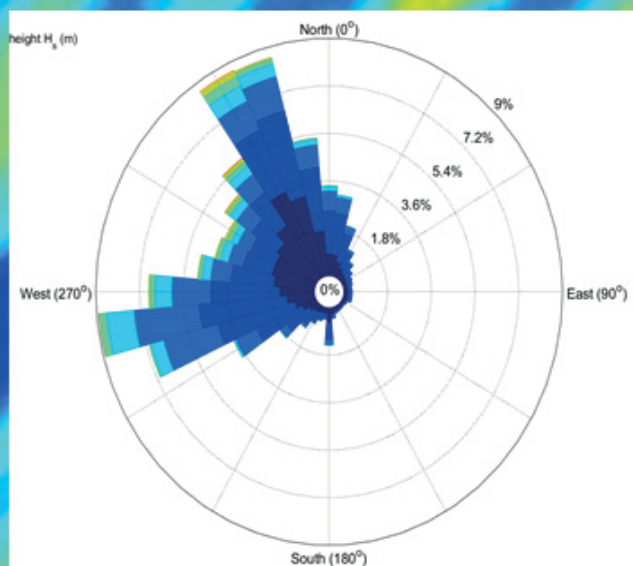




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Morphodynamic modeling of the Scheldt mouth

Effects of waves

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Nnafie, A.; Van Oyen, T.; De Maerschalck, B.; Plancke, Y.; Verwaest, T.; Mostaert, F.



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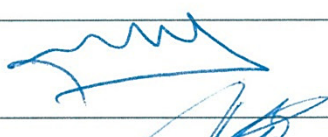
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Abstract

The specific aims of this study are 1) to set up a morphodynamic model for the Scheldt mouth that accounts for waves, 2) to examine sensitivity of model results to different wave conditions, and finally, 3) to present an example case of how this model can be applied to study the impact a construction of a new shipping channel might have on the morphodynamic evolution of the Scheldt estuary and its mouth area. To this end, the coupled Delft3D and SWAN models were used, which the latter modeling wave action.

The methodology employed is that, first, the model parameters (coupling time, morphological amplification factor) are optimized to reduce the simulation time as much as possible. Next, runs are conducted with and without waves, starting from an initially flat bed until a bottom pattern is obtained that is characterized by relatively small bed level changes compared with the initial changes (nearly morphodynamic equilibrium). In the experiments with waves, a highly simplified wave forcing (with dominant directions south- and northwest) as well as a more sophisticated forcing (with four different wave conditions) are considered, using the mormerge approach.

Results reveal that when accounting for waves, an ebb-tidal delta forms in the mouth area, which is flanked by two distinct southern and northern channels ("Wielingen" and "Oostgat"), which are large-scale features that are comparable to observed bathymetry in the Scheldt mouth. The fact that the model simulates two distinct channels ("Oostgat" and "Wielingen") in all cases without and with waves, means that tidal motion is the primary forcing that causes the formation of these channels. Furthermore, results from sensitivity experiments to different wave conditions show that in the case that waves are coming from the northwest, the obtained bedlevel does not fundamentally differ from the simulated bedlevel in case of southwesterly waves. In the case of applying four different wave conditions, however, the southern channel ("Wielingen") is less pronounced than that in the other cases using constant wave conditions. Model results suggest that the observed deepening of Oostgat is part of the natural solution of the system. A major problem in the model is that it simulates too deep channels compared with observations. Nevertheless, by means of an example case, it is shown that the model can be applied to study long-term morphodynamic effects of the presence of a new shipping channel in this area, under the condition that the depth of this channel should be rescaled in proportion to depths of other channels. Finally, due to the idealized approach applied in this model, the precise numbers obtained from the simulations should be considered as indications of orders of magnitudes.

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Nederlandse samenvatting

In deze studie wordt de impact van golven op de lange termijn morfologische evolutie van de Scheldemonding onderzocht, waarbij gebruik wordt gemaakt van het gekoppeld model Delft3D-SWAN. De methodologie die gevolgd wordt is als volgt: De model parameters (koppelingstijd en morfologische versnellingsfactor) worden eerst geoptimaliseerd om de simulatietijd zo veel mogelijk te beperken. Vervolgens worden het model opgespind met en zonder golven, daarbij startend vanuit een vlakke bodem totdat er een morfologische stabiele bodem ontstaat. Bij de simulaties met golven wordt zowel met een sterk geschematiseerd golfklimaat met constante golfcondities (golfhoogte, golfperiode en golfrichting) als ook met een meer geavanceerd klimaat gerekend (vier verschillen golfcondities).

Resultaten met constante golvencondities uit zowel het zuid- en noordwesten laten zien dat er in de monding een noordelijke en een zuidelijke geul met daartussen een ondiep gebied ontstaan, die te vergelijken zijn met Oostgat, Wielingen en de Vlake van de Raan. Kleinschalige niet-realistische geulen die vormen in absentie van golven verdwijnen in aanwezigheid van golven. Resultaten met een meer variabele golfcondities lijken op die verkregen met constante condities. Echter, de zuidelijke geul (Wielingen) in het eerstgenoemde geval is minder uitgesproken. Verder laten model resultaten zien dat de verdieping van de noordelijke geul (Oostgat) een natuurlijk proces is. Een tekortkoming van het model is dat de geulen te diep zijn vergeleken met metingen. Ten slotte wordt een voorbeeld gepresenteerd hoe het model kan worden gebruikt om de invloed van het aanleggen van een nieuwe vaargeul in de monding op de morfologische evolutie van dit gebied te onderzoeken. Merk hierbij op dat dit model enkel kan worden gebruikt voor kwalitatieve doeleinden, daar de exacte cijfers verkregen uit het model meer een indicatie zijn van orde grootten.

1 Introduction

Estuaries are often situated in very densely populated areas with high economic activities that often strongly conflict with their ecological values. Understanding of the long-term (order decades to centuries) morphodynamic evolution in estuaries is of great importance to successfully manage these areas (e.g. maintain the shipping routes) while preserving the estuarine ecosystem service. For centuries, geometry and bathymetry of estuaries (e.g., Oka estuary in Spain, Western and Eastern Scheldt in The Netherlands, San Francisco Bay in the United States, etc.) have been drastically modified through engineering works such as embanking, sand extraction, channel deepening, land reclamations, etc.

At present, the Flemish government is considering major future interventions in the mouth of the Western Scheldt estuary, among which the construction of a new shipping channel in order to improve ship accessibility to the port of Antwerp (Figure 16). While many studies over the last years (cf. Peters, 2006; Van Maren *et al.*, 2015; Wang *et al.*, 2009; Winterwerp and Wang, 2013) pointed out that the observed increase of the tidal range and turbidity in many estuaries (e.g., Scheldt, Ems, Elbe) is caused by human works, still little is known about the impacts of these interventions on the long-term morphodynamic evolution of estuaries (order decades to centuries).

The overall aim of this study is to develop an idealized morphodynamic model, with which the long-term morphodynamic evolution of a new shipping channel as well as the morphodynamic response of the Scheldt estuary to such an intervention can be studied. The specific aims of the present report are 1) to set up a morphodynamic model for the Scheldt mouth that accounts for waves, 2) to examine sensitivity of model results to different wave conditions, and finally, 3) to present an example case of how this model can be applied to study the impact a construction of a new shipping channel might have on the morphodynamic evolution of the Scheldt estuary and its mouth area. To this end, the morphodynamic model described in the previous report (WL2016_R14_094_5) is used in this study with the addition that it is now coupled with SWAN, which models wave action. This premises for this work is because waves could be important for the morphodynamic development of the ebb-tidal delta of the mouth area, as they stir up sediment at the bed resulting in higher sediment concentrations, and the wave-induced currents can significantly contribute to sediment transport.

In the next chapter a description of the model equations is given. Subsequently, in Chapter 3 an analysis of wave data collected in the Scheldt mouth is presented. In Chapter 4, the set-up of the model experiments is outlined. Results from these experiments are presented in Chapter 5. In Chapter 6, an example case of how the morphodynamic impact of constructing a new navigation channel in the Scheldt can be explored by the model. Finally, Chapter 7 contains a summary and the conclusions.

2 Model description

2.1 Delft3D: flow, sediment transport and bottom evolution

In this study the Delft3D hydro- and morphodynamic model is used in two-dimensional (depth-averaged) mode (for a detailed description see Lesser *et al.*, 2004). Below, equations that govern hydrodynamics, sediment transport and bed level update are presented.

The hydrodynamics considered are described by full nonlinear shallow water equations

$$\frac{\partial D}{\partial t} + \vec{\nabla} \cdot (D\vec{v}) = 0, \quad (1)$$

$$\frac{\partial \vec{v}}{\partial t} + \left(\vec{\nabla} \cdot \vec{v} \right) \vec{v} + f \vec{e}_z \times \vec{v} = -g \vec{\nabla} \eta - \frac{g \sqrt{u^2 + v^2}}{C^2 D} \vec{v} + \frac{1}{D} \left(\vec{\nabla} \cdot D \nu \vec{\nabla} \right) \vec{v}. \quad (2)$$

Here, D is the local water depth, $\vec{v}$ is the depth-averaged velocity with components u and v in the eastern (x) and northern (y) direction (Fig. 16), f is the Coriolis parameter, $\vec{e}_z$ is a unit vector in the vertical direction (indicated by the vertical coordinate z), g is the acceleration due to gravity, η is the sea surface elevation with respect to the undisturbed water level ($z = 0$), $\vec{\nabla}$ is the horizontal nabla operator (components $\frac{\partial}{\partial x}, \frac{\partial}{\partial y}$), C is the Chézy friction coefficient, ν is the horizontal eddy viscosity, and t is time.

The Van Rijn, 2007 sediment transport formula is applied in this model, which distinguishes between bed load and suspended load transport, and which accounts for effect of waves on sediment transport. The depth-averaged suspended sediment concentration is calculated with a depth-averaged advection-diffusion equation, which reads

$$\frac{\partial C}{\partial t} + \nabla \cdot (C\vec{v}) - \frac{1}{D} \left[\vec{\nabla} \cdot \left(\mu_s D \vec{\nabla} C \right) \right] = \frac{1}{D} (e - d), \quad (3)$$

where C is the depth-averaged suspended load concentration, μ_s is the horizontal eddy diffusion coefficient, e is the erosion rate of sand from the bed and d is the deposition rate of sand to the bed. The net sediment flux $e - d$ is determined based on the concept of equilibrium concentration:

$$(e - d) = w_s (C_{eq} - C_{ref}), \quad (4)$$

with w_s is the settling velocity of sediment, C_{eq} is the equilibrium near-bed sediment concentration and C_{ref} is the near-bed concentration, calculated at the interface between the bedload and suspended load, $z = Z_{ref}$.

Bed-slope effects are accounted for in both the direction of the local flow (longitudinal bed slope) and in the direction perpendicular to that (transverse bed slope). In the longitudinal direction, the sediment transport vector $\vec{q}_0$ is adjusted according to Bagnold, 1966:

$$\vec{q}_s = \alpha_S \vec{q}_0, \quad (5)$$

with

$$\alpha_S = 1 + \alpha_{BS} \left[\frac{\tan \phi}{\cos \left(\tan^{-1} \left(\frac{\partial z_b}{\partial s} \right) \right) \left(\tan \phi - \frac{\partial z_b}{\partial s} \right)} - 1 \right], \quad (6)$$

where α_{BS} is the bedslope parameter in the longitudinal direction (s) with default value of 1, ϕ is the internal angle of friction of bed material (assumed to be 30°), z_b is the bed level and $\frac{\partial z_b}{\partial s}$ is the longitudinal bed slope. In the transverse direction, an additional transport vector $\vec{q}_n$ is calculated following the method proposed by Ikeda, 1982 given by

$$\vec{q}_n = \alpha_{BN} \sqrt{\frac{\tau_{b,cr}}{|\vec{\tau}_b|}} \frac{\partial z_b}{\partial n} \vec{e}_z \times \vec{q}_s. \quad (7)$$

Here, α_{BN} is the bedslope coefficient in the transverse direction (for a discussion about its value, see Dissanayake *et al.*, 2009), τ_{cr} is the minimum bed shear stress that is needed to move sediment, $|\vec{\tau}_b|$ is the shear stress that acts on the sediment and $\frac{\partial z_b}{\partial n}$ is the transverse bed slope. The resulting sediment transport vector ($\vec{q}$) thus reads

$$\vec{q} = \vec{q}_s + \vec{q}_n. \quad (8)$$

The bed level change is determined by computing the divergence of sediment transport vector $\vec{q}$

$$\frac{\partial z_b}{\partial t} = -\frac{1}{1-p} \vec{\nabla} \cdot \vec{q}, \quad (9)$$

with p the porosity of the bottom layer (equal to 0.4). The morphodynamic time scale is much longer (order years to decades) than the hydrodynamic time scale (order days). This allows for accelerated bed level change by multiplying the time in the above equation by a factor α_{MOR} (Roelvink, 2006).

As proposed by Roelvink and Walstra, 2004, a combination of water-level boundary conditions ζ at the western boundary and Neumann boundary conditions at the southern and northern boundaries are applied (Fig. 16). Specifically, at the western boundary the model is forced by a tidal wave with three harmonic constituents (M_2 , M_4 and M_6) with amplitudes $\hat{\zeta}_2$, $\hat{\zeta}_4$ and $\hat{\zeta}_6$; angular frequencies ω , 2ω and 3ω ; and phases ϕ_2 , ϕ_4 and ϕ_6 , which travels from south to north boundaries. Sediment transport boundary conditions are set by an equilibrium sediment flux, which means sediment flux entering or exiting through the boundaries is nearly perfectly adapted to the local flow conditions and very little accretion or erosion is experienced near the boundaries (Deltares, 2016a).

2.2 SWAN: waves

The SWAN model is based on the discrete spectral action balance equation and is fully spectral (in all directions and frequencies). The latter implies that short-crested random wave fields propagating simultaneously from widely different directions can be accommodated (e.g. a wind sea with superimposed swell). SWAN computes the evolution of random, short-crested waves in coastal regions with deep, intermediate and shallow water and ambient currents. The SWAN model accounts for (refractive) propagation due to current and depth and represents the processes of wave generation by wind, dissipation due to whitecapping, bottom friction and depth-induced wave breaking and non-linear wave-wave interactions (both quadruplets and triads) explicitly with state-of-the-art formulations. Wave blocking by currents is also explicitly represented in the model. To avoid excessive computing time and to achieve a robust model in practical applications, fully implicit propagation schemes have been applied. The SWAN model has successfully been validated and verified in several laboratory and (complex) field cases (see Ris *et al.* (1999); WL | Delft Hydraulics (1999, 2000)). The SWAN model was developed at Delft University of Technology (The Netherlands). It is specified as the

new standard for nearshore wave modelling and coastal protection studies. It is therefore that Deltares is integrating the SWAN model in the Delft3D model suite. The SWAN model has been released under public domain.

Information about the wind-driven free surface waves is contained in the directional spectrum of wave energy density $E(\sigma, \theta)$, which describes the distribution of wave energy over intrinsic frequencies σ of the spectral components and propagation direction θ (i.e., the direction normal to the wave crest of each spectral component). The intrinsic frequency is defined as the angular frequency observed in a coordinate system moving at the velocity of the current $\vec{v}$; i.e., $\omega = \sigma + \vec{k} \cdot \vec{v}$, with ω the absolute angular frequency and $\vec{k}$ the wave number vector.

SWAN models the evolution of waves by solving the action density $N(\vec{x}, t, \sigma, \theta)$ in space $\vec{x}$ and time t . The action density, which is defined as $N = E/\sigma$, is a conserved quantity during wave propagation (Whitman, 1974) and is governed by the action balance equation (Mei, 1983; Komen *et al.*, 1994):

$$\frac{\partial N}{\partial t} + \vec{\nabla} \cdot [\vec{c}_g + \vec{v}] N + \frac{\partial c_\sigma N}{\partial \sigma} + \frac{\partial c_\theta N}{\partial \theta} = \frac{S}{\sigma}. \quad (10)$$

In this expression, $\vec{c}_g$ is the group velocity vector defined as $\vec{c}_g = \partial \sigma / \partial \vec{k}$, c_σ and c_θ are the propagation velocities in spectral space (σ, θ) , and S is a source/sink term representing all physical processes that generate, dissipate, or redistribute wave energy. Dissipation by whitecapping, bottom friction and depth-induced breaking, and the non-linear wave-wave interaction (quadruplets and triads) are accounted for in the model. For detailed formulations see Deltares, 2016b)

3 Wave climate Scheldt mouth

Table 1 – Overview of probability of occurrence (in %) per wave height/direction class at Deurlo station.

H_s (m)	θ ($^\circ$) 0-45	θ ($^\circ$) 45-90	θ ($^\circ$) 90-135	θ ($^\circ$) 135-180	θ ($^\circ$) 180-225	θ ($^\circ$) 225-270	θ ($^\circ$) 270-315	θ ($^\circ$) 315-360	Total (%)
0-1	7.56	1.95	1.41	1.79	3.31	16.45	15.82	23.58	71.89
1-2	1.80	0.096	0.02	0.17	0.47	10.16	5.39	6.90	25.00
2-3	0.018	0	0	0.003	0.005	0.59	0.99	1.19	2.80
3-4	0	0	0	0	0	0.012	0.097	0.20	0.31
> 4	0	0	0	0	0	0	0.001	0.003	0.004
Total (%)	9.37	2.05	1.43	1.97	3.79	27.21	22.30	31.88	100

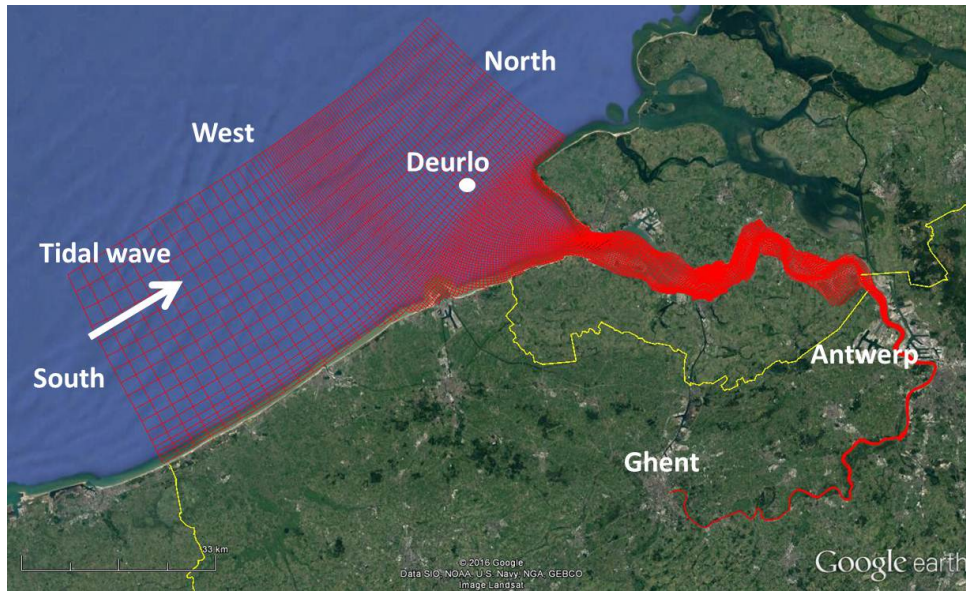
Significant wave height (H_s) and wave direction (θ) are sorted in 5 and 8 classes, respectively.

Waves are important for the morphodynamic development of the ebb-tidal delta of the mouth area, because they stir up sediment at the bed resulting in higher sediment concentrations, and the wave-induced currents can significantly contribute to sediment transport.

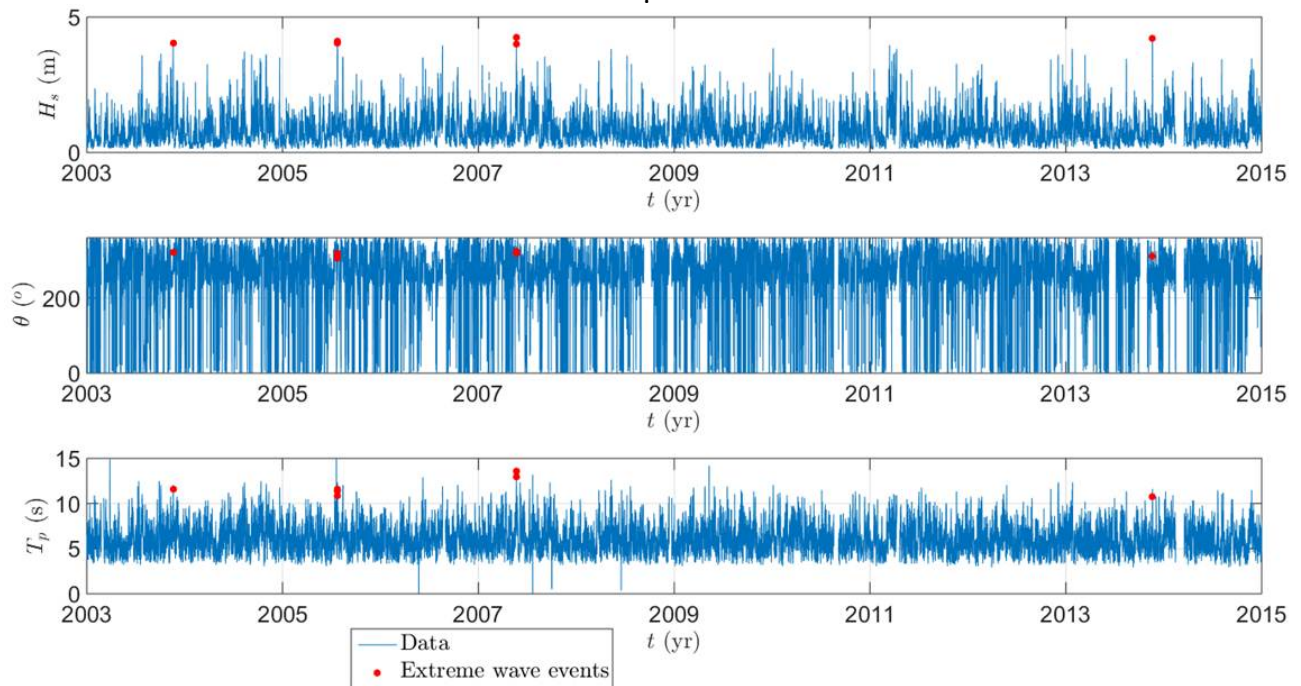
Time series of significant wave height (H_s , in m), wave direction (θ , in degrees with respect to North) and peak wave period (T_p , in s) collected by Rijkswaterstaat at Deurlo station between 2003 and 2015 (Figure 2) are used to derive a representative wave climate to force the model. By constructing the probability of occurrence (in %) for different classes of wave heights and directions (Fig. 3 and Table 1), it appears that approximately 81% of the wave events that occurred in this time period have directions ranging between $\theta = 225^\circ$ and $\theta = 360^\circ$. Particularly, wave events with directions between 225° and 270° (southwest) and between 315° and 360° (northwest) are dominant. The southwesterly waves have a mean (averaged over the entire time period) significant wave height $H_s = 1$ m, a mean peak wave period $T_p = 5.7$ s and a mean wave direction $\theta = 254^\circ$, and the northwesterly waves have $H_s = 0.9$ m, $T_p = 7.1$ s and $\theta = 345^\circ$.

Extreme wave events, which are defined here as those with significant wave height $H_s > 4$ m, occurred 4 times between 2003 and 2015 (indicated by red dots in Figure 2). This means that their probability of occurrence is ~ 3.1 events per 10 year. These events have a mean wave height of $H_s = 4.1$ m, a peak wave period of $T_p = 11.7$ s and a wave direction of $\theta = 316^\circ$. Note that all these events have a northwestern direction.

Figure 1 – Delft3D computational grid.

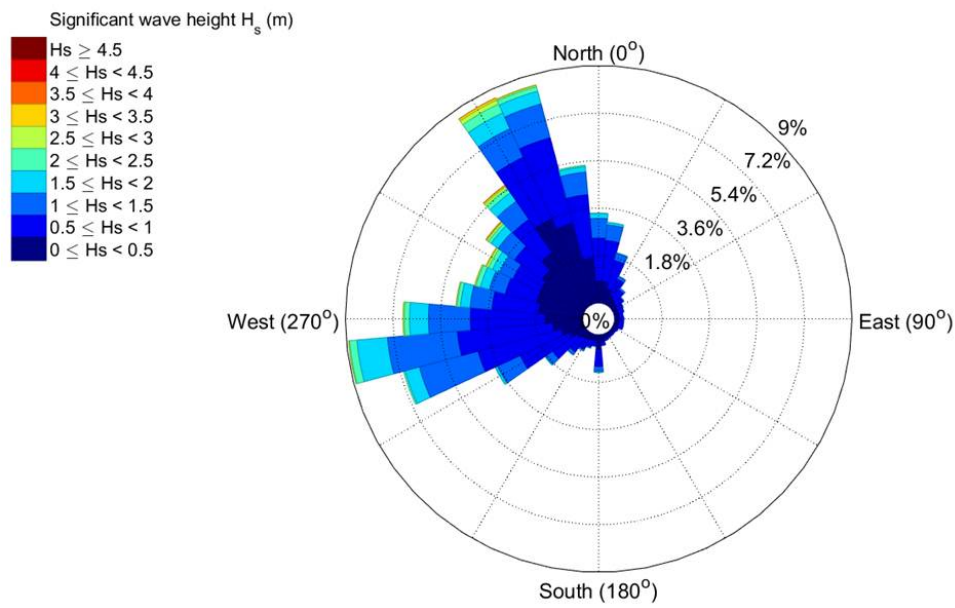


White dot indicates the location of wave station Deurlo.

Figure 2 – Time series of significant wave height H_s in m (top), wave direction θ in degrees with respect to North (middle), and peak wave period T_p in s (bottom)


Data collected by Rijkswaterstaat at station Deurlo (white dot in Figure 1) between 2003 and 2015.

Figure 3 – Wave rose showing percentages of occurrence of H_s (m) and θ at station Deurlo.



4 Methodology

4.1 Parameter configuration

In the Delft3D-Flow model, a curvilinear grid is created, which extends from Ghent to ~ 30 km seaward (Figure 1). Size of grid cells (defined as the the square root of the cell surface area) ranges between 200 m and 500 m in the area of interest (Scheldt mouth) and it increases to ~ 2.5 km at the offshore boundaries. A similar grid is used in the SWAN model, with the difference that the grid does not cover the landward part of the estuary, assuming that waves have a minor contribution in this area. See Figure 4.

Model experiments start from an idealized bathymetry, which is obtained by averaging the measured bedlevel z_b over the width of the domain. Non-cohesive sediment is assumed with a single size of 0.2 mm. An erodible layer with a uniform thickness of 50 m is used in the model. The morphological acceleration factor α_{MOR} is 200 (see Section 4.2). Values for the amplitudes and phases of the three harmonic constituents (M_2 , M_4 and M_6) imposed at the offshore boundaries are determined from a spatial interpolation between closest stations where tidal amplitudes and phases are known. Based on the wave data analysis in Chapter 3, first, the southwestern dominant wave conditions are considered, with a significant wave height $H_s = 1$ m, a peak wave period $T_p = 5.7$ s and wave direction $\theta = 250^\circ$. Other wave conditions are also considered (see Section 4.3). An overview of all model parameters is presented in Table 2.

4.2 Coupling of SWAN with Delft3D-Flow

When running an online coupled simulation with Delft3D-Flow and SWAN, data is exchanged between the two modules using a so-called communication file (com-file), which contains the most recent data of the flow and wave computations. These com-files are stored in the working directory and are continuously updated. A coupled SWAN Delft3D-Flow simulation has the following I/O-related stages (see Donners *et al.*, 2014 for further information):

- Delft3D-FLOW reads input,
- Delft3D-FLOW writes output,
- Delft3D-FLOW uses DelftIO to signal to Delft3D-WAVE that it can take over,
- Delft3D-WAVE reads the Delft3D-FLOW output
- Delft3D-WAVE writes SWAN input,
- SWAN reads input,
- SWAN reads start dump ('hotstart files'),
- SWAN writes output,
- SWAN writes start dump,
- Delft3D-WAVE reads SWAN output, converts it and writes Delft3D-FLOW input,
- and finally, Delft3D-WAVE uses DelftIO to signal to Delft3D-FLOW that it can continue.

Due to this way of (serial) communication between Delft3D-Flow and SWAN models, test runs revealed that most of the running time is spent during the above I/O-related stages, meaning that they are extremely time consuming. For e.g., a typical run of 400 years of morphodynamic evolution lasts ~ 5 days in the case without waves, and 30 to 40 days in case with waves. In order to keep the

simulation time below reasonable limits, it is crucial to limit the communication between SWAN and Delft3D-flow as much as possible without affecting model results. One way of reducing the communication between these models, is to optimize the coupling time period such that model results are not affected. In the literature (see e.g. Eelkema *et al.*, 2013; Ridderinkhof *et al.*, 2016), the used coupling time period is typically 60 minutes. To ensure that the used coupling time period does not affect model results, sensitivity experiments are carried out with coupling times ranging between 30 and 240 minutes (run series 'CouplingTime' in Table 3). Another way to speed up the coupled SWAN-Delft3D simulations is to increase the morphological amplification factor α_{MOR} as much as possible. To this end, a series of runs ('Morfac' in Table 3) are performed with α_{MOR} ranging between 25 and 400.

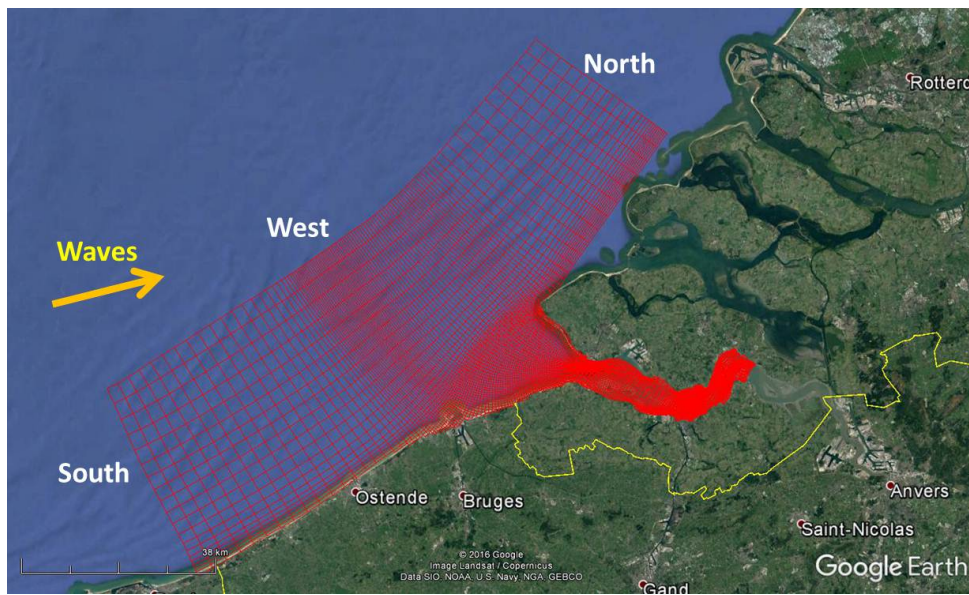
Table 2 – Overview model parameters.

	Parameter	Value	Description
Flow	f	$1.43 \times 10^{-4} \text{ s}^{-1}$	Coriolis parameter.
	C	$65 \text{ m}^{1/2} \text{ s}^{-1}$	Chézy coefficient.
	ν	$1 \text{ m}^2 \text{ s}^{-1}$	Eddy viscosity.
	$(\hat{\xi}_{2,S}; \phi_{2,S}) / (\hat{\xi}_{2,N}; \phi_{2,N})$	$(1.6 \text{ m}; 23^\circ) / (1.2 \text{ m}; 55^\circ)$,	(Amp.;Phase) M_2 South(<i>S</i>)/North (<i>N</i>).
	$(\hat{\xi}_{4,S}; \phi_{4,S}) / (\hat{\xi}_{4,N}; \phi_{4,N})$	$(0.1 \text{ m}; -11^\circ) / (0.1 \text{ m}; 113^\circ)$,	(Amp.;Phase) M_4 South(<i>S</i>)/North (<i>N</i>).
	$(\hat{\xi}_{6,S}; \phi_{6,S}) / (\hat{\xi}_{6,N}; \phi_{6,N})$	$(0.05 \text{ m}; -24^\circ) / (0.05 \text{ m}; 77^\circ)$,	(Amp.;Phase) M_6 South(<i>S</i>)/North (<i>N</i>).
Waves	ω	$1.405 \times 10^{-4} \text{ s}^{-1}$	frequency M_2 .
	H_s	1 m	Significant height southwesterly waves.
	T_p	5.7 s	Peak period southwesterly waves.
Sediment	θ	254°	Direction southwesterly waves.
	Van Rijn, 2007		Transport formulation
	Bagnold, 1966		Bedslope formulation
	α	1	Calibration coefficient.
	δ	1.65	Relative density of sediment.
	d_{50}	0.2 mm	Diameter grain size.
	α_{BS}	1	Longitudinal bedslope coefficient.
	α_{BN}	15	Transverse bedslope coefficient.
Numerics	p	0.4	Porosity bed.
	Δt	30 s	Time step.
	α_{MOR}	200	Morphological amplification factor.

Table 3 – List of model runs.

Name runs	Waves	H_s (m)	T_p (s)	θ ($^\circ$)	Coupling Time (min)	α_{BN}
Reference	Yes	1	5.7	254	60	200
NoWaves	No					200
SensToWaveDir1	Yes	0.9	7.1	345	60	200
SensToWaveDir2: Mormerge	Yes	[0.83,...,2.62]	[5.6,...,9.9]	[253,...,324]	60	200
CouplingTime	Yes	1	5.7	254	[30,...,240]	200
Morfac	Yes	1	5.7	254	60	[25,...,400]

Figure 4 – SWAN computational grid.



4.3 Other wave conditions: using mormerge

In the default configuration southwesterly waves are considered, which have a constant wave height, wave direction and wave period (run 'Reference' in Table 3). Effects of using other wave conditions on the morphodynamic evolution of the Scheldt mouth are quantified by conducting two additional experiments. In the first experiment (run 'SensToWaveDir1'), waves from the northwest are considered, with $H_s = 0.9$ m, $T_p = 7.1$ s and $\theta = 345^\circ$. In reality, waves with different wave heights, periods and directions enter in the study area. One way of quantifying effects of different waves conditions on the morphodynamic evolution is by applying the mormerge technique that is developed by Roelvink, 2006. The different wave conditions are run in parallel, assuming that the hydrodynamic time scales are much smaller than the morphodynamic time scales. All wave conditions are applied simultaneously, thereby sharing the same bathymetry, which is updated every time step according to the weighted averaged of the bed level changes due to each condition. A major drawback of this technique is that it is extremely time consuming. The simulation time can easily increased by a factor of 4. In the second experiment (run 'SensToWaveDir2'), first, the wave conditions described in Chapter 3, are sorted in the following four dominant wave classes:

Table 4 – Used wave conditions in the mormerge experiment (run 'SensToWaveDir2').

H_s (m)	θ ($^\circ$)	T_p (s)	Weight
0.83	253	5.6	0.48
2.41	275	8.6	0.01
0.70	346	6.4	0.50
2.62	324	9.9	0.01

Subsequently, these conditions are used to conduct a mormerge experiment.

4.4 Methodology to analyze results

A global growth rate σ (yr^{-1}) of bottom patterns is defined, following Garnier *et al.* (2006) and Nnafie *et al.* (2014), as

$$\sigma \equiv \frac{\iint_A h \frac{\partial h}{\partial t} dx dy}{\iint_A h^2 dx dy}, \quad (11)$$

with h the bedlevel change given by $h = z_b(x, y, t) - z_b(x, y, t = 0)$, and A is the surface area (m^2). The total simulation time period of model experiments is chosen such that growth rate σ decreases to less than 1% of its initial value σ_0 , with the latter defined as the average value over the first 10 years. Preliminary model runs show that a simulation period of 400 years fulfills the latter condition. Note that although σ becomes small during the simulation period, a perfect morphodynamic equilibrium (i.e., growth rate $\sigma = 0$) is never reached, even for longer time periods.

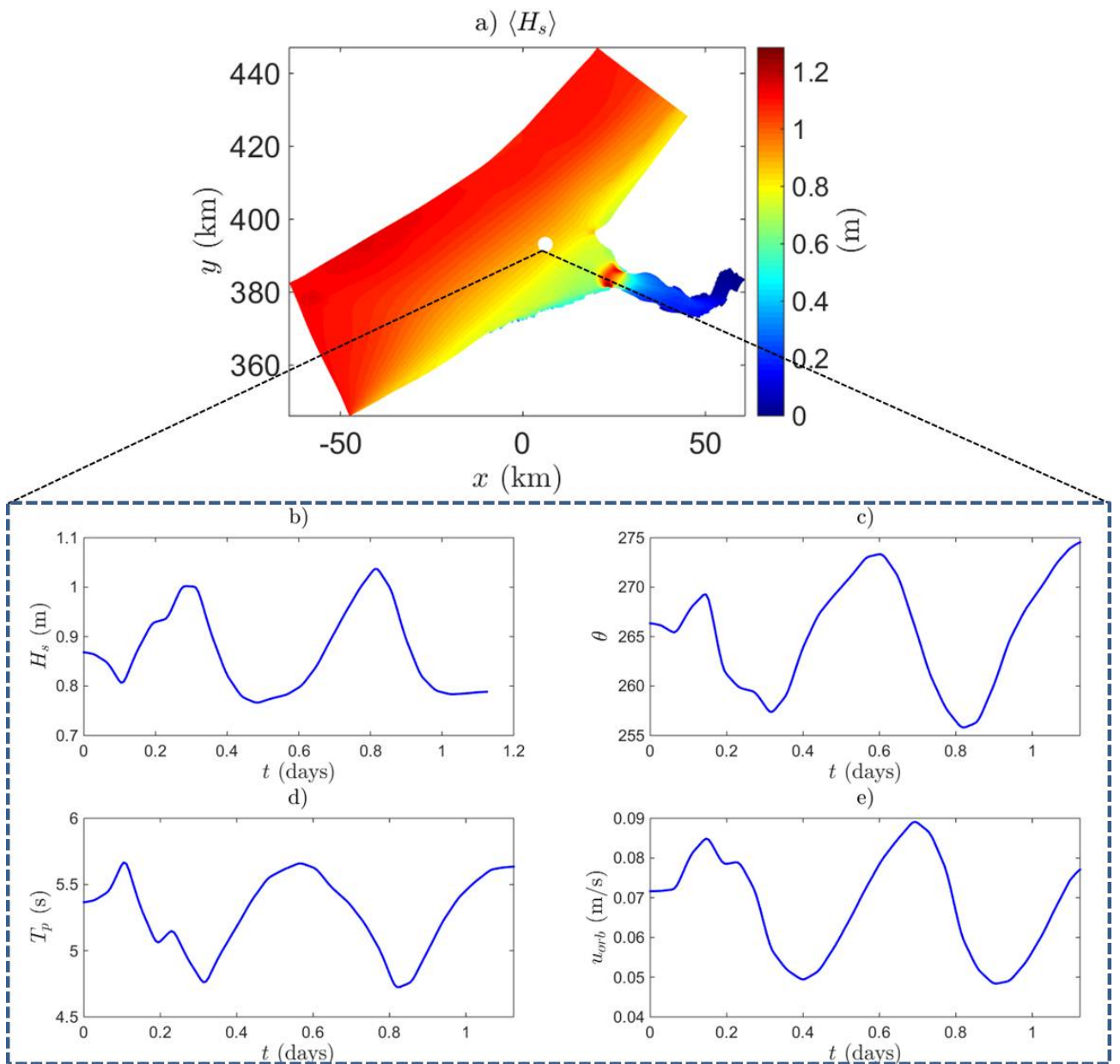
A comparison is made between present-day measured bedlevel and the bedlevel obtained from model experiments after a simulation period of 400 years. Following Van der Wegen and Roelvink (2012) and Guo *et al.* (2014), this comparison focuses on 1) the type and spatial location of large-scale bottom features (shoals and channels), 2) profiles of width-averaged bedlevel ($\langle z_b \rangle$), and on 3) hypsometries (i.e., distribution of horizontal surface area A that is located below a certain bedlevel z_b), which provide information about the relative surface area of tidal flats and channels within the domain.

5 Results and discussion

5.1 Hydrodynamic run with the coupled SWAN-Delft3D models

Figure 5 shows the spatial distribution of the tidally-averaged significant wave height $\langle H_s \rangle$ as simulated by the SWAN model in the case that waves are coming from the south west (run 'Reference' in

Figure 5 – a) Tidally-averaged significant wave height $\langle H_s \rangle$.



Time series of significant wave height H_s (b), wave direction θ (c), tidal peak period T_p (d), and near-bed orbital velocity u_{orb} (e) in the mouth area (denoted by the white circle in panel a).

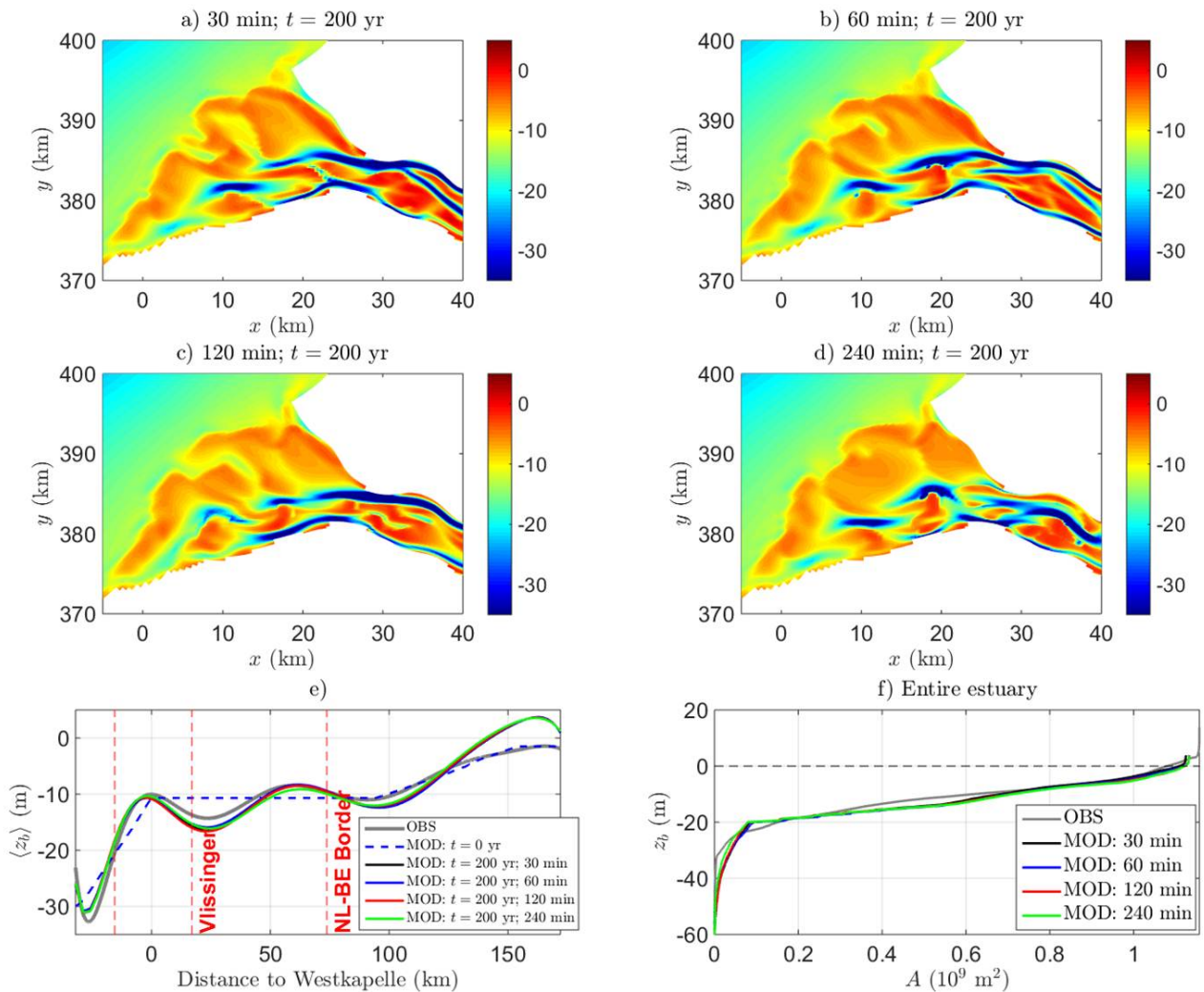
Table 3). The initial bathymetry (at $t = 0$) is used in this simulation. Panels b-e show time series of the significant wave height H_s (panel a), wave direction θ (panel b), tidal peak period T_p (panel c), and near-bed orbital velocity u_{orb} (panel d) in the mouth area. Note the oscillating behavior of these wave characteristics at the M_2 tidal frequency as a result of the wave-current interaction (Doppler effect) on the one hand, and the higher bottom friction during the ebb-phase as a result of a smaller water depth on the other hand. These two effects result in a rather complicated pattern of the wave characteristics in the mouth area. Furthermore, from panel a it appears that wave height increases at the transition between the mouth and the estuary due to focus of wave energy in this area.

5.2 Optimizing the coupling time and amplification factor

5.2.1 Coupling time SWAN-Delft3D

In the case of running an online coupled simulation with Delft3D-Flow and SWAN, data is exchanged between the two models using a so-called communication file (com-file), which contains the most recent data of the flow and wave computations. This way of communication is extremely time con-

Figure 6 – Effects of coupling times between Delft3D-Flow and SWAN, ranging between 30 min and 240 min.

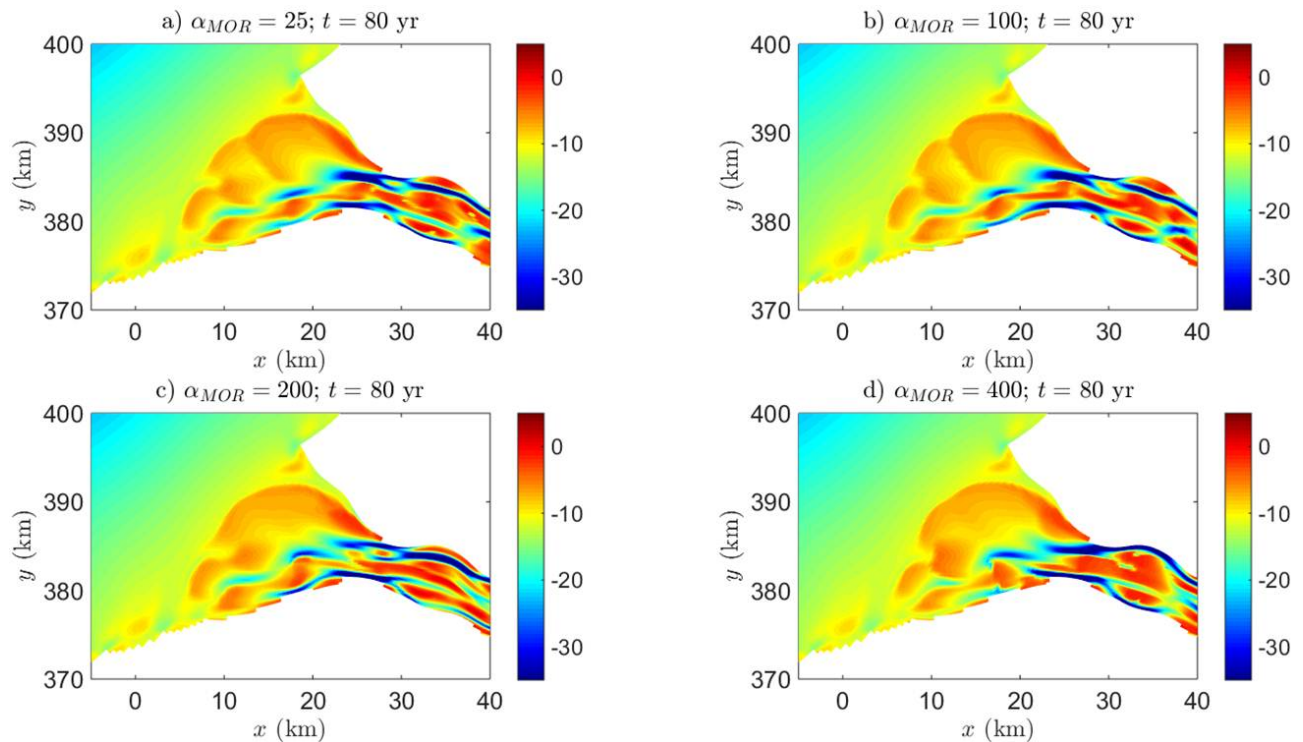


suming, as explained previously (see Section 4.2). In order to keep the simulation time below reasonable limits, a series of runs (series 'CouplingTime' in Table 3) are conducted to optimize the coupling time between SWAN and Delft3D-Flow models, without affecting model results. The coupling time is varied between 30 and 240 minutes. Results from these sensitivity runs are presented in Figure 6, which shows the obtained bed level after 200 years of morphodynamic evolution in the cases that the coupling time is 30 min (a), 60 min (b), 120 min (c) and 240 min (d). The simulated bed levels in cases of coupling times 30 and 60 min do not significantly differ from each other. Increasing the coupling time further (panels c, d) seems to introduce errors in the simulated bed level, although that the width-averaged bedlevels and hypsometries are approximately the same (panels e, f). In particular, the southern and northern channels in the mouth area seem less pronounced when the coupling times are too large. Based on these model results, a coupling time of 60 minutes was chosen in this study.

5.2.2 Morphological factor

Besides optimizing the coupling time between Delft3D-Flow and SWAN to reduce the simulation time as much as possible, additional sensitivity runs (series 'Morfac' in Table 3) are carried out to further reduce the simulation time by finding the optimum value for the morphological amplification factor α_{BN} . Results are shown in Figure 7, which compares the obtained bedlevel after 80 years of morphodynamic evolution in cases of using values $\alpha_{BN} = 25$ (panel a), $\alpha_{BN} = 100$ (panel b), $\alpha_{BN} = 200$ (panel c) and $\alpha_{BN} = 400$ (panel d). These results reveal that values up to 200 still yield approximately the same solution. The bedlevel in the case of using $\alpha_{BN} = 400$ deviates somewhat from those in case of smaller values, particularly in the Western Scheldt estuary. Nevertheless, it can be stated that all obtained bedlevels are not fundamentally different from each other. Based on the results from these test runs, an $\alpha_{BN} = 200$ is used in this study.

Figure 7 – Obtained bedlevel after 80 years in cases of using values $\alpha_{BN} = 25$ (panel a), $\alpha_{BN} = 100$ (panel b), $\alpha_{BN} = 200$ (panel c) and $\alpha_{BN} = 400$ (panel d).



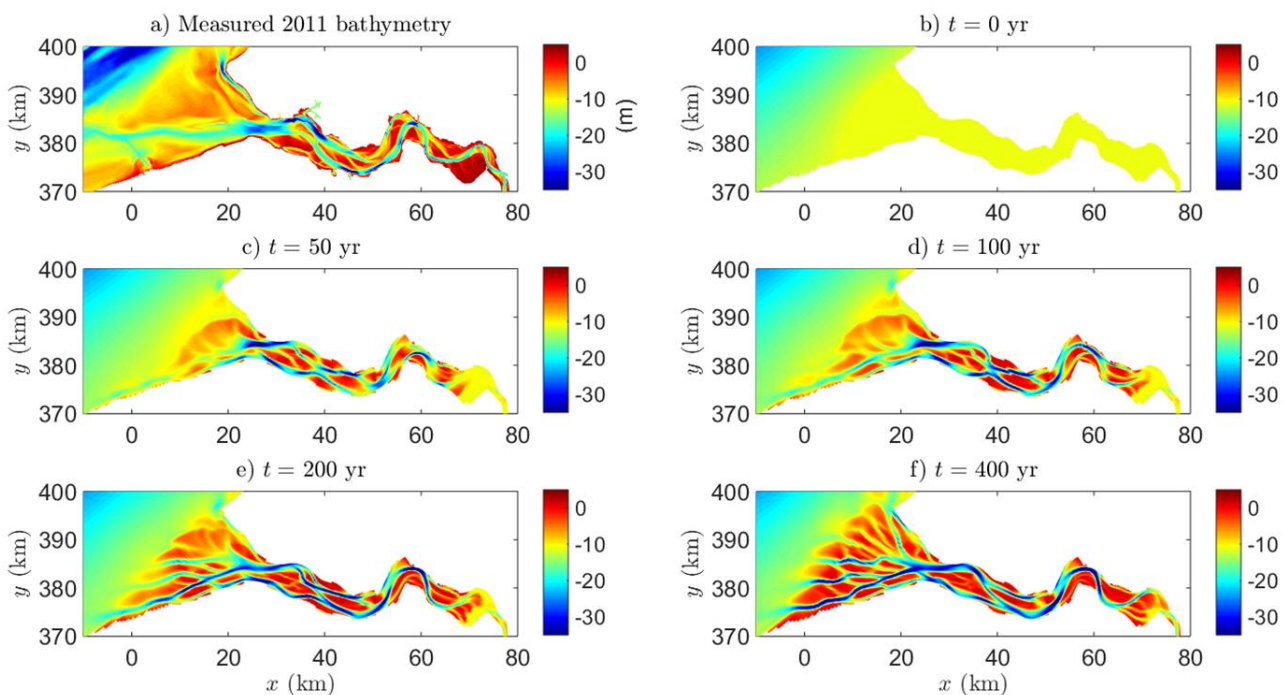
5.3 Effects of waves

5.3.1 Reference case: waves from the southwest

Figures 8 and 9 show snapshots of bedlevel development during the model spin-up in cases without and with waves, respectively, after 400 years morphodynamic evolution starting from a flat bed (runs 'NoWaves' and 'Reference' in Table 3). By way of comparison, present-day measured bathymetry is also shown (panel a). Clearly, the unrealistic small-scale secondary channels that occur in the mouth area in the case of no waves (see Figure 8, panel f) disappear in the case that waves are accounted for (panel f in Figure 9). From the latter panel (see also the zoom-ins in Figure 10) it is seen that a shallow region forms in the mouth of the estuary that is flanked by two distinct southern and northern channels (panel c), which are large-scale features that are comparable to observed bathymetry in the Scheldt mouth (panel a). Hereafter, the southern and northern channels will be referred to as "Wielingen" and "Oostgat", respectively.

By plotting the growth rate σ (Equation 11) as a function of time (Figure 11a), it appears that in both cases of without (black line) and with (blue line) waves, most morphodynamic activity takes place in the first 50 years. Overall, in the case with waves, the morphodynamic activity decreases more rapidly with increasing time compared with that in the cases that waves are neglected. A slight increase of growth rate appears in the former case after 250 years. Furthermore, Figure 11 (panel b) compares the width-averaged bedlevel profile (after applying a 10th order polynomial fit) after 400 years of morphodynamic evolution in the cases without (black line) and with (blue line) waves with observations (gray line). Starting from a linear initial bed (dashed blue line), the simulated bed profile in the case of no waves agree well with the measured profile in the Western Scheldt and mouth area. In the case with waves, the bed profile in these areas is deeper than the measured profile. A

Figure 8 – (b-f) Snapshots of bedlevel in case that waves are not accounted for between $t = 0$ and $t = 400$ years.



By way of comparison, measured bedlevel is plotted in panel (a).

larger mismatch exists between model results and observations in the landward part of the estuary (Sea Scheldt), which is due to neglecting of river discharge, as pointed out in the previous report (WL2016_R14_094_5). The reason of excluding river discharge in this study, is that river discharge requires a smaller time step, thereby slowing down the simulations considerably. As river discharge mainly affects the landward part of the estuary, which is not the focus of this study, it therefore neglected.

The overestimation of channel depth by the model in the case of waves can also be seen from Figure 12a, which shows that the distribution of channel and shoal area obtained from the model in the cases without and with waves (black and blue lines) roughly agrees well with observations (black lines). The simulated deep channels, however, are too deep compared with observation, particularly in the case with waves (blue lines). The overestimation of channel depth by the model occurs in both the mouth area (panel b) and the Western Scheldt (panel c). Other differences between model results and observations are that the shoal area in the mouth seems to be deeper, and that the overall bathymetry produced by the model has a weaker slope compared with observations.

By zooming in on the long-term evolution of the northern channel ('Oostgat'), results (Figure 13) reveal that this channel deepens in the course of time at a rate of about 5 cm/yr in both cases of without (panel b) and with waves (panel c). It seems that sand that is removed from the channel is deposited on the southern shoals. The deepening of this channel is slightly stronger in the case without than the experiments with waves, which can be understood by the fact that waves tend to redistribute sand from the shoals into the channels. Regardless of this slight difference between cases without and with waves, it can be stated that deepening of this channel, which causes major problems at the coast of Walcheren, is mainly driven by tidal motion. It is noted that the obtained rate of deepening from the model has the same order of magnitude as the observed rate of deepening in Oostgat between 1965 and 2010 (~ 10 cm/yr, see Elias and Van der Spek, 2015).

5.3.2 Other waves conditions

Results on effects of other wave conditions on the morphodynamic evolution of the Scheldt mouth are presented in Figure 14. In the case that waves coming from the northwest (run 'SensToWaveDir1'), the obtained bedlevel does not fundamentally differ from the simulated bedlevel in case of southwesterly waves (panel a). Also in the former case, the mouth features an ebb-tidal delta that is flanked by a southern and a northern channel, similarly to that in case of southwesterly waves. In the case of applying four different wave conditions using the mormerge technique (run 'SensToWaveDir1'), the southern channel ("Wielingen") is less pronounced than that in the other cases using constant wave conditions. It seems that by applying four wave conditions simultaneously, the redistribution of sand by waves is enhanced such that channels get shallower. However, a closer look into the morphodynamic evolution of the northern channel ("Oostgat") shows that (see Figure 15) the deepening of this channel in the cases of northwesterly waves and the four-wave conditions is stronger than that in the case of southwesterly waves, thereby suggesting that waves from the northwest likely contribute to deepening of this channel. The mormerge experiment calls for conducting other experiments of different wave conditions using other techniques, which are subject of future research.

Figure 9 – As in Figure 8, but in case southwesterly waves.

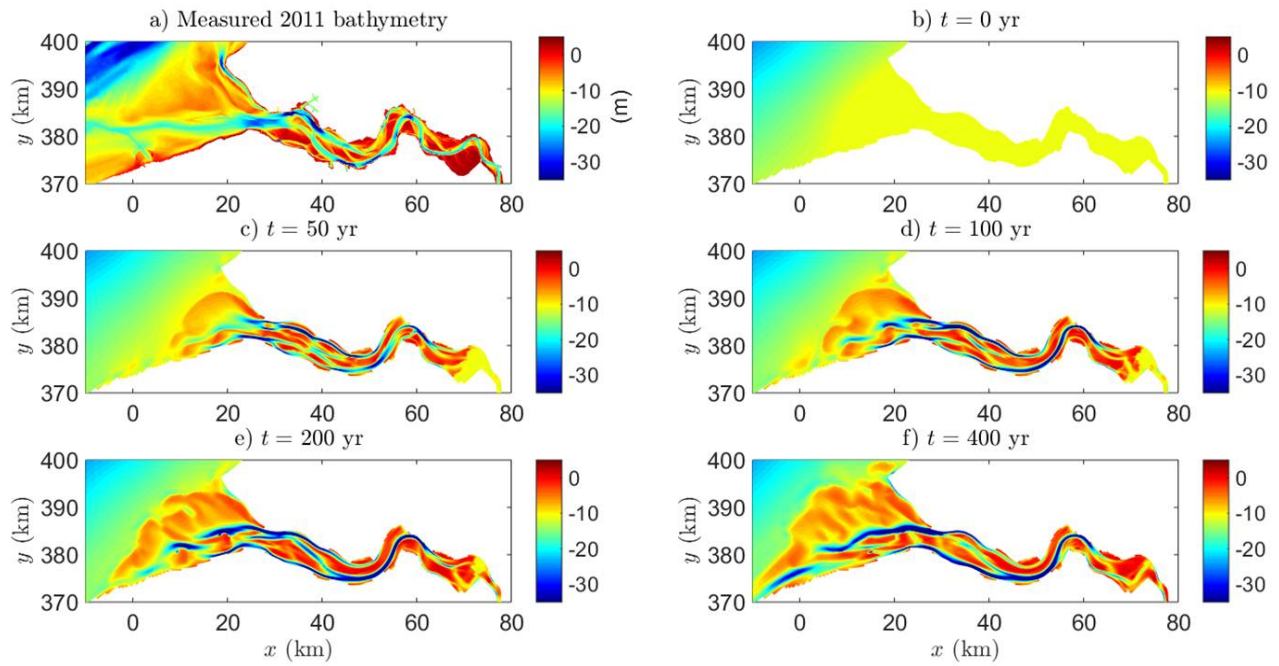


Figure 10 – Zoom-ins of panels a and f of Figures 8 and 9.

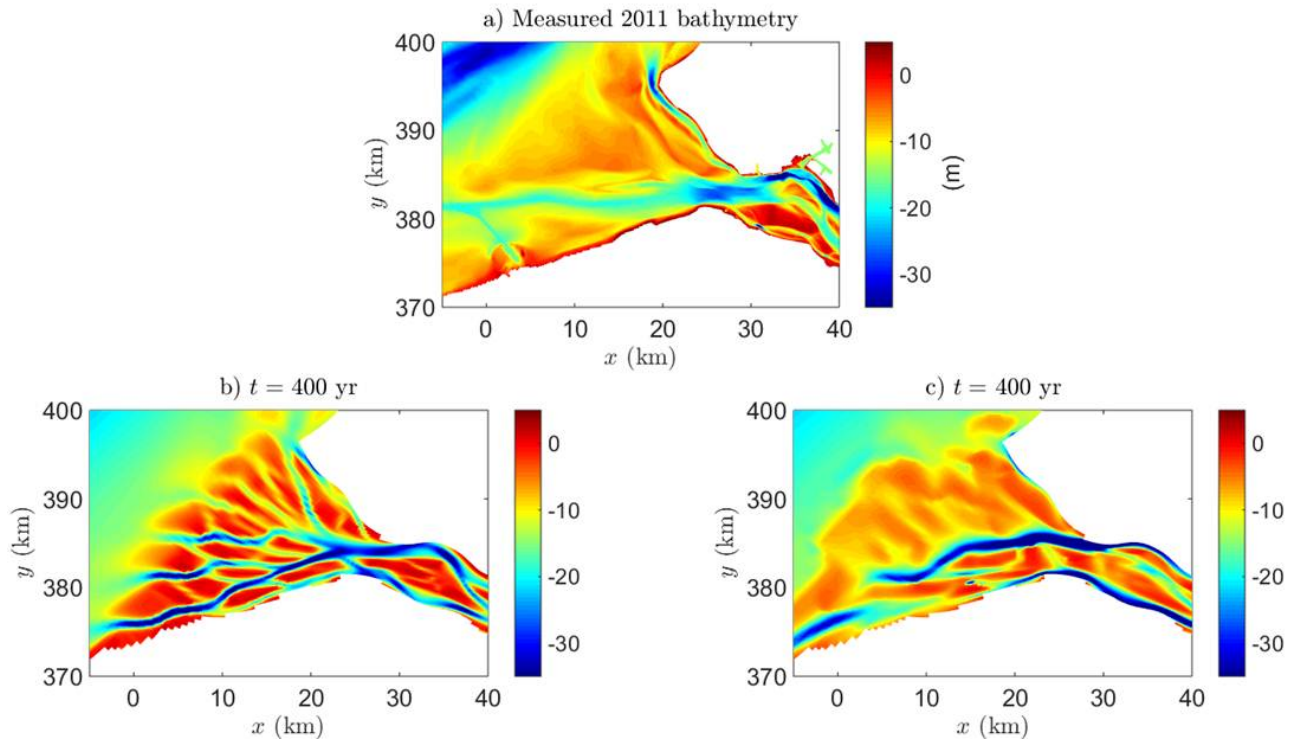
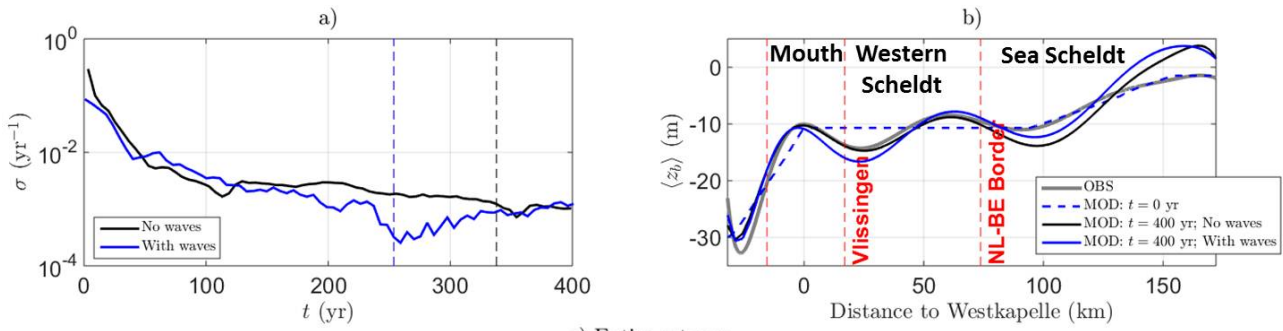


Figure 11 – (a) Growth rate σ (yr^{-1}) versus time in cases without (black) and with waves (blue). (b) Comparison between measured (gray line) and simulated width-averaged bedlevel $\langle z_b \rangle$ along the estuary axis in the cases without (black) and with waves (blue).



Dashed black lines mark the time at which σ is 1% of σ_0 . The initial bedlevel ($t = 0$) is also plotted (dashed blue line).

Figure 12 – (a) Comparison between measured (black line) and modeled (blue line) hypsometries in the default configuration for the entire area of the estuary. (b-c-d) As in a), but for mouth area (a), Western Scheldt (c) and Sea Scheldt (d).

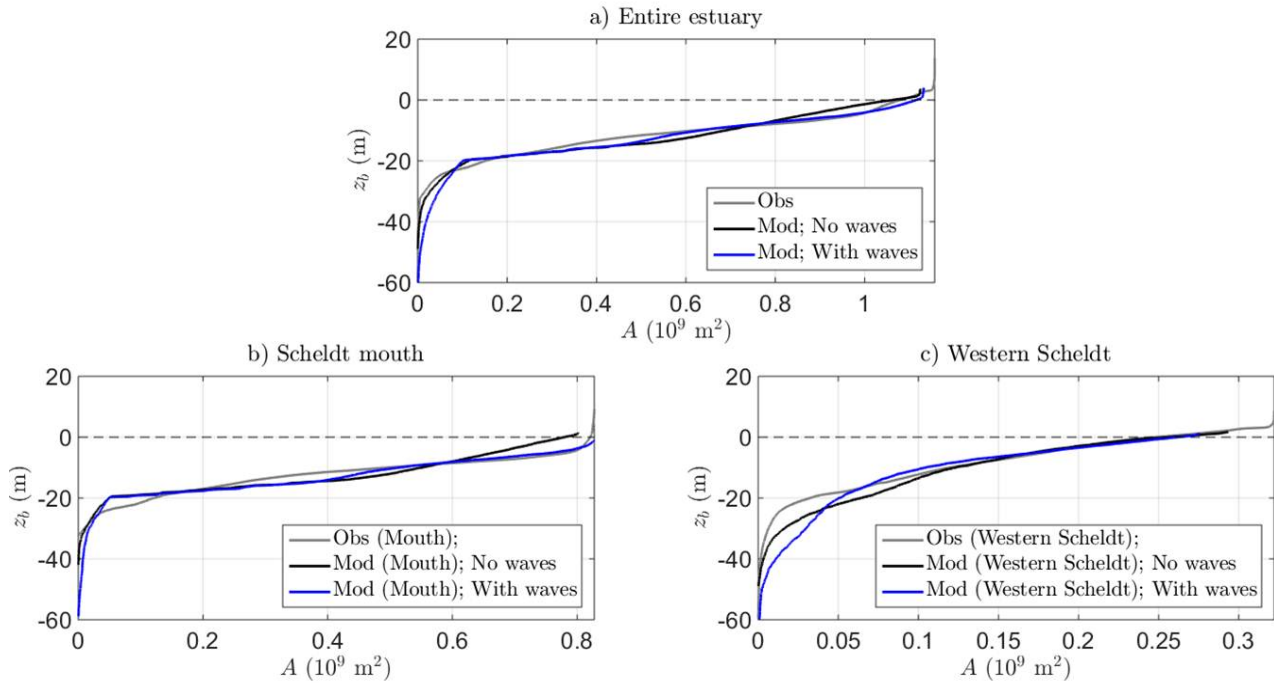
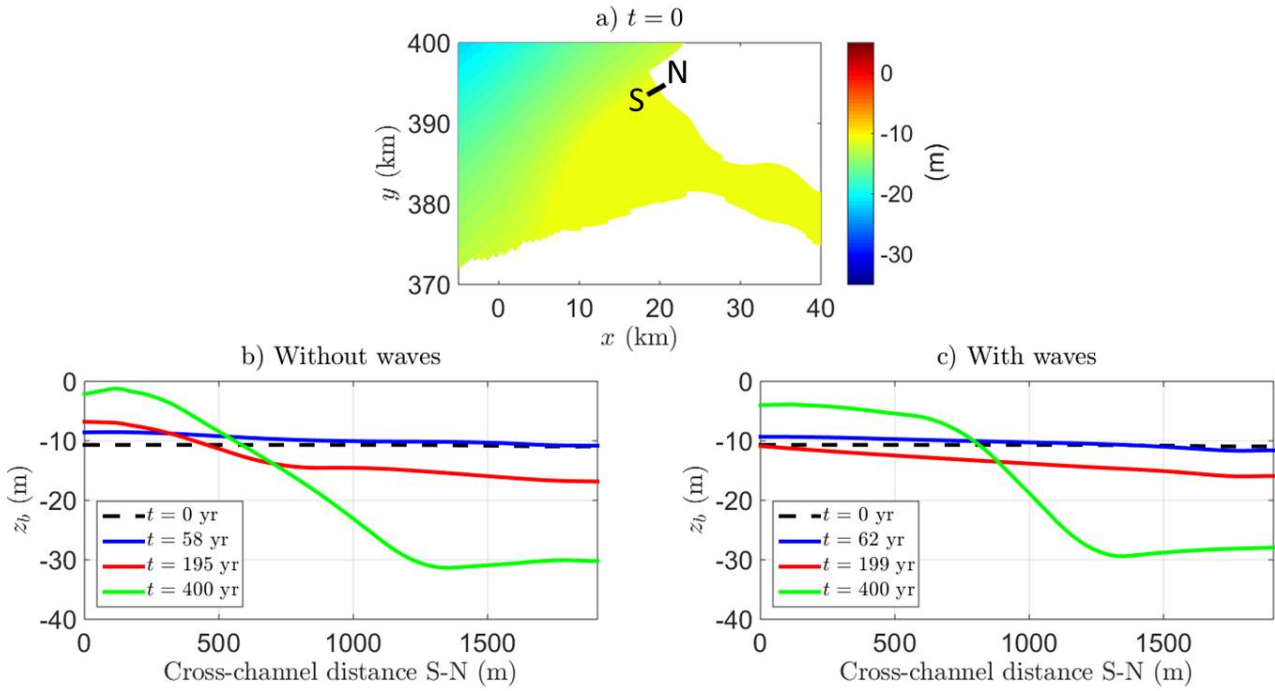
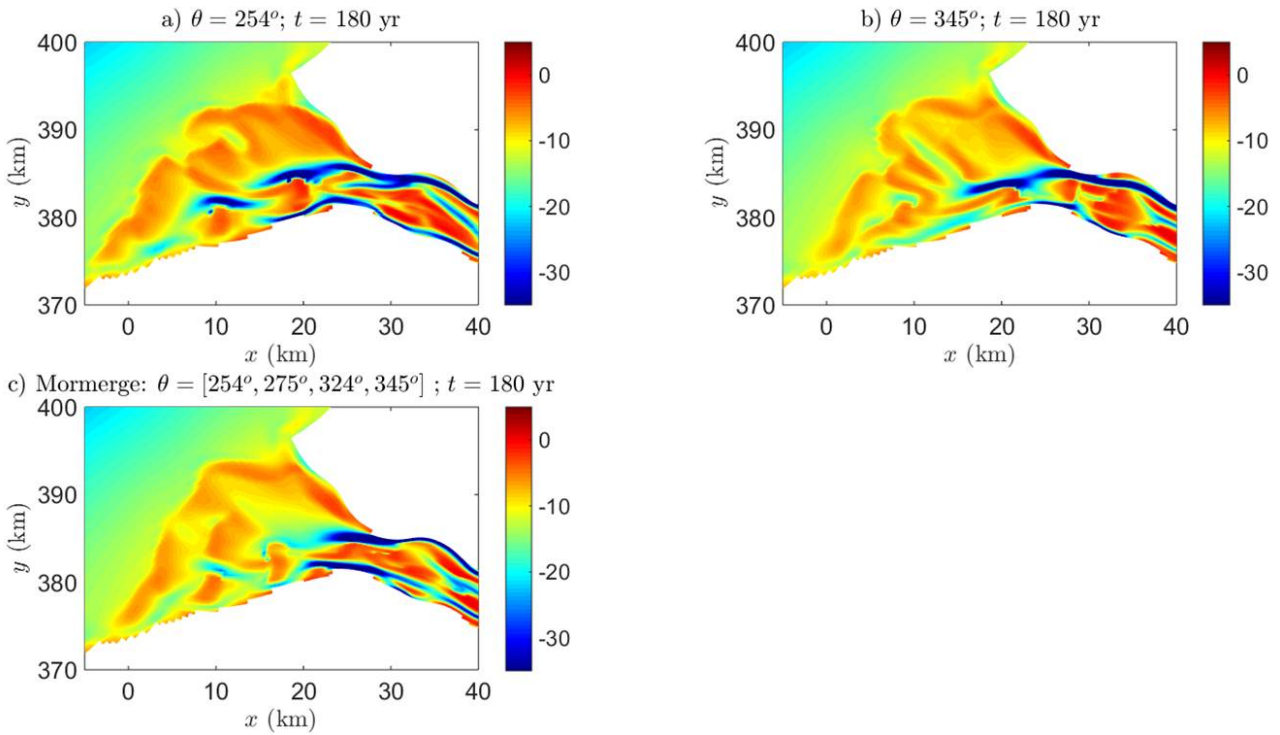


Figure 13 – Time evolution of bedlevel profiles along the cross-channel transect of "Oostgat" in cases without (b) and with (c) waves.



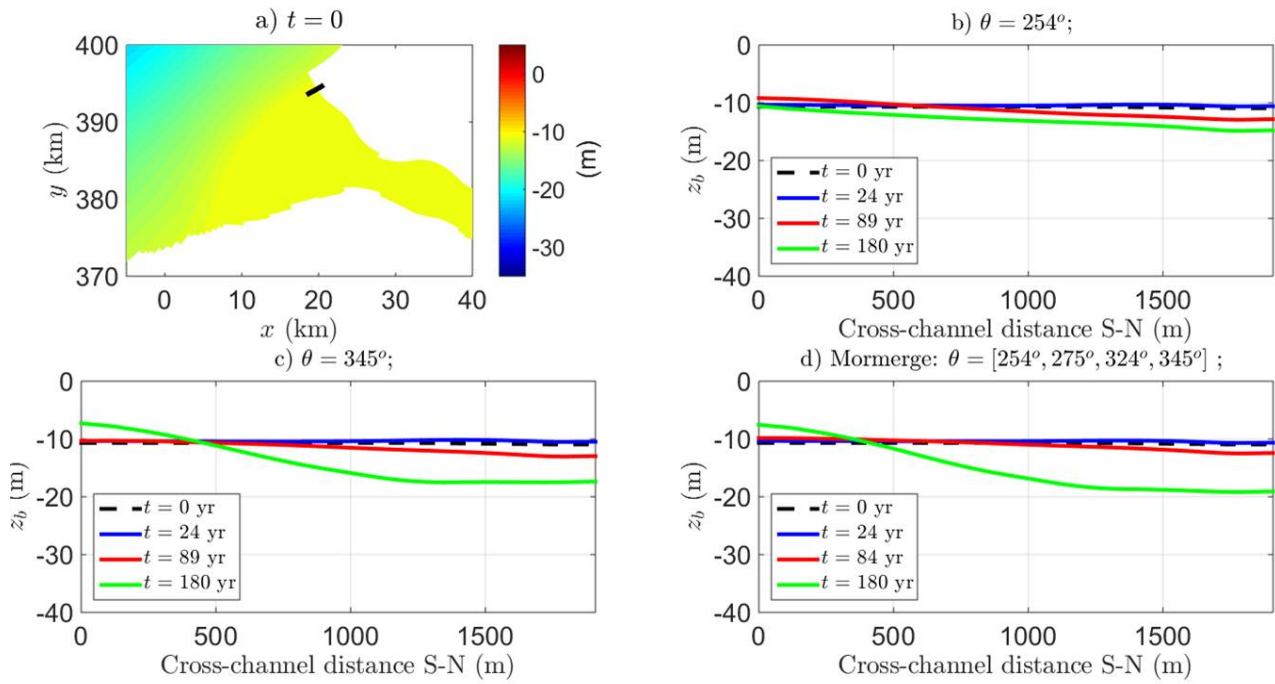
Location of transect is depicted in panel a.

Figure 14 – Results in case of considering southwesterly waves (a), northwesterly waves (b), and four different wave conditions (c).



Because of the high simulation time in case of the latter experiment, the comparison could be made up to a simulation time of 180 years.

Figure 15 – Time evolution of bedlevel profiles along the cross-channel transect of "Oostgat" in cases with southwesterly waves (b), northwesterly waves (c) and four wave conditions simultaneously (d).



Location of transect is depicted in panel a.

6 Model application: Morphodynamic effects of constructing a new shipping channel

At present, the Flemish government is considering major future interventions in the mouth of the Western Scheldt estuary, among which the construction of a new shipping channel (Walvisstaart) in order to improve ship accessibility to the port of Antwerp (Figure 16). For further information see De Maerschalck *et al.*, 2016. While many studies over the last years (cf. Peters, 2006; Van Maren *et al.*, 2015; Wang *et al.*, 2009; Winterwerp and Wang, 2013) pointed out that the observed increase of the tidal range and turbidity in many estuaries (e.g., Scheldt, Ems, Elbe) is caused by human works, still little is known about the impacts of these interventions on the long-term morphodynamic evolution of estuaries (order decades to centuries). This chapter describes an example case of how the model developed in this study can be used to investigate how a new shipping channel in the Scheldt mouth area will evolve over long time scales. Moreover, an example analysis of how the construction of such a channel will affect the morphodynamic stability of the entire region (mouth + estuary) will be given. The obtained bedlevel after 400 years of morphodynamic evolution in the reference run will be used to construct the new shipping channel. The reason of using such a bottom pattern is that it is characterized by relatively small bed level changes compared with the initial changes (nearly morphodynamic equilibrium). In this way, any changes that occur can be attributed to construction of the new channel, rather than to changes induced due to model spin-up. Furthermore, same methodology can be followed to study effects of different wave conditions on the stability of the new channel, and to explore sensitivity of model results to different channel configurations, such as the geometry of the channel (slope, orientation..).

Finally, it is important to note here that this model is based on many simplifications, meaning the quantitative numbers obtained from this idealized model are indications of orders of magnitudes rather than exact numbers. Therefore, the obtained values should be treated with caution. For a more quantitative study of the morphodynamic effects of the new shipping channel please refer to report WL2017R15_068_3, where results obtained from a more complex model are presented.

6.1 Channel implementation in the model

As described in the previous chapter, the model tends to simulate too deep channels. This rises the question of how to deal with the depth of the new navigation channel (Walvisstaart), which is in reality ~ 16.7 m. A way of overcoming this problem, is to rescale the depth of this channel in proportion to the depths of the simulated southern and northern channels, which are a factor ~ 2.4 deeper than those observed. This means that a shipping channel with a depth of 40 m should be implemented. Additionally, to examine how the used depth of the channel affects model results, it is recommended to also conduct runs where different channel depths are considered.

The obtained bedlevel after 400 years from the reference experiments is used to construct the new shipping channel. The implementation of this channel is shown in Figure 17. The volume sand that is dredged from the mouth area is deposited outside the domain. Subsequently, three runs are carried out. In the first run (reference case), the model is run without the new shipping channel. In the second run, the new shipping channel is implemented, which is allowed to evolve freely (run 'New-Channel'). To get an order of magnitude of the volume of sand needed for channel maintenance, a

third run is conducted where the new shipping channel is maintained at its initial depth (= 40 m). A total simulation time period of 200 years is considered. Results from these runs are presented in the following sections.

6.2 Morphodynamic stability new channel

From Figure 18, which compares bedlevel development between $t = 0$ and $t = 200$ years for cases without and with a new shipping channel (left and right panels, respectively), it appears that the new shipping channel still exists after 200 years of morphodynamic evolution. This implies that within this time period, the system does not show any tendency to go back to its original morphodynamic state, i.e., a state with two main channels in the Scheldt mouth ("Wielingen" and "Oostgat"). However, from Figure 19 it turns out that the landward and seaward parts of the channel undergo significant sedimentation (indicated by arrows).

With regard to dredge maintenance, Figure 20 shows that in case of maintaining the shipping channel at its initial depth of 40 m, a yearly-averaged sand volume of about $1.4 \times 10^6 \text{ m}^3$ must be dredged out of the channel (panels b and d). There is no clear tendency whether the dredged sand volume increases or decreases with time, but it rather fluctuates up and down.

6.3 Hydro- and morphodynamic response Scheldt estuary

6.3.1 Effects on hydrodynamics and sediment transport

Figure 21 shows that the discharge rate increases through the new shipping channel (dashed black line in panel b), which seems to go at the expense of the discharge trough "Wielingen" (red lines), which is decreasing. Northern channel "Oostgat" experiences a slight decrease of Q (blue lines) in the presence of the shipping channel. No significant changes in discharge appear at the transition between the estuary and the mouth (green lines). However, with regard to sediment transport at these locations (panel c), "Wielingen" and "Oostgat" experience less sediment activity in the presence of the shipping channel compared with the reference case. Moreover, in the presence of the shipping channel there is an increase in the sand export from the estuary (dashed green line), meaning that the estuary exports more sand in the new situation.

6.3.2 Effects on morphodynamic evolution Scheldt estuary

Figure 22 reveals that in the case of no intervention, the northern channel ("Oostgat") deepens in the course of time at a rate of about 5 cm/yr (panel b). It seems that sand that is removed from the channel is deposited on the southern shoals. Note that the obtained rate of deepening from the model has the same order of magnitude as the observed rate of deepening in Oostgat between 1965 and 2010 ($\sim 10 \text{ cm/yr}$, see Elias and Van der Spek, 2015). From panel d of this figure it appears that after constructing the shipping channel, the rate of deepening reduces by a factor of approximately 2.4.

With regard to the response of the southern main channel ("Wielingen") to construction of the new channel, it appears that the middle part of the southern channel "Wielingen" experiences an increasing sedimentation with time as a result of the presence of the new shipping channel (Figure 23b).

Moreover, the natural deepening of channel "Wielingen" in case of no intervention (panel a) reduces in the presence of the new channel (b). These results imply that the presence of the new channel weakens the southern main channel "Wielingen".

Concerning the response of the Scheldt estuary to construction of the new channel, model results (Figure 24) reveals that particularly the Western Scheldt experiences a decreasing sand volume in the course of time (dashed black line), which is consistent with previous findings that the estuary exports more sand after constructing the shipping channel (see Section 6.3.1). At $t = 200$ yr, a volume decrease of $\sim 110 \cdot 10^6 \text{ m}^3$ occurs with respect to the situation without shipping channel (solid black line), which corresponds with an overall depth decrease of the Western Scheldt of about 30 cm. The deepening of the estuary might lead to an increase of tidal range over time, albeit that from Figure 25a it is seen that no significant changes appear in the tidal range in the first 50 years. The latter figure further shows that in the first 50 years, the vertical tidal component M_2 does not change significantly, component M_4 slightly increases, and the velocity magnitude (averaged over one tidal cycle) slightly decreases.

Some methodology can be followed to study effects of different wave conditions on the stability of the new channel. Moreover, this model offers a great opportunity to explore sensitivity of model results to different channel configurations, such as the geometry of the channel (slope, orientation..).

Figure 16 – Bathymetric map of the Scheldt mouth area, which shows the new shipping channel.

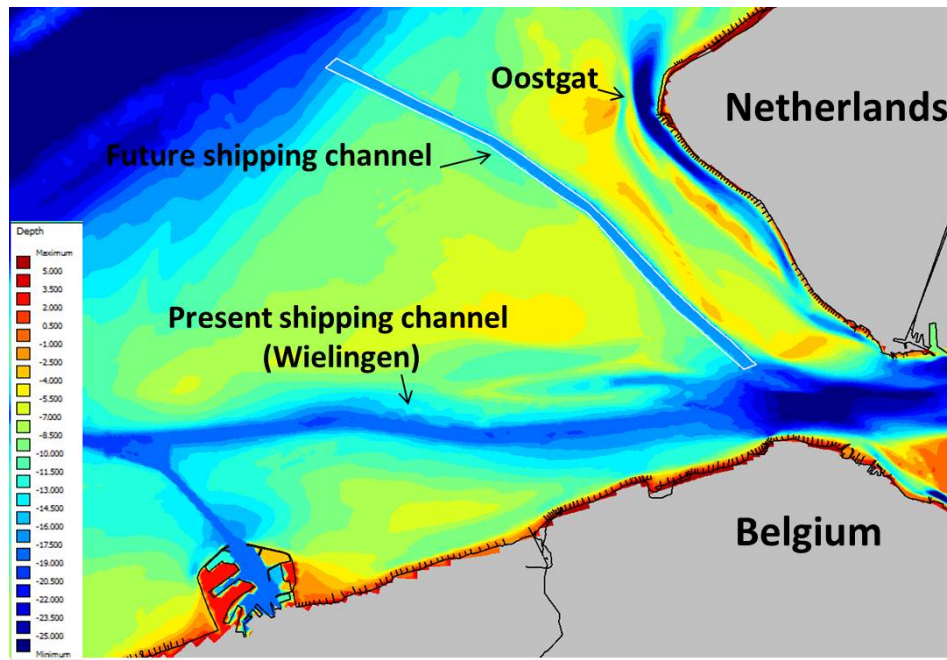


Figure 17 – a) Implementation of the new shipping channel using bedlevel obtained from spinup experiment with southwesterly waves. b) Initial bottom profile along the cross-channel transect depicted in panel a.

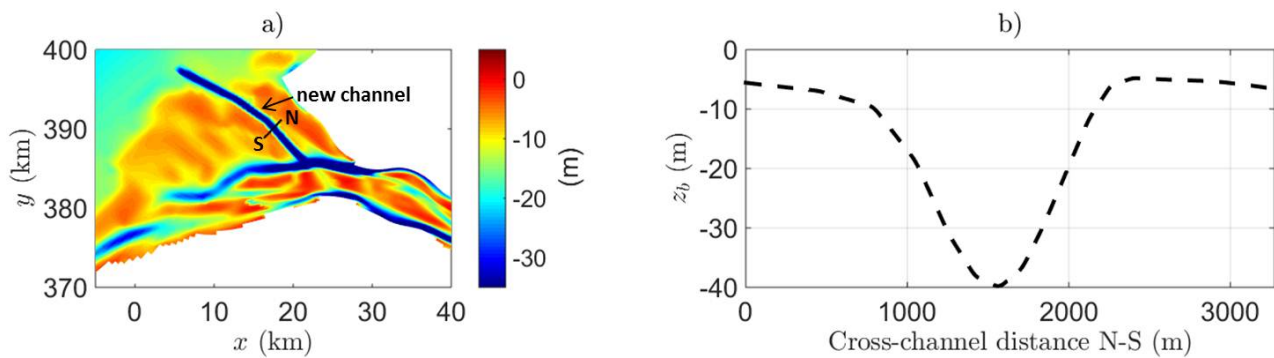


Figure 18 – Bedlevel development between $t = 0$ and $t = 200$ years for cases without (left) and with (right) a new shipping channel.

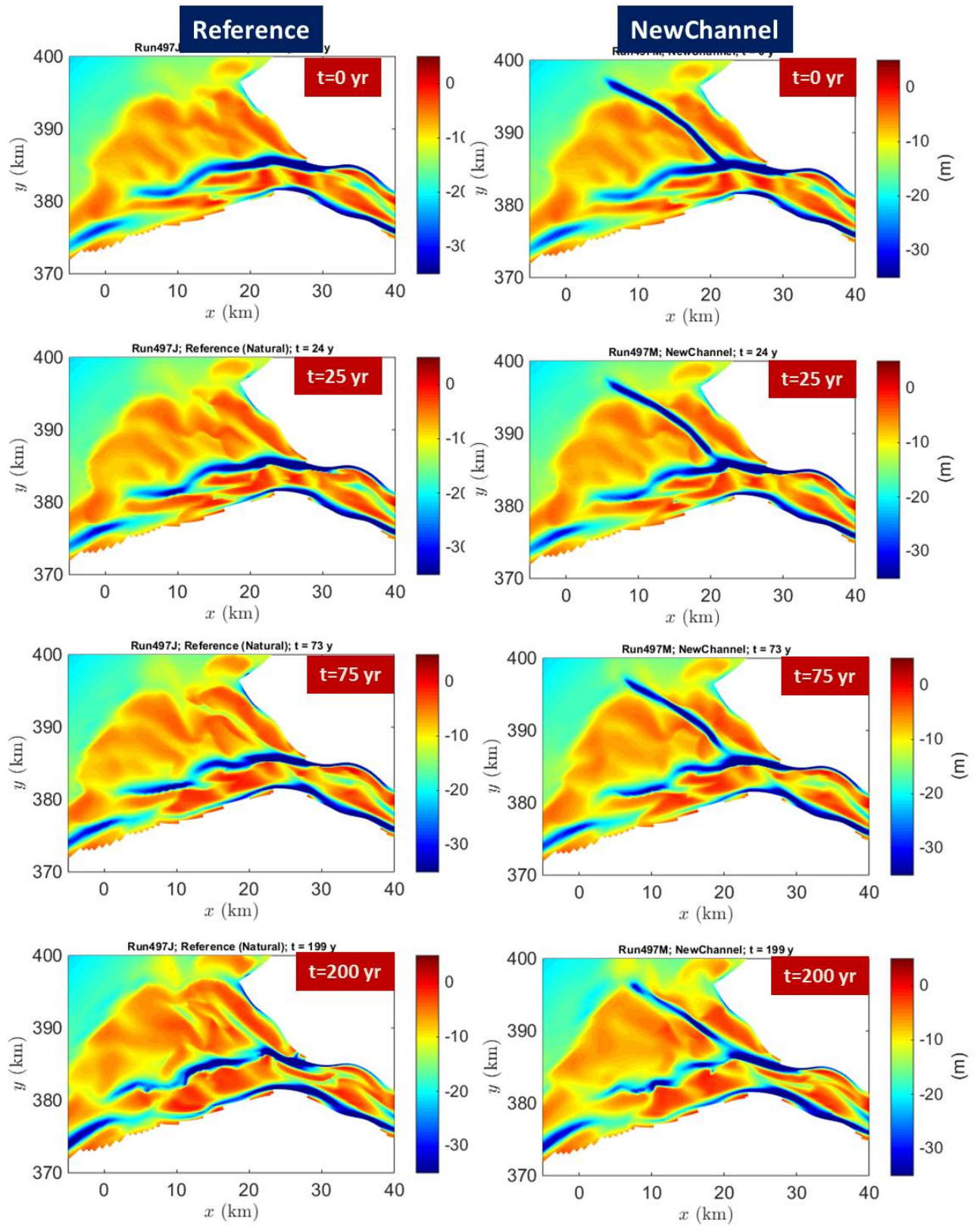


Figure 19 – As in Figure 18, but for the cumulative sedimentation and erosion.

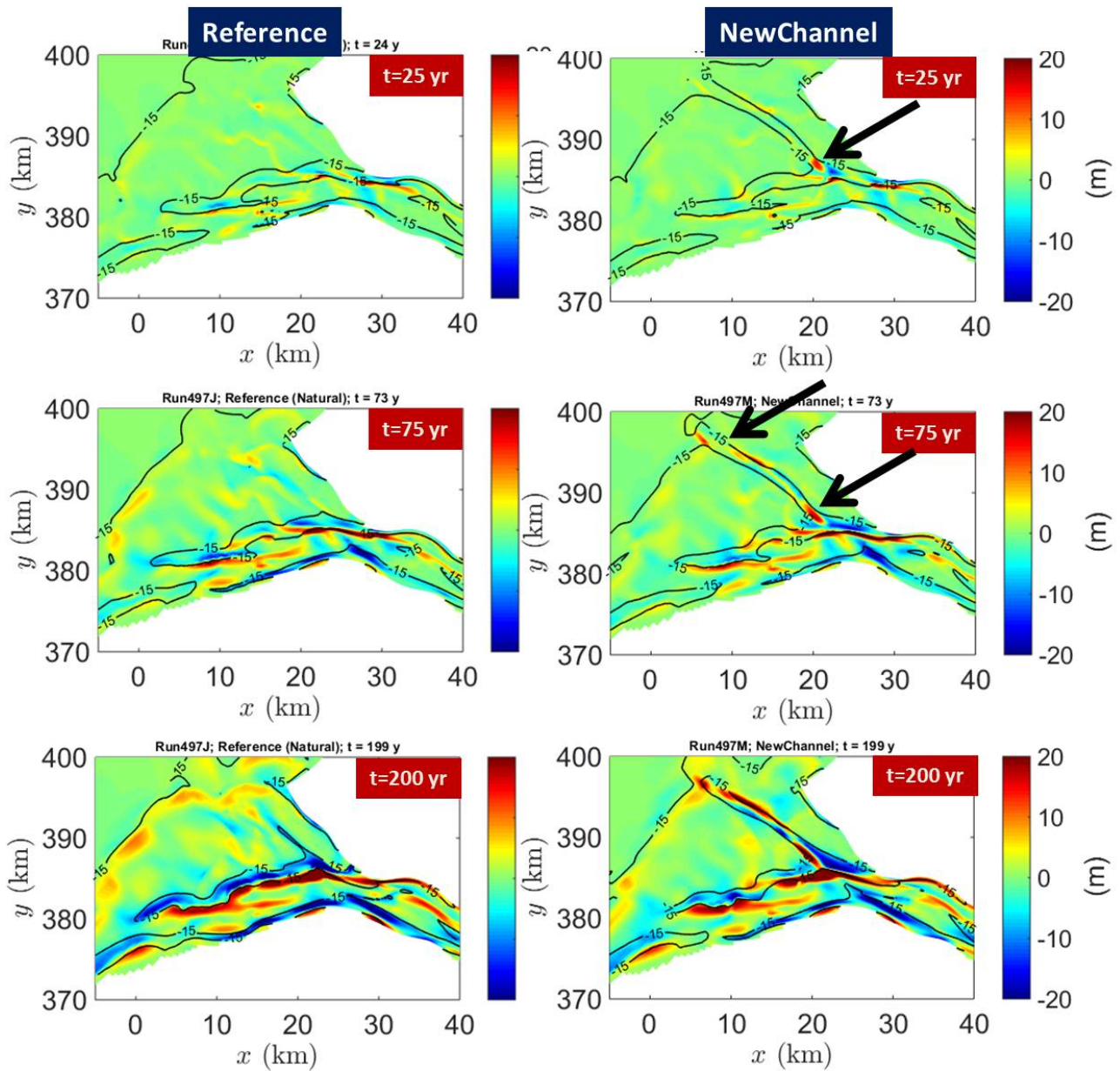


Figure 20 – a-b) Cumulative sedimentation in cases without (a) and with dredging maintenance of the shipping channel. c-d) Cumulative (c) and yearly-averaged (d) volume of dredged sand versus time.

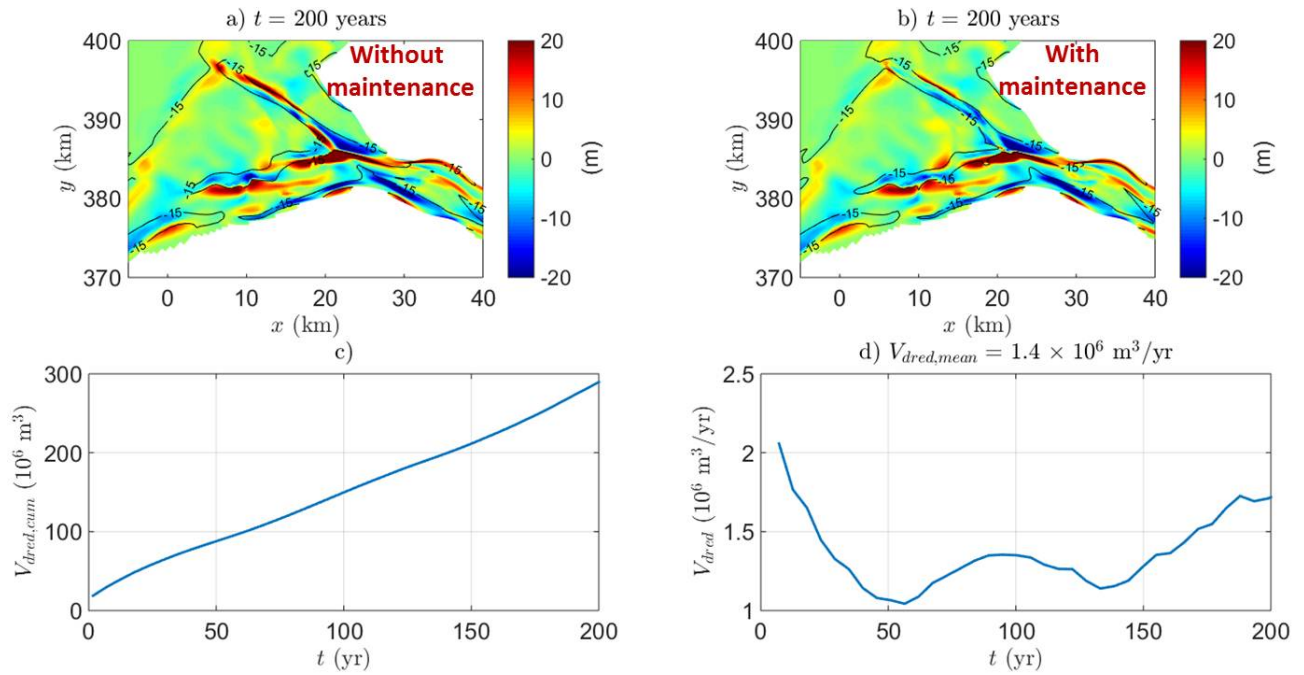
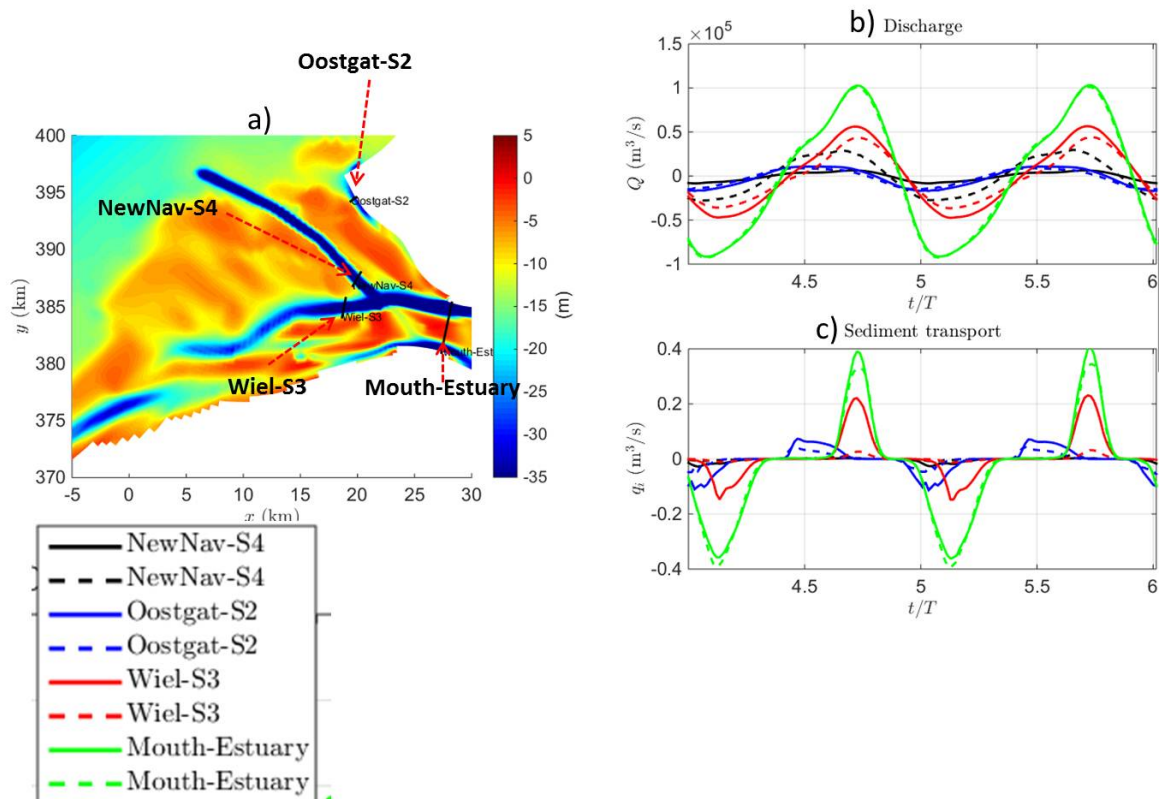
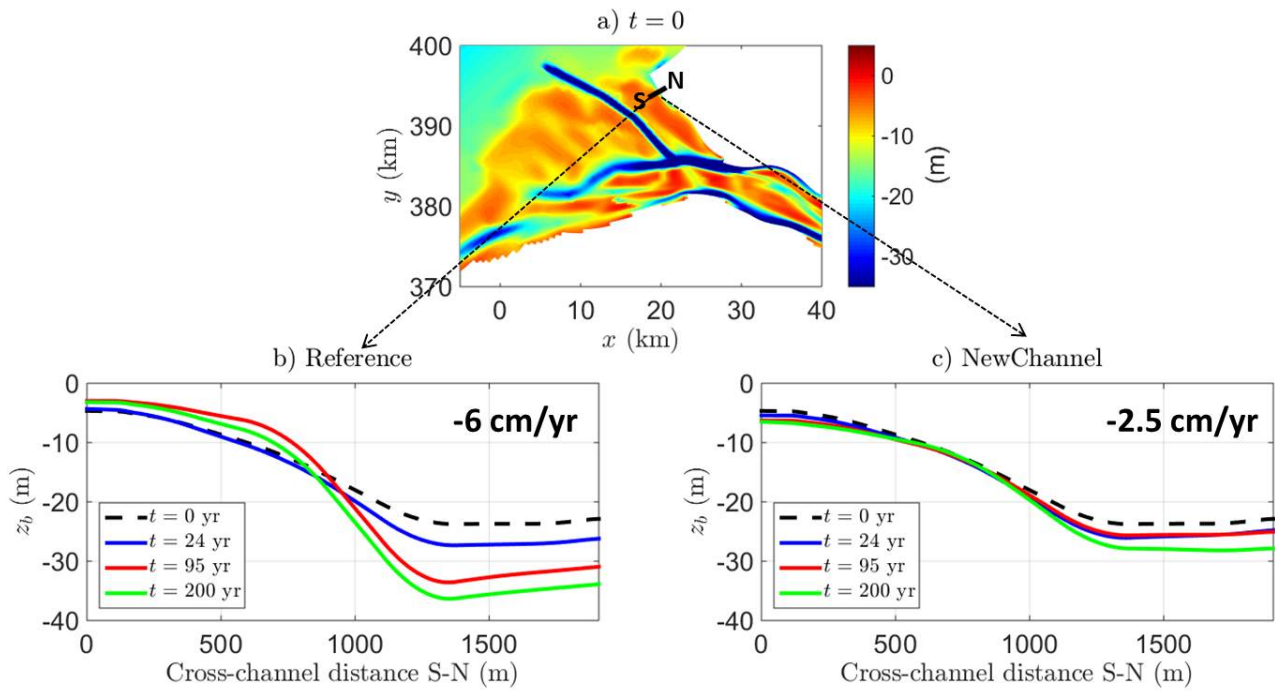


Figure 21 – b) Rate of discharge Q (b) and sediment transport q (c) along the transects depicted in panel a in cases without (solid lines) and with the shipping channel (dashed lines).



Black, blue, red and green lines represent values in the new shipping channel, "Oostgat", "Wielingen" and the transition between the estuary and the mouth, respectively.

Figure 22 – Time evolution of bedlevel profiles along the cross-channel transect of “Oostgat” in cases without (b) and with (c) a shipping channel.



Location of transect is depicted in panel a.

Figure 23 – Cumulative sedimentation after 200 years of evolution in cases without (left) and with (right) a shipping channel. Arrows indicate location of southern main channel (“Wielingen”).

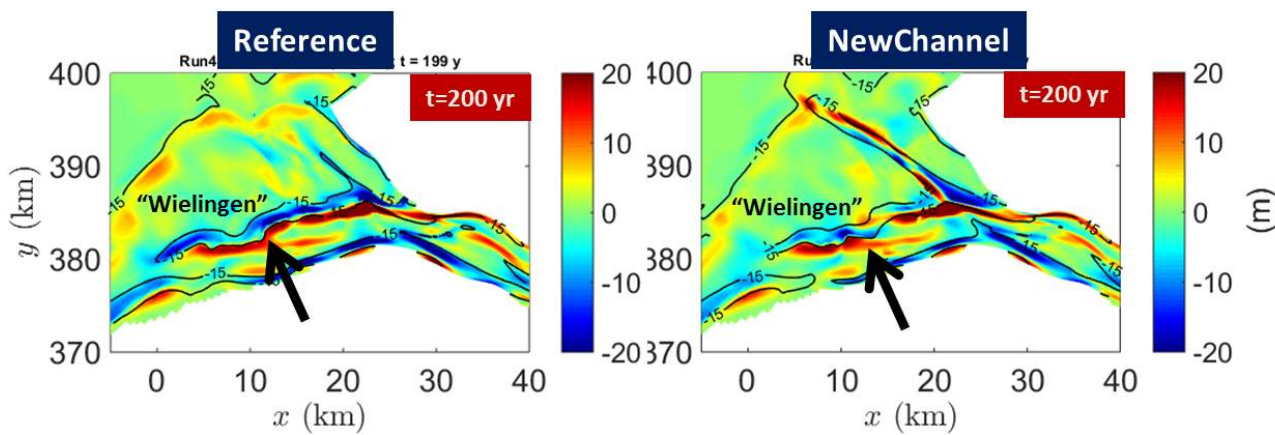


Figure 24 – Time evolution of the volume change (with respect to $t = 0$) of the Western Scheldt (black lines) and Sea Scheldt (blue lines) in cases without (solid lines) and with the shipping channel (dashed lines).

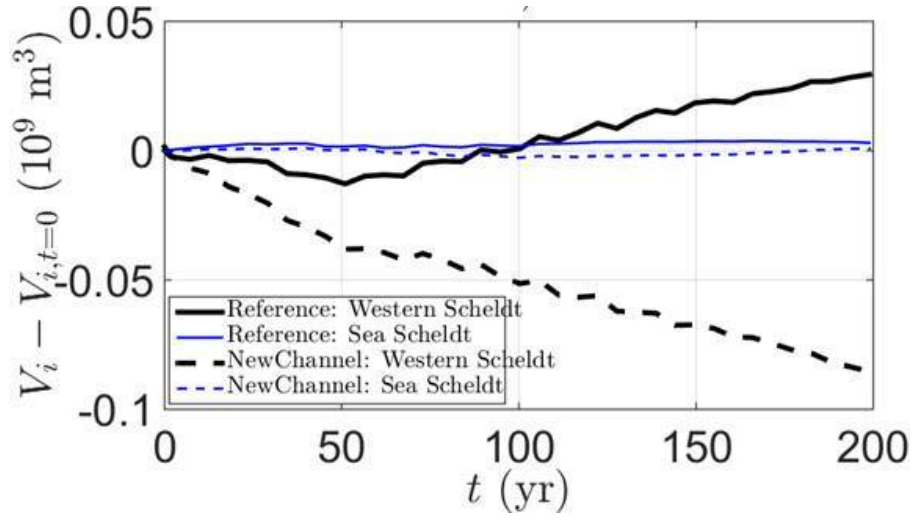
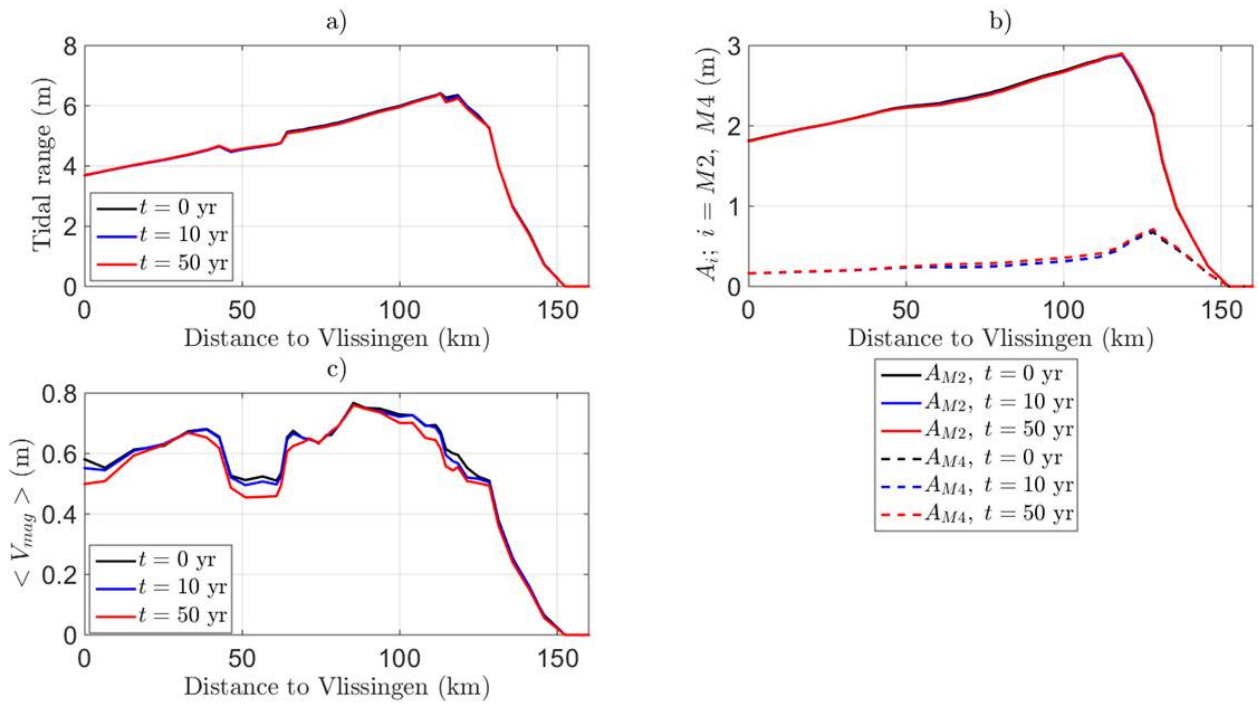


Figure 25 – Tidal range (a), amplitudes of vertical tidal components M_2 and M_4 (b) and time-averaged velocity magnitude (c) versus long-channel distance with respect to Vlissingen at times $t = 0, 10$ and 50 years.



7 Summary and conclusions

The specific aims of this study were 1) to set up a morphodynamic model for the Scheldt mouth that accounts for waves, 2) to examine sensitivity of model results to different wave conditions, and finally, 3) to present an example case of how this model can be applied to study the impact a construction of a new shipping channel might have on the morphodynamic evolution of the Scheldt estuary and its mouth area. To this end, the coupled Delft3D and SWAN models were used.

The methodology employed is that, first, the model parameters (coupling time, morphological amplification factor) are optimized to reduce the simulation time as much as possible. This is because a coupled morphodynamic simulation with Delft3D and SWAN models can be quite time consuming due to the fact that most of the simulation time is spent in reading/writing to so-called com-files, in which data is exchanged between the models. A simulation of 400 years morphodynamic evolution can easily last more than one month. In order to keep the simulation time below reasonable limits (order 1 to 2 weeks), the coupling time between Delft3D and SWAN and the morphodynamic amplification factor have been optimized by conducting a series of sensitivity runs. Results from these runs reveal that the use of a coupling time of 60 minutes and an amplification factor of 200 do not significantly affect model results.

Next, runs are conducted with and without waves, starting from an initially flat bed until a bottom pattern is obtained that is characterized by relatively small bed level changes compared with the initial changes (nearly morphodynamic equilibrium). A simulation period of 400 years fulfills the latter condition. In the experiments with waves, first, a highly simplified wave forcing is considered by assuming that this forcing remains constant in time at the offshore boundaries, and that waves come from one direction (southwest). Additional experiments are conducted with waves coming from the northwest, and with waves that come from four different wave directions and which have different wave heights and wave periods. In the latter experiment, all wave conditions are applied simultaneously, thereby sharing the same bathymetry, which is updated every time step according to the weighted averaged of the bed level changes due to each condition (mormerge approach).

Result reveal that when accounting for waves, an ebb-tidal delta forms in the mouth area, which is flanked by two distinct southern and northern channels ("Wielingen" and "Oostgat"), which are large-scale features that are comparable to observed bathymetry in the Scheldt mouth. Clearly, the inclusion of waves leads to a redistribution of sand from shoals into channels, thereby removing the small-scale secondary channels that form in case of neglecting waves. The formation of a northern and southern channel in both cases with and without waves implies that the tidal motion remains the primary force that causes the formation of these channels. Furthermore, the model simulates a width-averaged bed profile and a hypsometry that roughly agree well with the measured profiles, particularly in the case of neglecting waves. In the case with waves, however, the channels are a factor of 2-3 deeper than in the observations. The overestimation of channel depth by the model in the latter case occurs in both the mouth area and the Western Scheldt. Other differences between model results and observations are that the shoal area in the mouth seems to be deeper, and that the overall bathymetry produced by the model has a weaker slope compared with observations. By zooming in on the long-term evolution of the northern channel ('Oostgat'), it appears that this channel deepens in the course of time at a rate of about 5 cm/yr in both cases of without and with waves, which is comparable to the measured rate of deepening in Oostgat between 1965 and 2010. It can be stated that deepening of this channel, which causes major problems at the coast of Walcheren, is mainly driven by tidal motion.

Results on effects of other wave conditions on the morphodynamic evolution of the Scheldt mouth show that in the case that waves are coming from the northwest, the obtained bedlevel does not fundamentally differ from the simulated bedlevel in case of southwesterly waves. Also in the former case, the mouth features an ebb-tidal delta that is flanked by a southern and a northern channel, similarly to that in case of southwesterly waves. In the case of applying four different wave conditions using the mormerge technique, the southern channel ("Wielingen") is less pronounced than that in the other cases using constant wave conditions. A closer look into the morphodynamic evolution of the northern channel ("Oostgat") shows that the deepening of this channel in the cases of northwesterly waves and the four-wave conditions is stronger than that in the case of southwesterly waves, thereby suggesting that waves from the northwest likely contribute to deepening of this channel. Still, further research is needed to examine effects of different wave conditions (including extreme wave and wind events) using other techniques, which are future topics.

Finally, an example case was described of how the model developed in this study can be used to investigate the long-term evolution of a new shipping channel in the Scheldt mouth area and its potential impact on the morphodynamic stability of the entire region (mouth + estuary). The obtained bedlevel after 400 years of morphodynamic evolution was used to construct the new shipping channel. The reason of using such a bottom pattern is that it is characterized by relatively small bed level changes compared with the initial changes (nearly morphodynamic equilibrium). In this way, any changes that occur can be attributed to construction of the new channel, rather than to changes induced by the model spin-up. In this example case it was showed how the problem of too deep channels can be overcome by rescaling the depth of the new shipping channel in proportion to depths of other channels in the mouth. A similar methodology can be followed to study effects of different wave conditions (including extreme events) on the stability of the new channel, and to explore sensitivity of model results to different channel configurations, such as the geometry of the channel (slope, orientation..). Finally, it is important to note here that this model is based on many simplifications, meaning that the quantitative numbers obtained from this model should be interpreted as indications of orders of magnitudes rather than exact numbers.

In conclusion, the inclusion of waves is important when studying the morphodynamic evolution of the Scheldt mouth, as they cause sand redistribution in this area such that it counteracts the formation of unrealistic small-scale channels. The fact that the model simulates two distinct channels ("Oostgat" and "Wielingen") in all cases without and with waves, with the latter also having different directions and wave heights, means that tidal motion is the primary forcing that causes the formation of these channels. Model results suggest that the deepening of Oostgat is part of the natural solution of the system. The model can be applied to study long-term morphodynamic effects of human interventions in this area, under the condition that the precise numbers obtained from the simulations should be treated with caution. These numbers are more indications of orders of magnitudes.

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