Effect of perturbations by shoal margin collapses on the morphodynamics of a sandy estuary

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Key Points:

- Shoal margin collapses perturb the channel-shoal network of sandy estuaries.
- Disturbances cause long-term morphological changes.
- Disturbances amplify asymmetry and instability at channel junctions.

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Abstract

Shoal margin collapses of several Mm^3 have occurred in the Western Scheldt estuary, the Netherlands, more than five times per year over the past decades. While these collapses have considerable volumes, their effects on the morphodynamics are unknown. We hypothesise that collapses dynamicise the channel-shoal interactions, which could impact the ecological functioning, flood safety and navigation in the estuary. The objective of this study is to investigate how locations, probability, type and volume of shoal margin collapse affect the channel-shoal morphodynamics. We implemented an empirically-validated parameterization for shoal margin collapses and tested their effects on morphodynamics in a Delft3D schematization of the Western Scheldt. Three sets of scenarios were analyzed for near-field and far-field effects on flow pattern and channel-shoal morphology: 1) an observed shoal margin collapse of 2014, 2) initial large collapses on 10 locations, and 3) continuous collapses predicted by our novel probabilistic model over a time span of decades. Results show that single shoal margin collapses only affect the local dynamics in longitudinal flow direction and dampen out within a year for typical volumes, whereas larger disturbances that reach the seaward or landward sill at tidal channel junctions grows. The redistribution of the collapsed sediment is determined by the direction of the strongest tidally averaged flow. We conclude that adding the process of shoal margin collapses increase the channel-shoal morphodynamics, and that in intensively dredged estuaries shoal margin oversteepen that amplifies the number of collapses, but because of dredging the natural channel-shoal dynamics are ruined.

Keywords: estuary; shoal margin collapse; channel-shoal morphodynamics; tidal bars; Western Scheldt

1 Introduction

The process of channel bank failure and collapses of shoal margins has been recognized in estuaries and rivers around the world [*Coleman*, 1969; *Laury*, 1971; *Silvis and De Groot*, 1995; *Torrey*, 1995; *Dunbar et al.*, 1999; *Van den Berg et al.*, 2002; *Beinssen et al.*, 2014] but their effect on long-term morphodynamics remains unknown. Application of channel bank failure in a numerical morphodynamic model has been studied more often [*Kleinhans*, 2010; *Nicholas*, 2013a; *Schuurman et al.*, 2013] and mainly focus on outer bank erosion in rivers. Channel banks can also collapse at the inner side of rivers [*Nieuwboer*, 2012], while collapses of shoal margin at the inner side of a bend is more often observed in estuaries because these shoals consist of fine uniform sands [*Wilderom*, 1972; *Mastbergen and Van den Berg*, 2003; *Van Dijk et al.*, 2018]. Because of the relative large volume up to several million m^3 involved. The eroded scar and associated displaced sediment in the channel perturbs the channel, affecting channel geometry, e.g., the width-depth ratio, and channel morphodynamics. In tidal systems perturbations likely propagate in both directions because of ebb or flood flow, but how far and how fast has not been studied. Connections to the rest of the channel network may also determine whether perturbations excite or dampen these processes. We hypothesize that the transverse bed slope steepens due to continuous aggradation, which makes the slopes unstable and could lead to breaching and liquefied flow slides associated to shoal margin collapses [*Van den Berg et al.*, 2002; *Van den Ham et al.*, 2014; *Mastbergen et al.*, 2016; *Van Dijk et al.*, 2018]. We also hypothesize that such morphological perturbations within the system may amplify the morphodynamics in estuaries as much as extreme events imposed in the boundary conditions. This is important because morphological models of estuaries invariably evolve towards bar-scale equilibrium [*Van der Wegen and Roelvink*, 2012; *Dam*, 2017]. This means that the channel-shoal dynamics are presently underpredicted and the question is whether that is due to internal dynamics not captured in the model or due to the steady forcing conditions on the model boundaries, or both.

Effects of disturbances and perturbations on morphology in rivers and estuaries have been studied in the past century. The damping and lag associated with environmental disturbances propagating through a system are determined by the magnitude and timescale of the event [*Paola et al.*, 1992; *Whipple and Tucker*, 1999]. The nonlinear dynamics of sediment transport limits the potential to record and pass on physical environmental disturbances and perturbations [*Jerolmack and Paola*, 2010]. Such disturbances for fluvial systems have been subdivided into four categories [*Schuurman et al.*, 2016a]: (i) external temporal perturbation of the upstream inflow, (ii) external spatial perturbation, e.g. along the outer channel banks, (iii) external perturbation at the downstream boundary, and (iv) internal perturbations within the reach. Shoal margin collapses fall within the fourth group of disturbances as sediment is eroded from the shoal within the estuary system. Bank erosion results in local widening of the system [*Khan and Islam*, 2003; *Ashworth and Lewin*, 2012], and outer bank erosion is linked to bar (shoal) dynamics, as the eroded sediment is a source for bars [*Xu*, 1997; *Ahktar et al.*, 2011; *Van de Lageweg et al.*, 2014]. The role of eroding bars, i.e., shoals, on the morphodynamics remains unknown. Numerical models show that erodible floodplains result in major local braidplain widening of rivers [*Nicholas*, 2013b], while *Schuurman et al.* [2016a] found that self-generated disturbances propagate through the network of bars, branches and bifurcations in braided rivers. Disturbances trigger development of asymmetrical division of discharge and sediment through the branches. The effect of disturbances in systems with multi-directional flow is unknown. We therefore study perturbing effects of shoal margin collapses in estuaries, where flow is bi-directional due to tidal forcing.

To study the role of disturbance on the morphology of estuaries, most control is offered by numerical models. Numerical morphodynamic models are useful tools, but interaction with bank erosion processes introduces complications [*Canestrelli et al.*, 2016]. The forecasting of these interactions remains infrequently addressed because this requires coupling short term geotechnical processes and long-term morphological development. The use of curvilinear grids leads to some complications when modeling abrupt changes such as bank erosion or flow slides [*Kleinhans*, 2010], which might be overcome using unstructured grids and cut-cell techniques [*Olsen*, 2003; *Canestrelli et al.*, 2016]. Despite successes in including bank erosion processes [*Darby et al.*, 2002; *Simon and Collinson*, 2002; *Kleinhans*, 2010], erodible floodplains mainly experience outer bank erosion processes [*Nicholas*, 2013a,b; *Schuurman et al.*, 2013, 2016b], while flow slides such as liquefaction or breaching processes that also occur on the inner side of bends in estuaries are under-represented. However, their potential effects are considerable: a single shoal margin collapse can displace several Mm^3 within a single tide, such as observed for the collapse in 2014 in the Western Scheldt [*Van Schaick*, 2015; *Mastbergen et al.*, 2016; *Van den Berg et al.*, 2017; *Van Dijk et al.*, 2018].

Shoal margin collapses through flow slides often occur suddenly, which makes them difficult to predict in current numerical morphodynamic models, such as Delft3D. Liquefied flow slides and breaching occur at sufficiently high and steep slopes, but there is a difference in the sediment properties between these two types of flow slides [*Van den Ham et al.*, 2014]. Liquefaction requires loosely packed, non-lithified, and water-saturated sand or silt, whereas breaching requires the presence of a sufficiently large body of densely packed fine sand or silt [*Van den Ham et al.*, 2014]. These processes are studied by various models but not implemented in a numerical morphodynamic model. *Van den Ham et al.* [2014] argued that these theoretical liquefaction and breaching models quantify the relative influences of channel geometry and soil parameters but the reliability of the estimated probability remains limited. Therefore, *Van den Ham et al.* [2014] proposed a semi-empirical model that predicts the probability of shoal margin collapses on profiles, which was modified and extended for application on spatial bathymetry data by *Van Dijk et al.* [2018]. This predictor includes an empirical factor based on the frequency of historical flow slides in the Eastern Scheldt and Western Scheldt estuaries [*Wilderom*, 1979; *Van Dijk et al.*, 2018], which is applied in this study.

Our objective was to increase our understanding of the interactions between shoal margin collapses and the morphodynamics of a sandy estuary, the relevant timescales and the large-scale morphological effects. Research questions are: (i) what are the local (near-field) effects of individual shoal margin collapses, such as the observed 2014 shoal margin collapse? (ii) How do multiple shoal margin collapses affect the morphodynamics of the estuary (far-field effect)? Our method was to use the numerical morphodynamic model Delft3D, to implement a parametrization for shoal margin collapses in a calibrated model and to study how disturbances, such as multiple collapses, propagate and change the channel-shoal morphodynamics of the Western Scheldt; a sandy estuary. Furthermore, we test the role of grain-size and shoal margin collapse size and location of the associated collapsed deposit on the estuarine morphodynamics. In this paper, we first give a detailed description of the study area, the method for implementation of the shoal margin collapses in Delft3D, and the tested scenarios. Then, we present the near-field and far-field effects of shoal margin collapses on the short-term as well as the long-term morphodynamics of the Western Scheldt. Finally, we discuss the model performance and the implications of persistent perturbations on a sandy estuary.

2 Study Area

This study focuses on shoal margin collapses in the Western Scheldt. The Western Scheldt is located in the southwestern part of the Netherlands and is the seaward section (60 km) of the 200 km tide-dominated Scheldt estuary. The Scheldt is a well-studied and monitored estuary [e.g., *Wang et al.*, 1999; *Winterwerp et al.*, 2000; *Bolle et al.*, 2010; *Van der Wegen and Roelvink*, 2012] that provides access to various harbors, of which the port of Antwerp (Belgium) is the largest. The Western Scheldt is characterized by a convergent geometry, and has well-developed system of channels and shoals (Figure 1a).

Channel bank failure has been recorded systematically in the Western Scheldt for the past 200 years [*Wilderom*, 1961, 1979]. Over the years, bank protection measures have been implemented to protect the channel banks and dikes of the Western Scheldt against new failures and collapses. However, these measures did not fully prevent the occurrence of shoal margin collapses [*Wilderom*, 1972]. A recent study identifies 300 shoal margin collapses between 1959-2015 [Figure 1a, *Van Dijk et al.*, 2018]. The majority of the collapses are found at unprotected areas. Relatively fine sediment is found in the estuary, which affects the occurrence of shoal margin collapses [*Van den Ham et al.*, 2014]. In general, the D_{50} of the channel bed varies between about 200 μm and 300 μm, whereas at the higher elevation areas of the shoals the sediment size is generally finer than 200 μm [*Cancino and Neves*, 1999; *De Vriend et al.*, 2011]. Additionally, a significant percentage of mud can be found in the intertidal areas [*Braat et al.*, 2017].

The natural development of the morphology as well as the effect of perturbations is the result of interactions between water flow, sediment transport and bed elevation. An important factor causing bi-directional flow and mean sediment transport is the tidal forcing in the Western Scheldt [*Wang et al.*, 1999]. From the mouth of the estuary to the Dutch/Belgian border, the tidal range increases from 3.5 m to 5 m [*Jeuken*, 2000]. The tidal prism at the mouth is about two billion m^3 [*Wang et al.*, 1999], whereas the yearly-averaged river discharge of the Scheldt into the Western Scheldt is a negligible 120 m^3/s [*Cancino and Neves*, 1999; *De Vriend et al.*, 2011]. The Western Scheldt has several recirculation zones of sediment through the ebb and flood channels, which enclosed the intertidal flats [Figure 1b, *Wang et al.*, 1995; *Winterwerp et al.*, 2000]. The tidal flow is asymmetric, i.e., slower but longer ebb flows compared to flood flows, in the Western Scheldt (Figure 1c–d). The difference between the maximum flow velocity for ebb and flood illustrated that flood is generally stronger (Figure 1e) even in the ebb dominated channels illustrated by the tidally averaged flow (Figure 1b).

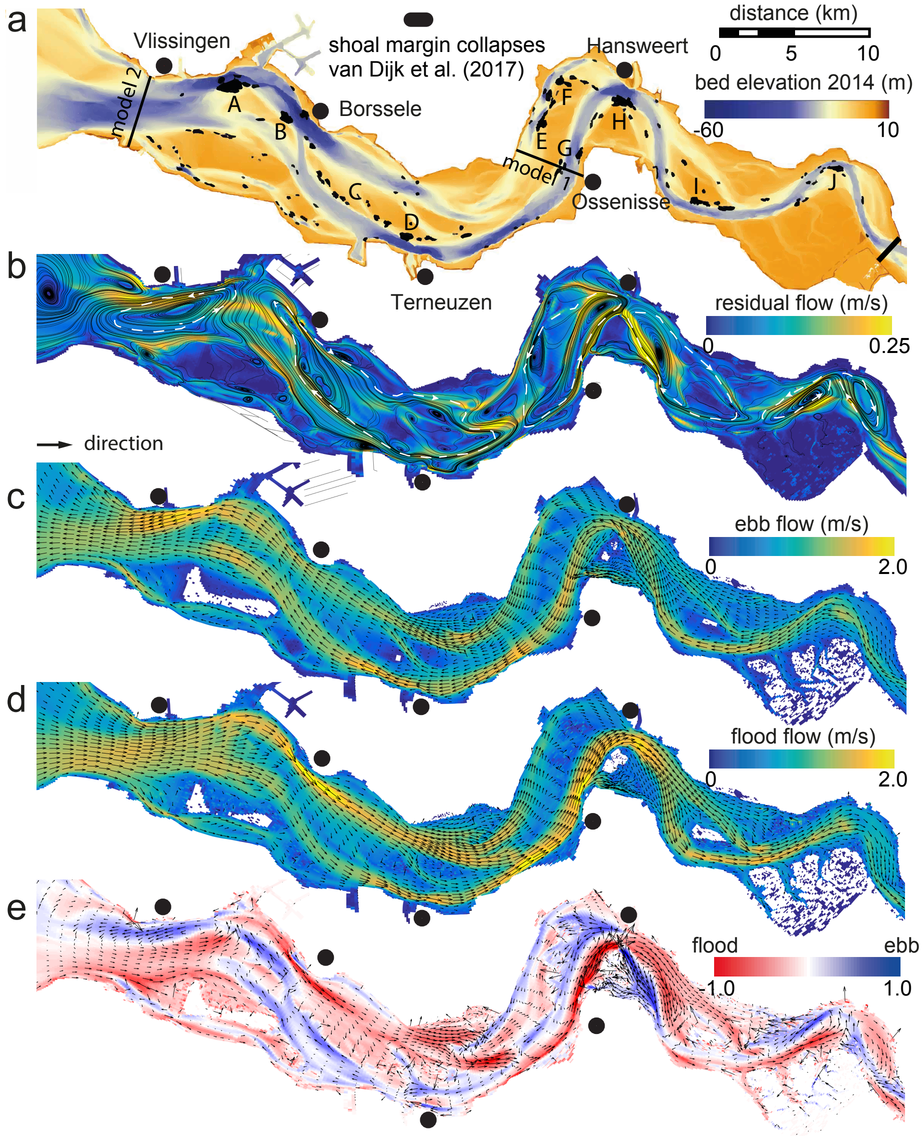


Figure 1. Overview of hydromorphodynamics in the Western Scheldt Estuary. a) Shoal margin collapse locations plotted on a digital elevation model of 2014 [*Van Dijk et al.*, 2018]. Seaward boundaries are indicated for the two morphological model schematizations in this study. A-J indicate locations susceptible to shoal margin collapses that are applied in the model scenario with ten initial collapses. b) Streamlines of the tidally averaged flow of the original NeVla-Delft3D flow model showing circulation cells that correspond largely to the macro cells indicated in white defined by *Winterwerp et al.* [2000] and *Bolle et al.* [2010]. c) Maximum flow velocity in the ebb-direction from the NeVla-Delft3D model. d) Maximum flow velocity in the flood-direction from the NeVla-Delft3D model. e) Difference between the maximum ebb and maximum flood velocity showing flood dominance in the main channels.

3 Model description and methods

3.1 Model setup and boundary conditions

In this study, we used two Delft3D schematizations that are both based on the NeVla-Delft3D model of the Scheldt estuary, which includes the upstream Flemish branches of the estuary, the Western Scheldt and part of the North Sea. The NeVla model is a state-of-the-art numerical model that has been optimized for hydrodynamics [*Maximova et al.*, 2009a,b,c; *Vroom et al.*, 2015] and morphology [*Grasmeijer et al.*, 2013; *Schrijvershof and Vroom*, 2016]. To study the effect of shoal margin collapses we focused on the Western Scheldt part of the NeVla model. Therefore, two nested models were produced from the NeVla-Delft3D model for reducing the computational time. The first nested model boundaries (model 1) were located around the tidal flat of Walsoorden (see boundaries in Figure 1a), which was used to study the morphodynamic response of the 2014 shoal margin collapses and the sensitivity to collapse sizes, grain-size of the collapsed material, and location of the collapsed deposits [see also *Van Schaick*, 2015]. *Van Schaick* [2015] validated the water level and discharge from the nested model with the NeVla-Delft3D model, and concluded that the errors were small enough to be neglected for the area of interest. The second nested model boundaries (model 2) include the Western Scheldt from the mouth at Vlissingen to the Belgian border (see seaward boundaries in Figure 1a), which was used for testing the effect of various shoal margin collapse locations as well as the effect of multiple shoal margin collapses in the Western Scheldt over time. The downstream boundary was chosen at the smallest but deepest part of the Western Scheldt to limit boundary effects. A single neap-spring cycle shows that the tidally averaged flow of this model (Supplementary Figure 4b) is comparable with the outcome of the full NeVla-Delft3D model (Figure 1b), except for small variation at the seaward end.

The nested model consists of a curvilinear grid with various grid sizes. The boundary conditions include a water level fluctuation due to tides at the seaward boundary and a current at the landward boundary. Sediment fraction was uniform with a median grain-size of 200 μm. For simplification of the boundary conditions, boundary conditions were selected from a single spring-neap tide cycle of January 2013 (about 14 days) and repeated for a 2 year period. Furthermore, we excluded the wind direction and magnitude from the NeVla model to reduce computational time as the effect of wind is negligible within the Western Scheldt. The roughness field in the model is defined in Manning n and is variable over the model domain [*Maximova et al.*, 2009a,b,c; *Vroom et al.*, 2015], which was 0.022 s·m$^{-1/3}$ for the eastern part, 0.027 s·m$^{-1/3}$ for the western part and 0.028 s·m$^{-1/3}$ for the Verdronken Land van Saeftinghe. The bed consisted of erodible and non-erodible layers [*Gruijters et al.*, 2004], the non-erodible layers are formed due to former deposits that are hardly erodible [*Dam*, 2013], and therefore the sediment thickness varies within the Western Scheldt model (see Supplementary Figure 1). Because sediment transport was calculated by *Van Rijn* [2007a,b], the bedload and suspended load transport could be distinguished.

3.2 Transverse bed slope and morphological factor

The Delft3D model (version FLOW 6.01.07.3574, 2 April 2014) has been applied in many scientific projects to compute hydrodynamics, sediment transport, and morphodynamics [*Roelvink*, 2006; *Deltares*, 2009; *Crosato and Saleh*, 2011; *Van der Wegen and Roelvink*, 2012; *Schuurman et al.*, 2013, 2016a; *Van Dijk et al.*, 2014]. In this study, we applied a 2D depth-averaged flow field, which meant that the effect of helical flow driven by flow curvature on bed shear-stress direction were parametrized [*Schuurman et al.*, 2013]. The parametrization affected the transverse bed slopes at the shoal margins, which influenced the moment that shoal margin collapses were predicted. Therefore, we performed a sensitivity analysis to determine how the sediment transport direction affects the slopes for various α_{bn} (see Supplementary Text S1). To reduce computational time, Delft3D in-

Table 1. Model scenarios

Scenario	Model	Test	duration	comments
1	1	2014 collapse	1 year	see *Van Schaick* [2015]
2	2	initial 10 collapses	40 years	see locations Figure 1a
3	2	yearly collapses	40 years	rule based on *Van Dijk et al.* [2018]
Sensitivity scenarios				
collapse size	1	100,000 m^3 vs. 1,000,000 m^3	1 year	see Supplementary
grain size	1	100 μm vs. 200 μm vs. 300 μm	1 year	see Supplementary
α_{bn}	1	1.5 vs. 30	1 year	see Supplementary

cludes a morphological acceleration factor M. We performed a sensitivity analysis determine what effect M has on the morphology of the estuary (see Supplementary Text S1). According to these both analyses we set α_{bn} to 30 and M to 20 as a default, so that that realistic dimensions of the slopes for long-term simulations were maintained (see Supplementary Figure 2).

3.3 Model scenarios and sensitivity

We assessed the effect of shoal margin collapses on the morphodynamics of a sandy estuary in three scenarios (see Table 1).

The first scenario was to understand the near-field effect of a single shoal margin collapse, such as the observed 2014 shoal margin collapse at the tidal flat of Walsoorden. Various sensitivity scenarios (see Supplementary Text S3) were applied to study the effect of the shoal margin collapse size, location of the collapsed deposits, and grain-size of the deposits. The collapsed size was tested because of the variation in size observed by *Van Dijk et al.* [2018] as well as its locations. Furthermore, the grain size of the deposited material was varied as the grain-size distribution in the field showed minor variation between 100 μm on the shoals and 300 μm in the channel [*Mastbergen et al.*, 2016]. This scenario and sensitivity tests were conducted on only the eastern part of the Western Scheldt (see seaward boundary of model 1 in Figure 1a).

The second scenario included a model run with initially shoal margin collapses of 1,000,000 m^3 at various locations within the Western Scheldt to test the far-field effect on the morphodynamics for the various location on a long-term (40 years). The various locations corresponded to observed shoal margin collapse locations described in *Van Dijk et al.* [2018] (Figure 1a).

The third scenario tested the role of multiple shoal margin collapses over a period of 40 years. These collapses were controlled by the implementation of shoal margin collapse rules in a Matlab environment as described in next section. Each of the three scenarios was compared to a control run without shoal margin collapses, so that natural variation of the morphodynamics could be excluded. These last two scenarios were applied on a different nested model (see Table 1), which includes the Western Scheldt from Vlissingen to the Belgian border (see seaward boundary of model 2 in Figure 1a).

3.4 Shoal margin collapses

Overestimating the transverse bed slope effect in the morphodynamic model [*Baar et al.*, 2018], causing more downslope sediment transport, may be necessary to flatten the morphology and compensate for subgrid bank erosion processes that usually does not occur in the numerical models [*Grenfell*, 2012; *Schuurman et al.*, 2013; *Van Dijk et al.*, 2014] but reduces morphodynamics within the model. Including the process of shoal margin collapses into a morphodynamic model might increase the morphodynamics. Currently, bank erosion is implemented by coupling horizontal bank retreat to bed degradation in Delft3D. Bank erosion occurs between an inundated grid cell and a dry grid cell, and thus is not restricted to the outer banks. Incision of the inundated grid cell could be equally divided over both grid cells or solely on the dry cell, so that the dry cell was lowered and the bank eroded [*Schuurman et al.*, 2016b; *Mastbergen and Schrijvershof*, 2016]. This process is continuous until the grid cell becomes inundated, but shoal margin collapses may occur suddenly at growing shoals that become less inundated.

The first step towards implementation of shoal margin collapses was the determination of locations that were unstable. In previous work, *Van Dijk et al.* [2018] modified a forecasting method of *Van den Ham et al.* [2014] for determining shoal margin collapse locations based on bathymetry data. *Van Dijk et al.* [2018] tested the accuracy of the prediction by corresponding higher probabilities with observed shoal margin collapse locations and showed the validity of the method. In this study, we applied this forecasting method into the morphodynamic model Delft3D. The first step towards determining shoal margin collapse locations was to determine the shoal margins. The shoal margins were determined by fitting a linear regression for the median bed elevation along the estuary channel [see also *Leuven et al.*, 2018a; *Van Dijk et al.*, 2018]. Elevation above the regression line was determined as shoal and below as channel. The boundary of the shoal was then extracted to determine the shoal margin. Subsequently, shoal margin collapse frequencies, F_{SC}, were calculated [adapted from *Van Dijk et al.*, 2018] as follows

$$F_{SC} = \left[\left(\frac{H}{11} \right)^{2.5} \left(\frac{9.5}{cot\alpha} \right)^{5} \right] \frac{SC_{avg}}{L_{sm}} \tag{1}$$

where H is the elevation of the local maximum between the center and the deepest part within a window size of 300 by 300 m on a 20 by 20 m interpolated grid of the bed elevation. α is the corresponding angle to H, SC_{avg} is an empirical value based on the average number of collapses observed per year [5.3 for the Western Scheldt, *Van Dijk et al.*, 2018], and L_{sm} is the measured total length of shoal margins [300 km for the Western Scheldt, *Van Dijk et al.*, 2018]. The form of equation 1 allowed frequency to be higher than 1, which was prevented by a transformation, namely a Poisson process, of the frequency into a probability (P_{SC}):

$$P_{SC} = 1 - e^{-F_{SC}} \tag{2}$$

Van Dijk et al. [2018] found that at a probability threshold (P_{SC}) value of 10^{-4} the true positive rate, defined as the number of cells that had shoal margin collapses in both the predictive probability and observed collapses divided by the number of observed locations of collapses, was almost 0.5, while the remaining identified locations had a low false positive rate, defined as the number of cells that had shoal margin collapses in the predictive probability but no observations of collapses divided by the number of cells with no shoal margin collapse observations. Because multiple locations at the shoal margin could have a probability value greater than the given threshold of 10^{-4}, we limited the number of collapses to a maximum of 1 per tidal flat (shoal margin) per time-interval. The time-interval was set to 1 morphological year. Eroding shoal margins were excluded, because these were already eroding by continuous channel migration, and collapses mostly occurred suddenly at vertical aggradational margins. Eventually, the highest probability above the critical probability of 10^{-4} was used to select the location of the shoal margin collapse per tidal flat. These slopes collapsed to a post-event slope whilst conserving mass, in which the size and geometric shape of the collapses followed a 1/3 ellipsoid according to the analysis of *Van Dijk et al.* [2018] of the geometric shape of the erosion scar (see supplementary Text S2).

3.5 Data analyses

The Delft3D model outcomes were analyzed for near-field and far-field effects, i.e., local and estuary scale. The analysis of the near-field effects on a short-term were mainly conducted on the 2014 shoal margin collapses, whereas for the Western Scheldt model (second and third scenario) the far-field effect on the long-term morphology was analyzed. For the near-field effect we analyzed the distribution of the collapsed sediment by labeling the collapsed deposit as a second sediment fraction with the same grain-size in the model. The model outcomes were also analyzed by looking at the Digital Elevation Model (DEM) of Difference (DoD) between a run with the collapse and a control run. The distribution of the collapsed sediment was plotted in time-space diagram for the cross flow-direction as well as longitudinal flow-direction. Furthermore, the width-averaged bed elevation was calculated and compared between the runs with and without collapses.

For analyzing the shoal margin collapse effects, the tidally–averaged flow and mean sediment transport were calculated over a spring-neap tide cycle. Eventually, the tidally–averaged flow and mean sediment transport were summarized by plotting the vectors for determining the net direction of the flow and of the sediment transport. For the second scenario, i.e., the 10 initial collapses of 1,000,000 m^3, the sediment transport direction was determined for the spring-neap tide cycle at the location of the collapse as well as for the location of the deposit. The smoothing of the bed elevation was determined by calculating the average bed elevation within the collapse as well as for the associated deposit location and compared to a rose diagram for the sediment transport direction.

We were specifically interested in the role of shoal margin collapses on the channel-shoal morphodynamics. Therefore, we used an existing tool to characterize the channel network. This network tool has been applied to braided rivers to determine the drainage network, so it includes channel bifurcations [*Kleinhans et al.*, 2017]. The tool uses the local lows of the channel bed to determine its lowest path. Specifically, the tool determines minimums, maximums and saddle points and connect the minimums through a saddle point, according to a descending quasi Morse-Smale complex [*Kleinhans et al.*, 2017]. The lowest path was then combined with striation, i.e., an ordered set of non-crossing paths, that subdivide the lowest path π into two parts around a maximum (green area in Figure 2a). Afterwards, the path is again divided into two parts around another maximum in that path (yellow areas in Figure 2a), and so on. To determine the scale of the channel network, a sand function (δ) is defined that represent the volume of sediment that has to be removed before two channels become one in the network, which volume is calculated from the elevation above the saddle point [Figure 2b *Kleinhans et al.*, 2017]. This made it possible to compute graphs representing the channel network, consisting of the lowest paths for various scales (Figure 2c). We named the various channel networks scales like the names used in the Western Scheldt [*Jeuken*, 2000], however, the identified channel network by the tool is not equal to the observations. The largest scale is the referred as the main channel, thee next scale is referred as the secondary channel, and the third scale is referred as chute channel, which in nature is referred to channels that connect the main with the secondary channel. After identifying the channel network for the various network scales, we analyzed the channel dimensions for the various network scales and between the model outcomes of the three long-term simulation scenarios.

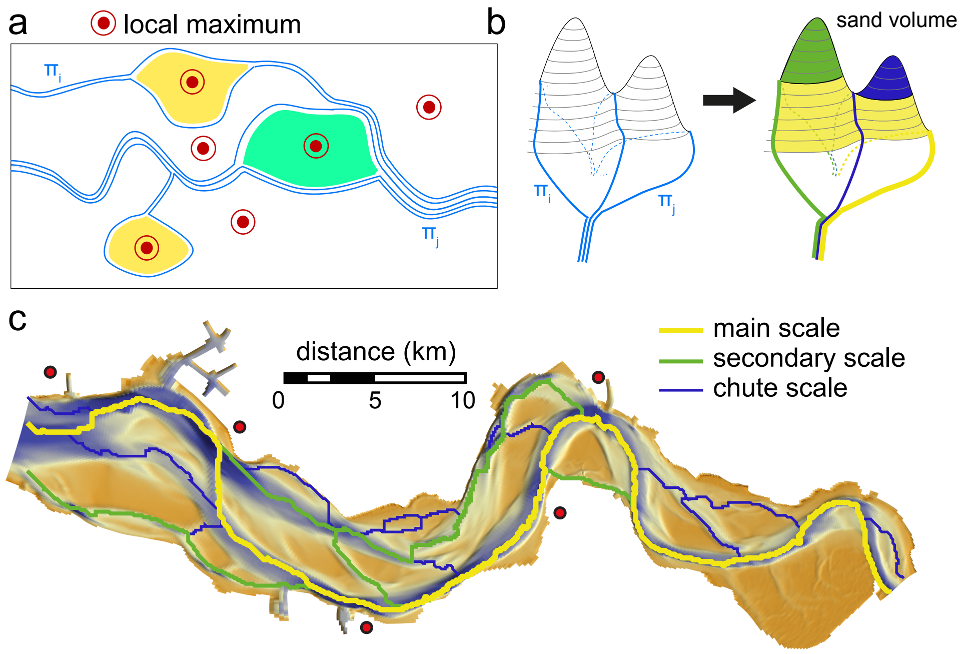


Figure 2. Illustration of the network identification tool. a) Example of how identification of the minimum, maximum and saddle point according to the Morse-Smale complex combined with striation analysis results in a channel network of multiple channels (π). b) Identification of different scales for the lowest paths (π) according to a sand function volume. The example indicates three scales, from the smallest sand volume up to the largest sand volume, in which the largest scale is referred to as the main channel scale, followed by the secondary channel scale and the chute channel scale. c) Example network in the Western Scheldt for the initial bathymetry.

4 Results

4.1 The 2014 shoal margin collapse

4.1.1 Hydrodynamics

Water level changes around the shoal margin collapse location as well as around associated deposits in the channel compared to the control run as result of the changes in bed elevation and associated bed friction. Over time, the water level fluctuates within 1 cm between both simulations under the same boundary conditions (Figure 3a, b). The main difference between the simulation with a collapse and the control run is found in transverse direction of the collapse (Figure 3c,d & g), whereas in longitudinal direction there is less change in the water level compared to the control run (Figure 3e, f). The largest difference in the water level change is observed at the scar of the shoal margin collapse (Figure 3d), which is inundated for a shorter time without the collapse because of the higher elevation. The water level difference between the two runs does not dominantly show lower or higher water levels around the collapse. The skewness of the change in the water level distribution indicates that water level increases for the shoal margin collapse deposit locations (Figure 3c, g), whereas the other locations show a decrease of the water level. The distribution of the water level changes varies between ebb and flood conditions for locations landward and seaward of the shoal margin collapse (Figure 3e, f), indicating that water level increases for flood conditions seaward and decreases for flood conditions landward.

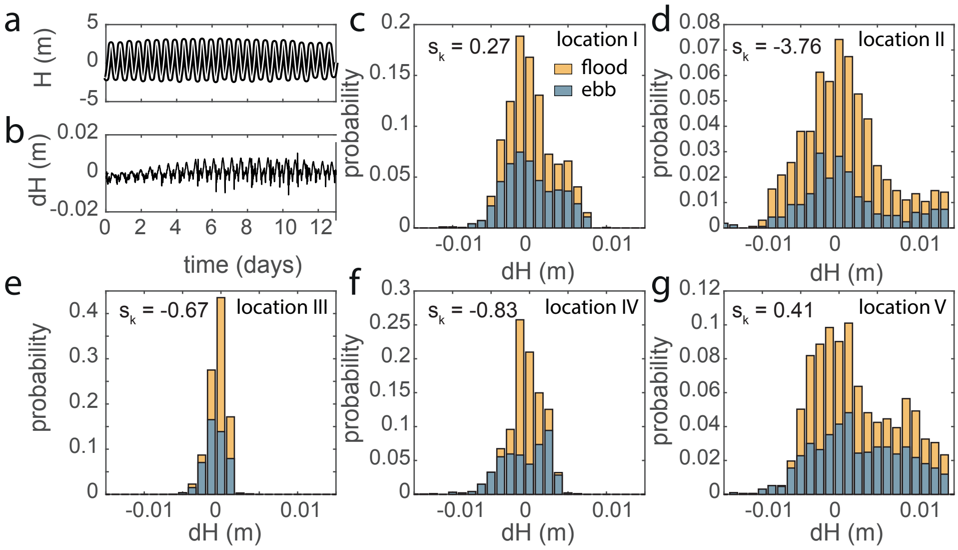


Figure 3. Changes in the water elevation relative to the control run at the 5 surrounding grid cells of the shoal margin collapse of 2014 (locations in Figure 4b). a) Water level at location of the collapsed sediment deposit (location I) for a simulation without (thick black line) and with the 2014 shoal margin collapse (thin white line on top). b) Difference in water surface elevation at the deposited collapsed sediment is within 1 cm. Positive values indicate water level rise following the collapse. c) Distribution of water level change shows a slight increase in the water level. Here, s_k indicates if the distribution is skewed to the left (negative) or right (positive) from the mean of the distribution, where the mean is 0 m for all distributions. The two different colors show differences between ebb and flood conditions but no systematic lower or higher water levels. d) The water level generally decreases. e) Seaward there is a slight difference in the water level, whereas f) landward there is more difference as in generally the water level lowers. g) Water level increases on the shoal margin.

Besides small changes in the water level around the collapse, we also observed small changes in the tidally averaged flow direction along the shoal margin. The control run shows that tidally averaged flow direction (Figure 4a) is comparable with the original NeVla-Delft3D model (Figure 1b) around the shoal margin of the ‘Plaat van Walsoorden‘. The simulation shows that the tidally averaged flow is affected by the shoal margin collapse, but mainly around the location of the collapse. The overall tidally averaged flow remains similar for both simulations but there is a slight change in direction and magnitude of the tidally averaged flow. For example, flow velocity increases along the shoal margin with 0.1 m/s because of the collapse (Figure 4b).

4.1.2 Sediment transport

Sediment transport is calculated with the *Van Rijn* [2007a,b] equation, which separates the bedload from suspended load transport. The mean total transport follows the direction of the tidally average flow. In the north side of the channel the total transport is towards the center, whereas in the center of the channel the transport is ebb dominated and south flood dominated (Figure 4c). The total sediment transport is the result of bedload as well as suspended sediment transport. The mean bedload transport follows the direction of the tidally averaged flow (Supplementary Figure 5a), which indicates a clear distinction in ebb and flood directed transport. The north side of the channel, along the shoal, is mainly ebb directed, while the south side is flood directed. The mean suspended sediment transport does not follow the tidally averaged flow direction at all locations, es-

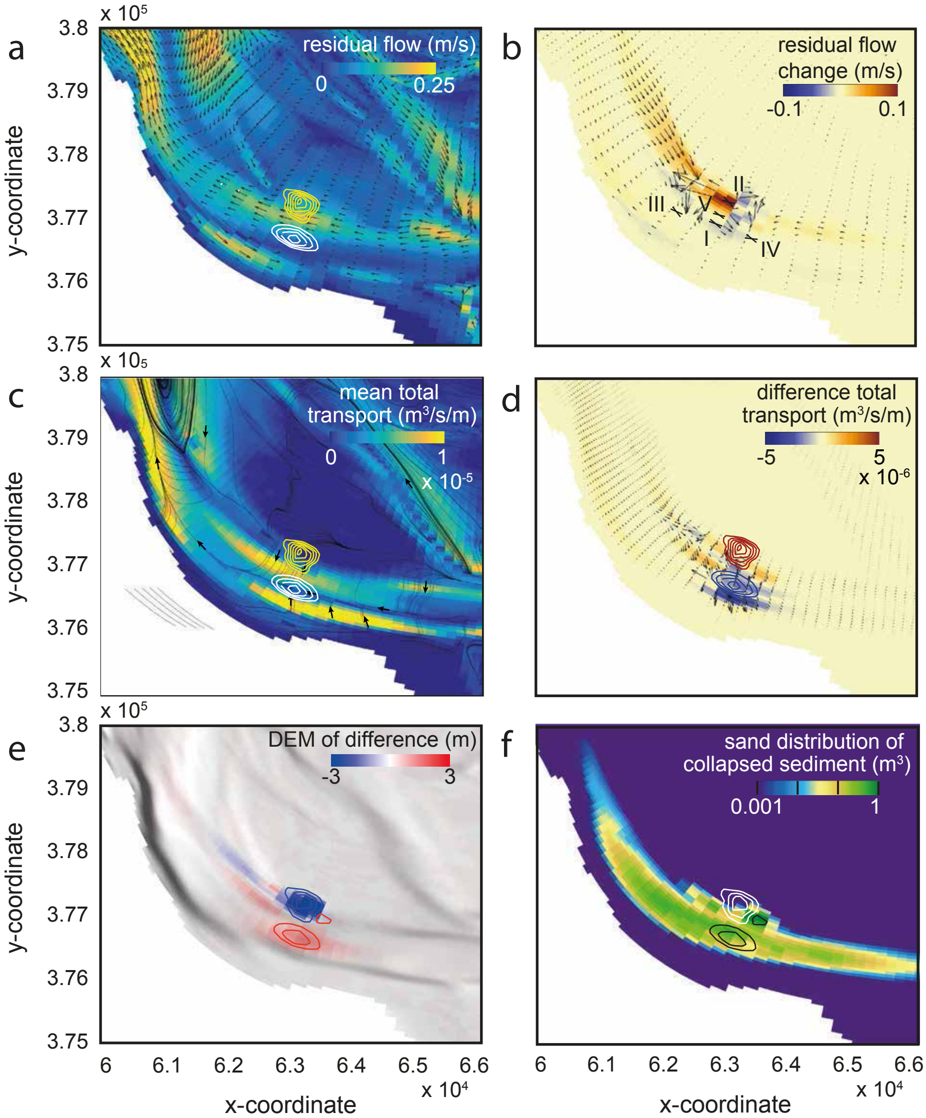


Figure 4. Hydromorphodynamics at a single shoal margin collapse after 1 year compared with a run without the collapse. a) The tidally averaged flow modeled for the control run shows ebb-dominated flow along the shoal margin collapse of 2014 (yellow), while at the deposit (white) it is around zero. The contour lines were plotted at 1 m elevation intervals. b) Tidally averaged flow increases along the shoal margin seaward of the collapse and slows down at the collapse. Crosses numbered I-V are the locations for water elevation shown in Figure 3. c) The mean total transport is ebb-dominated at the shoal margin (note vectors), but, as α_{bn} = 30, as a large transverse component into the channel along the Tidal flat of Walsoorden. d) The total transport reduces around the shoal margin collapse. e) The deposited sediment is spread only directly landward and seaward of the collapse, whereas the eroded collapse location remains unfilled. f) Sediment is dominantly spread in seaward direction in the channel along the vectors of the mean total sediment transport (see Figure 4c).

pecially in the main channel south of the tidal flat of Walsoorden (Supplementary Figure 5b). Here, a direction is observed opposite from the bedload transport, in which north of the channel transport is mainly flood directed, while south is ebb directed. We suspect that this is the result of the transverse bed slope predictor, which has no effect on the suspended sediment transport.

The direction of the sediment transport is more transverse compared to model runs with a α_{bn} of 1.5 (Supplementary Figure 5d), but the magnitude in longitudinal direction is comparable, which is important regarding the migration of the perturbation of the shoal margin collapse on the morphodynamics of the estuary. Because of the change in the tidally averaged flow due to the shoal margin collapse, sediment transport direction and magnitude is affected as well. For example, the run with the shoal margin collapse of 2014, the mean total transport, i.e., the effective sediment transport, reduces by a value that is 80% of the mean total transport for the control run at the location where sediment from the collapse deposited (Figure 4d). The mean total transport, however, increases along the shoal margin by 15% and especially increases within the shoal margin collapse. Less sediment transport means that erosion of the deposited sediment will take longer, whereas the increase in sediment transport would increase erosion along the shoal margin.

4.1.3 Morphodynamics

By comparing the run with the 2014 shoal margin collapse with the control run, changes in the morphology between the runs can be ascribed specifically to the shoal margin collapse because the natural variation in the morphology was excluded. The DEM of difference (DoD) shows that the bed elevation in the channel landward as well as seaward of the collapsed deposit is raised after about 1 year morphological time, whereas the location of the deposit is lowered from the start of the simulation (Figure 4e). This suggests smoothing of the profile after the collapse. The shoal margin collapse is still visible as it remains lower compared to the control run, and the process of sedimentation is less compared to the erosion that smooths the channel.

The difference in bed elevation shows the changes between the two runs but does not show how sediment from the collapse is distributed. Therefore, in the simulation with the 2014 shoal margin collapse the collapsed sediment is labeled, so that the spreading of the sediment could be traced. Figure 4f shows the distribution of the sediment from the collapse within the main channel at the ‘Plaat van Walsoorden‘. Large portions are deposited at the sides of the original location, which corresponds with the DoD. The distribution of the collapsed sediments is spread over a larger area in landward as well as seaward direction, which is less clear from the DoD because of the limited changes in bed elevation. Suspended sediment is supposed to travel a longer distance leading to distribution over a larger area, whereas bedload sediment affected more the bed elevation. Despite the transport in both directions there is a dominant distribution of the tracer sediment in ebb direction (Figure 4f).

4.2 Shoal margin collapse scenarios to determine sensitivity

In the supplementary we elaborate more in detail on the sensitivity of various scenarios, such as the size of the collapse, the location of the collapsed sediment and the role of grain-size. The results from this analysis is that migration rate of the disturbance is hardly affected by the collapsed volume, and that only large collapses, > 100,000 m^3 affect the far-field morphodynamics (Supplementary Figure 7). The location of the collapsed deposits along the Western Scheldt determines the dominant direction of the disturbance, which corresponds to the tidally averaged flow direction. Collapses that occurred more landwards are less reworked and transport direction is dominantly in seaward direction (Supplementary Figure 7). Model outcomes for different α_{bn} values do not change longitudinal displacement of the disturbance but do effect the distribution of the sediments in transverse direction (Supplementary Figure 5c, d). Besides the location of the collapsed deposit, also the grain-size of the deposit determines the direction of the disturbance. Finer material follows the same dominant longitudinal direction as the 200μm, but settles more at the sides of the channel, whereas coarse material follows not dominantly the tidally averaged flow but the strongest flow direction, while only the sediment in the deepest part of the channel is entrained (Supplementary Figure 6).

We conclude that shoal margin collapses locally affect the morphodynamics of the Western Scheldt leading to changes in sediment transport direction and morphology within the first year after occurrence, and that size and location of the collapse matters. In the next sections, we will test how these local collapses affect the regional morphodynamics of the Western Scheldt, especially what the effect is of multiple collapses over a period of 40 years, and if this will dynamicise the system as we hypothesized.

4.3 Shoal margin collapses in the Western Scheldt

Five shoal margin collapses occur per year at several locations within the Western Scheldt, ranging from very small collapsed volumes of 20,000 m^3 up to volumes of 3,000,000 m^3. The 2014 shoal margin collapse is one of the larger collapses that occurred but its effect in isolation on the estuary morphodynamics is limited. The historical analysis of *Van Dijk et al.* [2018] shows several locations that are susceptible to shoal margin collapses (Figure 1a). Here, we first identify how much effect each individual location susceptible to collapse (see specific collapsed locations in Supplementary Figure 4a) has on the morphodynamics, and second we apply our shoal margin collapse method to test if multiple yearly collapses over time would dynamicise the Western Scheldt estuary.

4.3.1 Multiple initial collapses

The Western Scheldt schematization (model 2) is used to test the long-term effect of multiple shoal margin collapses on the morphodynamics of the system for 40 years. In the first scenario, 10 shoal margin collapses of a volume of 1,000,000 m^3 are initially added to the bed elevation of the Western Scheldt. Examining the sediment transport direction for the various locations shows that sediment transport direction and rate varies. Most locations show sediment transport in two dominate directions corresponding with the ebb and flood current (Figure 5). Furthermore, at most locations the sediment transport is less for the location where the collapse originated compared to the location where it deposited. There are some exceptions, which is the result because of the collapse occurs under water, e.g., the ‘Spijkerplaat‘ (location A). Perpendicular to the ebb and flood flow sediment is transported on the transverse bed slope, probably because of the relative high α_{bn} of 30, which is specifically observed at the ‘Molenplaat‘ and ‘Plaat van Walsoorden‘ (locations F and I).

The sediment transport magnitude determines the rate that the shoal margin collapse is filled and the collapsed sediment is eroded from the main channel. The net sediment transport varies between ebb and flood flow as well as between spring and neap tidal cycles. The net sediment transport for neap tidal cycle is about $5{\cdot}10^5$ m^3 and for spring tidal cycle about $5{\cdot}10^6$ m^3 within the Western Scheldt estuary. The net sediment transport is slightly higher during rising tide than for falling tide. Locations with the highest sediment transport rates, such as the ‘Spijkerplaat‘ West and ‘Ossenisse‘ (locations A and H), show faster infilling of the shoal margin collapse (Figure 6a). The collapse at the ‘Plaat van Walsoorden‘ (location I) is less filled, which is also observed for the first scenario model outcome of the 2014 collapse, and can be associated to lower sediment transport rates, whereas observations showed faster filling of the scar (Figure 6a). Sediment transport rate also determines the rate of erosion of the collapsed sediment. In general, the erosion is faster than the infilling except for the deposits in the secondary channels (Figure 6b), e.g., the‘ Brouwersplaat‘ (E) and ‘Molenplaat‘ (F).

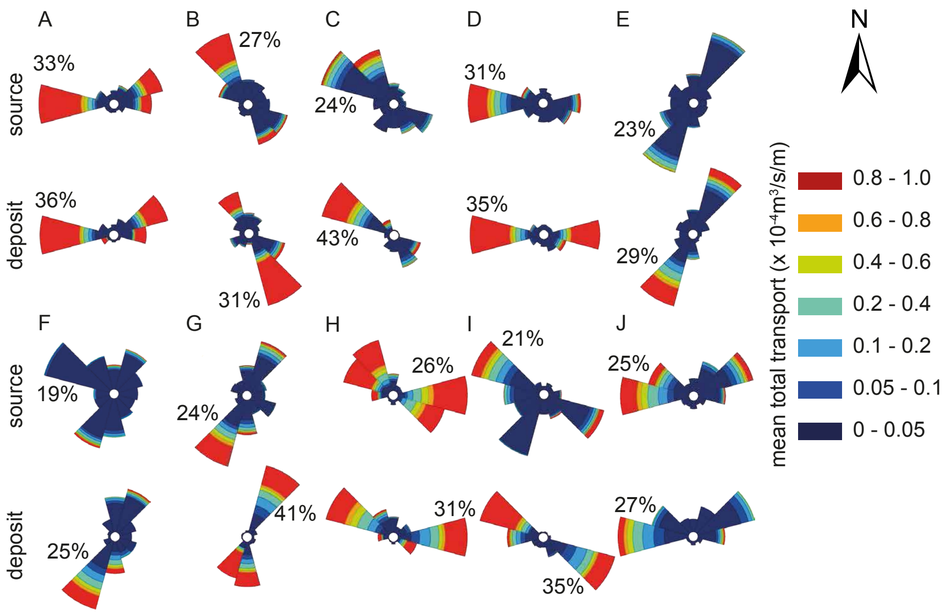


Figure 5. Total sediment transport magnitude and direction for various collapse locations (see locations in Figure 1a) show dominantly ebb and flood flow-related directions for the first year after the collapse. At the shoal margin collapse locations (top wind roses) less transport is calculated and at some locations a third dominant direction is observed because of the transverse bed slope effect (see F and I). Sediment transport is generally higher for the deposited sediment (bottom wind roses).

The sediment transport rate does affect the morphodynamics for the long-term changes in the estuary. The bed elevation difference and tracer sediment distribution map (Figure 7a) indicates that shoal margin collapses perturb the Western Scheldt differently depending on their location, which corresponds to the sediment transport direction and magnitude at the collapsed locations. Major changes are observed around the shoal margin collapse locations, when these disturbances enter areas that have less sediment transport but are morphodynamic active and controls sediment diversion, i.e., the junctions seaward or landward of the channel. Here, the bed elevation is not only affected in longitudinal direction but also in transverse direction into connected channels (Figure 7a), i.e., effectively following the sediment vectors. On a longer timescale, the shoal margin collapses affect the dynamics of the system, so that a total volume change of $4.53{\cdot}10^8$ m^3 was observed compared to the control run, in which less than 10% of the volume is directly the result of the collapses. The width-averaged mean bed level difference between the two simulation shows that changes excite, i.e., grow, over time (Figure 7b). At the beginning, there is a slight difference between the runs, which was also demonstrated with the 2014 collapse, but eventually the mean bed elevation across varies more than a meter (Figure 7b). This is particularly the result of migration of the junction around location C and landward of location H (Figure 7a). The sediment from the shoal margin collapse is mainly transported in longitudinal direction, landward as well as seaward (Figure 7a). Following the tracer sediment along the estuary gives more insights in the dominant migrating direction of the disturbance (Figure 7c), which vary with location but is dominantly landwards for the seaward collapses and seawards for the more landward collapses. Changes in the bed elevation even occur on the locations where no sediment is located that originates from shoal margin collapse, e.g., at 25 km (Figure 7b,c).

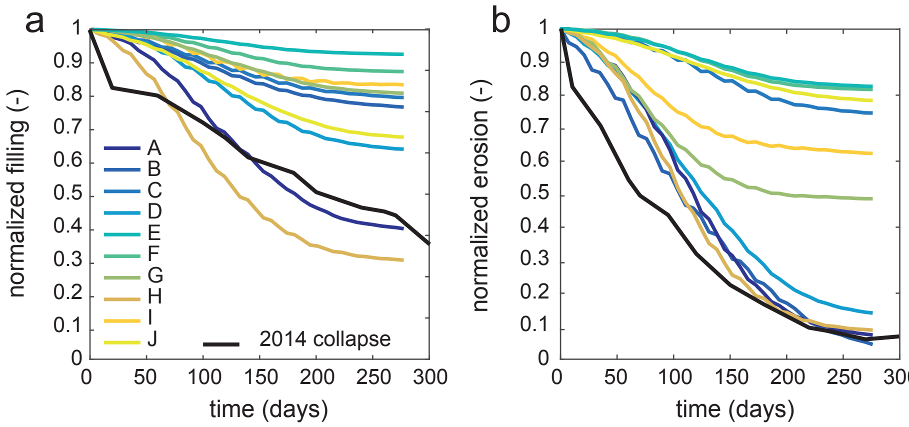


Figure 6. Development of shoal margin collapse scar and deposit volumes at various locations for the Delft3D simulation in the first year (see locations in Figure 1a). The shoal margin collapse of 2014, close to modelled location I, is shown for comparison [see *Van Schaick*, 2015]. a) Filling of the scar varies with location, but is never completed within a single morphological year. b) Deposit removal is faster than scar filling. In particular shoal margin collapses in secondary channels develop slowly, e.g. tidal flats of 'Brouwerplaat' (E) and 'Molenplaat' (F), and the less dynamic landward part of the estuary, 'Verdronken Land van Saeftinghe' (J). Wiggles indicate effects of neap-spring tidal cycles.

4.3.2 Multiple yearly collapses

In the third scenario, shoal margin collapses are added after each morphological year. Only one collapse could occur at a single shoal, which results in about 5 collapses per year equal to field observations of *Van Dijk et al.* [2018]. Our analysis focus specifically on the role of multiple shoal margin collapses on the morphodynamics of the system. The shoal margin collapses vary in size and location according to the given rules (see method section). After 40 year simulation 227 collapses occurred, i.e., 5.7 per year, at 58 locations of various tidal flats (illustrated by contour lines in Figure 8a), eroding a total volume of 40 million m^3, i.e., 1 million m^3 per year, which is more than the field observations. As shown in previous scenarios the distribution of the disturbance varies with location, showing mainly changes in the bed elevation in longitudinal direction, i.e., landward and seaward of the collapse (Figure 8a), whereas collapses near the junctions lead to changes in the bed elevation across the channel because of the channel is wider and shallower. The total bed volume change at the end of the model run compared to the control run is $4.63 \cdot 10^8$ m3, in which 20% of the volume is explained by the shoal margin collapses. The width-averaged bed level difference between the run with collapses and the control run (Figure 8b) illustrates migration of the disturbance in both directions, excitation of the disturbance over time and also dampening of the disturbance. Furthermore, there are some unexplained responses that are not directly associated with the collapses itself, such as observed between 25 and 30 km from the Western Scheldt mouth (Figure 8b). Because of the number of collapses and the yearly adding of new collapses, the effect of a single disturbance is difficult to follow. Most changes occur at the locations with several collapses. Because of general incision of the channel at the seaward boundary, we excluded the seaward effects for further interpretation and conclusions of the role of shoal margin collapses as this might be the boundary effect of the model. The total eroded and deposited volume is $2.31 \cdot 10^9$ m^3 for the run with collapses and $2.26 \cdot 10^9$ m^3 for the control run, which suggest the simulation are equally dynamic as only 10.0 million m^3 of the eroded volume is not explained by the collapsed volume of 40 million m^3.

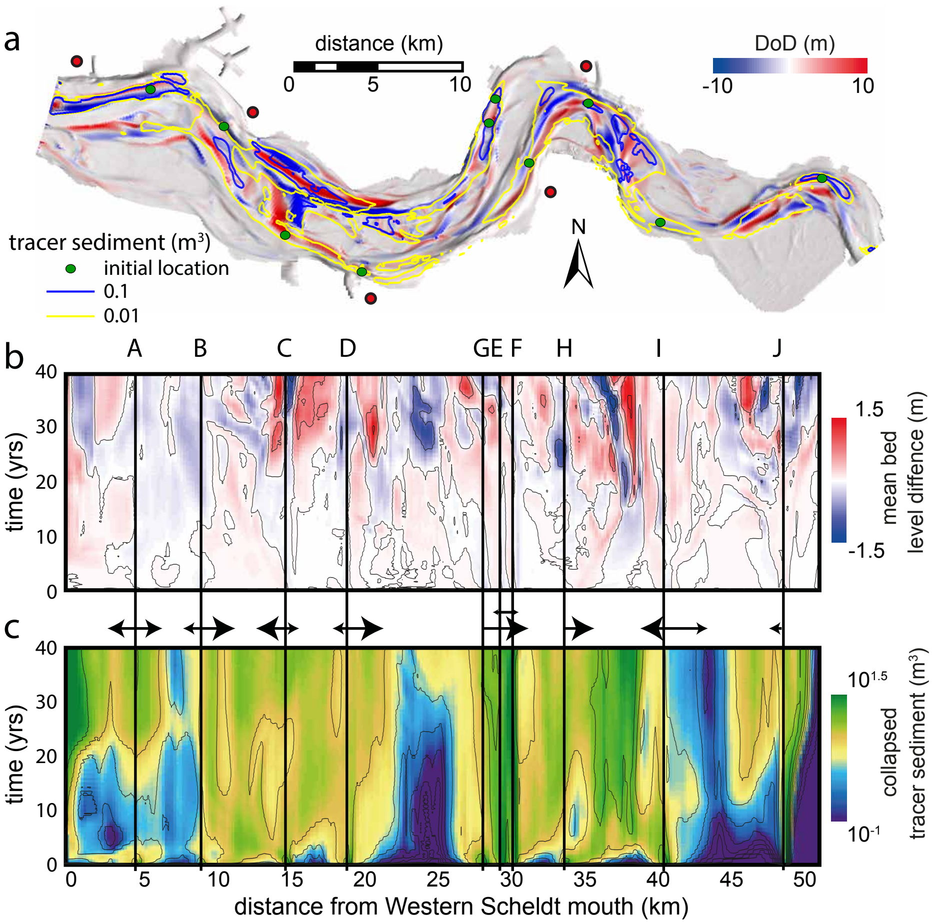


Figure 7. Effect of multiple initial collapses in the Western Scheldt. a) Elevation difference after 40 years between a simulation with and without 10 shoal margin collapses shows that for several locations the perturbation has migrated landward as well as seaward, whereas other collapses hardly migrated over 40 years, e.g., locations E and F (see Figure 1a). The colored contour lines show the spatial distribution of the collapsed material. b) Width-averaged bed elevation difference between the run with and without initial collapses shows some migration of the perturbations but mainly shows cumulative excitation effects after two decades. c) Spatiotemporal distribution of the collapsed sediment, showing spreading in both seaward and landward directions.

These volumes indicate that the system does not dynamicise more in the case of including shoal margin collapses compared to a control run, which we hypothesized.

4.4 Re-organization of the channel-shoal network by collapses

The addition of yearly collapses in the model leads to changes in the network structure and the scale at which channels are detected as compared to the control run (Figure 9a, b). While the main channel location and scale are generally the same between the two runs, many of the smaller scale channels are differently identified for the model run with yearly collapses. In the control run, less smaller scale channels, i.e. secondary and chute, are observed compared to the run with yearly collapses (Figure 9a-b), which means there is structural better connectivity among the channels for the model with yearly collapses. The scale, or sand function volume, at which channels are detected changes be-

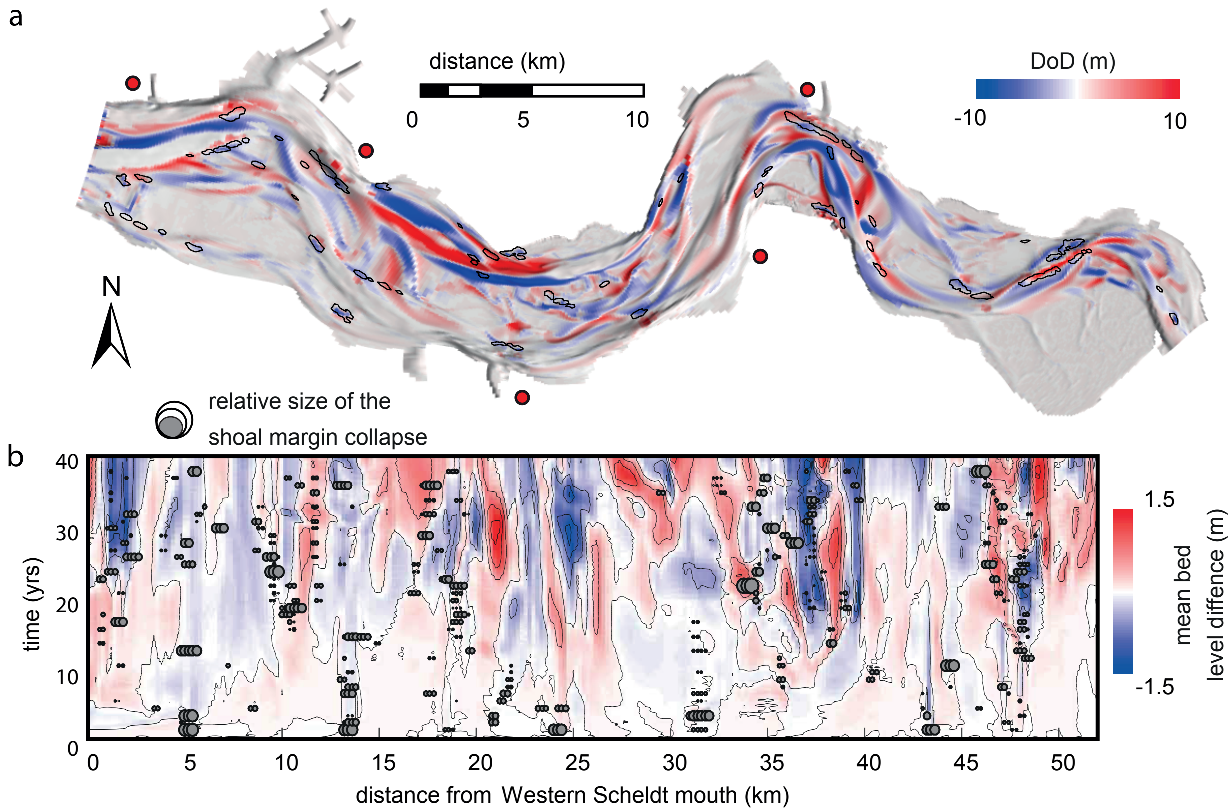
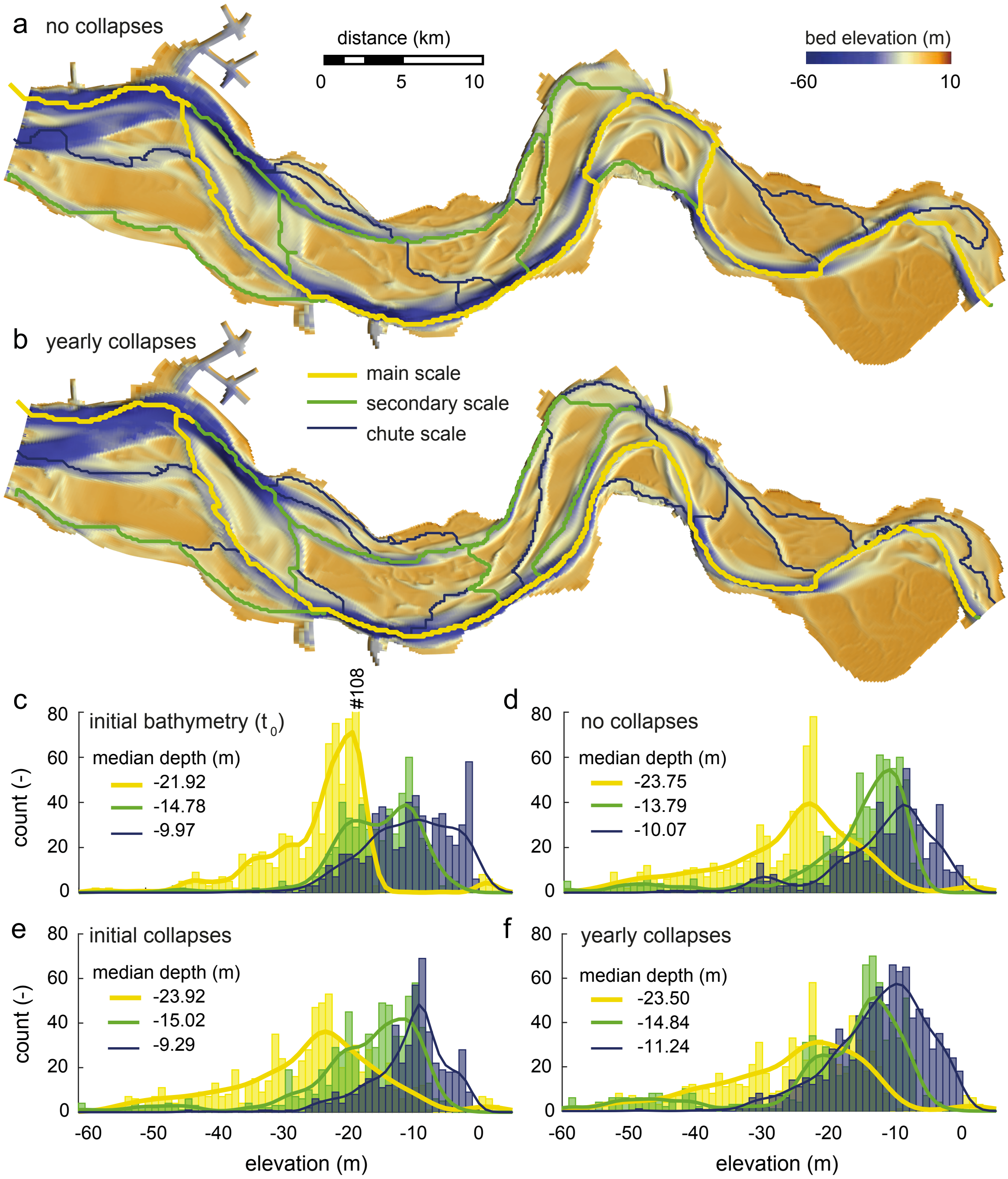


Figure 8. a) Bed elevation difference between a control run and a run with yearly shoal margin collapses (indicated by the contour lines) shows that the entire system is modified, especially at junctions forming ebb-flood channels (landward of location B and at location H). b) Width-averaged bed elevation difference between both runs shows location of incision and deposition that migrates, excites or dampens depending on the location of the collapse.

tween the runs as well. The shifting of scale is due to the differences in the morphological development of the system. In case of the collapses, the secondary channel network shifts (Figure 9b), probably because of sediment deposition in the channel which decreases the volume of sediment between adjacent channels, causing channels that were identified as secondary in the control run to be identified as chute channels in the run with collapses. When the volume of sand increases between channels increases, the opposite is true and chute channels become secondary channels.

The various channel networks are used to determine the depth distribution of the channels. The initial network shows a deep main channel (Table 2, Figure 9c) probably due to the dredging activities for maintaining a specific depth of the shipping fairway. After 40 years of morphological development, the main channel becomes deeper but the variation increases (Table 2), whereas there is an increase of the number of smaller scale channels (Figure 9d). Although, we observed some changes in bed elevation between the control run and the model run with initial 10 collapses (Figure 7), the bed elevation for the largest scale of the network is comparable (Figure 9d,e). Major changes are observed between the secondary and chute scale channels, the number of chute scale channels increases for the run with initial collapses, while the depth generally decreases. The depth of the secondary channel, however, increases for the run with initial collapses. The bed elevation of the main channel and secondary channel are shifting towards eachother for



618 **Figure 9.** Networks in (a) the control run without collapses and (b) the scenario with yearly collapses, showing that spatial channel shifts and changes in scale of channels after 40 years morphological development. c-f) Depth distributions of the channel networks shows a deep initial main channel (c), which becomes shallower when modeled (d). The depth distribution for the run with initial collapses develops towards the control run (e), whereas continuous yearly collapses lead to further shallowing of main channel in the estuary (f).

Table 2. Statistics of the mean μ and standard deviation σ of the depth for the various runs for all network scales.

	μ (m) scenario				σ (m) Scenario			
Scale	initial	control	2	3	initial	control	2	3
main	-23.91	-26.16	-25.79	-25.73	8.16	10.95	11.13	11.02
secondary	-15.65	-17.41	-17.88	-19.15	7.19	10.87	10.11	11.93
chute	-10.60	-12.23	-10.62	-12.35	6.60	8.00	5.95	7.09

the run with yearly collapses, mainly because the mean depth increases faster for the secondary channel (Figure 9f). Overall, the system with yearly collapses develops to a system with shallower channels because of collapses are mainly in the main-channel, and the secondary channels approaches the same depth distribution as the main channel on the long-term, whereas the number of chute channels increases.

5 Discussion

We introduced an effective parametrization for the process of shoal margin collapse, solely based on the local bed elevation and slope gradient. Here, we discuss how the response of the modeled collapses affects the morphodynamics and how this differs from observations. We also consider the implication of shoal margin collapses on perturbing the estuarine morphodynamics and compare these with larger perturbations caused by dredging and disposal activities.

5.1 Modeled collapses versus observations

The 2014 shoal margin collapse is used to test the near-field effects of a shoal margin collapse. This collapse is well studied by *Van Schaick* [2015] by analyzing field measurements and Delft3D simulations. *Van Schaick* [2015] concluded that some morphodynamics of the model differ from the observations [*Mastbergen et al.*, 2016]. According to field measurements, sediment deposited from the shoal margin collapse migrates in flood direction, while the model outcome suggests sediment transport in ebb direction for the bedload. The discrepancy in the direction of the sediment transport could be explained by the difference in the tidally averaged flow and tidal asymmetry. The collapsed deposit from the 2014 shoal margin collapse is located in that part of the channel were tidally averaged flow is ebb dominated but almost zero, whereas south from the deposit the tidally averaged flow and mean sediment transport suggest transport in flood direction. However, the flood current is generally stronger in the channel, which might have led to distribution in flood direction instead of the modeled ebb direction. The rate of infilling of erosion scars was less in the model compared to field observations. The focus of our study is not to calibrate the model to the observed development of the shoal margin collapse of 2014, but predict the effect of shoal margin collapses on the large-scale development of the estuary.

The shoal margin collapse parametrization leads to several collapses along the Western Scheldt Estuary. The location is based on the bed elevation, such that steep slopes collapses, whereas the collapsed size and volume is randomly drawn from a log-normal distribution. Locations for shoal margin collapses (Figure 8a) do vary from the observed locations (Figure 1a), probably because for the chosen probability threshold value the number of false positives is at least equal to the true positives, meaning that steep high slopes that are not susceptible to collapses are included [*Van Dijk et al.*, 2018]. Nonetheless, the collapses are widely distributed on tidal flats that do have collapses over time. Locations with rapid infilling of the scar relates to locations with multiple collapses, e.g., at Spijkerplaat (location A) and Ossenisse [location H, *Van Dijk et al.*, 2018]. Our parametrization differs from earlier attempts to prevent steep slopes of bars in rivers with Delft3D [*Nieuwboer*, 2012]. *Nieuwboer* [2012] applies two strategies to reduce steep slopes in Delft3D; 1) slope avalanching, and 2) slope slumping, in which avalanching stopped deposition of sediment on steep slopes and slumping leads to changing steep slopes to equilibrium. The slope slumping, however, leads to numerically unstable simulations because of large changes in the water levels. Here, no numerical instabilities were observed, because the collapses mainly occurred underwater and water depths are higher in the estuary setting compared to shallow rivers. Furthermore, sediment was not deposited in adjacent cells but spread in the deeper parts of the channel following the slope of the collapsed shoal.

Our parametrization is, however, limited in the prediction of the collapses as the original probability prediction of *Van den Ham et al.* [2014] includes also variables for sediment properties, such as grain-size, relative density and the amount of mud layers [*Mastbergen and Van den Berg*, 2003], whereas we solely calculated with uniform sediment size. These variations in sediment properties are formed when the channels migrates, forming new shoals on the inner banks whilst collapsing outer banks retreat into the layer-cake of sand and mud of past shoals and marshes [*Dalrymple and Rhodes*, 1995; *Van den Berg et al.*, 1996; *Fagherazzi et al.*, 2004]. Spatial information of the stratigraphy is however lacking for most systems because the limited availability of field data. Even for the well-studied Western Scheldt a model is used to predict clay availability within the tidal flats [*Dam*, 2017], but lacks the detailed information. The applied Western Scheldt schematization includes only a single fraction, but it will be of interest for future studies to calculate with multiple fractions, especially to construct a subsurface including variations in sediment properties, e.g., mud [*Braat et al.*, 2017].

5.2 Implications of shoal margin collapse perturbations on the morphodynamics

The rate of sediment removal and the volume of a single collapse determine the morphodynamics around the collapse. In the less dynamic secondary channels, the sediment is less spread, so that the collapse has less impact on the channel-shoal morphodynamics. Small collapses can be seen as noise to the system, while larger collapses can be seen as a perturbation of the system [*Kleinhans et al.*, 2015]. The shoal margin collapse firstly affects the local bed elevation by depositing sediments into the main channel, but over time this disturbance propagates through the channel network. The findings correspond partly with the conceptual model described by *Schuurman et al.* [2016a] for disturbances in braided rivers. In the estuary however, an adjustment in the channel leads to adjustments in downstream and upstream direction. The dominant direction depends on if the channel is ebb or flood dominant. The migration rate is low for the disturbance but larger than changes of the shoals (tidal flats) themselves, which are more or less fixed at their location [*Leuven et al.*, 2018b].

The initial 10 collapses show that the perturbations lead to excitation of the difference in bed elevation compared to a control run on the long-term. Specifically, the bed elevation difference between the runs increases rapidly after 20 years. Where after 40 years of morphological development, the modeled bed elevation difference between the control run and the run with initial collapses is only explained by less than 10% of the initial collapsed volume. In the case for the scenario with yearly collapse, the modeled bed elevation difference is explained by 20% of the collapsed volume, probably this percentage is less because the effect from the disturbances are still growing, the perturbations are less effective because of some smaller collapses, or small perturbations are overprinted by larger ones. In case of the initial collapses, the perturbation grows over time but besides some deepening of the secondary channel the channel network remains the same. On the other hand, the yearly collapses change the course of the secondary and main channel at a few locations (see Supplementary Animation 1).

Shoal margin collapses perturb the estuary differently depending on the location of the collapse within the channel network. In general, the shoal margin collapses change the channel-shoal network by shallowing of the major channels and forming new smaller channels on the tidal flats. The network tool provides a network at the final timestep (Figure 9), illustrating the overall changes between the control run and yearly collapse but did not illustrate changes that can be linked to the collapses themselves. Analysis of the channel depth for the various scales in time shows that the variation in channel depth increases in time, except for the secondary channels (Figure 10). The channel network changes part of the main channel into the secondary channel within the first 5 years for all runs, so that the secondary channel deepens and the main channel becomes shallower (Figure 10a, b). The collapses in the scenario with yearly collapses mainly affect the secondary and chute scale channel networks, which deviates from the control run (Figure 10b, c). A few collapse events can be directly related with changes in the channel network depth. For example, the collapses in year 22 results in shallowing of the secondary scale channel (Figure 10b). Changes in the depth of the larger channel network scales are not directly affected by the collapses but might be the result of multiple collapses that affected the chute scale channel networks. For example, the shallowing of the secondary scale channel network after 10 years corresponds to a deepening of the chute scale channel network that occurred a year before (Figure 10b, c).

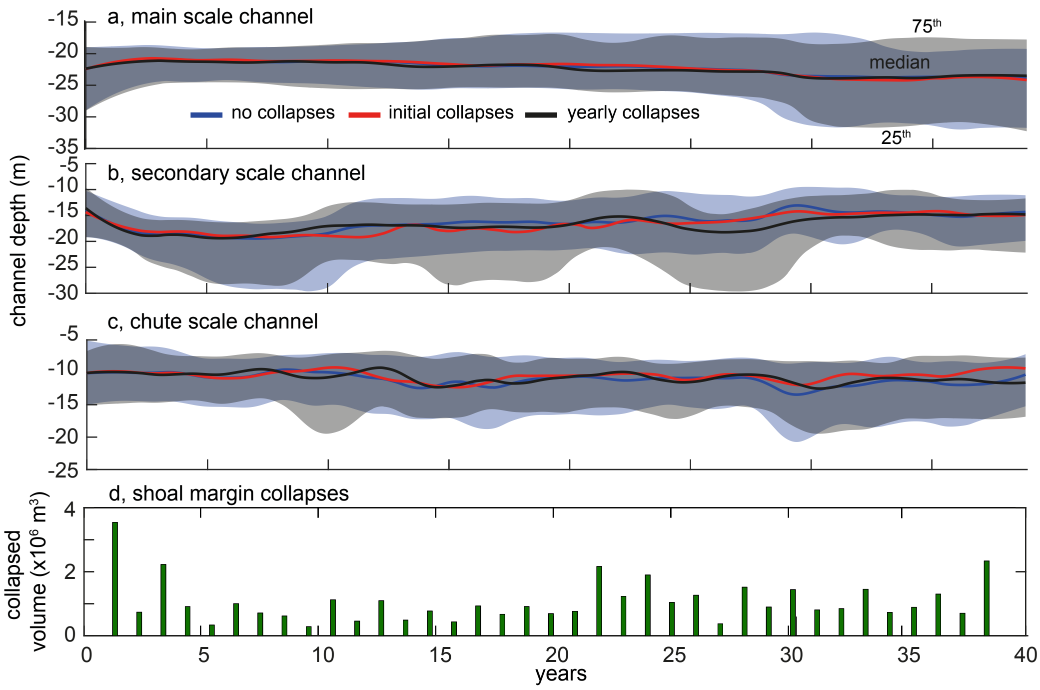


Figure 10. Depth over time for the three model runs illustrating an increasing variation in depth for the various network scales. a) Median depth for the main channel network over time shows minor differences with the control run. b) Secondary channel network deviates after 10 years for the run with yearly collapses. c) Chute channel network shows faster response time to collapses. Shading indicates quartiles. Considerable deviations are observed for the yearly collapses at 9, 18 and 30 years and for the initial collapses at 13, 27 and 36 years. d) Time and volume of shoal margin collapses.

The shoal margin collapses does not dynamicise the morphodynamics as we hypothesized, but does change the estuary morphodynamics compared to a control run without collapses. The most interesting responses from the collapses on the channel-shoal morphodynamics is observed near junctions (sills, Figures 7-8), corresponding to the overlapping sediment circulation cells [*Wang et al.*, 1995], the part with less bruto sediment transport but morphodynamic active part of the Western Scheldt [*Van Dijk et al.*, 2018] observed from DEM of differences for the last decades [*Grasmeijer et al.*, 2013] but not on the long-term sediment balance of the Western Scheldt that shows the development of channel-shoals for the period 1860-1955 [*Dam*, 2017]. This suggests that dynamics of the shoals have been decreased in the last decades and that perturbations, such as shoal margin collapses, efficiently are removed in the main and secondary channels and only affect the development at the shallower sills, channel junctions. The mean bed elevation at the junction does increase even when there is almost no direct deposition of the collapsed sediment (Figure 7b, c). A reason could be that collapsed sediment is spread over a larger/ wider distance, however the role of the junction is significant as this leads to excitation of the disturbance. Disturbances at the junction change the flow direction towards the successive shoal, like the successive bifurcation in a braided river [*Schuurman et al.*, 2016a], but also the flow direction towards the shoal itself as the tidally averaged flow circulates, i.e., marco cell, around the shoal (Figure 1b). This means that disturbances near a junction would have a larger effect on the channel-shoal morphodynamics. For example, the collapses near Borssele (location B) and at Ossennisse (location H) result in larger differences from the control run. In the field, however, the junction (sill) is well managed as this is part of the shipping fairway, and therefore its depth is maintained by dredging activities [*Verbeek et al.*, 1998], which means that the role of collapses cannot be observed in the field.

The role of the shoal margin collapses might affect the estuary differently compared to dredging and dumping activities, which is conducted to deepen the main channel. Dredging activities at the toe of the 'Platen van Ossenisse' ['Drempel van Hansweert' *Groenewoud*, 1997] might lead to deepening and increase the number of shoal margin collapses in the field, which is not included in our simulations. In this study, we have not included dredging and dumping, which would affect our finding. For example, dredging and dumping studies in the Western Scheldt estuary show that the dumping strategies affect the estuary differently. Till 1970, dredging was restricted to maintain depths for navigation in the main ebb channel, and the dredged sediment was disposed in the flood (secondary) channels because of the longer period before reaching the main ebb channel [*Meersschaut et al.*, 2004]. This is comparable to our findings that shoal margin collapse deposits in the flood channels take longer to spread towards the junction, i.e., sill, because of the lower sediment transport. Because of continuous disposal of dredge volumes in the secondary flood channels aggradation was observed in these channels [*Meersschaut et al.*, 2004], which formed a threat for the existence of the multiple channel network, a new flexible disposal strategy was introduced to steer the development of channels and shoals [*Meersschaut et al.*, 2004; *Vos et al.*, 2009]. This flexible disposal strategy encompasses redistributing sediment to feed areas that are eroding too much, e.g., the western tip of the 'Plaat van Walsoorden' (location I). Although, the extensive monitoring and model study of the flexible disposal strategy [*Vos et al.*, 2009; *IMDC*, 2011, 2015], it will be of interest to test the effect on the long-term channel network of various dredging-disposal strategies and the stability of the multiple channel network [*Wang*, 2015]. Dredged volumes are 10 times larger compared to shoal margin collapses in the Western Scheldt we would argue that therefore the role of shoal margin collapses on the morphodynamics in the Western Scheldt is hardly observable. The role of the shoal margin collapses might affect the estuary differently compared to dredging and dumping activities, which is conducted to deepen the main channel. Dredging activities at the toe of the 'Platen van Ossenisse' ['Drempel van Hansweert' *Groenewoud*, 1997] might lead to deepening and increase the number of shoal margin collapses in the field, which is not included in our simulations. In this study, we have not included dredging and dumping, which would affect our finding. For example, dredging and dumping studies in the Western Scheldt estuary show that the dumping strategies affect the estuary differently. Till 1970, dredging was restricted to maintain depths for navigation in the main ebb channel, and the dredged sediment was disposed in the flood (secondary) channels because of the longer period before reaching the main ebb channel [*Meersschaut et al.*, 2004]. This is comparable to our findings that shoal margin collapse deposits in the flood channels take longer to spread towards the junction, i.e., sill, because of the lower sediment transport. Because of continuous disposal of dredge volumes in the secondary flood channels aggradation was observed in these channels [*Meersschaut et al.*, 2004], which formed a threat for the existence of the multiple channel network, a new flexible disposal strategy was introduced to steer the development of channels and shoals [*Meersschaut et al.*, 2004; *Vos et al.*, 2009]. This flexible disposal strategy encompasses redistributing sediment to feed areas that are eroding too much, e.g., the western tip of the 'Plaat van Walsoorden' (location I). Although, the extensive monitoring and model study of the flexible disposal strategy [*Vos et al.*, 2009; *IMDC*, 2011, 2015], it will be of interest to test the effect on the long-term channel network of various dredging-disposal strategies and the stability of the multiple channel network [*Wang*, 2015]. Dredged volumes are 10 times larger compared to shoal margin collapses in the Western Scheldt we would argue that therefore the role of shoal margin collapses on the morphodynamics in the Western Scheldt is hardly observable.

6 Conclusions

Detailed analysis of the 2014 shoal margin collapse shows that the hydrological and morphological processes around the shoal margin collapse are affecting water levels and sediment transport direction. Model results show that single shoal margin collapses only affect the local dynamics in longitudinal direction and dampen out within a year when volumes are small. The extent of far-field effects is sensitive to the grain-size of the deposit, where finer sediments are transported further away and settles on the sides while larger grains are hardly entrained and only eroded during the stronger flood flow. The location of the deposit across the channel matters for disturbing the region around the collapse, where sediment transport is dominantly following the tidally averaged flow but coarser sediment follows the stronger flood flow. The perturbation by the shoal margin collapses increases channel migration rate, as the deposited sediment pushes the flow against the banks. These results imply that disturbances caused by dredging and dumping may likewise affect the dynamics of channel junctions as well, because dredging volumes are at least 10 times larger than the collapsed volumes.

We presented a parametrization for shoal margin collapses and coupled this to the Delft3D model, so that effects of multiple yearly collapses of various sizes on the morphodynamics could be tested. We found that near-field morphodynamics in the channel are slightly affected at a timescale of a year due to increasing bed elevation and changing water levels, but far-field effects such as the tidally averaged flow vectors are negligible affected by the collapses. When larger disturbances reach the seaward or landward junction at tidal channel junctions over a longer time span, the bed elevation at the junction increases on average and decrease the hydraulic geometry of the channel junctions. Here, the perturbation affects the morphology in longitudinal as well as transverse direction, and affect the channel network on a longer term when the flow and sediment distributions into the multiple channels are shifted. The initial collapses have no effect on the long-term channel-shoal morphodynamics, although bed elevation difference is only for 10% explained by the collapsed volume. The yearly collapses resulted in a shallowing of the main channel as they mostly occur along the main channel, and change the channel networks at the various scales. The secondary scaled channels become deeper, whereas the number of the chute scale channels increases when the system gets generally shallower. We conclude that multiple yearly collapses are changing the channel-shoal morphodynamics in estuaries, but that the role of the collapses is limited for heavily dredged systems such as the Western Scheldt. On the other hand, estuaries that are not intensively dredged may not develop oversteepened bar margins with frequent shoal margin collapses.

Acknowledgments

WMvD and MGK were supported by the Dutch Technology Foundation TTW (grant STW-Vici-016.140.316/13710 to MGK), which is part of the Netherlands Organisation for Scientific Research (NWO). MH and MGK were supported by the European Research Council (ERC Consolidator agreement 647570 to MGK). We gratefully acknowledge Marco Schrijver (Rijkswaterstaat), Dick Mastbergen, Marcel Taal (Deltares) and Jelmer Cleveringa (Arcadis) for insightful discussions. Reviewers will be acknowledged. The data used are listed in the references, figures and supplements.

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