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Modeling centuries of estuarine morphodynamics in the Western Scheldt estuary

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Key Points:
- A historic morphodynamic hindcast of an estuary has excellent skill on a century time scale
- System strives for equilibrium with minimum energy dissipation and stable morphology
- Long-term morphology is predictable due to equilibrium conditions, confinement of the estuary, and constant forcing

Supporting Information:
- Supporting Information SI

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Abstract We hindcast a 110 year period (1860–1970) of morphodynamic behavior of the Western Scheldt estuary by means of a 2-D, high-resolution, process-based model and compare results to a historically unique bathymetric data set. Initially, the model skill decreases for a few decades. Against common perception, the model skill increases after that to become excellent after 110 years. We attribute this to the self-organization of the morphological system which is reproduced correctly by the numerical model. On time scales exceeding decades, the interaction between the major tidal forcing and the confinement of the estuary overrules other uncertainties. Both measured and modeled bathymetries reflect a trend of decreasing energy dissipation, less morphodynamic activity, and thus a more stable morphology over time, albeit that the estuarine adaptation time is long (approximately centuries). Process-based models applied in confined environments and under constant forcing conditions may perform well especially on long (greater than decades) time scales.

1. Introduction

Estuarine morphology and its development over time have been the subject of research ever since estuaries became important navigational gateways to ports and their hinterland [*Reynolds*, 1887; *LeConte*, 1905]. Estuaries are unique ecosystems with important ecological functions like breeding ground for fish or feeding areas for migratory birds [*Gill et al*., 2001; *Barbier et al*., 2011]. Estuaries are put under increasing pressure by human activities (dredging of navigational channels and land reclamation works) and climate change [*Barbier et al*., 2011]. Understanding and forecasting estuarine morphodynamics is essential for adequate estuarine management and policy making.

Exploring morphological dynamics raises questions on the existence and character of morphological equilibrium. *Dronkers* [1986] states that external conditions in reality change continuously so that equilibrium conditions cannot be reached. One-dimensional and 2-D modeling approaches find equilibrium conditions under highly schematized settings [e.g., *Schuttelaars and de Swart*, 2000; *Lanzoni and Seminara*, 2002; *Hibma et al*., 2004]. Equilibrium can exist at smaller scales of channel-shoal patterns while larger scales (at basin size) have century long adaptation time scales [*Van der Wegen and Roelvink*, 2008; *Van der Wegen et al*., 2008]. At the same time, equilibrium can be dynamic due to cyclic behavior of channels and shoals or can be reached only by approximation due to long adaptation time scales.

Morphodynamic development may be investigated by empirical relationships [e.g., *O'Brien*, 1969], laboratory scale tests [*Reynolds*, 1887; *Tambroni et al*., 2005], or numerical models ranging from highly schematized to fully process based [*De Vriend et al*., 1993; *Murray*, 2003]. Schematized (or reduced complexity) modeling efforts have an inductive character by assuming (empirical) equilibrium relationships between forcing and elements of the estuarine morphodynamic system [*Kragtwijk et al*., 2004]. Any disturbance of the system will eventually strive toward equilibrium conditions. In contrast, process-based models have a strong deductive character by taking physical processes as a starting point without defining equilibrium conditions a priori.

Process-based models are widely used in the science and engineering community [*Lesser et al*., 2004; *Hervouet*, 2000; *Shchepetkin and McWilliams*, 2005]. In this paper we apply a two-dimensional depth-averaged process-based model in the horizontal plane [*Dam et al*., 2007; *Dam and Bliek*, 2013] to predict centennial time scale morphodynamics.

Many process-based models were originally developed to address the short-term morphological impact of engineering works [*Roelvink and Reniers*, 2011]. The essential part of these morphodynamic models is the feedback loop between topography, fluid dynamics, and sediment transport, the gradients of which result in morphodynamic change. The feedback can either be positive or negative. Positive feedback occurs when instabilities grow. Negative feedback is attributed to damping of the system. Switches between these states mark thresholds in morphodynamic behavior [*Cowell and Thom*, 1994].

By increasing computational power and clever morphological updating techniques, the models have evolved into scientific tools that are potentially able to calculate high-resolution (~100 m) morphological change over decades to millennia in large (~100 km) domains with a computation time of days to weeks on a standard PC. Numerous process-based studies describe stable centennial to millennial time scale morphodynamic development in highly schematized tidal basins under constant forcing conditions [e.g., *Hibma et al.*, 2003; *Van Maanen et al.*, 2013; *Bertin et al.*, 2005; *Zhou et al.*, 2014].

The potential for successful predictions in more realistic environments remains, however, questionable [*De Vriend et al.*, 1993; *Haff*, 1996, 2013; *Stive and Wang*, 2003]. Small errors in prediction, coupled with nonlinear interactions that are chaotic in nature, may eventually lead to unrealistic developments. Apart from numerical shortcomings, sources of uncertainty or error that may arise include [*Haff*, 1996] (1) model imperfection: e.g., application of an empirical sediment transport formula derived in a laboratory on a large morphodynamic scale; (2) omission of known and unknown processes: e.g., wave action plays a role in morphodynamics of shoals but is often ignored in long-term morphodynamic simulations of estuaries; (3) lack of knowledge of initial conditions: e.g., distribution of sediment characteristics over the domain and in the bed; (4) sensitivity to initial conditions: If estuarine morphology behaves chaotically, long-term morphodynamic prediction is not possible [*Philips*, 1992]; (5) unresolved, subgrid heterogeneity; and (6) unknown external forcing.

However, using a similar type of process-based model as we apply in the current study, successful decadal time scale hindcasts in complex estuarine environment of San Francisco Bay subembayments are possible, given a strong disturbance by excessive sediment supply gradients [*Ganju et al.*, 2009; *Van der Wegen and Jaffe*, 2013].

Thus far, the centennial time scale performance of morphodynamic process-based models in relatively undisturbed systems has been unclear. An important reason is that bathymetric data for model validation covering typical morphological time scales of decades to centuries are scarce.

For that reason we explore the skill of a process-based model in hindcasting morphodynamic development in the Western Scheldt estuary in the Netherlands. Model validation is based on a unique 110 yearlong bathymetric data set starting in 1860 and continuing with intervals ranging from 5 to 25 years. As a final step we extend the simulation to 250 years and analyze energy dissipation and morphodynamic activity.

We apply a two-dimensional process-based model called FINEL2d [*Dam et al.*, 2007; *Dam and Bliek*, 2013] that is based on the finite element method that solves the two-dimensional shallow water equations employing a Riemann solver [*Glaister*, 1993], a sediment transport formulation, followed by a bed update method based on the “online approach” [*Roelvink*, 2006]. Settings and details of the model, including the computational grid, are described in the supporting information.

To objectively compare measured and modeled bed changes, we use the Brier-Skill Score (BSS), see equation (1) [*Sutherland et al.*, 2004].

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

where X is the measured bed level (m), Y is the modeled bed level (m), B is the initial bed level (m), and the brackets denote an arithmetic mean, i.e., averaged over the model domain in this case.

The second term of equation (1) can be split in the numerator and the denominator, which we define as error (equation (2)) and signal (equation (3)):

$$\mathrm{Error} = <|Y - X|> \tag{2}$$

$$\mathrm{Signal} = <|B - X|> \tag{3}$$

The error is the difference between model and measurement in meters; the signal is the change in measured bed level since start of computation in meters, both averaged over the model domain.

The following rating of the BSS for morphological models is used [*Sutherland et al.*, 2004]:
Bad: <0
Poor: 0.0–0.1
Reasonable/fair: 0.1–0.3
Good: 0.3–0.5
Excellent: 0.5–1.0.

As a reference, weather forecasting considers a BSS over 0.2 to be a useful prediction [*Murphy and Epstein*, 1989].

2. The Western Scheldt Estuary

The Scheldt estuary is located in the southwest of the Netherlands and Belgium (51°25′N, 4°E). The Western Scheldt is the Dutch part of the Scheldt estuary and is the focus area of our study. The Western Scheldt is a mesotidal to macrotidal estuary, is approximately 50 km long by 5 km wide, and is a multiple-channel system with distinct ebb and flood channels. It forms the navigational access to the Port of Antwerp. For that reason the bathymetry of the Western Scheldt has been recorded over more than a century. River inflow and fluvial sediment supply are limited, and salt and fresh water are well mixed [*Van der Spek*, 1997]. River input over a tide is only 0.6% of the tidal prism (see also supporting information). The estuarine bed mainly consists of fine sand [*Wartel*, 1977]. Mud is mainly found in intertidal areas. Erosion-resistant layers are present in the estuary in the form of clay and peat layers [*Gruijters et al.*, 2004; *Dam*, 2013], sometimes located directly at the bed surface, see Figure S2 in the supporting information. In the considered period (1860–1970) some minor dredging works took place in the navigational channel in the eastern part of the estuary. Since the 1970s major dredging works have deepened the navigational channel considerably. Dredging works from that moment on have significantly influenced the morphodynamics [*Dam et al.*, 2013].

The Western Scheldt developed during the early Middle Ages, when the tidal inlet Honte connected to the Scheldt river. Floodings and military inundations expanded the surface area of the estuary over the next centuries. The estuary's largest surface area is in the seventeenth century with many side branches and connections to the Eastern Scheldt estuary. Over time the side branches silted up and were embanked. The connections to the Eastern Scheldt estuary also silted up and were closed off in 1867 and 1871. Mud most likely was responsible for a large portion of this sedimentation. The land reclamations decreased the intertidal storage area from 295 km^2 in 1650 to 196 km^2 in 1800 to 104 km^2 in the recent Western Scheldt ($>$1970) [*Van der Spek*, 1997]. The surface area decreased from 410 km^2 in 1860 to 323 km^2 in the recent Western Scheldt. The morphology of the estuary changed significantly from 1860 to 1970 (Figure 1). The main channels all migrated, shoals were eroded and created, and numerous secondary channels appeared and disappeared again. Given the morphological changes, it is clear that the estuary is not in equilibrium in 1860. Since the tidal forcing at the mouth did not change significantly and the sea level rise was limited (15 cm/century), it is unlikely that these external conditions are the cause of the morphodynamic changes. It is more likely that the mentioned changes in the centuries before 1860 resulted in a morphodynamic response of the estuary.

Model assumptions are the following: (1) outline of 1871 is assumed as starting point of the simulation in 1860; (2) constant yearly averaged river discharge; (3) we excluded the period after 1970 from our analysis, because we are interested in natural morphodynamic developments of the estuary; (4) we only model the sand fraction since we are interested in the main estuarine body that mainly consists of sand; and (5) sea level rise of 15 cm/century is included in the simulation.

3. Results

Model results initially do not compare well to the measurements, but after a few decades, the results compare increasingly better to the measurements over time. This is reflected by qualitative visual comparison of erosion and sedimentation patterns for the 1860–1970 run (Figure 2) and quantified by an increasing BSS (black line of Figure 3a).The supporting information provides erosion-sedimentation figures with measurement-model comparisons for the 1878, 1890, 1905, 1931,1955, 1960, and 1965 bathymetries. Figure 3a shows that the BSS is initially negative but increases to become 0.52 (excellent) after 110 years for the 1860–1970 run.

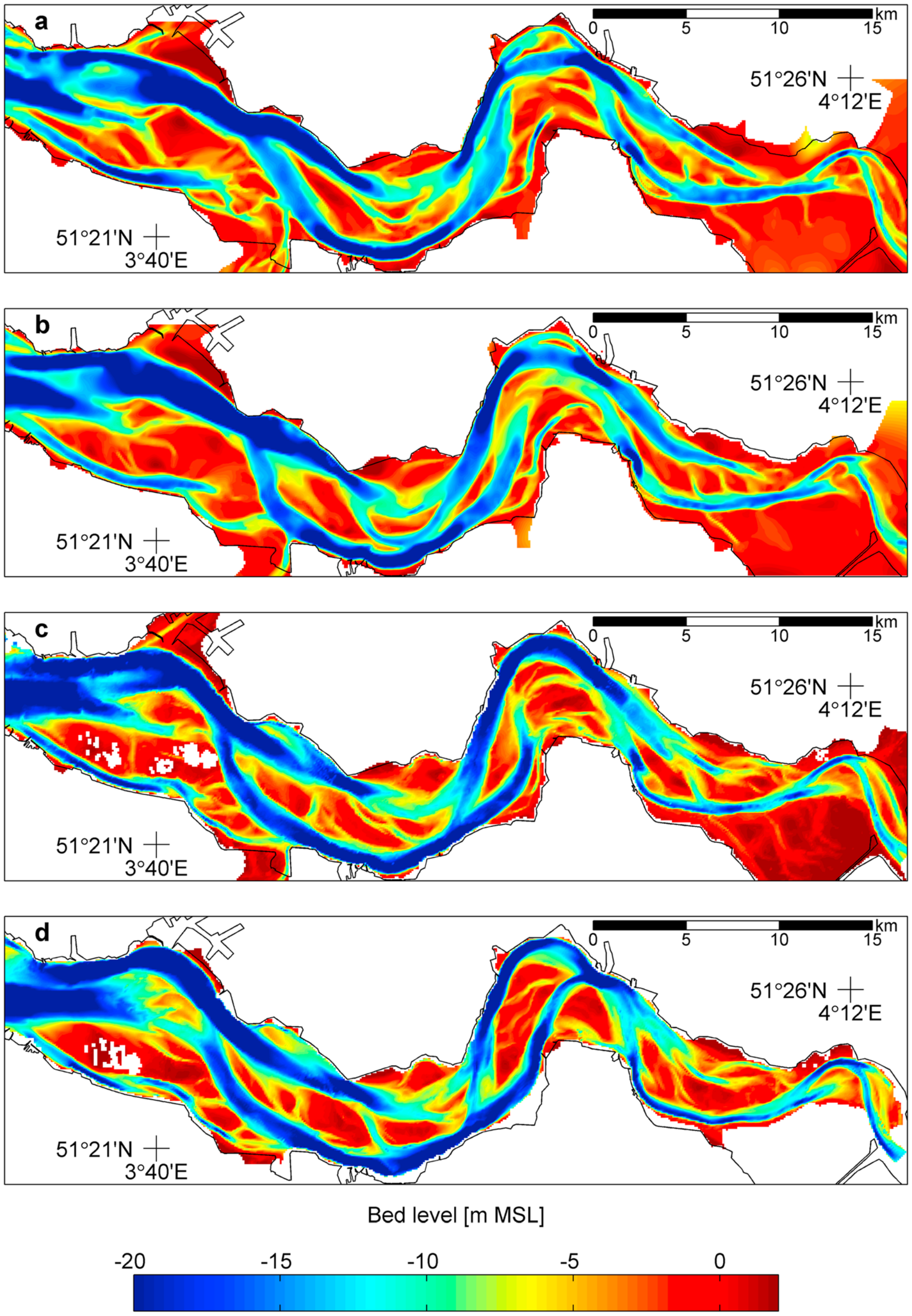

Figure 1. Four measured bed levels with respect to mean sea level (msl) of the Western Scheldt. (a) 1860. (b) 1905. (c) 1931. (d) 1970. Black line indicates the present-day plan form.

The model exercise is repeated using the available measured bed levels in the years 1878, 1890, 1905 1931, 1955, and 1960 as initial condition for the bed level in a new computation. These runs also simulate the period until 1970 and BSS values are determined at the available bed level data. Initially, the BSS decreases and has a minimum around 15–20 years after start of the computations (Figure 3a). After this period the BSS increases for all simulations, and the model results compare better to the measurement in the longer term. This conclusion is not dependent of the initial condition.

The BSS results can be split into the model error (equation (2)) and the signal (equation (3)), see Figure 3b. Although the model error indeed increases and is initially even higher than the signal, the signal increases eventually even more leading to a decreasing error to signal ratio over time for all runs with a simulation time greater

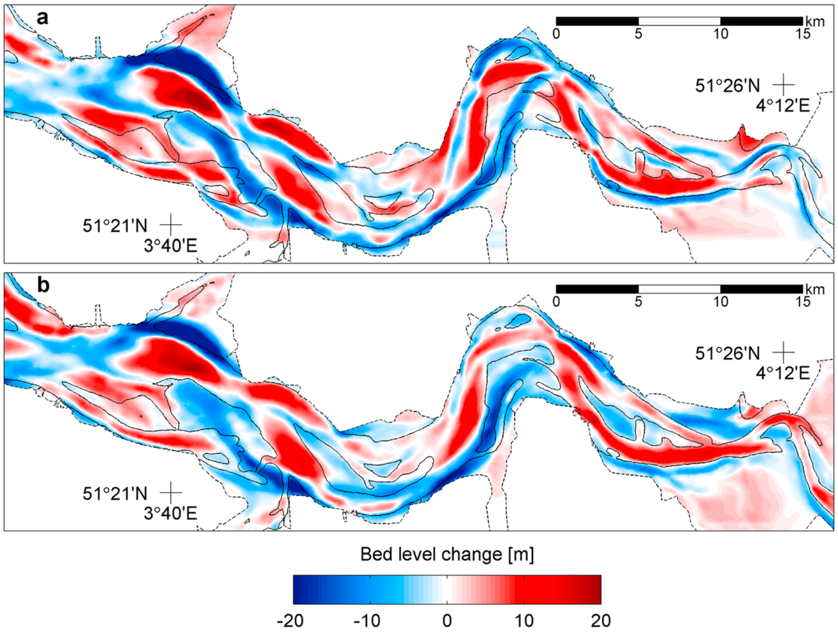

Figure 2. Erosion and sedimentation patterns over the 1860–1970 period. (a) Measured. (b) Modeled. Black dashed line indicates the 1860 plan form. Black solid line indicates the −5 m contour line of the 1860 bed level.

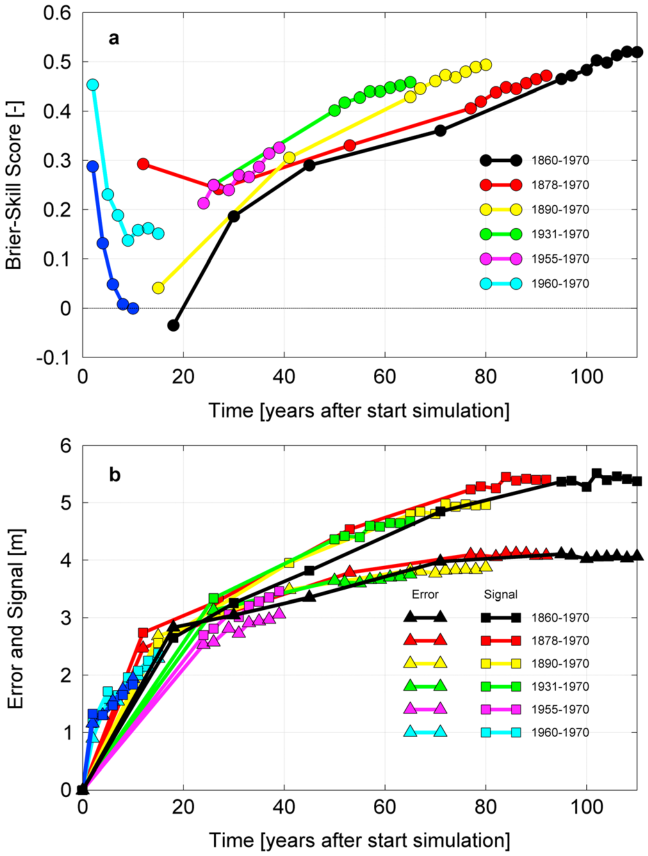

Figure 3. Brier-Skill Score and error versus signal for seven simulations with different start years. (a) BSS. (b) Error and signal. Markers indicate comparisons between model and data; solid lines interpolate between subsequent comparisons. BSS, error, and signal are determined over entire Western Scheldt area.

than 30 years. After 70 years the error remains relatively constant whereas the signal continues to increase, albeit at a decreasingly lower rate.

We performed a sensitivity analysis for the 1860–1970 simulation using different parameter settings, see also supporting information. Generally, the same positive trend of the BSS over time is found in all runs. The results that are presented in Figure 3 are the results of calibration with a maximum BSS of 0.52 for the 1860–1970 simulation. Several simulations with different parameter settings (morphological roughness and constant grain size) show positive BSS values after 110 years with a BSS of minimum 0.3 (good) to maximum 0.52 (excellent). A simulation from 1860 to 1970 without the erosion-resistant layer resulted in a BSS of 0.4. This means that the confinement of the erosion-resistant layer increases the skill of the model, but the effect is not so strong that the model skill is seriously affected.

4. Trends in Morphodynamic Activity

Given that the model reflects realistic developments, we now closely analyze

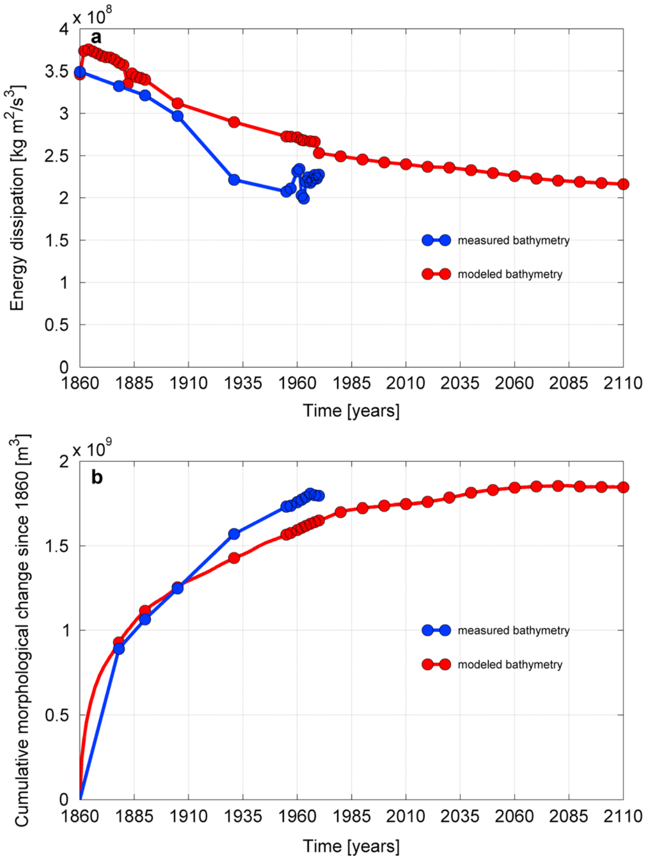

Figure 4. Results of energy dissipation and morphological change. (a) Energy dissipation over time. (b) Cumulative morphological change since 1860, defined as erosion volume + deposition volume since 1860. Markers indicate time points when a measured bathymetry is available; after 1970, model results are calculated every 10 years. Lines interpolate between these results.

the morphological behavior of the system. Morphodynamic systems under constant forcing conditions tend to minimize energy dissipation due to bed resistance [*Langbein*, 1963]. This will eventually lead to morphological equilibrium [*Cowell and Thom*, 1994; *Woodroffe*, 2002] characterized by lower spatial gradients in shear stress and sediment transport [*Rodriquez-Iturbe et al.*, 1992; *Townend and Dun*, 2000]. A highly schematized process-based morphodynamic model of a tidal basin (similar to the model applied in this study) indeed leads to decreasing energy dissipation levels over long time scales (greater than decades) [*Van der Wegen et al.*, 2008]. The current study provides an excellent opportunity to evaluate the development toward equilibrium for a more realistic case study under constant forcing conditions.

We determine energy dissipation on both measured and modeled bathymetries for the 1860 run. The energy dissipation is determined by running the hydrodynamic model over a spring-neap tidal cycle without morphodynamic updating. Same parameter settings are used for all the simulations. The energy dissipation levels are subsequently averaged over the model domain and over time [*Van der Wegen et al.*, 2008] (see supporting information for further explanation). In this way trends and differences between measured and modeled bathymetries can be made clear. To explore future developments of the system, we also extended the simulation time of the morphodynamic run from 1860 to the year 2110, so that a total of 250 years of morphological development is simulated. Both the measured and modeled bathymetries show similar declining (rates of) energy dissipation levels over time (Figure 4a). The total cumulative morphological change from 1860 onward show for both the measured bed levels and the computed bed levels a pronounced trend to less morphodynamic activity over time and are in the same order of magnitude (Figure 4b).

After 250 years the energy dissipation and morphodynamic activity of the model appear to have reached a minimum. We attribute the small irregularities of the trend of measured bathymetries to inaccuracies in the (old) bathymetric recordings and subsequent interpolation errors on the computational grid. Land reclamations are included in the simulations causing a reduction of the total energy dissipation. Since these areas do not convey water but rather store it, reducing their surface area also reduces the tidal prism. Consequently, the tidal discharge in the channels decreases involving less energy dissipation. The sudden decreases in energy dissipation level of the modeled bathymetries around 1885 and 1962 can be attributed to this. Sensitivity runs with and without land reclamations, however, indicate that they are not the cause of the overall declining energy dissipation levels.

5. Discussion

The model skill is initially weak but increases after decades to become excellent after 110 years. The question why the results become excellent after a century is attributed to the slow, but ultimately governing development of the large-scale channel-shoal patterns. Small-scale morphological features as secondary channels or the effect of storms may be more dominant on the short term but are overruled over the long-term by cumulative larger-scale developments that have a typical morphological time period of decades to centuries.

A further explanation for the low initial BSS is that the model initially adjusts the bathymetry according to uncertain parameter settings, boundary forcing and process descriptions. Examples are constant and uniform roughness values, the sediment grain size, or schematized forcing conditions, like storm surges.

After this period of morphodynamic spin-up, the cumulative effect of other subtle but eventually governing processes becomes more pronounced. The probable governing process is the interaction of the tidal forcing with the estuarine geometry (i.e., fixed bank lines and erosion-resistant layers) determining the allocation of channel-shoal patterns [*Van der Wegen and Roelvink*, 2012].

This suggests that process-based models applied in the confined environment of an estuary (where the morphology is influenced by fixed banks, erosion-resistant layers, etc.) and subject to constant tidal and river forcing conditions perform well especially on long (greater than decades) time scales, which makes the approach potentially suitable for centennial time scale forecasts related to, for example, sea level rise or other gradual changes in forcing with a similar time scale.

The inclusion of other processes such as mud and sand mud interaction does not necessarily have to lead to a better BSS. Adding processes could even cause extra weakening of the initial BSS due to the larger uncertainties associated with the process formulations. On the other hand, longer-term BSS could benefit from the extra dynamics. This remains subject of future research.

In contrast to chaotic systems like the atmosphere with a reliable weather forecast time of only several days [*Lorentz*, 1963], our model results confirm that estuarine morphodynamics strives for minimum energy dissipation [*Langbein*, 1963], eventually leading to morphodynamic equilibrium [*Philips*, 1999]. Estuarine morphodynamics is thus a self-regulating (organizing) system in which negative feedback of the large channels and shoals is dominating the morphological developments.

The results of this paper suggest that this morphodynamic equilibrium is predictable because of self-organization characterized by the tendency for minimum energy dissipation. The degrees of freedom in which the morphology can develop are limited by the plan form, the presence of erosion-resistant layers, the well-predictable tidal forcing [*Haff*, 2013], and the limited impact of extreme events like storms on long-term morphology [*Van der Wegen and Roelvink*, 2012].

The results found in this paper make that the general opinion of morphodynamic models should be revised. Process-based morphodynamic models are generally used for short-term simulations (i.e., maximum a few years), since it is assumed that the model results drift away from reality over time. Low BSS values that are found during this period are interpreted as bad model behavior. The conclusion from this paper is that the low BSS values might well be due to the morphodynamic spin-up time of the model and unresolved scales and that the morphodynamic changes during the initial simulation period are due to model limitations.

In principle, the results that are found in this paper are applicable to other confined estuaries and morphodynamic systems. Still it leaves the question open to define “confined” in a strict manner. Obvious important indicators for a systems’ confinement are channels aligned with headlands, dikes, rocky outcrops, etc. Other important parameters are the autonomous (without lateral boundaries) meander amplitude in relation to the basin width. Further research should attempt to model other estuaries and systems including river and wave forcing and the presence of mud, for example, to explore a wider validity of the results presented in this paper.

6. Conclusion

We hindcast morphodynamic change of the tide-dominated Western Scheldt estuary using a 2-D process-based model. Initially, the skill is bad, but after 110 years the skill of the model is excellent. The model error increases over time, but the signal increases eventually even more leading to high skill rates. This conclusion does not dependent on the initial condition. The interaction of the constant tidal forcing with the estuarine geometry (i.e., fixed bank lines and erosion-resistant layers) is determining the allocation of channel-shoal patterns. We find that both the system and the model strive for morphodynamic equilibrium, characterized by the tendency for minimum energy dissipation.

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