NUMERICAL MODELLING OF LONG-TERM MORPHOLOGY IN THE SURF ZONE OF THE BELGIAN COAST

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Longshore sediment transport in the surf zone plays a considerable role in the long-term morphological behaviour of the Belgian coast. In order to be able to analyse coastal protection measures in the future, a 2D morphology model is developed within the Delft3D software suit using a curvilinear grid which follows the coastline closely. A schematised tide and wave climate is used as boundary conditions for the model. In addition, a constant morphological acceleration factor (MorFac) and the MorMerge online-parallel approach are employed to achieve modelling of the long-term morphology within reasonable computation time. Qualitatively, most major morphological changes are well captured by the model. The modelled sedimentation/erosion is further quantitatively compared with beach erosion/deposition trends of the last 25 years presented in Houthuys (2012). The model still shows a reasonable agreement and its quality is discussed.

Keywords: longshore transport, surf zone; Belgian coast; morphology model; Deflt3D; MorMerge

PROBLEM DEFINITION

The Belgian coast is 65 km long and characterised by a sandy bed with a fairly uniform bathymetry and a gentle slope with a shore connected tidal sandbank. The beach and shoreface are important parts in the coastal protection. The semidiurnal macro tidal regime has a tidal range of about 4 m. The wave climate is dominated by waves coming from the North and West quadrant. Both result together in a net current and longshore transport from the South West to the North East. The longshore sediment transport in the surf zone plays a considerable role in the long-term morphological behaviour of the beach and shoreface. Beach and shoreface nourishments are required at several locations in order to maintain coastal protection. This highly urbanized area is protected by numerous engineering structures placed along most of the coast. One of the main manmade features is the port of Zeebrugge (Figure 1). This port was extended in 1986 with breakwaters which exceed 3 km, that strongly interfere with the littoral drift in the area. One of the consequences is a fast accumulation of sediment next to the western dam of Zeebrugge.

The long-term morphological behaviour of the beach and shoreface is a complex result of many processes on different scales in time and space. A better understanding of these processes will advantage our coastal protection in the future in an optimal way. For instance, the efficiency and effectiveness of beach or shoreface nourishments can be optimised when more insight is gained in the long-term morphological behaviour of the beach and shoreface. Detailed numerical modelling of the hydrodynamics (of waves, tidal currents, water levels), sediment transport and changing morphology is the main tool to gain insight in the long-term processes, to predict future changes and to set up an integrated sand policy in the coastal zone.

Figure 1. Satellite image of the Belgian coast, a major feature is the port of Zeebrugge.

This study aims to develop a numerical model which can be employed as a reliable tool to evaluate the long-term morphological evolution of the surf zone along the Belgian Coast. For this purpose, a 2D

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sediment transport model covering the Belgian coast is developed within the Delft3D software suit, with boundary conditions consisting of a schematised tide and wave. The model is then used to simulate ten year of sedimentation/erosion in the surf zone of the Belgian Coast and modelling results are analysed and discussed.

METHODOLOGY

Models

Delft3D is a model package which is composed of several modules for the simulation of flows, sediment transports, waves, water quality, morphological developments and ecology in coastal, river and estuarine waters. The FLOW module solves the depth-averaged or 3D shallow water equations on a rectilinear or curvilinear grid. In the WAVE module, the wave transformation is computed by the third-generation wave model SWAN (Booij et al., 1999; Ris et al., 1999). It includes wave propagation, wind induced wave generation, non-linear wave-wave interaction and dissipation. The FLOW and WAVE modules are coupled online at regular interval to account for the effects of waves on the flow and to provide flow boundary conditions for the wave transformation. Sediment transport under combined waves and currents is computed with an advection-diffusion equation and morphology can be sped up with a morphological acceleration factor (MorFac). More details about the Delft3D model can be found in Lesser et al. (2004).

Basic settings

The Delft3D model extends approximately from Nieuwpoort to Breskens to the East along the coastline, and after crossing the Scheldt estuary it covers the coastline from Vlissingen to Domburg (further referred to as the N2V model for "Nieuwpoort to Vlissingen", cf. Figure 2). It has a global size of about 70km alongshore by 25km cross-shore, with a resolution of around 150x1200m offshore, with the surf zone being refined up to 150x15m nearshore. In total the model contains around 56,000 cells. The model grid is shown in Figure 2. The resolution is refined in the surf zone in order to be able to model the long-shore transport even under calm wave conditions as well. The mouth of the Scheldt Estuary is included in order to prevent boundary effects in areas of interest on the Eastern Belgian coast. The hydrodynamic boundary conditions are provided by nesting the model in a larger calibrated model (Verheyen et al., 2013). Neumann type boundary conditions are applied on the lateral boundaries and a water level at the offshore boundary. For sediment transport, equilibrium concentrations are applied since sand transport is expected to adapt quickly to changes in hydrodynamics. A time step of 12s is used for the flow computations and a uniform Manning roughness of $0.022 s/m^{1/3}$ is chosen (close to the default Chezy value of $60 m^{0.5}/s$ for the local depth, but it yields better results in flow accelerations and in shallow areas). The eddy viscosity and diffusivity are set to $1 m^2/s$.

For morphological modelling the option CstBnd has been enabled to prevent the formation of artificial boundary layers along the domain boundaries due to normal components of the advection terms (Deltares, 2011), and onshore wave transport factors have been set to zero due to the inadequate implementation of cross-shore transport in a 2D Delft3D model (Trouw et al., 2012).

In the wave model, a directional spreading power m of 2 instead of the default value of 4 has been used to match measured wave spectra. White-capping is computed with the formulation of Van der Westhuysen et al. (2007) because it significantly improves the modelled wave periods (Holthuysen et al., 2012). A resolution of 10° is used for the wave discretisation. A uniform wind field is applied, the wind condition depends on the wave class selected (Lesser, 2009). Boundary conditions for the waves are provided by an existing calibrated wave model covering a larger domain than the N2V model (Doorme et al., 2009).

The N2V model is then used to simulate wave, flow and sediment transport simultaneously in 2D horizontal. Salinity is not taken into account. Wave-current interaction is taken into account by modelling wave-driven currents only, the effect of currents on wave is not modelled. The same wind as in the wave model is applied and can result in residual circulations. The Coriolis force is taken into account. A uniform sediment fraction consisting of 200µm sand is assumed, with unlimited supply from the bed. The port of Zeebrugge has been modelled as dry points in the flow model and is delimited by non-reflecting obstacles when the same grid is used as a wave model. Coastal groynes are not included since they require a much finer gird. The relative crest height of the groynes is 1m or lower, so the influence on the longshore transport is not enormous. It will be examined further how the groynes can be incorporated without an unrealistic computation time. Figure 3 shows the bathymetry of the area.

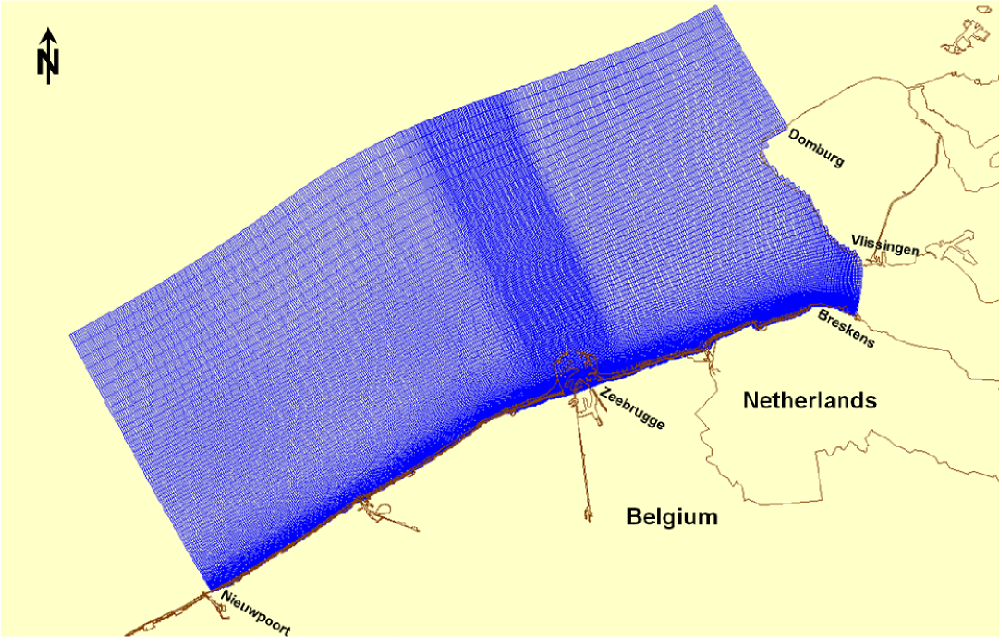

Figure 2. Grid of the N2V model with refinement in the surf zone and near the port of Zeebrugge.

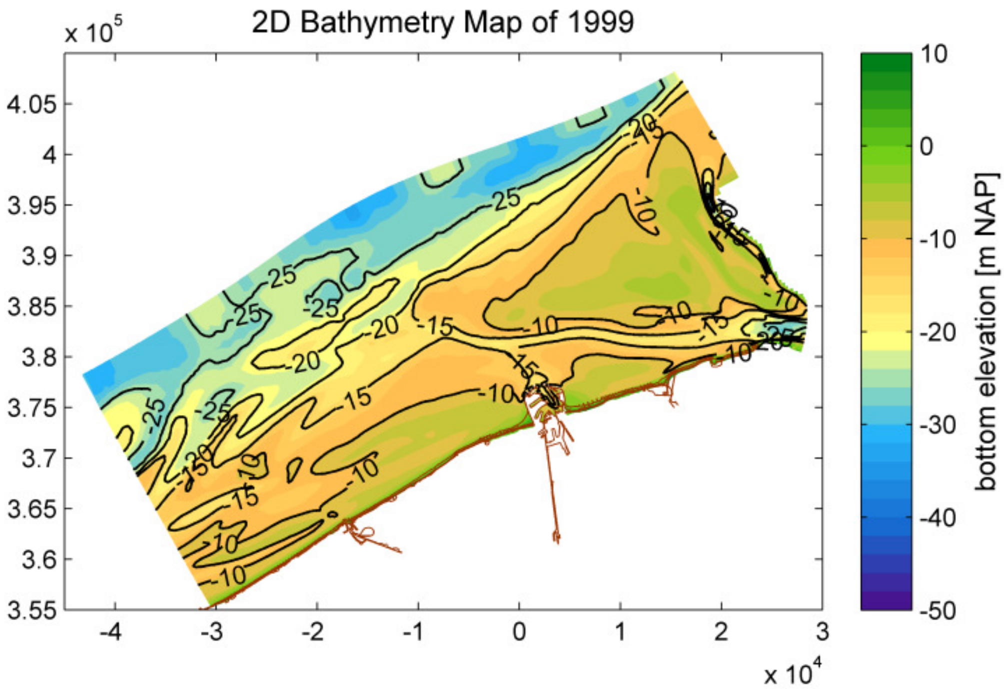

Figure 3. Bathymetry of the N2V model, in RD Parijs coordinates and relative to NAP level (equivalent to MSL).

Upgraded settings

In earlier work of Zimmermann et al. (2012), a morphological model has been developed within the Delft3D software suit for the coastal zone around Blankenberge and Zeebrugge. This model has been developed to simulate long term morphology with tide and waves over a time horizon of one year by taking advantage of input reduction which consists in simplifying the forcing conditions to simulate a longer period without the entire time series. The input reduction has derived a representative tide of 24h50min for daily inequality according to the method of Latteux (1995), and a representative wave climate composed of 11 wave-wind conditions following the OPTI procedure (Mol, 2007).

This study extends the model to a time horizon of ten years over a larger spatial domain. In order to manage this within reasonable computation time, a few upgrades in settings are made as follows:

- The MorMerge online-parallel approach is used replacing a representative time series of wave conditions (Roelvink, 2006). With the online-parallel approach, at each time step the bathymetry map is updated by merging the separate weighted bed change caused by each wind-wave condition, as a result of which substantially shorter simulation time is needed compared to calculating the wave-wind conditions in time series, and history effects arising from the fact that each wave condition is calculated at a different phase in the tidal cycle are avoided. Because it is equivalent to a constant averaging of the forcing parameters, it yields a much smoother and more stable bed evolution than a single time series. This increased stability allows to increase the morphological acceleration factor (MorFac) even further.

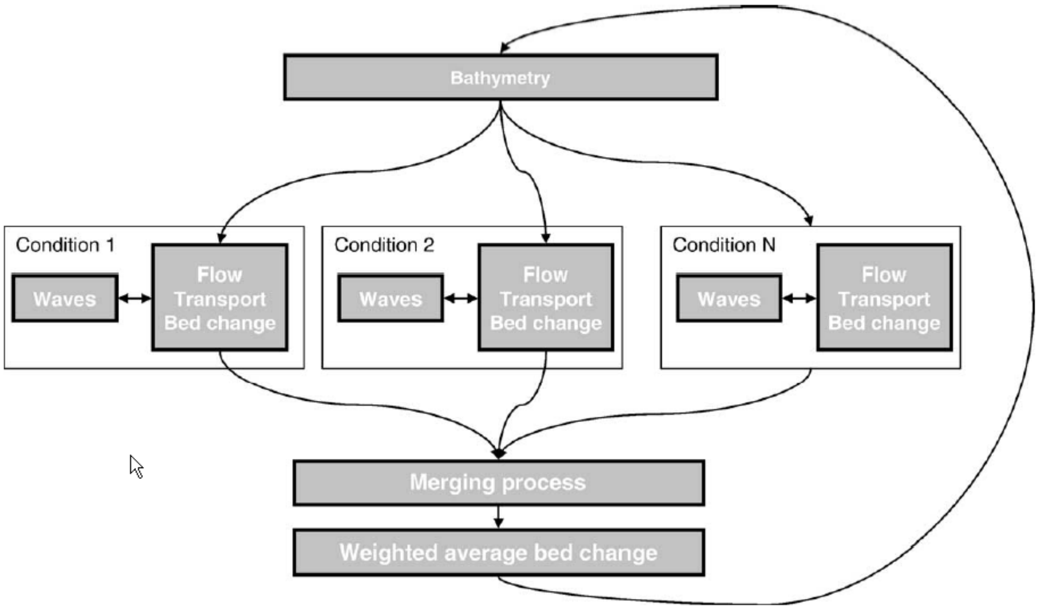

Figure 4. Schematisation of the MorMerge process for morphological modelling with a reduced wave climate. Figure from Lesser (2009).

- The option of dry cell erosion is switched on allowing erosion of the coastline, which consists of points at the water-land interface. This also decreases the effect of instabilities and therefore the risk of a simulation crash.
- The number of wave conditions has been further reduced from 11 to 4 conditions (with new weighting factors in Table 1) following the OPTI routine. This speeds up convergence of the total wave computation and also frees up computation power for other tasks at the expense of model accuracy. In addition, it should be specifically mentioned that the sum of weighting factors is not necessarily equal to 1 but less than 1 in the OPTI routine.

Table 1. Representative wave conditions and their weighting factors.

wave condition: direction from, significant wave height	weighting factor
Southwest, 1.25m (SW125)	0.4254
North, 1.75m (N175)	0.1934
West, 1.75m (W175)	0.0683
West, 2.75m (W275)	0.0220

- The morphological acceleration factor (MorFac) has been increased from 36.5 to 125.1. This factor decouples the time scales of hydro- and morphodynamics. It hence determines how much faster the morphodynamics evolve compared to the hydrodynamics.
- The update interval between two wave computations has been increased from 10 minutes to 1 hour. This results in a strong decrease of the computation time of the wave field, but it can lead to more instabilities in shallow coastal zones.

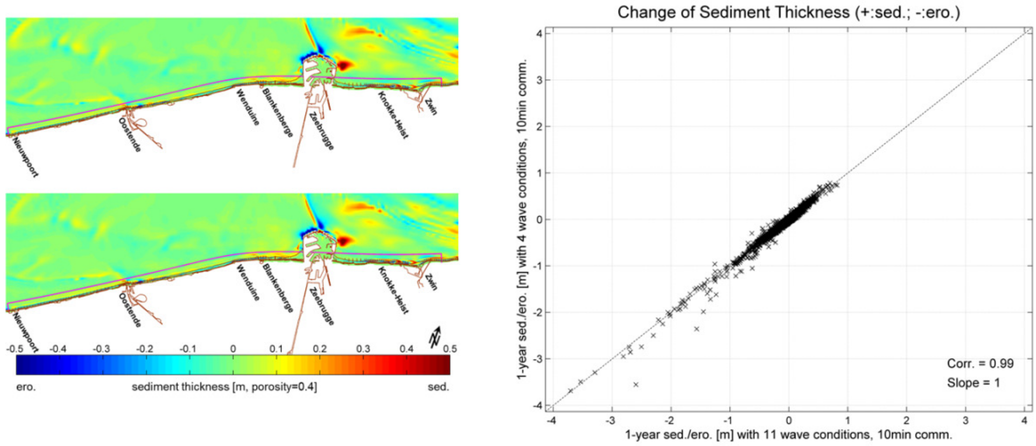

Figure 5. 1-year sedimentation/erosion with 11 (left upper) and 4 (left lower) wave conditions and correlation graphs (right, x-axis: 11 wave conditions, y-axis: 4 wave conditions).

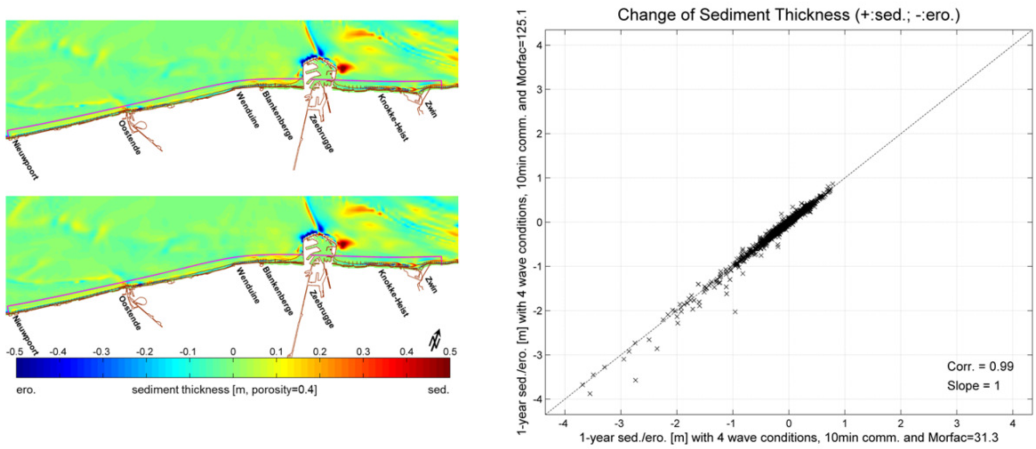

Figure 6. 1-year sedimentation/erosion with MorFac = 31.3 (left upper) and 125.1 (left lower) and correlation graphs (right, x-axis: MorFac = 31.3, y-axis: MorFac = 125.1).

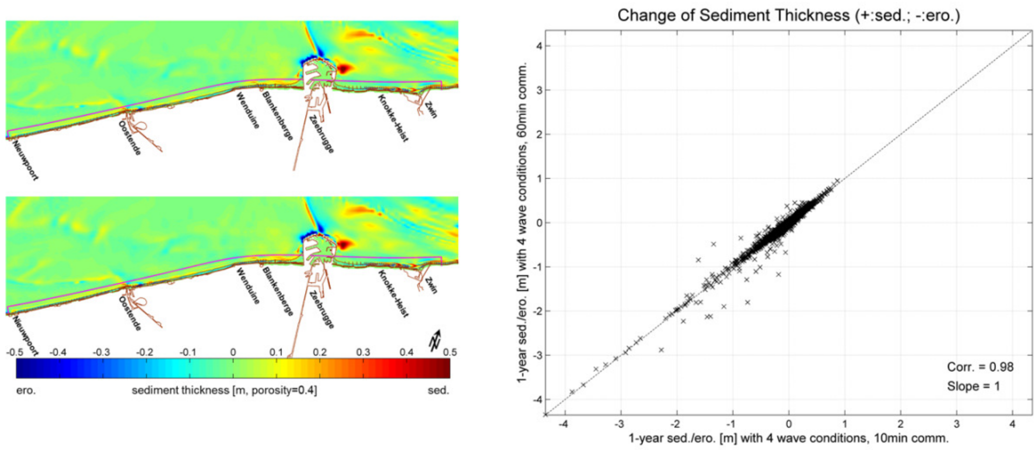

Figure 7. 1-year sedimentation/erosion with 10 minutes (left upper) and 1 hour (left lower) for the update interval between two wave computations and correlation graphs (right, x-axis: 10 minutes, y-axis: 1 hour).

Figure 5 firstly shows a comparison of 1-year morphological change in the surf zone between simulations with 4 and 11 wave conditions using MorFac = 31.3 and 36.5 and a same update interval 10 minutes for the wave computation. It should be pointed out that the MorFac is accordingly adjusted from 36.5 to 31.3 due to the fact that the sum of weighting factors of 4 wave conditions is lower than that of the previous 11 wave conditions. Figure 6 subsequently shows the comparison between simulations using MorFac = 125.1 and 31.3 with the same 4 wave conditions and same update interval

10 minutes between two wave computations. Finally, Figure 7 shows the comparison between simulations with the update interval 1 hour and 10 minutes for the wave computation using MorFac = 125.1 in the 4 wave conditions. The excellent correlation obtained in all these comparisons gives confidence in the upgraded settings to model 10-year morphological change in the surf zone. It also suggests that the morphological developments modelled are robust features which do not depend too much on the wave climate reduction.

RESULTS DISCUSSION

There are two observed data sources available to evaluate the modelled 10-year morphology: the Quest4D project (Janssens et al, 2012) and the annual surveys of coastal profiles and sand volumes done by the Coastal Division of the Flemish Government.

Comparison to the Quest4D dataset

The Quest4D project uses topography and bathymetry data over the period 1997-2010 to visualize the observed long term morphological evolution of the Belgian coast and shelf. The modelled erosion-sedimentation pattern is compared to this data.

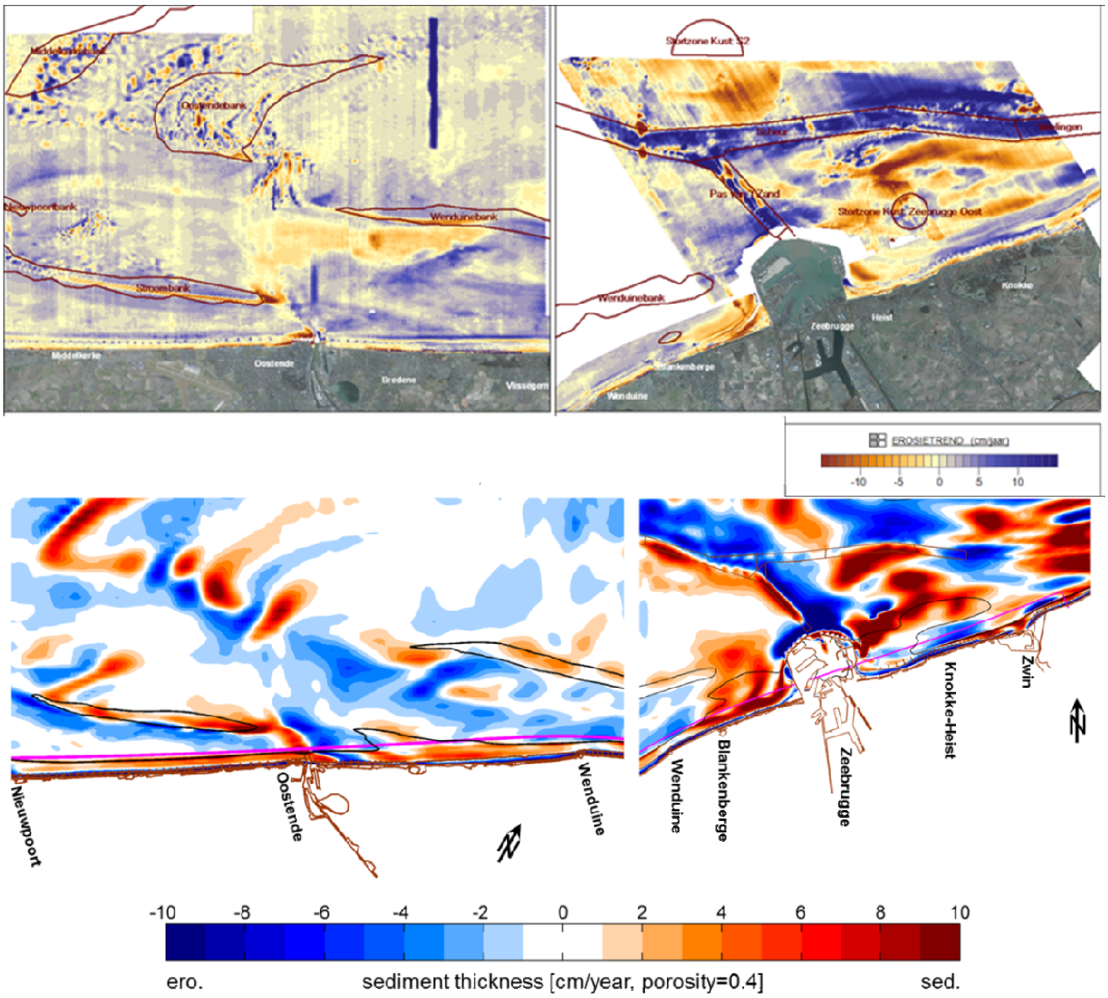

Figure 8. Observed (upper) and modelled (lower) sedimentation/erosion within the whole Belgian coast.

On the shelf, the agreement between the modelled and the observed erosion-sedimentation patterns is qualitative too poor (Figure 8). Initial dune fields flatten out during the computation because the local resolution is too coarse and because their growth would involve 3D effects which are not modelled. Near the coast, the target of the model, it could be found that most main patterns are well reproduced by the model: sedimentation at Oostende, erosion at Wenduine, sedimentation near the western dam of the Zeebrugge port and erosion at Knokke-Heist. However the sedimentation in the bay next to the eastern dam of the Zeebrugge port is not captured by the model. This is investigated in the subsequent quantitative comparison in the section **kp 39 ~ kp 43**.

Comparison to coastal profiles

The analysis of annual coastal profiles along the coast allows to measure changes in sand volumes on the dry beach, the wet beach and the sea floor, after correction for anthropogenic impacts such as nourishments to estimate the natural erosion-sedimentation trend of the last 25 years (Houthuys, 2012). The modelled erosion-sedimentation volumes along the coast are compared to this data.

To validate the morphology model in a quantitative way, a comparison between modelled results and measured data is made in section by section (Figure 9):

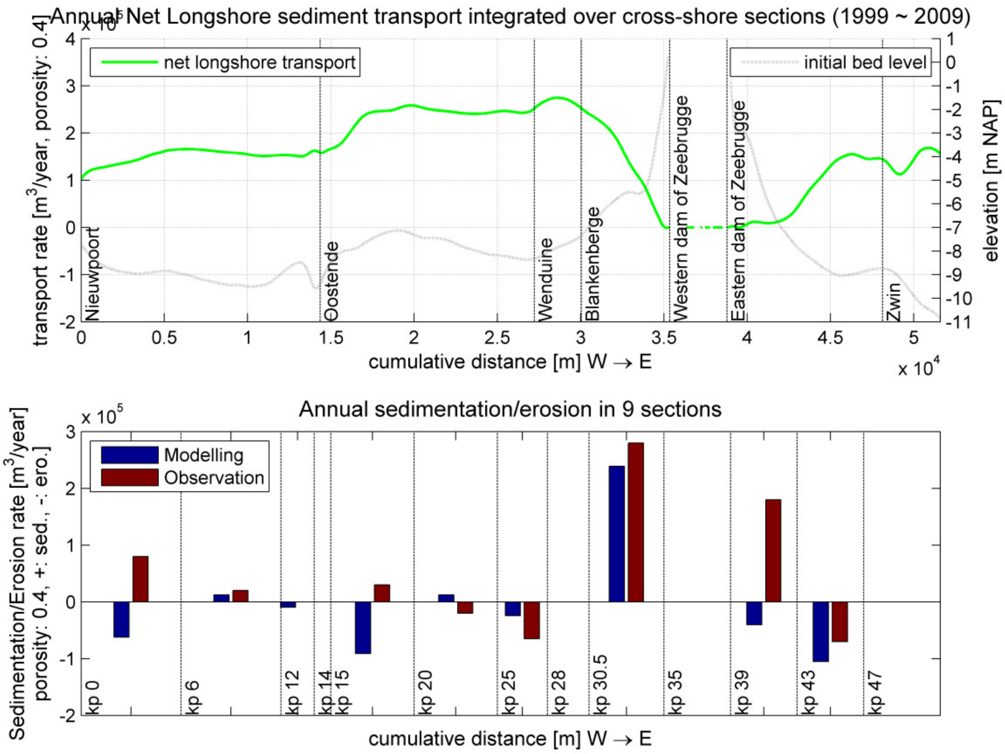

Figure 9. Modelled annual net longshore sediment transport integrated over cross-sections (in the magenta box of lower panel, Figure 8) during the period from 1999 to 2009 (top), and comparison of erosion-sedimentation volumes between modelling and observation along the coast (bottom).

- **kp 0 ~ kp 6**

The model shows an beach erosion of about 62,000m^3/year. The data show for this area an accretion of 80,000m^3/year. The difference is probably associated with boundary effects and poor bathymetry data of offshore sand banks.

- **kp 6 ~ kp 12**

A stable situation is given in the model (12,000m^3/year accretion). The data show an accretion of 20,000m^3/year, which is relatively small and can be also considered as stable.

- **kp 12 ~ kp 14**

The model gives a small erosion around 10,000m^3/year. The observed trends (data) are difficult to interpret due to the recent infrastructural works (extension harbour groynes, realignment navigation channel, large nourishments since 2004).

- **kp 15 ~ kp 20**

The modelled net longshore sediment transport increases by 90,000m^3/year, leading to a beach erosion of the same magnitude. The data indicate an erosion of 30,000m^3/year (after correction for 1 very suspicious measuring point in 2003). The difference is relatively large. A possible cause is the influence of recent infrastructural works in Ostend, which might result in somewhat more erosion (visible in the model) compared to the past 10 years (visible in the observed trends).

- **kp 20 ~ kp 25**

The net modelled longshore sediment transport is stable (accretion ca. 12,000m^3/year). The data show an erosion of 20,000m^3/year. The difference is relatively small.

- **kp 25 ~ kp 28**

The model gives an increase in net longshore sediment transport of 100,000m^3/year (or a beach erosion) in the zone starting 400m West up to 400m East of Wenduine. The data show over the same area an erosion of 50,000m^3/year. In the next 1200m the model predicts a sedimentation of 60,000m^3/year, while the data show an erosion of 15.000m^3/year. Integrated over the whole section, the model gives an erosion of 24,000m^3/year, while the data show an erosion of 65,000m^3. The large difference is related to the beach extent: in reality, nourishments keep the isobaths more offshore, causing more erosion, while in the model, the erosion results in a retreat of the coastline, decreasing the erosion rate. It can be concluded that the model represents the data well, but the distribution over the area is somewhat different.

- **kp 30.5 ~ kp 35**

The model gives 24,000m^3 erosion just East of the port of Blankenberge and 240,000m^3 accretion in the whole section, while the data show 110,000m^3 erosion just East of the port of Blankenberge, 280,000m^3 accretion in the whole section. In terms of the whole section, the modelled result is only around 14% lower than the data. Despite the fact that the port of Blankenberge is not incorporated in detail in the numerical model, the model reproduces the data quite satisfactorily.

- **kp 39 ~ kp 43**

The model gives an erosion of about 40,000m^3/year. The data show a net sedimentation of 180,000m^3/year. The reason for the difference is the input of sand coming around the port of Zeebrugge. This quantity is estimated at 200,000m^3/year and is eroded near the eastern dam of Zeebrugge. The eroded and transported sand is very fine (grain size around 100µm) and settles down at the bay next to the eastern dam. In the numerical model the sand is uniform (200µm). Also in the model, the erosion near the eastern dam is visible, but the sand settles down much more offshore due to the much higher settling velocity.

- **kp 43 ~ kp 47**

The model shows that a net longshore sediment transport increases with 110,000m^3/year (or a beach erosion). The data show an erosion of 70,000m^3/year. The difference can be probably attributed to the absence of the groynes in the numerical model.

CONCLUSION

With the MorMerge online-parallel approach and switch-on option for dry cell erosion, the further reduction of the wave climate, an increase of the MorFac of the update interval for wave computation together enable to successfully extend time horizon from 1 year to 10 years without impact on model accuracy. In particular, the MorMerge approach particularly avoids history effects produced by the representative time series of wave conditions in the previous work (Zimmermann et al., 2012) because it computes the mean effect of the full climate at each time step.

The comparison between the modelling results and measured data shows that the long-term morphology model is, aside from local deviations, sufficiently well calibrated to be used in practical applications. The model reproduces major longshore transport trends in the coastal zone, both qualitatively and quantitatively, with the exception of uncertainties at the western model boundary (Nieuwpoort and Oostende) and related to the sedimentation in the bay near to the eastern dam of Zeebrugge.

Further research will focus on how to model with multiple sediment fractions, in particular be able to reproduce the remarkable sedimentation observed in the bay next to the eastern dam of Zeebrugge. This calibrated morphology model can be potentially nested to provide boundary conditions for small-scale models in the detailed study of specific locations along the Belgian coast.

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