

## **Impact of harbour basins on mud dynamics Scheldt estuary**

In the framework of LTV

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**Summary**

This report discusses the 2009 activities and results in the framework of LTV-mud. Firstly, developments of the hydrodynamic model are discussed. Secondly, developments of the mud transport model are discussed. Subsequently, the model is applied to two management issues, i.e. the impact of harbour basins at Terneuzen and Antwerp on the mud dynamics of the Scheldt estuary.




The model improvements have resulted in a better reproduction of the turbidity maximum at Antwerp and the overall mud balance of the system. The model now meets the demands defined at the start of the project in 2006.

The impact of the harbours at Terneuzen on turbidity levels is small. This is caused by the relative small dumping flux ( $< 1$  MT/yr) compared to the gross sediment flux passing through the estuary (computed at about 40 MT/yr at Vlissingen). A 3 km shift of dumping locations turns out to be favourable for siltation reduction, although the reduction remains small (1–2%). Temporarily and locally, harbour maintenance does result in a significant increase in suspended sediment concentration at Terneuzen ( $> 20\%$ ), but averaged over a longer time and larger area, overall turbidity levels are hardly affected. This can be explained as sediment dumping (+ term) is balanced by harbour siltation (– term).

As the size of the harbour basins at Antwerp are larger than at Terneuzen, notably relative to the tidal fluxes of water and sediment, the impact of these basins on turbidity levels of the Scheldt is more pronounced. For example, a down-estuary shift of the dumping location of sediments from Deurganckdok results in a 40 mg/l reduction of the near-surface concentration in the estuarine turbidity maximum (ETM) near Antwerp. Optimisation of dredging and dumping strategies has therefore substantial potential benefits at Antwerp.

**References**

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# 1 Introduction

In 2006, a work plan was conceived for the development of a mud transport model for the Scheldt estuary in the framework of LTV (Long Term Vision) (Winterwerp and De Kok, 2006). The purpose of this model is to support managers of the Scheldt estuary with the tools to evaluate a number of managerial issues.

Five phases have been defined in the work plan:

- 1 set-up of mud model
- 2 elaboration of managerial questions
- 3 year simulations
- 4 detail studies
- 5 sediment mixtures.

In 2006, the first two phases were initiated. The set-up of the hydrodynamic and mud transport model was reported in Van Kessel et al. (2006), whereas the managerial issues were elaborated in Bruens et al. (2006). In 2007, the activities were based on the original work plan (items 1 through 3), but also took into account the findings from the set-up of the mud model and the discussions with Scheldt estuary managers during 2006. In short, most activities for 2007 fell into the following two categories, which are reported in more detail in Van Kessel et al. (2007):

- 1 further improvement of the mud transport model;
- 2 providing support for managerial issues: dredging and dumping strategy at Sloe harbour.

In 2008, phases 3 and 4 were initiated, i.e. year simulations with the hydrodynamic and mud model and the first development of a detailed model near Zeebrugge, required to optimize local dredging and dumping strategies. Also the impact of the second deepening of the Scheldt on typical sediment concentration levels, fluxes and harbour siltation was investigated. Finally, more attention was paid to the use and analysis of remote sensing regarding near-surface suspended sediment concentration in the water and sediment composition of tidal flats.

This report discusses the 2009 activities and results. In Chapter 2, developments of the hydrodynamic model are discussed. In Chapter 3, developments of the mud transport model are discussed. In Chapters 4 and 5, the model is applied to two management issues, i.e. the impact of harbour basins at Terneuzen and Antwerp on the mud dynamics of the Scheldt estuary. Conclusions are drawn in Chapter 6. Finally, recommendations on future work are made in Chapter 7.

The present report is a collaborate effort with contributions by Deltares (mud model and application Terneuzen) and Flanders Hydraulics Research (hydrodynamic model and application Antwerp).





## 2 Hydrodynamic model

For a comprehensive description of the hydrodynamic model, the reader is referred to Vanlede et al. (2009). Only the relevant model properties are reproduced in this report.

The hydrodynamic model is nested in the ZUNO model, as shown in Figure 2.1. The nesting is performed using a combination of two velocity boundaries perpendicular to the coast, and a Riemann boundary parallel to the coast.

The hydrodynamic model has six layers, the thicknesses of which are specified in Table 2.1. This layer distribution approximately corresponds with a logarithmic layer distribution, with the top layer split in two. This gives the model results the necessary vertical resolution near the bottom, while maintaining a sufficiently small layer at the top for comparison with satellite measurements.

The 3D hydrodynamic model is calculated in TRIWAQ, a module of SIMONA. 3 months of hydrodynamics are simulated, from 01/10/2006 to 01/01/2007.

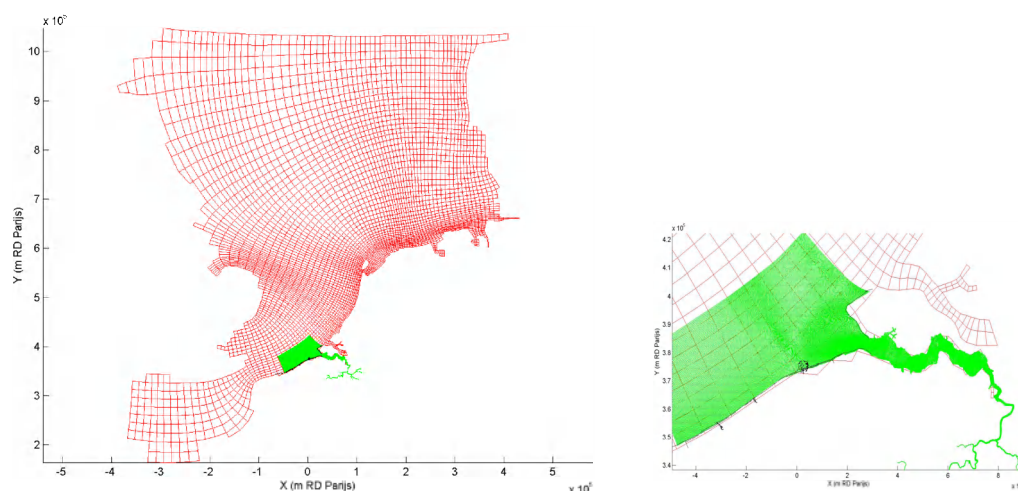


Figure 2.1: LTV model, nested in the ZUNO model.

Table 2.1: Layer thickness in the model.

Layer	Thickness (%)
1 (top)	10
2	20
3	30
4	20
5	15
6 (bottom)	5

During calibration of the model it became apparent that the model “imported” a phase error in the M4 and M6 components from its boundaries. Therefore, the boundary conditions were corrected with 40° in the phase of M4, and 15° in the phase of M6. Furthermore the grid had some minor updates upstream to improve overall stability of the model. An error in the upstream fresh water boundary at Melle was corrected, which resulted in a better reproduction of salinities. This is important as the salinity gradient along the estuary is the driving force behind the gravitational circulation which drives the estuarine turbidity maximum around Antwerp.

Figure 2.2 shows that the propagation of the tidal wave is modelled correctly. The error on M2 amplitude is less than 1%, the error on S2 is 3% on average. M2 phase is modelled with an average error of 3°, S2 phase with an average error of 2°.

High and low waters are typically 10 to 15 minutes late in the model, as compared to the measurements. The root-mean-square error (RMSE) of the water levels in the estuary is typically between 20 cm and 30 cm. The major part of this error is however induced by the non-harmonic part of the tidal signal.

Figure 2.3 shows a low-pass average of the error of the model in predicting water levels at Vlissingen. Similar graphs are obtained along the estuary, which indicates that this type of non-tidal error is introduced at the boundary, and is probably also present in the ZUNO model, from which the boundary conditions of the LTV model are derived.

Modelled velocities were checked at station Wandelaar and station Bol van Heist. Figure 2.4 shows close to one spring neap cycle of modelled and measured velocities at station Wandelaar. In both stations, velocities appear to be too low, both during ebb as during flood tide. A sensitivity analysis shows that the modelled velocities at stations Wandelaar and Bol van Heist are not very sensitive to typical calibration parameters such as roughness and viscosity. As the velocity data only came available at a later stage during the project, further calibration is certainly advised as the velocity field is the most important input for the transport modelling of suspended sediment.

Figure 2.5 shows the modelled and observed salinity values around boei 97. The model results show that the model accurately describes the long-term salinity variations in response to changes in fresh water inflow. A good reproduction of salinity is important in order to reproduce the gravitational circulation in the model.

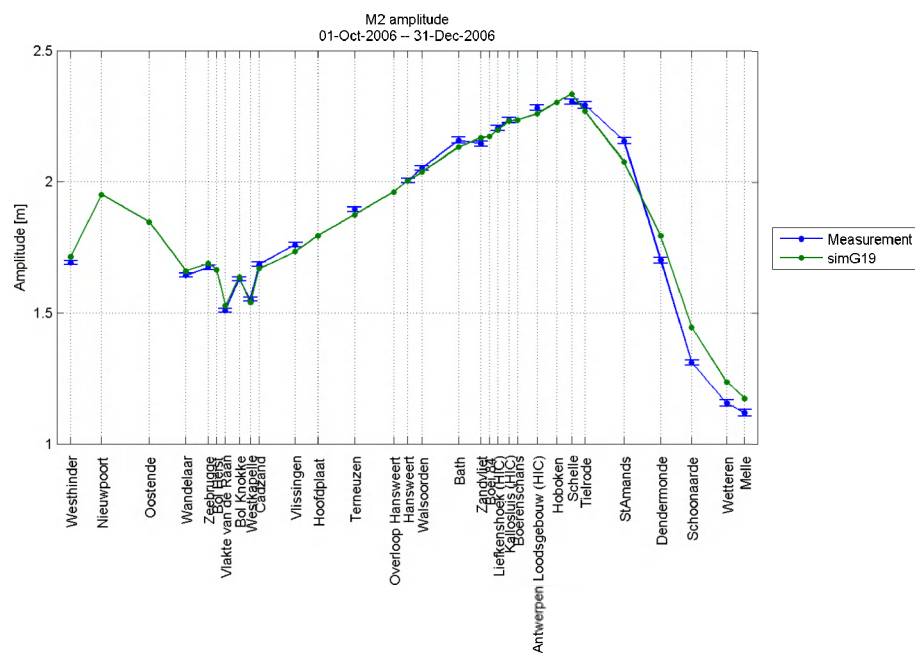


Figure 2.2: M2 tidal component along the estuary.

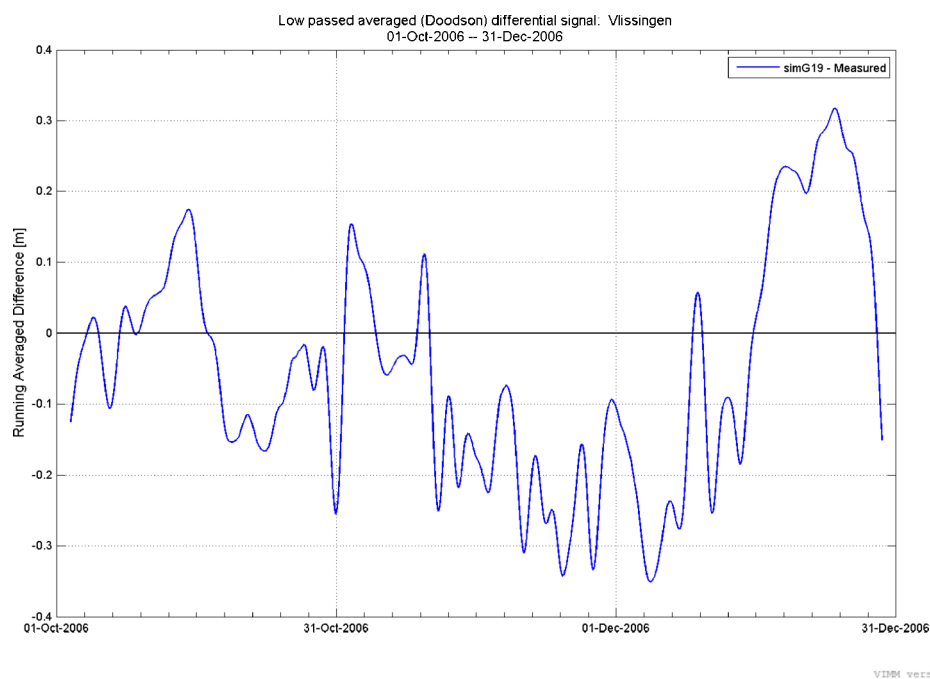


Figure 2.3: Low-pass average of error of water levels at Vlissingen.

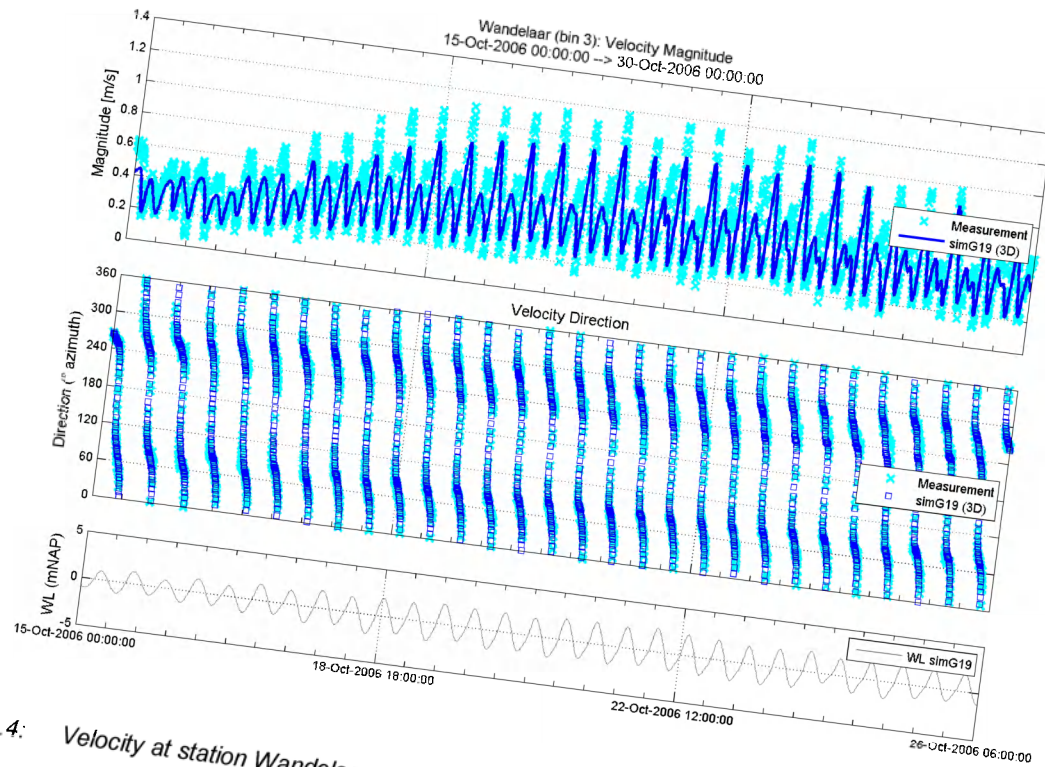


Figure 2.4: Velocity at station Wandelaar.

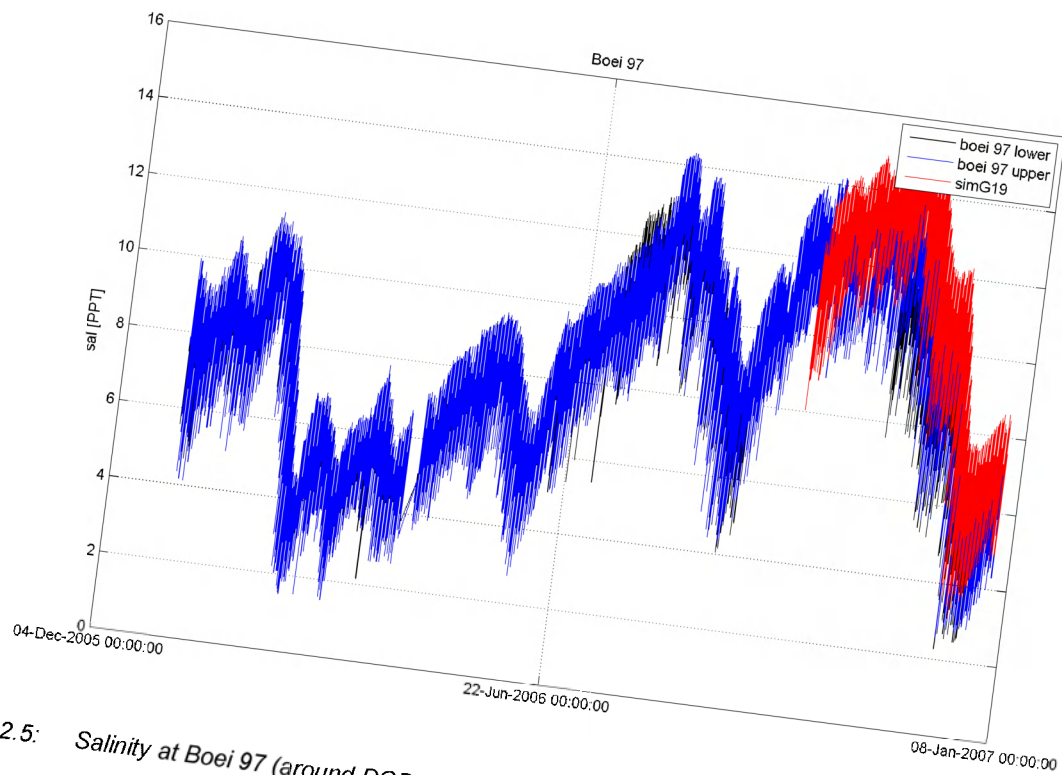


Figure 2.5: Salinity at Boei 97 (around DGD).

### 3 Mud transport model

For a description of the mud transport model of the Scheldt area reference is made to previous reports (e.g. Van Kessel et al. 2006, 2007 and 2008). The model grid is based on the hydrodynamic model grid, but the possibility exists to aggregate the grid (either locally or globally) to set an optimal balance between computation time and local detail.

Although the majority of the requirements to the mud model defined prior to its development have been met in the period 2006 – 2008, its performance remained insufficient with regard to suspended sediment concentration levels within the estuarine turbidity maximum (ETM) near Antwerp. To arrive at realistic concentrations in the ETM, the dumping rate was set at a higher value (2.0 MT/yr) than the siltation rate in the harbour basins (1.5 MT/yr). However, this resulted in a net seaward sediment flux from the ETM, causing a net sediment export towards the North Sea. Such export contradicts recent estimates based on field observations on the mud balance of this system (Wartel et al., 2007).

Therefore the effort on model improvements has been focussed on this shortcoming. Three modifications were made:

- 1 the most recent version of the hydrodynamic model was used, in which the freshwater discharge was better represented (see Chapter 2);
- 2 the near-bed sediment concentration was increased by introducing a deposition probability;
- 3 excessive sediment deposition in the upper reaches of the tributaries was suppressed (notably in the Rupel basin), thereby enhancing the fluvial sediment flux at Rupelmonde.

Although the first modification resulted in a small increase in total suspended matter (TSM) levels, it did not improve the model performance sufficiently.

The second modification aims at enhancing the effect of estuarine circulation on sediment transport. It is hypothesised that for the original settings for settling velocity and deposition, near-bed concentration peaks during slack do not form sufficiently. The explanation is that for a vertically uniform concentration distribution, the deposition flux towards the bed  $F_{\text{dep}}$  equals the sedimentation flux  $F_{\text{sed}}$  through the water column near the bed:  $F_{\text{sed}} = F_{\text{dep}} = w_s C$ . By introducing a deposition probability  $p < 1$ , near bed concentration peaks do form during slack, as  $F_{\text{dep}} < F_{\text{sed}}$  and the excess sedimentation flux accumulates near the bed. By estuarine circulation, resulting in a near-bed residual current directed towards the ETM, these high-concentration peaks may be transported towards the ETM and enhance or maintain its elevated concentration level. As an alternative for the deposition probability, it is recommended to apply other than constant settling velocity formulations as well, e.g. as proposed by Manning and Dyer (2007) and Winterwerp et al. (2006). These formulations take flocculation into account.

The third modification is applied as modelled sediment deposition in the Scheldt tributaries (270 kT/yr), notably in the Rupel basin, much exceeds observed deposition on tidal marshes (12 kT/yr; Wartel et al., 2007). Without this modification, only 46% of the fluvial sediment input of 500 kT/yr reaches the Scheldt at Rupelmonde ( $500 - 270 = 230$  kT/yr). The cause for the modelled excessive deposition in the tributaries lies in the grid and bathymetric schematisation of these branches. In a number of cells, the computed average bed shear

stress is very close to zero, explaining rapid deposition. Detailed grid optimisation and calibration is required to improve this. Another option is to set the local critical shear stress for deposition at zero, thus avoiding deposition. This approach has presently been adopted.

The combination of the introduction of a deposition probability and the prevention of excessive deposition in tributaries turns out to be effective in maintaining realistic TSM levels in the ETM near Antwerp for a total dumping rate exactly equal to the deposition rate in the (dredged) harbour basins. Such equilibrium can be automatically achieved with the dredging module in DELWAQ. This improvement also results in a more realistic mud balance for the estuary, with a long-term near-equilibrium between import and export. However, on a short term, significant import and export occurs due to storm and high river discharge events.

Based on the system description and data analysis, the following desiderata regarding the performance of the mud transport model were formulated (Van Kessel et al., 2006):

- 1 global spatial concentration distribution (e.g. location of ETM's): mean Western Scheldt ca. 50 mg/l
- 2 intra-tide TSM concentration fluctuations: factor 2 to 5
- 3 neap/spring TSM concentration fluctuations: factor 1.5 to 2
- 4 vertical concentration gradients: factor 2 to 10
- 5 a proper overall mud balance, including a sensible mass of 'active' mud in the system
- 6 the spatial distribution of sandy and muddy areas (conform McLaren soil data)
- 7 seasonal TSM concentration fluctuations, including response time of freshwater discharge peaks and storms: factor 2
- 8 siltation rate of intertidal areas and salt marshes (order 1 – 2 cm/y), siltation rate in harbours (up to 1 cm/day)
- 9 ratio between fluvial and marine mud according to Verlaan (1998)
- 10 available mass of sediment (Van Maldegem, 2002):
  - o 13 MT in the bed
  - o 0.1 – 0.4 MT suspended
  - o load from sea and upstream: 0.2 MT/y
  - o load from dumping: 1.5 MT/y
- 11 long-term equilibrium between dumping from harbour maintenance and harbour siltation

Following the most recent modifications, these desiderata have now all been met.

The present report is not intended as a validation document of the mud model. For this is referred to previous reports and papers in press (Van Kessel et al. 2006, 2007 2008 and 2009; Van der Wal et al., 2009). Also, a final journal paper will be written on model calibration and validation including the latest improvements.

However, a few figures are presented herein to give the reader an impression of the model performance, notably with regard to recent improvements.

Figure 3.1 shows the TSM concentration at Boei 84 (near Antwerp) harbour for both original (green) and new (red) settings compared with OBS observations (blue). For both computations, a closed balance exists between harbour siltation and sediment dumping. Maintenance dredging and dumping is assumed to take place at a weekly interval. The dredging module of the model removes all sediment in the harbour in excess of a pre-described quantity and releases this material at a pre-described position with a pre-described rate. Concentration peaks due to sediment dumping are clearly visible. For the new settings, the equilibrium concentration in the ETM increased about fourfold with respect to the original settings and are in much better agreement with observed TSM levels in the ETM. It is remarked that a close match is not expected, as the modelled schematised dumping scenario will be different from the (unknown) factual maintenance scheme. For the new settings, computed siltation in the access channels of Zandvliet and Kallo and in Deurganckdok basin amounts to 1.7 MT/yr, whereas for the original settings the computed siltation is 0.7 MT/yr only. The former number agrees better with observed siltation rates (estimated at 2 MT/yr).

Figure 3.2 shows the sediment flux through the estuary mouth (transect Vlissingen – Breskens) in kT/day. The ingoing flux is shown in green, the outgoing flux in red. The residual (net) flux over 25h is shown in blue<sup>1</sup>, the cumulative flux in black. The gross in- and outgoing flux is steered by the tide and by wave-induced resuspension in the outer estuary. The neap-spring tidal cycle can be discerned in the gross fluxes. Apart from spring tide, also periods with high wind speed result in elevated concentration levels and gross fluxes (see also Figure 3.3 for correlation between residual sediment flux and wind speed). The residual flux over 25h (two tides) oscillates around zero, with alternating periods with net import and net export. Typically, the residual flux (peaking at 50 kT/day<sup>1</sup>) is quite small compared to the gross flux (peaking at 1 MT/day). Cumulative over 3 months, the net sediment flux is –180 kT (export). This small number is in line with estimates based on observations. The actual number will change from period to period, as a single storm or a period with high freshwater discharge may change the residual sediment flux strongly. The gross sediment flux over the same 3-month period is 9.8 MT export and 9.6 MT import (i.e. gross exchange about 40 MT/yr).

Figure 3.4 shows a map of the average near-bed TSM concentration in the Scheldt estuary for the period 1/10 – 31/12 2006. Two turbidity maxima are clearly observed: one near Zeebrugge, another near Antwerp. The first is caused by the local residual current pattern steered by the tide, the second by estuarine circulation steered by longitudinal salinity gradients. The locations of these maxima agree well with observations.

Figure 3.5 shows the TSM concentration on 23/10/2006 8:00h in a transect along the thalweg between Vlissingen (0 km) and Rupelmonde (105 km). The ETM at Antwerp is obvious, with depth-averaged sediment concentration over 200 mg/l.

1. Note that the magnitude of the scale for the 25h residual flux has been multiplied with 10 for better visibility.



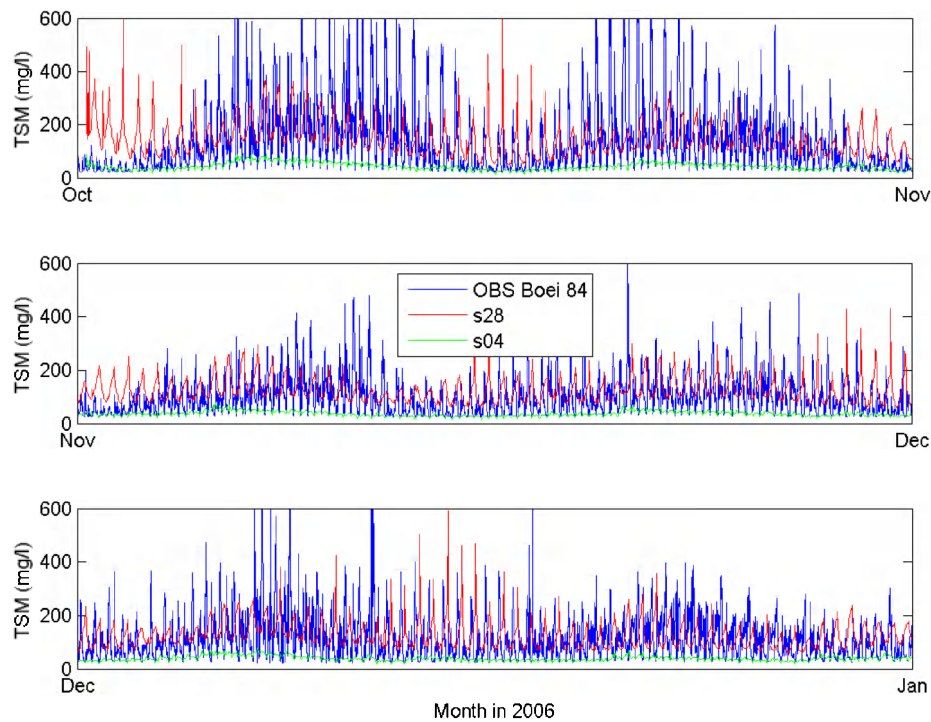


Figure 3.1 Near-bed TSM concentration (mg/l) at Boei 84 (Antwerp harbour). Period 1/10 – 31/12 2006. Blue: OBS observations; Green: original settings; Red: new settings with enhanced ETM.

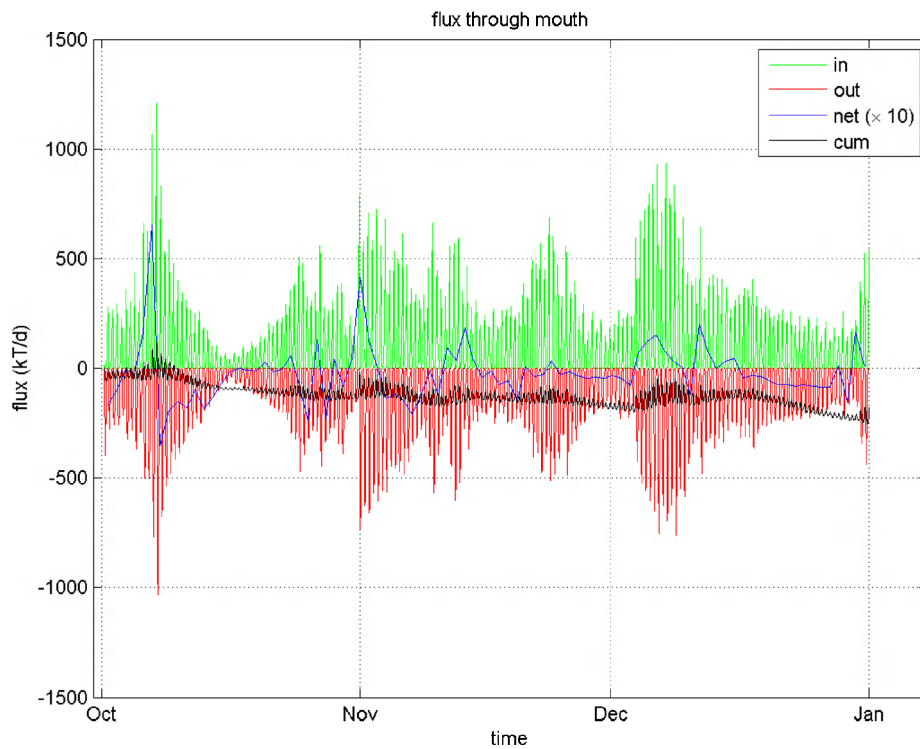


Figure 3.2 Sediment flux through estuary mouth (transect Vlissingen – Breskens). Period 1/10 – 31/12 2006. A positive flux means import.



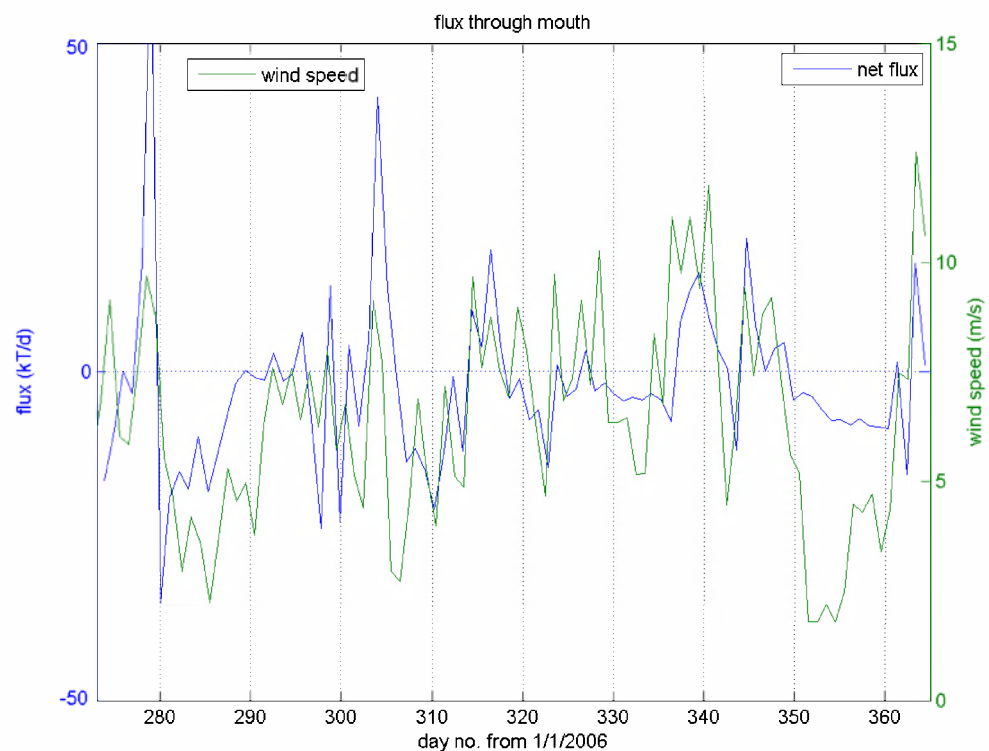


Figure 3.3 Residual sediment flux through estuary mouth (transect Vlissingen – Breskens) and day-average wind speed. Period 1/10 – 31/12 2006.

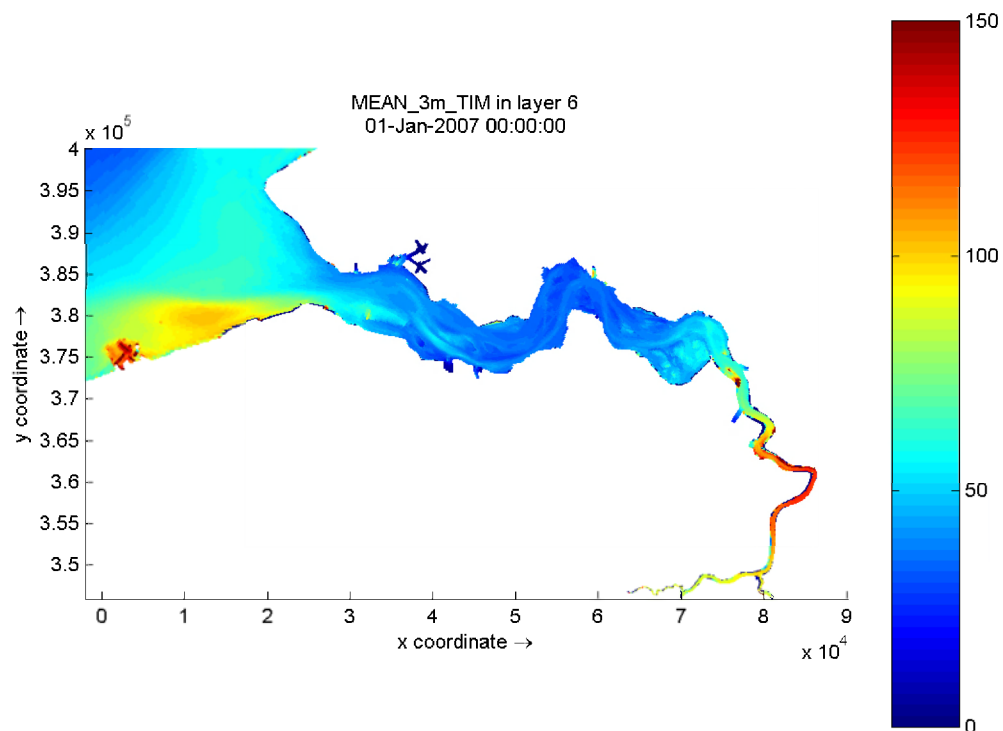


Figure 3.4. Time-averaged near-bed TSM concentration (mg/l). Period 1/10 – 31/12 2006.

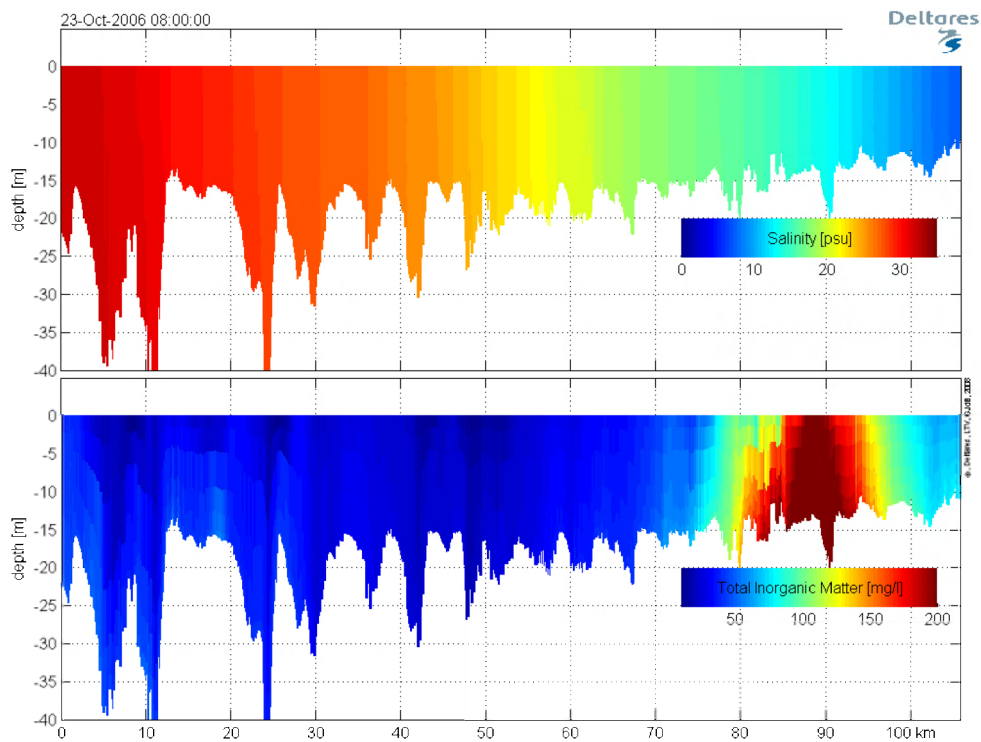


Figure 3.5. Salinity (upper panel) and TSM concentration (lower panel) in thalweg at 23/10/2006 8:00h between Vlissingen ( 0 km) and Rupelmonde (105 km).

## 4 Application 1: Terneuzen

The application at Terneuzen has two objectives:

- 1 for harbour managers it is important to know how a shift in dumping location affects siltation in harbour basins;
- 2 for estuarine managers it is important to know how sediment dumping affects the estuary in terms of turbidity levels and siltation rates at intertidal areas and bed composition of intertidal areas.

To investigate the impact of harbour maintenance at Terneuzen, five computations have been made, namely:

- 1 the present situation (reference);
- 2 dumping location at Braakman shifted towards the west;
- 3 dumping location at Terneuzen shifted towards the east;
- 4 no maintenance dredging and dumping;
- 5 no harbours.

Comparison of the 2<sup>nd</sup> and 3<sup>rd</sup> computation with the 1<sup>st</sup> reveals the sensitivity of spatial turbidity and siltation patterns for a shift in dumping location. Comparison of the 1<sup>st</sup> computation with the 4<sup>th</sup> and 5<sup>th</sup> reveals the impact of the harbour compared to a situation in which no dumping would occur. In computation 4 harbour siltation does still occur. Siltation has been suppressed in computation 5 to make a fair comparison with the historic situation (both without dumping and harbour siltation, as harbours did not yet exist).

The computations have been made on a 2×2 aggregated grid, except for the vicinity of Terneuzen, where the full resolution has been maintained (see Figure 4.1). The simulation period is 1/10/2006 – 1/1/2007, i.e. 3 months. The applied shift in release locations is illustrated in Figure 4.2. Dumping area W15, presently located east of the Braakman harbour entrance, is shifted to the west over a distance of 3 km. Dumping areas W7, W8 and W14, presently located near Terneuzen harbour entrance, are shifted to the east over a distance of 2.5 km.

Figure 4.3 shows the computed change in time-averaged TSM level (in mg/l) caused by the applied shift in release locations. As might be expected, a shift towards the east results in higher TSM levels in the east and lower TSM levels in the west, and vice versa. As the released mass at W15 (800 kT/yr)<sup>2</sup> is larger than the sum of W7, W8 and W14 (275 kT/yr), the impact of a shift of location W15 is larger than that of locations W7, W8 and W14. However, the computed concentration differences remain small for both computations. Close to the new release location(s), the time-averaged concentration increases with a few mg/l, whereas close to the original release location(s), it decreases with a few mg/l. Typically, at a short distance (< 1 km) from the release location, the computed concentration difference remains below 1 mg/l. Compared to the natural background level (about 50 mg/l) and tide-induced variations herein, the impact is very small (order 2%).

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2. The rates of 800 and 275 kT/yr originate from existing dumping permits, corrected for the mud fraction in harbour deposits. Actual release rates may be lower, not higher. As Q4 of 2006 is characterised by rather low observed TSM levels (see observations in Figure 4.4 and Figure 4.5) compared to long-time average TSM levels, a lower actual siltation rate is expected from Q4, 2006. This is indeed reflected in the computed siltation rates in Table 4.1.

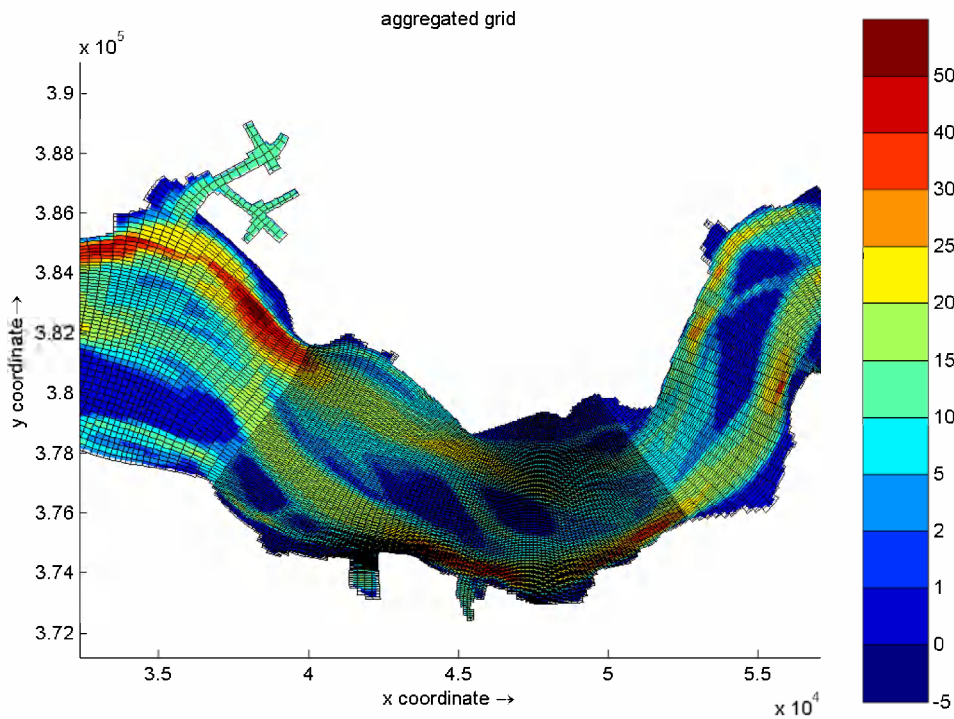


Figure 4.1 Grid and bathymetry for Terneuzen testcase.

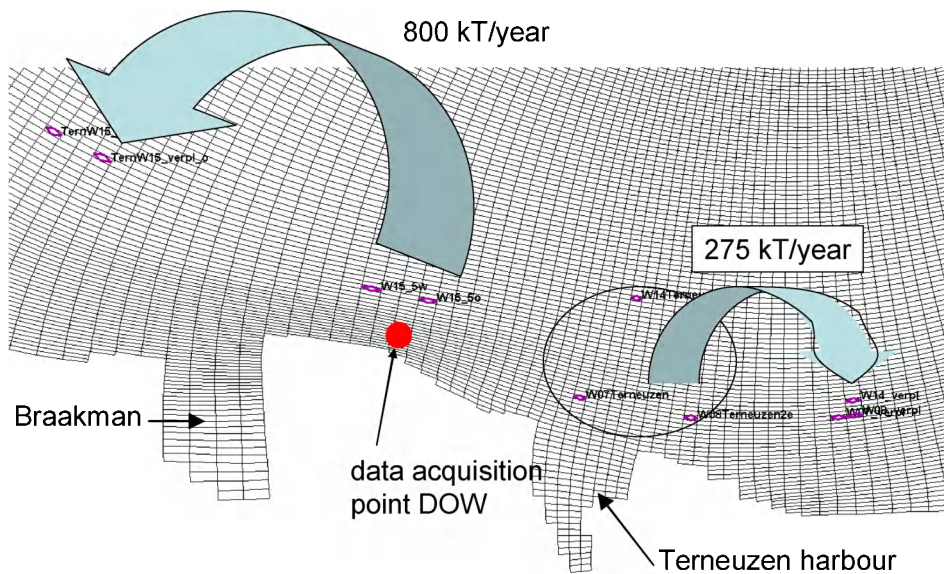


Figure 4.2 Illustration of shift of sediment release location W15 to the west (2<sup>nd</sup> computation, 800 kT/yr) and locations W7, W8 and W14 to the east (3<sup>rd</sup> computation, 275 kT/yr).

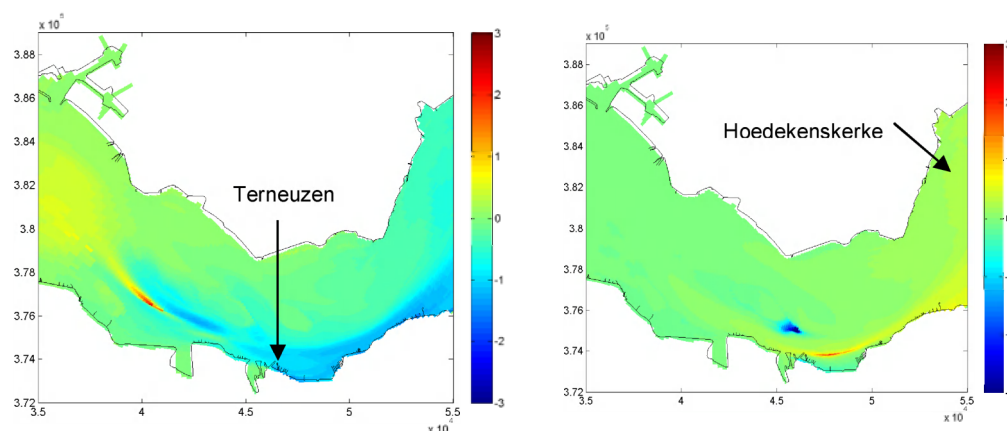


Figure 4.3 TSM difference (mg/l) averaged over a 3 month period caused by a shift of sediment release location towards the west (left) and towards the east (right).

This is also illustrated in Figure 4.4 and Figure 4.5, in which the time series of the TSM concentration is shown at Hoedekenskerke and Terneuzen boei 20, respectively. These locations, for which also some field observations are available (indicated as open circles), are indicated in Figure 4.3. Three lines are shown: the present situation in red, the westward shift in green and the eastward shift in blue. As these lines overlap each other strongly, the red and green lines are hardly visible. It is concluded that compared with natural tide-induced variations, the effect of a shift in release location is very small indeed. A plausible reason why the impact is small is the small ratio between dumping rate ( $< 1$  MT/yr) and background flux (about 40 MT/yr at Vlissingen, see Chapter 3).

The small changes in TSM levels are reflected in small changes in siltation rates at Braakman and Terneuzen harbours, see Table 4.1. According to the computations, a 3 km shift to the west of release location W15 results in a 1–2 % reduction of siltation at Braakman and Terneuzen harbours, respectively. A eastward shift of release locations W7, W8 and W14 has an even smaller impact. Taking into account sailing time of dredging vessels, a westward shift of location W15 may or may not be economically attractive. Such evaluation is beyond the scope of the present report (and the LTV-programme in general).

The results of these computations can be used as input for an ecological model, which is presently under construction in the framework of the LTV-programme (Van Duren, 2009).

Table 4.1 Computed siltation (kT/yr) at Braakman and Terneuzen harbours for present situation and for a shift of release locations to the west or east. Period 1/10/2006 – 1/1/2007.

simulation	Braakman (kT/yr)	Terneuzen (kT/yr)
present	147.8	131.0
shift to west	146.0 (-1.2%)	127.7 (-2.5%)
shift to east	147.2 (-0.4%)	130.7 (-0.2%)



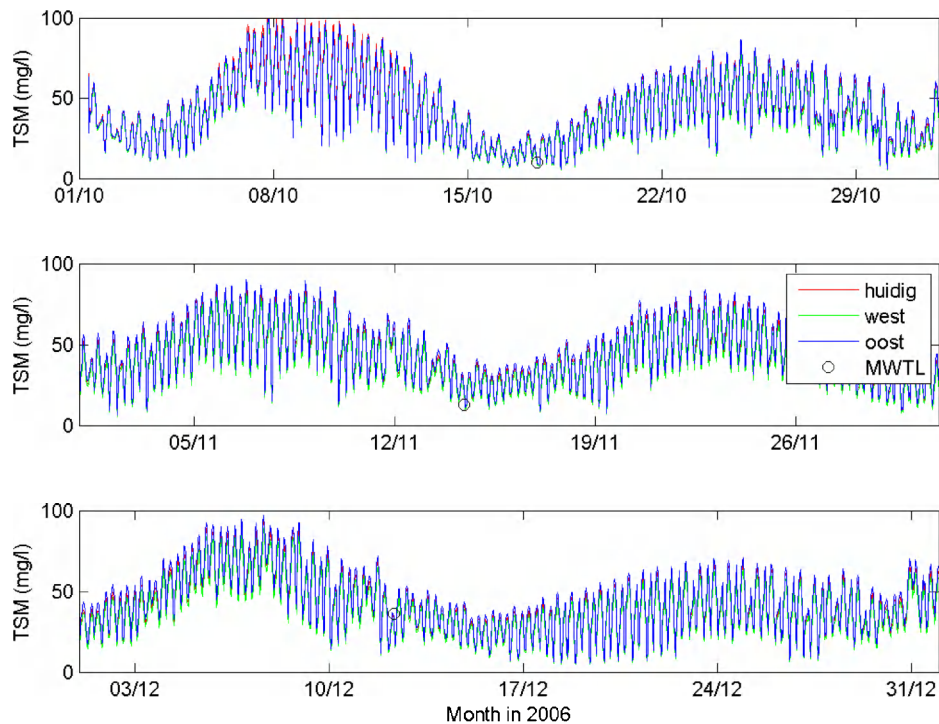


Figure 4.4 Computed TSM concentration (mg/l) at Hoedekenskerke for the present situation (red) and for a shift of release location to the west (green) or to the east (blue). Open circles indicate measured concentration. Because of small differences, the red and green lines are often covered by the blue line.

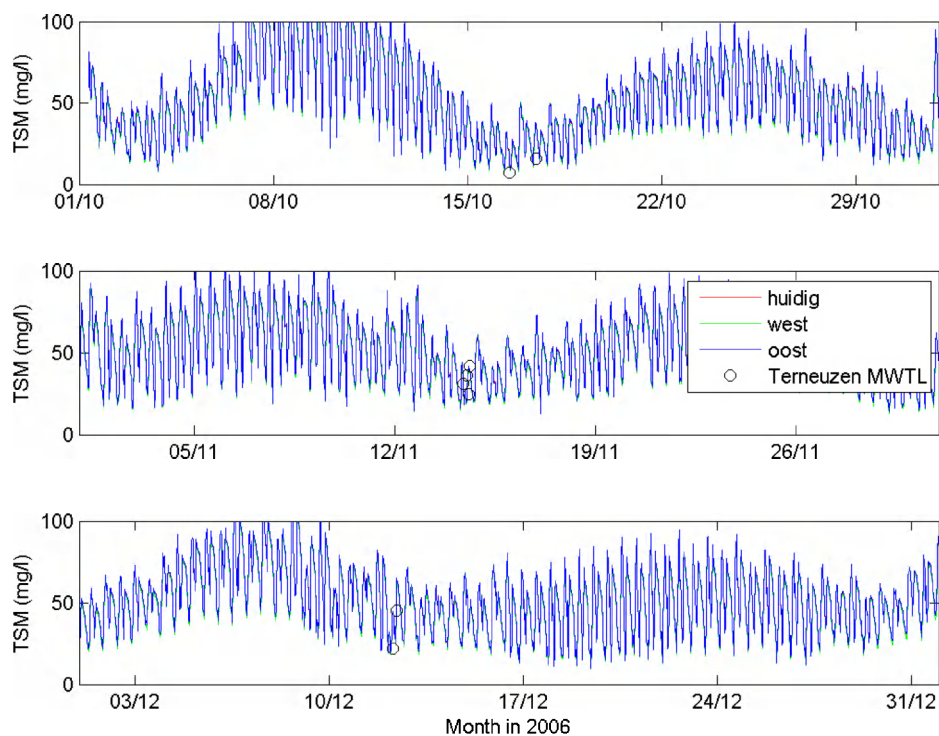


Figure 4.5 Computed TSM concentration (mg/l) at Terneuzen boei 20 for the present situation (red) and for a shift of release location to the west (green) or to the east (blue).

As a next step, an assessment has been made of the presence of Braakman and Terneuzen harbours on turbidity levels in the Scheldt estuary. In simulation 4, the sediment dumping due to harbour maintenance has been discontinued. However, harbour siltation is still possible. This will result in lower-than-natural TSM levels, as in an estuary free of human intervention, no (artificial) harbours are present. Therefore in simulation 5 not only sediment dumping has been stopped, but also harbour siltation is prevented by setting the critical shear stress for deposition at zero inside the harbour basins. It would have been more accurate to remove the harbour basins from the hydrodynamic grid and bathymetry, but for this multiple hydrodynamic simulations would be required, taking a lot of computer time and pre- and postprocessing. Therefore only changes are made to the mud transport model.

Figure 4.6 shows the time-average difference in TSM levels between the scenario with and without harbour maintenance. It is obvious that the concentration decreases significantly, typically with about 5 mg/l (i.e. about 10% of the natural background concentration) over a large area of the Western Scheldt. Towards the mouth of the estuary the effect becomes smaller. The computed concentration increase in the mouth of Braakman harbour is remarkable. This is probably caused by occasional resuspension from the harbour mouth, which does not or less occur in the computation with maintenance dredging, in which harbour deposits are frequently artificially removed.

Figure 4.7 shows the time-average difference in TSM levels between the present and historic (i.e. without harbour siltation and dredging/dumping). Compared to Figure 4.6, effects are much less pronounced. In the major part of the area considered, the computed concentration difference is between -2 and +2 mg/l, i.e. less than 4% difference with respect to the background concentration. Again, the computed concentration increase in the mouth of Braakman harbour is remarkable. For this simulation, sediment in the harbour is neither removed by dredging nor by deposition. As a result, a high near-bed concentration is computed in the harbour, part of which will be transported out of the harbour at ebb tide and move seawards. If the harbour would have been removed from the hydrodynamic grid, the effect would not have occurred.

Figure 4.8 shows the variation of the TSM levels at Terneuzen boei 20, close to the dumping locations for the reference computation (blue, 'present'), the computation without dumping but with harbour siltation (green, 'intermediate') and the computation without dumping and harbour siltation (red, 'historic'). The time axis ranges from 27/12/2006 to 1/1/2007, implying that the last 5 days of the 3-month simulation period are shown. On 27/12, the present and historic scenarios show nearly equal concentration levels, whereas the intermediate scenario shows a lower level. On 28/12, the SPM level for the present scenario suddenly increases, as the dredging module releases all sediment accumulated in the harbour basins during the past 15 days (about 50 kT) in about 1.25 day (prescribed release rate 40 kT/day). Within a day, the concentration peaks at about 100 mg/l, whereas in the historic scenario the concentration peak at about 60 mg/l only. After the end of the release (on 29/12) the concentration difference starts to diminish and approaches pre-dumping levels towards the end of the simulation, after about 3 days.

Concluding, the harbours at Terneuzen do somewhat change the spatial and temporal distribution of suspended matter, but averaged over a longer period (typically 1 week) and larger area (typically 5×5 km) their impact on TSM levels is small.

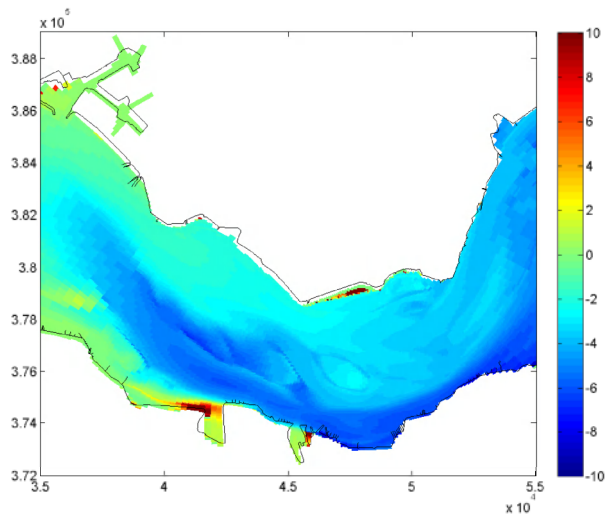


Figure 4.6 TSM difference (mg/l) averaged over a 3 month period caused by a discontinuation of sediment release for harbour maintenance.

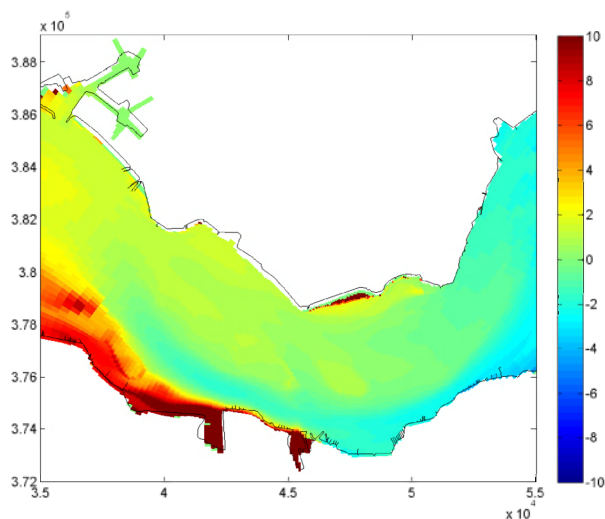


Figure 4.7 TSM difference (mg/l) averaged over a 3 month period caused by a discontinuation of both sediment release and harbour siltation.

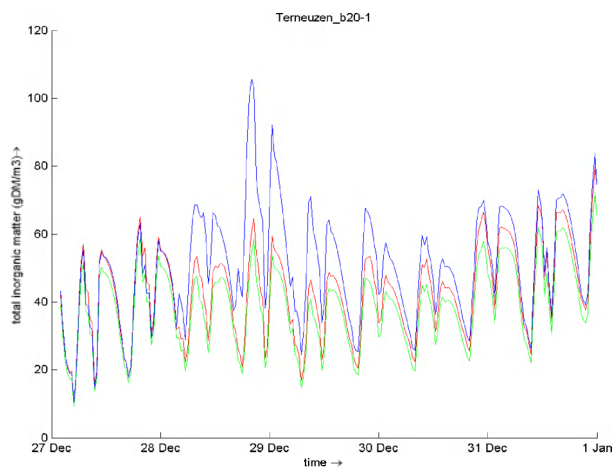


Figure 4.8 Computed TSM concentration (mg/l) at Terneuzen boei 20 for the present situation (blue), without dredging/dumping (green) and without dredging/dumping and harbour siltation (red).



## 5 Application 2: Antwerp

The application at Deurganckdok (DGD) has similar objectives as the application at Terneuzen:

- 1 How does a shift in dumping location affect the siltation in other harbour basins?
- 2 How does sediment dumping affect turbidity levels?

To investigate the impact of harbour maintenance at DGD, three computations have been made. These are listed in Table 5.1. The computations have been made on an aggregated grid. The hydrodynamic grid is aggregated 2x2 downstream of the Belgian-Dutch border and upstream of Antwerp. For the region around DGD, the full resolution is maintained. The aggregation is shown in Figure 5.1. This figure also shows the applied shift in dumping location in run WL9.

Table 5.1: Overview of computations for the Deurganckdok case

Run	Description
s28_Antw_WL6	The present situation (reference)
s28_Antw_WL9	Dumping location shifted downstream, to “Schaar Ouden Doel”
s28_Antw_WL10	Suppressed siltation in DGD (“no harbour”)

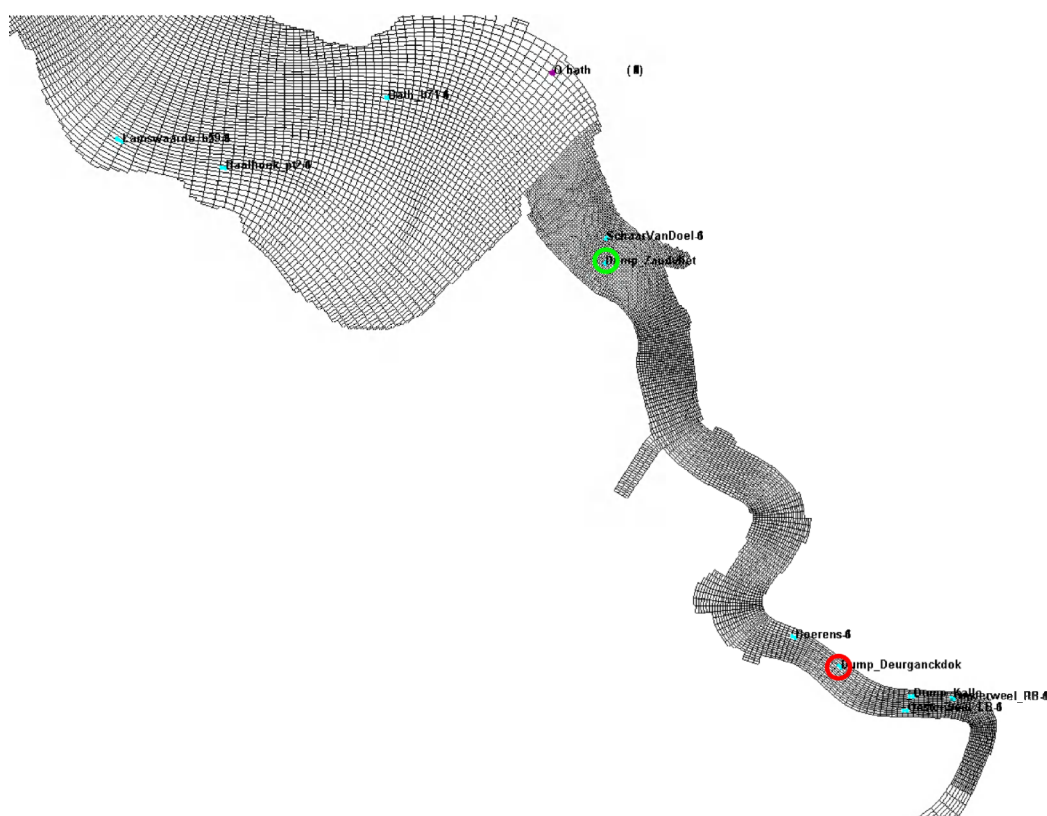


Figure 5.1: Aggregated grid for DGD testcase. The red circle indicates the dumping location for dredged material in DGD in the reference run (WL6, location Oosterweel). The green circle indicates the dumping location in the scenario run (WL9, location “Schaar Ouden Doel”).

## 5.1 Present situation

Table 5.2 gives the measured and modelled amount of dredged material for the Kallo access channel in  $10^3$  TDS/yr. The material that is dredged from the Kallo access channel is dumped at "Plaat van Boomke" and Oosterweel, and to a lesser extent at "Punt van Melsele".

The measured amount of dumped material is taken from the annual dredging reports (prepared by aMT). The volumes that are reported in these reports have been converted to weight of dry matter using  $\rho_{\text{beun}} = 1350 \text{ kg/m}^3$  and  $\rho_{\text{dry}} = 530 \text{ kg/m}^3$ . In the reference run, all dredged material is dumped at only one location, being "Plaat van Boomke". Table 5.2 shows the large (natural) variability in the amount of material that needs to be dredged from the Kallo access channel. The modelled siltation rate of Kallo access channel is well within the bounds of the measured values, indicating a good representation of the estuarine turbidity maximum. It is noted that 2007 is the first year where material dredged from Deurganckdok is dumped back into the system (see Table 5.3).

Table 5.3 shows the measured and modelled amount of dredged material for DGD. Due to modelling restrictions, the dredged material from a harbour in the model can only be dumped at one location, which is "Punt van Melsele" in the reference run, and "Schaar Ouden Doel" in the scenario run with a shift in dumping location. As the dredging report for 2008 was not yet made available, there is no indication of the natural variation in siltation of DGD. It is clear, however, that the modelled amount of dredging in DGD is in close approximation with the measured amount in 2007.

Table 5.2: Dumping of dredged material of Kallo access channel.

	observed			computed
$10^3$ TDS/yr	2005	2006	2007	Run WL6
Punt v Melsele			42.8	
Plaat v Boomke	54.9	103	161	299
Oosterweel	48.7	103	267	
Total	104	206	470	299

Table 5.3: Dumping of dredged material of Deurganckdok

	observed	computed	
$10^3$ TDS/yr	2007	Run WL6	Run WL9
Punt van Melsele	230	636	
Plaat van Boomke	123		
Oosterweel	332		
Schaar Ouden Doel			620
Total	684	636	620

## 5.2 Shift of dumping location

Figure 5.2 shows the effect of shifting the dumping location for DGD downstream on the mean surface SSC over a 3 month period. This has a clear effect on the surface SSC values around Antwerp, which drop from an average of 140 mg/l to 100 mg/l.

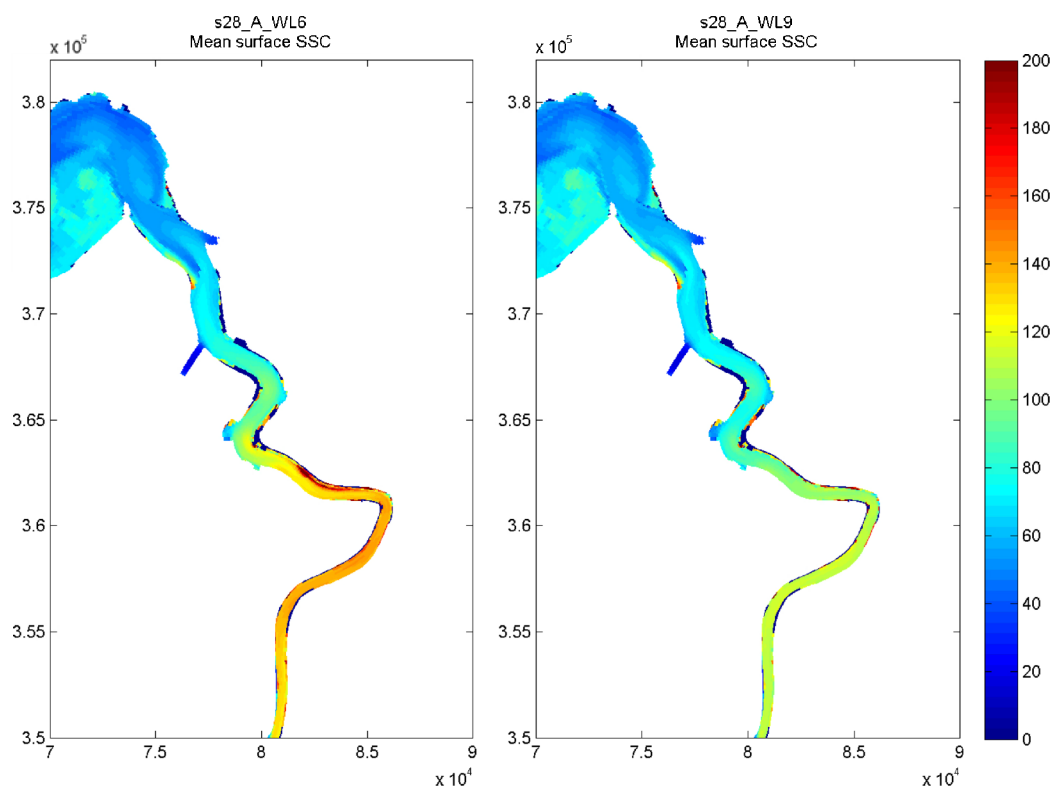


Figure 5.2: Mean surface SSC over a 3-month period for the reference run (WL6, left) and with the dumping location for DGD sedimentation shifted downstream (WL9, right)

### 5.3 Reduction of siltation in DGD

A reduction of the siltation in DGD is realised by locally changing the model-parameters describing how suspended sediment in the bottom cell of the water column can migrate to the bottom layer. This approach cannot totally prevent material from depositing in the dock (because of the high residence times of suspended matter in the dock). The material that does deposit is subsequently dredged in the model. The total amount of material that is dredged from Deurganckdok is significantly reduced (by more than 90%) by the local suppression of siltation in DGD.

Figure 5.3 shows the effect of reducing the siltation in DGD on the mean surface SSC over a 3 month period. The reduction of siltation in the model also greatly reduces the amount of material that is dumped at “Punt van Melsele” in the model, so that a similar effect on the surface SSC in the vicinity of Antwerp is observed in the model.

Figure 5.4 shows the effect of the scenario with reduced sedimentation on surface SSC levels at Oosterweel.

Figure 5.5 shows that the reduced average surface SSC as observed in Figure 5.3 is due to the reduced dredge and dump cycle. The dumping location of DGD is situated near the monitoring station Oosterweel, so every dumping event at Oosterweel is visible as a higher surface SSC signal at monitoring station Oosterweel. When the sedimentation in DGD is suppressed (scenario WL10), this dredge-dump cycle stops almost completely, thus resulting in lower average surface SSC values around Antwerp. A similar mechanism explains the lower SSC values in Oosterweel when the dumping location for material dredged in DGD is moved downstream (scenario WL9).

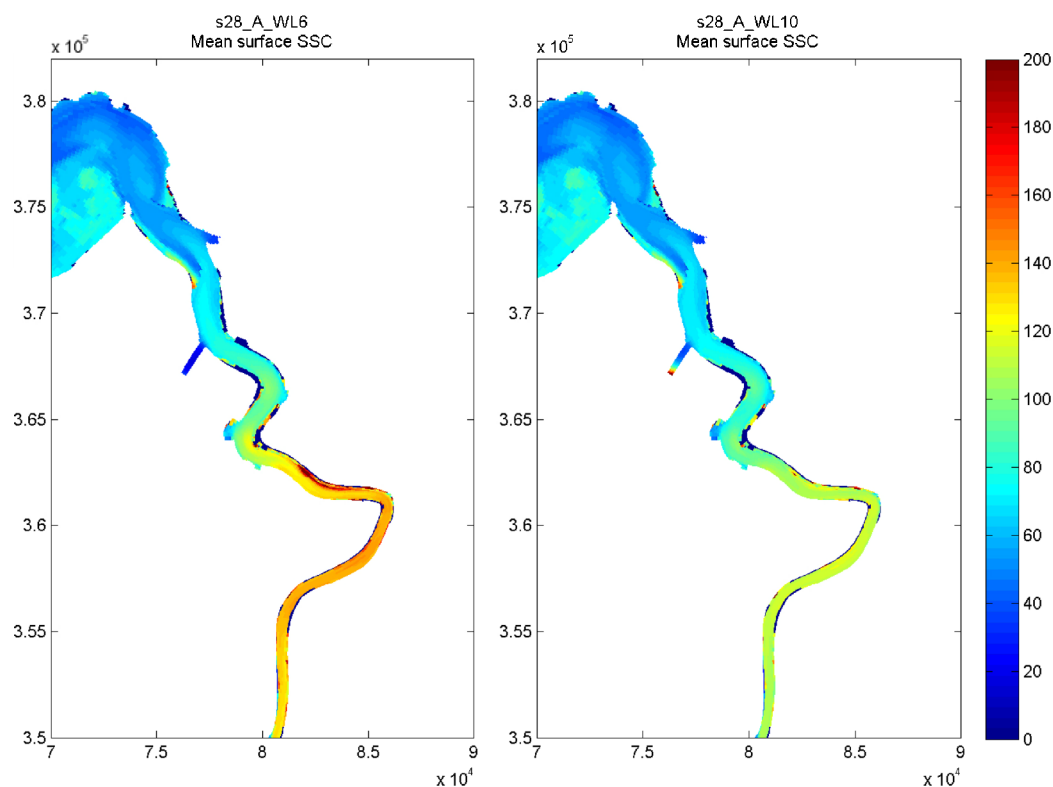


Figure 5.3: Mean surface SSC over a 3-month period for the reference run (WL6, left) and with sedimentation in DGD reduced (WL10, right)

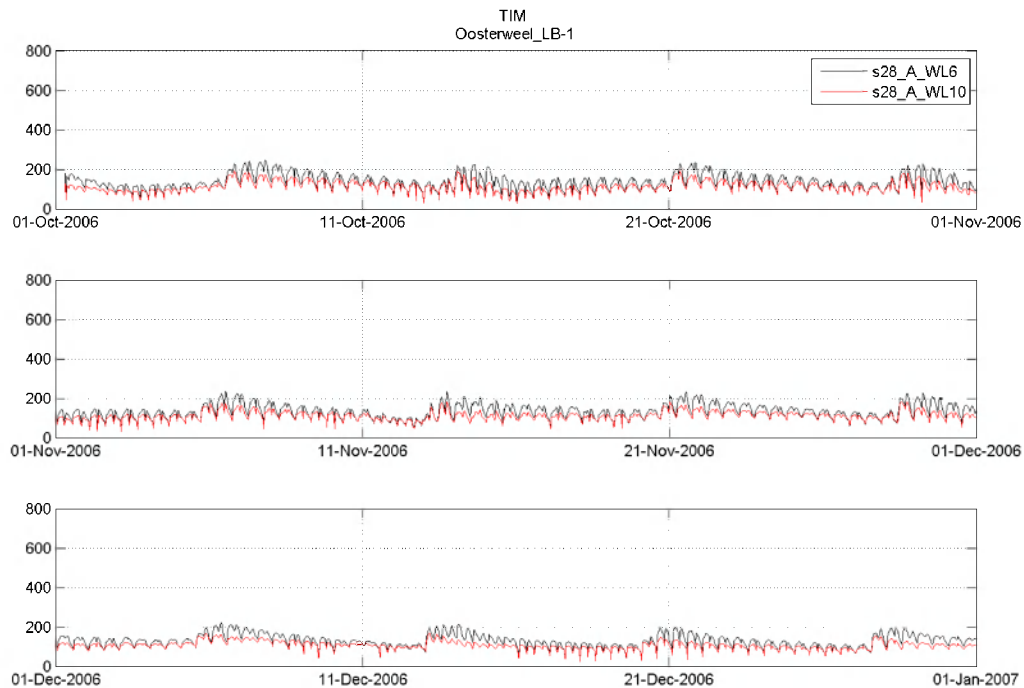


Figure 5.4: Surface SSC at Oosterweel for the reference run (WL6) and with reduced sedimentation in DGD.

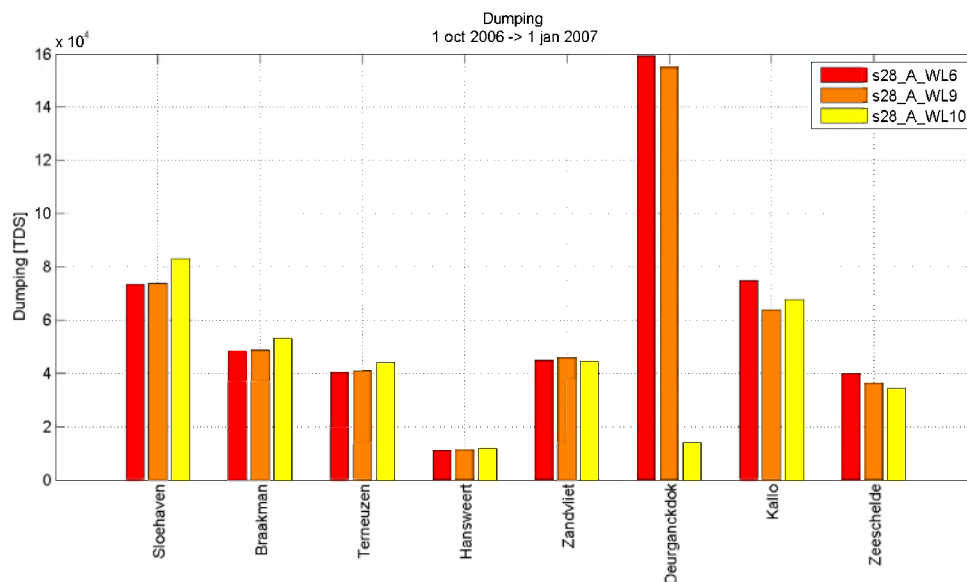


Figure 5.5: Amount of dumped material in  $10^4$  TDS from harbours in the estuary over a 3-month period

Table 5.4 quantifies the effect of both scenarios on the modelled siltation in the different access channels in the Western and Sea Scheldt. These amounts are calculated in TDS for a three-month period, so they have to be multiplied by four in order to obtain the relevant values for an entire year. When the dumping of dredged material from DGD at location “Punt van Melsele” drops, not surprisingly the sedimentation and thus the need for dredging in the areas close to “Punt van Melsele” drops.

Table 5.4: Totals of dumped material ( $10^3$  TSD) from harbours in the estuary over a 3-month period

	s28_A_WL6 Reference	s28_A_WL9 Shift of dump location	Change	s28_A_WL10 Reduced sedimentation DGD	Change
Sloehaven	73.4	73.7	0%	83.1	13%
Braakman	48.4	48.7	1%	53.0	10%
Terneuzen	40.5	40.9	1%	43.9	9%
Hansweert (WS)	11.2	11.3	1%	12.0	7%
Zandvliet	44.9	45.9	2%	44.7	0%
Deurganckdok	159	155	-3%	14.2	-91%
Kallo	74.8	63.8	-15%	67.6	-10%
Zeeschelde	39.9	36.3	-9%	34.4	-14%

On the whole, however, the suppression of siltation in DGD increases the average suspended sediment concentrations in the Western Scheldt, thus leading to higher amounts of dredged material in the access channels in the Western Scheldt. The extent of this effect is unexpected and is subject to further investigation.

Concluding, the model in its present state is able to reproduce fairly accurately the amount of material that needs to be dredged from the access channels in the Belgian part of the Scheldt estuary. This gives trust in the correct representation of the ETM around Antwerp.

The SSC values around Antwerp are higher than their natural background value, because of dumping of dredged material at locations "Plaat van Boomke", "Punt van Melsele" and "Oosterweel". The effect on surface concentrations around Antwerp is about 40 mg/l. This effect diminishes both upstream and downstream.

## 6 Conclusions

Further improvements have been implemented to the hydrodynamic and mud transport model for the Scheldt estuary. These improvements regard the reproduction of the turbidity maximum at Antwerp and the overall mud balance of the system. The model now meets the demands defined at the start of the project in 2006.

The model has been applied to investigate the impacts of harbour maintenance at Terneuzen and Antwerp.

The impact of the harbours at Terneuzen on turbidity levels is small. This is caused by the relative small dumping flux ( $< 1$  MT/yr) compared to the gross sediment flux passing through the estuary (computed at about 40 MT/yr at Vlissingen). A 3 km shift of dumping locations turns out to be favourable for siltation reduction, although the reduction remains small (1–2%).

Temporarily and locally, harbour maintenance results in a significant increase in suspended sediment concentration near Terneuzen ( $> 20\%$ ), but averaged over a longer time and larger distance, overall turbidity levels are hardly affected. This can be explained as sediment dumping is balanced by harbour siltation (after all the cause for maintenance dredging). While dumping results in a concentration increase, siltation results in a similar decrease, on average.

As the size of the harbour basins at Antwerp are larger than at Terneuzen, notably relative to the tidal fluxes of water and sediment, the impact of these basins on turbidity levels of the Scheldt is more pronounced. For example, a down-estuary shift of the dumping location of DGD sediments results in a 40 mg/l reduction of the near-surface concentration in the estuarine turbidity maximum (ETM) near Antwerp. Optimisation of dredging and dumping strategy, for instance regarding frequency or release location, has therefore substantial potential benefits at Antwerp.





## 7 Recommendations on future work

For the next year, the following activities might be carried out in the framework of LTV-mud:

- Further cross-fertilisation with data and data acquisition programmes such as MONEOS. Additional data that would much support further model validation are remote-sensing data providing synoptic pictures for a number of years and high-frequency turbidity data from fixed stations for a long period (multiple years). Even without any model, such data are highly valuable for system understanding and system monitoring with regard to its present state and historic or future trends.
- Additional work on quantification of model (un)certainty and accuracy.
- Hindcast of turbidity levels over the past 20 years. Such hindcast will increase the understanding of interannual variability (such as induced by wind climate and freshwater discharge) and the long-term mud balance. For manageable computation times, this hindcast would require the application of an aggregated hydrodynamic grid. A comparison with long-term MWTL data will reveal to what extent observed long-term variability can be explained with physical processes included in the model.
- Model application to investigate the effect of autonomous trend on turbidity levels and the mud balance, e.g. trends in freshwater discharge, wind climate, water level.
- Model application to investigate the effect of human interventions such as harbour construction, fairway deepening and set-back of dikes.
- Coupling with the ecological model under development in the framework of LTV. Biological forcing functions on sediment stability and settling velocity can be easily included if available.
- Construction of a real-time operational model accessible via internet. The actual turbidity climate could be inspected with advanced visualisation techniques such as based on Google Earth.

Proposed activities are open for discussion with estuarine managers and should be prioritised. Also, other activities may be proposed or some activities may be skipped altogether.

It is noted that in the framework of other projects such as 'VOP-slib', Ecoshape's 'Mud Dynamics' and TO Eems-Dollard and Wadden Sea, new modules will become available describing water-bed sediment exchange and flocculation in more detail. It is proposed to apply these modules to the LTV-mud model as soon as they become available. In this way the state-of-the-science character of this model is maintained.



## 8 References

- Bruens, A., J. Vanlede, T. van Kessel (2006). Notitie beheersvragen LTV-slibmodel. WL | Delft Hydraulics report Z4210.75 (in Dutch).
- Manning A.J. and K.R. Dyer (2007). Mass settling flux of fine sediments in Northern European estuaries: Measurements and predictions. *Marine Geology* 245, pp. 107–122.
- Meire, Patrick & Tom Maris (2008). MONEOS, geïntegreerde monitoring van het Schelde-estuarium. Onderzoeksgroep Ecosysteembeheer Universiteit Antwerpen, ECOBE, Rapport 08-R-113.
- Van der Wal, D., T. van Kessel, M.A. Eleveld, J. Vanlede (2009). Spatial heterogeneity in estuarine mud dynamics. Submitted to *Ocean Dynamics*.
- Van Duren, L. (2009). Programme LTV-ecology. Deltares, Delft, The Netherlands.
- Van Kessel, T., J. Vanlede, A. Bruens (2006). Development of a mud transport model for the Scheldt estuary in the framework of LTV. WL | Delft Hydraulics & WL Borgerhout report Z4210.
- Van Kessel, T., J. Vanlede, J. de Kok (2007). Development of a mud transport model for the Scheldt estuary in the framework of LTV. Phase 1. WL | Delft Hydraulics & WL Borgerhout report Z4375.
- Van Kessel, T., J. Vanlede, J. de Kok (2009). Development of a mud transport model for the Scheldt estuary. To be publ. in *Continental Shelf Research*, Special Issue INTERCOH 2007, Brest, France.
- Van Kessel, T., J. Vanlede, M. Eleveld, D. van der Wal (2008). Mud transport model for the Scheldt estuary in the framework of LTV. Deltares report Z4594, Delft, The Netherlands.
- Vanlede J.; Schramkowski G.; De Mulder T.; Mostaert F. (2009). Mud transport model for the Scheldt estuary: Hydrodynamics report. WL Reports, 756\_06. Flanders Hydraulics Research: Antwerp, Belgium.
- Vanlede, J.; Boudewijn Decrop; Bob De Clercq; Stefaan Ides; Tom Demulder; Frank Mostaert (2008). Permanente verbetering modelinstrumentarium. Verbetering Randvoorwaardenmodel. Deelrapport 2: afregelen 2D-Scheldemodel. WL Rapporten, 753. Waterbouwkundig Laboratorium en IMDC: Borgerhout, België.
- Van Maldegem D. (2002). Overzicht gegevens voor LTV-slibmodel Schelde-estuarium. Werkdocument RIKZ/AB/2004.821x. RIKZ.
- Van Maren, D. S., J. C. Winterwerp, and R. E. Uittenboogaard (2007). New developments in the mud transport module of Delft3D, report II: Implementation, sensitivity analysis, calibration and validation. Delft Hydraulics report Z3824.55, Delft.
- Verlaan, P.A.J. (1998). Mixing of marine and fluvial particles in the Scheldt estuary. Ph.D. thesis Delft University of Technology, The Netherlands.
- Wartel, S., M. Chen, G.T.M. van Eck, D. van Maldegem (2007). Influence of harbour siltation on mud accumulation in the Scheldt estuary. *Aquatic Ecosystem Health & Management*, 10(1), pp. 107–115.
- Winterwerp J.C., A.J. Manning, C. Martens, T. de Mulder, J. Vanlede (2006). A heuristic formula for turbulence-induced flocculation of cohesive sediment. *Estuarine, Coastal and Shelf Science* 68, pp. 195–207.
- Winterwerp, J.C. and De Kok, J. (2006). Plan van aanpak LTV-slib: modelinstrumentarium t.b.v. beheersproblematiek slib. Intern document no. Z4210.95 – M756/01.