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LTV O&M Actieplan 2004 voor morfologisch onderzoek, Modelinstrumentarium Mike11

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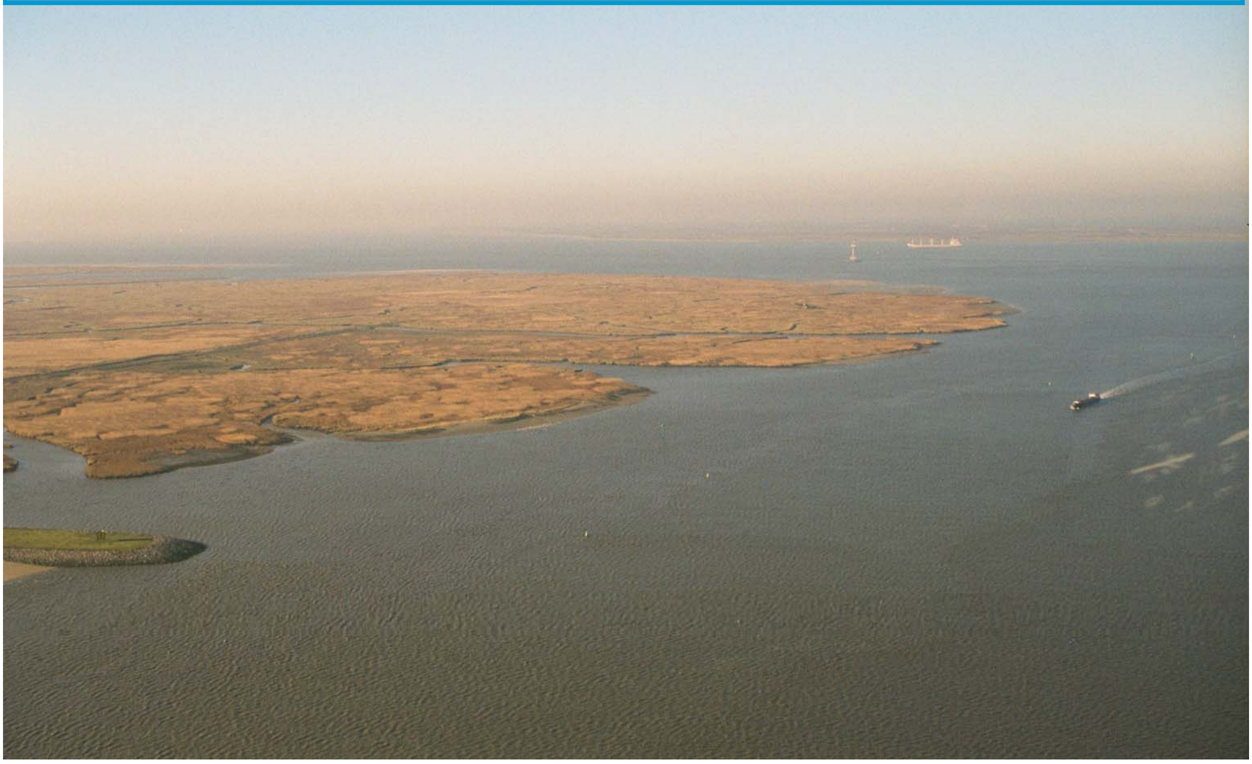
Verdronken Land van Saeftinge



Report 2: morphologic model

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1. INTRODUCTION

The MER commission "*Strategische milieueffectrapport ontwikkelingsschets 2010 Schelde-estuarium",* has recommended the development of a set of operational morphological models in order to provide technical assessment during the deepening of the Western Scheldt. Based on this recommendation, the Technical Scheldt Commission (TSC) has established an action plan for the morphological modelling of the Western Scheldt.

As part of the Dutch and Flemish Long Term Vision project, and within this "action plan 2004 for morphological research", it was concluded that the current set of models could no longer consist only of Delft- 3D and therefore should be extended. IMDC was invited to present an offer in order to develop a morphological model of the Western Scheldt and Lower Sea Scheldt based in the existing MIKE 11 SIGMA-model.

The terms of reference for this study were prepared by the "Administratie Waterwegen en Zeewezen, Afdeling Waterbouwkundig Laboratorium en Hydrologisch Onderzoek" (16EB/04/16).

1.1. Objective of the study

The objective of the present study is to transform the existing MIKE 11 1D model of the Western Scheldt and Sea Scheldt, built as part of the "actualization of the SIGMA Plan", into a 1D morphological model comparable to the SOBEK model developed by WL/Delft Hydraulics. This 1D model should be able to perform morphological simulations in order to evaluate different scenarios for the deepening of the navigation channel to the port of Antwerp.

To achieve this goal the existing MIKE 11 1D hydrodynamic numerical model has first to be adapted. This modified 1D model should be able to reproduce the water levels and discharges along the estuary, as well as the distribution patterns of the discharges in such a way that the residual discharges along the different branches (ebb and flood channels) are properly reproduced.

1.2. Overview of the study

The present report is the first of two reports describing the results of the study:

- Report 1: Hydrodynamic model (I/RA/11278/06.014/FPE).
- Report 2: Morphological model (I/RA/11278/06.015/FPE).

1.3. Structure of the report

This report gives a general description of the development of the 1-D morphological model of the tidal reach of the Scheldt, from Ghent to the mouth in the North Sea.

Section 2 presents a general characterization of the study area and the morphological characteristics. The morphological modelling approach including a description of specific calibration parameters is provided in section 3. Section 4 comprises model set-up, calibration and validation.

Finally, section 5 provides recommendations with respect to the 1-D morphological modelling approach and hence the applicability of the model as a dredging management tool.

2. THE SCHELDT ESTUARY

2.1. General description

The Scheldt originates in the north of France near Saint-Quentin at an altitude of 100 m above sea level and discharges into the North Sea approximately 350 km downstream. During its trajectory, the Scheldt receives different names:

- Upper Scheldt, from its origin down to Ghent.
- Sea Scheldt, from Ghent to the Dutch border.
- Western Scheldt, from the Belgian/Dutch border to the mouth in the North Sea.

The Upper Scheldt is a non-tidal river connected to the Sea Scheldt by means of the control structures of Zwijnarde and Merelbeke, which avoid the tidal waves to propagate up-stream and at the same time regulate the water levels in the ring-channel around Ghent.

The Sea Scheldt and Western Scheldt form together the Scheldt estuary, which constitutes the study area of the present project. Along the estuary 4 zones are distinguished for their geometry as well as for the local physical processes (De Kramer, 2002):

- The Upper-Sea Scheldt, which corresponds to the reach between Ghent and the Rupel: In this reach the tidal effects are still noticeable but the influence of upstream discharges dominates the behavior of the river. The width of the estuary increases from 50 m in Ghent to 300 m at the confluence with the Rupel. This fresh water reach receives most of the major tributaries of the Scheldt in the study area.
- The so-called Lower-Sea Scheldt, which stretches from the confluence with the Rupel to the Belgian/Dutch border: In this zone, the width of the estuary increases to nearly 2 km. This reach constitutes a transition area from slightly to highly brackish water.
- The Western Scheldt: This reach has a funnel shape, the width of which increases from 2 km at the border to over 5 km at the mouth in the North Sea. The salt concentration increases in the direction of the sea.
- Finally the mouth area in the North Sea corresponds to the delta-area situated between Vlissingen and Westkapelle, Zeebrugge/Oostende.

The most important area related to morphological changes is the Western Scheldt, which can be described as a typical multiple flood and ebb channel network. The ebb channels are deeper and have a sill at the seaward end where they join the flood channels. The flood channels are shallower and have a sill at the landward side (Peters, 2004).

From 1800 the influence of men starts to be important with land reclamation activities and from 1970 with dredging activities. One of the major changes in the last decades is the change of behavior at Middelgat and the Gat van Ossenisse, where the flood- ebb channel behavior has been exchanged at the two branches. However since 1970 the Gat van Ossenisse has remained as Flood channel. Figure 2-1 taken from Kramer (2002), illustrates the cyclical changes at this area.

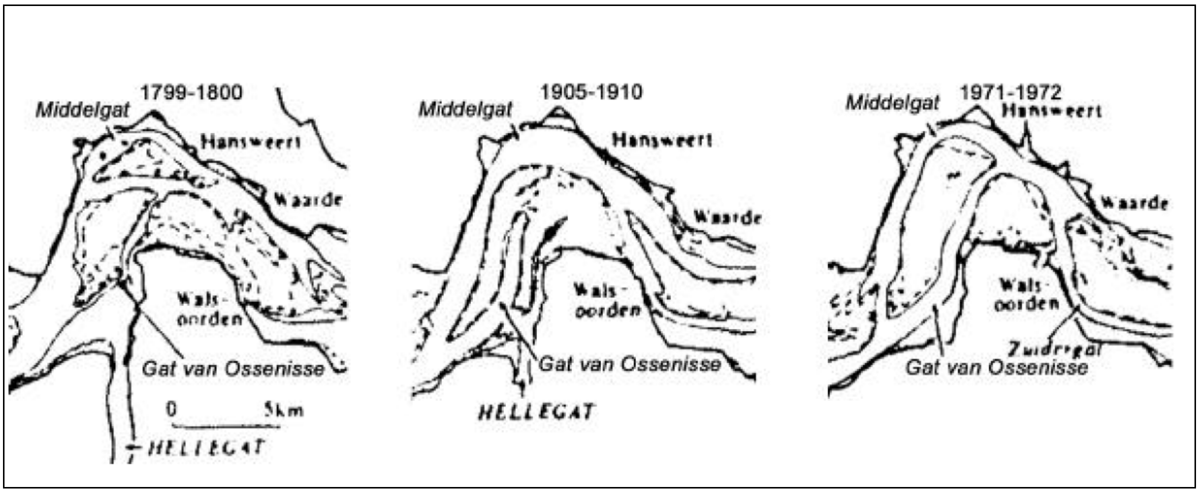


Figure 2-1: Cyclic changes in the position of the main channel close to Hansweert (Kramer,2002 after Coen, 1988)

According to Kuijper C. (2004) the sediment in the Western Scheldt consists mainly of sand with less than 10% mud in the channels and on the shoals (Dutch: platen), see van Eck (1999). Characteristic values for the median diameter (d50), as given by (van Eck, 1999) are:

- Channels: d50 > 150 µm;
- Shoals: d50 = 50-150 µm;
- Estuarine margin (intertidal areas and salt marshes): d50 < 125 µm.

In the upstream estuarine sections the grain size diameter in the channels is somewhat finer than in the downstream sections, with values ranging from 90 to 120 µm in the Sea Scheldt.

According to Kramer (Kramer, 2002), the first dredging works occurred at the sill of Bath and took place around 1905. Since 1925 a yearly program for deepening the navigational route of the Sea Scheldt has taken place. According to Meersschaut (Meersschaut et al., 2004), till 1970 dredging was restricted to maintaining depths on crossings in the navigation channel, formed by the main ebb channels. Traditionally, the sediments were disposed in the flood channels, with the assumption that it would take a rather long time before coming back into the main ebb channel.

With the demand for increased navigation depth, a first deepening started in 1970 and the dredged sediments were still disposed in the flood channels. Later a second deepening took place in the 90's. The location of dredging and dumping areas at the Western Scheldt for the year 2000 are indicated in Figure 2-2.

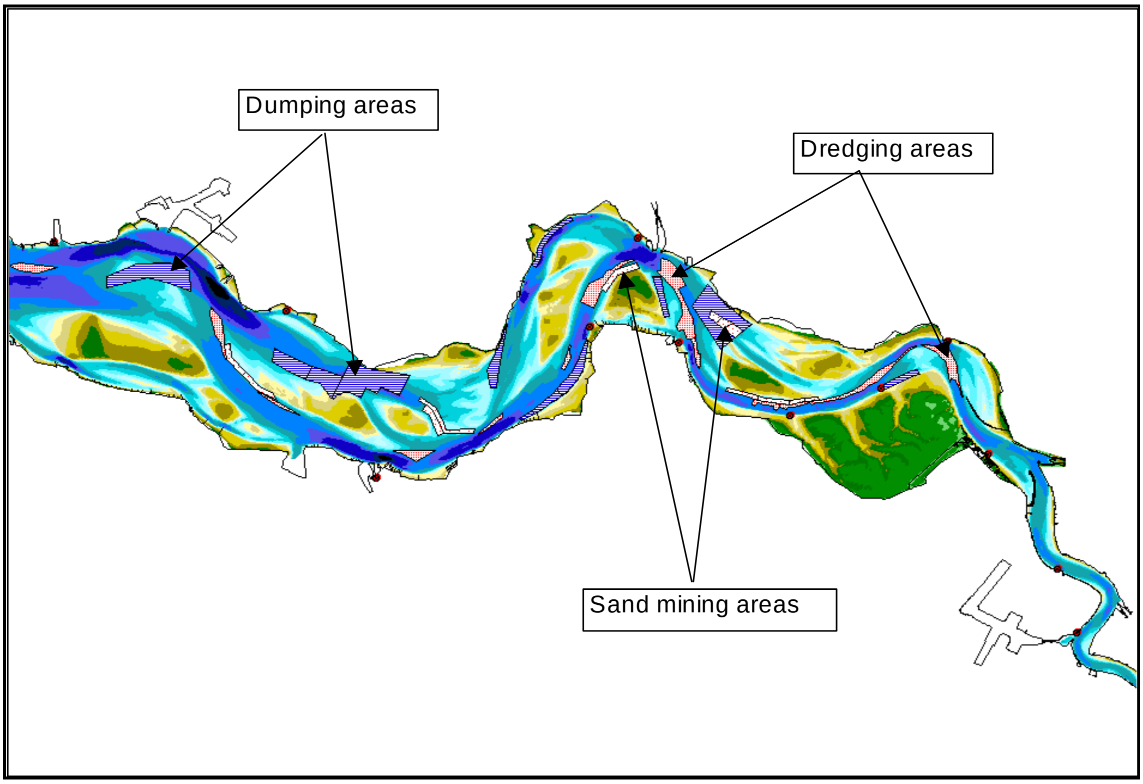


Figure 2-2: Location of the dredging and dumping areas in the Western Scheldt, year 2000.

3. APPROACH AND METHODOLOGY

For long-term prediction of river morphology, it is relevant to apply 1D modelling, which is cost-effective in terms of computation time. This could assist in prediction of long-term effects of different dredging and dumping strategies, river training measures and other projects in the Scheldt Estuary. Considering the timescale associated with the morphological changes in the estuary, the application of more adequate 3-D models, often lead to unacceptable long simulation times in terms of CPU time. Thus from a practical engineering and management point of view a more simplified approach is often preferred. One approach is to conduct short-term simulations (say a neap spring tidal cycle) with a 3-D model and extrapolate the results to a longer time period. Although appealing and often applied there is a large uncertainty with such an approach due to the very non-linear morphological processes. Alternatively one may apply a more simplified 1- D approach, realizing of course the limitations with this approach, and make model simulations covering the entire period of typically 10 to 20 years. The latter approach is the one investigated in the present project.

The study objective is to transform the original SIGMA 1D model of the Western Scheldt and Sea Scheldt into a 1- D morphological model.

In this context the MIKE 11 NST module has been used. NST is an abbreviation for Non Cohesive Sediment Transport thus only the sandy non-cohesive part of the sediment can be considered. A detailed technical description can be found in Appendix B.

However, in order to tailor the standard MIKE 1- D models to the Scheldt estuary additional features have been implemented into the MIKE 11 software:

- A flow direction dependent bed friction term and local energy losses in junctions in order to account for asymmetric bed forms and the apparent problems in a 1 - D model with respect to inertia forces in bifurcations. The need and reason for a flow dependent bed friction term in a 1- D model description has been argued in previous investigations. (Fokkink, 1998).
- Automatic calculations of net sediment deposit volumes (m^3) in each time step and in each computational grid point. Standard model results from MIKE 11 NST comprise sediment transport (bed load and suspended load depending on the morphological model description applied), accumulated transport and bed elevation. The bed elevation corresponds to the lowest level in the cross-section. In order to facilitate comparison with the observed data it was therefore decided to develop additional output from MIKE 11 in terms of net sediment deposit volumes. Alternatively the simulated accumulated sediment transports combined with the dredging / dumping and mining activities can be used to establish the sediment balance on macro cell level.

3.1. 1D Model Schematisation Issues

The original SIGMA model of the Western Scheldt is displayed below.

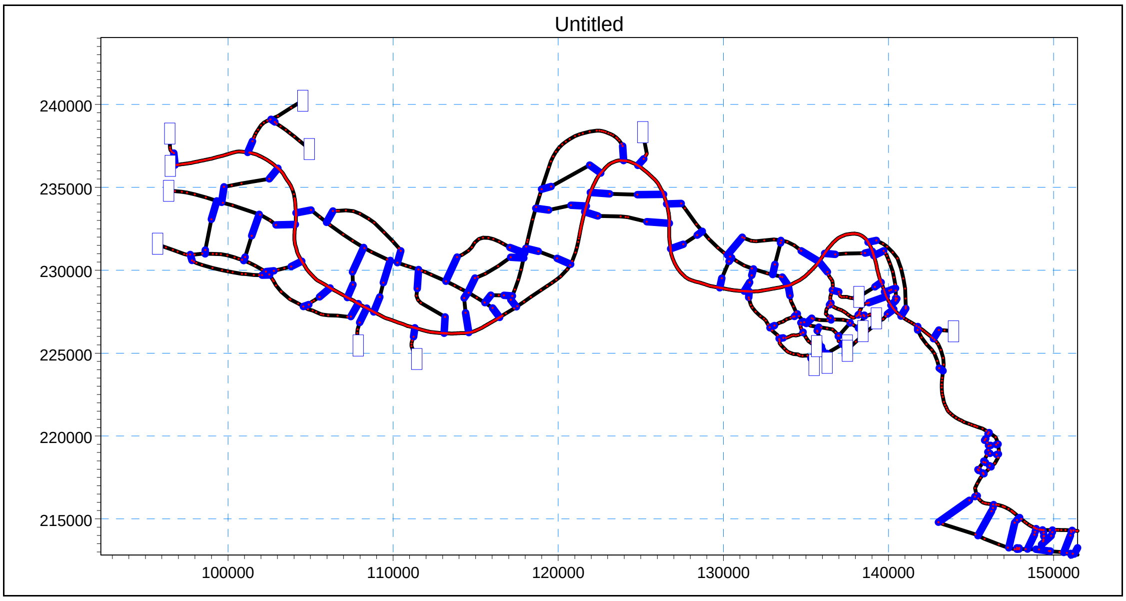


Figure 3-1 Original SIGMA network

For the long-term sediment transport modelling with the 1D model, three conditions need to be fulfilled:

1. The location of the main channels must remain the same, i.e. the discretisation of the main branches are valid throughout the study period
2. The ebb and flood channels are adequately described in the 1D model, i.e. the horizontal circulation patterns must be reproduced.
3. The shape of the cross-sections can be assumed to be the same throughout the study period, as a 1D model cannot by definition predict changes in width/depth ratios.

The existing model was developed focussing on flood forecasting and comprise a comprehensive network of branches and computational grid points. An especially large effort has been put into the description of upstream-inundated areas during high flows, which requires an extensive number of computational grid points. The accuracy of the morphological model does, however, not justify a large number of grid points as the cross-sections are changing anyway in response to wavelengths larger than those resolved in riverbed soundings. Instead representative cross-sections have been selected. Using this concept (as sketched below) the number of cross-sections in the existing model (and hence computational grid points) has been reduced significantly.

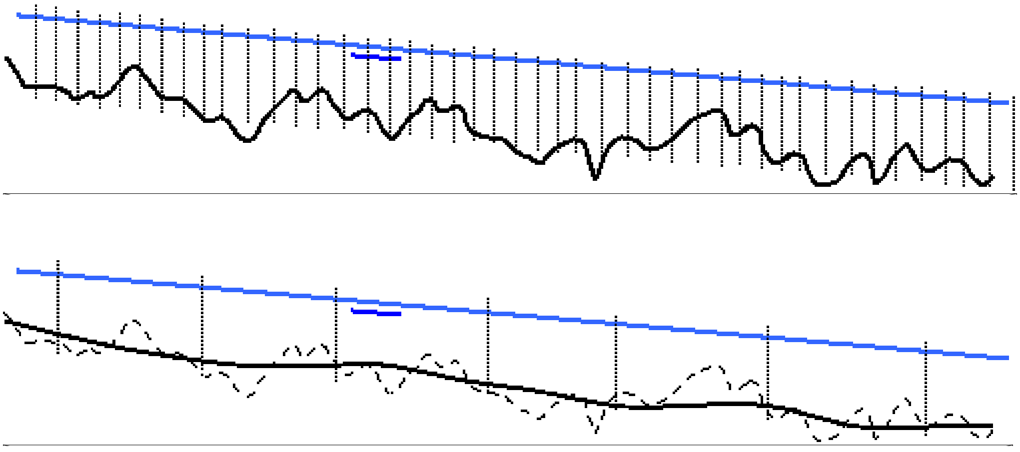


Figure 3-2:Model layout for sediment transport model.

In the same way the description of inundated areas has been simplified, however, in such a way that the tidal volume entering and leaving the estuary during a tidal cycle is unchanged.

The reduction in grid point implies shorter CPU time, which is highly relevant considering the objective of establishing a practical management tool for assessment of various dredging scenarios.

3.2. Flow in bifurcations

By definition, a 1D model is not capable of simulating the 2D flow distribution in nodal points. This has to be defined a priori. Take as an example the flow in a bifurcation. Assume that the two identical channels, B and C, join at location D.

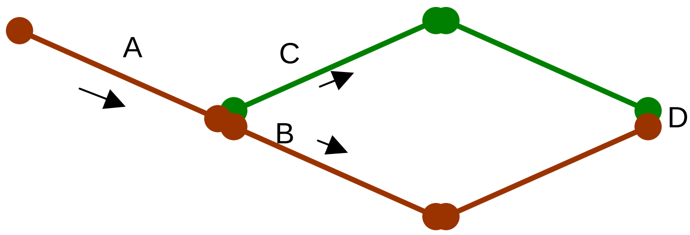


Figure 3-3:Bifurcations

In reality, the approach channel A (a flood channel), will lead more water into the flood channel B and less water into the ebb channel C, because of the platform alignment and the inertia forces causing the flow to be directed towards B. In a 1D model the flow distribution will simply depend on the conveyance (natural flow capacity) in the two channels C and B. Thus the real flow momentum and direction can only be represented in the 1D model, if an energy loss due to abrupt flow direction is included in the set-up. Such an additional energy loss description has been included in MIKE 11 as part of the project.

A flow direction dependent bed friction term has also been introduced into MIKE 11. The need for such a description in order to reproduce net circulations on a "macro cell" level has been demonstrated in several papers by Delft (Fokkink, 1998). This feature can also be used to control a flow direction dependent distribution in junctions by simply increasing the resistance in Channel C in Figure 3.3 above.

3.3. 1 D Cross-sectional flows

The description of flow within the cross-section must be subject to particular attention.

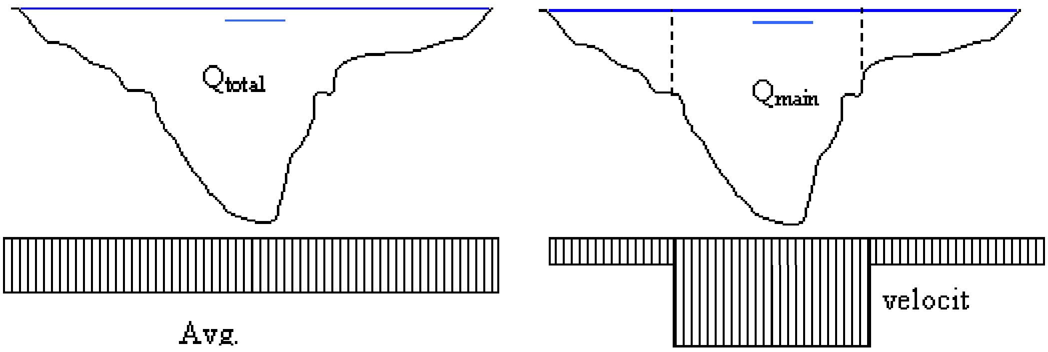


Figure 3-4: Definition of average flow

Because of the non-linear nature of sediment transport, it is important to have a consistent description of the average flow velocity (or shear stress) in every cross-section. The simplest way is to divide the entire channel discharge with the entire cross-section area. However, this will give another value of the representative bed shear stress than to use a value based on the main channel discharge divided by the effective cross-section area in the main channel, as demonstrated above. Within MIKE11 there is an option to define an effective area for sediment transport, the so-called morphological divide level of division which can be defined in each cross-section as illustrated below. The level of morphological divide will generally be selected at the vertical dividing the inter-tidal flats and the deeper navigational parts (in Figure 3-5). Although not general for all cross-sections the level of divide in the Western Scheldt estuary is typically around level 0 m T.A.W. The level of divide approach is applied to the ebb- and flood channels and specified separately in MIKE 11 for each cross-section.

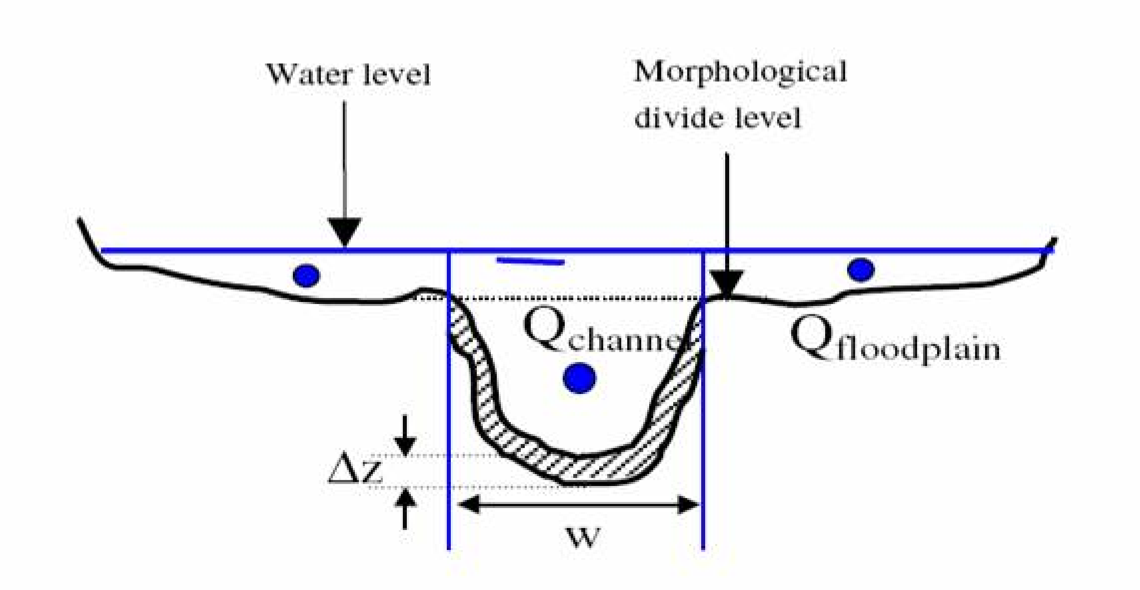


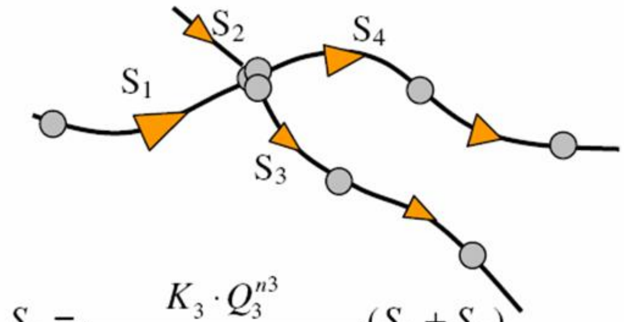
Figure 3-5: Morphological level of divide

3.4. Sediment Transport Formula

A range of sediment formulas exist within MIKE 11 such as Ackers & White, Engelund Hansen, Smart & Jaeggi (total load models), Meyer- Peter&Müller, van Rijn, Engelund Fredsøe, Lane-Kalinski, Ashida, and tailored empirical formulas. However, based on the studies already carried out by Delft with the 3- D model (Kuijper, 2004) it was decided to use the van Rijn model. According to this study sensitivity analysis with respect to sediment models revealed little difference between the van Rijn model and e.g. the Engelund Hansen model. All though it can not be concluded that 1D MIKE 11 simulations will reveal similar small differences the scope of the present study does not allow for a sensitivity study with respect to the sediment transport model.

3.5. Sediment Split Function

At a bifurcation point, the water discharge is distributed according to the downstream conveyance. The distribution of sediment transport at a nodal point is less easy to parameterise because of the inherent two-dimensional pattern in a bifurcation point. A sediment split function with two calibration parameters for each joining branch exists in MIKE 11. The calibration parameters can be different in different nodal points.



$$S_3 = \frac{K_3 \cdot Q_3^{n3}}{K_3 \cdot Q_3^{n3} + K_4 \cdot Q_4^{n4}} (S_1 + S_2)$$

S Sediment transport (m^3/s)
Q Discharge
K,n Calibration coefficients

Figure 3-6:Sediment split function

3.6. Passive branches

The possibility of defining morphological passive branches saves CPU time and at the same time eliminates potential problems with morphological simulation of branches not contributing to the sediment balance. A typical example is the flood plains in the upstream end of the Scheldt estuary. In general only the ebb- and flood channels and the upstream part comprised by Sea Scheldt are defined as being active. All other branches are defined as being passive. Passive imply that sediment can be transported into the channel but there is no sediment transport out of a passive channel. Nor can there be erosion or deposition in a passive channel. This implies that link channels will act as a sediment trap and one should be careful when using this feature. However, the link channels in the present set-up carry little flow and sediment compared to the ebb and flood channels in the Scheldt estuary. Consequently the impact on the sediment budget from the passive branches is considered insignificant.

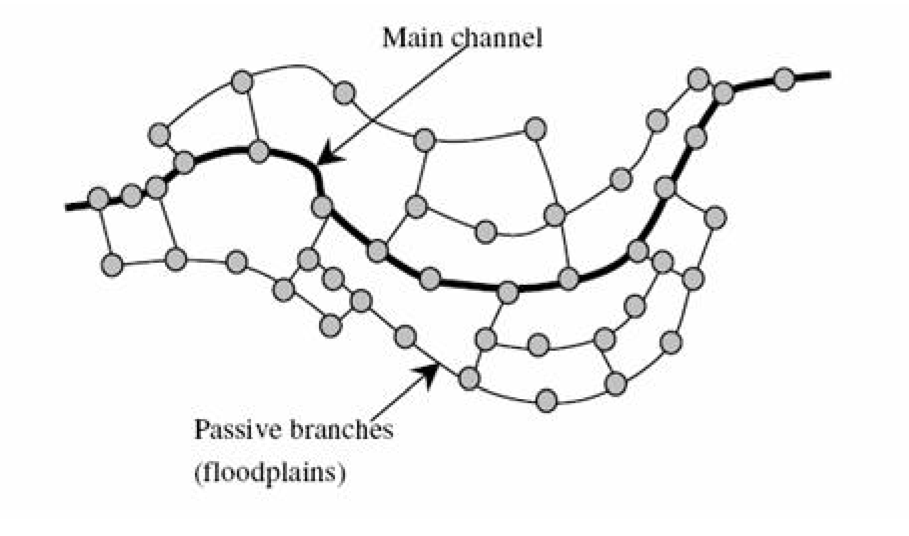


Figure 3-7:Passive branches

3.7. Boundary Conditions

The hydrodynamic boundary condition is recorded water levels at the seaward boundary at Vlissingen for a continuous period from 1968 through 2004 combined with average upstream inflows covering the same period. Average inflows are based on the entire simulation period 1968 through 2004.

The seaward sediment boundary condition is established utilising a variation in bed level as recorded during the simulation period. Thus, the inflow (during flood) sediment boundary is controlled by the natural sediment transport capacity with the given bed elevation at the boundary. A similar type of boundary condition is applied at the upstream boundary in Sea Scheldt, i.e. it is assumed that the riverbed is locally in equilibrium at the upstream boundary. A zero flux boundary is applied at all other external boundaries.

3.8. Dredging, dumping and sand mining

The man-intervention in terms of dredging, dumping and mining activities has a significant impact on the sediment balance and hence the morphological development in the estuary. Thus the actual dredging and dumping quantities have been included as sink and source terms into the sediment balance in the MIKE 11 model. The data are processed into the model via time series of sediment extraction (where sediment is dredged) and supply (where sediment is dumped). Detailed information on the spatial and temporal resolution of these activities is available to the project and has been utilised to produce corresponding time series (in m^3/ sec). A total of 121 sources and sinks have been generated accounting for 98% of the dredging, dumping and mining works. The remaining 2 % have for all practical reasons been ignored. The 121 sources are associated with the nearest computational grid point in the model set-up. The distributed dredging and dumping activities, however, are lumped into single computational points, which of course may lead to unrealistic local erosion or deposition in the model. In such cases the activities will have to be redistributed to the neighbouring points. It is not possible to distinguish between activities on the intertidal parts of the cross-sections and the deeper parts in the navigational channel. Thus all activities will be assumed to be available in the morphological active part of the cross-section. That is below the level of morphological divide. The actual locations of sink and sources can be found in the MIKE 11 system files for the “SIGMA morphological” model. For future simulations beyond 2003 one has of course to update the point sources in the model to reflect actual or planned future activities.

3.9. Simulation period, time step and morphological updating

It is envisaged to simulate the entire calibration and validation period from 1968 through 2004 utilising the recorded tide. A time step of 7.5 minutes has been applied, and the model is morphologically updated at each time step. Thus the riverbed (profile) is automatically updated during simulations to account for impacts of morphological changes.

3.10. Model calibration issues

Prior to calibration of the morphological model the net circulation on macro cell scale from flood to ebb channels has to be reproduced. In this context the flow direction dependent flow resistance has been utilised.

4. MODEL SET-UP AND RESULTS

The model calibration of the MIKE 11 morphological model initially comprises optimisation and recalibration of the MIKE 11 hydrodynamic model, which is the platform for all sediment transport calculations. During execution of the MIKE 11 NST model the two models run in a coupled mode with updating of the river bed at each time step based on the computed erosion or deposition at each grid point. Consequently there is also feed back to the hydrodynamic computations at each time step due to the change in bed morphology. During the initial calibration process a model set-up without extension into the North Sea has been applied. Subsequently the model has been extended into the North Sea in order to match the complete study area as comprised by the Sobek model. The different steps involved during model calibration are summarised in Appendix A. Appendix A also provides a complete overview of the various versions of the SIGMA model.

4.1. Optimisation and recalibration of the MIKE 11 HD model

The original SIGMA model ("Existing SIGMA-HD model") has been optimised for the morphological simulations in such a way that the model, although significantly reduced when it comes to computational grid points, provides the same tidal dynamics (flows and water levels) in the main flood and ebb channels. The reduced network is shown in Figure 4-1 below. The total number of computational grid points has thus been reduced from 18628 in the original SIGMA model to 3500 in the North Sea extended "SIGMA morphological" model and to 974 in the "SIGMA-Morphological-reduced" model. It should be emphasized that this model should not be used for flood forecasting as no attempt has been made to validate the simplified model against extreme high waters. As can be observed the complex network describing e.g. "Verdronken Land van Saeftinge", has been replaced by a single branch reproducing the tidal volume entering this area during high water only.

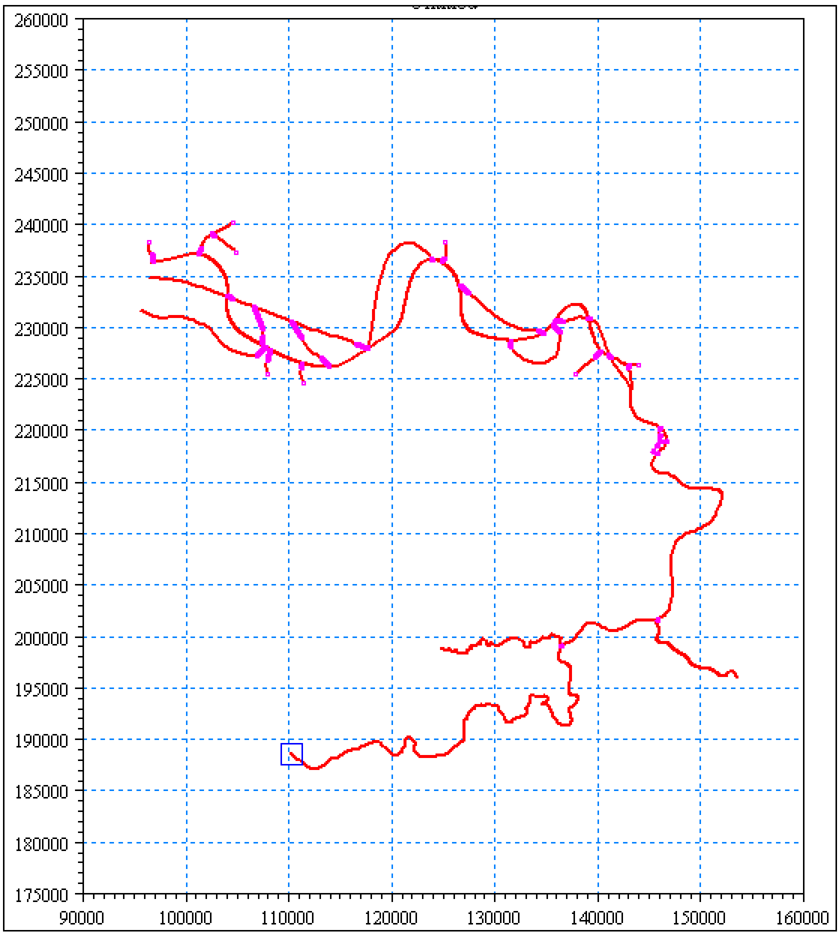


Figure 4-1:"SIGMA morphological reduced" model set-up

Particular focus has been on the reproduction of the net circulations in the hydrodynamic model. Based on historically estimated tidal volumes entering and leaving the estuary during a tidal cycle (data received from RIKZ) it is possible to establish an estimate of the net flow in the ebb and flood canals.

Utilising the 1968 bathymetry the "Reduced-Modified-SIGMA-HD" model has been adjusted to capture the observed average tidal net flows or residuals. Only by activating the flow direction dependent bed resistance (Manning number) as developed for the present project in MIKE 11 it has been possible to obtain satisfactory results. Generally an increased resistance has been applied during outflows in the flood canals hence leading to increased outflow in the ebb canals. This feature results in the observed anti clockwise circulations as observed around the macro cells (See Figure 4-2 for definition of macro cells). The results are depicted in Figure 4-3. As can be seen there is generally a good agreement between model results and the estimated circulations. Only in macro cell 6 the simulated net circulation is significantly weaker than the one estimated. Subsequently the same flow dependent bed resistance variation has been applied to the existing model utilising the most recent bathymetry data from 2001. Model comparison with measured circulation, in the period 1988 to 1991, likewise provides a good agreement between model results and measurements. This observation seems to further justify the choice of flow dependent parameters. It should be noted that is has been necessary to introduce a significant increase in resistance (30-60 %) during outflow in the flood channels. Such an increase can not be justified by the bed forms alone. Thus the applied increase likewise account for other effects not resolved in a 1-D model as discussed in section 3.2.

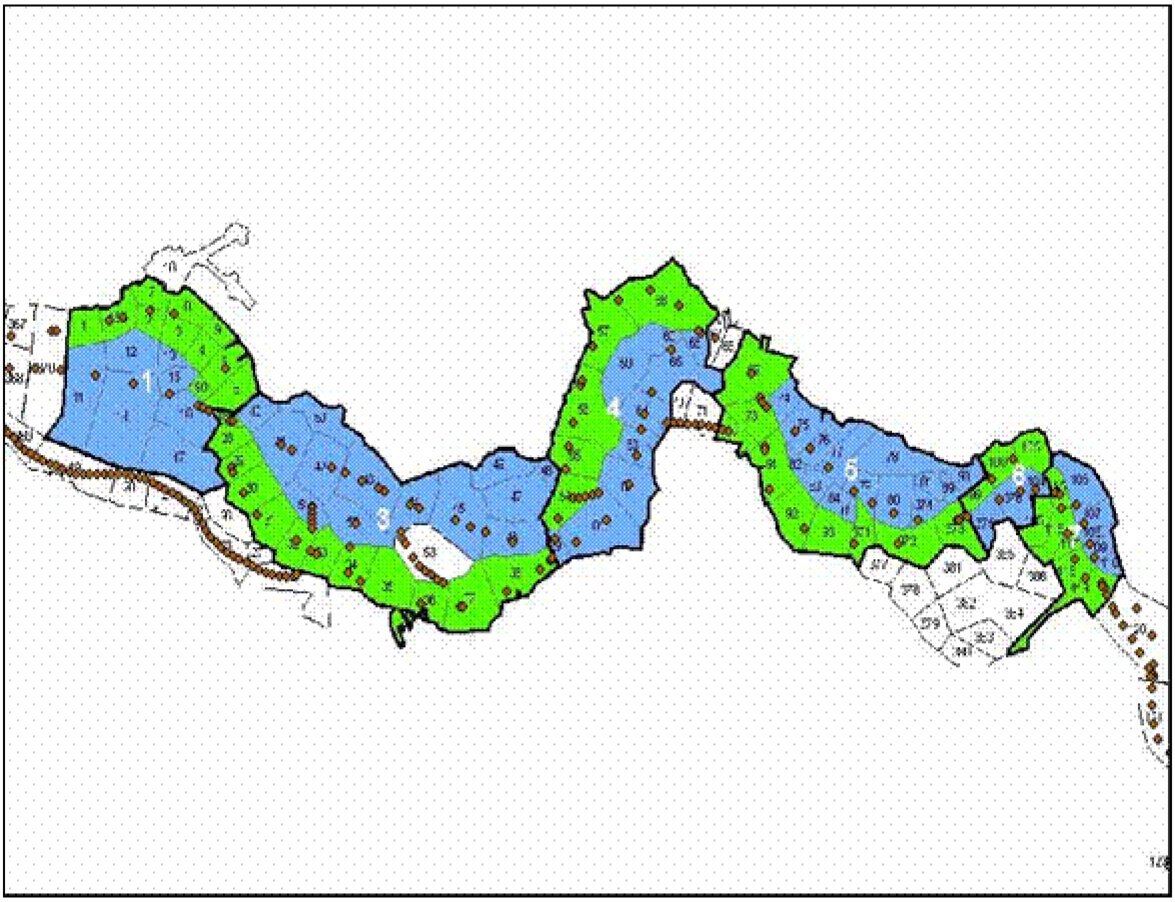


Figure 4-2: Location of Sobek micro and macro cells. Orange dots representing MIKE 11 computational points.

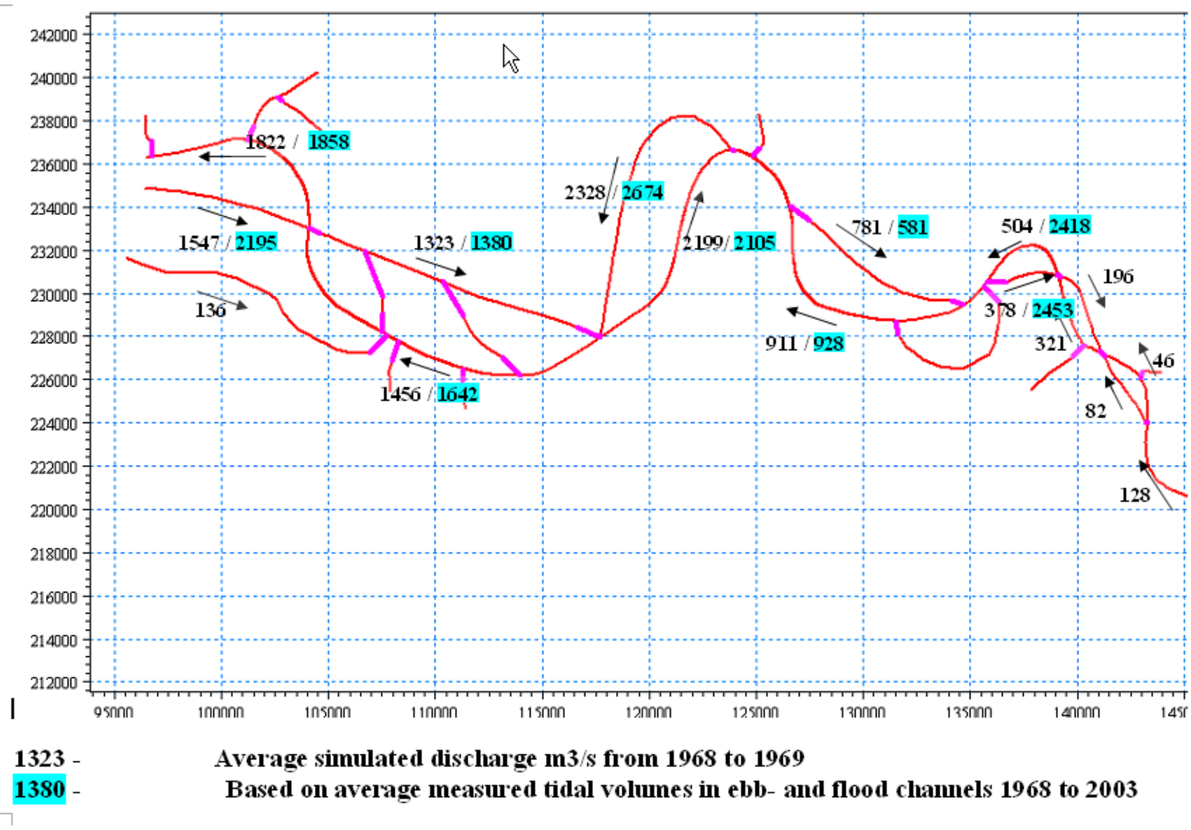


Figure 4-3: Simulated and estimated net circulations utilising a 1968 bathymetry.

4.2. Conditions of 1D Morphological modelling concept

Focus is on the three conditions that need to be fulfilled with respect to the 1-D modelling concept, namely:

- The location of the main channels must remain the same, i.e. the discretization of the main branches is valid throughout the study period
- The ebb and flood channels are adequately described in the 1D model, i.e. the horizontal circulation patterns must be reproduced.
- The shape of the cross-sections can be assumed to be the same throughout the study period, as a 1D model cannot by definition predict changes in width/depth ratios.

It has been demonstrated that the hydrodynamic model is capable of reproducing the circulations. In Figure 4-4 and Figure 4-5 cross-sections at two different locations in the Western Scheldt are depicted. It is remarkable to note that the cross-section in the estuary mouth has moved almost 300 m during the period from 1968 to 2001. This observation is in principle in disagreement with the first of the above assumptions. However, inspection of the historical bathymetry data seems to confirm that this phenomenon is limited to the most seaward part of the estuary only and one can conclude that the location of the main channels remains more or less the same in the remaining part of the estuary. Further up in the estuary the morphological changes generally seem to be a combination of bank erosion/ deposition and deepening of the deeper part of the navigational channels. It should be noted that the 1- D model is not suited to describe the morphological changes on the inter-tidal flats (also comprised by the cross-sections) and a morphological divide has been introduced typically at a level corresponding to zero. This implies that only the area below the morphological division is considered morphologically active and only this part of the cross-section is updated in the model.

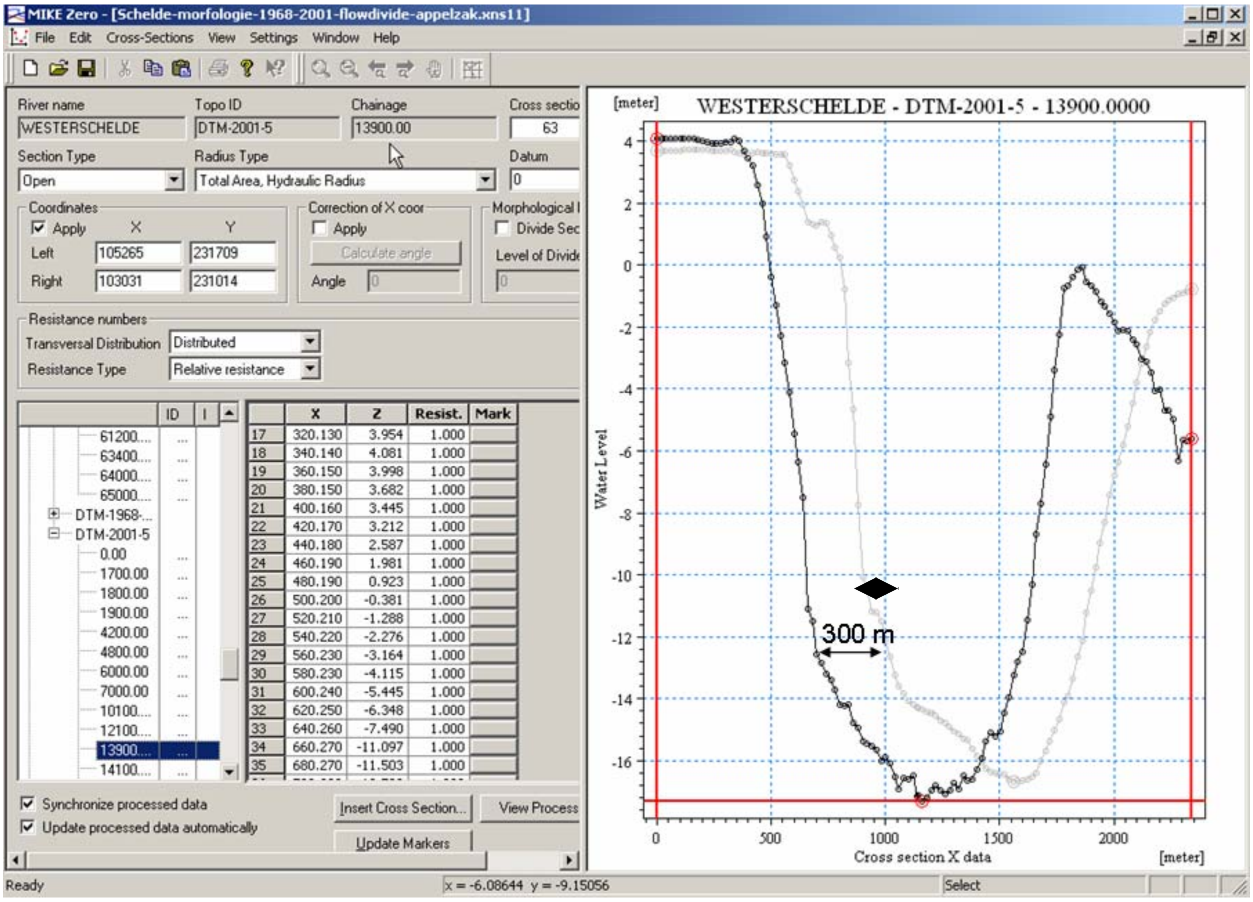


Figure 4-4: Channel cross-section in 1968 (grey contour) and 2001 (black contour) in the Western Scheldt near Vlissingen.

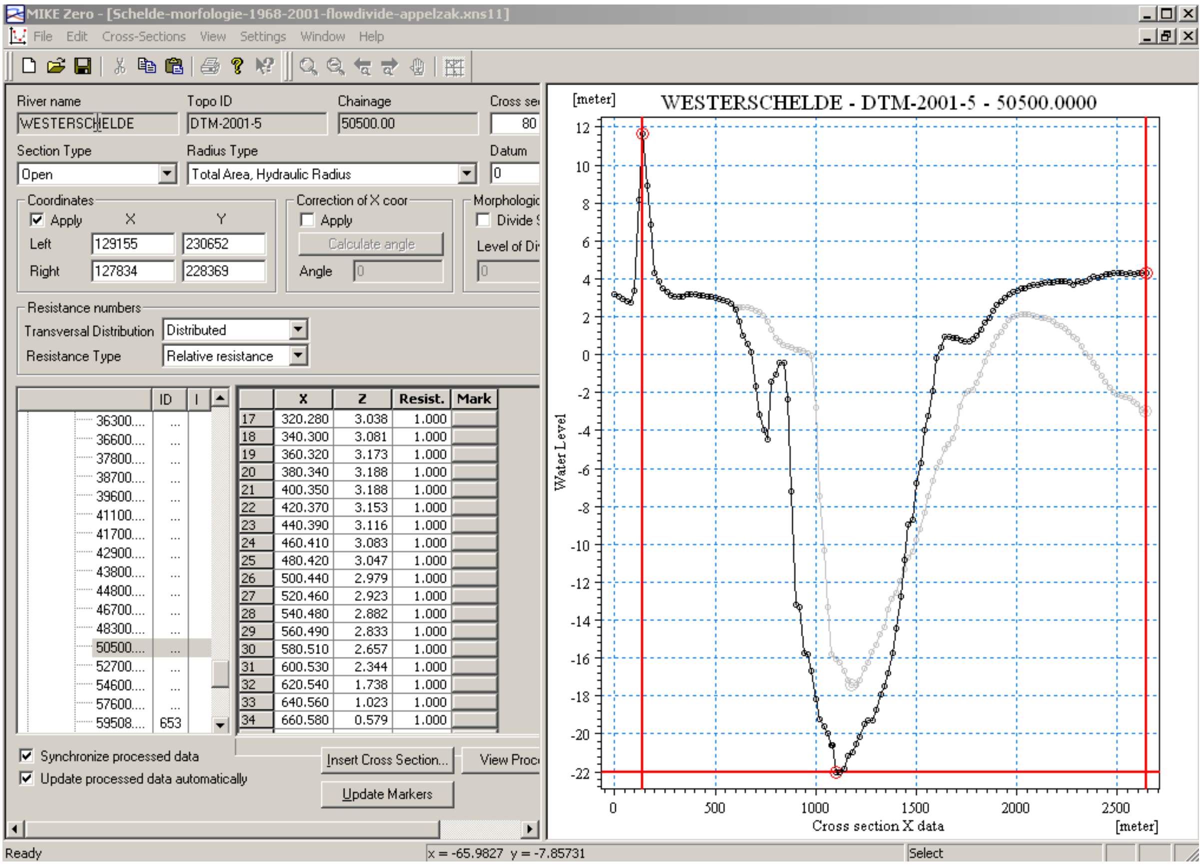


Figure 4-5: Channel cross-section in 1968 (grey contour) and 2001 (black contour) in Western Scheldt, chainage 50500 within macro cell 5.

4.3. Morphological updating mode

In principle there are 5 different modes of updating as shown in Figure 4-6.

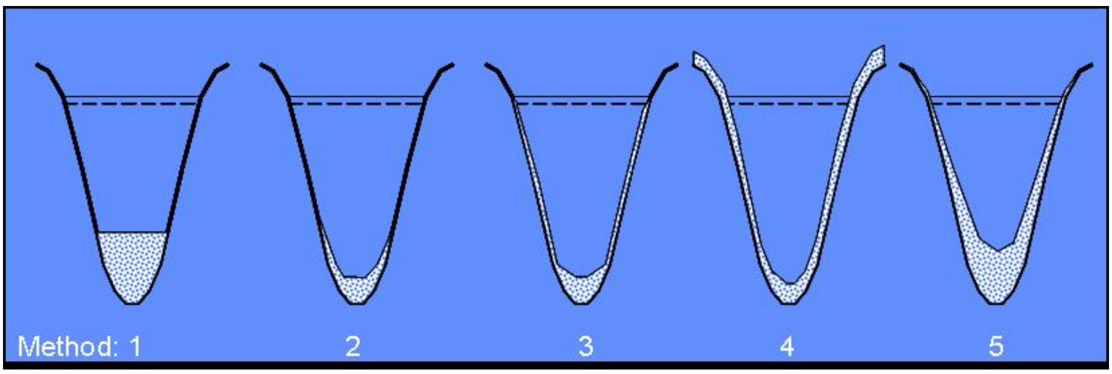


Figure 4-6: MIKE 11 morphological updating modes

Inspection of the cross-sections seems to justify an updating mode number 4. This is by no means consistent everywhere but seems to be the best compromise. It should be noted that it is only possible to have one global update mode for the entire network in MIKE 11.

4.4. Grainsize of the mobile bed material

Inspection of the available bed samples with respect to sediment particle diameter, reveals a variation in the range from 100 to 300 micron with the more coarse sediment in the western part of the estuary, see Figure 4-7. The bed composition (represented by the D_{50} sediment grain diameter) is an important input parameter to the morphological model. If D_{50} is underestimated locally, the sediment transport equation overestimates the actual transport and the model will react by erosion and visa versa.

Initially an average diameter of 200 micron was selected for the entire model area.

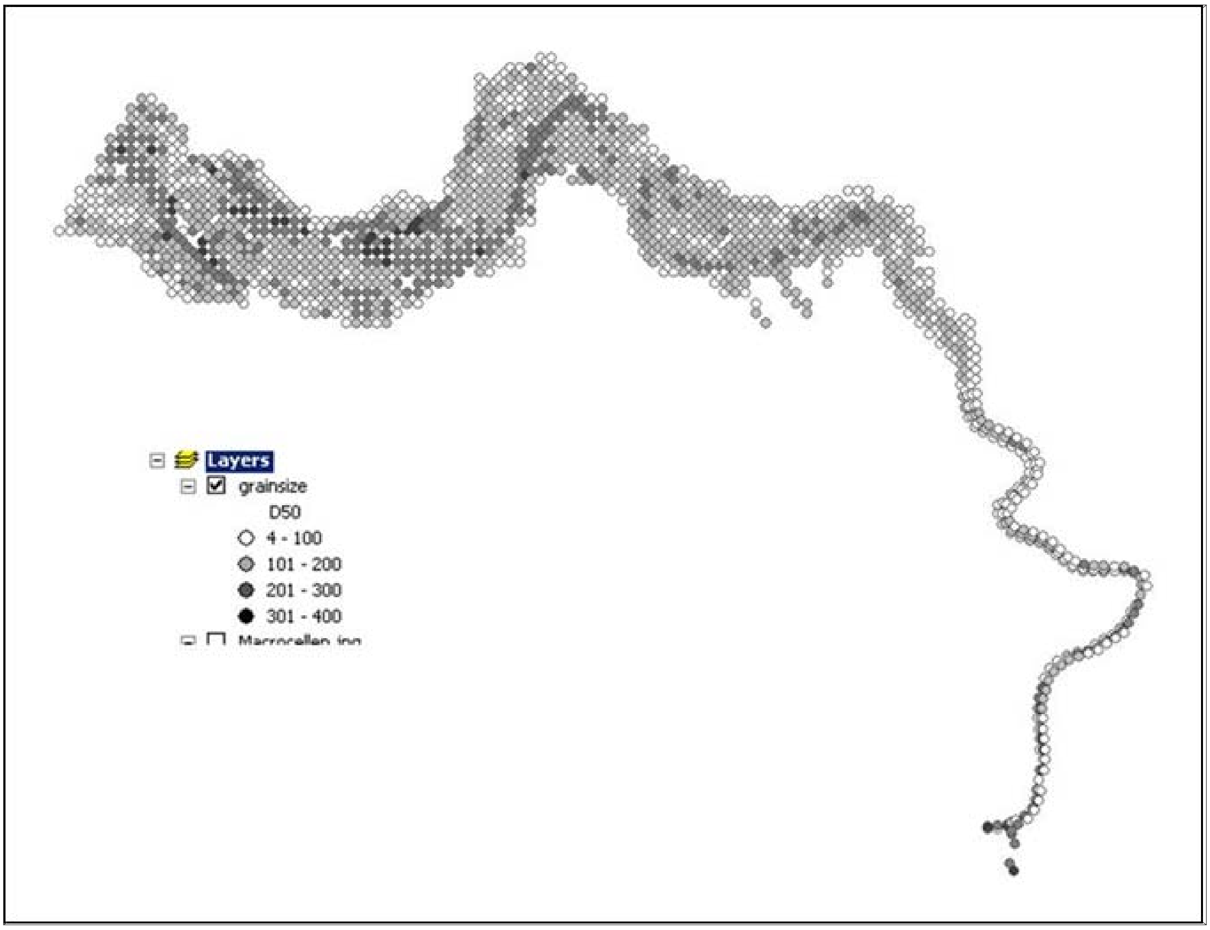


Figure 4-7:Variation in sediment grain diameter D_{50} (micron)

5. CALIBRATION

The morphological model comprises several calibration parameters such as:

- Sediment split function at junctions
- Scaling factor applied to the computed bed and suspended load transport

In addition calibration will comprise

- Adjustment of sediment grain diameter D_{50}. A spatial variation may also be applied if the data support such a variation.
- Tuning of effective transporting area in each cross-section (using the morphological division option in MIKE 11)

The model calibration period extends from 1968 through 1994. Subsequently a verification period from 1994 to 2004 is envisaged. Considering the time scale associated with morphological changes the model will be run for the entire period 1968 through 2004. If the model is restarted in 1994 with a new bathymetry, the model results may be disturbed by the new “initial “ condition introduced by the 1994 bathymetry (new cross-sectional data). With respect to verification (from 1994 to 2004) focus will be on the model-simulated development in bed evolution compared to the observed changes.

The calibration comprises comparison with:

- Measured sediment transport rates during selected tidal cycles in the period 1988 through 1990
- Accumulated (observed) sediment volume changes for the ebb and flood canals on a macro cell level as defined in the WL Delft Estmorf and Sobek models. In this context data has been provided by WLH on micro cell level and has been aggregated to macro cell level as a part of the present project.

5.1. Calibration Parameters

Model calibration parameters comprise scaling of the computed sediment transports and split functions to control sediment transport distributions in bifurcations. In order to adjust the scaling factor with respect to transports model simulations were compared with actual sediment transport measurements carried out in selected transects during a tidal cycle. Such measurements are associated with substantial uncertainty. Particularly the bed load is difficult to measure. Nevertheless the measurements have been used to control the scaling factor in the model. The measurements comprising typically two verticals in an ebb and flood canal were simply integrated over the cross-section in order to obtain cross-sectional average sediment transports. The model results are shown in Figure 5-1 through Figure 5-4. Generally there is a good agreement between model simulations and measurements. A significant difference in phase between measurements and model simulations is observed in the flood channel in Macro Cell 3.(Figure 5-3). This difference is believed to be due to a mistake in the processing of measured data, however, no attempt has been made to investigate this in more details. The general good agreement leads to the conclusion that the model is capable of reproducing the recorded sediment transport with respect to phase and amplitude and thus there is no need for scaling of the simulated transports at these locations. Only in the flood channel Schaar Spijkerplaat in Raai 9 the simulated transport during ebb flows seems less than observed. It should be noted that the model results comprise transports during single tidal cycles obtained after 20 years of simulation. As can be clearly seen in Figure 5-1 the model results vary significantly from neap to spring tide and also from spring tide to spring tide reflecting the very dynamic flows in the estuary.

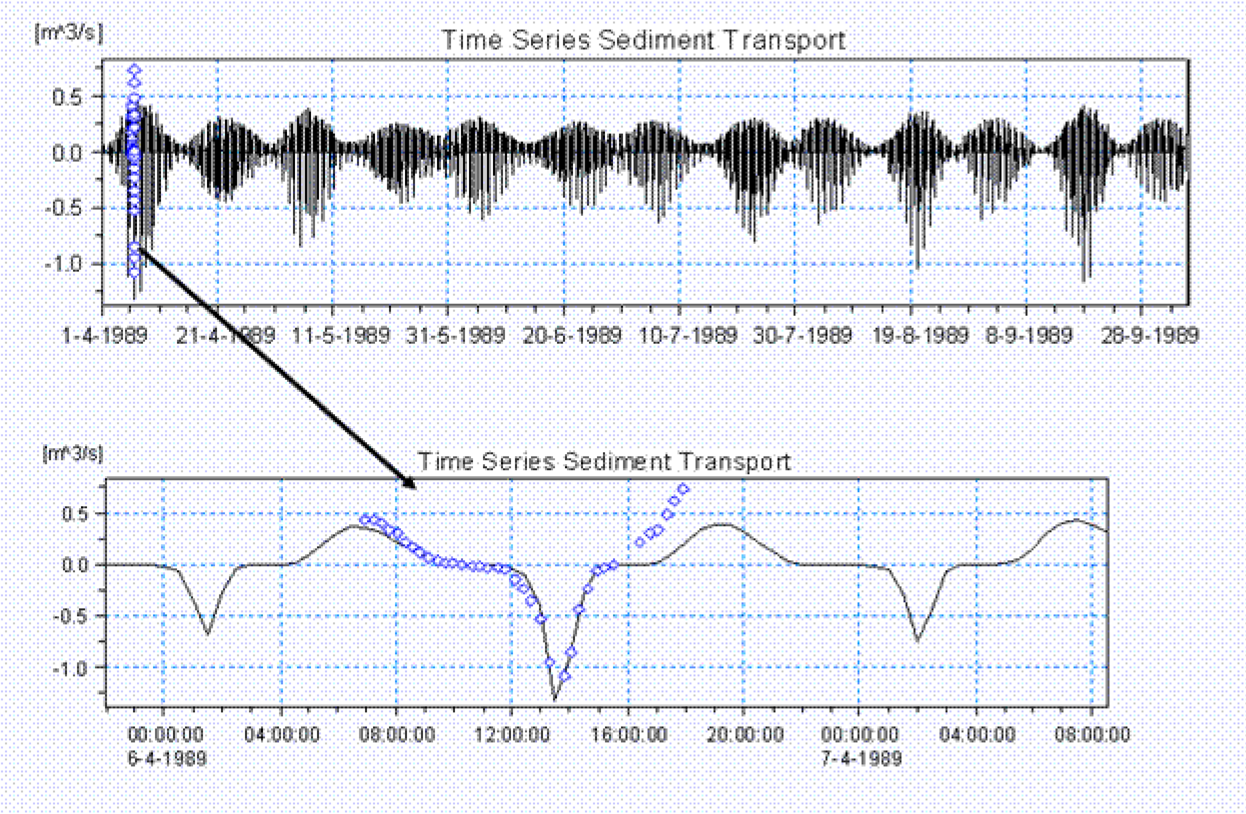


Figure 5-1:Simulated and measured sediment transport in the flood channel Everingen, Raai 7 in Macro Cell 3.

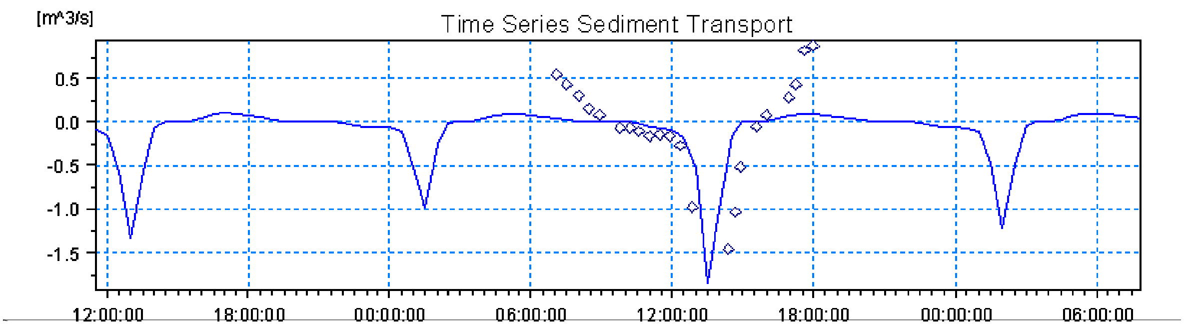


Figure 5-2: Simulated and measured sediment transport in the ebb channel Pas van Terneuzen, Raai 7 in Macro Cell 3

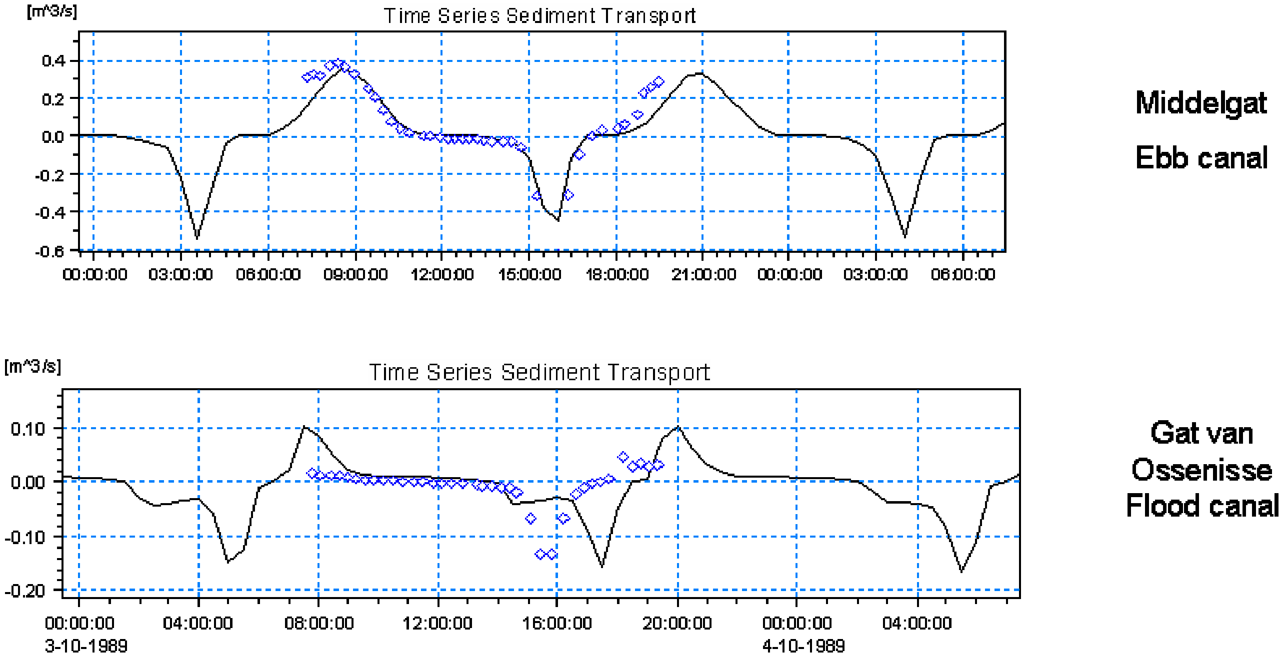


Figure 5-3: Simulated and measured sediment transport in the ebb and flood channel, Raai 6 in Macro Cell 4

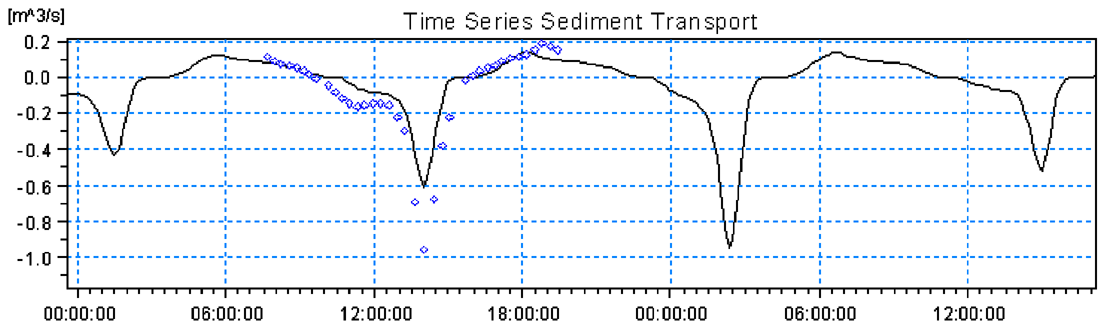


Figure 5-4: Simulated and measured sediment transport in the ebb- channel Western Scheldt Raai, 1 in Macro Cell 7

A number of trial simulations with different parameters have subsequently been carried out in order to reproduce the observed long-term morphological changes from 1968 though 2003. The use of additional energy losses in bifurcations was abandoned as it leads to instabilities in the HD model.

The morphological model can get unstable when the water level is too small. Such problems were often encountered after 10 to 15 years of simulations. The main reason was local deposition causing “dry out “. Smoothing of the local dumping works over more grid points reduced these problems significantly.

The remaining “calibration factors” comprise the sediment grain diameter D_{50}, the sediment split function and in principle also the level of morphological divide. Although the level of morphological divide controls the average flow velocity and hence the bed shear stresses it was decided to leave it unchanged during calibration. The location of morphological divide was determined inspection of each MIKE 11 cross-section in the ebb- and flood channels. Generally a level of zero has been used.

The sediment split function was used to control the distribution of sediment transports in the junctions. The final selection of parameters is depicted in Figure 5-5. Note that the values correspond to K in Section 3.5. The exponent “n” is one in all junctions

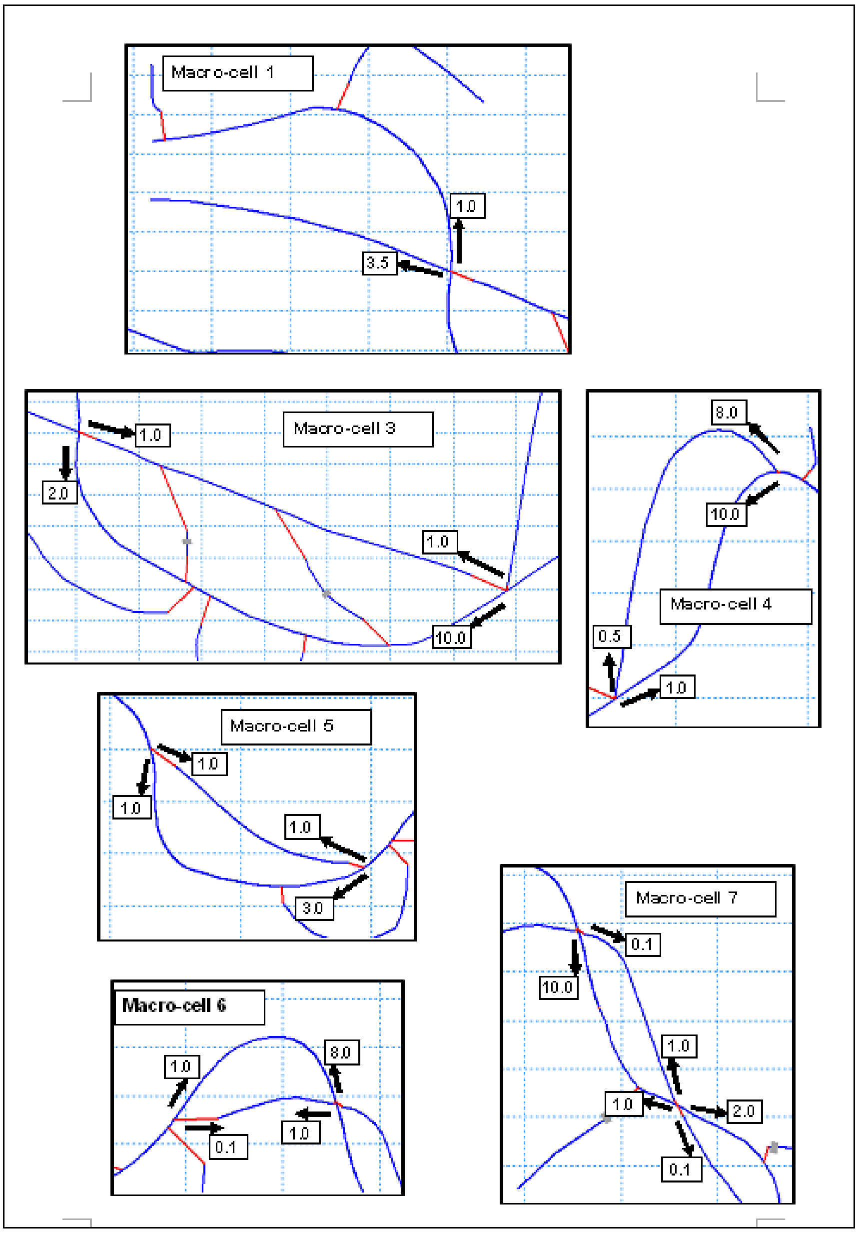


Figure 5-5:Final selection of split function parameters

The model results are very sensitive to the selection of sediment grain diameter. If the diameter is to small it may lead to extensive erosion and vice versa. The final spatial resolution in the sediment grain diameter is provided in Table 5.1 below. As can be seen in Figure 4-7 there is a tendency toward finer bed material in the upstream reaches of the estuary. Assuming that circulations within each macro cell mainly control the morphological changes, it can be justified to use different grain sizes. The spatial variation of D_{50} implies that the diameter remains constant during the entire simulation (according to the pre-specified diameter for each of the network branches) independent of the up-or downstream sediment transport.

Table 5.1: Final selection of sediment grain diameter D_{50}

Location	**Sediment Grain Diameter [micron]**
Macro-Cell 1	300
Macro-Cell 3	300
Macro-Cell 4	200
Macro-Cell 5	200
Macro-Cell 6	150
Macro-Cell 7	150
Zeeschelde, ch. 10129	150
Zeeschelde, ch. 17185	130
Zeeschelde, ch. 19942	130
Zeeschelde, ch. 25038	120
Zeeschelde, ch. 31632	120
Zeeschelde, ch. 99699	100
Globally	150

Annex A provides a more complete overview of the calibration process.

5.2. Results of the final calibration

Figure 5-6 through Figure 5-20 shows simulated and observed accumulated changes in the sediment budget on a macro cell level. It is important to note that only changes below level zero have been processed. The model computes the accumulated bed sediment budget for each computational grid. Subsequently the results from all grid points within the boundaries of the macro cells have been aggregated in order to compare with the observed changes. Likewise the man interventions in terms of dredging, dumping and mining activities are presented on the same figures. Although not consistent in all macro cells the general trend in the observed morphological development is toward natural erosion in flood channels and deposition in ebb channels. This development is compensated by dumping in flood channels and vice versa in ebb channels. The result presented as 'MIKE 11 Results' in Figure 5-6 through Figure 5-20 presents absolute values of accumulated sediment volume changes including all dredging, dumping and mining activities defined in the simulations. As such, these results should be directly comparable to the actual observations of volume changes in each macro cell. The volume changes on macro cell level have been established by aggregating volume changes on micro cell level below 0 NAP. In this context data have been provided by the client on micro cell level and have been aggregated to macro cell level as a part of the present project

Considering the assumptions and limitations of a 1- D model approach and of course the uncertainty on the observed volume budgets one should be careful comparing absolute values after a simulation period corresponding to 35 years.

Looking at the model results from one macro cell to another it is also clear that the model can not reproduce the observed long term changes accurately. It can also be noted that the model results often primarily reflect the dredging and dumping activities introduced as sink and sources to the MIKE 11 model.

In the ebb channel in macro cell 1 (Figure 5-6 and Figure 5-7) the model boundary condition has a strong influence and it was required to scale down the computed transports to 10 % of the transports by the van Rijn equations (over 5 kilometres from the seaward boundary) in order to match the observed net sedimentation. In macro cell 1 the natural sediment transports seem to be in almost equilibrium with the dredging and dumping works.

In the ebb channel in macro cell 3 (Figure 5-8 and Figure 5-9) the model predict long term erosion where as the observed changes reflect a system in more equilibrium. In the corresponding flood channel it is clearly seen how the model react to the extensive dumping from 1996 through 2003. One of the underlying assumptions made in the model is that all dredging and dumping activities takes place in the morphological active part of the cross section, normally below level zero. This is of course a rough assumption. Thus actual dumping say on the tidal flats are interpreted by the model as taking place in the deeper part. It has been confirmed that sediment dumped in the Western Scheldt always take place in the deeper part of the channel below -5 m NAP.

In the ebb- and flood channels in macro cell 4 (Figure 5-10 and Figure 5-11) the model predict a system relatively in equilibrium where as the observations show that deposition and erosion respectively has actually taken place in the ebb and flood channels. In the ebb channel in macro cell 5 (Figure 5-12 and Figure 5-13) the dredging seems to be the main responsible for the long-term development. This is likewise reflected by the model. In the flood channel, however, the model seems to overestimate the deposition.

There is generally a good agreement between simulations and observations In macro cell 6 (Figure 5-14 and Figure 5-15). In Appelzak, the flood channel in macro cell 7 (Figure 5-17, the model simulates long term deposition rather than erosion as observed in this reach. In the upstream reaches in the Sea Scheldt the observed data are very scarce. In Vak 122 and 125 (Figure 5-18 and Figure 5-19) the model simulations seem to follow the dredging and dumping activities respectively and there is little agreement with the few observations. In Vak 127 (Figure 5-20) the model results again deviate form the few observations. It should be noted that the accumulated changes in the Sea Scheldt are much lower than those observed and simulated in the Western Scheldt.

Finally Figure 5-21 and Figure 5-22 show longitudinal profiles of the simulated bed evolution along the flood and ebb channels respectively in the period 1968 through 2003.

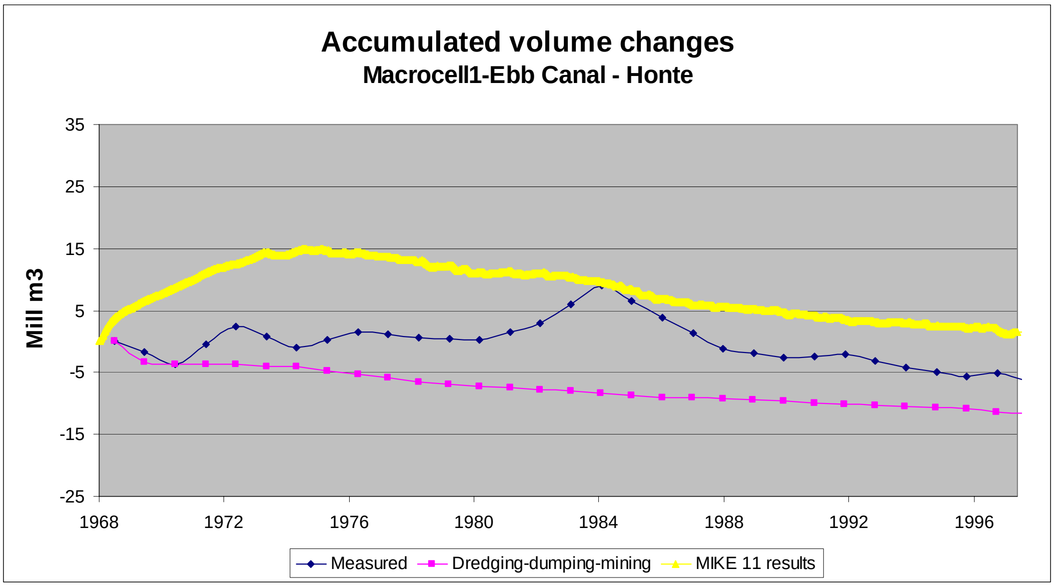


Figure 5-6: Simulated and observed accumulated sediment budget (million m^3) in the ebb channel of Macro Cell 1

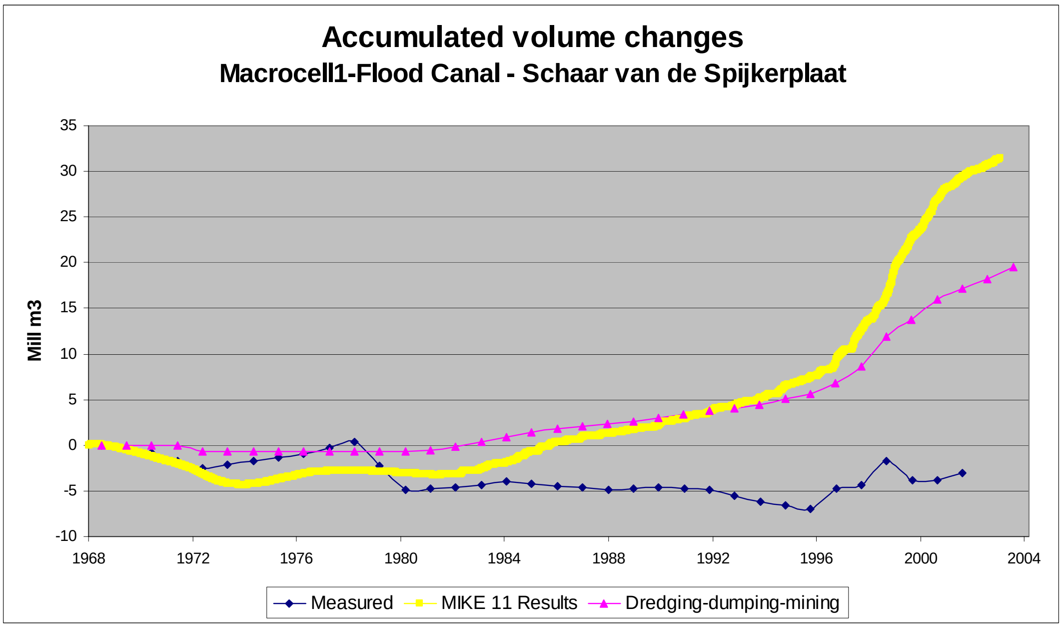


Figure 5-7: Simulated and observed accumulated sediment budget (million m^3) in the flood channel of Macro Cell 1

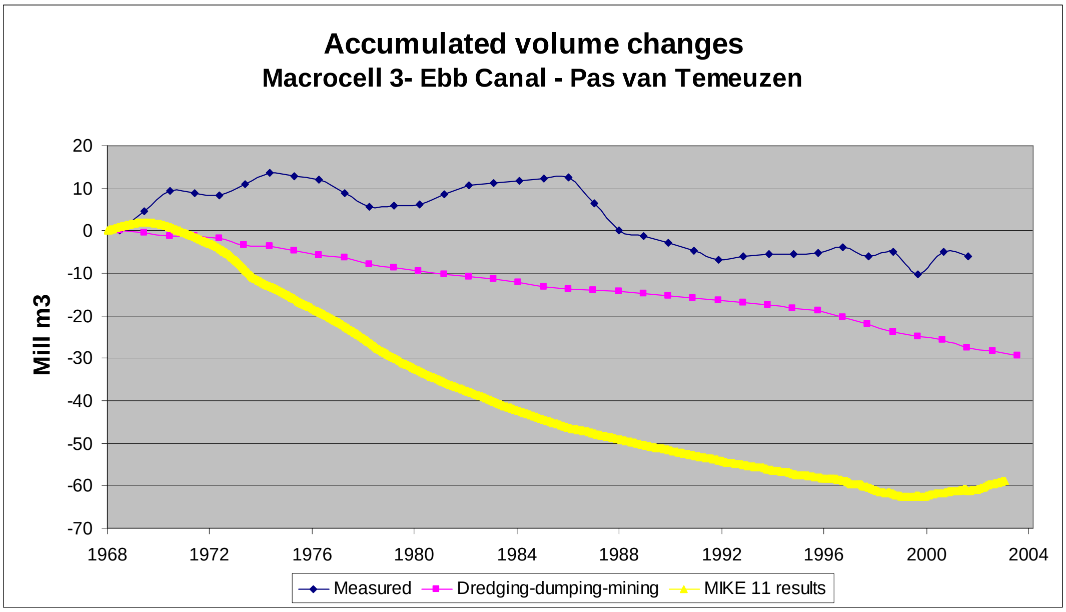


Figure 5-8: Simulated and observed accumulated sediment budget (million m^3) in the ebb channel of Macro Cell 3

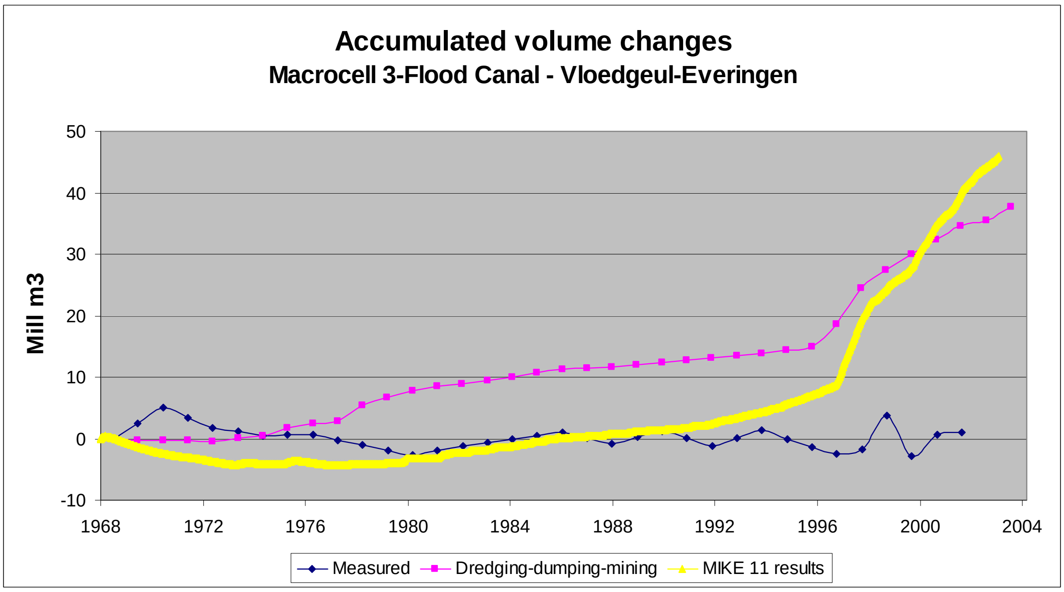


Figure 5-9: Simulated and observed accumulated sediment budget (million m^3) in the flood channel of Macro Cell 3

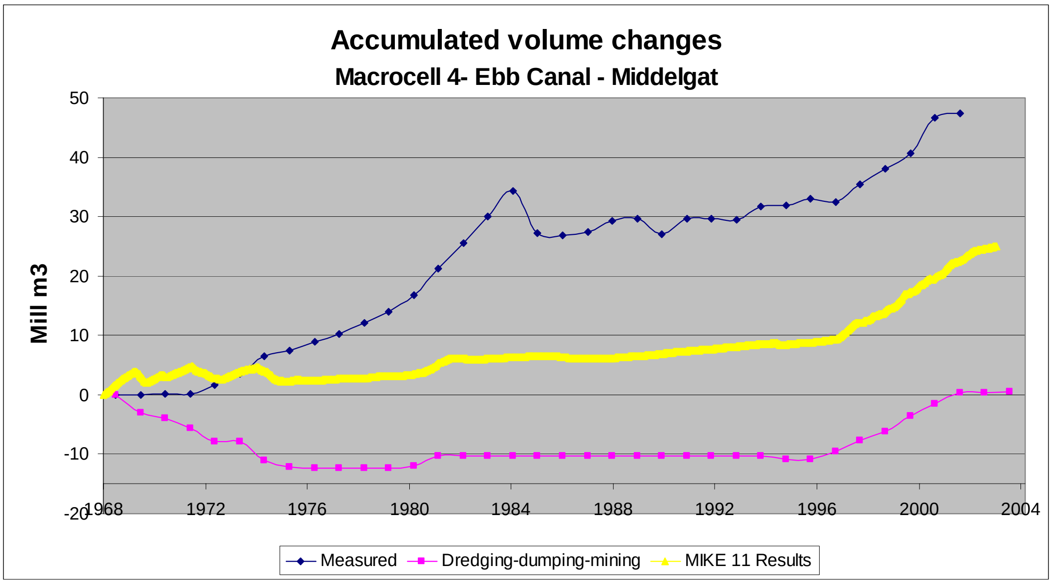


Figure 5-10: Simulated and observed accumulated sediment budget (million m^3) in the ebb channel of Macro Cell 4

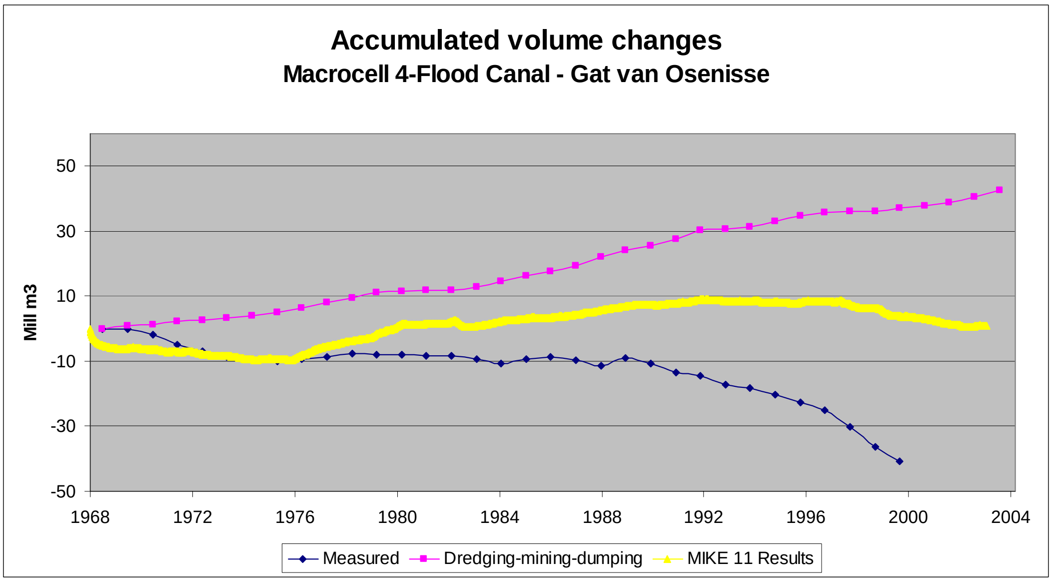


Figure 5-11: Simulated and observed accumulated sediment budget (million m^3) in the flood channel of Macro Cell 4

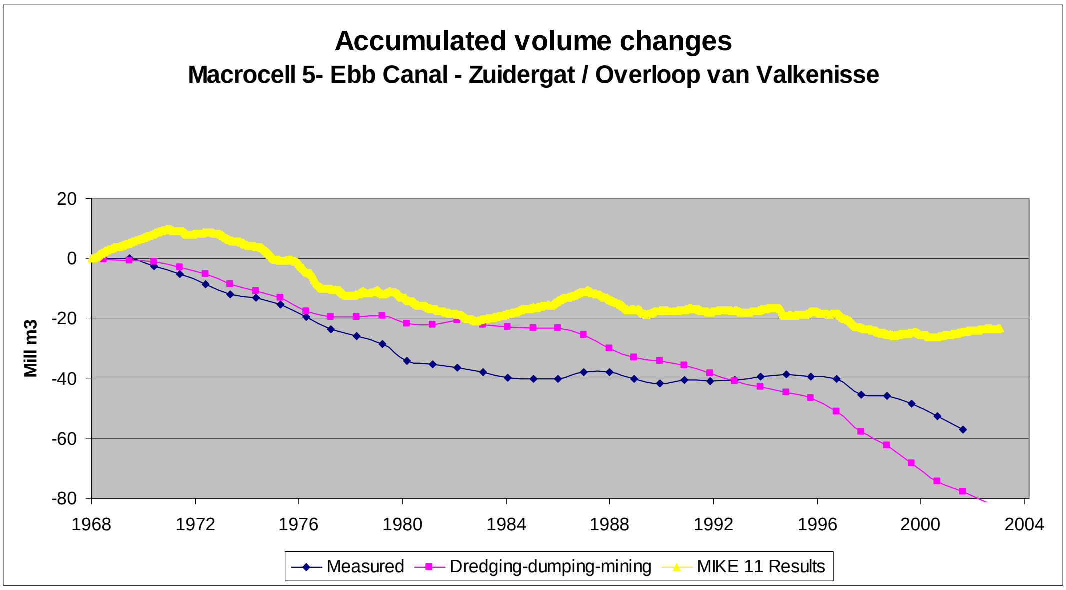


Figure 5-12: Simulated and observed accumulated sediment budget (million m^3) in the ebb channel of Macro Cell 5

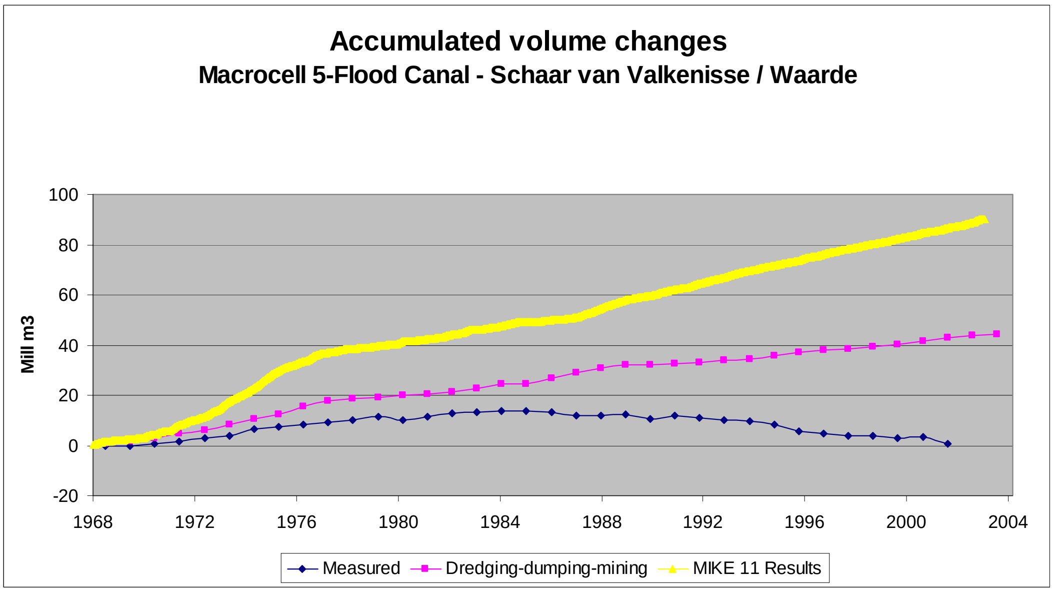


Figure 5-13: Simulated and observed accumulated sediment budget (million m^3) in the flood channel of Macro Cell 5

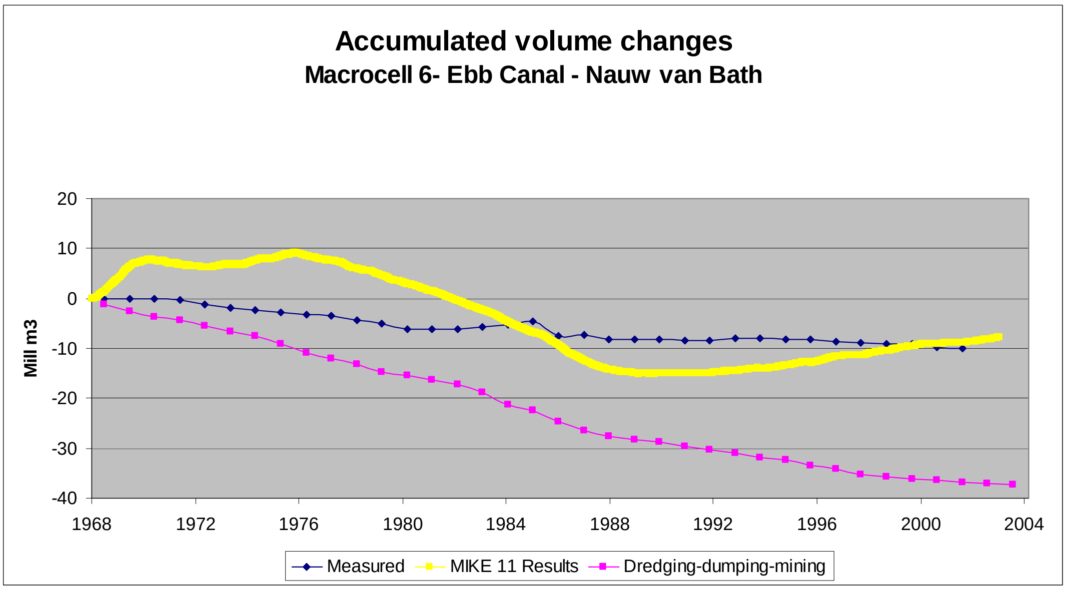


Figure 5-14: Simulated and observed accumulated sediment budget (million m^3) in the ebb channel of Macro Cell 6

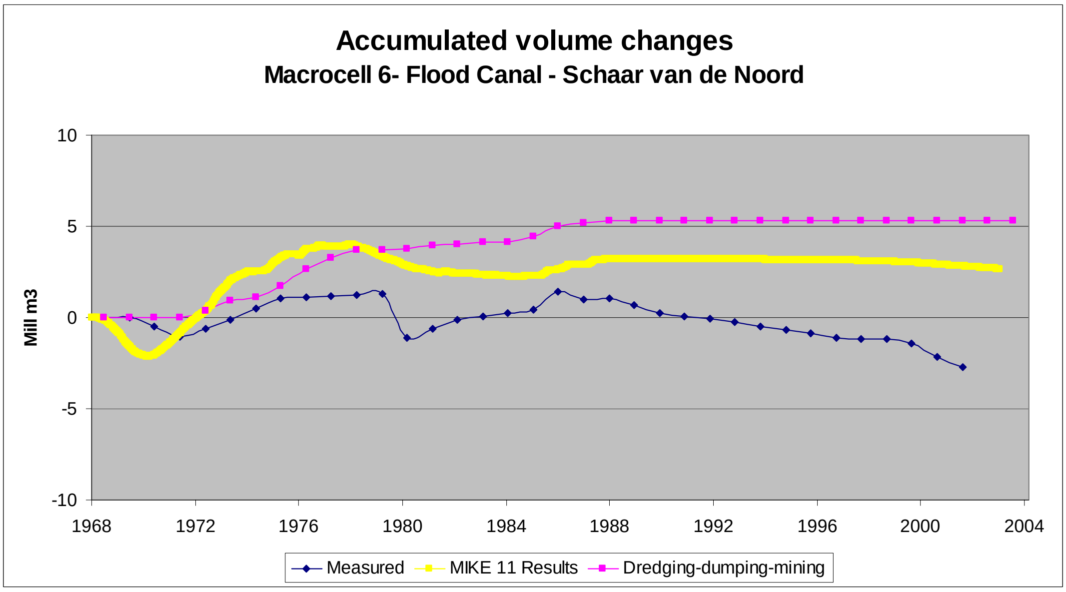


Figure 5-15: Simulated and observed accumulated sediment budget (million m^3) in the flood channel of Macro Cell 6

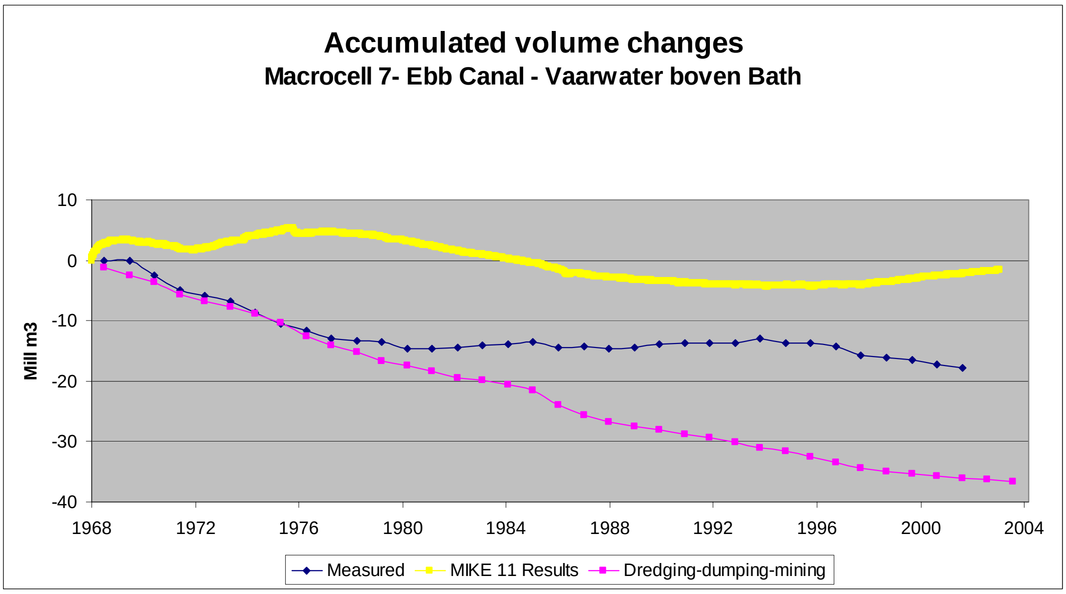


Figure 5-16: Simulated and observed accumulated sediment budget (million m^3) in the ebb channel of Macro Cell 7

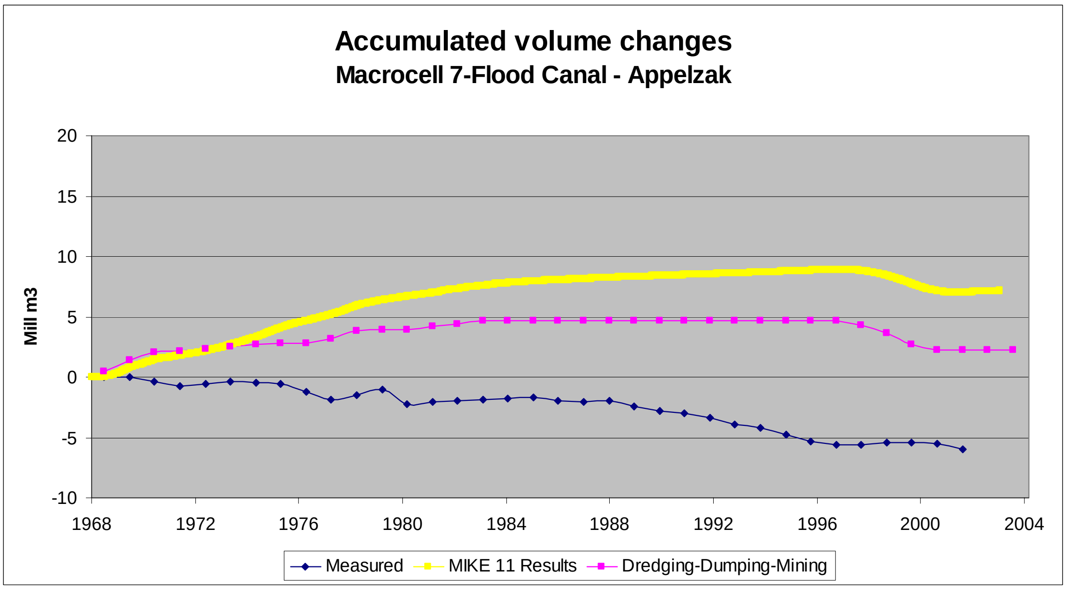


Figure 5-17: Simulated and observed accumulated sediment budget (million m^3) in the flood channel of Macro Cell 7

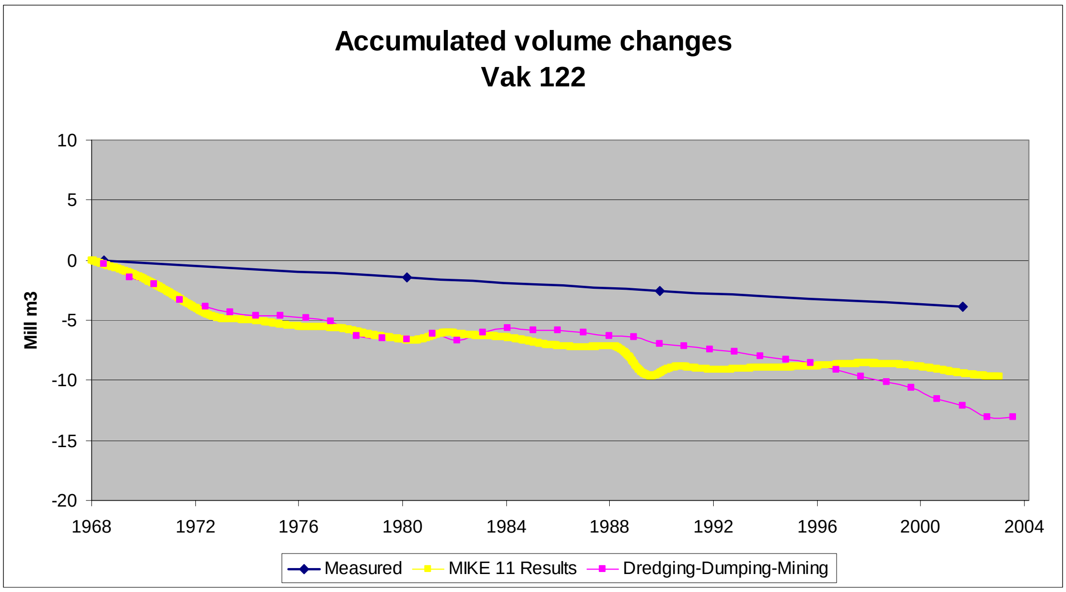


Figure 5-18: Simulated and observed accumulated sediment budget (million m^3) in "Vak 122" in the Sea Scheldt .7

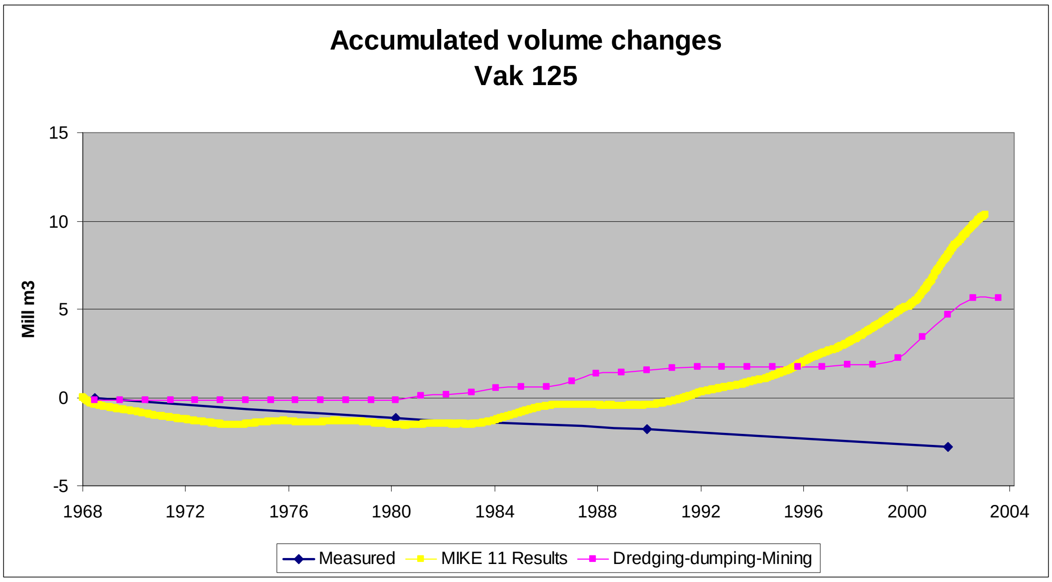


Figure 5-19: Simulated and observed accumulated sediment budget (million m^3) in "Vak 125" in the Sea Scheldt .

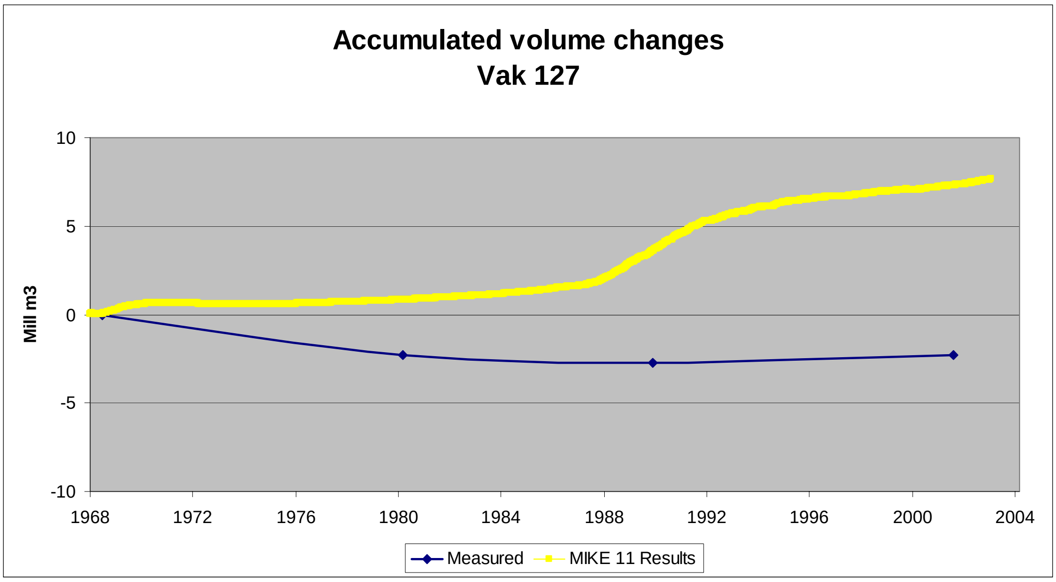


Figure 5-20: Simulated and observed accumulated sediment budget (million m^3) in "Vak 127" in the Sea Scheldt .

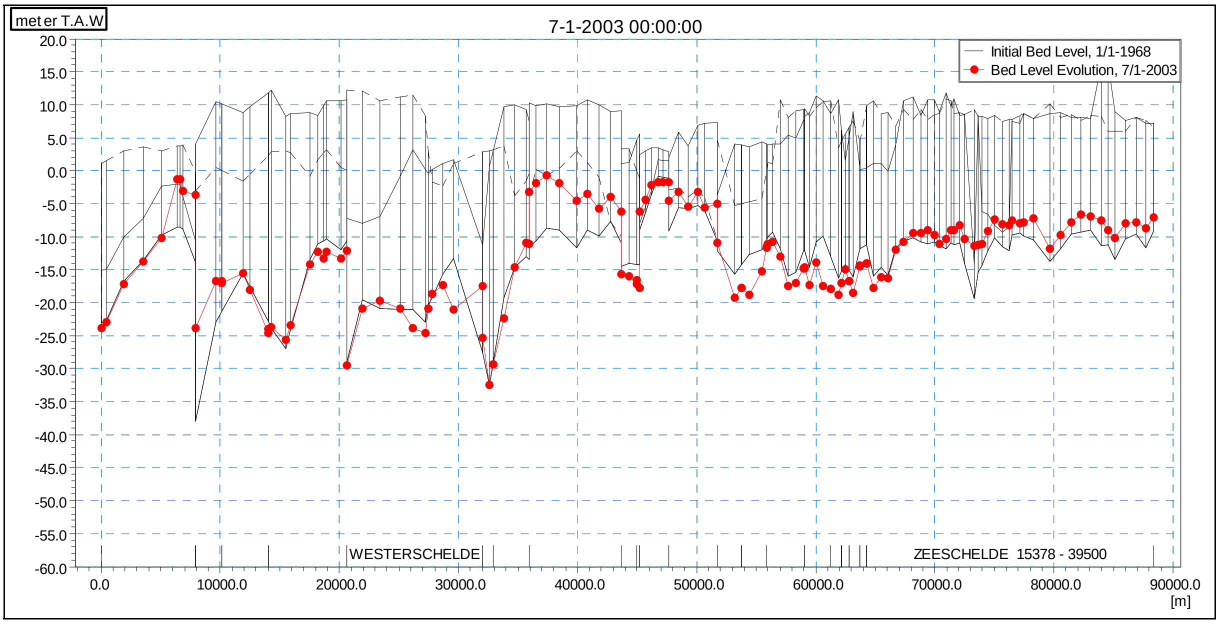


Figure 5-21: Simulated evolution in the rive bed (in TAW) from Rupel and along the flood channel from 1968 through 2003.

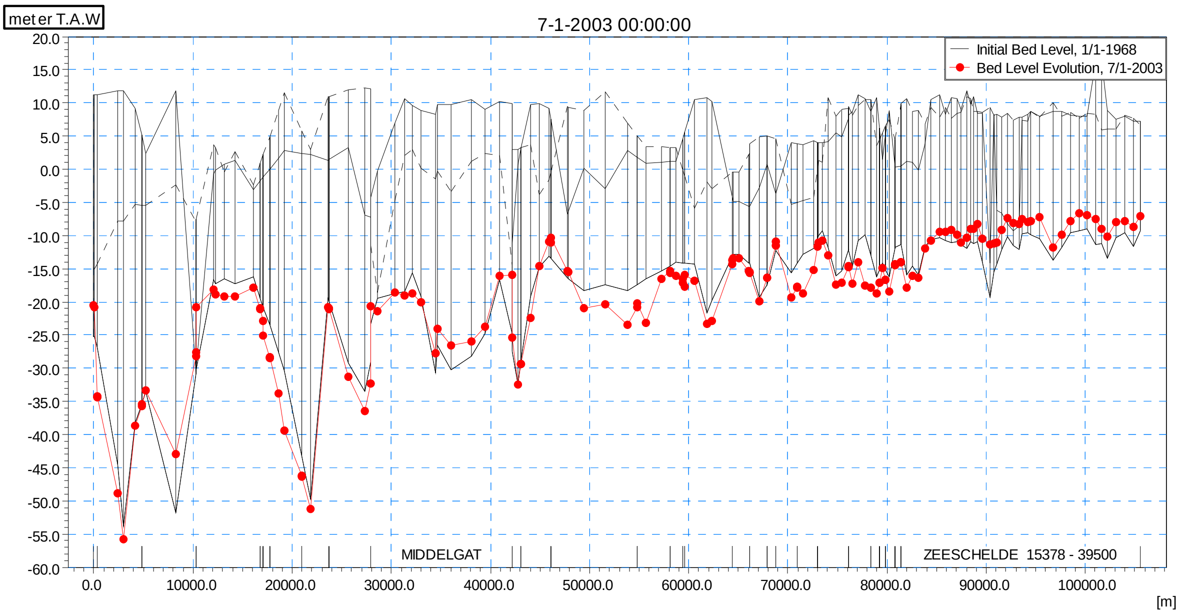


Figure 5-22: Simulated evolution in the riverbed (in TAW) from Rupel and along the ebb channel from 1968 through 2003.

5.3. Results of the extended model into the North Sea

The hydrodynamic and morphological model has been extended into the North Sea in order to match the complete study area as comprised by the Sobek model. Based on the information provided by WL Delft, a new configuration of the hydrodynamic model has been built; the "Extended SIGMA-HD" model. In order to be comparable with the Sobek model, the boundary conditions in the North Sea should be similar to those applied in the Sobek model. In this context boundary conditions were provided for the 8 extended boundaries in the North Sea. The data comprise a neap spring tidal cycle in September 2002. The discussion of extension and verification of the hydrodynamic model is provided in sections 3.4 and 5.1 in "Report 1: Hydrodynamic model".

However, the morphological model set-up has been further simplified for several reasons as discussed in Section 4.1. The reduced network ("SIGMA-Morphological-reduced") without extension is shown in Figure 5-23 below and the North Sea extension model ("SIGMA Morphological" model) is depicted in Figure 5-24 . It should be noted that during the process of extending the Hydrodynamic model the Manning numbers have been changed in relation to those applied in the morphological model (Appendix A provides a more detailed description of the calibration process regarding Manning numbers). Thus in the extended version of the morphological model the Manning numbers have been updated accordingly. In contrast to the morphological modelling carried out without extension, the long-term hydrodynamic boundary condition (1968 through 2003) for the extended morphological model has been established by simple extrapolation of the September 2002 neap--spring tidal cycle. A constant bed elevation boundary condition has been applied for the sediment transport model at the 8 seaward boundaries.

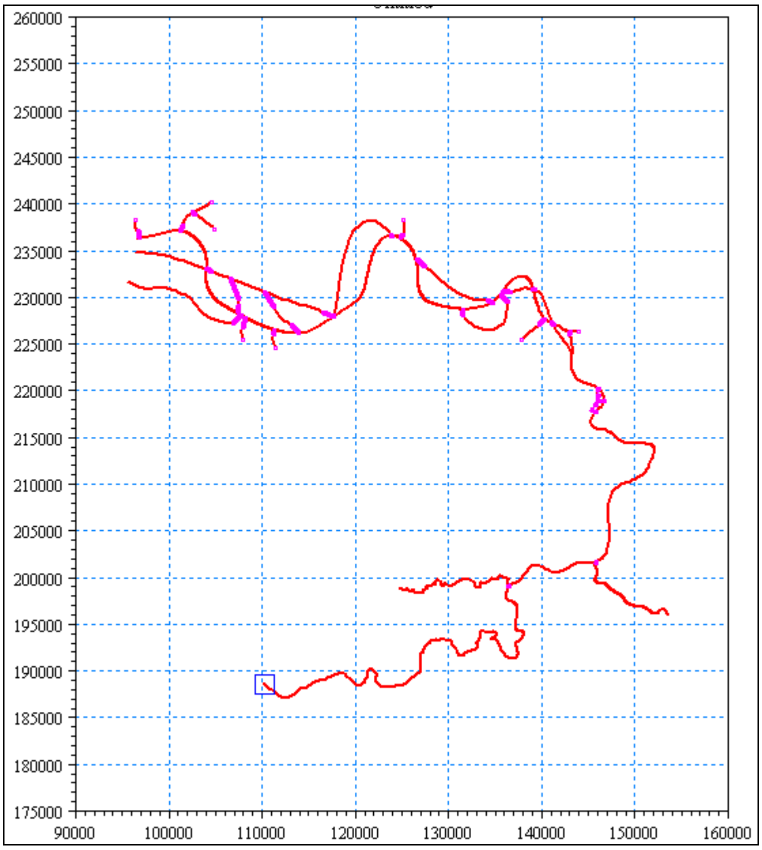


Figure 5-23: "SIGMA Morphological reduced" model set-up

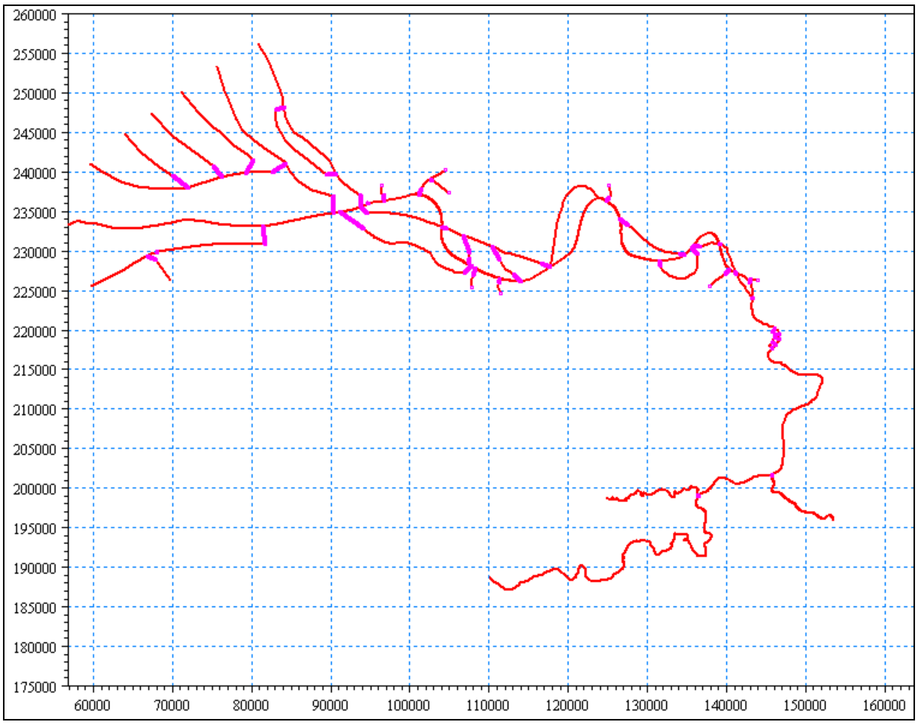


Figure 5-24: "SIGMA Morphological" model set-up with North Sea extension.

The long-term morphological model simulations (1968 through 2003) have been repeated with the extended model. The results with and without extension respectively are shown in Figures 5-25 through 5-39 for the different macro cells. In order to assess both results, observed accumulated changes and dredging, dumping and mining activities are likewise shown.

Besides model extension as provided in the MIKE 11 network files the model input parameters and hence calibration parameters have been changed (relative to the simulations without extension into the North Sea) as follows:

- The Manning numbers have been modified slightly in the Western Scheldt, Everingen and Sea Scheldt in order to have a better match with the observed water levels and residual flows.
- In the model without extension the model boundary condition has a strong influence and it was required to scale down the computed transports to 10 % of the transports by the van Rijn equations (over 5 kilometers from the seaward boundary). This downscaling of sediment transports has been removed in the extended model.
- In contrast to the simulations without extension into the North Sea the simulations have been carried out with a long-term "synthetic" tide composed of repeated spring- neap tidal cycles as established for September 2002.

Other calibration parameters such as level of morphological divide, sediment grain diameter, flow direction dependent resistance and sediment split functions have not been changed.

Looking at the model results from one macro cell to another one may draw the conclusion that the results are somewhat better than those achieved with the model without extension. Only in the flood channels in macro cell 1 and 5 (figure 5-26 and 5-32 respectively) the results with the extended model deviate significantly from the results without extension into the North Sea.

The difference in model results is most likely due to a combination of changes in boundary conditions (in space and time) and modifications to the Manning numbers. The effect of modifications to the Manning number is depicted in Annex A.

If the focus is on the area closer to the sea it is recommended to use the extended model to reduce uncertainties with respect to the morphological boundary condition.

Figure 5-40 show the total simulated and observed accumulated volume changes in Macro cells 1,3,4,5,6 and 7 in the Western Scheldt. As seen both simulations and observations confirm a net erosion or export of sediment from the estuary in the period 1968 through 2003 (changes below level 0 NAP). The simulations, however, overestimate the net export.

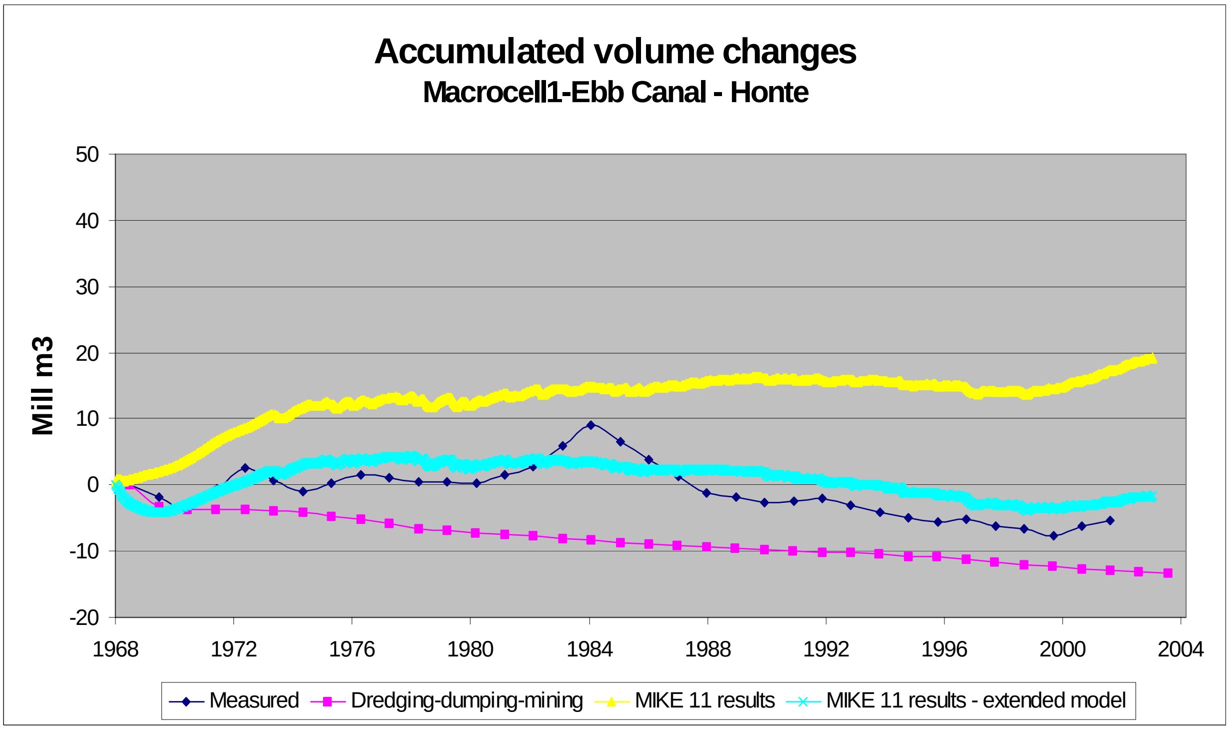


Figure 5-25: Extension into the North Sea. Simulated and observed accumulated sediment budget (million m^3) in the ebb channel of Macro Cell 1

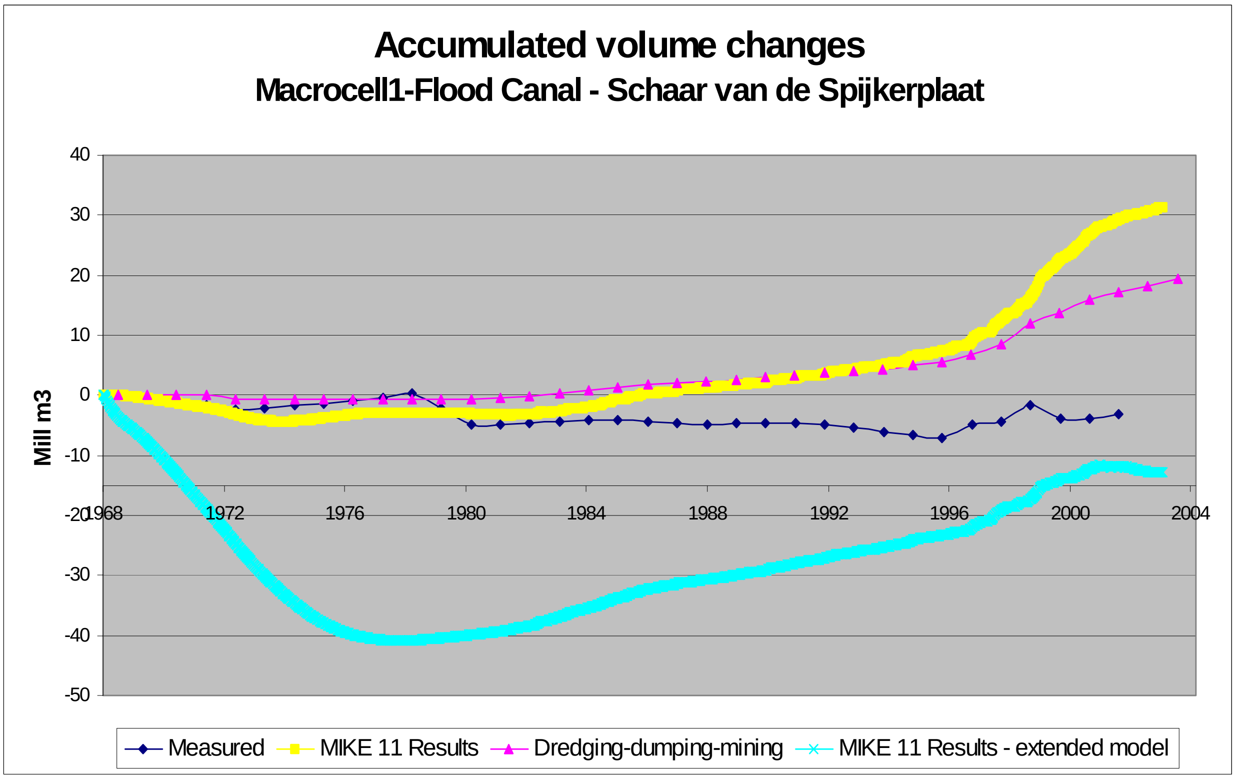


Figure 5-26: Extension into the North Sea. Simulated and observed accumulated sediment budget (million m^3) in the flood channel of Macro Cell 1

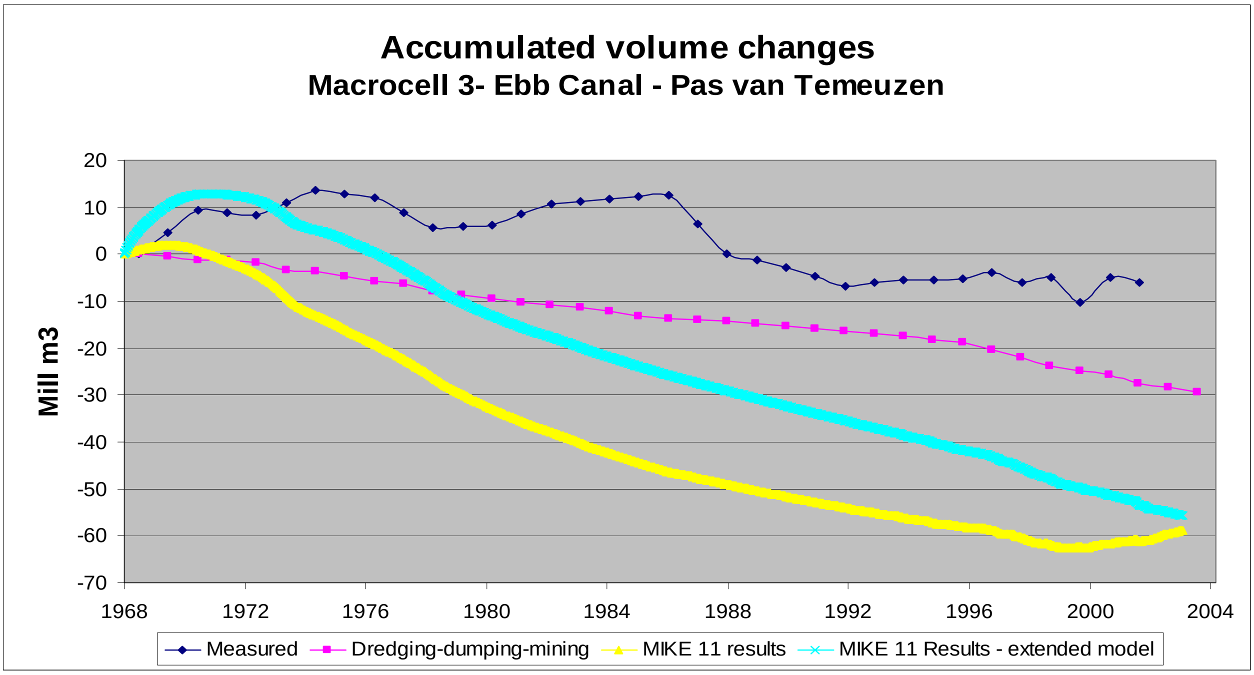


Figure 5-27: Extension into the North Sea. Simulated and observed accumulated sediment budget (million m^3) in the ebb channel of Macro Cell 3

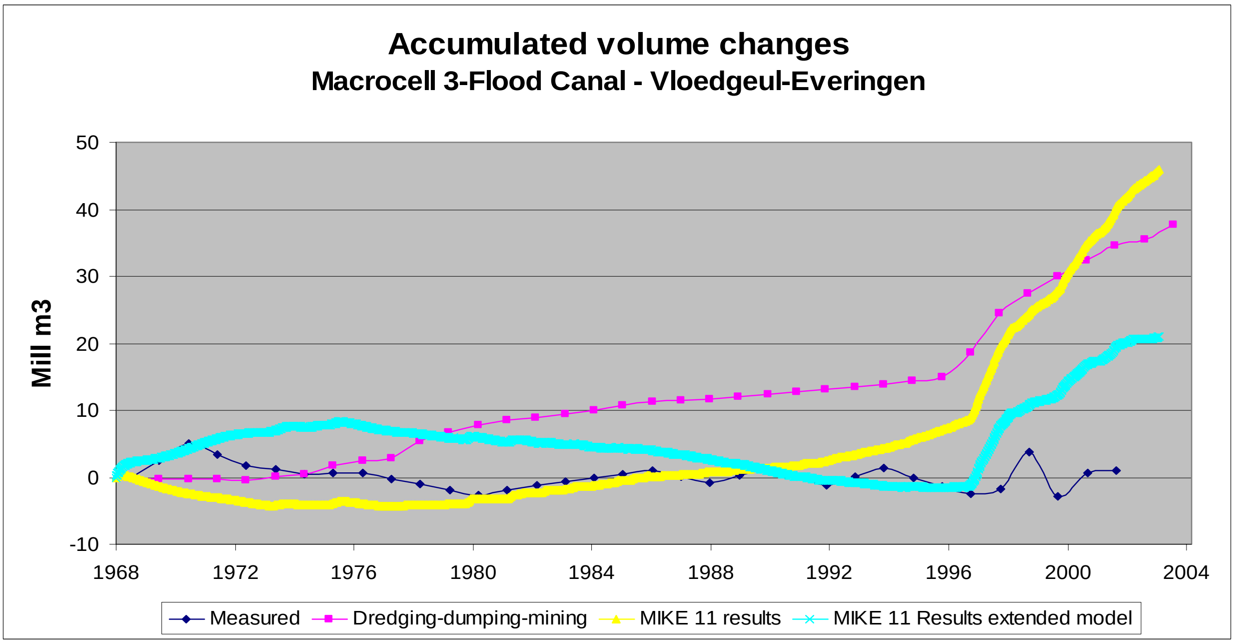


Figure 5-28: Extension into the North Sea. Simulated and observed accumulated sediment budget (million m^3) in the flood channel of Macro Cell 3

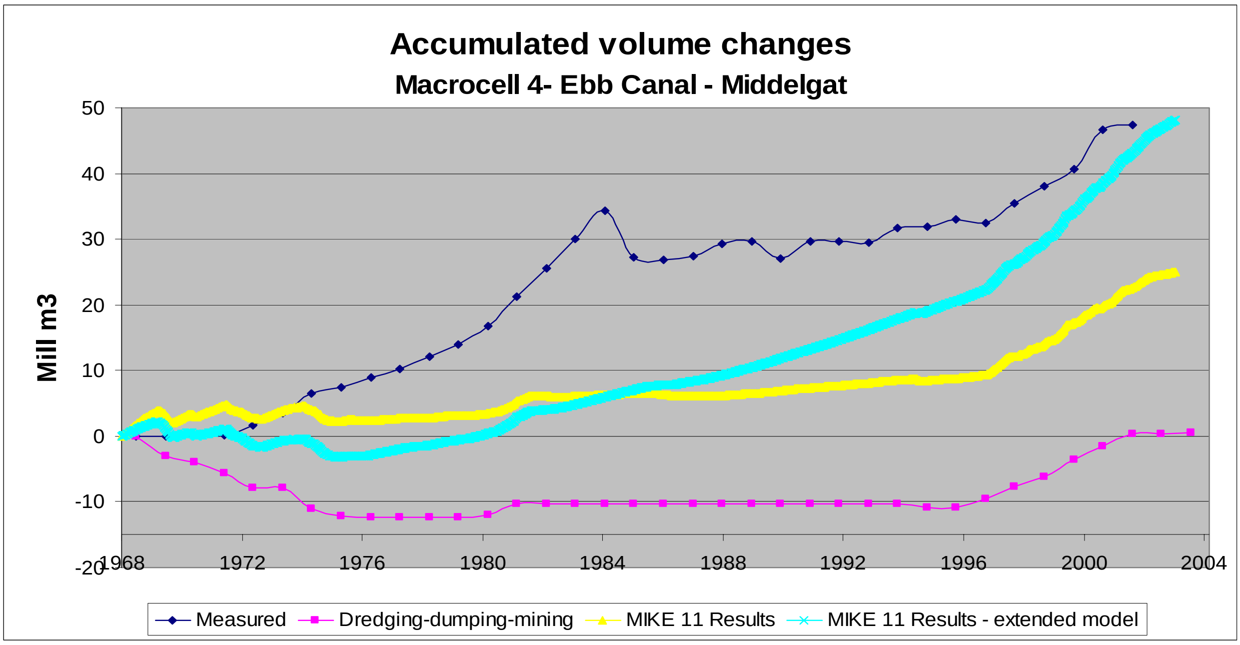


Figure 5-29: Extension into the North Sea. Simulated and observed accumulated sediment budget (million m^3) in the ebb channel of Macro Cell 4

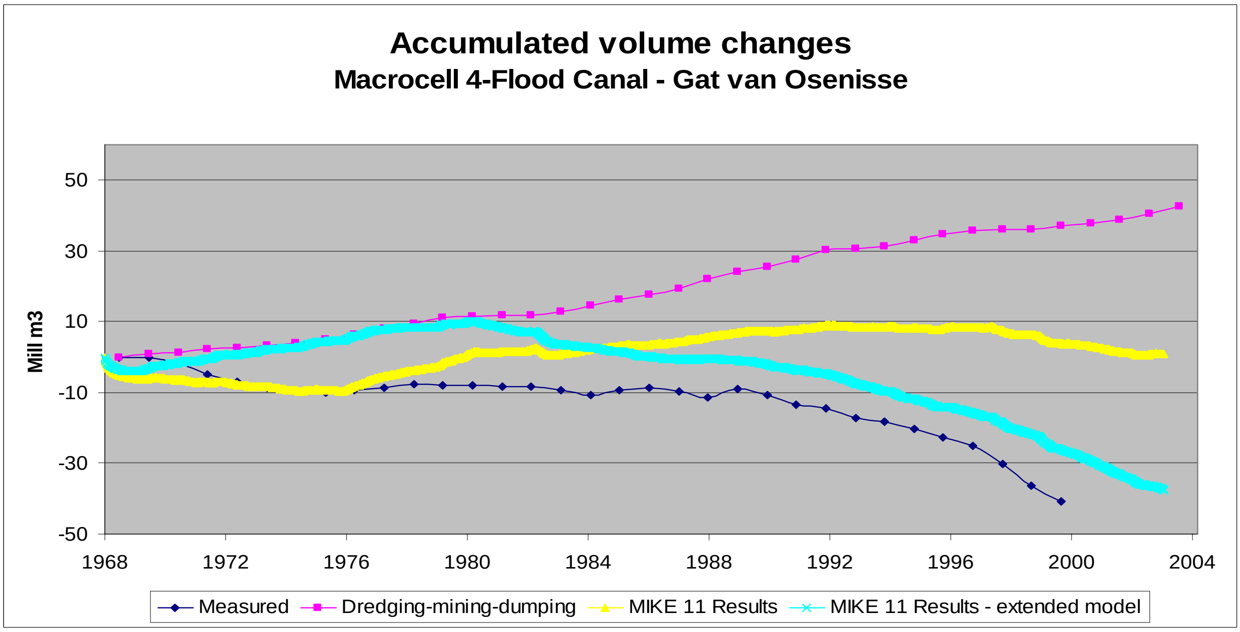


Figure 5-30: Extension into the North Sea. Simulated and observed accumulated sediment budget (million m^3) in the flood channel of Macro Cell 4

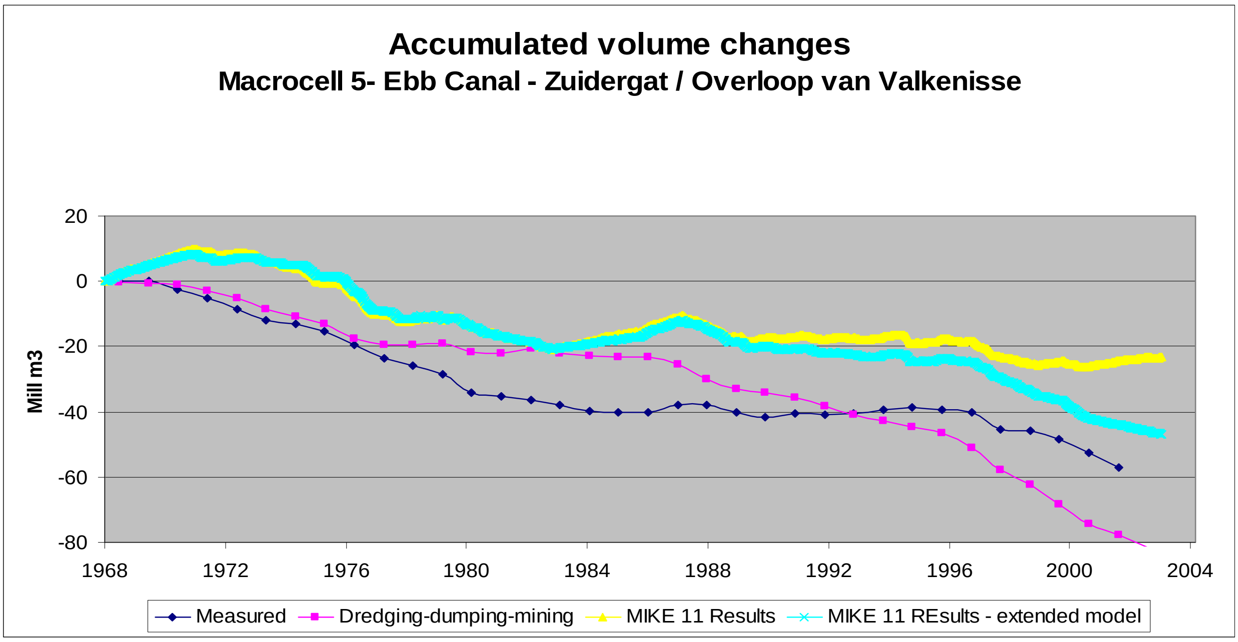


Figure 5-31: Extension into the North Sea. Simulated and observed accumulated sediment budget (million m3) in the ebb channel of Macro Cell 5

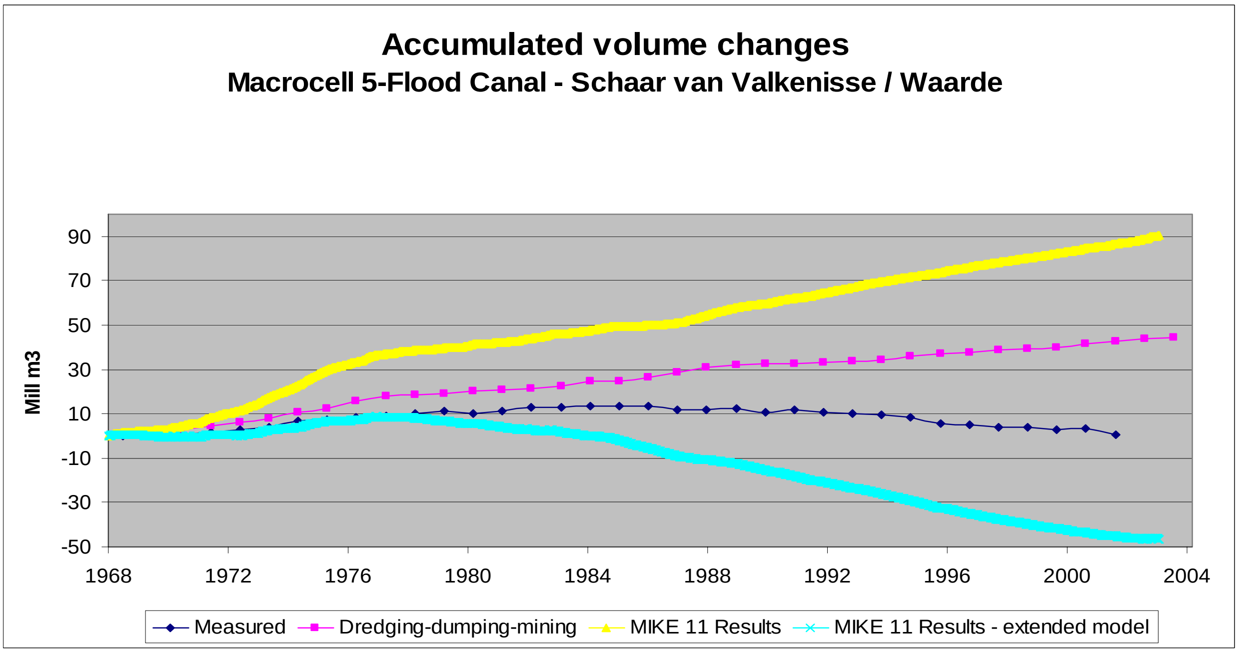


Figure 5-32: Extension into the North Sea. Simulated and observed accumulated sediment budget (million m^3) in the flood channel of Macro Cell 5

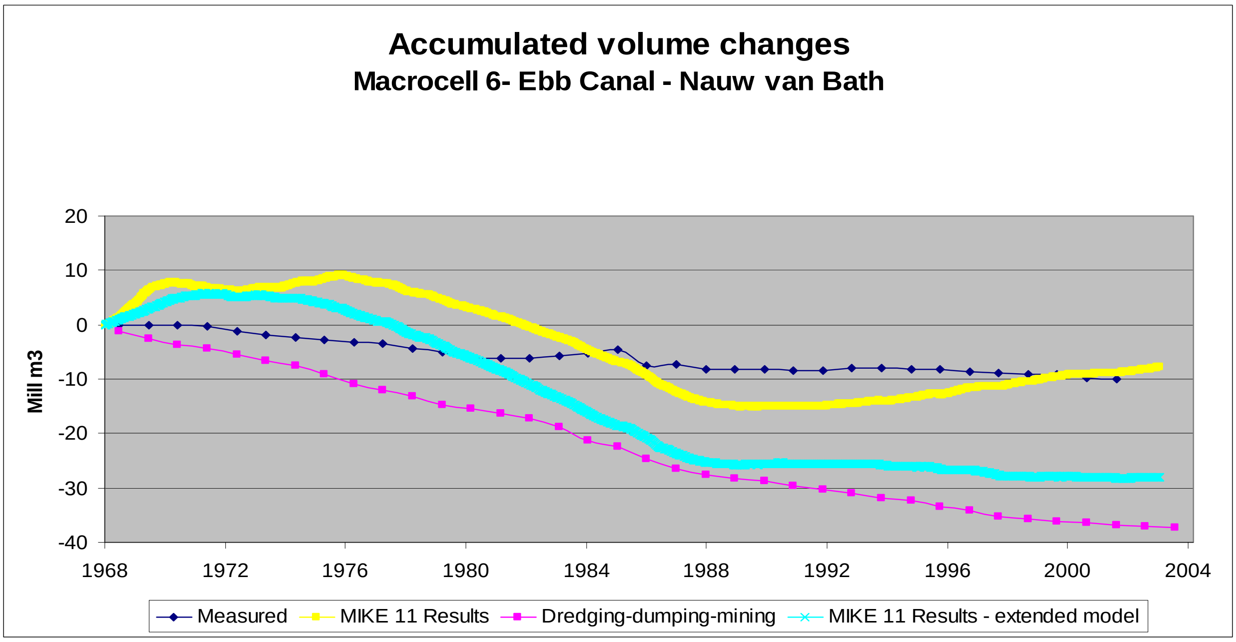


Figure 5-33: Extension into the North Sea. Simulated and observed accumulated sediment budget (million m^3) in the ebb channel of Macro Cell 6

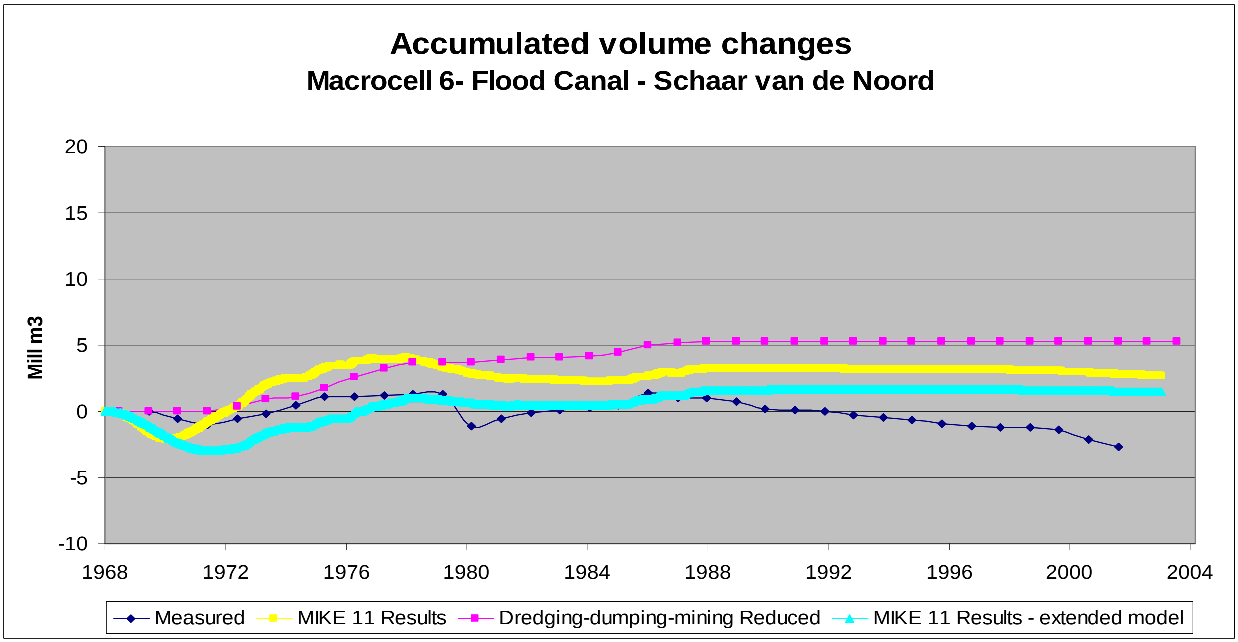


Figure 5-34: Extension into the North Sea. Simulated and observed accumulated sediment budget (million m^3) in the flood channel of Macro Cell 6

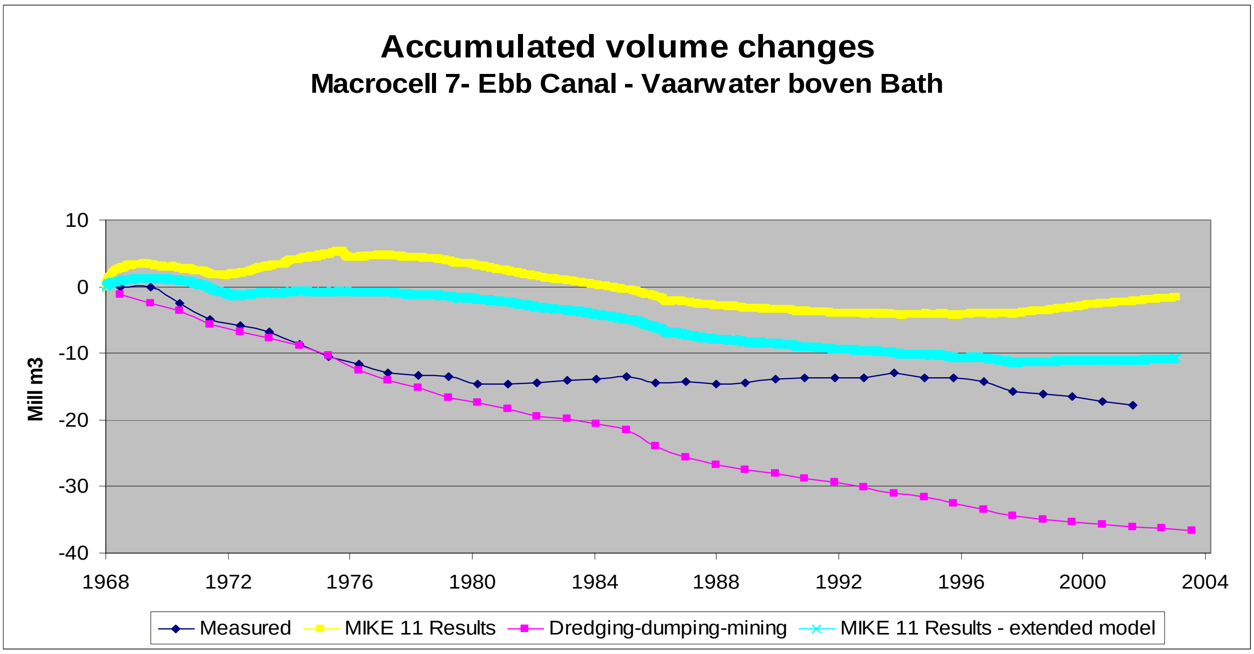


Figure 5-35: Extension into the North Sea. Simulated and observed accumulated sediment budget (million m^3) in the ebb channel of Macro Cell 7

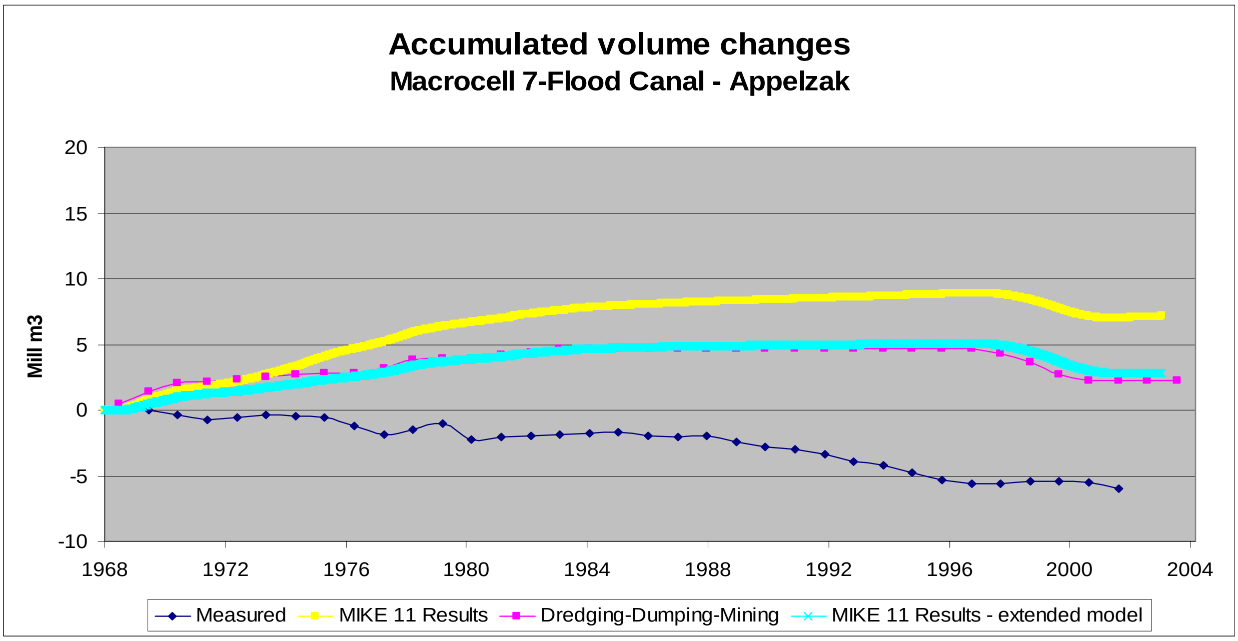


Figure 5-36: Extension into the North Sea. Simulated and observed accumulated sediment budget (million m^3) in the flood channel of Macro Cell 7

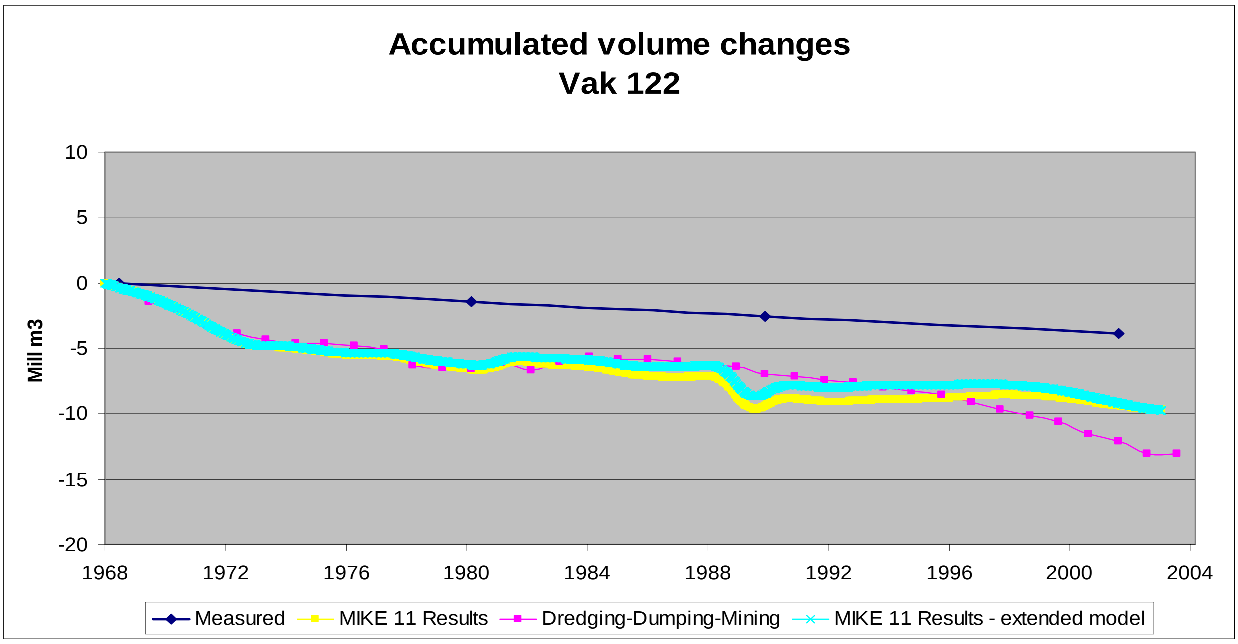


Figure 5-37: Extension into the North Sea. Simulated and observed accumulated sediment budget (million m^3) in "Vak 122" in the Sea Scheldt .7

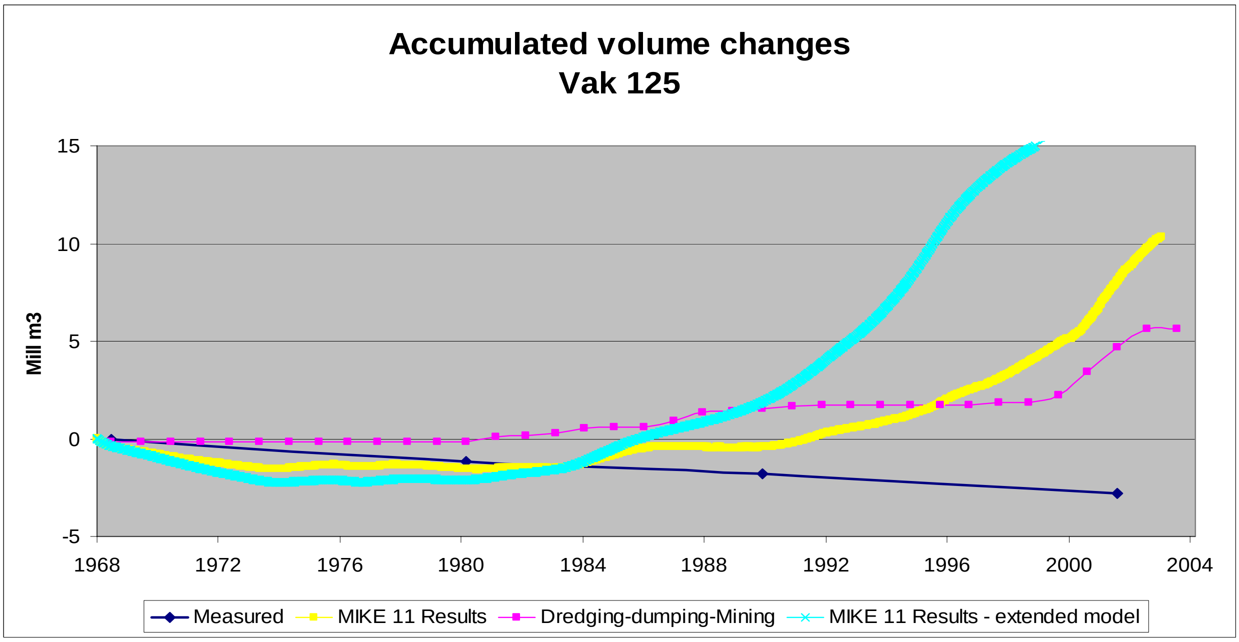


Figure 5-38: Extension into the North Sea. Simulated and observed accumulated sediment budget (million m^3) in "Vak 125" in the Sea Scheldt .

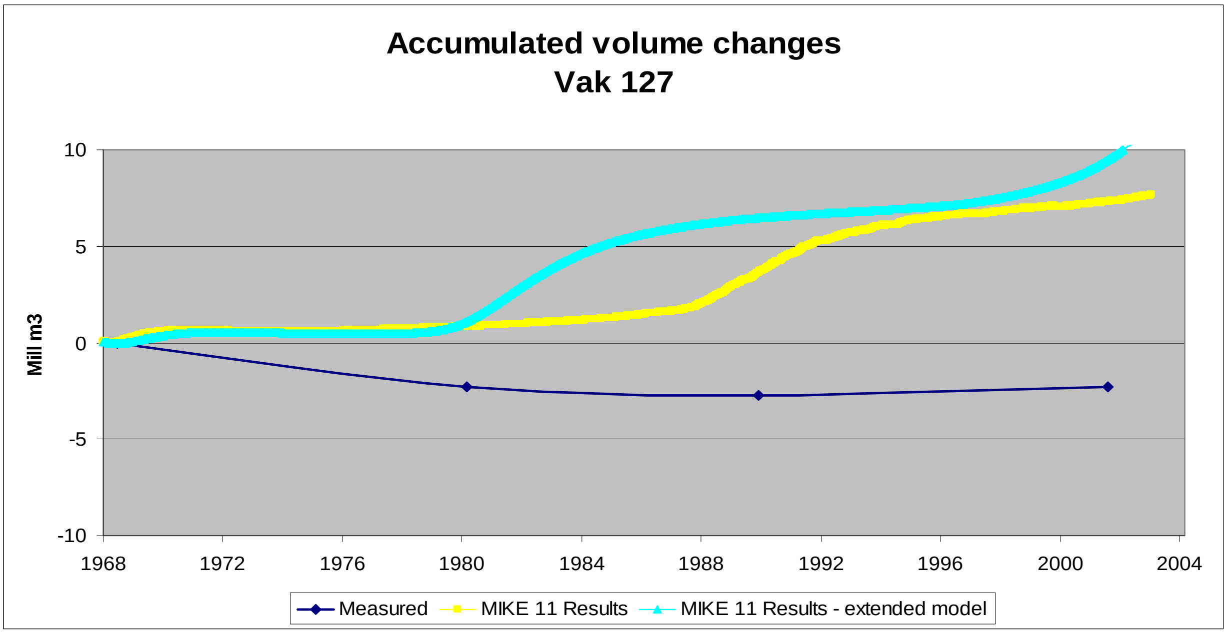


Figure 5-39: Extension into the North Sea. Simulated and observed accumulated sediment budget (million m^3) in "Vak 127" in the Sea Scheldt.

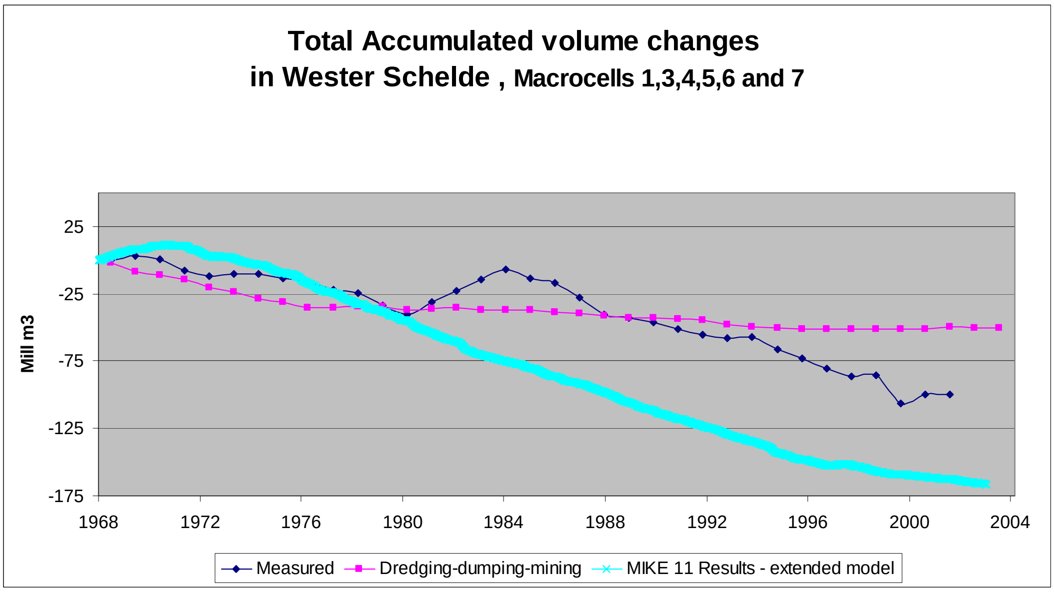


Figure 5-40: Extension into the North Sea. Total simulated and observed accumulated sediment budget (million m^3) in Macrocells 1,3,4,5,6 and 7 in the Western Scheldt.

6. VALIDATION

The model calibration period extends from 1968 through 1994. Subsequently a verification period from 1994 to 2004 was proposed. However, as discussed in section 3.10, the model is very sensitive to the initial conditions. If the model is restarted in 1994 with a new bathymetry, the model results may be disturbed by the new "initial " condition introduced by the 1994 bathymetry (new cross-sectional data). From the results starting in 1968 it seems that initial conditions may influence the results the following 2 - 4 years. It was therefore decided to run the entire period 1968 through 2004.

6.1. Validation results

In order to focus on the validation period 1994 to 2004 the results with the extended model have been processed. Furthermore, the observed accumulated changes have been reprocessed to capture changes during the period 1994 to 2004. The results of the reprocessing are provided in Figures 6-1 – 6-12.

Inspection of the isolated results from the validation period does, however not lead to any new conclusion regarding the model performance with respect to agreement between observations and model simulations.

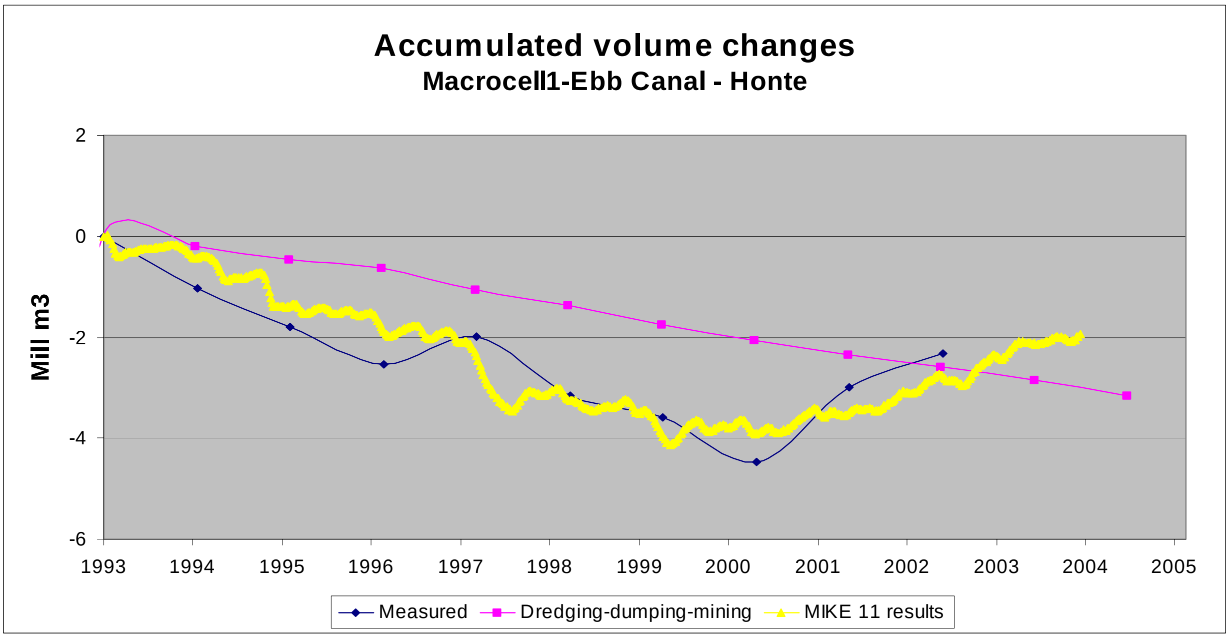


Figure 6-1: Extension into the North Sea. Simulated and observed accumulated sediment budget (million m^3) in the ebb channel of Macro Cell 1- Validation 1993-2004

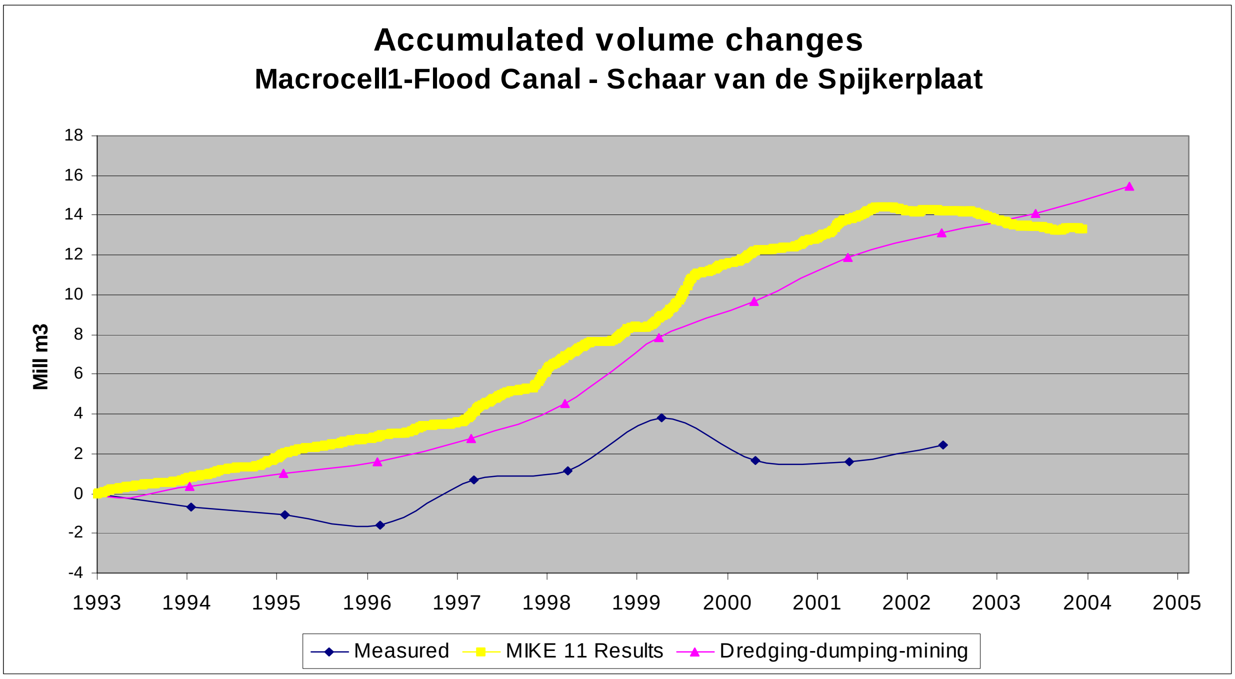


Figure 6-2: Extension into the North Sea. Simulated and observed accumulated sediment budget (million m^3) in the flood channel of Macro Cell 1- Validation 1993-2004

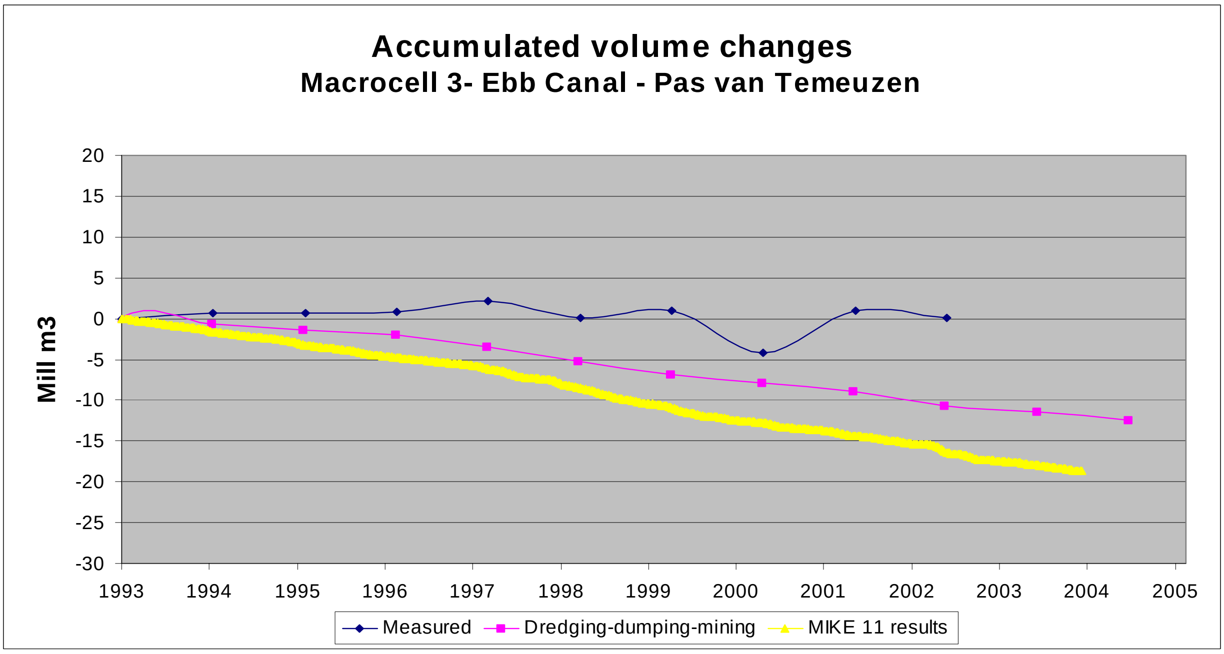


Figure 6-3: Extension into the North Sea. Simulated and observed accumulated sediment budget (million m^3) in the ebb channel of Macro Cell 3 - Validation 1993-2004

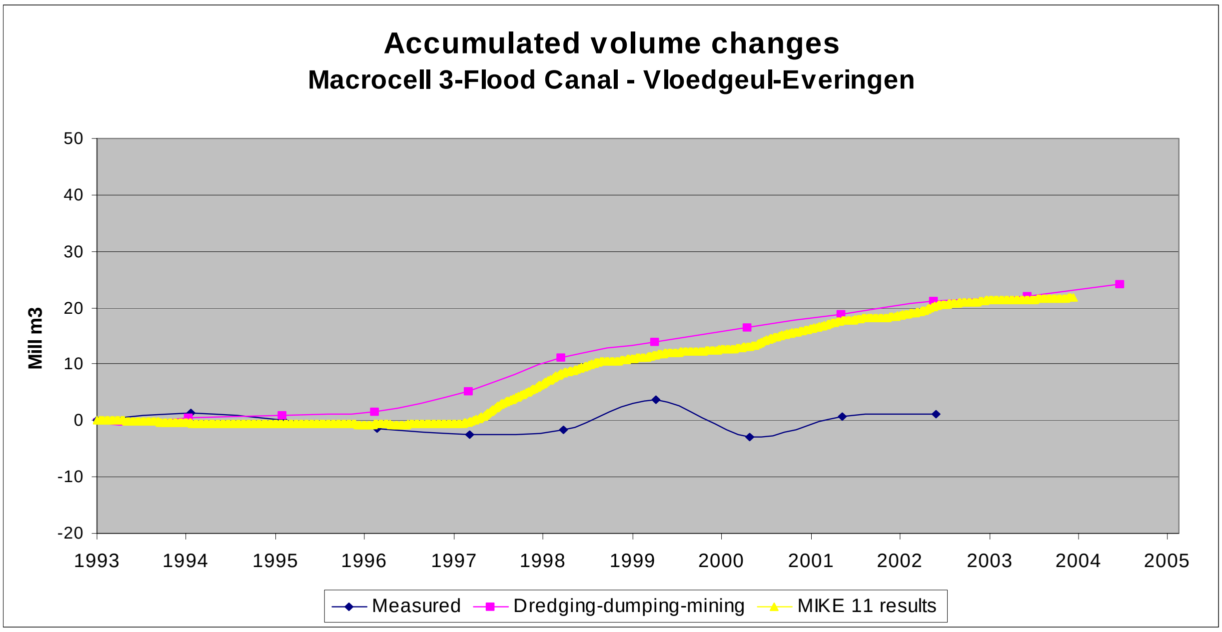


Figure 6-4: Extension into the North Sea. Simulated and observed accumulated sediment budget (million m^3) in the flood channel of Macro Cell 3 - Validation 1993-2004

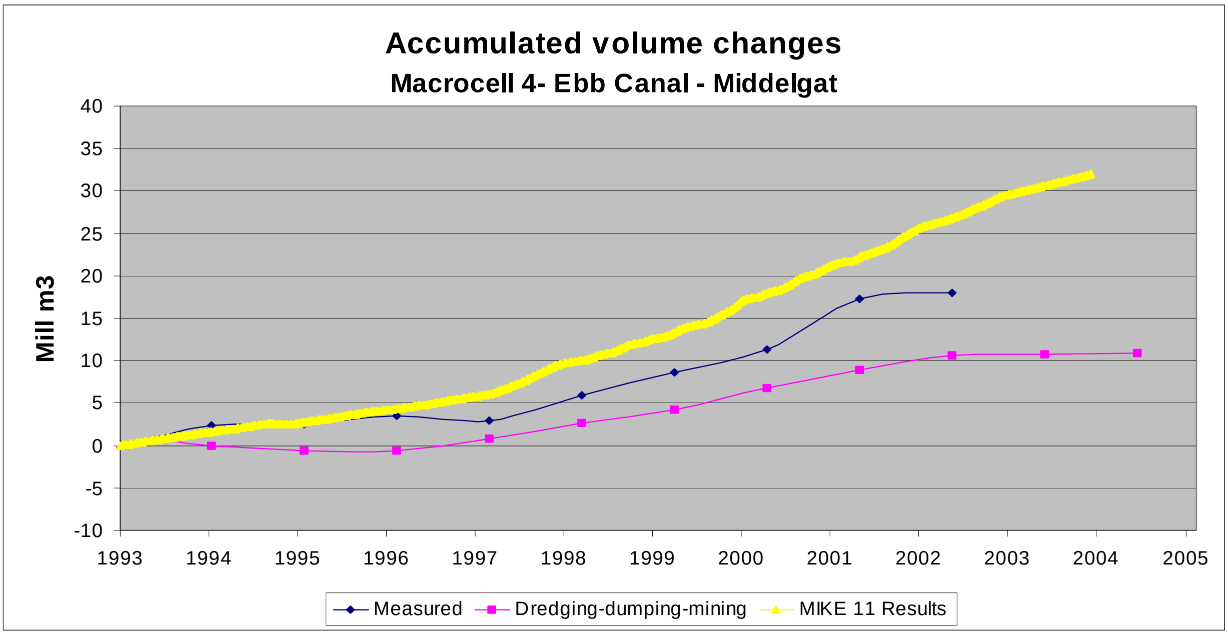


Figure 6-5: Extension into the North Sea. Simulated and observed accumulated sediment budget (million m^3) in the ebb channel of Macro Cell 4 - Validation 1993-2004

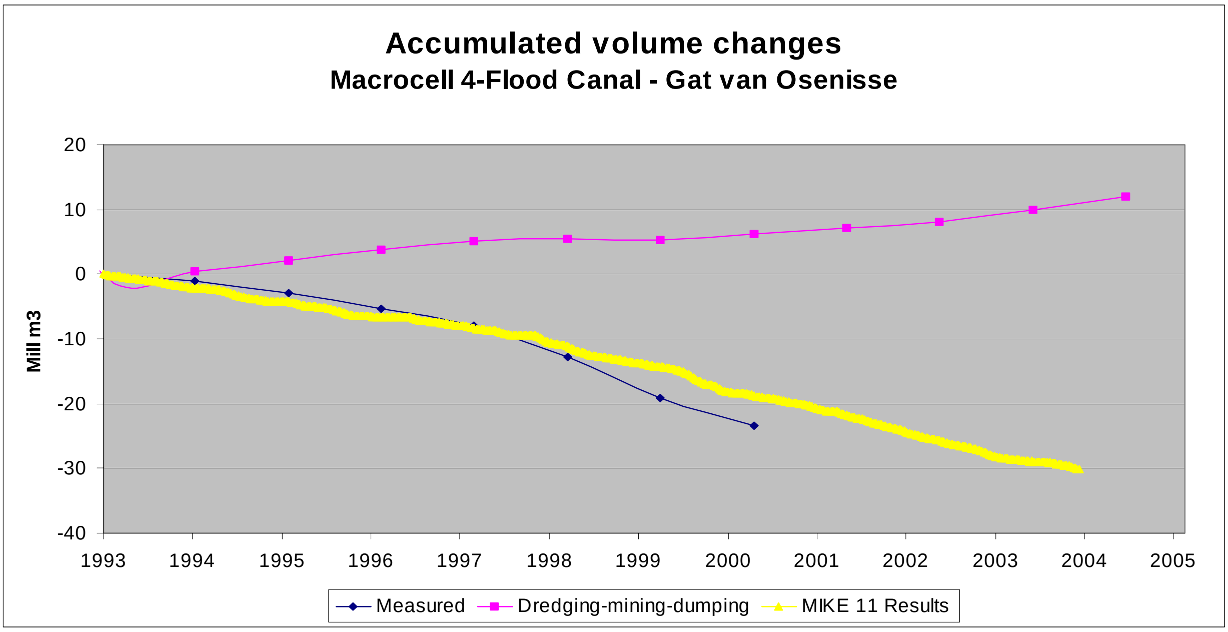


Figure 6-6: Extension into the North Sea. Simulated and observed accumulated sediment budget (million m^3) in the flood channel of Macro Cell 4 - Validation 1993-2004

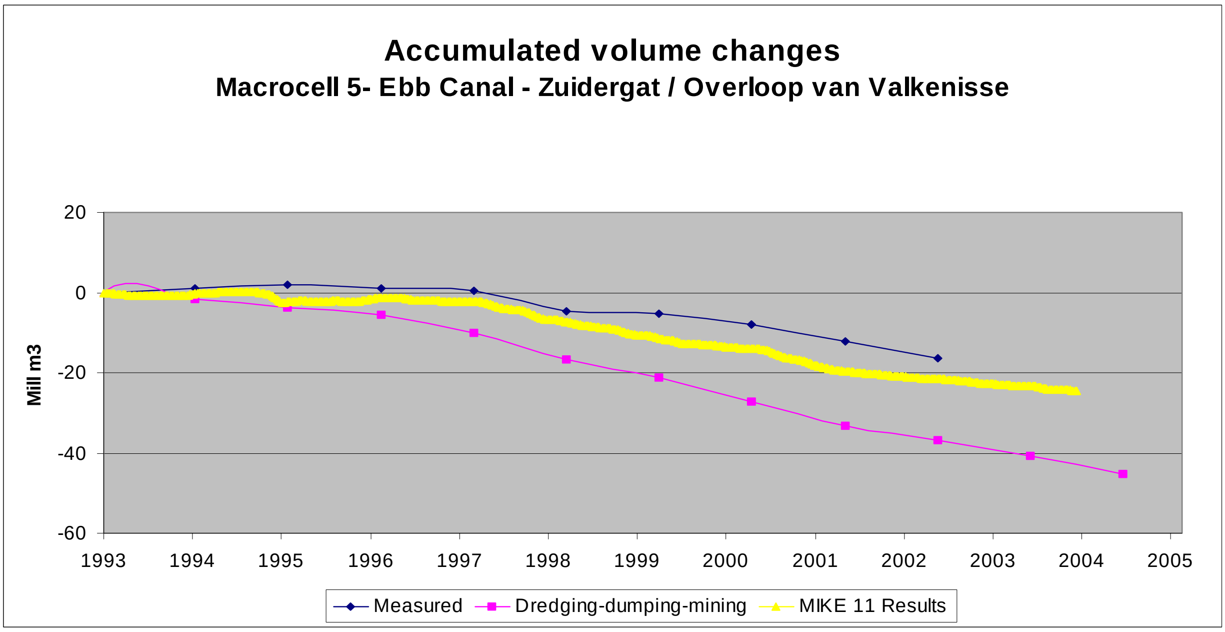


Figure 6-7: Extension into the North Sea. Simulated and observed accumulated sediment budget (million m^3) in the ebb channel of Macro Cell 5 - Validation 1993-2004

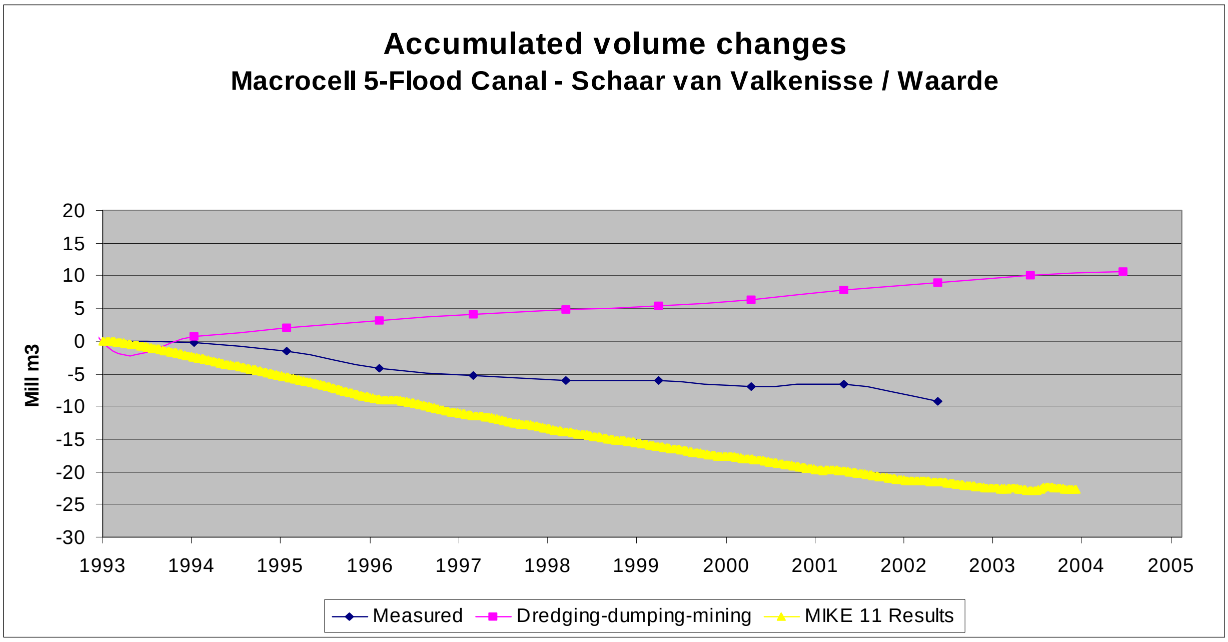


Figure 6-8: Extension into the North Sea. Simulated and observed accumulated sediment budget (million m^3) in the flood channel of Macro Cell 5 - Validation 1993-2004

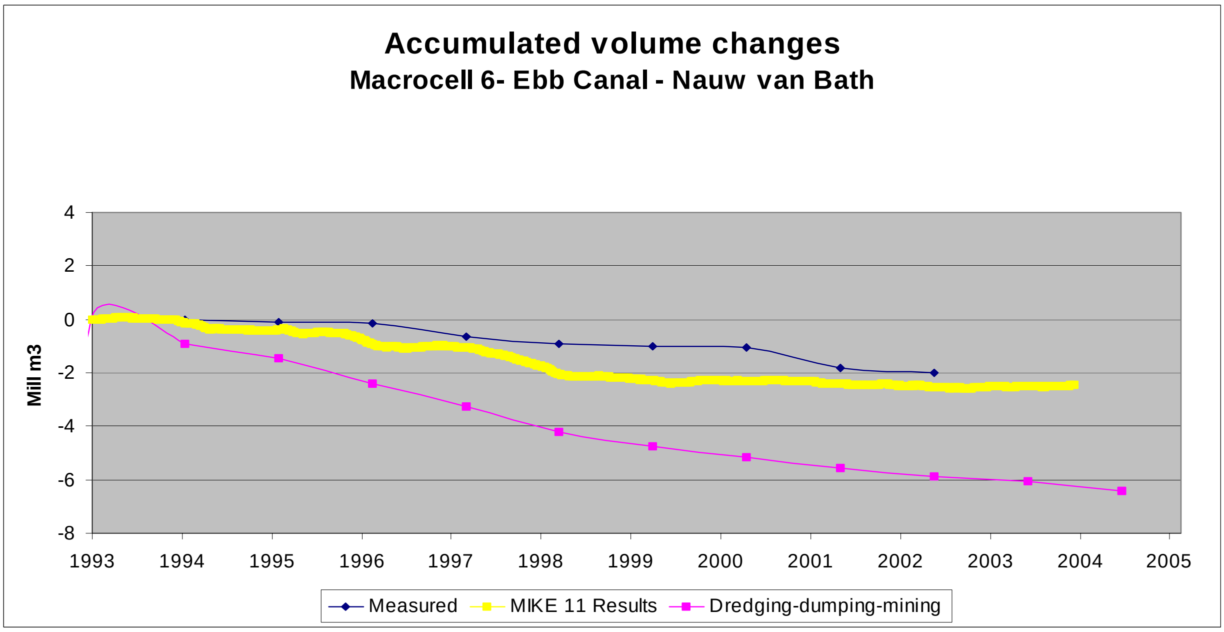


Figure 6-9: Extension into the North Sea. Simulated and observed accumulated sediment budget (million m^3) in the ebb channel of Macro Cell 6 - Validation 1993-2004

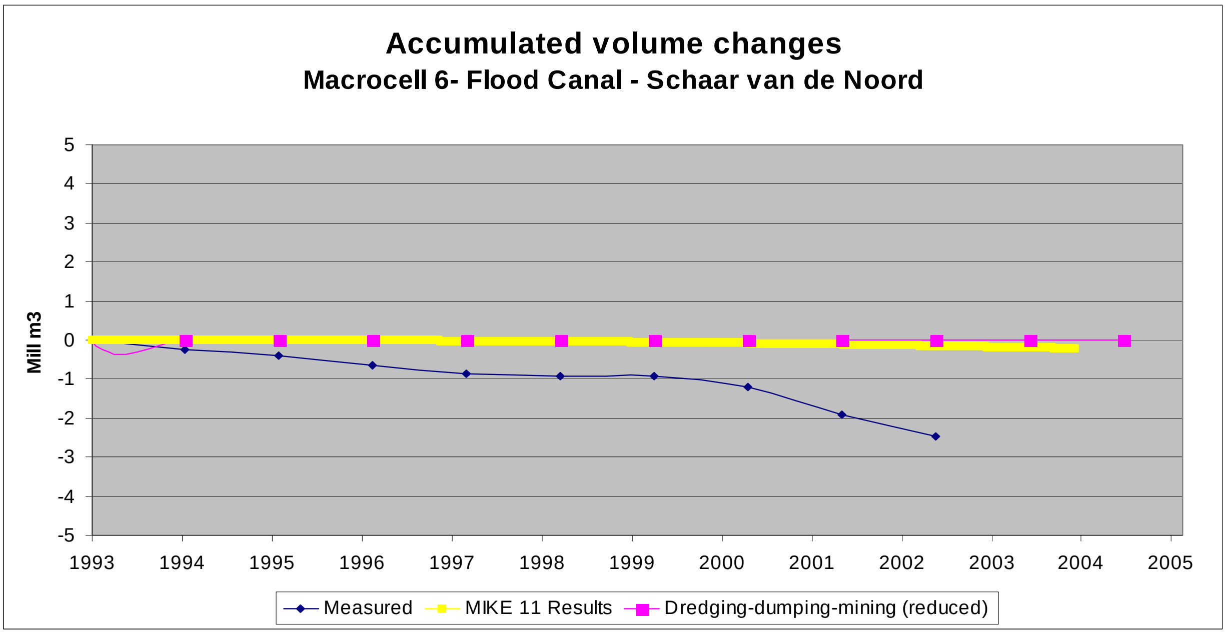


Figure 6-10: Extension into the North Sea. Simulated and observed accumulated sediment budget (million m^3) in the flood channel of Macro Cell 6 - Validation 1993-2004

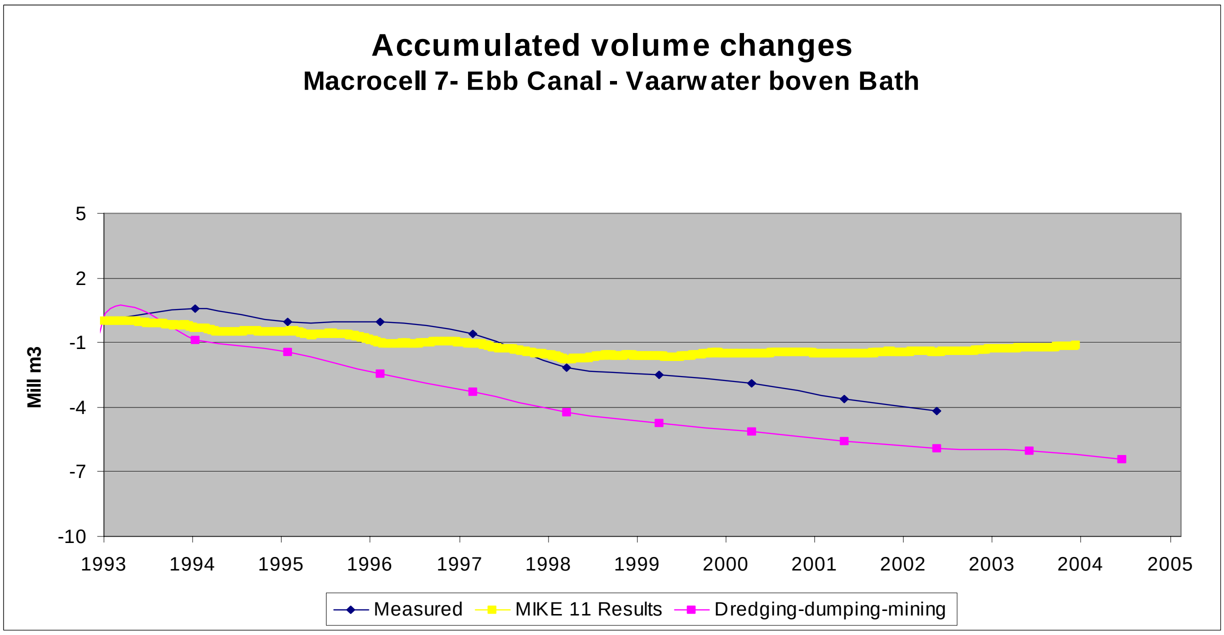


Figure 6-11: Extension into the North Sea. Simulated and observed accumulated sediment budget (million m^3) in the ebb channel of Macro Cell 7 - Validation 1993-2004

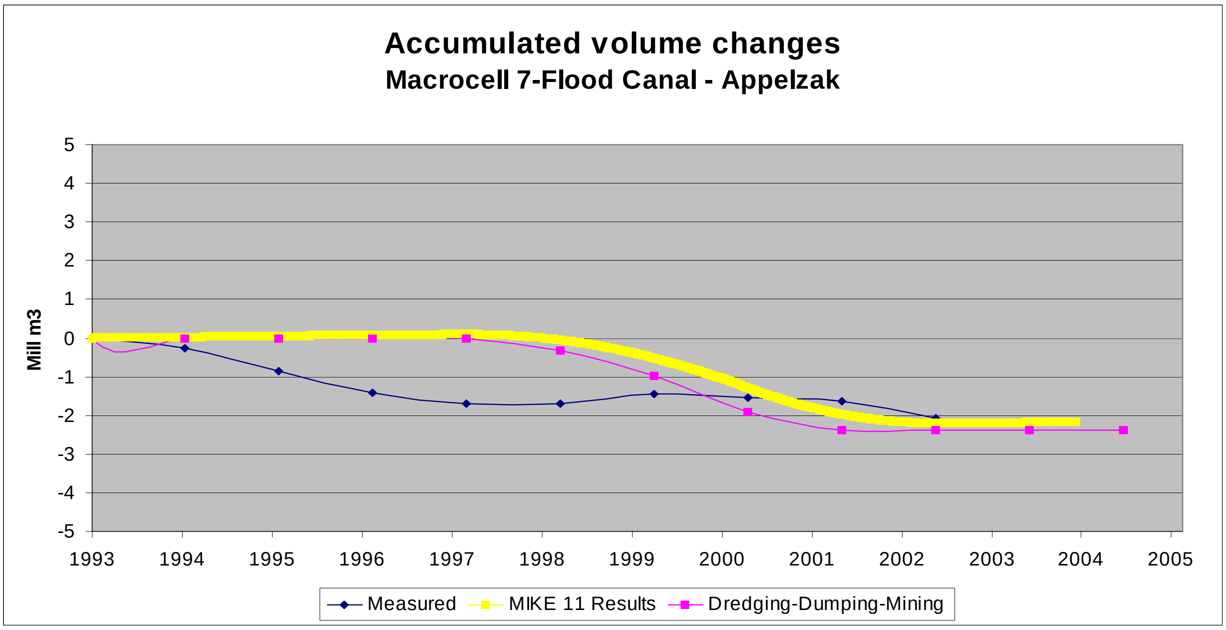


Figure 6-12: Extension into the North Sea. Simulated and observed accumulated sediment budget (million m^3) in the flood channel of Macro Cell 7 - Validation 1993-2004

7. COMPUTATIONAL ASPECTS

The reduced coupled MIKE 11 HD-NST model uses a time step of 10 minutes with a morphological model update at each time step. The CPU time is approximately 25 minutes per simulation year utilising a 3.0 GHZ Processor. Thus a full simulation from 1968 through 2003 can be accomplished within 13 hours utilising an equivalent processor.

The model extension into the North Sea increase the CPU time to 20 hours for a full simulation from 1968 through 2003

8. UNCERTAINTY AND PREDICTABILITY

In the following is provided a more general discussion regarding uncertainty in relation to the morphological modelling.

In the discussion of model results and the overall predictability, it is necessary to distinguish between different types of uncertainties. One way is to define the following categories:

- Natural uncertainty
- Data uncertainty
- Model uncertainty
- Model parameter uncertainty
- Operational uncertainty

<u>Natural uncertainty</u>
The stochastic behaviour of processes may impede long-term predictions. Braided rivers are (seen in a long-term perspective) chaotic systems: A small change one year is amplified in the strongly non-linear physical processes over the following years. In a bifurcation, the main channel may go either to one side or another. In the large braided unregulated sandy rivers in Bangladesh, model studies with multidimensional models have revealed that a reliable prediction period (deterministic) is less than say 2-3 years. In a regulated estuary like Scheldt with substantial river training, dredging and dumping, the reliability will most likely be much longer. Small differences will, however, be amplified in a 35 year simulation, and the reliability on e.g. local water depth prediction at a specific location will inherently be very small.

<u>Data uncertainty</u>
No model is better than the data provided for the model set-up and calibration. Data uncertainty is related to e.g. bathymetry measurements, discharge data, downstream water level data, and not least volumes, space and time for dredging and dumping. It is the impression, that the data uncertainty is limited compared to the other uncertainties in this project.

<u>Model uncertainty</u>
The parameterisation of the reality into a model is subject to uncertainty. Will the true dynamics be captured in the idealised model? Thus, model uncertainty is about model type (physical, mathematical etc.), model dimension (1D, 2D, 3D), flow equations (fully dynamic, quasi-steady, steady etc.), handling of “sub-grid processes”, i.e. parameterised processes which are not directly described in the grid (such as sediment split function in a bifurcation in a 1D model), sediment transport formulas (bed load, suspended load descriptions), alluvial resistance model (fixed bed resistance, bed resistance updated throughout the simulation etc.). The 1D flow model simulation has severe limitations for long-term predictions because 1) the alignment of channels are unchanged, 2) the geometry of cross-sections are unchanged, 3) the flow distribution mechanism and the sediment distribution mechanism are based on 1D whereas in reality it is 2D and 3D phenomena.

<u>Model parameter uncertainty</u>
A given model, whether it is 1D and 2D or 3D, needs to be calibrated. The quality of the calibration is related to the model parameter uncertainty. Ideally, a calibration should be repeated several times with several data set. For each data set, a new value of the optimal model parameter can then be found. The range of such values of a given model parameter shows the model parameter uncertainty. In most cases, only one or two data set are available.

This project has shown, that there is substantial uncertainty of some of the calibration parameters like flow-dependent bed resistance, grain size and sediment transport rate. Uncertainty in the model parameter combined with uncertainty in the actual type of model makes the overall model application very uncertain.

<u>Operational uncertainty</u>
The experience and expertise of the modelling team is obviously a crucial element. Compared to the other main sources of uncertainty (=natural, model and model parameter), this source is very small because of the expertise in the modelling team.

9. CONCLUSION AND RECOMMENDATIONS

It has been demonstrated that a 1-D model can reproduce the observed net circulation within the macro cells. This phenomenon is considered to be one of the controlling factors for the natural exchange of sediments between flood and ebb channels. However, the present investigation has clearly demonstrated that a 1- D model description should not be used to provide accurate values that can be used for more detailed dredging planning.

Even though the model can simulate the sediment transport dynamics during a tidal cycle and during a neap tidal cycle the timescale for larger morphological changes is years or decades as clearly seen from the observed changes on macro cell level. Thus small changes to the model set-up with respect to discretisation, sediment transport scaling factors and other calibration factors have a significant impact on the model results when comparing accumulated effects over a long period. Thus a small change in calibration parameter can hardly be noticed when considering a single tidal cycle. However the accumulated effect over a long period proves to be quite significant. Changing the sediment grain diameter, as an example, may change a general sedimentation pattern to erosion and changes in the sediment split function in bifurcation have a similar impact. At present 35 years are simulated with the model starting with the 1968 bathymetry. Thus the present choice of parameters provides the best match with respect to observed long term morphological changes in the estuary.

Obviously two- or three-dimensional effects (e.g. strong lateral variation of flow in river bends) cannot be resolved in the one-dimensional model. Nor is it possible to describe the lateral morphological change within a cross-section. Thus observed isolated bank erosions or dumping on inter tidal flats comprised by the cross-sections cannot be resolved in a 1- D model.

A constrained section will generally erode during high flow and deposit during low and medium flow. Finally, an entire reach may erode or deposit due to e.g. overloading or deprivation of sediment or change of hydraulic conditions. However, only this type of more general erosion and deposition processes can be adequately resolved with a 1D model. To study more local processes and elimination of inaccuracies caused by unresolved processes, two- or three-dimensional models are required.

The 1- D model should only be used carefully to investigate relative differences between different dredging strategies in the main navigational channels. Final design should be carried out using 2- or 3 D models. It is important to emphasize that if the model is used to predict changes say from 2007 and 10 to 15 years ahead it should be started minimum 5 years earlier to eliminate unbalances in initial conditions. If the focus is on the area closer to the sea it is recommended to use the North Sea extended model (SIGMA Morphological" model) to reduce uncertainties with respect to the morphological boundary condition.

The advantage of the 1D model is that it is possible to make long-term simulations within a relatively short timeframe. The present MIKE 11 sediment model set-up uses 13 CPU hours to simulate 35 years with a time step of 10 minutes. The extended MIKE 11 sediment model set-up uses 20 CPU hours to simulate 35 years with a time step of 10 minutes.

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ANNEX A. CALIBRATION PROCESS

The calibration process comprises numerous trial simulations with different parameters before the best set of model parameters have been identified. The calibration process comprised the following steps:

1. *Definition of morphological divide* - The level of morphological divide is generally selected at the vertical dividing the inter-tidal flats and the deeper navigational parts. All though not general for all cross-sections the level of divide in the Western Sheldt estuary is typically around level 0 m T.A.W. The level of divide approach is applied to the ebb- and flood channels and specified separately in MIKE 11 for each cross-section. The level of divide is not changed in the calibration process.
2. *Net circulations in macro cells*. The bed roughness expressed through the Manning number has been established during the calibration of the Hydrodynamic model and is not changed in the morphological simulations. However the reproduction of the net circulations observed in the macro cells required adjustment of the flow dependent bed roughness. A relative increase has been introduced during outflows in the flood channels. The relative increase is kept unchanged during the remaining part of the calibration process.
3. *Sediment transport model*. The van Rijn model was selected as sediment transport model and no other transport model has been tested during the calibration process
4. *Sediment grain diameter*. Initially a sediment grain diameter D_{50} was applied in the entire model area. However, the final set of grain diameters varies from macro cell to macro cell with decreasing diameters when going upstream in the estuary (from 300 micron in macro cell 1 and 3, down to 120 micron upstream in the Sea Scheldt).
5. *Sediment transport scaling factor*. The simulated sediment transport rates were compared with measured values during campaigns in 1988 through 1990. There was generally a good agreement with measured transport even without scaling thus this scaling parameter for suspended and bed load transport was not changed further during the calibration process.
6. *Sediment split function at junctions*. The split function was varied from junction to junction in order to obtain the best agreement with the observed accumulated sediment volume changes.

The calibration process is a very iterative process and particular steps 4 and 6 have been repeated iteratively to obtain the best set of parameters.

Figures A-1through A-15 show the effect of modifying the bed resistance in the Sigma Morphological model.

Various versions of the model have been used serving different purposes. The names used for the different versions are listed below:

- **“Existing-SIGMA- HD”** model: The original SIGMA model with all flood plains, based in the bathymetry 2001.
- **“Reduced-SIGMA-HD”** model: The original SIGMA without flood plains, but where the wetlands of “Verdronken land van Saeftinge” and the harbours in the Western Scheldt are well included
- **“Modified-SIGMA-HD”** model: It is a simplified version of the “SIGMA-reduced-HD” with less computational points, where the Western Scheldt is re-schematized, and it has

been used to calibrate the discharges and circulations. This model has as downstream boundary condition the water levels at Vlissingen.

- **"Extended-SIGMA-HD"** model: It is similar to the former one but with extension in the North Sea.
- **"Reduced-Modified-SIGMA-HD":** Is a reduced version of the "Modified -SIGMA-HD" model, where only the Rupel and the Durme are modeled as tributaries, and the wetlands of "Verdronken land van Saeftinge" are simplified. This model uses the bathymetry of 1968.
- **"SIGMA-Morphological-reduced".** Is the former configuration, but when the Non-Coehesive Sediment Transport (NST) module is applied.
- **"SIGMA-Morphological",** is the same than before but where the study area has been extended in the North Sea.

The calibration process regarding selection of manning numbers has been carried out as follows:

- The results shown in Figures 4-13 to 4-27 represent the results of the morphologic simulation without extension into the North Sea. The Manning numbers used in this simulation (here called "preliminary Manning numbers") are listed in the table below, and correspond to the calibrated manning numbers with the "Modified-SIGMA-HD" model. That means calibrated with a constant Manning.

- Later the model was extended into the North Sea. The bathymetry of 1968 was used, and at the downstream boundary simulated (not historical) water levels were applied. The same HD manning numbers were applied ("preliminary Manning numbers"). The results are given Figures B-1 through B-15 (yellow lines).

- Finally the hydrodynamic simulations were improved by means of the use of a flow dependant Manning. A "final set on manning numbers" was found and used in the final morphological simulations. These simulations were carried out with the "SIGMA-Morphological" model (extended model). The results are given in Figures 5-25 through 5-39.

The below table provides an overview of Manning numbers that have changed:

Table A- 1: Overview of selected Manning Numbers

River Name	Chainage	Location	Sigma HD	Preliminary Manning numbers	Final set of Manning Numbers
SCHAAR-SPIJKERPLAAT	0		0.025	0.030	0.020
SCHAAR-SPIJKERPLAAT	9700		0.025	0.030	0.020
WESTERSCHELDE	0	monding noordzee	0.025	0.030	0.022
WESTERSCHELDE	10100	end-raai-9	0.025	0.030	0.022
WESTERSCHELDE	29100	End-raai-7	0.026	0.024	0.025
WESTERSCHELDE	31000	Begin-Raai-6	0.026	0.023	0.022
WESTERSCHELDE	41700	+o- Hasweert	0.027	0.022	0.020
WESTERSCHELDE	54600		0.027	0.022	0.020
WESTERSCHELDE	59508		0.027	0.022	0.020
WESTERSCHELDE	62100	Bath	0.027	0.022	0.020
ZEESCHELDE2	100		0.029	0.020	0.022
ZEESCHELDE2	6600		0.029	0.020	0.024
ZEESCHELDE2	10129		0.029	0.020	0.024
ZEESCHELDE	10129		0.024	0.020	0.024
ZEESCHELDE	15678	Kallosluis	0.024	0.020	0.024
ZEESCHELDE	23005	Oosterweel	0.024	0.020	0.024
ZEESCHELDE	24708	Antwerpen	0.024	0.020	0.024
ZEESCHELDE	37998	Schelle	0.024	0.020	0.024
ZEESCHELDE	46787	Temse	0.024	0.020	0.024
ZEESCHELDE	50195	monding durme	0.024	0.020	0.025
ZEESCHELDE	51597	Driegoten	0.024	0.020	0.026
ZEESCHELDE	65507	sint Amands	0.027	0.020	0.029
ZEESCHELDE	70100	Dendermonde	0.028	0.024	0.029
ZEESCHELDE	81158	Schoonaarde	0.031	0.024	0.029
ZEESCHELDE	99799		0.035	0.024	0.035
EVERINGEN	0		0.025	0.028	0.025
EVERINGEN	5900		0.025	0.028	0.025
EVERINGEN	10100		0.025	0.028	0.025
EVERINGEN	14400		0.025	0.028	0.025
SCHAAR-WAARDE	0		0.027	0.022	0.020
SCHAAR-WAARDE	9600		0.027	0.022	0.020

That means that after the modifications respect to the sigma model, the “n” was increased in the mouth area around Vlissingen. By doing so the discharges were better modeled but the water levels showed a shift in phase and were lower. Therefore it was necessary to reduce the “n” from the end of “raai” 7 and further upstream.

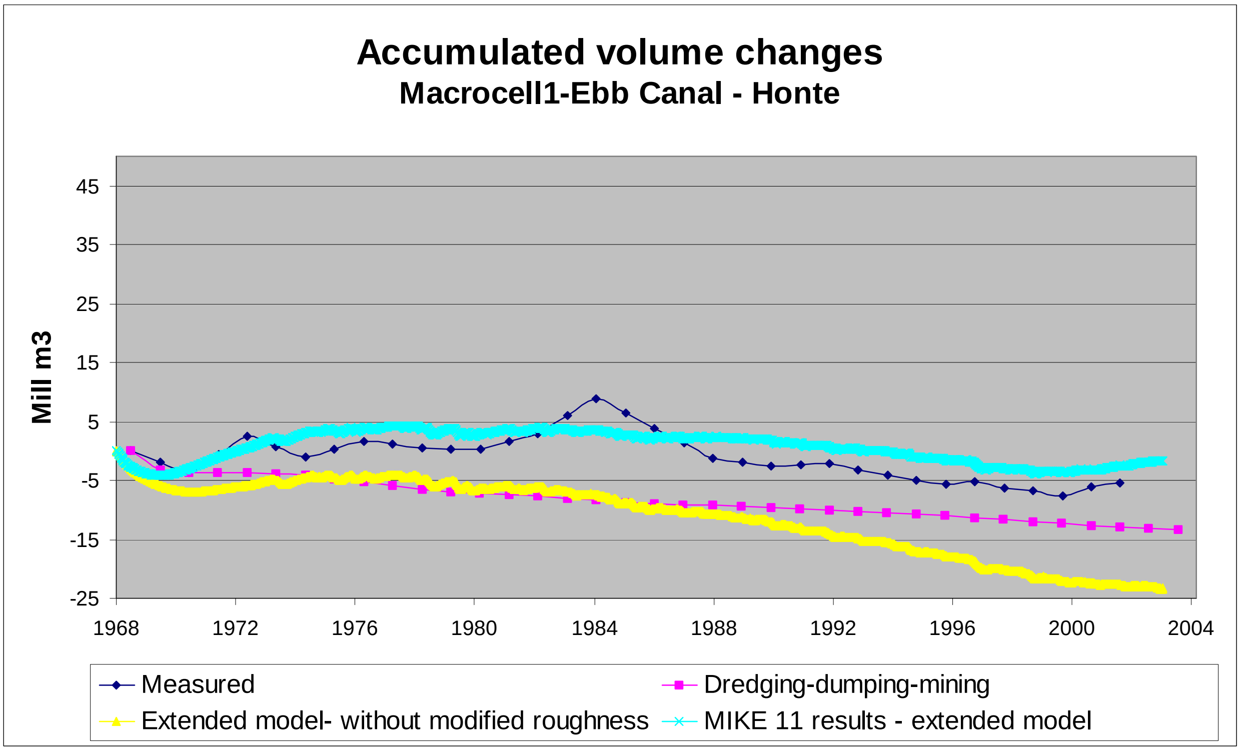

Figure A- 1:Effect of modification of roughness ,Macro Cell 1

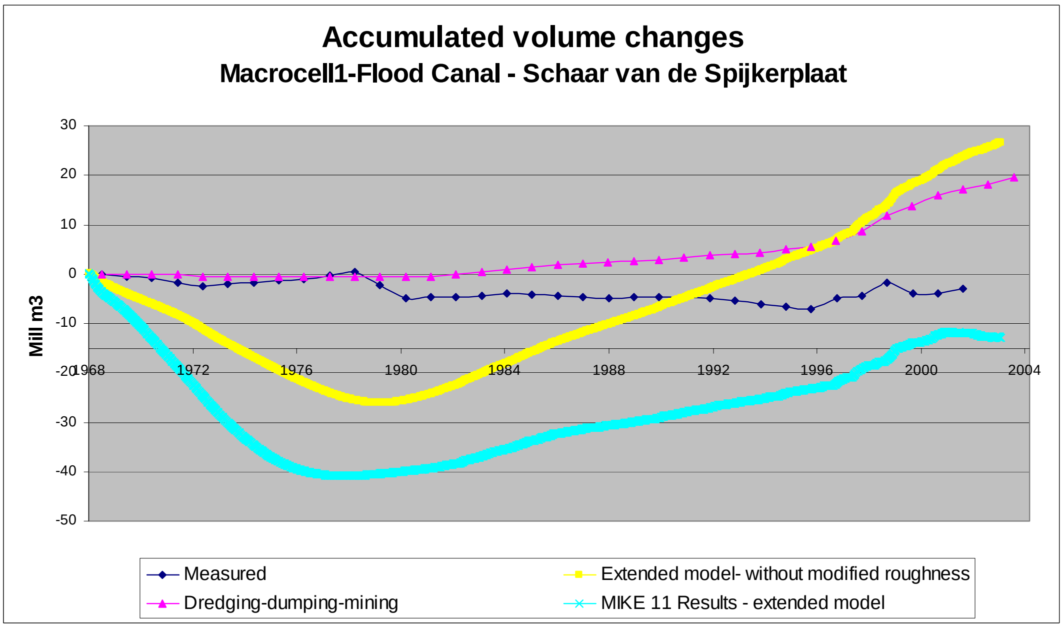

Figure A- 2:Effect of modification of roughness, Macro Cell 1

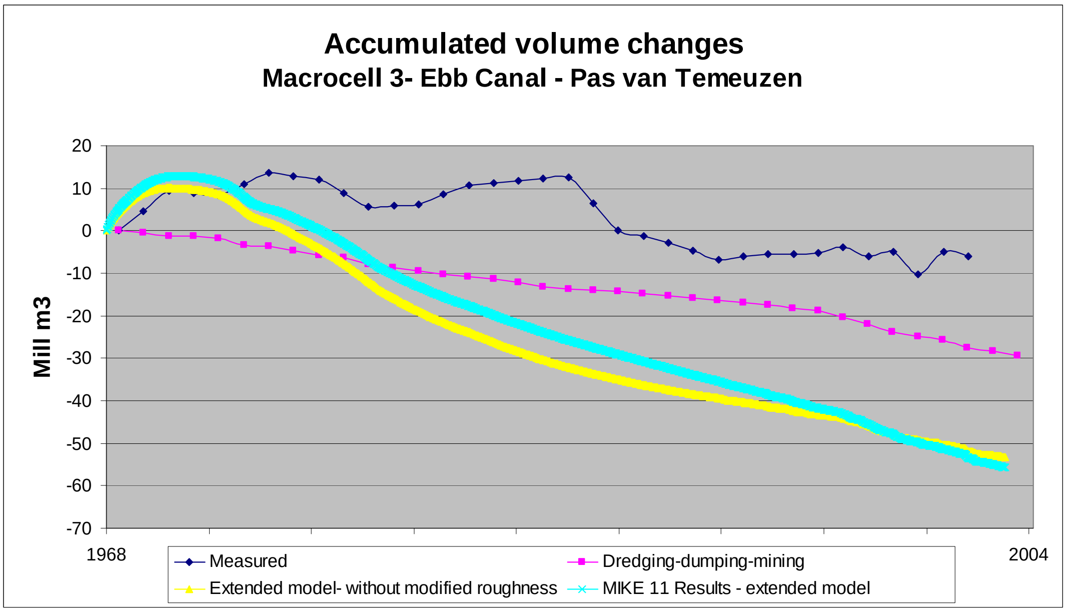

Figure A- 3:Simulated Effect of modification of roughness, Macro Cell 3

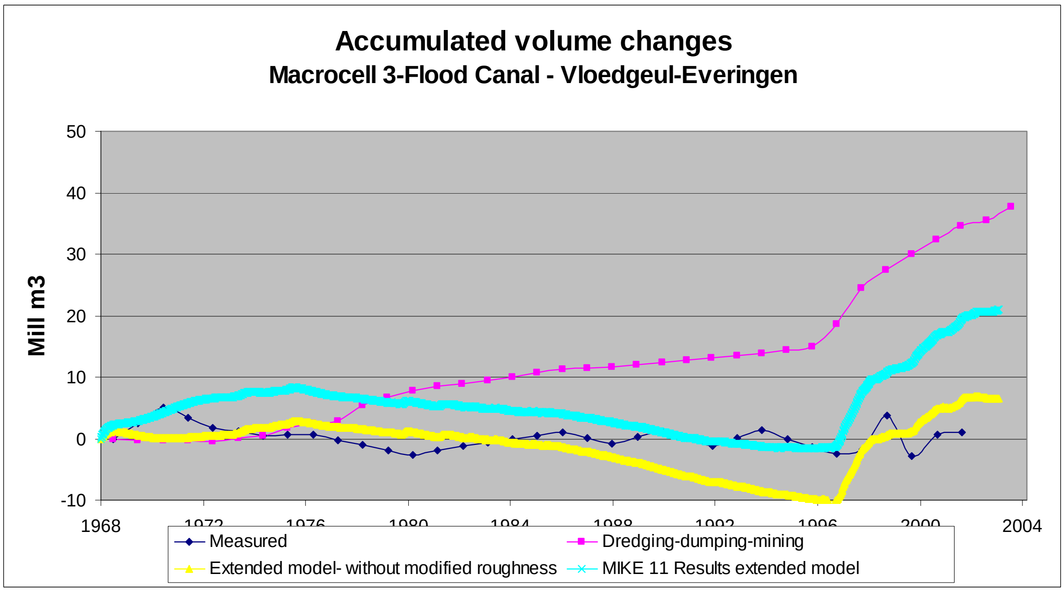

Figure A- 4:Effect of modification of roughness, Macro Cell 3

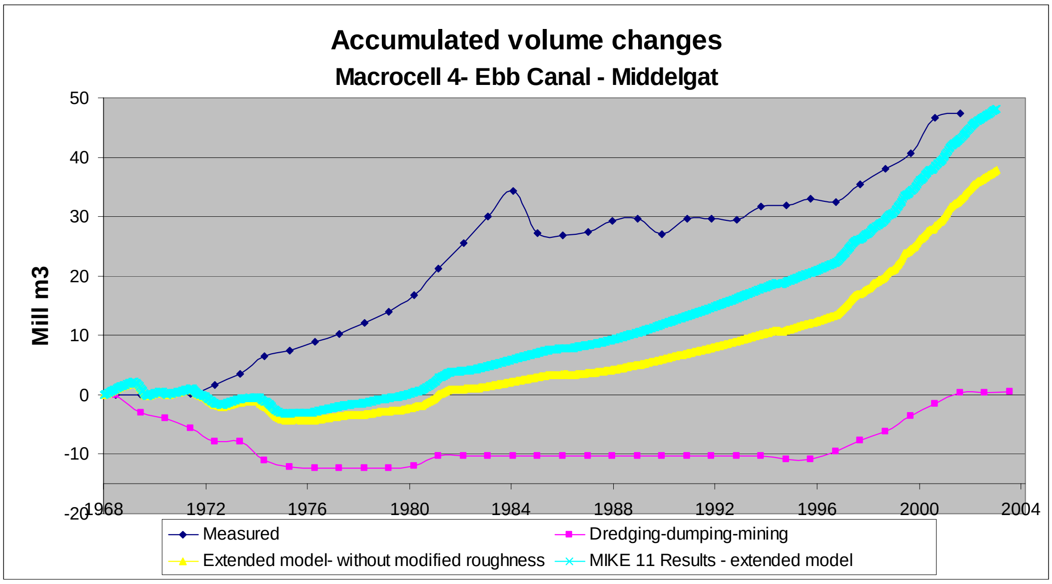

Figure A- 5:Effect of modification of roughness ,Macro Cell 4

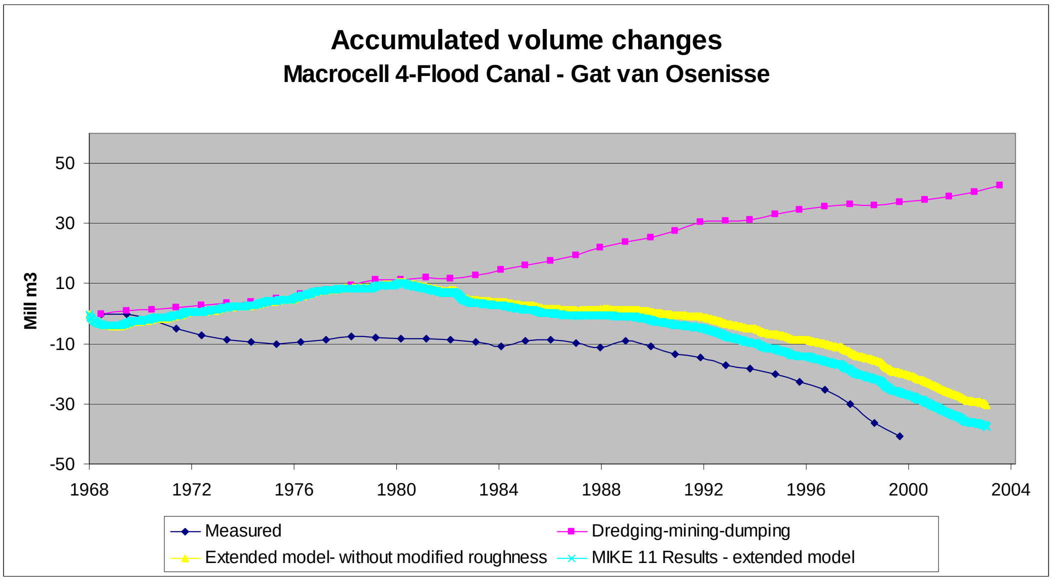

Figure A- 6:Effect of modification of roughness, Macro Cell 4

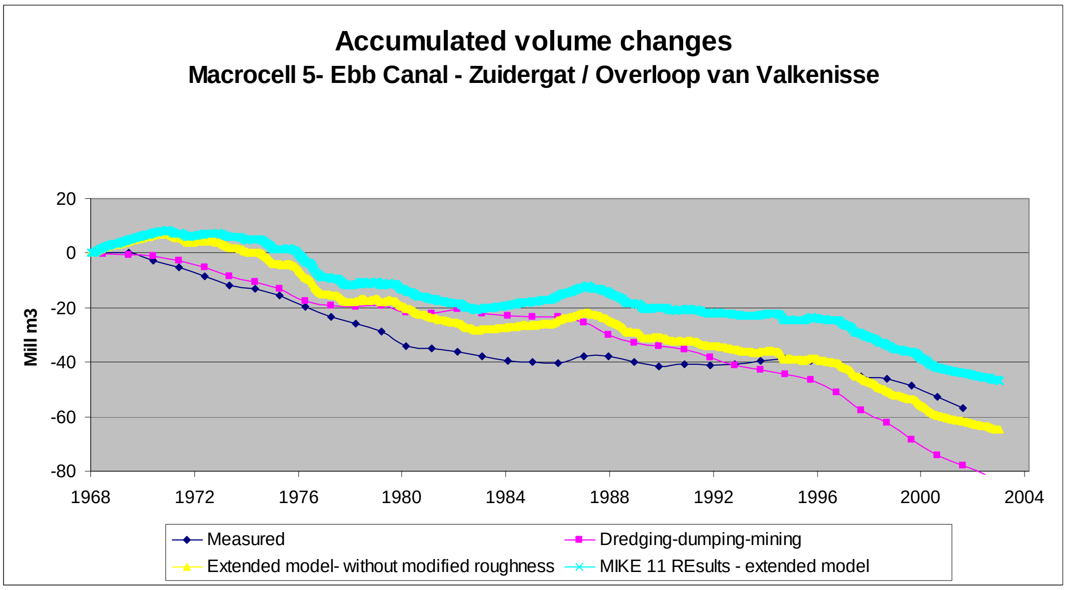

Figure A- 7: Effect of modification of roughness, Macro Cell 5

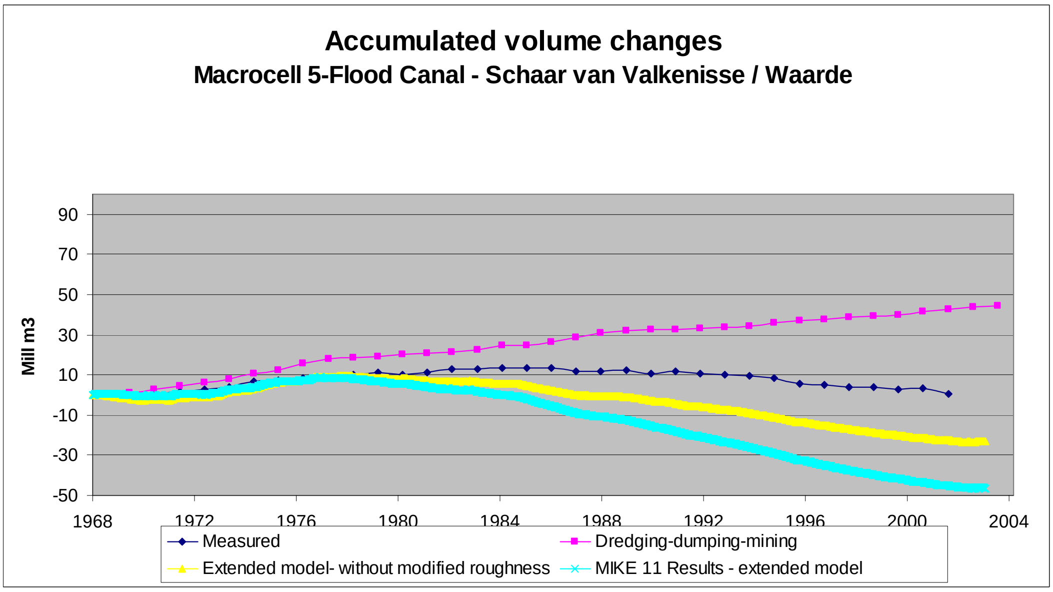

Figure A- 8: Effect of modification of roughness, Macro Cell 5

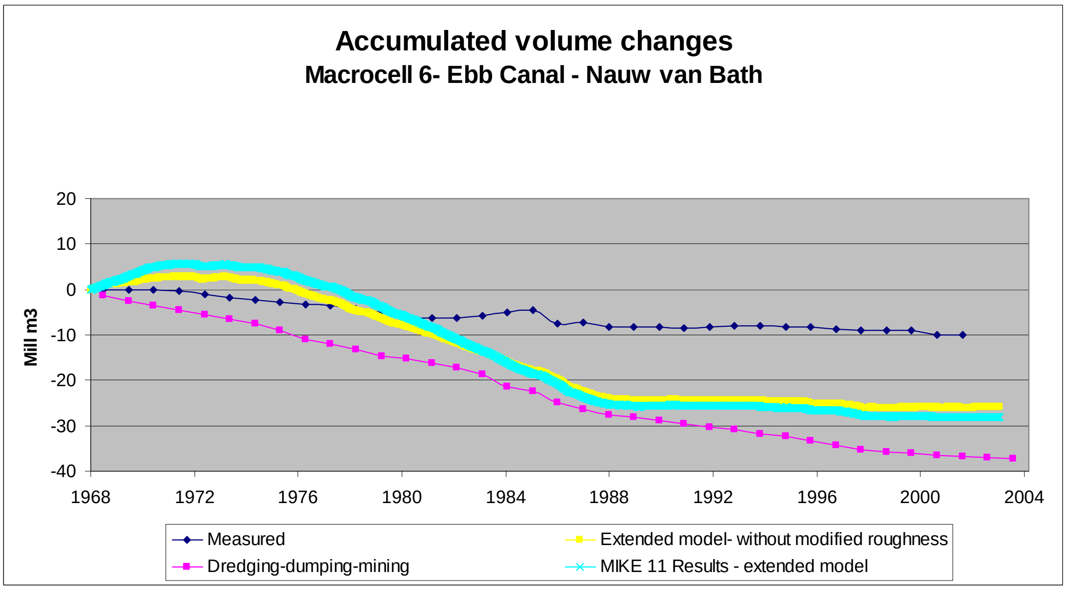

Figure A- 9:Effect of modification of roughness, Macro Cell 6

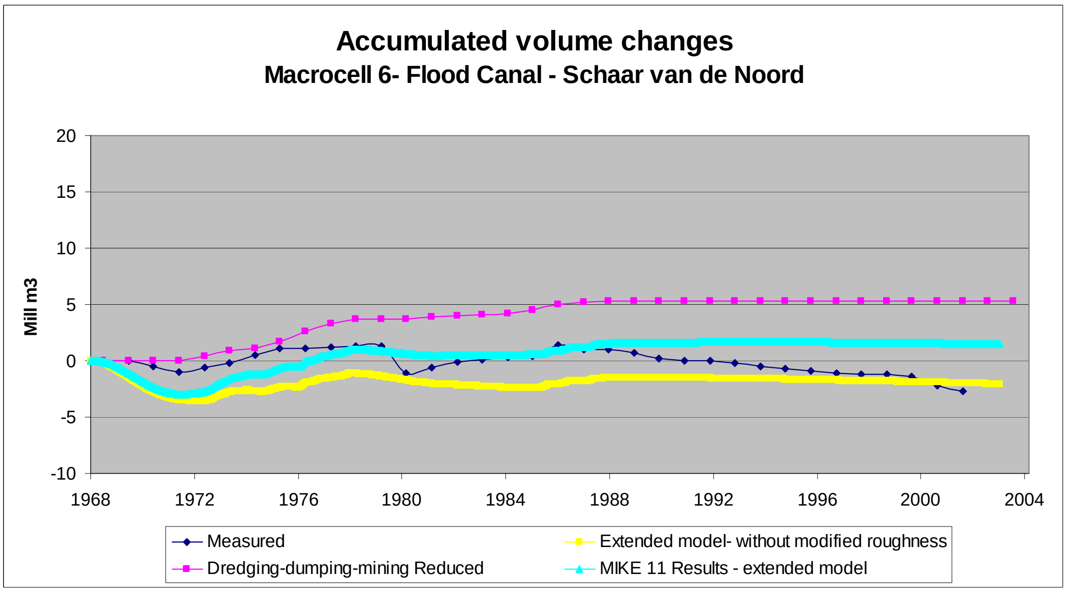

Figure A- 10:Simulated Effect of modification of roughness, Macro Cell 6

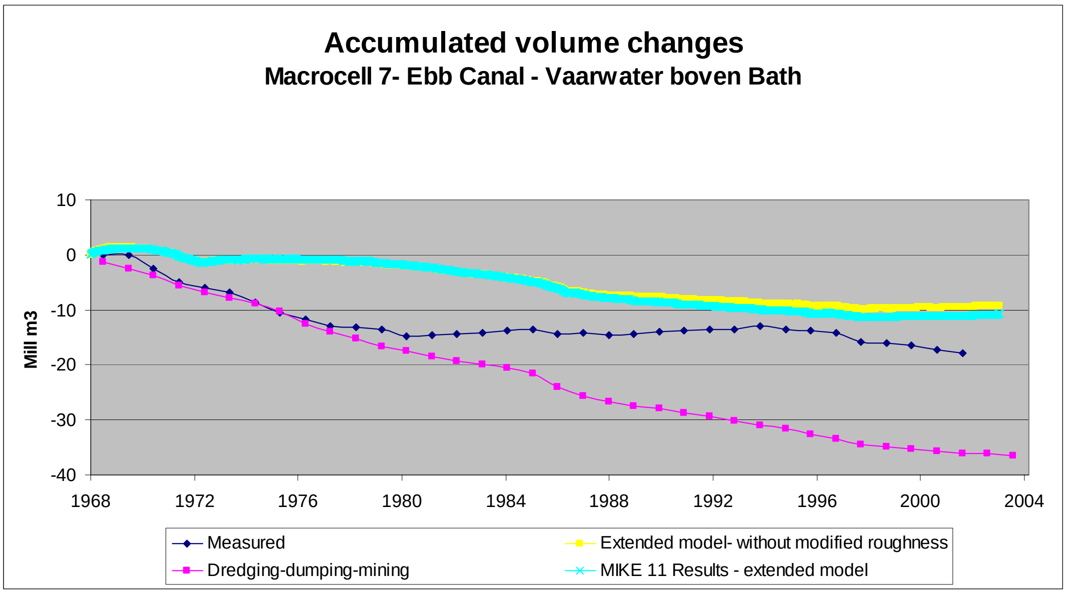

Figure A- 11:: Effect of modification of roughness, Macro Cell 7

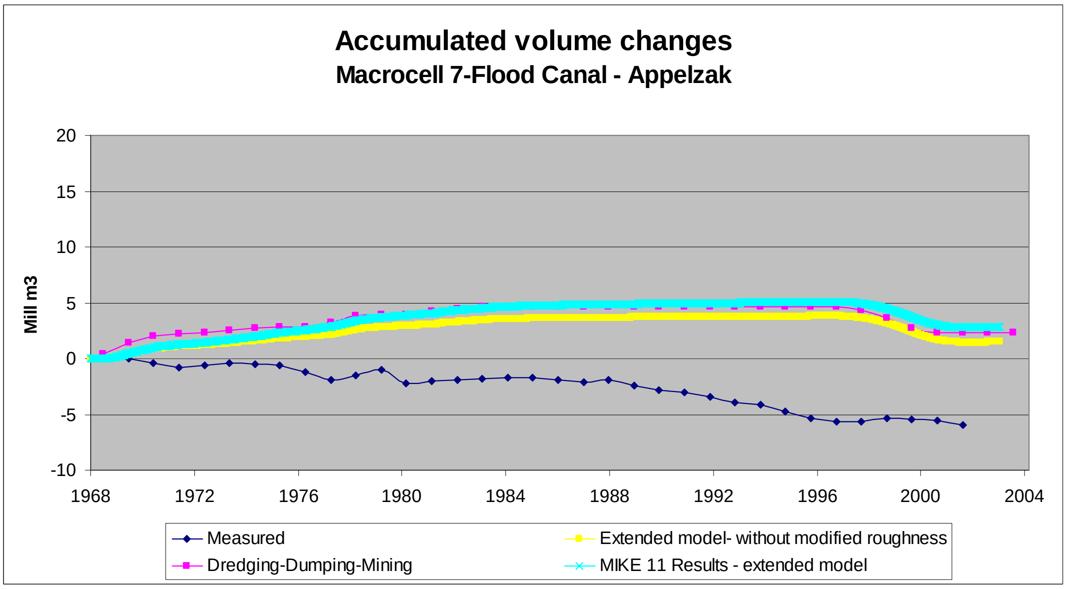

Figure A- 12:Effect of modification of roughness, Macro Cell 7

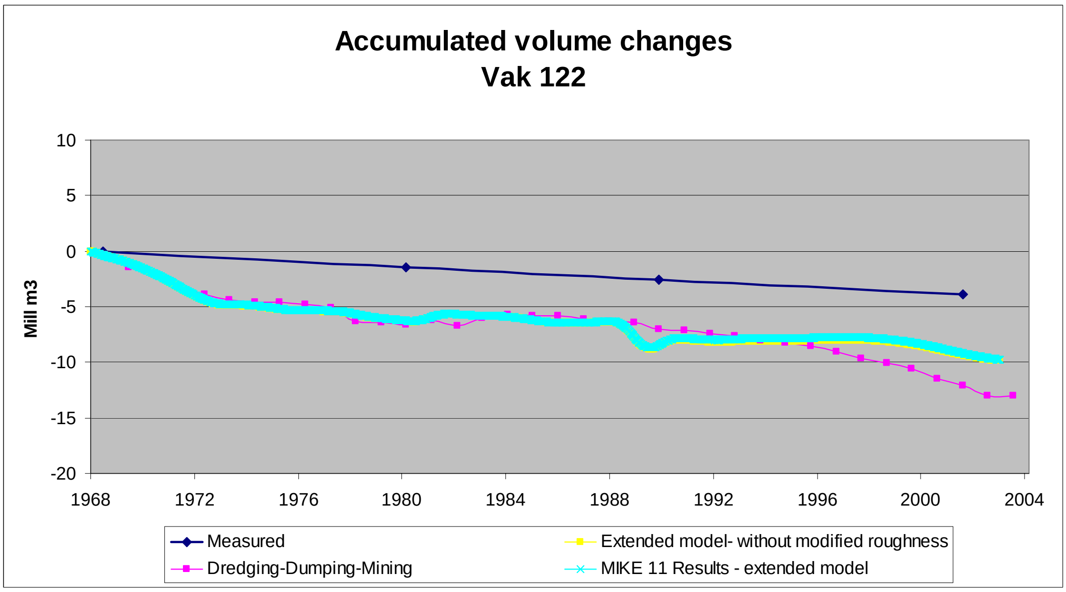

Figure A- 13:Effect of modification of roughness ,"Vak 122" in the Sea Scheldt .7

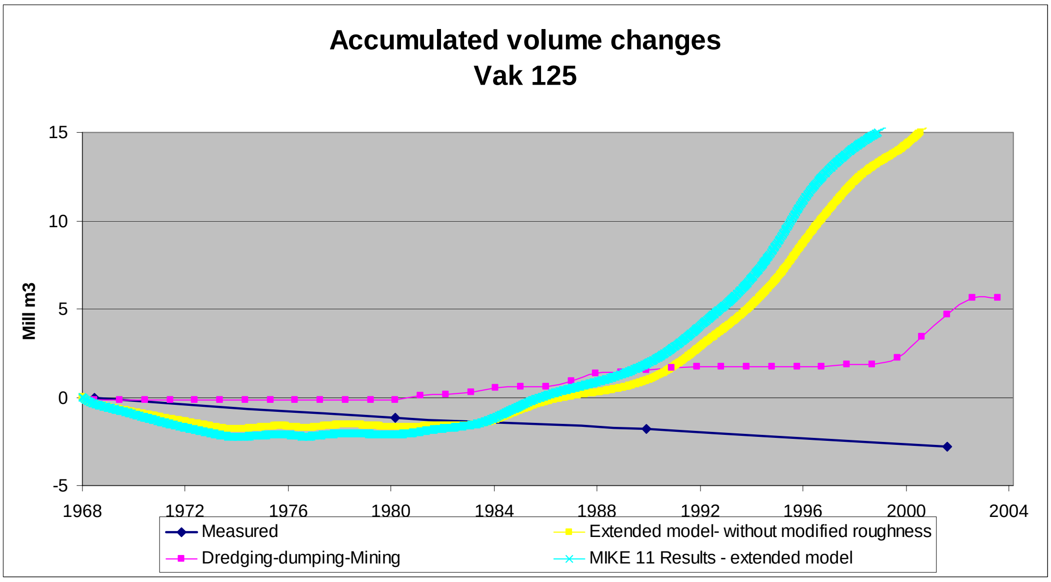

Figure A- 14:Effect of modification of roughness in "Vak 125" in the Sea Scheldt .

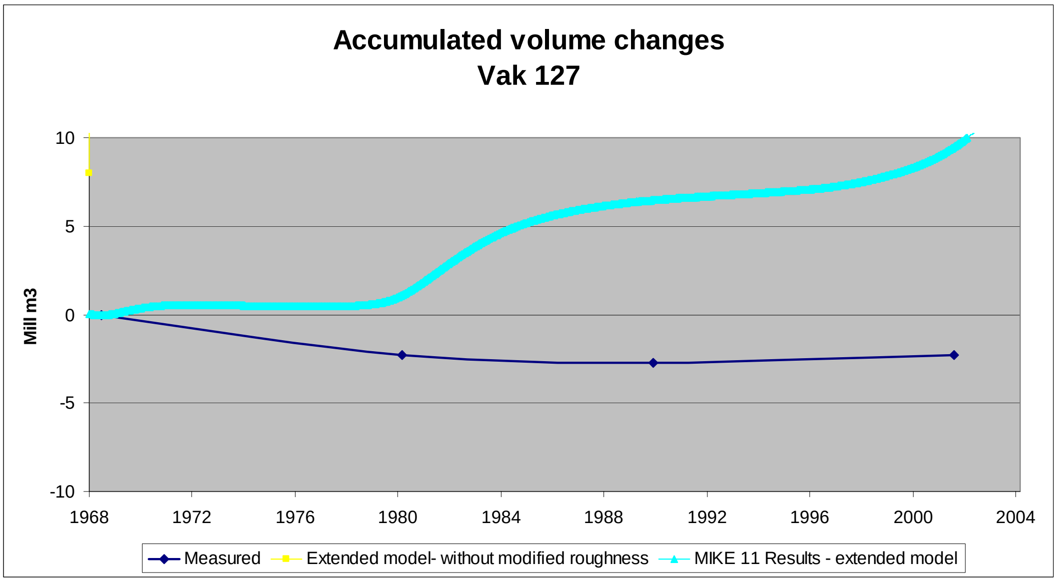

Figure A- 15:Effect of modification of roughness, “Vak 125” in the Sea Scheldt

ANNEX B. REFERENCE MANUAL NON-COHESIVE SEDIMENT TRANSPORT MODULE OF MIKE-11