LONGSHORE TRANSPORT AND SEDIMENTATION IN A NAVIGATION CHANNEL AT BLANKENBERGE (BELGIUM)

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The harbour of Blankenberge in Belgium experiences strong sedimentation in its entrance channel requiring frequent dredging. In order to investigate under which conditions this sedimentation is the most pronounced, the instationary coastal model XBeach is used. This paper presents results of long-term morphology modelling of channel sedimentation after applying a specific methodology for input reduction. A reduced time series representative of the annual wind-wave climate is run in combination with a representative tide and a constant morphological acceleration factor (*morfac*) to cover one year of erosion-sedimentation. While this approach does come with side effects, it has the important advantage to be easy to implement and to preserve part of the climate history compared to other approaches such as MorMerge and a time-varying morfac approach (described in the paper). With this approach and default settings, XBeach is shown to reproduce both qualitatively and quantitatively well the measured sedimentation. Results show that tide, wind and waves all contribute significantly to the total sediment transport, and that both continuous transport and individual storm events cause strong sedimentation. Some aspects of morphological modelling methodologies are discussed, relative to the calibration, input reduction and long-term modelling methods.

Keywords: morphological modelling; XBeach; input reduction; channel sedimentation ; acceleration

PROBLEM DEFINITION

Blankenberge is located in Belgium in the Southern North Sea, 6 km West of the large port of Zeebrugge, on a stretch of sandy and gently sloping coast defended by groynes. Its small port basin is used as a marina and is connected to the sea by an entrance channel which is regularly dredged, and which is delimited on each side by a pier and a groyne close to each other. All groynes in the area are low sloping structures until the low water line, with a relative height above the bed varying between 0 and 1m depending on whether the beach is locally accreting or eroding.

Sediments are more muddy further to the East as we come closer to the Western Scheldt river delta. Many sand banks are present in front of the Belgian coast, one of which is connected to the shore near Blankenberge (Figure 3). The continental shelf has a depth between typically 5 and 30m in the first 15km offshore. 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 port of Blankenberge experiences strong sedimentation of its basin and in particular of its entrance channel (Figure 1), which in the absence of maintenance dredging becomes too shallow for navigation within approximately 6 months (Teurlincx et al., 2009).

Teurlincx et al. (2009) estimate the long-term sedimentation from difference maps of bathymetric surveys carried-out five times per year between 1997 and 2008. Figure 1 shows the estimated yearly sedimentation extrapolated from the observed sedimentation during periods without dredging. Based on the work of Konings (1989), Teurlincx et al. (2009) identify four different sedimentation areas in the access channel to the port of Blankenberge : seaward of the groynes (subsequently named zone A), between the two piers and groynes (zones B and D), and in the channel near the dune foot (zone C). The causes of sedimentation are presumed to be the longshore transport from the West in zones A (120 000m³/year) and B (35 000 m³/year), the longshore transport from the East in zone D (10 000 m³/year) and aeolian transport in zone C (2 500 m³/year). The resulting sedimentation estimated at 167 500 m³/year is in reasonably close agreement with the dredged volumes of 140 000 m³/year when averaged over the last 30 years (Figure 2). Although the data in Figure 2 may include a time lag between the occurrence of sedimentation and the period of dredging, an exercise based on model results has shown that the variability found in dredging also corresponds to the variability in yearly sedimentation. The sedimentation zones clearly correspond to the dredged deeper zones in the otherwise approximately straight and uniform bathymetry.

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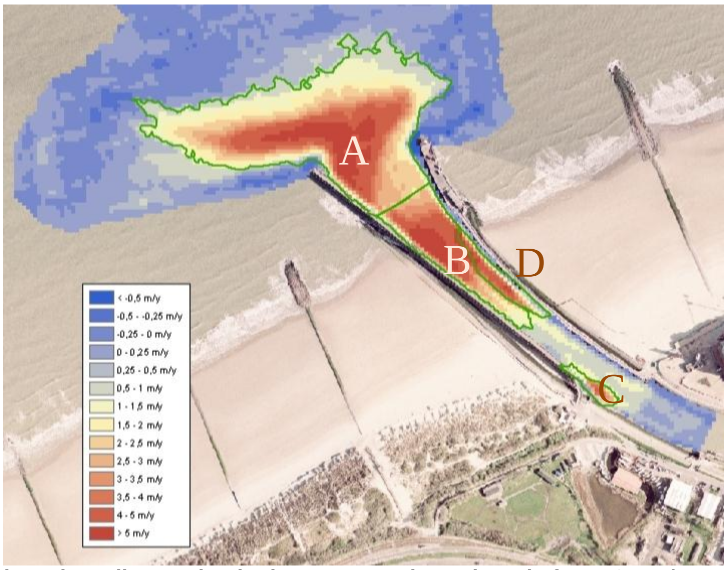

Figure 1: Estimated yearly sedimentation in the entrance channel, scale from -0.5 m/year (blue) to +5 m/year (red) (reproduced from Teurlincx et al., 2009).

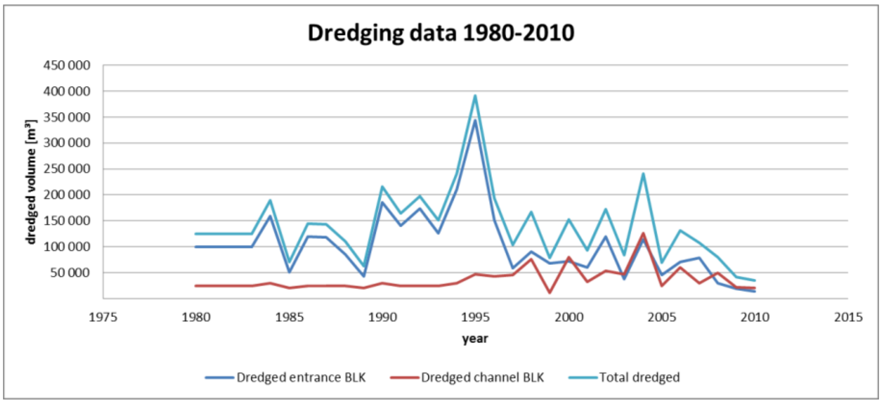

Figure 2 : Dredged volumes in the entrance channel of Blankenberge (Houthuys, 2012), seaward of the groynes (dark blue), between the groynes (red) and total dredged volumes (light blue).

The entrance channel has a width of around 80 m at the entrance, reducing to 45 m at the narrowest point. It is dredged in steps to a design depth ranging from -3.8 to -6.35 m NAP (Teurlincx et al., 2009). Estimated sedimentation rates therefore essentially mean that the channel fills up to a level about equal to the low water line in the six months separating two dredging campaigns. Bathymetric data also strongly suggests that individual storm events contribute significantly to total sedimentation : the channel has been shown to fill up in less than a month, while during other periods hardly any sedimentation is visible. When compared to the cross-shore profile, the locations of the sedimentation peaks grossly correspond to the breaker lines of average waves at low and high water.

Teurlincx et al. (2009) estimate a long-term sedimentation in front of the Western breakwater of Zeebrugge of 370 000 m^3/year, which is assumed to be an indicator of net longshore transport. The study further estimates the ratio of eastward to westward components of longshore transport at 3.5:1, based on wave energy considerations with the CERC formula and on results of the profile model Litdrift (DHI, 2009) with a yearly wave climate but without tidal velocities.

This study aims to reproduce the observed sedimentation with the morphological model XBeach. For this purpose, a 2D sediment transport model of the Northern half of the Belgian coast is developed in Delft3D, to provide boundary conditions, a reduced tide climate and a reduced correlated wind-wave climate to a detailed 2D morphological model of Blankenberge in XBeach. The reduced input is then used to simulate one year of erosion-sedimentation in the entrance channel of Blankenberge. Morphological modelling methodologies and results are discussed.

METHODOLOGY

Models

Delft3D is a model package which consists of several modules to compute amongst other the flow (FLOW), wave (WAVE) and morphology (MOR, included in FLOW) in coastal 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, generation by wind, non-linear wave-wave interaction and dissipation. The WAVE and FLOW 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).

XBeach is a 2D morphological model developed to assess the natural coastal response to time-varying storm and hurricane conditions, including dune erosion, overwash and breaching. It applies a non-stationary long wave flux at the boundary, which then serves to solve the propagation of the short wave envelope, the non-stationary shallow water equations, sediment transport and bed update. Avalanching is used to compute dune erosion and cross-shore transport relies on a special formulation to compute the balance between onshore sediment transport by wave skewness and asymmetry and offshore transport by the return flow. The wave solver used is based on the second generation HISWA model. More details about the XBeach model can be found in Roelvink et al. (2009).

The main differences between the two models concern the wave solver and the implementation of some nearshore processes. In Delft3D avalanching and long wave run-up are not present, and cross-shore transport can only be computed properly in a 3D model, because the return flow is not taken into account in the advection-diffusion equation for sediment transport. In practice cross-shore transport has to be turned off completely in a 2D Delft3D model. Waves and currents are further only coupled at a fixed time interval in Delft3D (20min by default) instead of at each time step in XBeach. On the other hand, wave processes in XBeach do not include wind-induced wave growth, white-capping and diffraction, triads are present but differ from SWAN and wave-current interaction is optional but is said to not work well yet (Roelvink et al., 2010). In SWAN, triads transfer energy from the peak frequency to higher frequencies (short waves, super-harmonics), whereas in the modified HISWA model they transfer energy from the peak frequency to lower frequencies (long waves, sub-harmonics). In XBeach the short waves period is also considered to be constant in space and time. Finally the transport formulation used is slightly different : Delft3D uses the formulation of Van Rijn (1993) and XBeach uses the parameterization of Soulsby-Van Rijn of the same formulation (Soulsby, 1997).

Delft3D is therefore used for the offshore zone and XBeach for the nearshore zone. The version 4.0 of Delft3D and the Easter 2012 release of XBeach are used. Both are open source.

Settings

The Delft3D model extends approximately from Oostende to the West to Knokke to the East (further referred to as the OKNO model). It has a global size of 30km alongshore by 15km cross-shore, with a resolution of around 100*220m offshore, with the surf zone being refined up to 70*15m nearshore (around 40 000 cells). The model is used to simulate wave, flow and sediment transport in 2D horizontal, but no salinity. 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. Figure 3 shows the bathymetry of the area.

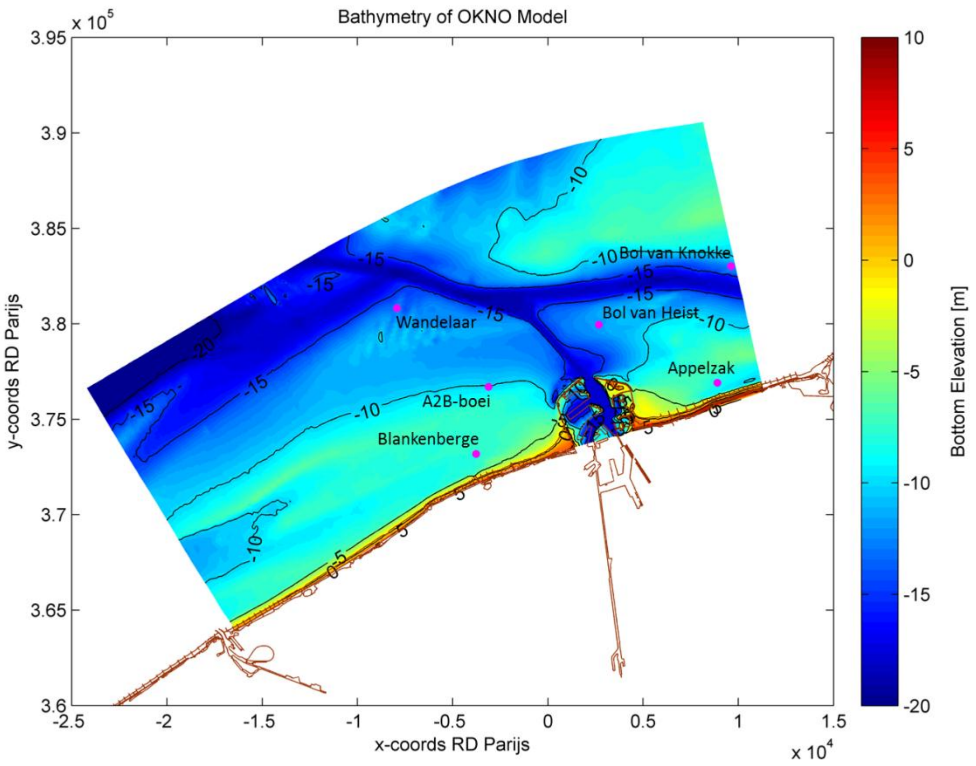

Figure 3 : Bathymetry of the Delft3D OKNO model, elevation in m NAP (equivalent to MSL).

Boundary conditions for the flow and the waves are provided by a set of calibrated larger models (Leyssen et al., 2012 ; Doorme et al., 2009). For sediment transport, equilibrium concentrations are applied since sand transport is expected to adapt quickly to changes in hydrodynamics. Time series of currents are applied on the lateral boundaries and a Riemann condition at the offshore boundary. A uniform Manning roughness of 0.022 s/m$^{0.33}$ is chosen (close to the default Chezy value of 60m$^{0.5}$/s for the local depth) and shown to be the best value for the little calibration data available in Blankenberge. Eddy viscosity and diffusivity are set at 1m^2/s. A time step of 20s is used for the flow computations and an update interval of 60min instead of 20min for online coupling with the waves to reduce computation time.

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, onshore wave transport factors have been set to zero due to the bad implementation of cross-shore transport in a 2D Delft3D model, and the depths have been specified at the cell centres to define correctly the depth near groynes.

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, and 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 (see input reduction).

The XBeach Blankenberge model has a global size of around 3.6km alongshore by 2.2km cross-shore, with a resolution between 70*45m offshore and 6*6m in the entrance channel (around 20 000 active cells). The cross-shore cell size in the surf zone is mostly lower than 10m to resolve the longshore transport under small waves. The same processes as in the OKNO model are simulated except the wind, and morphology is added. Wind-driven currents of the OKNO model can however propagate through the lateral boundaries. Groynes are modelled as hard layers in the bathymetry, and piers have not been modelled. For the channel depth, a survey has been chosen which corresponds to measurements shortly after dredging to design depth. Figure 4 shows the bathymetry of the area.

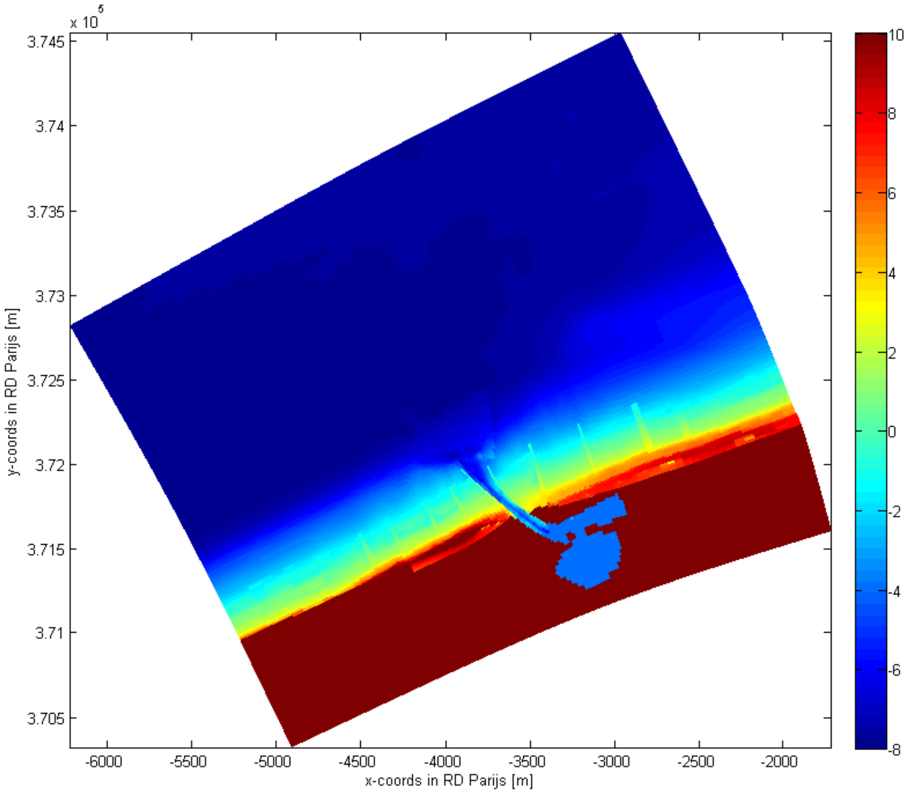

Figure 4 : Bathymetry of the Blankenberge model, in RD Parijs coordinates and relative to NAP level (equivalent to MSL).

Best results with XBeach are given when using the release of Easter 2012 with its default settings. The effect of wind on the flow is not modelled. The flow is driven on the lateral boundaries by time series of water level and the waves are applied at the offshore boundary as spectrum files, all generated in the Delft3D OKNO model. A resolution of 10˚ is used for the wave discretisation. The time step is computed internally.

Calibration

The water levels and velocities of the OKNO model have been calibrated against a limited set of available data at Blankenberge. Modelled water levels agree reasonably well with measurements in the entire model domain, with an accuracy of ±25cm equivalent to that of the forcing model. Velocities can only be verified at one measurement point at Blankenberge. Agreement at that point is also reasonably good, with an error of 0-7 cm/s depending on the tidal component, and a deviation of the main current axis of 10°. Accuracies are comparable to those of the hydrodynamic models used in the same area in other projects (Dujardin et al., 2010), deviations cannot be investigated without more data.

Sediment transport is not calibrated because one of the purposes of the model is to provide alternative (uncalibrated) transport estimates to understand sediment budgets better. An exercise has been done to estimate residual sediment transport with a variation on the method proposed by Van de Kreeke and Robaczewska (1993) and Hoitink et al. (2003). Results show that these methods are very case-specific and that residual transport contributions which are not mentioned in the studies can be important as well.

Some general remarks can be made regarding the calibration of a morphological model. Concerning the flow, the roughness is often used as the main calibration parameter. With morphology two points require extra attention. Firstly a change in roughness can impact currents and sediment transport in the surf zone much more than in deeper waters, so a small improvement in flow velocities offshore can actually seriously degrade the quality of the sediment transport model. Secondly space-varying (roughness) fields should not contain any discontinuity, because they will translate into transport discontinuities and will result in strong local erosion or deposition. Sediment transport calibration should be relatively easy for mud in unidirectional current (river) when the velocity and the concentration can be measured easily, but it is much more difficult for sand in a tidal environment with waves, because transport is mainly near-bed and net transport is a small difference of two large quantities.

Input reduction

Ideally time series of all input parameters are needed to obtain the most realistic results (wind, wave, tide, discharge, low-frequency fluctuations, source-sinks), but this generally results in unrealistically large computation time for long-term morphology simulations. Lesser (2009) identifies four ways of reducing the computation time : model reduction, computer power, input reduction and morphological acceleration. Since the two former are often limited, the two latter need to be used. Parallel computing is possible in XBeach but not in Delft3D v4.0 with morphology.

For a thorough discussion on input reduction the reader is referred to Lesser (2009) and Walstra (2011). Lesser (2009) shows that input can be reduced with very little loss of accuracy, but that the quality of the input reduction depends on a good understanding of the system, or the choice of the reduction target.

Morphological acceleration is done here by multiplying bed changes by a factor at each time step (*morfac*). The *morfac* is not well understood yet but it has been shown to work well in several studies (Roelvink, 2006 ; Van der Wegen and Roelvink, 2008). Ranasinghe et al. (in prep.; cited by Walstra, 2011a ; see also Liang, 2010 ; Ranasinghe et al., 2011) show that the *morfac* induces a phase and an amplitude error on bed form propagation under steady current, but that these errors are an order of magnitude lower than errors due to the numerical implementation. The accuracy of the *morfac* in more complex cases with oscillating tide and waves has not been investigated yet. Roelvink (2006) discusses other coastal morphodynamic evolution techniques in more detail.

For the tide reduction, a representative tide is chosen over two consecutive tides for daily inequality according to the method of Latteux (1995). The objective is to reproduce closely the gross and net sediment transport over a full neap-spring tidal cycle. The tide which reproduces the best the transport pattern (correlation) is not the one with the best transport values (slope). There are several ways to correct this :

- Transport can be scaled directly via a transport coefficient in the model. However once adding the waves it will scale the full transport due to the current and waves instead of only scaling the tidal contribution. This option can hence only be used if the current contribution is dominant, or if the waves have been added beforehand in the tidal reduction.
- Transport can be scaled via the morphological factor. Transport values are then left wrong but bed updates are corrected. Like the transport coefficient however the contribution from waves will be scaled.
- Transport can be scaled via the boundary conditions. Sediment transport is assumed to be a power of the velocity (equal to that used in the model), and the velocity is scaled to yield the correct transport values. Water levels are scaled equally assuming a linear relation between water level and velocity. This method yields correct transport values, but currents and water levels are impacted. Waves can be superimposed to the current with this method.

Scaling has been done here with the third method. Figure 5 shows that the selected representative tide reproduces very well the net sediment transport in most of the model domain, and in particular in the area of interest (accuracy ±10%). Locally large deviations as a percentage correspond to very low transport rates. To make the tide cyclic, the representative tide is repeated, provided there is no strong discontinuity in velocity between consecutive cycles.

A detailed wind reduction has been done which takes into account the important wind-wave correlation (Lesser, 2009). The wind direction has been chosen equal to the wave direction and the wind speed has been derived by linear regression for each wave direction class. This was necessary to account for the effect of wind coming from land with limited fetch. Each wind-wave condition is run for one representative tide, and the yearly wave climate is recomputed from model results and the probabilities of occurrence of each wave condition. The wind reduction is globally good at an offshore test point (RMSE on wave height of 3% for directions from sea, 93% of occurrence), with a local deviation of the modelled wave height (-11% average) and of the modelled wave direction (RMSE of 10°) only for small waves coming from land (7% of occurrence). Deviations are much larger if wind and wave are not correlated.

The wave reduction has been performed with the OPTI procedure (Mol, 2007). The 160 wave classes of the full climate have first been reduced to 91 wave classes by removing the conditions occurring less than one hour per year. They have then been further reduced to 11 wave classes to reproduce closely the gross and net transport obtained with the full wave climate, the representative tide and the wind reduction. The selected reduced set comprises low and high waves covering all important directions. Figure 6 shows that the reduced wave climate reproduces very well the net sediment transport of the full wave climate in most of the model domain and in particular in the area of interest (accuracy ±10%). Locally large deviations as a percentage correspond to very low transport rates.

Overall the input reduction is not expected to be the limiting factor for further use of the model.

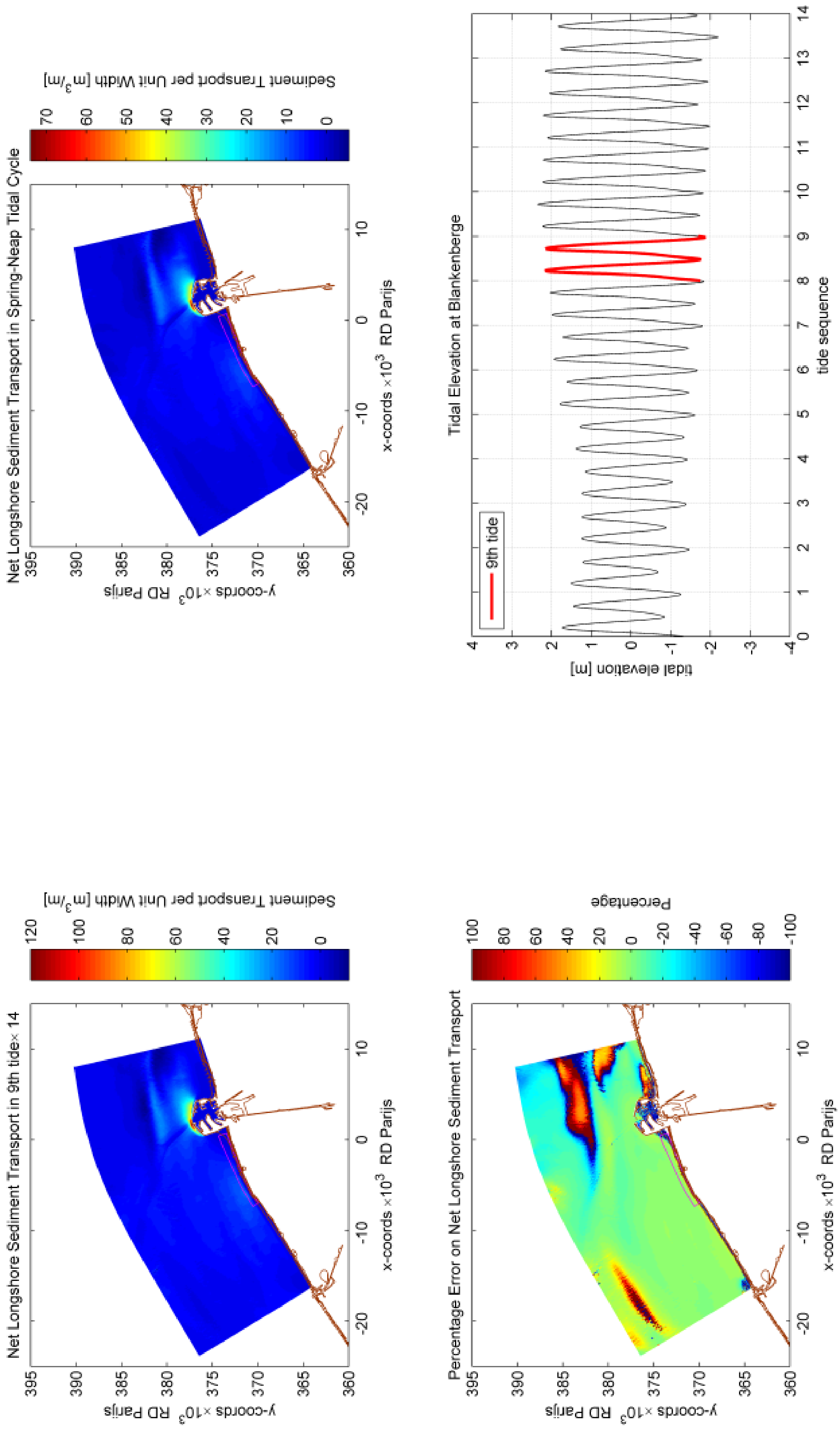

Figure 5 : Net alongshore sediment transport in 14 representative tides (upper left), in the full neap-spring cycle (upper right), reduction error once scaled for the average transport ratio between the two (lower left) and tidal cycle (lower right).

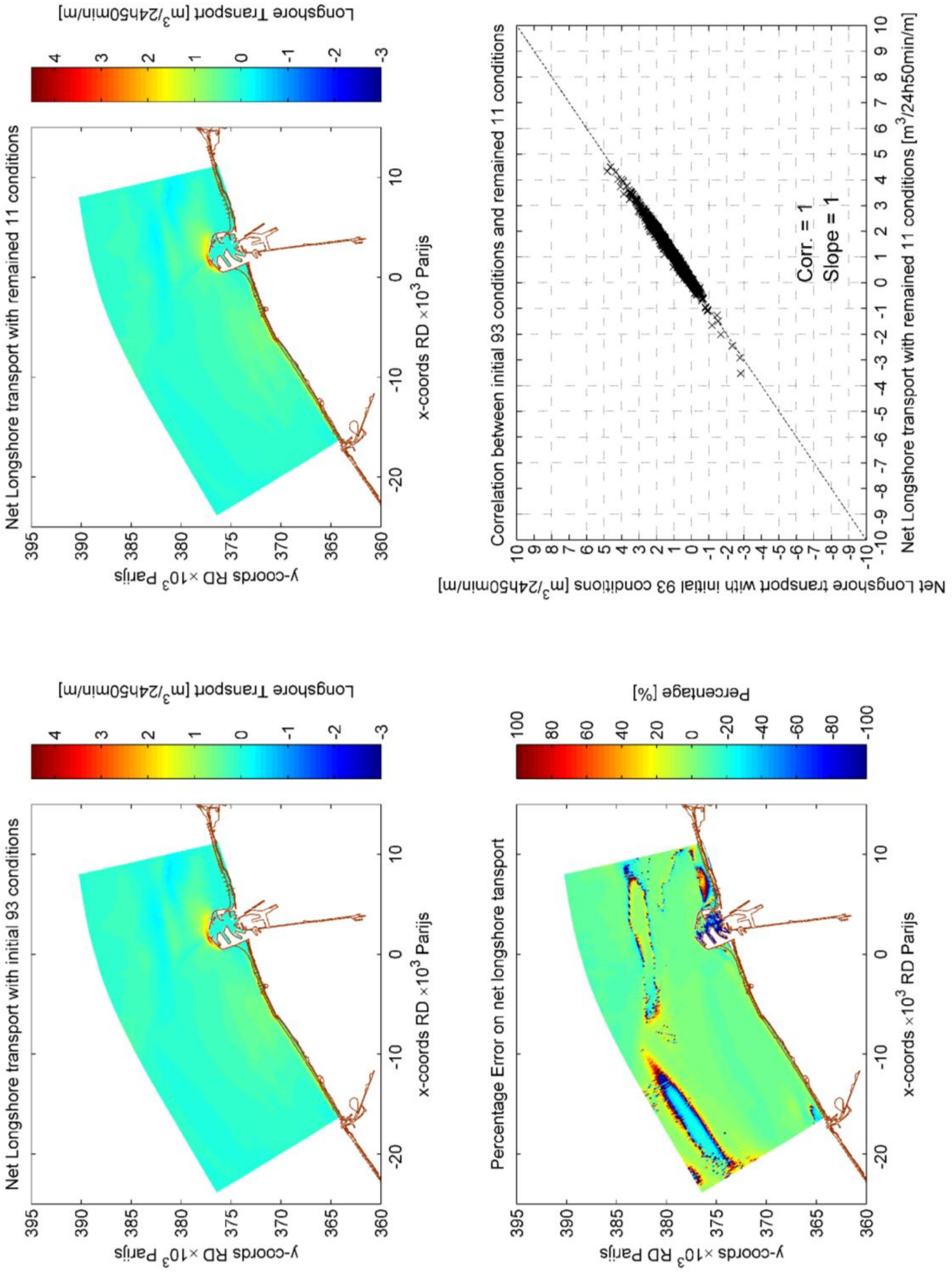

Figure 6 : Net alongshore sediment transport integrated over the representative tide with the full yearly wave climate (upper left), the reduced wave climate (upper right), reduction error as a percentage (lower left) and correlation graph (lower right). Solid discharges (no porosity).

Long-term morphology

The model is used to investigate the issues presented in introduction. Transport rates presented in this chapter have all been corrected for a porosity of 0.4 to be comparable to sedimentation values. They are hence not solid discharges.

Once the wind, the wave climate and the tide have been reduced, the simplified conditions with their weights have to be recombined to model their long-term effect on the morphology with a morphological acceleration factor (morfac). Several methods exist in Delft3D :

- MorMerge : In the MorMerge system, the effect on morphology of each wave condition of the reduced climate is computed at each time step and merged according to weights specified at the beginning (Figure 7). This method avoids history effects because it is like computing the mean effect of the full climate at each time step. It can also be used with a higher morfac than other methods.
- Time-varying morfac : The different weights of each wave condition can be taken into account with a time-varying morphological acceleration factor (morfac) and a constant duration of each condition. Mild conditions which occur often can be accelerated more than storm conditions which occur rarely. Such a method requires special care during the setup of the time series of waves. A transition tide with morfac zero is needed between two successive conditions, and the morfac change should better happen at the turn of the tide, when the suspended sediment concentration is low, to avoid mass balance effects (Lesser, 2009). History effects may be present.
- Constant morfac : The different weights of each wave condition can be taken into account with a constant morfac and a different duration for each condition. In this method the morfac is however limited by the duration of the shortest condition, reduction of computation time may not always be sufficient. History effects may be present.

An exercise by Ali Dastgheib (Unesco-IHE, personal communication) shows that the MorMerge and time-varying morfac methods yield very comparable results. In XBeach only the third method is available, it is the one presented here.

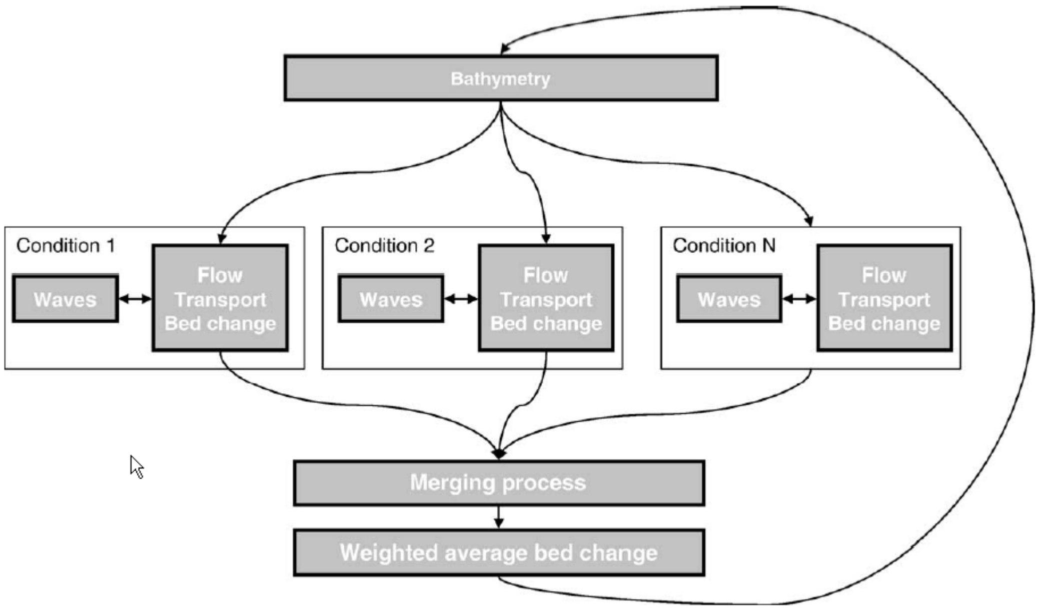

Figure 7 : Schematisation of the MorMerge process for morphological modelling with a reduced wave climate. Figure from Lesser (2009).

An XBeach simulation has been set up to simulate a full year of morphological changes in the Blankenberge model. A random time series of wave conditions has been set up with the same properties as the reduced annual wave climate, a total duration of 8 representative tides of 24h 50min, and used with a morfac of 44.1 to cover an entire morphological year (Figure 8). As an indication the simulation ran in about a week on 16 processors.

From the weight associated to a given condition, its total duration in the time series can be calculated. Each hour a new wave condition is randomly selected among the remaining wave conditions until none remain. Each condition has a minimum duration of 30min and a maximum duration of 90min. This means that if the total duration of that condition is, say, 152min, it will first appear as twice a period of 60min and a last period of 32min. A minimum duration is needed to average out the instationarity in the model results. A duration of 60 hydrodynamic minutes corresponds to slightly less than 2 morphodynamic days.

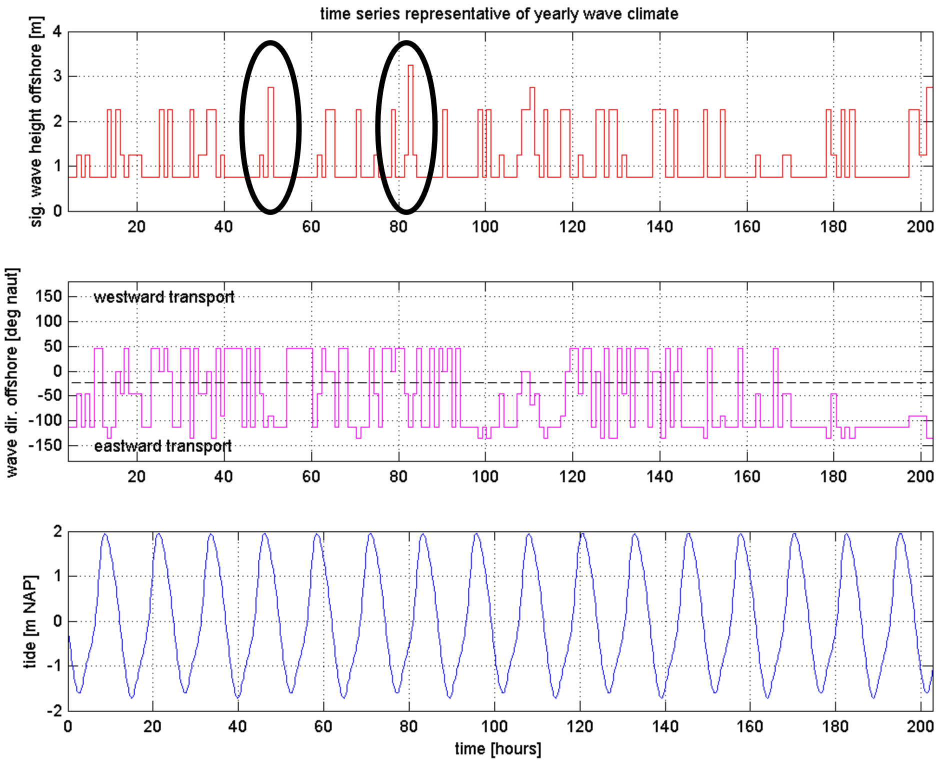

Figure 8 : Time series of wave conditions used at the offshore boundary of the Delft3D model in the constant morfac approach, with significant wave height (red), wave direction (magenta) and water level (blue). Storm events mentioned in Figure 12 are circled in black.

RESULTS DISCUSSION

Figure 9 to Figure 11 show the evolution of the modelled sedimentation in the entrance channel over time. After three months the sedimentation in zones A and B is already clearly visible, sedimentation in zone D is also present but somewhat hidden by the reworking of a steep slope present in the initial bathymetry, and sedimentation in zone C is due to aeolian transport and cannot be modelled in XBeach. After six months the sedimentation covers the entire channel width, and after one year the entire channel is covered with around 3m of sediment. Overall results display a very good qualitative and even quantitative agreement with measurements, which is particularly surprising given that close to no calibration has been done.

The shape of the sedimentation zone is however not exactly equal to measurements (Figure 1). Several effects can explain this. Firstly the sedimentation estimated from bathymetric campaigns has been averaged over many datasets and extrapolated to cover a full year. As such it is not really representative of a realistic time series, nor are the volumes fully comparable with model results which do not account for dredging activities every six months. In practice the importance of dredging in each zone depends on the occurrence of storms during the season. Secondly model results still contain an important artefact : due to the morphological acceleration, a storm of one hydrological hour corresponds to almost two morphological days. The duration is acceptable, however the water level during these two days remains almost constant (medium to high water during storms circled in black in Figure 8). As a consequence the strong sedimentation during storms is not modulated sufficiently by the tide. This also explains why the relative importance of sedimentation offshore (A) and in the channel (B and D) varies during the simulation, and why the annual sedimentation does not extend as far offshore as in the measurements. Sedimentation will be the most offshore during a combination of low water level and high waves, when waves break the earliest. The representative tide also limits the lowest water level applied.

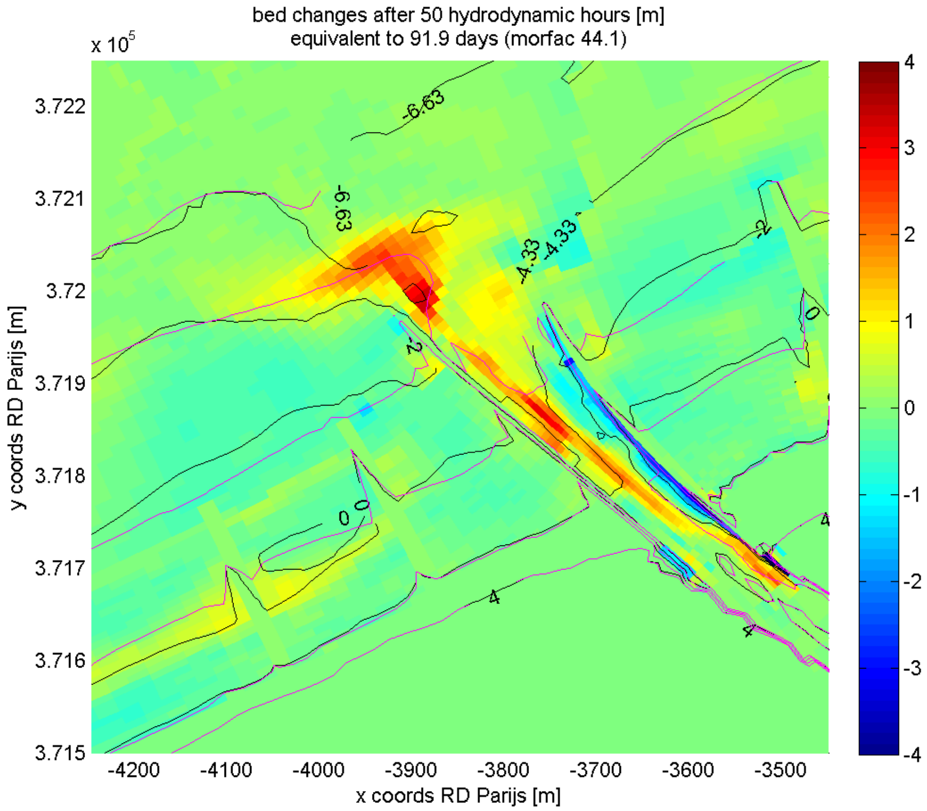

Figure 9 : Modelled erosion-sedimentation pattern after three months.

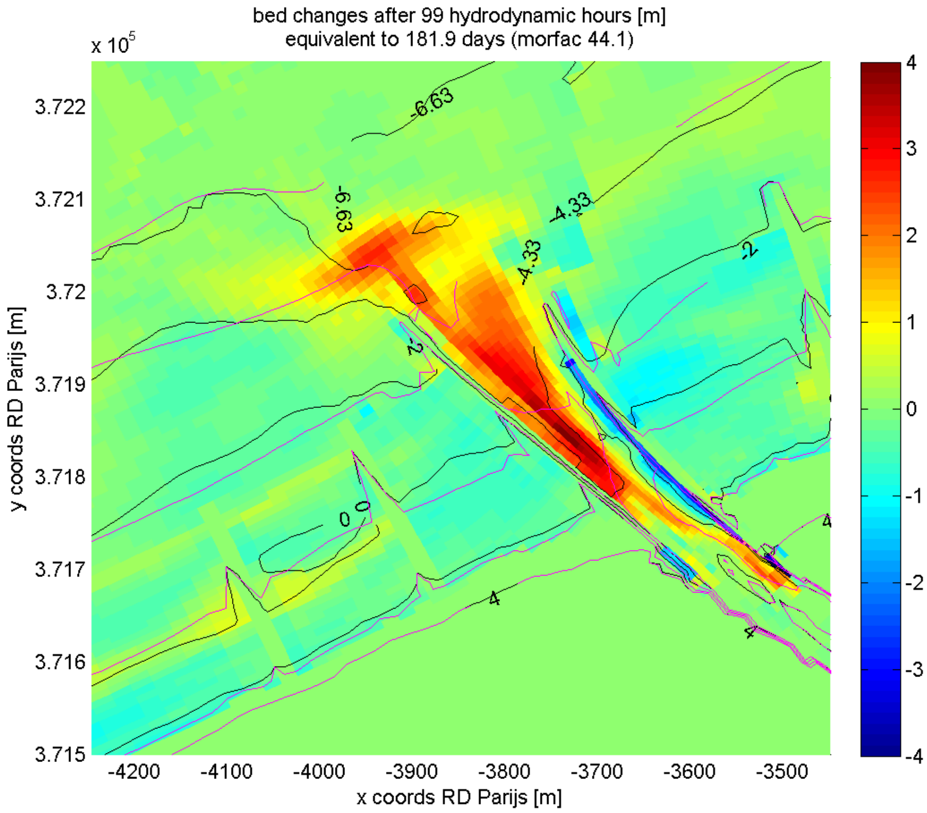

Figure 10 : Modelled erosion-sedimentation pattern after six months.

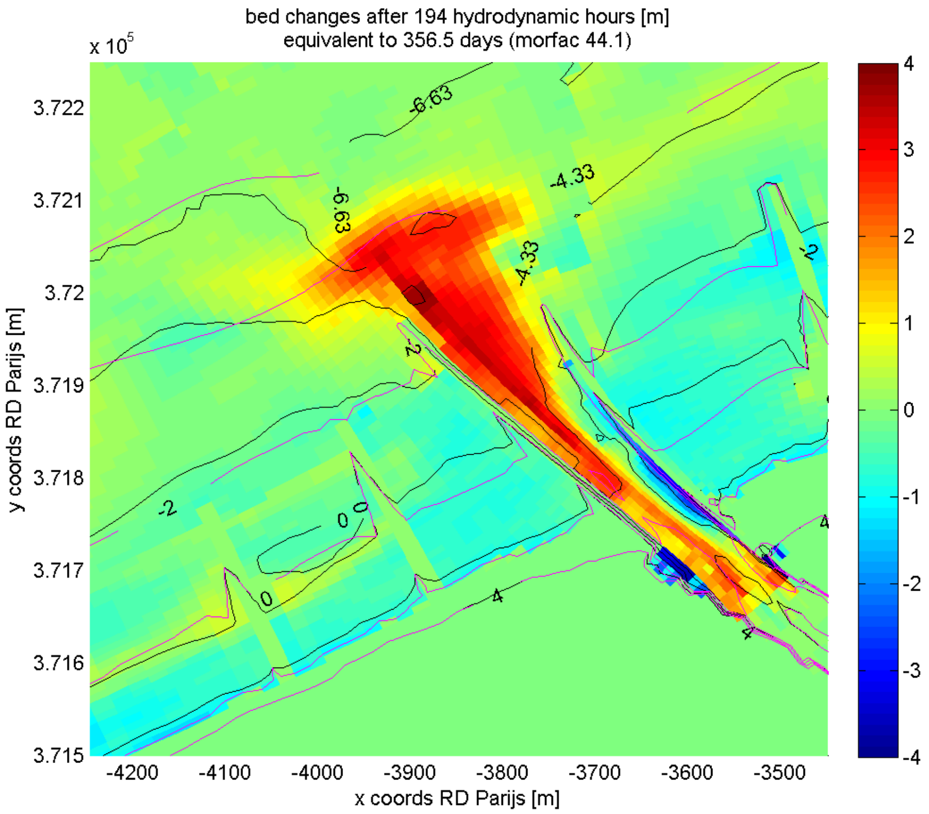

Figure 11 : Modelled erosion-sedimentation pattern after around one year.

Cumulative erosion-sedimentation volumes have also been computed in the entrance channel and between each two successive groynes. The channel location is defined according to the measured erosion-sedimentation pattern.

The sedimentation in the channel is continuous with strong contribution of individual storm events. Two storms around days 90 (waves 2.75m from West) and 150 (waves 3.25m from West-South-West) contribute to more than 20 000 m³ sedimentation each, or around 15% of the yearly sedimentation each (Figure 12). Other groyne sections follow an initial adjustment of the order of six months before stabilizing. Groyne sections at the West then remain stable while groyne sections at the East erode, in accordance with observations and with transport mainly coming from the West being interrupted by the entrance channel. Overall sedimentation seems to slightly slow down over time, although it might be due to the absence of storm in the second half-year. Further tests are needed to investigate this.

The total sedimentation volume in the entrance channel is in the order of 120 000 m³. This is close to the long-term average dredging volumes of 140 000m³/year but some 45 000 m³/year (18%) smaller than the annual sedimentation estimated from measurements. The lower volumes could partly be due to the absence of dredging after six months in the model. Overall, volumes are currently very realistic. Adding wind-driven currents would probably increase these numbers.

Cross-shore profiles also remain very stable in model results throughout the year, confirming the very good default settings of XBeach.

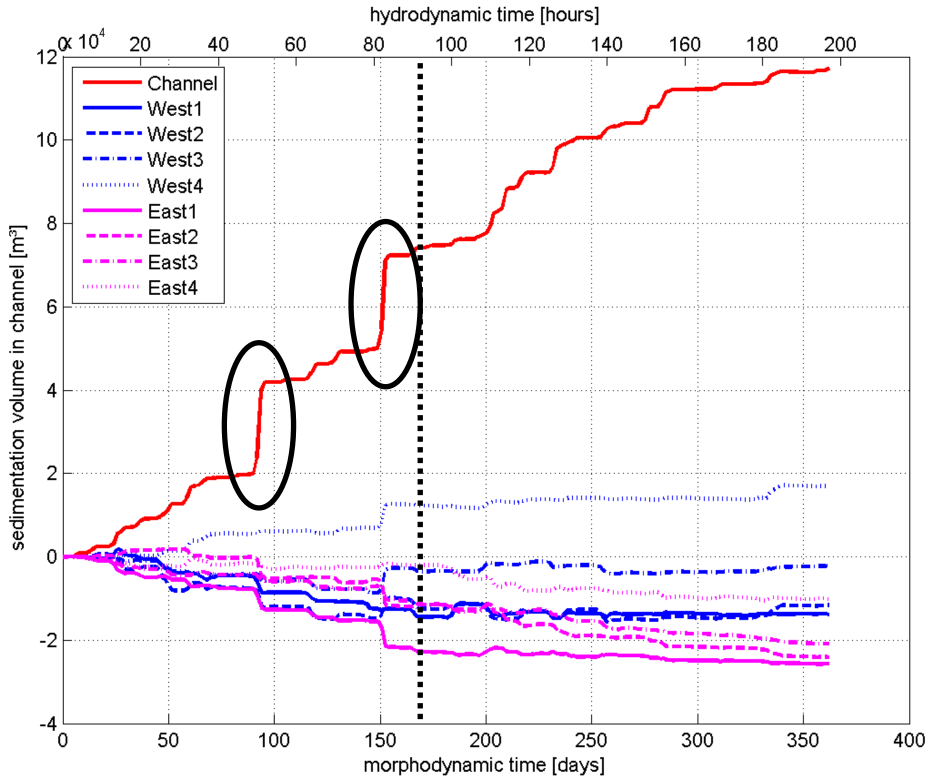

Figure 12 : Cumulative erosion-sedimentation in the entrance channel of Blankenberge and in each groyne section on both sides of the channel (numbered from 1 to 4: closest to furthest from the channel). Black circles correspond to storm events leading to strong sedimentation in the channel.

In the model a large asymmetry is visible between transport and sedimentation due to longshore transport from the West and from the East (visible on Figure 1). The ratio of longshore transport from the West to longshore transport from the East has been estimated with the CERC formula at 3.5:1 for waves only, with Delft3D model results at 6:1for waves and tide, and at 10:1 with wind, waves and tide. This large asymmetry is due to the combination of tidal asymmetry and a threshold velocity for sediment transport of around 0.4m/s around Blankenberge (200µm sand, 8m depth), which is only exceeded during a couple hours at maximum flood and ebb. Including wind also enhances the asymmetry. Tide, wind and waves all contribute for a large fraction of the total transport rates.

Model results show little bypass of sediment past the entrance channel. Since the sedimentation volumes are realistic, it implies that the long-term sedimentation of 370 000 m³/year in front of the Western breakwater of Zeebrugge is not an indicator of total longshore transport. Delft3D model results strongly suggest that the tidal contribution to net alongshore transport outside of the annual surf zone plays an important role.

CONCLUSION

The harbour of Blankenberge in Belgium experiences strong sedimentation in its entrance channel requiring frequent dredging. In order to investigate under which conditions this sedimentation is the most pronounced, the instationary coastal model XBeach has been used. A reduced time series representative of the annual wind-wave climate has been run in combination with a representative tide and a constant morphological acceleration factor (morfac) to cover one year of erosion-sedimentation.

Because tide, wind and waves all contribute significantly to the total longshore transport, more simple models could previously not fully explain the system behaviour. Longshore transport from both directions is trapped in the entrance channel, both during continuous transport under normal conditions and suddenly during individual storm events. Such events are shown to contribute to a large fraction of the annual sedimentation. The model also confirms that the groynes West of the entrance channel are not effective any more in stopping sediment transport due to the beach sedimentation. The two sedimentation peaks visible in measurements inside the channel are shown to result from the combination of tidal modulation and flow constriction in front of the entrance groynes. In order to reduce the dredging frequency, the buffer volume for sand storage has to be increased, for instance by heightening the entrance groynes and extending them until the end of the surf zone. Model results are also in agreement with previous studies.

XBeach is found to adequately model both qualitatively and quantitatively the annual channel sedimentation at Blankenberge with default settings. The cross-shore profile also remains very stable throughout the simulation. The quality of the results directly depends on the quality of the input reduction and on special attention about sediment transport during the hydrodynamic calibration: Conclusions from this work are consistent with those obtained in studies such as from Latteux (1995) and Lesser (2009). The roughness should be used with caution to calibrate the hydrodynamics, because it has a very strong impact on transport rates in shallow waters such as in the surf zone. A good input reduction requires to choose carefully the reduction target and to keep existing correlation as between the wind and wave climates. A single representative tide works well here to reduce the tide climate, however it is better to select a tide which reproduces well the transport pattern rather than its value. To get the good values, the choice of the scaling method is important because different methods have different side effects. With waves it is suggested to scale the boundary conditions to avoid errors on the relative contribution of tide and waves in the total transport. Finally, while in a constant *morfac* approach the maximum morphological acceleration is limited by the duration of the shortest wave condition applied, it allows to set up a random time series, to visualize history effects and the impact of storm events. Although it requires special attention to avoid side effects, it is still an easy modelling method compared to alternative methods such as MorMerge and a time-varying morfac. The latter methods are more difficult to implement and have their own side effects.

Further research will focus on decreasing undesired effects such as the lack of variation in water level during a storm, and on increasing the time scale of morphological modelling with XBeach to up to 10 years. Both may be partly achieved by decreasing the duration of an individual wave condition in the time series applied and by increasing the morfac. The method used to generate the random time series can also be improved.

REFERENCES

Booij, N., Ris, R. and Holthuijsen, L. (1999). A third-generation wave model for coastal regions, Part I, Model description and validation. *Journal of Geophysical Research*, vol. 104 (C4), pp. 7649-7666.

DHI (2001). *LITPACK 2001, Longshore current and littoral drift, Litdrift User Guide.* Danish Hydraulic Institute, Denmark.

Doorme, S.; Verwaest, T.; Trouw, K.; Verelst, K. (2009). Determination of the wave climate for the Belgian coastal waters. In*: 1st international SWAN workshop*, TUD, Delft (NL), 8-10 June 2009.

Dujardin, A.; Van den Eynde, D.; Vanlede, J.; Ozer, J.; Delgado, R.; Mostaert, F. (2010a). *BOREAS - Belgian Ocean Energy Assessment: A comparison of numerical tidal models of the Belgian part of the North Sea. Version 2_0.* WL Rapporten, 814_03. Flanders Hydraulics Research, Soresma & MUMM: Antwerp, Belgium. BELSPO contract SD/NS/13A

Hoitink, A.J.F., Hoekstra, P., and Van Maren, D.S. (2003). Flow asymmetry associated with astronomical tides: Implications for the residual transport of sediment. *Journal of Geophysical Research*, vol. 108 (C10), p. 3315.

Holthuijsen, L., Van Vledder, G., Zijlema, M., Salmon, J. (2012). SWAN variations of waves in a North Sea super storm. *Proceedings of the International Conference on Coastal Engineering 2012*, Santander, Spain.

Houthuys, R. (2012). *Update of the sediment budget for the nearshore of Blankenberge Zeebrugge. Version 1.0.* WL Rapporten, 744_30. Flanders Hydraulics Research & IMDC: Antwerp, Belgium.

Konings, P. (1989). Shallowing of the Blankenberge harbour entrance: morphodynamical evolution and sediment transport processes. *Natuurwetenschappelijke tijdschrift* (Gent, Belgium), 71, pp. 121-143.

Latteux, B. (1995). Techniques for long-term morphological simulation under tidal action. *Marine Geology*, vol. 126, pp. 129-141.

Lesser, G. R., Roelvink, J. A., van Kester, J. A. T. M. and Stelling, G. S. (2004). Development and validation of a three-dimensional morphological model. Coastal Engineering, vol. 51, pp. 883-915.

Lesser, G.R. (2009). *An approach to medium-term coastal morphological modelling.* PhD dissertation, Unesco-IHE Institute for Water Education and Delft University of Technology, The Netherlands.

Leyssen,G.; Vanlede, J.; Decrop, B; Van Holland, G; Mostaert, F. (2012). *Modellentrein CSM-ZUNO. Deelrapport 2: Validatie* (in Dutch). WL Rapporten, 753_12. Waterbouwkundig Laboratorium & IMDC: Antwerpen, Belgium.

Liang, L. (2010). *A fundamental study of the morphological acceleration factor.* MSc thesis, Delft University of Technology, The Netherlands.

Mol, A.C.S. (2007). *R&D Kustwaterbouw Reductie Golfrandvoorwaarden. OPTI Manual.* Rapport H4959.10, WL|Delft Hydraulics, Nederland.

Ranasinghe, R., Swinkels C., Luijendijk A., Roelvink J.A., Bosboom J., Stive M.J.F. and Walstra D.J.R (2011). Morphodynamic upscaling with the morfac approach: dependencies and sensitivities. *Coastal Engineering*, 58 (8), pp. 806-811.

Ris, R., Booij, N. and Holthuijsen, L. (1999). A third-generation wave model for coastal regions, Part II: Verification. *Journal of Geophysical Research*, vol. 104 (C4), pp. 7649-7666.

Roelvink J.A. (2006). Coastal morphodynamic evolution techniques. *Coastal Engineering*, vol. 53, pp 277-287.

Roelvink, D., Reniers, A., van Dongeren, A., van Thiel de Vries, J., Lescinsky, J. and McCall, R. (2009). Modelling storm impacts on beaches, dunes and barrier islands. *Coastal Engineering*, vol. 56, pp. 1133-1152.

Roelvink, D., Reniers, A., van Dongeren, A., van Thiel de Vries, J., Lescinski, J., and McCall, R. (2010). *XBeach model description and manual.* Unesco-IHE Institute for Water Education, Deltares and Delft University of Technology, Report 1002266, version 6.

Soulsby, R. (1997). *Dynamics of marine sands.* Thomas Telford Publications, London, UK.

Teurlincx, R.; Van der Biest, K.; Reyns, J.; Verwaest, T.; Mostaert, F. (2009). *Haven Van Blankenberge - Verminderen van de aanzanding van de havengeul en het voorplein: Eindrapport* (Dutch). Versie 1_1. WL Rapporten, 643_12. Waterbouwkundig Laboratorium: Antwerpen, België.

Van de Kreeke, J., and Robaczewska, K. (1993). Tide-induced transport of coarse sediment : Application to the Ems estuary. *Netherlands Journal of Sea Research*, vol. 31 (3), pp. 209-220.

Van der Wegen, M., and Roelvink, J.A. (2008). Long-term morphodynamic evolution of a tidal embayment using a two-dimensional, process-based model. *J. Geophysical Research*, 113, C03016.

Van der Westhuysen, A., Zijlema, M. and Battjes, J. (2007). Nonlinear saturation-based whitecapping dissipation in SWAN for deep and shallow water. *Coastal Engineering*, vol. 54, pp. 151–170.

Van Rijn, L.C. (1993). *Principles of Sediment Transport in Rivers, Estuaries and Coastal Seas*. Aqua Publications, The Netherlands.

Walstra, D.J. (2011a). Process-based Long Term Morphological Modelling: the present state-of-the-art and the way ahead. Deltares webinar, November 10th 2011. Avail. at http://oss.deltares.nl/web/morphology/long-term-modelling

Walstra, D.J. (2011b). How to perform realistic morphodynamic simulations with acceptable run-times. Deltares webinar, December 14th 2011. Avail. at http://oss.deltares.nl/web/morphology/inputreduction