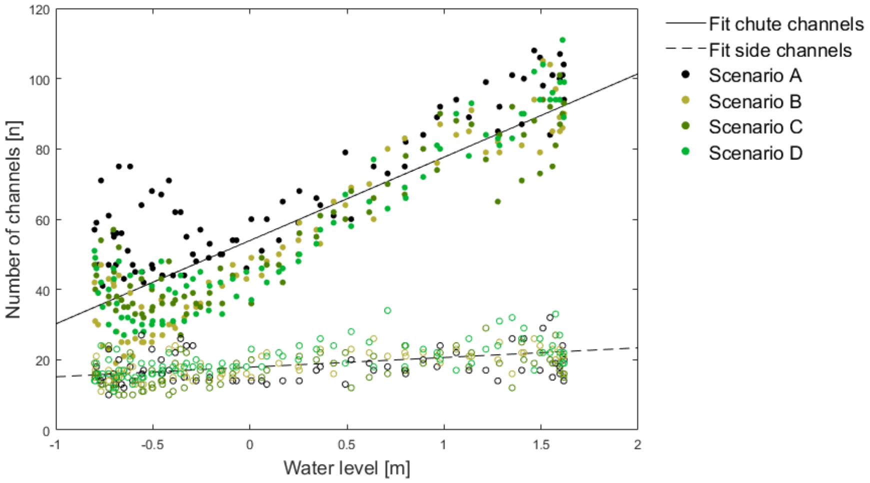


Figure 16. The relation between water level fluctuations and the active channel number.

Total of group	Equation	R^2	RMSE
Side channels	2.75x+17.88	0.29	3.75
Chute channels	23.73x+53.92	0.81	10.21
Chute channels			
A	21.25x+63.42	0.78	9.52
B	26.27x+49.07	0.90	7.86
C	21.13x+51.67	0.84	8.44
D	25.83x+51.64	0.88	8.24
Side channels			
A	1.922x+17.45	0.14	3.95
B	2.798x+17.85	0.40	3.09
C	2.765x+16.74	0.32	3.68
D	3.461x+19.51	0.42	3.61

Table 2. The linear fit per channel group and per scenario or every channel group between water level and channel number.

5.2.1. The effect on the average number of active chute and side channels

Hypothesis 7: The mean number of active chute channels is reduced as a result of dredging and disposal.
Hypothesis 8: The mean number of active side channels is reduced as a result of dredging and disposal.

Regardless of whether or not there is sediment disposed of in the side channels, the number of chute channels decreases with dredging and disposal. In all three examined dredging and disposal protocols, the mean number of chute channels decreases by between 12 and 14 channels, or 17% and 20% (figure 17, figure 18). The expectation was that disposal in the side channels, in scenarios B and C, would result in the strongest reduction of chute channels; however, in scenario D, the number of chute channels is reduced similarly while the mean number of chute channels in the three dredging and disposal scenarios do not differ significantly (figure 18). Moreover, a lower amount of dredged cumulative volume (scenario C) seems to not result in a smaller decrease in the number of chute channels. Regarding the side channels, the mean is relatively stable, with a slight increase in the number of side channels in two of the dredging and disposal scenarios by one or three channels (figure 17, figure 18). Still, there is a significant increase in the mean number of active channels in all three dredging and disposal scenarios compared to scenario A (figure 18).

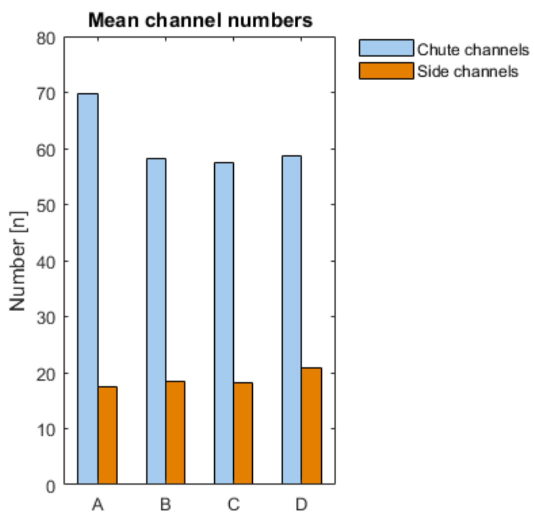


Figure 17. Mean number of chute and side channels per scenario averaged over 165 hours (13 tidal cycles).

From these results, it can be concluded that dredging and disposal significantly reduces the mean number of chute channels and that hypothesis 7 can be accepted. The opposite is true for hypothesis 8, which is rejected: dredging and disposal increases the mean number of side channels significantly, especially when dredging and disposal protocol D is implemented. Overall, the total number of active channels decreases as a result of the change in the number of chute channels. This means that the complexity of the channel network is reduced by dredging and disposal, with the largest impact in scenario C, followed by scenario B and then scenario D. Scenario D has a higher total number of active channels than the other two dredging and disposal scenarios.

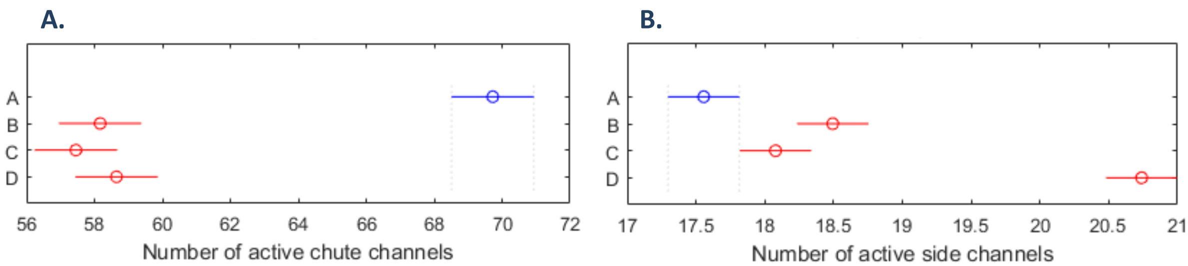


Figure 18. (A) The mean active chute channels number and (B) active side channel number per scenario averaged over 165 hours (13 tidal cycles). The dredging and disposal scenarios decrease the chute channels by 17% -D, 19% -B, 20% -C and increase the side channels by 16.7% -D, 5.5% -B, 0% -C. The circle displays the mean, the line indicates the comparison interval, which is the standard error of the mean.

5.2.2. The effect on the active channel variability

Hypothesis 9: There is a lower range in the number of active channels with dredging and disposal.

Overall, the dredging and disposal scenarios show an increase in range and interquartile (IQ) range for the number of both chute and side channels, which resulted in the rejection of hypothesis 9 (table 3). The range and interquartile range are used as measures of variability. The increase variability is greatest in scenario B, followed by scenario D and then scenario C. The range in the number of active chute channels is larger, while the range in the active number of side channels is much smaller (table 3). The range and IQ range for the number of active chute channels is greater due to the larger decrease in channel numbers at low water levels relative to the decrease in the number of channels at high water levels (figure 15, figure 19).

In terms of the data spread and pattern of the active chute channel numbers, scenario C seems to come closest to the baseline scenario A, while scenario B and D exhibit a larger data spread and narrower peaks (figure 15, figure 19). The narrow peaks in scenario B and D mean that there are fewer time steps with high numbers of active channels, but the high number of active channels still comes close to the baseline scenario A.

The side channels, however, display a different pattern. The variability of the number of side channels is less, but dredging and disposal seems to increase the influence of water levels on the number of side channels (table 3). Moreover, the side channel pattern in the baseline scenario shows two distinct local maxima, while in the other scenarios there are smaller, less significant peaks. Aside from this, the spread of the data is similar for all four scenarios; only scenario D has a slightly greater range in active side channels.

	Channel group	A	B	C	D
IQ Range	Chute	34	39	34	37
	Side	6	6	6	7
Range	Chute	80	91	82	86
	Side	21	21	23	24

Table 3. The range and inter quartile range (IQ range) for both channel groups per scenario. The ranges do not include outliers. Values on which the ranges are based can be found in appendix C.2.

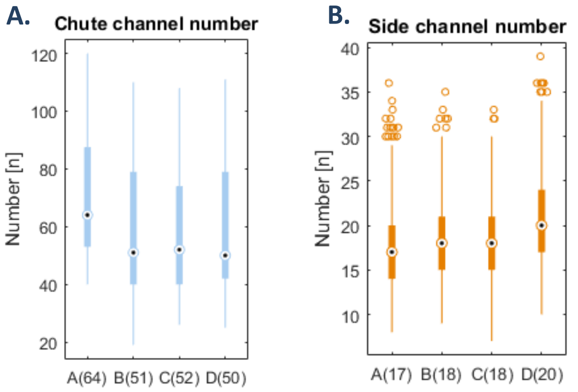


Figure 19. Distribution of active (A) chute and (B) side channel numbers per scenario over 165 hours (13 tidal cycles).

Conclusions

- The variation in the number of active channels is related to the tidal cycles: water level fluctuations affect chute channels much more than side channels. The correlation between the number of active channels and the water level increases with the dredging and disposal strategies, especially flexible disposal (scenario B) and disposal in the main channel scours (scenario D). This seems to correspond with a dampened effect of the peak flow velocity on the number of active channels.
- The mean number of chute channels decreases by about 20% when the Western Scheldt is dredged, regardless of the volume of dredged sediment and the locations of disposal. Disposal only in the main channel scours results in a slightly lower decrease in the number of chute channels, though the difference is not significant.
- The mean number of side channels increases with dredging and disposal, and this is most pronounced with disposal in the main channel scours where the average number increases by 17%.
- Overall, the dredging and disposal scenarios have a larger range and interquartile range than the baseline scenario, for both the number of active chute and side channels.

5.3. The effect of dredging and disposal on the flow conditions in the channels

This subchapter examines the effect of dredging and disposal on the flow conditions at each channel scale. This is done by analysing the changes in average flow velocity at each channel scale and the changes in average flow velocity along the main channel. All flow velocities are the result of 40 years of implementation of the scenarios, the flow conditions during this time are not accounted for in the analysis.

The expectation was that dredging would increase the flow velocity in and along the main channel and that disposal in the side channels (in scenarios B and C) would decrease the flow velocity in these channels. The increase in flow velocity in the main channels was expected to result in less flow through the chute channels. It was thus expected that dredging would lower the flow velocity in the chute channels as well and promote infilling of these channels.

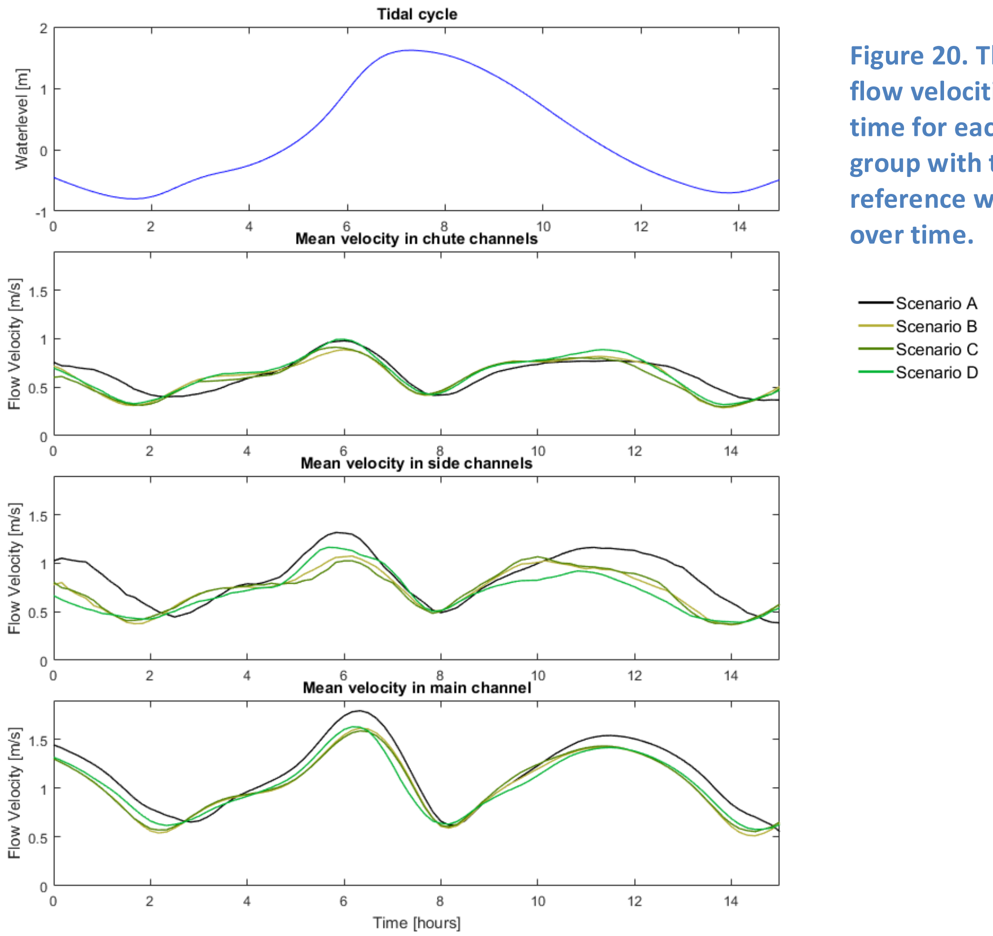


Figure 20. The average flow velocities over time for each channel group with the reference water level over time.

Figure 20 shows the average flow velocity per channel group over the course of one tidal cycle. It is clear that the differences between scenarios are most pronounced after the moment of HWS (high water slack) until LW is reached, during this period peak ebb velocity occurs. The decrease in flow velocity during this period is largest for the average side channel velocity (figure 20). The main channel also shows a sizable velocity decrease, as the expectation is that dredging on average increases the flow velocity in the main channel. There only seems to be a slight increase in the average velocity in the main channel immediately following LW in the scenarios with dredging (figure 20). Lastly, the side and main channels have a lower peak velocity in the scenarios with dredging (1 hour before HW). This in contrast to the chute channels, where the average flow velocity is comparable across all scenarios. Figure 21 shows the distribution of the average channel velocity per channel group, indicating that the larger channels have a larger range of commonly occurring velocities than the smaller chute channels.

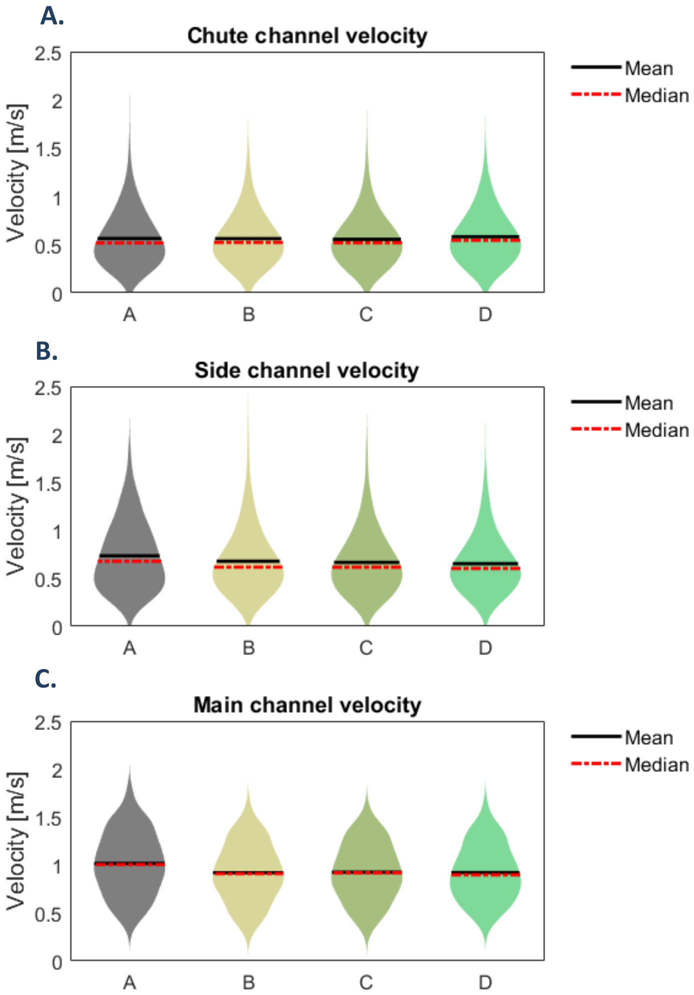


Figure 21. The distribution of the average channel velocity displayed with a violin plot (function developed by Hoffman, 2015) for (A) the chute channels, (B) the side channels and the (C) main channel.

5.3.1. Changes in main channel flow velocity

Hypothesis 10: Dredging and disposal increases the average flow velocity in and along the main channel.

The average flow velocity in the main channel is significantly lower in all three dredging and disposal scenarios than the flow velocity in the baseline scenario, a finding that is different than initially expected (figure 22). The expectation was that dredging would increase the flow velocity in the main channel, as it reduces bed friction (Nichols, 2018). However, based on these results, that does not seem to be the case. While the average flow velocity over time decreases significantly, there can be flow velocity variations along the main channel that are overlooked this way (figure 23).

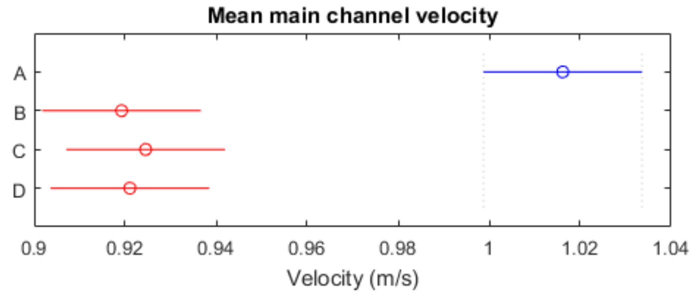


Figure 22. The mean velocity in the main channel per scenario averaged over 165 hours (13 tidal cycles). The circle displays the mean, the line indicates the comparison interval, which is the standard error of the mean.

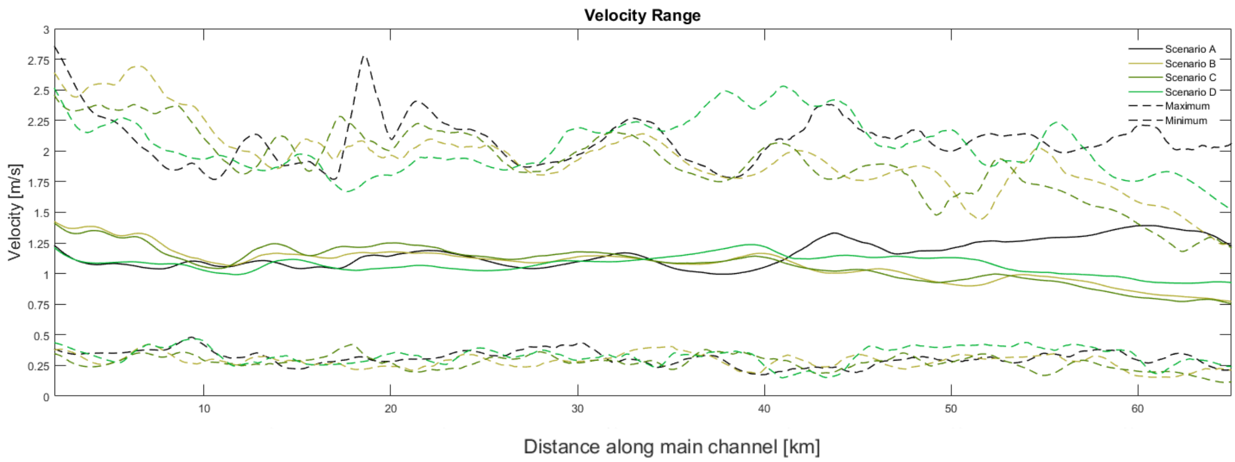


Figure 23. The average flow velocity along the main channel over one tidal cycle (12.5 hours). Averaging over all tidal cycles does not change the general pattern, only lowers the magnitude of the minima, therefore the velocity is represented for one tidal cycle. The velocity profiles were smoothed using a weighted average filter.

The lower average flow velocity in the last 20 km of the channel is actually large enough to bring the overall average down to what is shown in figure 22. Figure 23 shows that along most of the length of the main channel the average flow velocity is equal or higher than scenario A, while at the end of the main channel the average flow velocity is lower with each dredging and disposal scenario. The seaward half of the main channel (32.5 km) has a significantly higher average flow velocity in scenarios B and C than in the baseline scenario A (figure 24a). In fact, up until 48.5 km, both scenario B and C have a significantly higher average flow velocity, while scenario D, on the other hand, has a significantly lower average flow velocity for this same stretch of the estuary (figure 24a). In the inland half of the main channel, all dredging and disposal scenarios show a lower average flow velocity than the baseline scenario A (figure 24b).

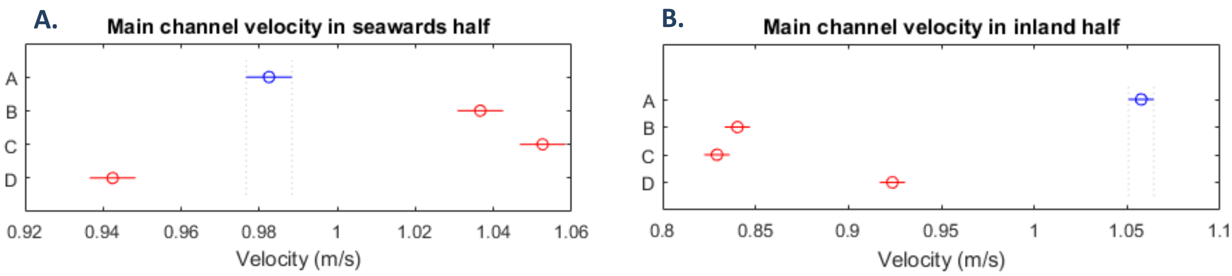


Figure 24. The mean velocity in the main channel per scenario in (A) the seawards share, extending 32.5 km inland and (B) the inland share, starting at 32.5 km inland and extending to the end of the channel - over 165 hours (13 tidal cycles).

5.3.2. Changes in chute and side channel flow velocity

Hypothesis 11: Disposal in the side channels decreases the average flow velocity.
Hypothesis 12: Dredging and disposal reduces the average flow velocity in the chute channels.

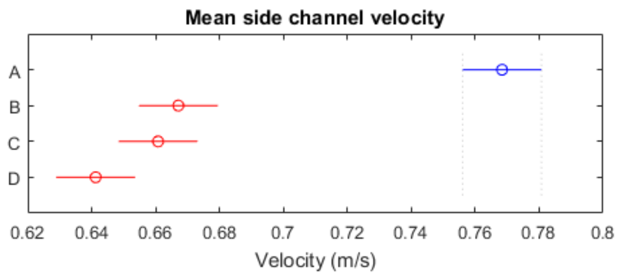


Figure 25. The mean velocity in the side channels, averaged over 165 hours (13 tidal cycles). The circle displays the mean, the line indicates the comparison interval, which is the standard error of the mean.

Each dredging and disposal protocol results in a significantly lower average flow velocity in the side channels, even when no disposal takes place in the side channels as in scenarios B and C (figure 25). It was expected that disposal in side channels would reduce the average flow velocity the most. However, the decrease is even larger in scenario D, where disposal only takes place in the main channel scours. This might be related to the increase in the number of active side channels in scenario D. This result in figure 25, emphasizes that dredging and disposal affects the whole system and can result in unexpected impacts.

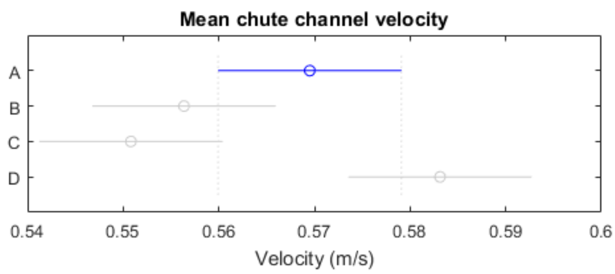


Figure 26. The mean velocity in the chute channels, averaged over 165 hours (13 tidal cycles). Scenario D has a significantly different mean than Scenario B and C. The circle displays the mean, the line indicates the comparison interval, which is the standard error of the mean.

The average chute channel velocity is significantly higher in scenario D than scenarios B and C (figure 26). The higher average flow velocity would result in less sedimentation in the chute channels, and is likely the result of more sediment being retained in the main channel in scenario D. In the two other dredging and disposal scenarios B and C, where more locations are used for disposal, dredged sediment is distributed throughout the system more. The higher average flow velocity in scenario D is a positive development seen from an environmental standpoint, where the goal would be maintaining the ecologically valuable chute channels. Still, the results in subchapter 4.2 on the active channel numbers, indicate that this increase in chute channel velocity still comes with a sizable reduction in chute channel numbers.

The lower average flow velocity in scenario B and C could lead to more infilling of the chute channels. However, while the average chute channel velocity is lowered in scenario B and C and increases in scenario D, none of the values in the dredging and disposal scenarios differ significantly from that of the baseline scenario A (figure 26).

The changes in average flow velocity observed in this subchapter for the main, side and chute channels do not entirely agree with the already known effects of dredging and disposal on flow velocity. Changes in tidal dominance – the subject of the following subchapter 5.4. – might provide more insight into the effects of dredging and disposal on the flow velocity in the channels.

Conclusions

- Dredging and disposal significantly reduces the average flow velocity in the main channel, due to a lower velocity the inland share of the estuary.
- Dredging and disposal also all results in significantly lower average velocities in the side channels, even when disposal does not take place in the side channels.
- The chute channel velocity is significantly lower in with flexible disposal (scenario B) and disposal in the side channels and main channel scours (scenario C) than with disposal in the main channel scours (scenario D). The higher average flow velocity with disposal in the main channel scours could mean less sedimentation in the chute channels, due to more sediment retention in the main channel. This is a positive development seen from an environmental standpoint, with as goal to maintain the ecologically valuable chute channels.

5.4. The effect of dredging and disposal on the tidal dominance on the estuary

Dredging and disposal can have a large effect on the tidal flow dynamics and the tidal asymmetry of the Western Scheldt. This subchapter explores some of these changes by looking into the peak velocities, the tidal range and the tidal asymmetry of the estuary. The peak velocities are analysed per channel group, but also per estuary part to make a distinction between the effects over the length of the estuary and the effects on the different channel scales. The peak velocities moments shift along the estuary, due to its length of the Western Scheldt.

5.4.1. Effect on the peak velocities in the estuary

Hypothesis 13: There is spatial variation in the effect of dredging and disposal on the average peak ebb and flood velocity.

The differences in mean peak flood and ebb velocities between scenarios become larger with increasing distance from the coast (figure 27). In the outer share of the estuary, differences between scenarios are small. In the middle and inland share of the estuary, the mean peak velocities decrease in the dredging and disposal scenarios. This decrease is slightly smaller for scenarios D than it is for scenario B and C. From figure 27 we can conclude that there is spatial variation in the impacts of dredging and disposal strategies on the flow velocities in the estuary. This means that, the impact of dredging and disposal does not only vary in the main channel, where a decrease in flow velocity was observed in the inland share of the channel (section 5.3.1), but also throughout the estuary.

The spatial variation in the impact on flow is likely related to the morphology and the impact of the different dredging and disposal protocols on this. The potential reasons behind this are explored in the discussion.

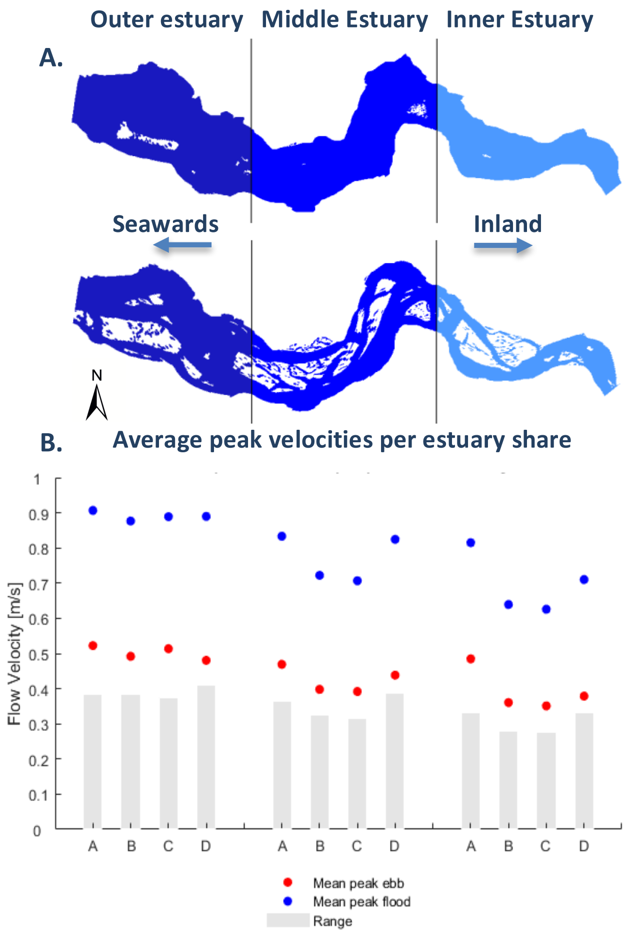


Figure 27. (A) The three shares into which the estuary was divided for analysis of the peak velocities. For the calculation of the peak velocities cells with a zero flow velocity (on banks) were excluded. Upper figure displays the surface area included in the mean peak flood velocity. Lower figure displays the surface area included in the mean peak ebb velocity. (B) The mean peak velocities per estuary share and the range between the mean peak ebb and mean peak flood velocity.

5.4.2. Effect on the peak velocities in the channel groups

Hypothesis 14: There is channel scale variation in the effect of dredging and disposal on the average peak ebb and flood velocity.

Hypothesis 15: The difference in peak ebb and flood velocity between the main channel, versus side and chute channels increases.

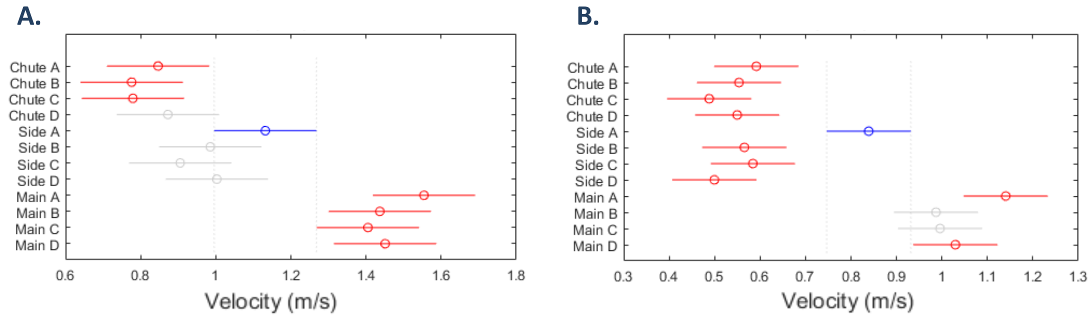


Figure 28. (A) the mean peak flood velocity per channel group and (B) the mean peak ebb velocity per channel group. The only significant decrease takes place at the side channel scale: each dredging and disposal strategy results in a significantly lower peak ebb velocity relative to the baseline scenario (in blue). In red are all means that are significantly different from the baseline mean peak velocity in the side channels.

For almost all cases, the mean peak velocity decreases with dredging and disposal (except for the mean peak flood velocity in the chute channels in scenario D), but only in the case of the mean peak ebb velocity in the side channels is this significant (figure 28). When a difference is significant in figure 28a and 28b, it is displayed with non-overlapping confidence intervals (the lines). If the confidence intervals do overlap, then it cannot be stated with certainty that the difference is significant.

The peak velocities were used in this study as an indicator of the propagation of the tidal wave through the channel scales. The assumption is made that a higher peak velocity indicates a higher tidal wave propagation speed. Although there is a phase lag between the peak flood velocity and high tide as well as the peak ebb velocity and low tide, a higher peak velocity would indicate that the water, and thus tidal wave, moves through that channel at a faster rate.

Like the peak velocity, the tidal wave propagates at different rates through channels of different scales, depending on the ease with which flow moves through the channel. In general, the tidal wave propagation speed is higher through the main channel than it is through the smaller channels. This results in a time lag in tidal wave propagation between the channel scales, that can be changed by dredging and disposal. If the relative range in mean peak velocities between the different channel scale groups increases, the time lag in tidal wave propagation between channel scales also becomes larger.

Range in mean peak velocity per group*		***Absolute range***	***Relative range***
Main - Chute	A	*0.63 m/s*	*47%*
	B	*0.55 m/s*	*45%*
	C	*0.57 m/s*	*47%*
	D	*0.53 m/s*	*43%*
Main - Side	A	*0.36 m/s*	*27%*
	B	*0.44 m/s*	*36%*
	C	*0.46 m/s*	*38%*
	D	*0.49 m/s*	*39%*

Table 4. The range between the mean peak velocity in the main channel and the side and chute channels per scenario. On average there is a decrease in the range between the main and the chute channel velocity and an increase in the range between main and side channels velocity. See appendix C.3. for actual peak velocity values.

The difference in peak (ebb and flood) velocity between the main and the side channels becomes larger with dredging and disposal (figure 28, table 4). The range increases because the reduction of mean peak velocity in the side channels is larger than the reduction in the main channels (around 0.2 m/s and 0.15 m/s, respectively) for the dredging and disposal scenarios (figure 28). There is a 9%, 11% and 12% increase for scenarios B, C and D, respectively (table 4). This means that the lag in tidal wave propagation between the side and main channels increases in the dredging and disposal scenarios, relative to the baseline scenario. Still, the decrease in mean peak velocities shown in figure 28 indicates that through both channel groups the tidal wave actually propagates slower than in the baseline scenario.

On the other hand, the difference in peak velocity between the main channel and the chute channels becomes smaller with dredging and disposal. The relative range between the mean peak velocity in the main to the chute channels decreases by 2% in scenario B and 4% in scenario D, while the range does not change in scenario C (table 4). While the difference in tidal wave propagation speed between the main and chute channels becomes smaller with dredging and disposal, the time lag is still larger than that between the side and main channel.

Noteworthy is the overall breakdown of the changes in the main, side and chute channels; with dredging and disposal, the mean peak velocity in the side channels has a higher resemblance to the chute channel velocity, especially peak ebb velocity (figure 28). The relative range in peak velocity changes least with flexible disposal (scenario B), while scenario D has the strongest effect on the relative peak velocity range (table 4). If the relative range in peak velocity is a good indicator for the time lag in tidal wave propagation, this would mean that the lag in tidal wave propagation is changed least in scenario B. Overall, based on the changes in the relative peak velocity range with dredging and disposal, the lag in tidal propagation between the chute and side channel groups becomes smaller, while the lag increases between the main and side channels.

5.4.3. Amplification of the tidal wave

Hypothesis 16: Dredging and disposal amplifies the tidal wave in the main channel with each of the dredging and disposal strategies.

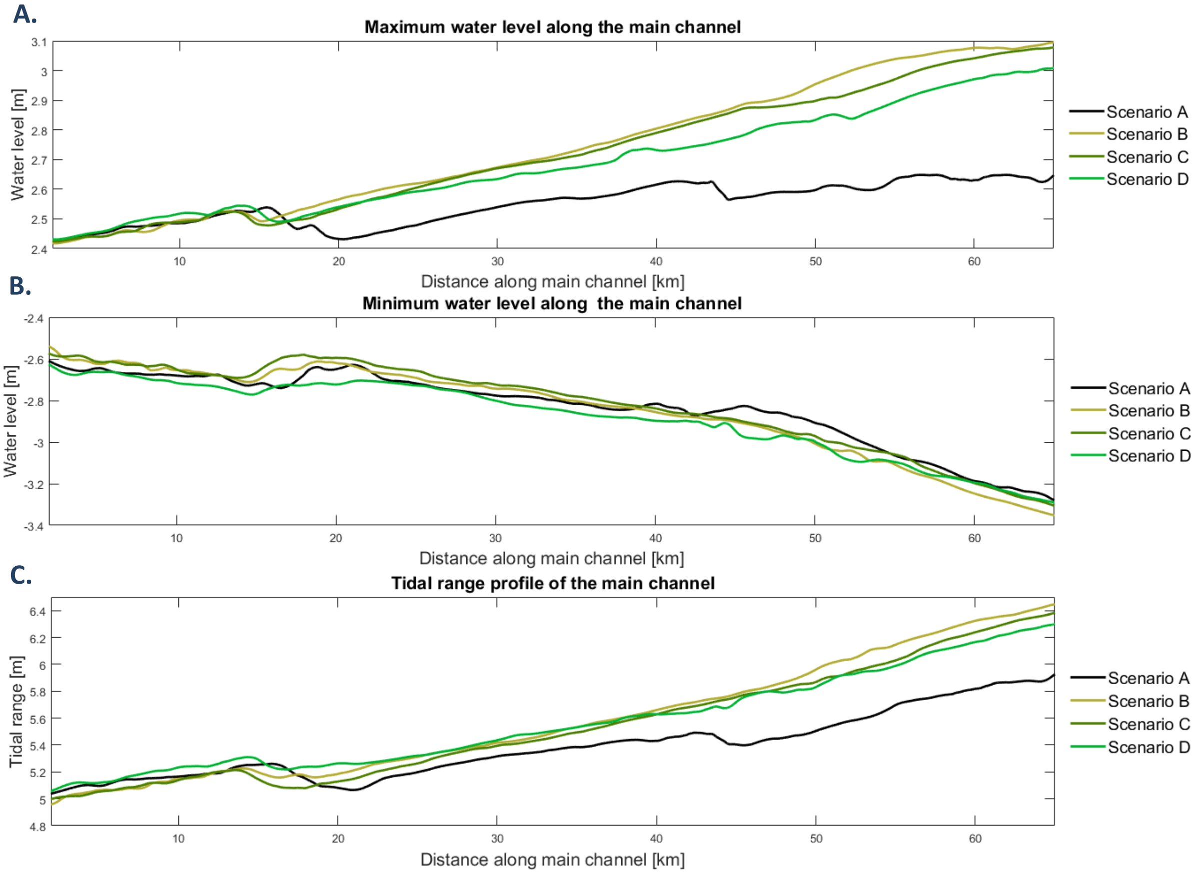


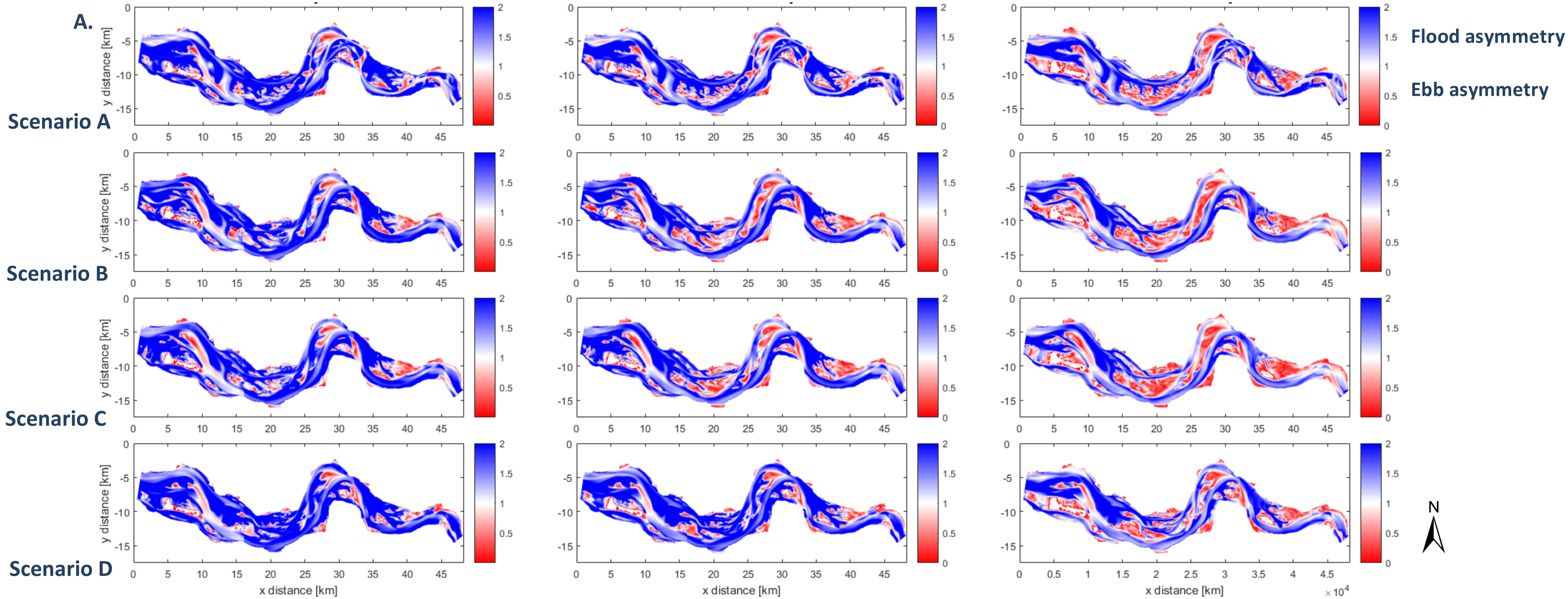
Figure 29. The (A) maximum and (B) minimum water level and (C) tidal range per scenario along the main channel over 165 hours (13 tidal cycles).

There is an increasing tidal range with increasing distance from the coast in the main channel for all scenarios (figure 29). When the tidal range in an estuary increases in the upstream direction as a result of convergence being stronger than friction, the tidal wave is amplified (Savenije, 2006). Beyond the point at which friction becomes more pronounced, there is a reduction in tidal amplification, followed by tidal damping. The damping process is enhanced by river discharge, which increases friction (Savenije, 2006). The Western Scheldt is an example of an estuary that experiences this type of tidal amplification followed by dampening (Savenije, 2006). The tidal wave moves with a higher propagation celerity when it is amplified and slower when it is dampened. In the Western Scheldt, the tidal range increases from the mouth up until Antwerp and decreases between Antwerp and Gent, but the stretch of the estuary analysed in this study includes only the amplified portion.

Tidal amplification is enhanced by dredging and disposal, primarily the result of an increase in the maximum water level (figure 29). All three dredging and disposal scenarios have a significantly ($P=2.03e-49$ with a multiple comparison test) higher tidal range than the baseline scenario and the difference in tidal range increases more in the inland direction. From the coast to end of the channel, scenarios A, B, C and D have tidal ranges that increase by 0.85, 1.5, 1.4 and 1.25 m, respectively. The maximum tidal range of the main channel in scenarios A, B, C and D is 5.9, 6.45, 6.4 and 6.3 m at the end of the channel, respectively. Still, however, the tidal range averaged over the whole estuary is lower.

5.4.1. Changes in tidal asymmetry

Hypothesis 17: There is an increase in ebb asymmetry and decrease in flood asymmetry with each of the dredging and disposal strategies.



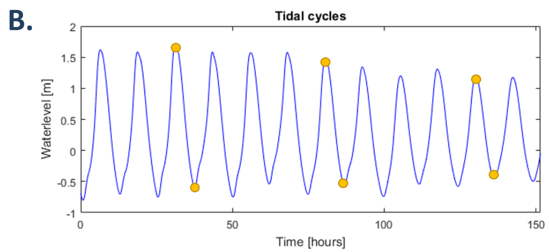


Figure 30. (A) The peak velocity ratios for the Western Scheldt per scenario for three tidal cycles with decreasing tidal range. Supratidal shoal areas were excluded from the calculation. (B) The tidal cycles for which the peak velocity ratios above are given. Tidal ranges vary per scenario, but are in the order of 4m, 3.5m, 3m respectively from left to right corresponding to the peak velocity ratios above. Additional flow fields on which the ratios are based can be found in Appendix B.

5.4.1.1. Division of tidal asymmetry in the estuary

When looking at the maps in figure 30 there appears to be an increase in ebb asymmetry with decreasing tidal range. Figure 31 proves that there is a clear relation between the tidal range and the amount of flood asymmetric area.

Moreover, in scenario D, disposal only in the main channel scours does not result in a decrease in flood asymmetry, unlike scenarios B and C, flexible disposal and disposal in the side and main channels figure 31; table 5). The relations between the flood asymmetric area and the tidal range in figure 32 per scenario indicate that scenarios A and D have a higher amount of flood asymmetric area for any given tidal range than scenarios B and C.

Considering the relation between the tidal range and flood asymmetric area with the increase in tidal range inland of the estuary in section 5.4.3., it is likely that the decrease in flood asymmetry by the dredging strategies will be counteracted to some degree by the increase in tidal range in scenario B and C (figure 29). In scenarios B and C, there are steeper increases in flood asymmetric area with increasing tidal range, and the amount of flood asymmetric area has a higher correlation with tidal range (figure 31, table 5). This means that an increase in the mean tidal range will likely be accompanied by an increase in overall flood asymmetry. This would also take place in scenario D, but the effect would be less pronounced because the increase in tidal range is less than in scenarios B and C (section 5.4.3) and the slope of the correlation between flood asymmetry and tidal range is lower (figure 29 & 31).

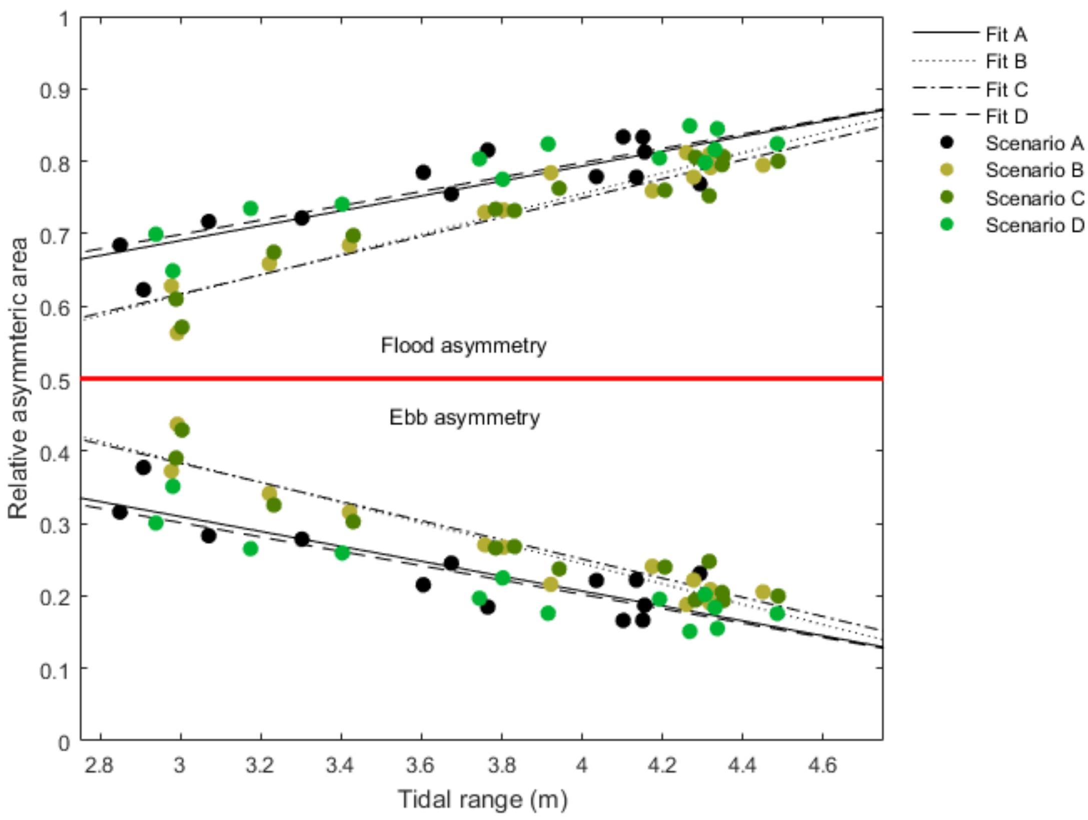


Figure 31. The total flood asymmetric area (y) versus the tidal range (x) per scenario. Linear fits were generated for each scenario. The total area of the Western Scheldt estuary is 267.2 km^2. The total area where flow occurs is on average 260.13 km^2, meaning that there is around 7 km^2 of supratidal shoal area for which no peak velocity ratio was calculated.

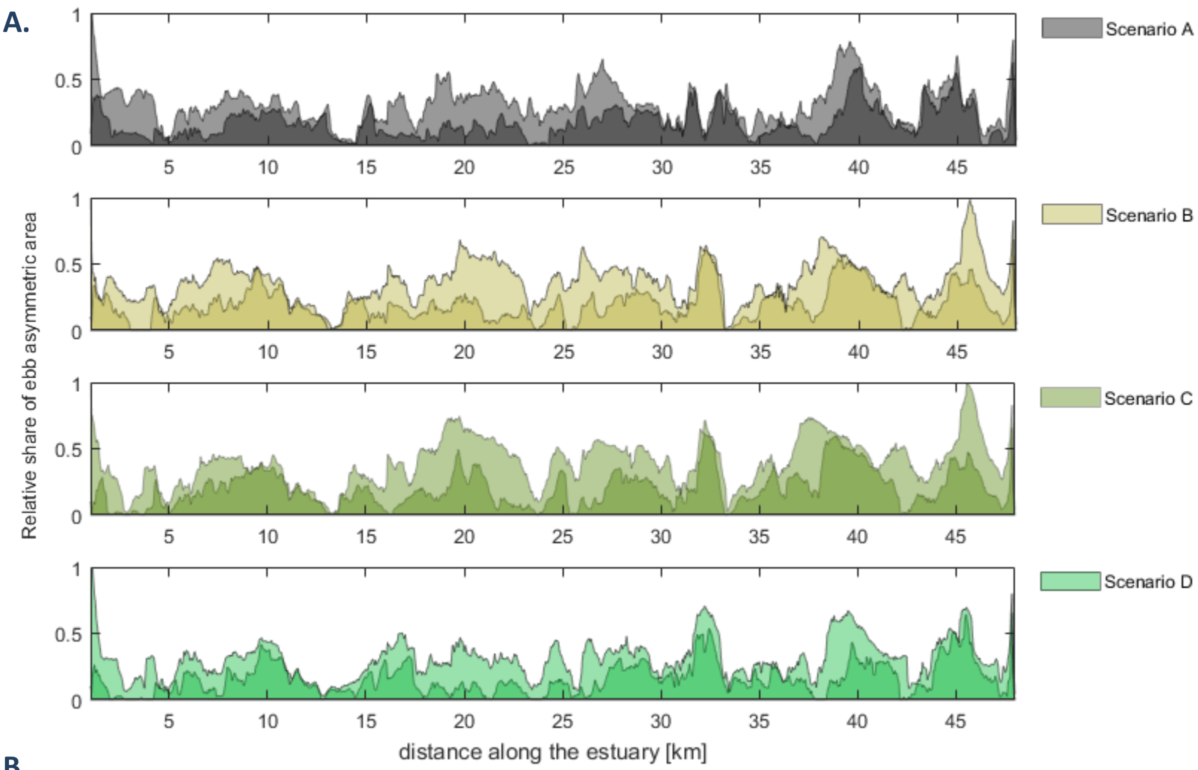
Scenario	Total estuary area (km^2)	Flood asymmetric area (km^2)	Relative Flood area	Ebb asymmetric area (km^2)	Relative Ebb area	R^2	RMSE	RMSE (%)
A	259.35	197.76	76.25%	61.6	23.75%	0.72	9.57	3.62%
B	260.46	190.95	73.31%	69.51	26.69%	0.90	6.70	2.61%
C	260.37	190.41	73.13%	69.97	26.87%	0.89	6.75	2.60%
D	260.33	203.61	78.21%	56.72	21.79%	0.82	7.28	2.77%

Table 5. The average division of asymmetric area per scenario and quality of the fit between the tidal range and the amount of asymmetric area.

The differences in the average division of asymmetric area between scenarios are small: scenarios B and C have a slightly lower mean flood asymmetric area and higher ebb asymmetric area than scenario D. There is no significant difference between the total flood and ebb asymmetric areas of the scenarios (P=0.26 with a multiple comparison test). Still, there is a decrease in total flood asymmetric area in scenario B and C, while there is a small increase in flood asymmetric area in scenario D (table 5). From an estuary management standpoint this is important, as it means that a small change in the dredging strategy can influence the tidal asymmetry and sediment transport. Increasing ebb asymmetry can mean an increase in sediment import (depending on the tidal duration, which is required to establish the net sediment transport), this is a positive development for the system dynamics in the estuary.

Relative share of ebb asymmetry along the length of the estuary

A.



B.

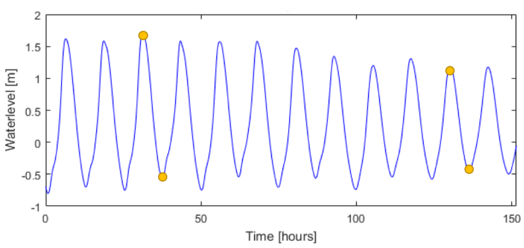
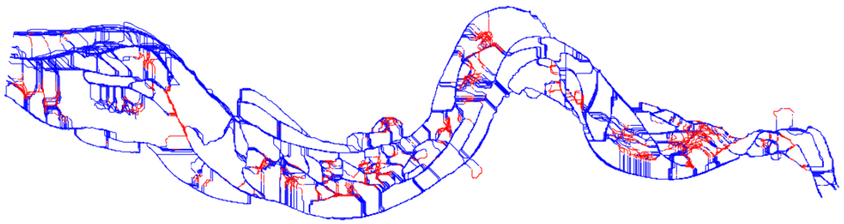


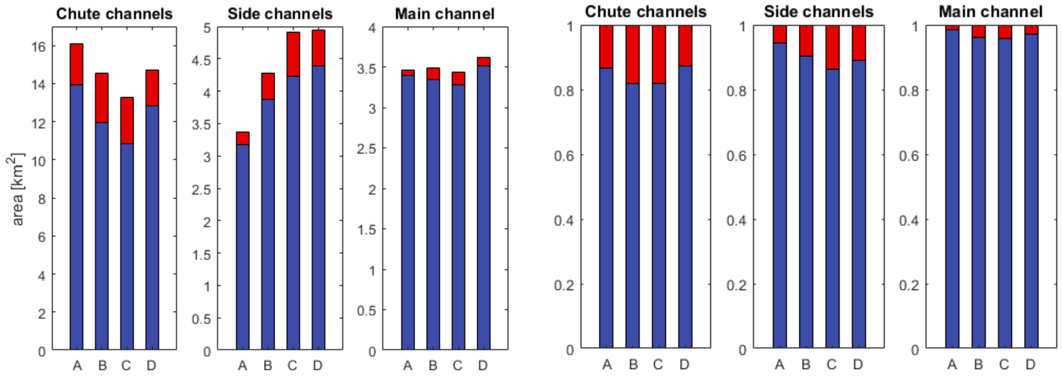
Figure 32. (A) The relative share of ebb asymmetry over the length of the estuary for the largest and smallest tidal range. Darker color indicates overlapping of the ebb asymmetry share. Lighter colored area indicates range of ebb asymmetry share. Given per scenario A to D from upper to lower figure. (B) The two tidal cycles for which the ebb asymmetry is displayed.

When looking at the changes in relative ebb asymmetry over the length of the estuary, a similar pattern to that seen for relative flood asymmetry appears (figure 32). Both scenario B and C have a higher amount of ebb asymmetry, while scenario D has a lower amount. At spring tide, these differences are all significant (P=4.63e-13 with a multiple comparison test), while at a smaller tidal range only B and C are significantly higher (P=2.36e-7 with a multiple comparison test). Thus, while the total area in the estuary does not change significantly, the relative area over the length of the estuary does change significantly. Scenario B, flexible disposal, and scenario C, disposal in the side and main channels, increase the amount of ebb asymmetric area, while scenario D, disposal in the main channel scours, seems to have an opposing effect. In scenario D, there is even less ebb asymmetric area than in the baseline scenario A, although this difference is not always significant. Still, this finding is important because it is generally thought that dredging and disposal results in a tendency towards ebb asymmetry, thereby decreasing the flood asymmetric area, but these findings suggest there is a strategy that results in the opposite effect and increases the flood asymmetric area, even if only slightly.

A. Tidal asymmetry in channels during peak flood

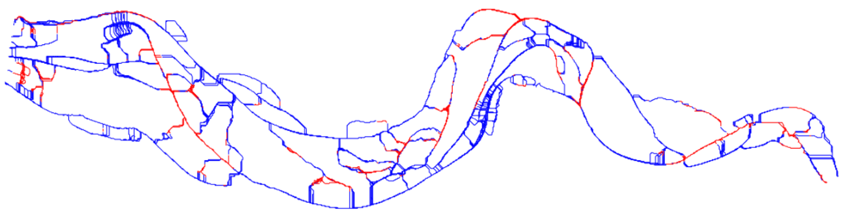
Channel networks for Scenario A





B. Tidal asymmetry in channels during peak ebb

Channel networks for Scenario A



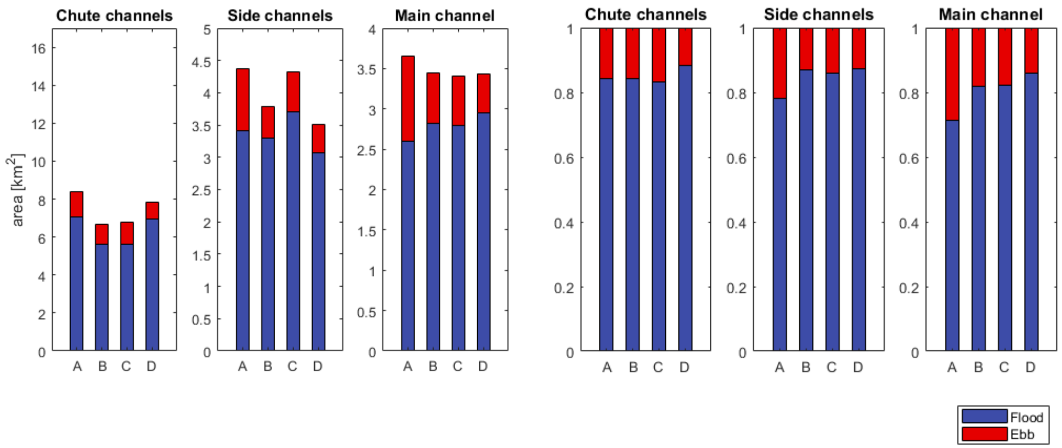


Figure 33. (A) The tidal asymmetry during peak flood: classified networks for scenario A (Left) summarized per scenario in the absolute (Middle) and the relative (Right) division of flood and ebb asymmetric area per channel group. (B) The tidal asymmetry during peak ebb: classified networks for scenario A (Left) summarized per scenario in the absolute area (Middle) and the relative share (Right) of flood and ebb asymmetry per channel group. All figures summarize data for 13 tidal cycles that take place over the course of a week.

5.4.1.2. Division of tidal asymmetry in the channels

Apart from examining the division of tidal asymmetry in the estuary, I also look at the division in the channels (figure 33), as most sediment transport takes place in the channels (Bolle et al., 2010). Therefore, changes in tidal asymmetry in the channels would influence morphodynamics most. The differences between the total relative tidal asymmetry of all channels are small; scenario C has a lower flood asymmetry while scenario D has a higher flood asymmetry, and scenario B is only a fraction lower than scenario A (table 6). Therefore, while the total amount of flood asymmetry is lower across the whole estuary in scenario B, the relative flood asymmetry in the channels is still similar to the baseline scenario (table 5; table 6).

Scenario	Flood asymmetry all channels (%)	Chute channels	Side channels	Main channel
A	85.46	85.86	85.09	84.47
B	85.22	82.59	88.81	89.10
C	84.56	82.36	86.05	89.00
D	88.55	87.69	88.31	91.60
Scenario	Ebb asymmetry all channels (%)	Chute channels	Side channels	Main channel
A	14.54	14.14	14.91	15.53
B	14.78	17.41	11.19	10.90
C	15.44	17.64	13.95	11.00
D	11.45	12.31	11.69	8.40

Table 6. The relative flood & ebb asymmetric area in all channels and per channel scale.

In the main channel there is a relative decrease in ebb asymmetric area for all dredging and disposal scenarios; this decrease is the largest in scenario D, and close to equal in scenarios B and C (figure 33; table 6). In the side channels, the ebb asymmetric area during peak ebb decreases with dredging and disposal and increases during peak flood, while the average ebb asymmetric area decreases in the side channels with all dredging and disposal scenarios (figure 33). In the chute channels the average ebb asymmetric area increases in scenario B and C but decreases in scenario D (figure 33; table 6). In scenarios B and C, the ebb asymmetric area increases in the chute channels but decreases in the side and main channels. At the same time, in the baseline scenario the division between flood and ebb asymmetry is approximately equal in all channel groups. Especially in scenario B and C (but also in scenario D), the differences in tidal asymmetry between the three channel groups increase as compared to the baseline scenario. Overall, flexible disposal and disposal in the side and main channel lead to a relatively larger amount of ebb asymmetry in the channels, while disposal only in the main channel reduces ebb asymmetry (table 6).

Scenario	Ratio	Chute channels	Side channels	Main channel
A	1.4419	1.5078	1.4517	1.4224
B	1.5469	1.4937	1.5705	1.4999
C	1.5132	1.5041	1.5303	1.4790
D	1.5583	1.5913	1.5971	1.4808

Table 7. The average peak velocity ratio in all channels and per channel scale.

The value of the peak velocity ratio increases for all dredging and disposal protocols (table 7). For the baseline scenario the peak ratio decreases from the smaller chute channels to the side channels and the main channel. For the dredging scenarios, the side channels have a higher peak ratio than the chute and main channels in every instance. Scenario D is different than the other three in the sense that the peak ratio is very similar in the chute and side channels.

Furthermore, there is a strong fluctuation in tidal asymmetric area between the peak ebb and peak flood moment (figure 33). This fluctuation is largest in the main channel, lower in the side channels and barely present in the chute channels (figure 33). Although there is a strong variation in the area the chute channels cover between peak flood and ebb (figure 33), the fluctuations in tidal asymmetry are clearly largest in the baseline scenario. For all dredging and disposal scenarios the fluctuation in tidal asymmetry decreases by a similar amount. In the side channels, dredging and disposal results in a relatively stable proportion of the area being ebb asymmetric, but the fluctuation in area covered increases in the main channel: the main channel covers less area during peak ebb and covers more area during peak flood (the opposite occurs in the baseline). The fluctuation in the division of tidal asymmetry for all the channels is not present in scenarios B and C, while the fluctuation is present in scenario D, but not as much as baseline scenario A (figure 33).

Conclusions

- There is spatial variation in the impact of the dredging and disposal scenarios on peak velocity. The decrease in peak velocity becomes larger further inland and the largest decrease is caused by flexible disposal (scenario B) and disposal in the side channels and main channel scours (scenario C).
- There is channel scale variation in the effect of dredging and disposal on peak velocity. The side channels are most heavily affected by dredging and disposal, especially during peak ebb. The peak velocities in the side channels lag increasingly behind those in the main channel, while the trend is reversed for the chute channels.
- There is a larger amount of tidal wave amplification with dredging and disposal. The effect is strongest for flexible disposal, followed by side and main channel disposal, and is lowest when disposal only takes place in the main channel scours (scenario D).
- On average, there is a larger flood asymmetric area when disposal only takes place in the main channel scours compared to flexible disposal and disposal in the side and main channels. The fluctuations in tidal asymmetry in all the channels between peak flood and peak ebb are smaller with dredging and disposal.

6. Discussion

This chapter reviews the implications of the findings that follow from the scenario comparison. This is done by focusing on three main topics that are closely related to each other: the tidal flow dynamics, the morphology and the channel network complexity. In addition, I discuss the effects that dredging and disposal have on estuaries in general, not just the Western Scheldt estuary.

This is followed by an assessment of the two types of channel networks: bathymetry based networks and the novel flow field based networks. I discuss which new insights we can acquire from the comparison of the two network types and what we can learn from flow field based networks about the tidal flow dynamics. Of course, using flow fields currently still has its uncertainties and limitations, so these will not be overlooked. A set of recommendations is given for management of the Western Scheldt, based on the scenario comparison in chapter 5 and the implications of the findings that are discussed here, in subchapter 6.1 and 6.2. The study closes of with a few ideas for future research.

6.1. Implications of the changes in tidal flow dynamics with dredging and disposal

This study focused on the changes in tidal flow dynamics, specifically the mean flow conditions, peak flow velocity, tidal amplification & the tidal asymmetry, and how these are affected with dredging and disposal. This section goes over the implications of the changes in tidal flow conditions that stem from dredging and disposal. It discusses what effect a change in tidal asymmetry could have on the sediment transport, explores the changes in the tidal wave in comparison to previous studies, and examines why the impact seems to be larger in the eastern Western Scheldt and in the eastern share of the main channel.

6.1.1. Changes in tidal asymmetry

Tidal asymmetry is a major forcing factor of morphological change in estuaries, influencing both erosion and sedimentation rates (Moore et al., 2009). This study indicates that dredging in the main channel scours (scenario D) results in a lower ebb asymmetric area and higher flood asymmetric area, while the ebb asymmetric area increases with flexible disposal (scenario B) and disposal in the side and main channels (scenario C). The latter two findings are in line with previous research, which found deepening of the channel (i.e. dredging) leads to a decrease in flood dominance and an increase in ebb dominance (Bolle et al., 2010; Wang et al., 2002), and a scaled experiment, where a tendency towards ebb asymmetry with dredging and disposal was found (Cox, 2019). When disposal only takes place in the main channel scours (scenario D), however, this study finds that the tendency towards ebb asymmetry is absent. The amount of flood asymmetric area is then even higher than in the baseline scenario, and both scenarios A and D have similar relations to tidal amplitude.

The research also shows an increase in flood asymmetry with increasing tidal range, which is in line with previous research stating that high tidal amplitudes enhance flood dominance (Fortunato & Oliviera, 2005). As there is a significant increase in the average tidal range with dredging and disposal, and high tidal ranges are thought to enhance the flood asymmetry, one might expect there to be a concomitant increase in flood asymmetric area with dredging and disposal. The opposite, however, is true, as there is a larger amount of ebb asymmetric area with flexible disposal (scenario B) and disposal in the side and main channels (scenario C) for any given tidal amplitude. The increase in ebb asymmetric area indicates a larger area where sediment is transported seawards. When assuming an unchanged tidal duration, this would result in an increased sediment export. Depending on the amount by which the sediment export increases, this could result in a negative sediment balance. Especially, when taking into account that the import of sediment is similar to the amount removed by sand mining (Wang et al., 2015), it is possible that even small changes can alter the overall net sediment transport direction. Already, the mouth of the Western Scheldt estuary is exporting sediment rather than importing it, which is thought to be related to exceedance of a critical threshold depth of the estuary (Bolle et al., 2010; Wang et al., 2015).

6.1.2. Tidal dominance and the net sediment transport direction

To truly understand changes in the net sediment transport direction, it is important to take the tidal duration into account as well. The tidal asymmetry examined in this study, indicates the direction of the sediment transport, but does not indicate the duration of transport in that direction. The tidal duration does, and therefore needs to be taken into account to calculate the net sediment transport and determine the implications for the sediment budget. While the tidal duration is not incorporated in this study, Brown & Davies (2010) conclude that bottom friction promotes tidal flood duration, while build-up of tidal flats promotes tidal ebb duration. As dredging in the Western Scheldt has resulted in a smoothening of the bathymetry, which reduces bottom friction (Nichols, 2018), and leads to an accumulation of sediment of the shoals (Cox, 2018), ebb tidal duration is likely increasing with dredging and disposal.

The increase in ebb tidal duration was confirmed in a scaled dredging experiment (Cox, 2018). Although further research would be needed to prove this trend for the Western Scheldt, it could mean that the estuary is becoming more ebb dominant and experiencing sediment export or a decrease in sediment import, depending on the volume changes influencing the sediment balance. An increase in ebb dominance would be a negative development as ebb dominance is linked to higher erosion rates (Moore et al., 2009) and loss of protective capacity (Bij de Vaate, 2018). While flood dominance is associated with higher sedimentation rates (Moore et al., 2009), which leads to infilling and better coastal protection (Bij de Vaate, 2018).

On the other hand, the deepening of the main channel with dredging and disposal would be accompanied by a decrease in the ebb tidal duration, based on a higher propagation of LW with increasing depth (van der Spek, 1997). This would suggest a decreasing ebb tidal dominance. It therefore depends on the strength of each change what the final effect is on the net sediment transport. As the findings show for the asymmetric area, the changes and their magnitude differ per dredging and disposal protocol. The implemented protocol can thus have a large effect on the final outcome.

6.1.3. Consequences of tidal amplification

Dredging and disposal has been shown to increase tidal amplification, by altering the intertidal surface area, the convergence length of the estuary, channel depth and effective hydraulic drag (Winterwerp, 2013). The increase in tidal amplification with dredging and disposal has been confirmed by this study: it was largest with flexible disposal, followed by disposal in the side and main channel and smallest with disposal in the main channel scours. Added tidal wave amplification and acceleration of the tidal wave in the estuary decreases the difference in net water level between neighbouring channels (Swinkels et al., 2009). The temporal evolution of chute channels is primarily driven by these net water level differences (van den Berg et al., 1996; Swinkels et al., 2009). Consequently, the chute channels are negatively affected by the increase in tidal amplification and respond by a decline in size or reduction in number of chute channels. This is confirmed by the average active chute channel numbers in this study, which significantly decrease (between 17% and 20%) with dredging and disposal. A lower number of chute channels is harmful for the ecological value of the ecosystem, as well as for the network complexity and system dynamics, as connecting channels exhibit high migration rates (van den Berg et al., 1996).

6.1.4. Impacts on the eastern Western Scheldt

This study observed a decrease in peak velocities with dredging and disposal, but only on the eastern share (e.g. inland share) of the Western Scheldt, getting larger from the middle to the most eastern part (5.4.1., figure 28). The peak velocity decrease is not observed in the outer share of the Western Scheldt. A probable reason for this is that the most intense dredging activities take place in the eastern part of the Western Scheldt, which is the result of several shallow sills there (Bolle et al., 2010; Swinkels et al., 2009). The change in peak velocities would then be related to the change in depth caused by dredging (for bathymetries see Appendix A.1). A brief look at the bathymetry of each scenario shows that the depth is on average one meter deeper in the eastern share of the estuary with dredging and disposal, and one meter shallower in the outer share for scenario B and C (Appendix A.2.). The depth in the middle share, on average, decreases slightly relative to the baseline scenario (10cm to 30cm; Appendix A.2.). Dredging and disposal therefore has a variable impact on the average depth per estuary share and increases the average depth in the eastern share of the estuary.

Additionally, the flow velocity in the eastern share of the main channel decreases with dredging and disposal, while the rest of the main channel has a significantly higher flow velocity with dredging and disposal; this is further discussed below.

6.1.5. A flow velocity reduction in the main channel

There is a decrease in mean flow velocity with dredging and disposal, not only in the side and chute channels, but also in the main channel, while the expectation was that dredging increases the flow velocity in the main channel, as it reduces bed friction (Nichols, 2018). A profile of the flow velocity in the main channel showed that the decrease in flow velocity was mainly taking place in the most inland 25 km of the main channel (figure 23). The first 48.5 km of the main channel still has a significantly higher flow velocity in dredging and disposal scenarios B and C. This is in line with findings of the VNSC (2013), who found higher flow velocities in the seaward sections of the Western Scheldt.

One of the mechanisms that leads to dredging increasing the flow velocity, is reduction in channel depth variability in the main channel, which takes place when shallow and deeper sections in the channel are removed (Cox, 2018). The reduction in channel depth variability, reduces friction and, in theory, increases the flow velocity through the main channel, as well as further amplifying the tidal wave. The tidal amplification is present in this study and is actually largest in the eastern/inland share, where the main channel flow velocity significantly decreases.

Relative to the baseline scenario A, the main channel has lower peak ebb velocities especially in the most eastern bend of the main channel with dredging and disposal, for the peak flood velocity it is less clear (figure 34, location 1; negative velocities indicate a higher velocity in the baseline scenario and a lower velocity in the dredging and disposal scenario). A possible explanation for this observed reduction in flow velocity in the main channel with dredging and disposal is related to the model set up. The main channel in the baseline scenario A seems to become deeper as a result of the transverse bed slope predictor used in Delft3D that influences channel incision (Appendix A.1 & A.3). In all but the baseline scenario, this final bend of the main channel is dredged (figure 35). Dredging interferes with the channel incision and results in a smoother channel floor with a lower depth variability, relative to the more incised main channel in the baseline scenario. All in all, the deeper incision of the main channel occurring in baseline scenario, seems to increase the flow velocity in the channel.

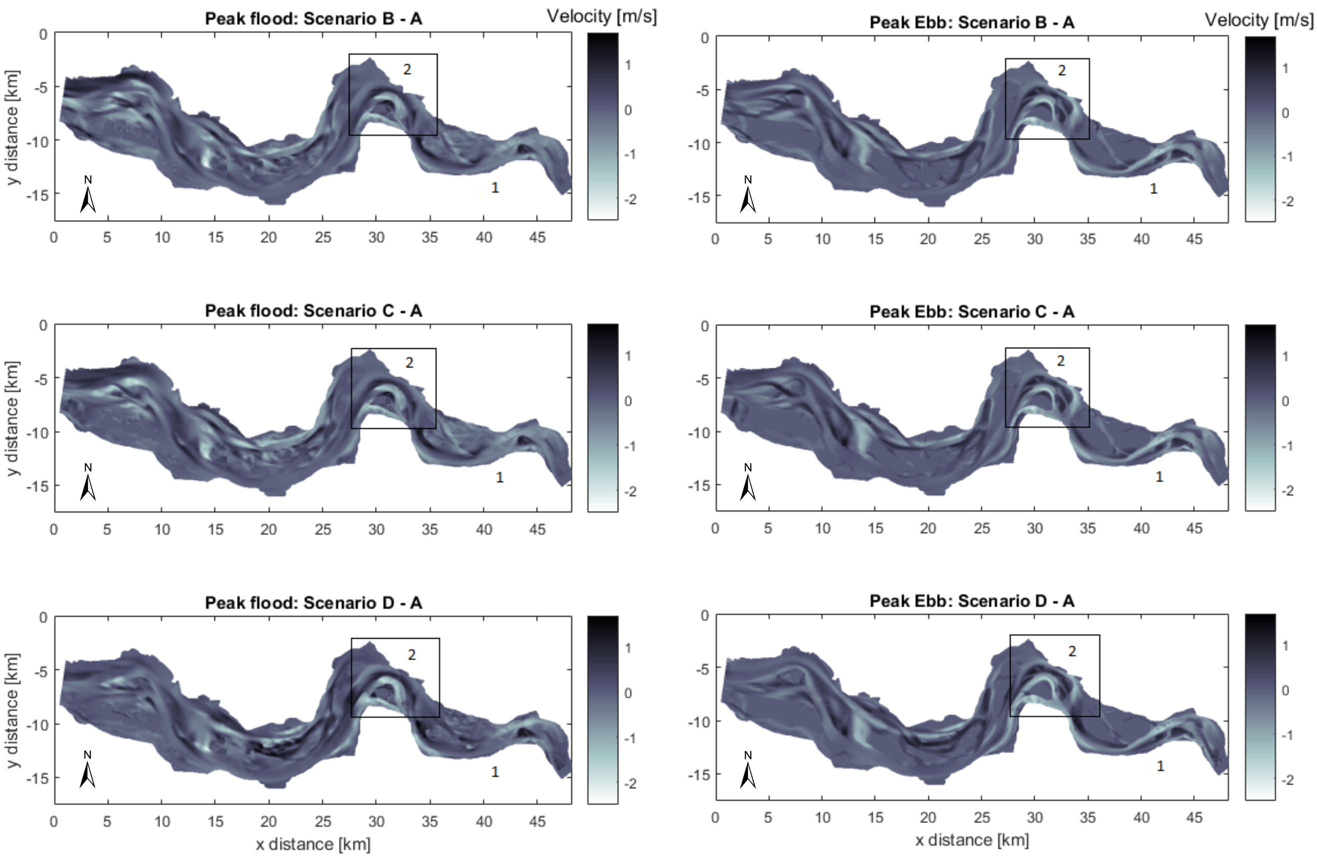


Figure 34. The velocity difference between the dredging scenario and the baseline scenario to assess where the baseline velocity is higher than the dredging and disposal velocity. The merged flow fields are used, per scenario for the spring tide after 40 modelling years. The peak flood flow fields on the left and the peak ebb flow fields (without ebb threshold) on the right.

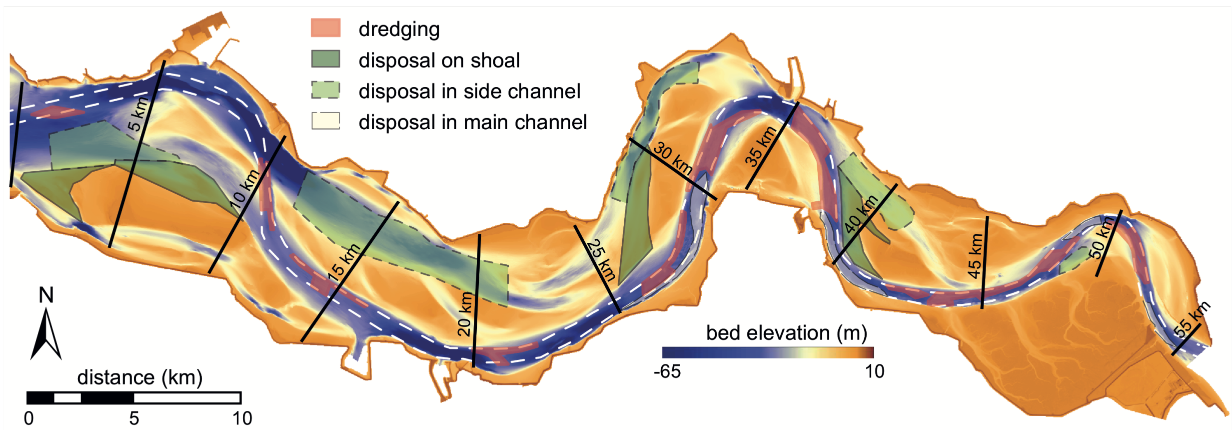


Figure 35. The locations that are dredged in the main channel in each of the scenarios & the locations used for disposal. In scenario B all three disposal locations are used, scenario C uses the main and side disposal locations and scenario D only uses disposal locations in the main channel (Figure from van Dijk et al., 2019b).

6.2. Implications of the changes in Network complexity with dredging and disposal

This research is one of the first to use flow field based networks, and compare them to bathymetry based networks, to establish the network complexity of the estuary and the changes that take place in this complexity with dredging and disposal. The network complexity depends on the number of channels in the network at different scales and has been intensively studied for the Western Scheldt, as dredging and disposal is thought to decrease the network complexity (Hibma et al., 2008; Jeuken & Wang, 2010). A decrease in network complexity of the multichannel system is undesirable, as this means a decrease in the ecological value of the estuary and affects the ecosystem services the Western Scheldt offers (de Vet et al., 2017). This study looks at the network complexity in terms of the flow patterns, which are dynamic and ever-changing. The following subsections compare the findings of this study, based on the flow field based networks, to previous studies examining the network complexity of the Western Scheldt and other estuaries in terms of the channel numbers and dynamics of the channel system.

6.2.1. Maintaining the multi-channel system

A decrease in network complexity is one of the main concerns with intensive dredging and disposal operations (Jeuken & Wang, 2010). It is thought that over time a certain threshold can be reached, after which the estuary shifts to a different equilibrium with a lower network complexity. This theory was introduced by Wang & Winterwerp (2001), who estimated the threshold to be around 10% of the total transport capacity of a macro cell in the Western Scheldt estuary. The theory is further elaborated by Jeuken & Wang (2010), who estimate the critical level for closure of side channels to be 5-10% of sediment transport capacity of the channels. This theory was also confirmed by Cox (2018), who observed in scaled experiments that the natural ebb-flood channel system becomes unstable when dredging and disposal reach a critical level, after which the system becomes a single channel system. The current study did not find a shift to a single channel system, but there was a clear decrease in network complexity with dredging and disposal.

When comparing the flow fields and channel networks from the baseline scenario to the dredging and disposal scenarios there are already clear differences in the network and its complexity. The baseline scenario has 4 flow paths at location 2 in figure 33, while the other scenarios have one clear main flow path at this location. It could be that when the system dynamics are limited over a long time by dredging and disposal fewer active flow paths are present.

The outcome is that dredging and disposal indeed changes the active channel number, but the effects differ per channel scale: the chute channels decrease, while the side channels increase slightly or remain equal. The reduction in the active chute channels is in line with the predictions of Swinkels et al. (2009), who stated that dredging can reduce the number of chute channels through a change in the depth ratio between channels of different scales. The number of active side channels actually increases by 17% compared to the baseline scenario when disposal does not take place in these channels, but is only taking place in the main channel scours. The average side channel velocity, however, decreases the most with this strategy. The expectation would be that this results in more sedimentation, resulting in less flow along the active side channels, but the effect of disposal in the side channels seems to be stronger. Disposal in the side channels causes and promotes the infilling of these channels, more so than a decrease in flow velocity does. The infilling of side channels is proven by the decreasing depth of side channels over time, when used for disposal of dredged sediment (van Dijk et al., 2019b).

In reality, the network complexity could show a smaller absolute decrease in channel numbers by 2055, as the total channel number in this study is quite high in relation with the present channel number. This study examines changes in active channel numbers as a measure of network complexity. The active channel number is used as an active braiding index and describes all active flow paths in the estuary, so while a lower amount of active channels indicates that there are less chute channels present in the bathymetry, it still is only an approximation of the actual channel number.

While known that dredging and disposal can have a negative impact on the network complexity, flexible disposal, as currently implemented, is thought to have a lower negative impact on the network complexity than previous strategies (Roose et al., 2008). However, the results of this study show that the differences regarding channel number between the three dredging and disposal scenarios tested are small – for both chute and side channels in the range of three channels. It is actually disposal in the main channel scours that results in the highest network complexity; this results in the highest amount of active side and chute channels out of the three examined dredging and disposal strategies. As a high number of chute channels is desirable from an ecological standpoint (Swinkels et al., 2009), disposal in main channel scours could be the best strategy to maintain a high network complexity while implementing dredging and disposal.

In addition, there are other factors that can influence the network complexity, such as the vegetation species, density and distribution (Bij de Vaate, 2018). For instance, one of the important criteria for the maintenance of the multichannel system, a high overall width-to-depth ratio of the channels, can be reduced by vegetation due to its the stabilizing effect on channel banks which fixes the channel width (D'Alpaos et al., 2006). In addition, deepening of the dredged channel and disposal in the side channels results in an disequilibrium in the width-depth-ratio between the main and the other channels, destabilizing the multichannel system (van Dijk et al., 2019b).

6.2.2. Developments in estuary morphodynamics

Dredging and disposal can limit the system dynamics in the Western Scheldt by interfering with natural sediment transport patterns and reducing chute and side channel migration (Jeuken & Wang, 2010; van Dijk et al., 2019b). Changing the disposal locations only minimally counteracts the effect on channel migration (van Dijk et al., 2019b). If no dredging would occur and the natural system dynamics take their course, this study shows there would be a much higher network complexity, with a significantly higher chute channel number. An increase in the number of rapidly migrating chute channels would mean that the system dynamics also increase (Swinkels et al., 2009). With dredging and disposal there are fewer chute channel flows, which would result in a less dynamic system.

While dredging and disposal reduces the overall system dynamics of the estuary, SLR is expected to increase the dynamics of side and chute channels (van Dijk et al., 2019b). Thus, SLR provides an opportunity to restore the system dynamics in the Western Scheldt. On the other hand, the main channel is expected to become fixed even further with SLR (van Dijk et al., 2019b).

At the same time, SLR can help restore ecologically valuable intertidal area, which, on average, is decreased by dredging and disposal (van Dijk et al., 2019b). The intertidal area declines as a result of the overall increase in tidal flat elevation (de Vet et al., 2017). Similar to intertidal flats in other dredged channel-shoal systems, such as Tieshan Bay (Wang et al., 2014) and the Yangtze estuary (Wang et al., 2015). If the sea level and tidal flat elevation increase at the same rate, the amount of intertidal area will remain somewhat constant (van Dijk et al., 2019b). This could prevent a loss of intertidal area, which would prevent a decrease in ecological value and loss of important habitat, and increased flood risk. Moreover, as tidal flats can enhance ebb dominance (Fortunato & Oliviera, 2005), SLR might counteract the increasing extent of the tidal flats at or above mean water level, thereby lessening the enhancement of ebb dominance by the tidal flats.

6.3. Flow field versus bathymetry based channel networks, and the Network Tool

The following section compares the use of flow field based networks and bathymetry based networks. I assess what we can learn about channel networks from the comparison between flow field based networks and bathymetry based networks performed in this study, and what the current uncertainties and limitations are affecting the use of flow field based networks.

6.3.1. Comparison of flow field and bathymetry based networks

Tidal flow patterns change at a much shorter timescale than does the morphology of a river system; tidal flow therefore results in highly variable flow field based channel networks that follow the ever-changing high velocity flow paths. These flow paths do not only flow along the actual elevation based channels. Rather, there are many more highest flow paths occurring, covering a large surface area over time. It is likely that prevalent active channel flows in the flow field based networks result in actual channels in the topography, by cutting through the banks and forming or shaping a channel. The three channel scales (e.g. main, side and cute channels) in the networks are therefore not one and the same as the bathymetry based channel scales. In the bathymetry based channel network, the channels are all visible in the morphology, while for instance chute channels in the flow field based network describe an active flow path that is classified as being of a chute channel size.

All of the above makes a one-to-one comparison between the two networks complicated, even though the channel networks are closely related and exhibit many similarities as well. Especially at LW, the channel network follows flow paths similar to the bathymetry based network. This is of course to be expected, as there then is less water in the estuary, which accumulates along the lowest elevation pathways. Occasionally, channels are classified differently between the networks types (e.g. a side channel in the bathymetry based network is classified as a chute channel in the flow field based network, or vice versa). These classifications depend on the discharge going through the channel and the elevation of the channel.

Overall, the Network Tool is an efficient way to generate channel networks, especially for multichannel systems. It provides a good method to analyze tidal flow dynamics, making it possible to efficiently analyze flow dynamics and tidal dominance at a channel scale. The flow field based networks are accurate for analysis of flow velocity and water level changes, but the networks are less useful for analyzing change in depth on a long timescale. Since the flow paths do not only occur along the lowest elevation channels, but cover a much larger surface area. If flow field based networks were used for the purpose of channel depth analysis, the flow field based networks would likely suggest a much higher depth variation than is actually the case in the channels, as the flow paths are highly variable. Over a tidal cycle, depth analysis could show a clear difference in channel depth between ebb and flood, because there are more shallow active chute channels at flood. Besides this, using bathymetry based networks would be more computationally efficient on a long time scale, as flow field based networks require small time intervals. Bathymetry based networks are useful for analysis of both longer timescales, where the aim is to assess morphologic change, and short timescales, which does make them more versatile.

It should also be noted that the workings of the Network Tool are currently still being fine-tuned. This could mean that the calculation used to generate the flow field networks may still be altered. For instance, the use of the threshold scale set for the sand function could be made more straightforward, by creating a formula for the threshold scale that is dependent on the magnitude of the input variable, the grid size and the river type. Rather than setting it manually and changing it by trial-and-error per input type and case study.

6.3.2. Limitations of flow field based channel networks

The channel networks of the flow fields modelled in Delft3D after 40 morphologic years show a stark increase in chute channel numbers (89% for the flow field based networks and 46% for the bathymetry based networks), compared to the flow field based networks after 0 morphologic years. This is caused by the long time span of the modelling in Delft3D and adds uncertainty to a comparison between the 0 and 40 morphologic year networks, as an increase in the number of chute channels of this magnitude is not in the line with the current expectations. If this does take place, it would mean that regardless of dredging and disposal, the network complexity increases over time. The opposite is currently expected, with dredging and disposal implemented (Hibma et al., 2008).

Furthermore, when the Network Tool is used with flow fields as input, it is currently still unclear what the exact meaning of the 'sand' function and threshold scale value (used for this function) is. The function within the Network Tool is used to calculate the difference between channels. In the bathymetry based networks the difference is indicated by the volume of sediment separating the channels; using the depth (m), a volume (m^3) above the saddle point (e.g. point in channel network that is the local minimum one direction and local maximum in the other direction) is calculated. For the bathymetry based networks the function and the threshold value make sense, as the volume is an indicator of the amount of reworking required to cut through the bar and merge the channels (van Dijk et al., 2019b). For the flow field based networks the meaning of the function is less clear, but it is certain that the threshold scale value still describes the minimum discharge difference (m^3/s) between two flow paths. The difference the function calculates is smaller for low flow velocities than it is for high flow velocities. During ebb, the flow is (close to) zero in a larger area of the estuary due to LW, which results in little to no differences between flow paths on the shoals and leads to fewer small channels being defined as sufficiently different in the network. At flood, the velocities on shoals are more variable, which results in higher differences between flow paths and a larger number of small channels. A decrease in the threshold scale value would, for both network types, result in a larger number of sufficiently different channels.

For the flow field based networks in this study, the threshold value was decreased by tenfold compared to the threshold used for bathymetry based networks. The threshold scale value should be altered for different input variables and different river systems, in order to avoid networks with unrealistically high or low channel numbers. For future studies the threshold value used here (1000 m^3/s with flow fields and 10.000 m^3 with bathymetry) could be fine-tuned further for the Western Scheldt, but these threshold values are already a good approximation.

6.4. Recommendations

Currently, a new management plan for dredging and disposal in the Western Scheldt is being prepared for implementation starting in 2022 (VNSC, 2017). This provides the opportunity to adjust the current flexible disposal strategy or change to a new strategy. Moving away from disposal in side channels would be desirable, based on previous research (Swinkels et al, 2009; Roose et al., 2008; Wang & Winterwerp, 2001; van der Wal et al., 2011; Hibma et al., 2008). A new strategy could be disposal in the main channel scours only, based on the findings of this study that there is a decrease in ebb asymmetry, the lower tidal amplification and a lower reduction in peak velocities. On the other hand, the difference in the total channel number between the three dredging and disposal strategies examined is small. Nonetheless, both the number of chute channels and side channels are slightly higher with disposal in the main channel scours only.

As for disposal in scours in the main channel, the location of disposal is an important factor determining the success of this strategy (Cox, 2018). Disposal in the scours of main channels can be a desirable strategy, depending on the implementation and locations of disposal. Disposal in highly erosive locations leads to rapid entrainment of the disposed sediment. It seems that larger scours in which lower volumes are disposed are more likely to erode, while small scours in which large volumes are disposed of are more likely to act as sediment traps (Cox, 2018). Still, there seems to be significant spatial and temporal variation, causing the relation between scour area and depth to the likelihood of erosion to not be statistically significant (Depreiter et al., 2012; Cox, 2018).

If the aim is to achieve the highest complexity network as possible, no dredging or perhaps dredging and disposing a lower volume would be preferable. This is in agreement with the conclusion drawn by van Dijk et al. (2019b) who state that the current dredging and disposal strategies are not sustainable. Overall, the actual effects of the dredging and disposal protocols depend strongly on the exact locations and volumes chosen. More importantly, to reduce the impact of dredging and disposal, the disposal strategy should be given as much consideration as dredging itself (van Dijk et al., 2019b). Therefore, careful planning of the operations is another important factor determining the success of the strategy.

6.5. Further research

There are many possibilities for future use of the Network Tool, especially since it will become publicly available in the near future. Various other studies have already been done using the Network Tool, such as analysis of bifurcations in estuaries (Vlaming, 2018), depth changes in the Western Scheldt (van Dijk et al., 2019b) and extensive testing of the Network Tool on various estuaries (Hiatt et al., 2019). In regard to the Western Scheldt, analysis of present day and historical flow fields would be a welcome research direction, as this study mainly focussed on modelled scenarios. This would provide more insight into historical change in tidal flow conditions, such as tidal asymmetry and tidal dominance. These findings would also put the outcomes of this research into perspective, as this study did not incorporate the current situation of the tidal flow conditions in the Western Scheldt. Moreover, analysis of the changes in tidal duration with each dredging and disposal strategy would be a good addition to the findings of this study, as the tidal duration, in combination with the peak flow velocity ratio, is needed to establish the change in net sediment transport per scenario. From this, the changes in sediment budget related to the different dredging and disposal strategies could be examined.

7. Conclusion

The primary aim of this study was to assess the impacts of three different dredging and disposal strategies on the flow network complexity and tidal flow conditions in the Western Scheldt estuary. This was done by using flow field based channel networks generated with the Network Tool, to analyse the impacts of dredging and disposal at the channel scale and on the whole estuary. The secondary aim was to assess the novel use of flow fields to generate channel networks.

One of the most significant findings is the ~20% decrease in the number of active chute channels with each of the dredging and disposal strategies. The reduction in active channel complexity is highest with disposal in the side and main channels, followed by flexible disposal. Disposal in the main channel scours results in a smaller decrease and is therefore the preferred strategy if the goal is to maintain the highest network complexity of flow paths possible with dredging and disposal taking place.

A second important finding is that disposal in the main channel scours results in an increase in flood asymmetry, relative to the decreases with both flexible disposal and disposal in the side channels and main channel scours. A decrease in flood asymmetry and an increase in ebb asymmetry means that sediment transported seawards increases and transported inland is reduced; this could mean a decrease in sediment import, depending on the tidal duration, which reduces the system dynamics. Therefore, if the goal is to maintain a dynamic multichannel system, disposal in the main channel scours would be the best strategy.

Until now, research has predominantly found that there is a tendency towards ebb asymmetry with dredging and disposal, however this study shows that there is a disposal strategy where the opposite effect takes place. This highlights the importance of the disposal strategy for future estuary management in the Western Scheldt, especially since an increase in ebb dominance suggests higher erosion rates and decreased coastal protection.

Finally, there is a larger decrease of the (peak) flow velocity in the inland share of the estuary and in the side channels with each of the dredging and disposal strategies, showing that the effects of dredging and disposal vary spatially and by channel scale. A flow velocity reduction in the side or chute channels can result in increased sedimentation, causing infilling of these channels. Flexible disposal would be the best strategy to prevent infilling of the side channels, but sedimentation in the chute channels would be lower with disposal in the main channel scours. If the goal is to preserve the ecological value of chute channels, the latter strategy might be preferred. However, the amount of sedimentation along the flow paths resulting from a reduction in flow velocity is not known, which may have significant implications for decision-making; as such, this effect should be further explored.

Overall, this study has demonstrated that the use of flow field based networks allows the researcher to efficiently analyze tidal flow dynamics at a channel scale. To summarize, disposal in the main channel scours seems to have a lower negative effect on the flow network complexity and tidal dominance in Western Scheldt estuary on the long term. This assessment is based on the flow field networks, which overall, provide a good method to analyze tidal flow dynamics.

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Appendix A. Bathymetry

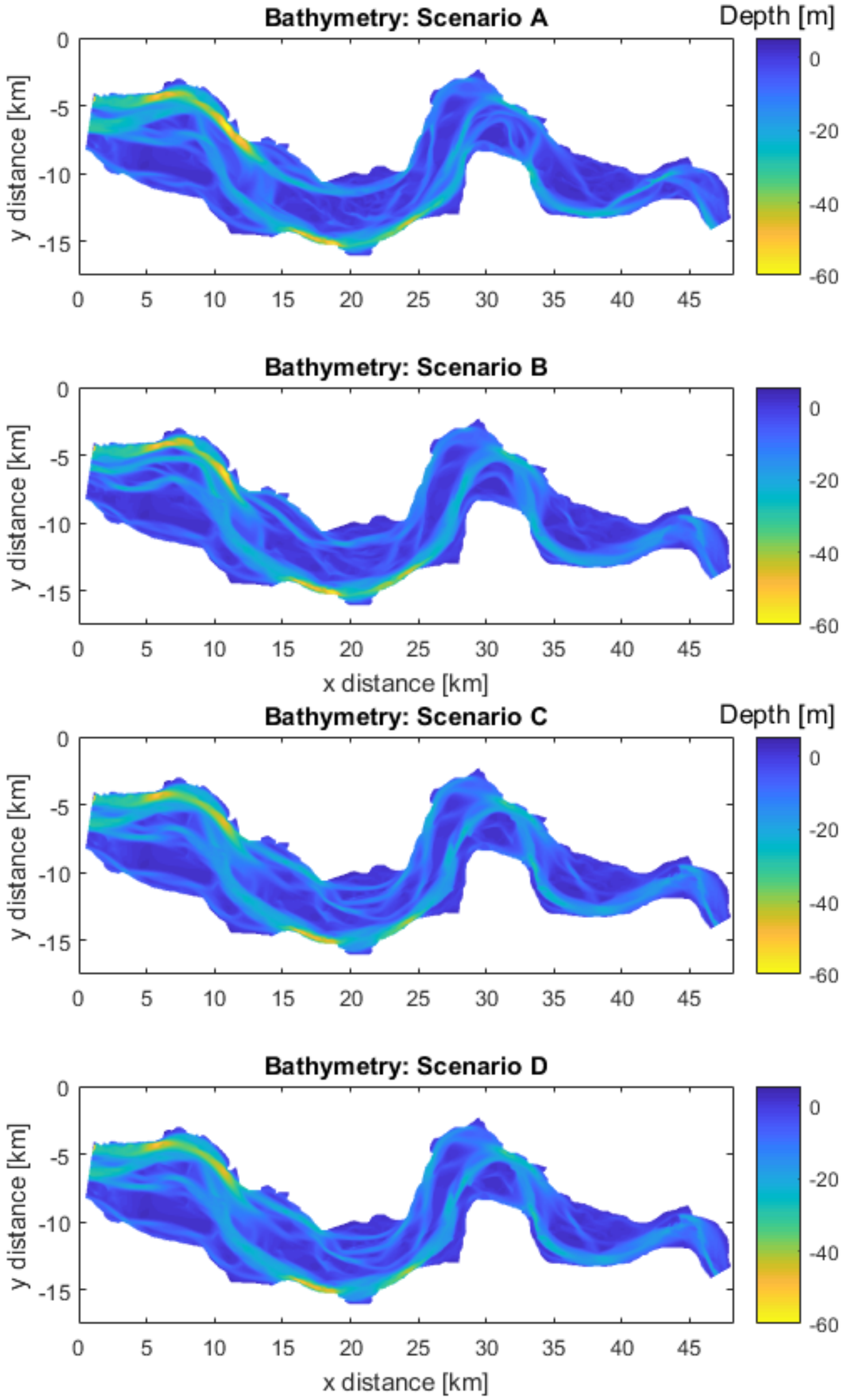

Figure A.1 The bathymetry of the Western Scheldt for each scenario after the 40-year model run. These bathymetries were used as input for the flow field modelling in Delft3D. Scenario A is the baseline scenario (no dredging or disposal), scenario B: Flexible disposal, scenario C: side and main channel scour disposal, scenario D: main channel scour disposal (referred to in 4.1.2. and 6.1.4.)

Mean depth (m) per estuary share	***A***	***B***	***C***	***D***
Outer share	11.98	10.54	10.76	11.56
Middle share	8.74	8.78	8.87	9.00
Inland share	6.20	7.33	7.36	7.40

Table A.2 The average estuary depth [m] (meters below sea level) for the bathymetry of each scenario (after 40 morphological years) (referred to in 6.1.4.). On average the outer share of the estuary becomes a meter shallower for scenarios B and C, while the inner share of the estuary becomes a meter deeper with dredging and disposal.

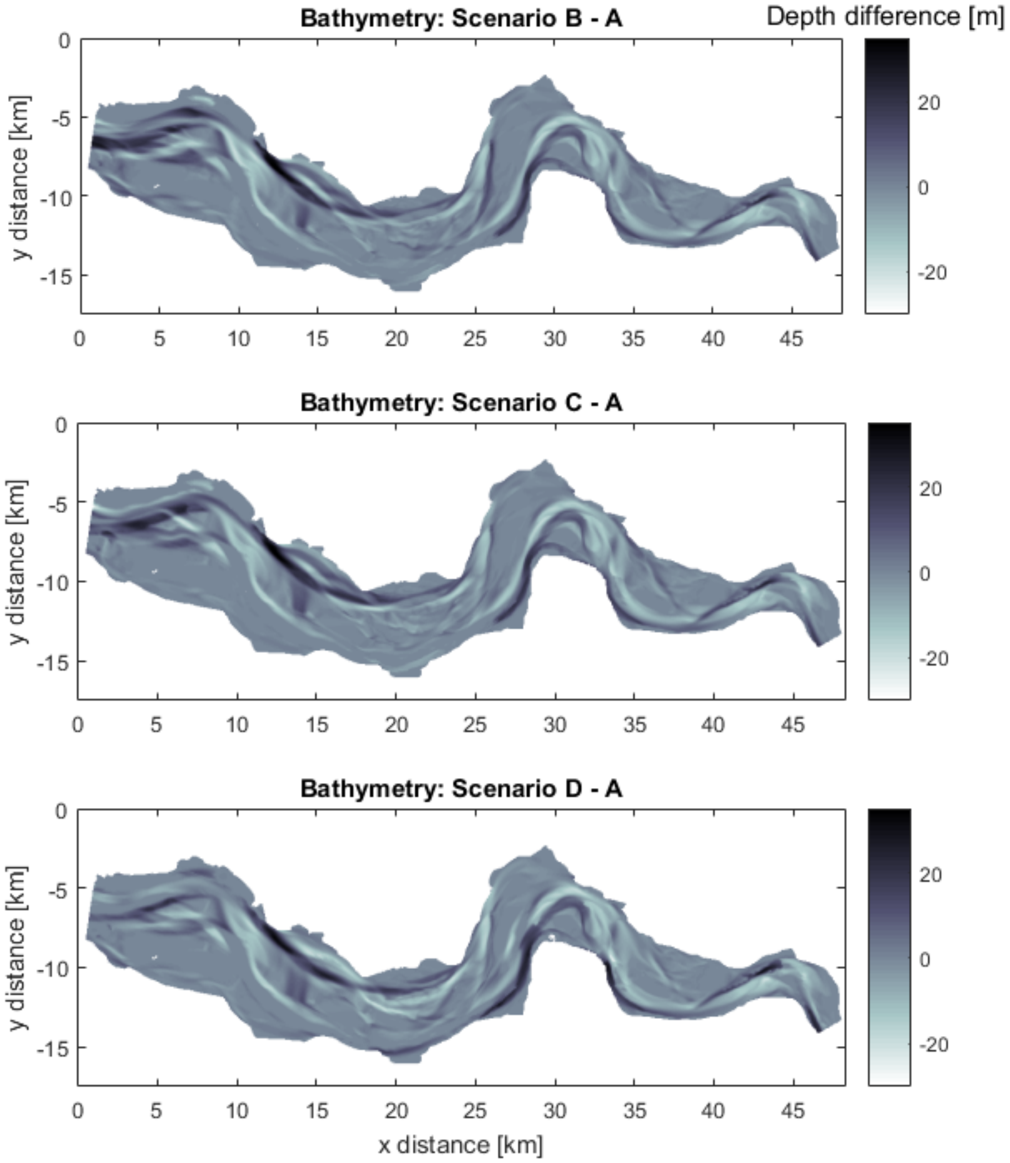

Figure A.3 The difference in depth between each dredging scenario relative to the baseline scenario after the 40-year model run to assess where the estuary becomes deeper with dredging and where it is shallower with dredging. On average the outer (left) share of the estuary becomes a meter shallower for scenarios B and C (positive difference in depth), while the inner (right) share of the estuary becomes a meter deeper with dredging and disposal (negative difference in depth). Scenario A is the baseline scenario (no dredging or disposal), scenario B: Flexible disposal, scenario C: side and main channel scour disposal, scenario D: main channel scour disposal (referred to in 4.1.2. and 6.1.4.).

Appendix B. Peak velocity ratio

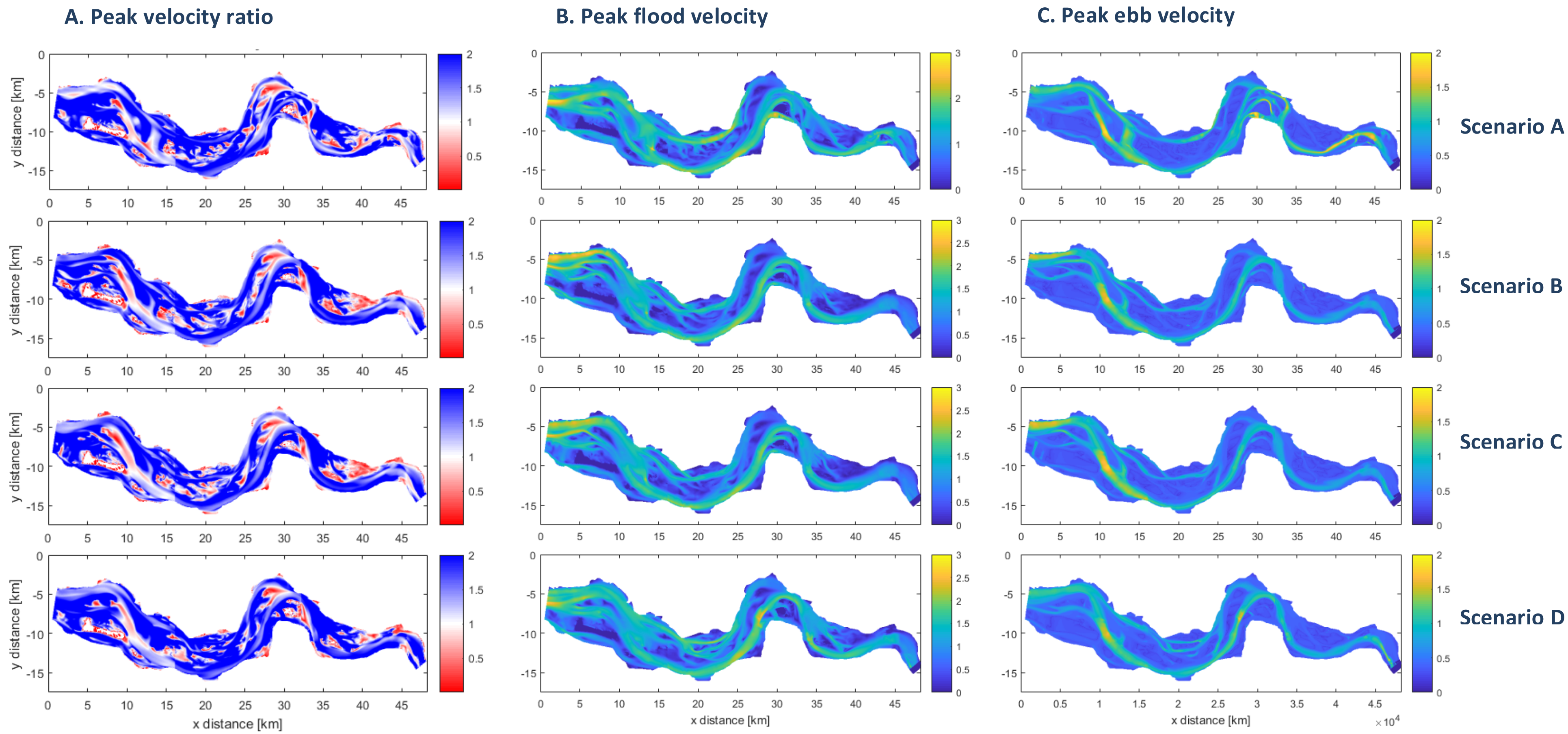

Figure B.1 (A) The peak velocity ratio (blue=flood asymmetry, red=ebb asymmetry), calculated by dividing the peak flood with the peak ebb velocity. Supratidal areas are excluded. (B) The peak flood flow fields per scenario. (C) The peak ebb flow fields (with the threshold ebb velocity implemented). All for a large tidal range (Spring tide) ± 4 m. Scenario A is the baseline scenario (no dredging or disposal), scenario B: Flexible disposal, scenario C: side and main channel scour disposal, scenario D: main channel scour disposal (referred to in 5.4.4.)

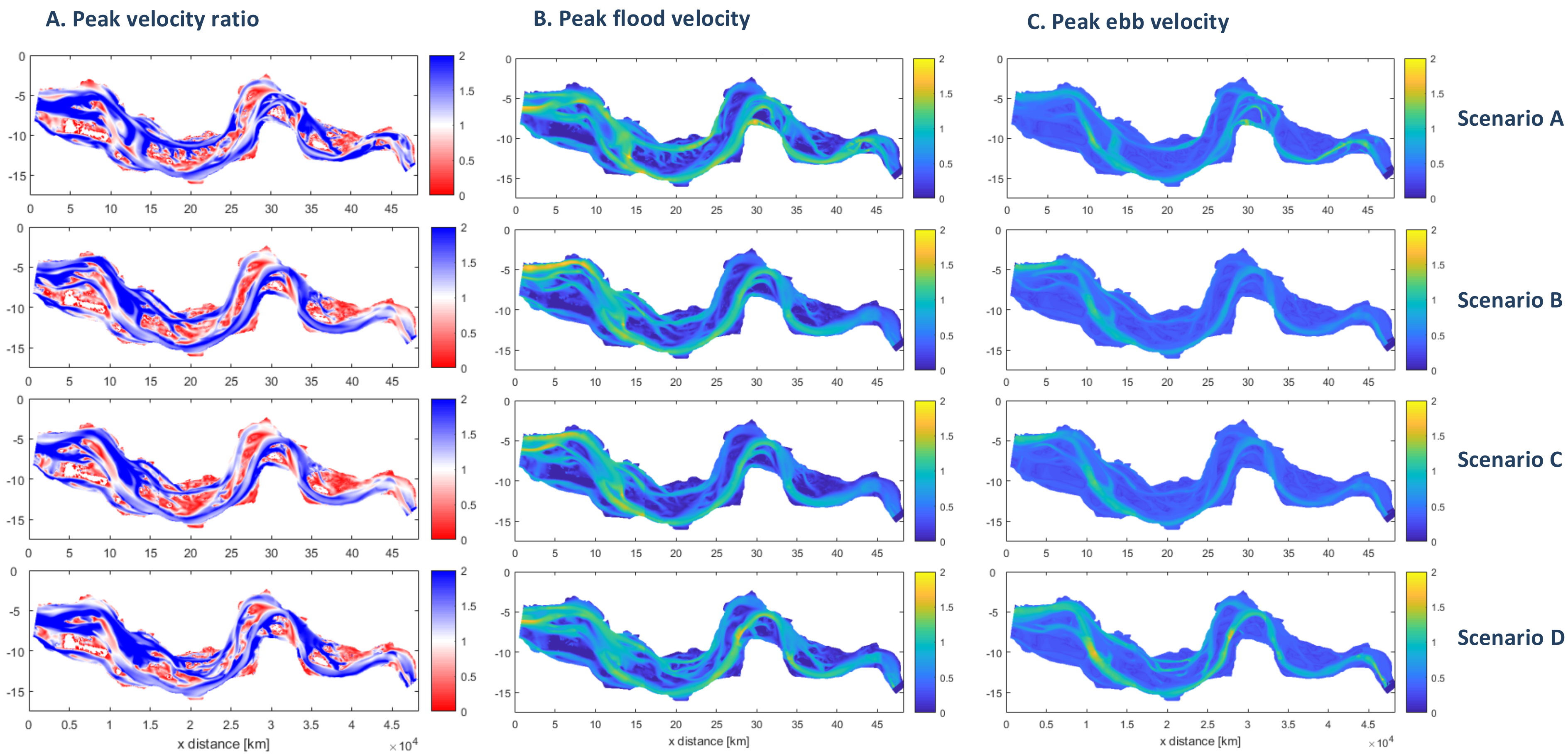

Figure B.2 (A) The peak velocity ratio (blue=flood asymmetry, red=ebb asymmetry), calculated by dividing the peak flood with the peak ebb velocity. Supratidal areas are excluded. (B) The peak flood flow fields per scenario. (C) The peak ebb flow fields (with the threshold ebb velocity implemented). All for a small tidal range (close to neap tide) ± 3 m. Scenario A is the baseline scenario (no dredging or disposal), scenario B: Flexible disposal, scenario C: side and main channel scour disposal, scenario D: main channel scour disposal (referred to in 5.4.4.).

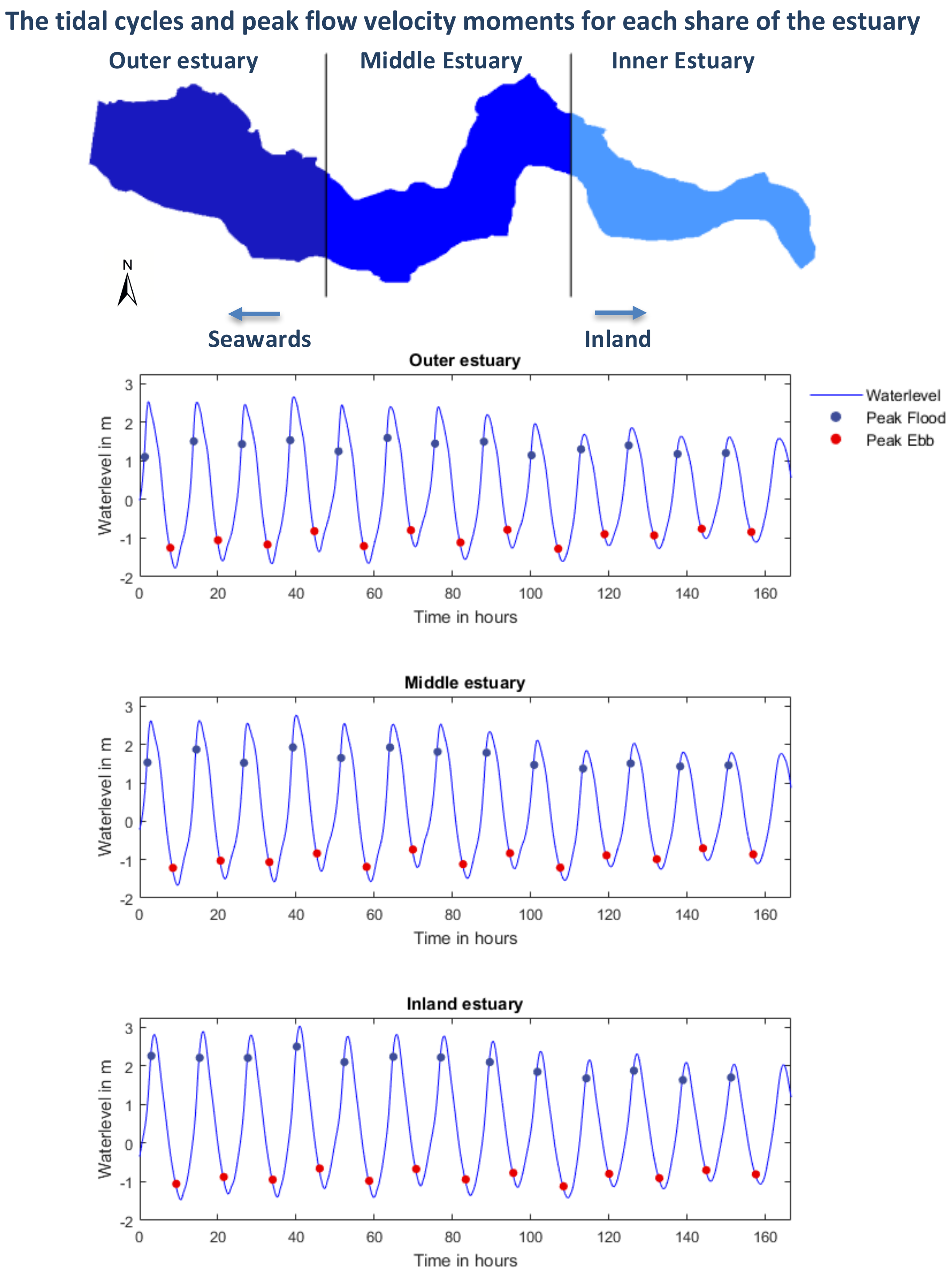

Figure B.3 The tidal cycles and the peak flow velocity moments, established with the use of these tidal cycles due to the lack of a directional component in the flow velocity data. The peak flow moments are established using a phase lag ϕ of 60 minutes between the HW and LW and the peak flow velocity moments that is constant throughout the estuary (van der Spek, 1997). This is a simplification of the actual situation and could be improved for further research, by implementing a phase lag gradient that increases with distance inland (Hibma et al., 2003), and by increasing the phase lag between LW and the peak ebb velocity moment (Dam et al., 2015). Between every estuary share there is on average a 30-minute shift in the timing of the peak flow velocity moment.

Appendix C. Additional data

C.1. The peak ebb velocity [m/s] with the peak ebb threshold per scenario (referred to in 4.3.5). The peak ebb threshold compensates for low values of the peak ebb velocity on the shoals. To test the effect of the peak ebb threshold, which is implemented for the peak velocity ratio calculation.

Means per group	***A***	***B***	***C***	***D***
Chute	*0.660*	*0.630*	*0.580*	*0.610*
Side	*0.870*	*0.640*	*0.650*	*0.590*
Main	*1.140*	*0.987*	*0.996*	*1.030*

C.1. The peak ebb velocity [m/s] without threshold per scenario (referred to in 4.3.5). To test the effect of the peak ebb threshold, which is implemented for the peak velocity ratio calculation.

Means per group	***A***	***B***	***C***	***D***
Chute	*0.590*	*0.550*	*0.490*	*0.550*
Side	*0.840*	*0.570*	*0.580*	*0.500*
Main	*1.140*	*0.987*	*0.996*	*1.030*

C.2. The first quartile (Q1) and the third quartile (Q3) per scenario A to D used to calculate the interquartile (IQ) range in active chute and side channel numbers for each of the scenarios (referred to in 5.2.1).

IQ range	**A Q1**	**A Q3**	**B Q1**	**B Q3**	**C Q1**	**C Q3**	**D Q1**	**D Q3**
Chute	53	87.5	40	79	40	74-	42	79
Side	14	20	15	21	15	21	17	24

C.2. The minimum (min) and the maximum (max) per scenario A to D used to calculate the range in active chute and side channel numbers for each of the scenarios, disregarding outliers (referred to in 5.2.1).

Range	**A min**	**A max**	**B min**	**B max**	**C min**	**C max**	**D min**	**D max**
Chute	40	120	19	110	26	108	25	111
Side	8	29	9	30	7	30	10	34

C.3. The average peak velocity [m/s] (without an ebb peak threshold) used to calculate the absolute and relative range between the main and side channels and the main and chute channels (referred to in 5.4.2).

Means per group	***A***	***B***	***C***	***D***	***Sig difference***
Chute	*0.72*	*0.66*	*0.63*	*0.71*	*No*
Side	*0.99*	*0.78*	*0.74*	*0.75*	*Yes: C*
Main	*1.35*	*1.21*	*1.20*	*1.24*	*No*