LONG-TERM PERFORMANCE OF PROCESS-BASED MODELS IN ESTUARIES

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Abstract

This paper presents a 110 year morphodynamic hindcast for the Western Scheldt using a process-based model. The time period of 1860-1970 is simulated starting with the 1860 bathymetry. It is shown that the model can reproduce most major morphological changes in the estuary. A Brier-skill score of 0.48 is obtained at the end of the simulation, which means that the model has significant skill. Despite general concerns on the value of process-based models reproducing long-term morphological changes, it is concluded that this model captures important long-term morphological changes in the Western Scheldt.

Key words: long-term morphodynamics, process-based models, sediment transport, estuaries, Western Scheldt

1. Introduction

The Western Scheldt is a tide dominated estuary and highly morphological active. The tide and the morphology are inter related, i.e. any change in tide causes a change in morphology and vice versa. Managing the estuary requires deepened knowledge and sophisticated decision making tools to be able to safeguard all the functions of the estuary with regard to nature, safety and access to the Port of Antwerp. The morphological timescales of large scale impacts, such as land reclamation, deepening of the navigational channel, sand mining and sea level rise are in the order of decades to century. For this reason investigating these impacts requires long-term morphological models. Until now long-term morphological predictions were mainly carried out by using (semi)-empirical models, like ESTMORF (Wang et al., 1999) and ASMITA (e.g. Kragtwijk et al., 2004). Process-based morphological models were not yet able to reproduce the morphological development very well over decades, partly because of the large amount of computational time involved and partly because it was believed that process-based models could not model very well over long timescales (more than a few years).
Focus of long-term research using process-based models was mainly on highly schematised tidal basins like Hibma et al. (2003) and Van der Wegen and Roelvink (2012). More realistic hindcasts for specific estuaries over decadal to century timescales are still scarce. Van der Wegen et al. (2011) and Van der Wegen and Jaffe (2013) are amongst the first to show the value of morphodynamic, process based models on a decadal time scale for a confined basin. It is important to test these models on these long time scales with other case studies. In Dam (2007) a long-term morphological model of the Western Scheldt was presented that successfully hindcasted the 1965-2002 period. Using the same model as Dam (2007) in this paper a 110 year hindcast is carried out for the 1860-1970 period and its performance on this century timescale is investigated.

2. Long-term modeling using process-based models

This section summarizes a literature survey on the ability of process-based models to simulate morphodynamic changes . Stive and Wang (2003) claim that the ability to hindcast or predict the evolution

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of tidal inlets at decadal to century time scales remains questionable. According to De Vriend et al. (1993) the long-term behaviour of models may be even be inherently unpredictable since the natural system is a nonlinear interaction between water, sediment motion and bed topography. Furthermore hindcasting decadal-timescale bathymetric change in estuaries is prone to error due to limited data for initial conditions, boundary forcing, and calibration (Ganju et al., 2009). Small deviations in for example parameter settings might cause large errors in the long term since the errors begin to accumulate (Roelvink and Reniers, 2011). Haff (1996) points to different sources of uncertainty or error that arise in attempting to model at longer time scales : (i) model imperfection, (ii) omission of important processes, (iii) lack of knowledge of initial conditions, (iv) sensitivity to initial conditions, (v) unresolved heterogeneity, (vi) occurrence of external forcing, and (vii) inapplicability of the factor of safety concept. Generally hindcast periods greater than a few years are considered unreliable.

The overview suggests that long-term modeling is difficult, if not impossible. However several studies have shown that starting from a flat bed patterns emerge that are observed in reality. Hibma et al. (2003) were the first to show that self-organisation of pattern formations in a highly schematised estuary could be simulated with a process-based model that gives reasonable resemblance with patterns found in reality. The reason why the model was capable of simulating these patterns is a positive feedback between currents and bathymetry. After 100 year the pattern stabilized. Van der Wegen and Roelvink 2008, Van der Wegen et al. (2008, 2010) extended this research for longer timescales (millennia) and concluded that a relative simple process-based model can describe at least in some degree the morphodynamics of estuaries. The positive feedback mechanism between currents and bathymetry is responsible for more or less stable results after long timescales with little sensitivity to the model settings or sediment transport formula. Van der Wegen and Roelvink (2012) also showed that a process-based model is capable of reproducing the channel-shoal pattern using the Western Scheldt geometry with considerable skill starting from a flat bathymetry. The reason is that the interaction between tidal forcing, sediment availability and the basin geometry plays a major role in the morphological development of a tidal dominated basin. Other researchers also concluded that starting from a flat bed process-based models can produce realistic patterns in tidal inlets (Cayocca, 2001; Marciano et al., 2005; Dastgheib et al., 2008; Dissanayake et al., 2009).

The excercises of Hibma et al. (2003, 2004) and Van der Wegen et al. (2008, 2010), Van der Wegen and Roelvink (2010, 2012) all started from a flat bathymetry, in which almost no spin-up time is needed. If a model starts with a real measured bathymetry the model requires a spin-up time; the bathymetry of a morphological model needs to adjust to the model settings, small scale perturbations in the bathymetry due to interpolation to the model grid will disappear, and so model results in the spin-up time are not reliable. Adequate spin-up time on the order of years is required to initialize models, otherwise the solution will contain a bathymetric change that is not due to environmental forcing, but rather improper specification of initial conditions and model parameters (Schoellhamer et al., 2005). They found a spin-up time of 10 years for a cohesive transport model of San Francisco Bay.

To conclude: most research on long timescales using a process-based model has been carried out for schematised estuaries, where they have shown to produce patterns that are observed in reality. Real hindcasts over decadal to century timescales are still lacking. It is therefore important to test these models on these time scales.

3. Case study: Scheldt estuary

We take the Western Scheldt as a case study to test the ability of process-based morphological models on long time scales. The Scheldt estuary is one of the major estuaries of North-West Europe. The estuary is approximately 160 km long and is located both in Dutch and Belgian territory. The down-estuarine part (last 60 km) is called the Western Scheldt (Figure 1) and is characterised by a width of almost 5 km near the mouth and 1 km near the Dutch-Belgian border. The mean tidal range increases from 3.8m at the mouth to over 5.0m near Antwerp almost 80 km from the mouth of the estuary (see Figure 1). The morphological changes in the Scheldt estuary are dominated by the tidal motion. The river discharge is of minor importance since the fresh water discharge, on average 120 m³/s, is only 0.6% of the tidal prism at the mouth (Van der Spek, 1997). The estuary is well-mixed.

The Western Scheldt incorporates large areas of tidal flats and salt marshes. Nature is therefore an important function and stringent EU and national legislation is maintained to safeguard its natural values. Equally important are the functions of the estuary in the safety against flooding and the access to the Port of Antwerp.

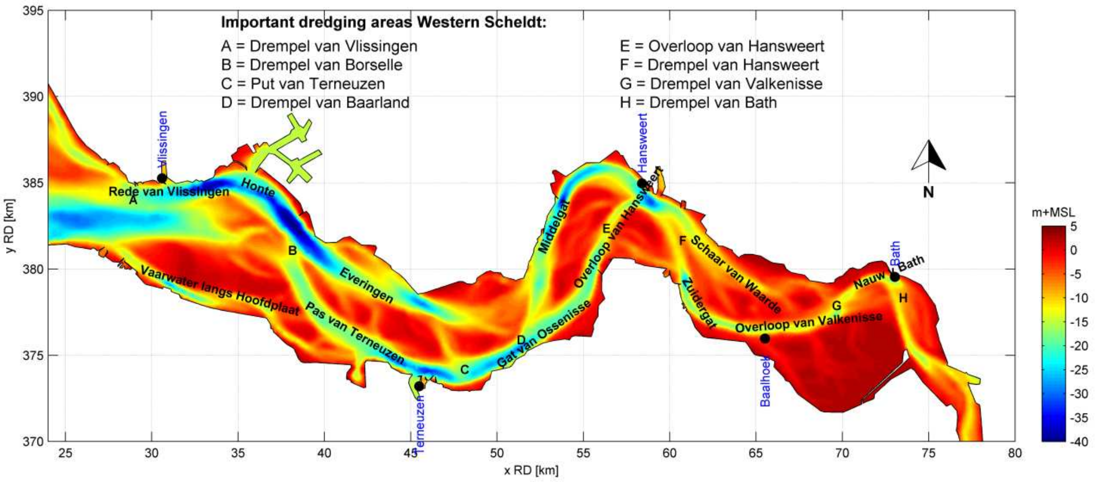

Figure 1. Layout of the Western Scheldt around 1970 with names of important channels and dredging areas and tidal stations

The Western Scheldt has a multiple channel system. Ebb and flood channels show an evasive character separated by inter tidal shoals (Van Veen, 1950). The ebb channel has a meandering character, while the flood channel is straighter. The ebb flow reaches it maximum velocity near mean sea level (MSL), while the flood flow reaches its peak one hour before high water (Van den Berg et al., 1996). As a consequence the ebb flow is more concentrated in the channels, resulting in deeper ebb channels. The ebb channel is therefore generally designated as the navigational channel in the Western Scheldt.

In this paper the 1860-1970 period is investigated. Figure 2 shows the observed bathymetries from 1860 to 1970. In this period large morphodynamic changes have occurred as can be seen from Figure 3. In this period large morphodynamic changes have occurred as can be seen from Figure 2. The ebb channels tend to migrate to the outer bank. In the 1970's and 1990's a deepening and widening of the navigational channel has been carried out to allow vessels with greater draught to enter the port of Antwerp. Recently, in 2010, a third deepening has been completed. Dredging volumes after 1970 range in the order from 5-14 million m^3 per year in the estuary. Before 1970 the dredging operations concentrated to a few sills in the eastern part of the estuary. The hindcast is therefore focused on the period till 1970, before the major dredging operations started, in order to answer the question if we are able to hindcast the natural morphodynamic behaviour of the system over this 110 year period.

In the past centuries large land reclamations have narrowed the estuary, resulting in increasing tidal levels. The land reclamations in the period 1860-1970 are shown in Figure 3 and are taken into account in the simulation, as will be explained in the next section.

The tide and morphology are inter related. In Wang et al. (2002) this is described by saying that (1) changes in morphology lead to (2) changes in tidal levels, which lead to (3) differences in ebb and flood velocities that (4) causes residual transport of sediment, with a feedback into (1). In principle this feedback loop is described by a process-based model, although its value in long-term morphodynamic calculations has not been proven yet.

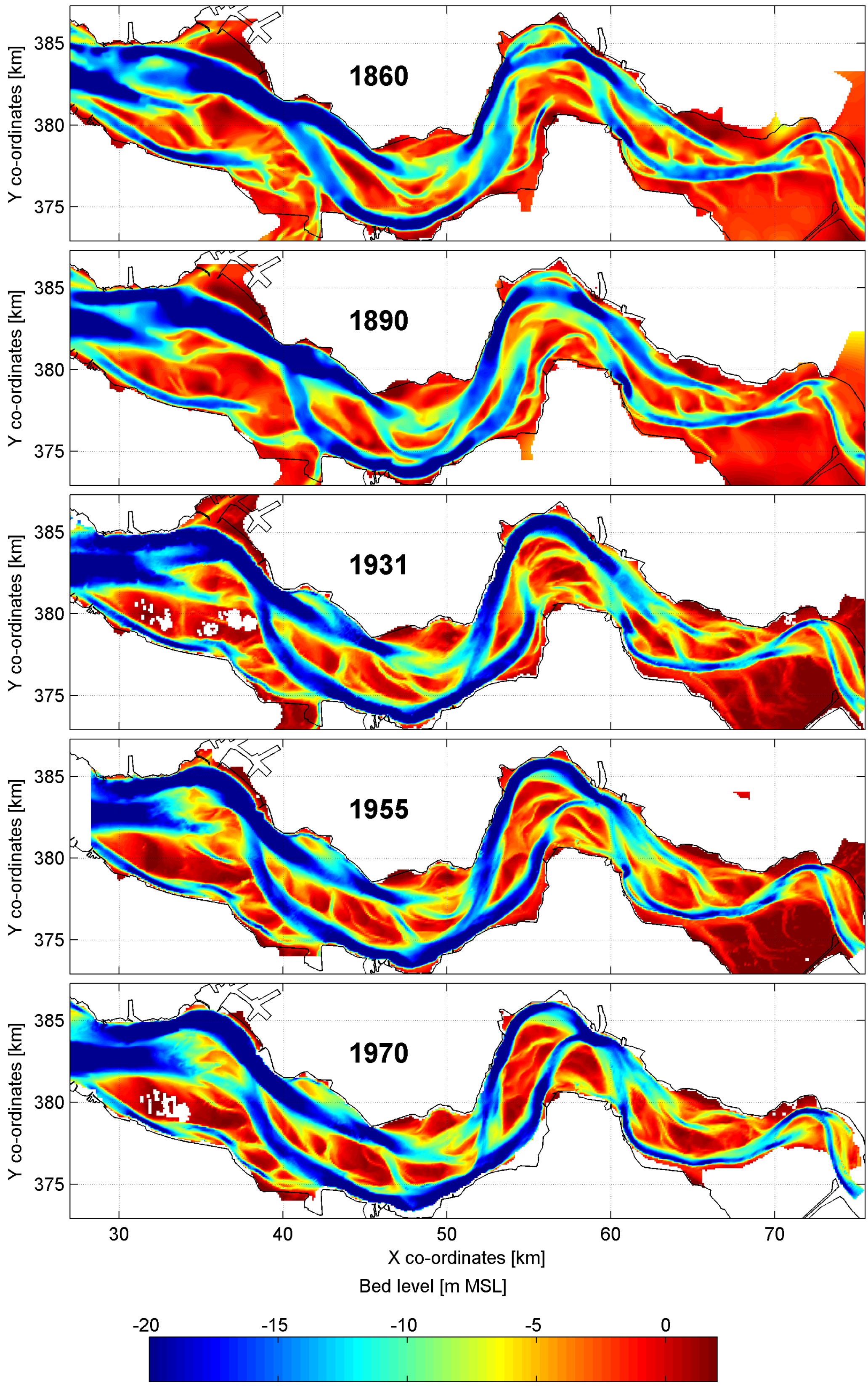

Figure 2. Bathymetric observations of the Western Scheldt from 1860 to 1970.

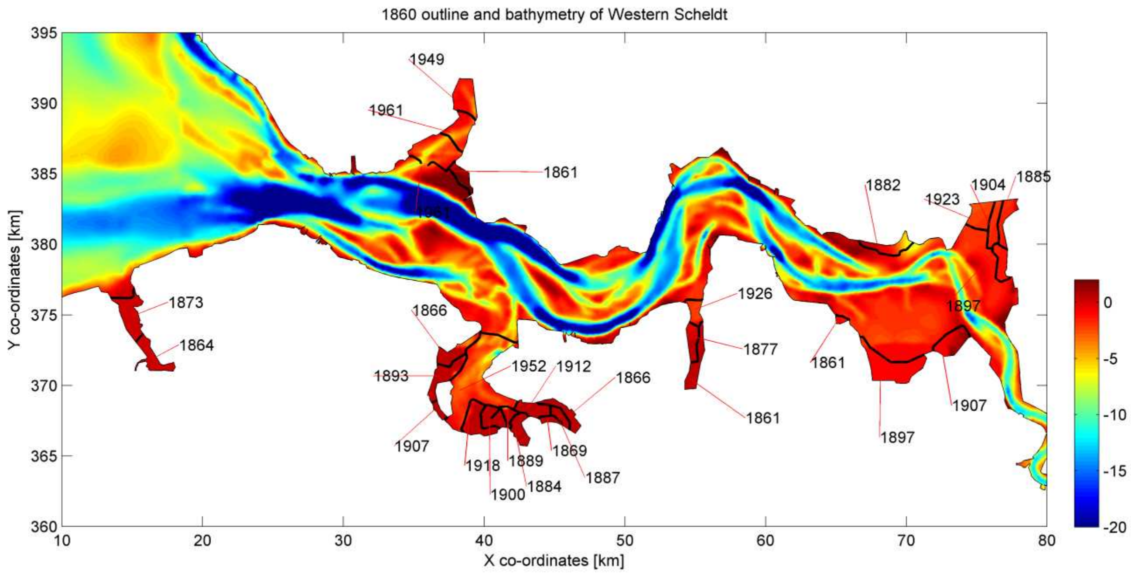

Figure 3. Layout of the Western Scheldt in 1860 together with land reclamations from 1860 to 1970.

4. Process-based model: FINEL2d

The process-based model that is applied in this study is called FINEL2d. The model is a 2DH process-based model based on the finite element method. The depth-integrated shallow water equations are the governing equations of the flow module. For details about FINEL2d reference is made to Dam et al. (2007). Other examples of the FINEL2d model are Dam et al. (2005, 2009) and Dam and Bliek (2013).

FINEL2d uses an unstructured triangular grid. The advantage of such a mesh in comparison to for example a finite difference grid is the flexible mesh generation. In FINEL2d no nesting techniques are required in regions of specific interest, where a higher degree of resolution is needed, while arbitrary coastlines and complex geometries can be resolved very well.

The seaward boundaries of the computational mesh of the Western Scheldt are chosen approximately 40 km away from the coastline and coincide with the boundaries of existing models. The latter can be used to obtain the corresponding boundary conditions. The major part of the Scheldt-estuary in Belgium is also included in the schematisation. In Figure 4 the overall mesh is shown. In the area of interest, the Western Scheldt, the average grid size is approximately 1.1 ha (see lower panel of Figure 4). Near the seaward boundaries the grid size is approximately 2.5 km^2. The total number of elements (triangles) of the mesh is 59,937.

On the seaward side of the grid tidal boundary conditions are given, while on the river side constant (yearly averaged values) river discharges are taken. Only the influence of the tidal action on the morphology is taken into account. Wave action is ignored for simplicity reasons, although intertidal areas can be influenced by wave action. To speed up the morphological calculation a morphological acceleration factor (MF) is used every timestep to multiply the bed level changes (Roelvink, 2006). In this case a MF of 24.75 is applied in accordance with Dam et al. (2007). One neap-spring cycle for the water motion represents a morphodynamic year with this setting. A parameterisation of the spiral flow was implemented according to Kalkwijk and Booij (1986).

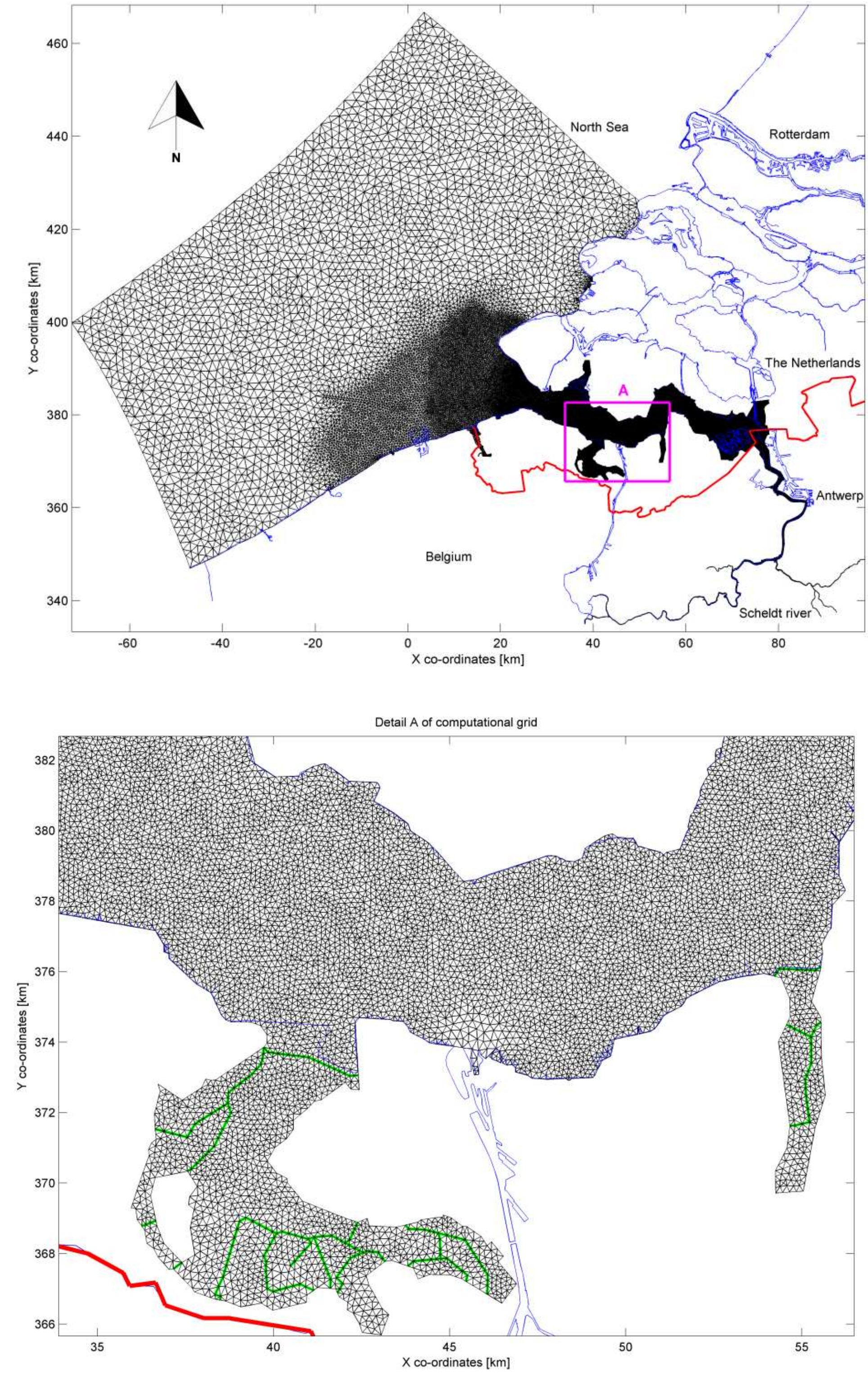

Figure 4. Computational grid of 1860 (black), land reclamations (green), present day land boundary (blue) and Dutch-Belgian border (red).

The calibration of the model on the water motion and the sandy morphology for the entire Scheldt estuary is carried out in Dam et al. (2007) with an update in 2013 (Consortium Deltares-IMDC-Svasek-Arcadis, 2013). The model was first calibrated on water levels at the main tidal stations (not presented here). This resulted in a global k-nikuradse roughness of 0.01 m. The model was validated for tidal currents in both the channels and inter tidal areas. The model showed good agreement between observations and model results (Consortium Deltares-IMDC-Svašek-Arcadis, 2013).

The optimal settings for the morphodynamic model found in the calibration are given in Table 1. These settings are used in the model computations discussed in this paper.

The land reclamations are taken into account in the computation. The borders of the land reclamations coincide with the computational mesh. At the year of closure a weir is implemented in the model, so that this section is closed off from the tidal influence and morphodynamic activity in the closed-off section stops. The year of closure is given in Figure 1. A hindcast of the years 1965 to 2002 is described in Dam et al. (2007), which was updated recently (Consortium Deltares-IMDC-Svasek-Arcadis, 2013).

Table 1. Model settings.

Parameter	Value
Sediment transport formula	Engelund Hansen (Engelund-Hansen, 1967)
Grain size (d_{50})	Variable (150 μm up to 300 μm)
Fall velocity of sand	0.015 m/s
Morfological acceleration factor (MF)	24.75
Morphological start-up period	1 year
Non erodible layers	From government data
Hydraulic roughness	1 cm

5. Results of the 110 year hindcast: 1860-1970

Figure 5 shows the simulated and observed erosion/sedimentation pattern. The simulated and observed pattern have large similarities. For example the model reproduces the migration of the Pas van Terneuzen westwards quite well (Location A in Figure 4). Also the migration of the Honte to the north (D) and the creation of an intertidal flat at the location of the original channel (E) is shown nicely. The bar in the mouth of the estuary called Hoge Platen shows sedimentation in both the model and observations (F), the creation of a bar near the landward side of the estuary is also simulated well (G). The formation of a new channel Overloop van Hansweert is shown in the model (H), while the opposite channel “Middelgat” shows a migration to the outer bank in both the model and observation (B). The simulation of a new intertidal shoal between these two channels can also be seen in the observations (I). The migration of the Zuidergat channel to the outer bank can be seen both in the model as observations (C). In the eastern part near locations J and K the reproduction is not very well. This is thought to be because of the dredging that takes place here since at least the 1930’s and this is not included in the model, resulting in unrealistic morphological changes. Furthermore many small scale features are not represented, like secondary channels with a size comparable to the grid size, but large scale features seem to be reproduced quite well.

In order to objectively quantify the model results the Brier-skill score (BSS) is used as defined in equation 1 (Sutherland et al., 2004). The Brier-skill score reflects how good the model results are in comparison to the observed change.

$$BSS = 1 - \frac{\left\langle (Y - X)^2 \right\rangle}{\left\langle (B - X)^2 \right\rangle} \tag{1}$$

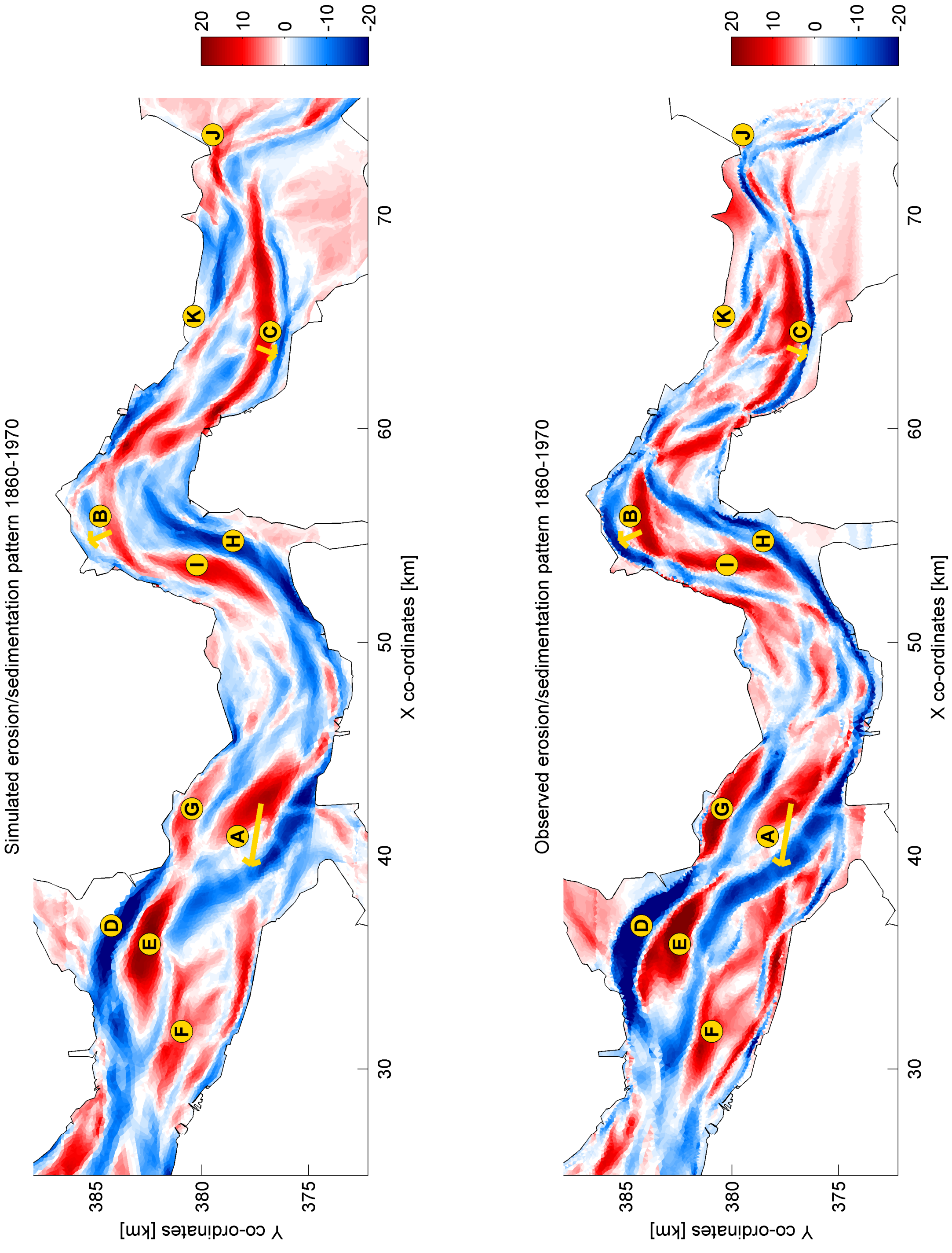

Figure 5. Simulated erosion and sedimentation pattern (left) and observed (right) for 1860-1970.

In which:

X	=	computed bed level [m]
Y	=	measured bed level [m]
B	=	initial bed level [m]

And the <> denote the arithmetic mean.

Van Rijn et al. (2003) defined the following classification of the BSS:

Excellent	: 1.0 - 0.8
Good	: 0.8 - 0.6
Reasonable/fair	: 0.6 - 0.3
Poor	: 0.3 - 0.0
Bad	: < 0

A BSS of 1 means a perfect match between measurements and model results, while a result below 0 suggests that the model result is worse than zero bed changes. The BSS is calculated using the measured erosion/sedimentation pattern and the modelled erosion/sedimentation pattern as shown in Figure 5. A BSS of 0.48 is obtained using the 1970 results. This means that the model has significant skill and can be qualified as reasonable/fair according to Van Rijn et al. (2003).

A regression coefficient between observed and simulated bed level changes results in a R^2 of 0.55. Furthermore the amount of gridcells with a correct sign (erosion or sedimentation) is 70% after the 110 year period.

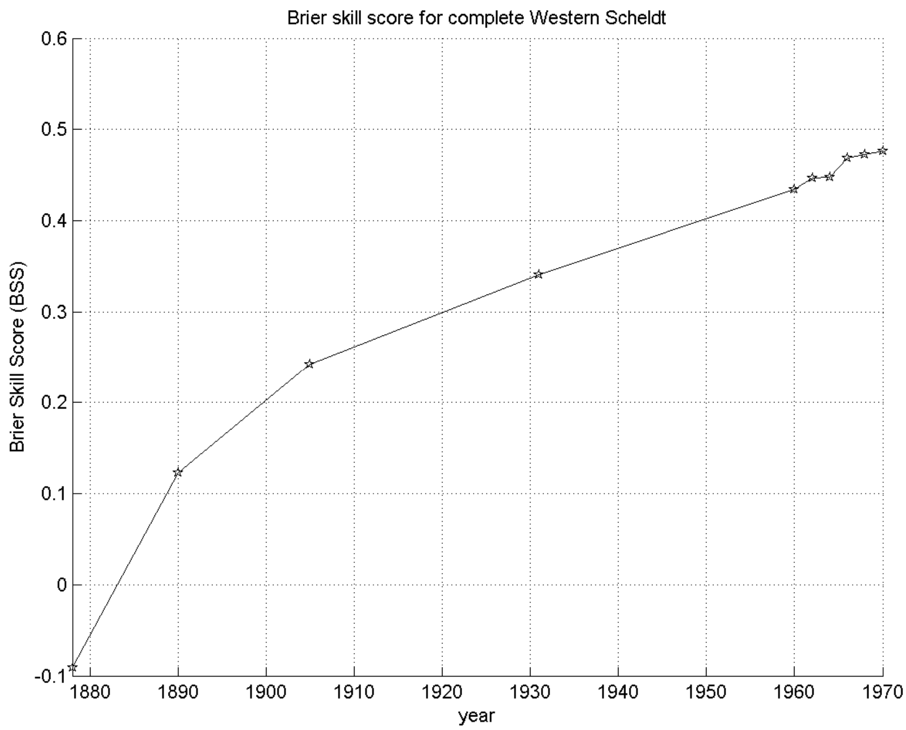

Figure 6. Brier-skill score over the period 1860-1970.

In order to see the performance of the model over time the BSS is determined for each available bathymetry, see Figure 6. Interestingly the BSS is increasing over time. The first 25 years of the simulation a negative BSS is calculated. Each subsequent year where a bathymetry is available the BSS improves. This would mean that the model performance is improving over time. From the erosion/sedimentation pattern of Figure 5 it becomes clear that after 110 year period the large-scale patterns do come out of the model. Therefore it is concluded that in this case long-term morphological modelling using a process-based model is possible. Furthermore short-term results should be interpreted carefully, since this might well be in the spin-up time of the model, resulting in negative BSS scores. The reason why long-term modelling is possible in this case might be that the geometry is an important factor in the morphology of the Western Scheldt (Van der Wegen and Roelvink, 2012). Also the tide is the most important forcing in the Western Scheldt. The tide can be predicted well by a process-based model, so there is limited uncertainty involved in the major driving force for morphological change. Furthermore heterogeneity issues concerning sediment fractions are probably not a big issue in this specific case, since the Western Scheldt consists mainly of fine non-cohesive sediments; only at inter tidal areas mud can be found. This hindcast using only one sand fraction is sufficient to reproduce most morphological changes that have occurred from 1860-1970.

6. Conclusion

Despite general concern that process-based models are not capable of simulating morphodynamic changes very well over long timescales, in this paper a model is presented that is capable of simulating most observed morphodynamic changes after a 110 year period in the Western Scheldt estuary. The model has a Brier-Skill Score of 0.48 at the end of the simulation, this means that the model has significant skill.
Future work includes other periods, simulating both sand and mud and other estuaries.

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