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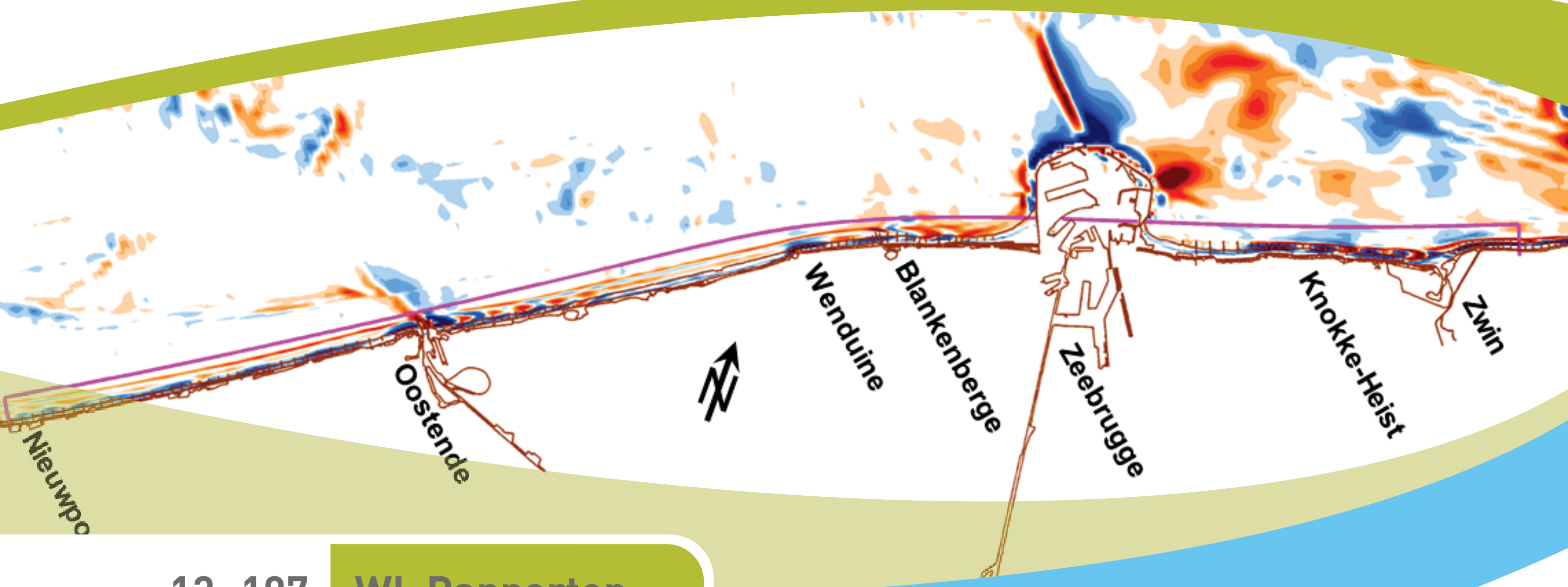
Openbare Werken

Scientific support regarding hydrodynamics and sand transport in the coastal zone

CALIBRATION OF A LONG TERM MORPHOLOGICAL MODEL OF THE BELGIAN SHELF



12_107 WL Rapporten

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Scientific support regarding hydrodynamics and sand transport in the coastal zone

Calibration of a Long term morphological model of the Belgian shelf

Wang, L.; Zimmermann, N.; Trouw, K.; De Maerschalck, B.; Delgado, R.; Verwaest, T.; Mostaert, F.

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Waterbouwkundig Laboratorium

Flanders Hydraulics Research

Berchemlei 115
B-2140 Antwerp
Tel. +32 (0)3 224 60 35
Fax +32 (0)3 224 60 36
E-mail: waterbouwkundiglabo@vlaanderen.be
www.waterbouwkundiglaboratorium.be

International Marine and Dredging Consultants

Coveliersstraat 15
B-2600 Antwerp
Tel. +32 (0)3 270 92 95
Tel. +32 (0)3 235 67 11
info@imdc.be
www.imdc.be

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Approval

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Abstract

Longshore sediment transport in the surf zone plays a considerable role in the long-term morphological behaviour of the Belgian coast. Based on previous efforts (Zimmermann et al., 2013b; Zimmermann et al., 2013), this report firstly presents a 2D numerical model which covers almost the entire Belgian coast from Nieuwpoort to the Zwin. With the MorMerge online-parallel approach the time horizon for modelling long term morphology in the surf zone was successfully increased to 10 years. Compared with the measurement data, most major morphological changes in the surf zone are well captured qualitatively by the 2D numerical model with an exception of the sedimentation in the Baai van Heist. The modelled sedimentation/erosion is further quantitatively compared with beach accretion/erosion trends of the last 25 years reported in Houthuys (2012). This model still shows a reasonable agreement and its quality is discussed. The sedimentation in the Baai van Heist is specially investigated by an updated 2D and later a new 3D model. For a further validation of the model used in this study, another 3 models OKNO, Zeebrugge and MU-HEIST are introduced and their results are compared with that of the model used in this study. After a series of sensitivity tests a roughness map is employed to update the 2D model, but the updated 2D model seems to be still unable to reproduce the sedimentation in the Baai van Heist properly, especially from the quantitative point of view. To avoid the Gallapatti time scale, a new 3D model is built up, and driven by boundary condition of full spring-neap tides rather than representative ones imposed in the 2D model. With the technique of time-varying MorFac and multiple sediment fractions, the 3D model shows a quite good potential to reproduce the sedimentation in the Baai van Heist. Based on the promising result produced by the 3D model, additional work is proposed for further investigation and research in the future.

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1. Introduction

1.1 The assignment

In the frame of the project “Scientific support for hydrodynamics and sand dynamics in the coastal zone” executed by IMDC for Flanders Hydraulics Research (specification WL/09/23), tools are being developed in order to help answering morphology-related questions for Flanders Hydraulics Research itself and the relevant governmental services. The development of a numerical model allowing the evaluation of the long term morphological behaviour of the coast is one of these tools.

1.2 Aim of the study

The objective of the numerical model of the Belgian coast presented in this report is to provide a reusable tool that can be applied to evaluate the long term morphological evolution of problem zones along the coast. This evolution can be either natural or driven by human activity. The field is first restricted to sand dynamics only, in accordance with the frame of the project, although in some applications mud may play a role as well. Examples of practical applications of long term sand morphology are:

- Evaluation and mitigation of causes for local erosion along the coast (Wenduine, Knokke)
- Evaluation and mitigation of harbour sedimentation (Blankenberge; Zimmermann et al., 2013a)
- Evaluation of the impact of artificial islands along the coast (shelf; Zimmermann et al., 2013b)

Some of these applications may require local models: in this case the numerical model should allow to investigate the causes on a larger scale and to provide boundary conditions for future nested models.

Problems at the coast usually include both the tide and waves. While modelling long term morphology with tide only is a relatively mature field, including waves lead to certain complications which limit the modelled time horizon (Zimmermann et al., 2012). This numerical model therefore builds on previous efforts (Zimmermann et al., 2013b; Zimmermann et al., 2012) to increase the time horizon for long term morphology to a minimum of 10 years. Calibration efforts focus on the coastal stretch East of Zeebrugge (Baai van Heist to Zwin inlet), since this is where the first application is expected.

1.3 Overview of the study

The study comprises the following main steps:

- The setup of a morphological model with a time horizon of 10 years, based on previous efforts for a time horizon of one year reported in Zimmermann et al. (2013b) and Zimmermann et al. (2012);
- The evaluation of model results and the investigation of model shortcomings in the Baai van Heist;
- The additional investigation of 2D/3D model for the Baai van Heist.

1.4 Structure of the report

This report is structured in the following way:

- Chapter 1 is an introduction.
- Chapter 2 presents the model setup, including a summary of previous calibration work.
- Chapter 3 presents the model results and compares them to available morphological data.
- Chapter 4 investigates the 2D/3D modelled sedimentation in the Baai van Heist, an area in which the initial model does not reproduce the observed sedimentation trend.

2. Model setup and calibration

2.1. Conventions

Horizontal coordinates are defined in RD Parijs, the vertical reference level is relative to NAP and MET time has been chosen. For the sake of simplicity, the NAP level can be assimilated to the mean sea level (MSL).

Dutch conventions instead of Belgian conventions have been chosen, because the Dutch Zuno model has been used to generate flow boundary conditions for a legacy model on which the present work is based.

2.2. Model setup

2.2.1. Past work

In Zimmermann et al. (2012), a morphological model has already been set up in Delft3D for the coastal zone around Blankenberge and Zeebrugge. This model is called the OKNO model (Oostende to Knokke) and is driven by boundary conditions obtained from the larger Zuno model. It has been developed to simulate long term morphology with tide and waves over a time horizon of one year. It is the starting point of the present model methodology. It could however not be used directly for applications East of Zeebrugge because of its limited spatial extent (East boundary around Knokke) and the too coarse resolution of the Zuno model at the same East boundary.

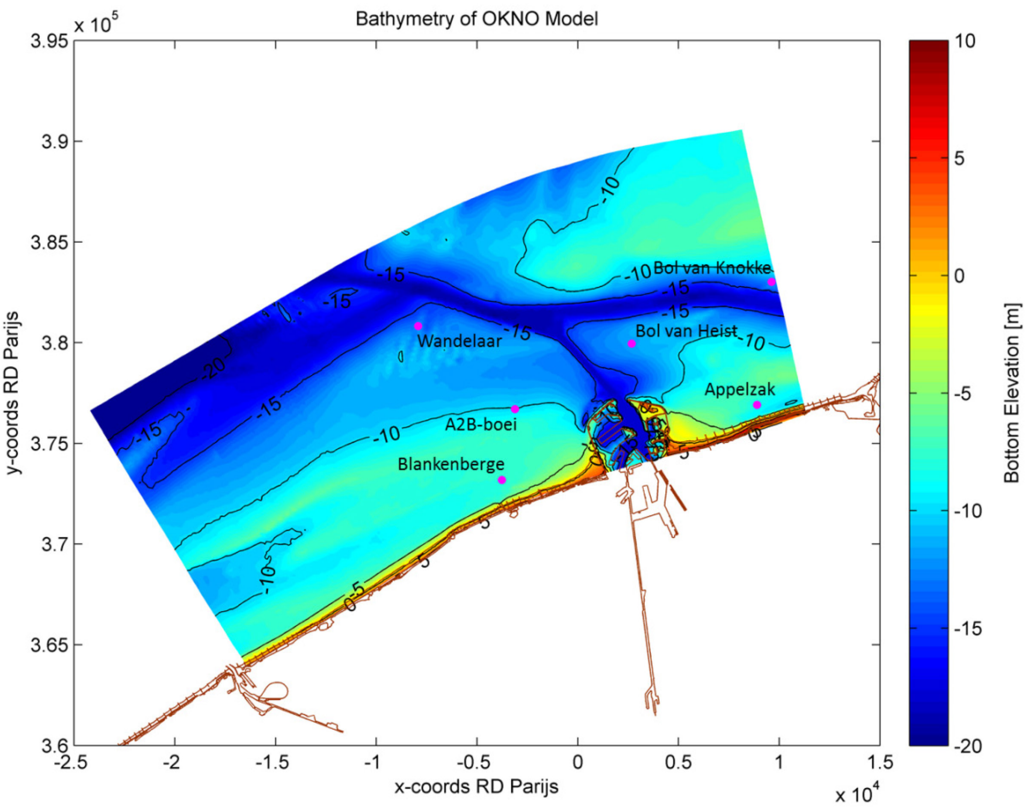

Figure 2-1: Bathymetry and extent of the OKNO model, elevation in m NAP.

For this reason the N2V model has been created (Nieuwpoort to Vlissingen) in Delft3D as well. The N2V model has been developed to satisfy the following additional requirements:

- It should ideally cover the entire Belgian coast, from the French to the Dutch border, while keeping computation time under control by limiting the number of grid cells.

- It should be driven by boundary conditions with a finer resolution than the Zuno model at its East boundary.
- If needed it should be able to provide boundary conditions to nested models along the coast. One of its foreseen applications concerns the coast East of Zeebrugge, with the sedimentation in the Baai van Heist, the erosion in Knokke and the evolution of the Zwin inlet.
- In view of the foreseen applications, it should have a time horizon of at least 10 years.

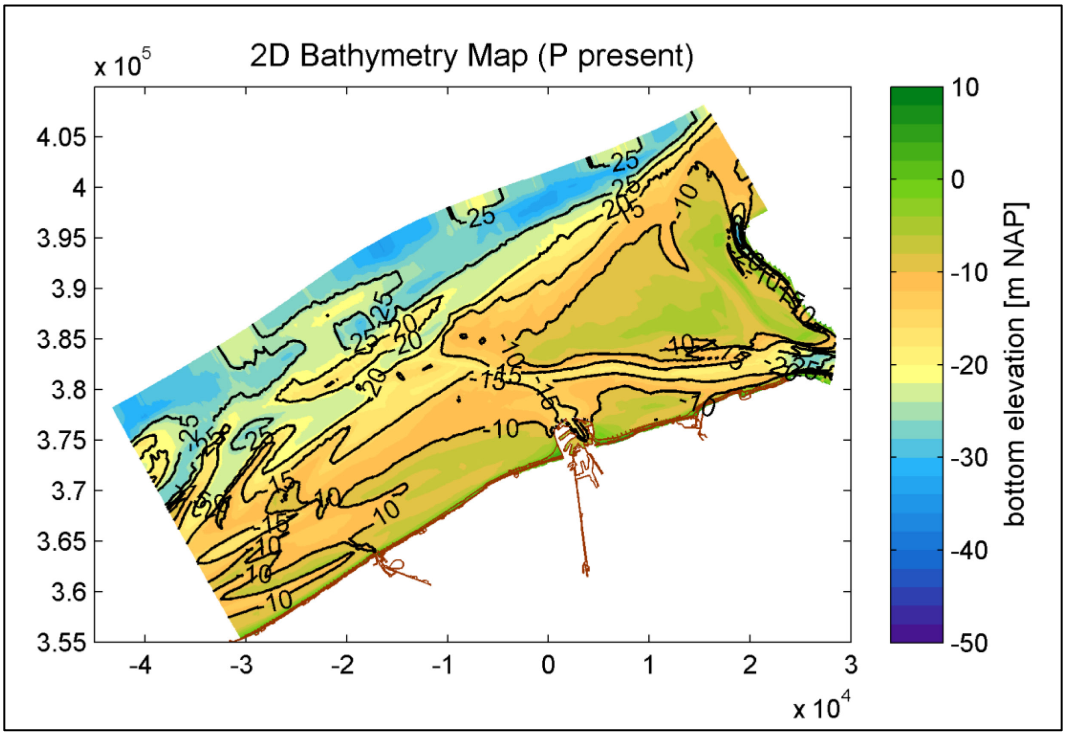

Figure 2-2: Bathymetry of 2010 and extent of the N2V model, elevation in m NAP.

The only model available for this study which can provide the required boundary conditions at the East coast is the LTV NEVLA model (Nederland-Vlaanderen ; Verheyen et al., 2013) for the Westerschelde. This model has been extensively calibrated and contains in particular corrections for specific tidal components relevant to residual sediment transport. It is therefore used to generate boundary conditions, although it does not cover the entire Belgian coast. The present model can be extended to the entire Belgian coast in the future, once a refined and improved version of the Zuno model is available (personal communication WL).

The N2V model grid has already been used with the OKNO model setup in Zimmermann et al. (2013b) to evaluate the impact of artificial islands on the seafloor and coastal evolution. Details of the setup, calibration and validation of the N2V model with a time horizon of one year are described therein. A short summary of the calibration and the input reduction is given respectively in paragraph 2.3 and 2.4.

2.2.2. Present work

The present work extends the N2V model used in Zimmermann et al. (2013b) to a time horizon of 10 years. This is achieved with the following changes in settings (an overview of the settings is given in paragraph 2.2.3):

- A <u>further reduction in the number of wave conditions</u> simulated (4 conditions instead of formerly 11 conditions). This frees up computation power for other tasks at the expense of model accuracy ;

- An increase of the morphological acceleration factor (morfac) from 36.5 to 125. This factor decouples the time scales of hydro- and morphodynamics. It hence determines how much faster the morphodynamics evolve compared to the hydrodynamics ;
- An increase of the update interval between two wave computations from 10 minutes to 1 hour. This results in a strong decrease of the computation time of the wave field, but it can lead to more instabilities in shallow coastal zones ;
- The use of dry cell erosion to allow erosion of the coastline, which consists of points at the water-land interface. This also decreases the effect of instabilities and therefore the risk of a simulation crash.
- The use of the Mormerge tool instead of a representative time series of wave conditions. The Mormerge tool is a numerical technique used to simulate at each time step all wave conditions, each on one processor, and to recombine their weighted effect on the sea bed to determine the bed level used at the next time step. Because it is equivalent to a constant averaging of the forcing parameters, it yields a much smoother and more stable bed evolution than a time series. This increased stability allows a larger morfac to be used.

2.2.3. Settings

The model grid is shown in Figure 2-3. It is refined in the surf zone and around the port of Zeebrugge. The model bathymetry has been shown in Figure 2-2.

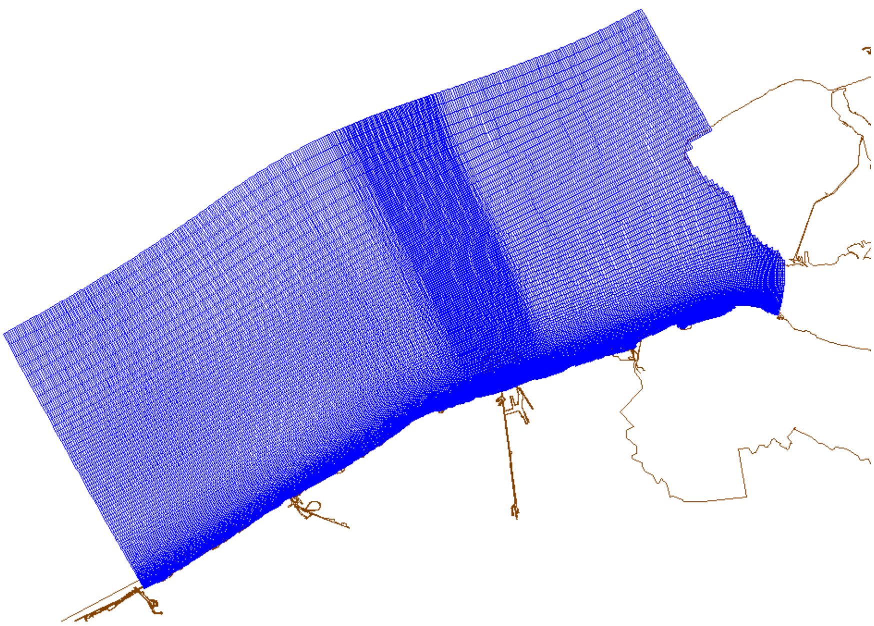

Figure 2-3: Grid of the N2V model with refinement in the surf zone and near Zeebrugge.

The model is driven by a representative tide generated with the LTV NEVLA model, and by four representative wave conditions computed with a calibrated wave model of the Belgian coast (IMDC, 2009). The wave field of each representative wave condition is recomputed every hour based on the new water level and current field. The wave results are used by the flow model to compute radiation stresses induced currents, such as the longshore current. All wave and flow results are used at each time step to compute the bottom shear stress, the sediment transport and subsequently to update the bathymetry at each time step. The latter is done with the Mormerge tool of Delft3D.

The Table 2-1 gives an overview of the model settings. Note that cross-shore transport has been turned off in the model for the reference simulation, because it uses a formulation which is developed for 3D applications and which is flawed in 2D (Zimmermann et al., 2014). The settings yield morphological changes equivalent to a period of 10 years.

Table 2-1: Overview of settings of the N2V morphological model

Parameter	Value
Conventions	XY in RD Parijs, Z in NAP, T in MET
Grid	See Figure 2-3
Depth	See Figure 2-2, data of 2010 except mentioned otherwise (years 1986, 1999 and 2010 used)
Structures	Zeebrugge port as dry points in FLOW, no-reflection obstacles in WAVE
Time frame	21 hydrodynamic days (1 day for spin-up), time step 12s
Flow boundaries	Representative tide generated by the LTV NEVLA model (Annexes A and B in Zimmermann et al., 2013b) + keyword CstBnd for correct longshore current
Wave boundaries	Wave field from calibrated wave model of the Belgian coast described in IMDC (2009) + 4 wave conditions in parallel with Mormerge tool
Wave spectrum	Full circle 36 directions with 10° resolution, 24 frequencies from 0.05 to 1 Hz
Wave-current interaction (WCI)	Online WAVE-FLOW coupling every 1h, SWAN 3rd generation model Effect of waves on currents (radiation stress), not of currents on wave (frequency shift)
Wave dissipation	White-capping with Van der Westhuysen, breaking with Battjes and Janssen, bottom friction with JONSWAP formulations. Wave growth by uniform wind field.
Wind	Spatially uniform wind correlated to wave condition, described in Zimmermann et al. (2012)
Roughness	Uniform Manning coefficient 0.022s/m$^{0.33}$ Partial slip with wall roughness length 0.15m for the breakwaters of Zeebrugge
Water density	1023 kg/m³
Eddy viscosity	1 m²/s
Eddy diffusivity	1 m²/s
Sediment	Uniform grain size d50 = 200µm, unlimited supply (50m thickness), equilibrium concentration at the boundaries Onshore wave transport factors to scale bed load and suspended load set to 0 instead of 1 (default setting is for 3D model) to prevent artificial beach steepening (=no cross-shore transport)
Morphology	Mormerge, morfac 125 after spin-up period, dry cell erosion factor set to 1
Numerics	Depth specified at grid cell centres, default accuracy and iterations

2.3. Calibration

The calibration of the hydrodynamics of the N2V model is presented in Zimmermann et al. (2013b), Annex A. The results of the NEVLA model have been chosen as ground truth since the N2V model has been calibrated against these results.

Locally small deviations of the current velocity are found near the West and East model boundaries, otherwise the agreement between the two models is reasonable along the entire coast from Oostende to Breskens (example at Wandelaar in Figure 2-4).

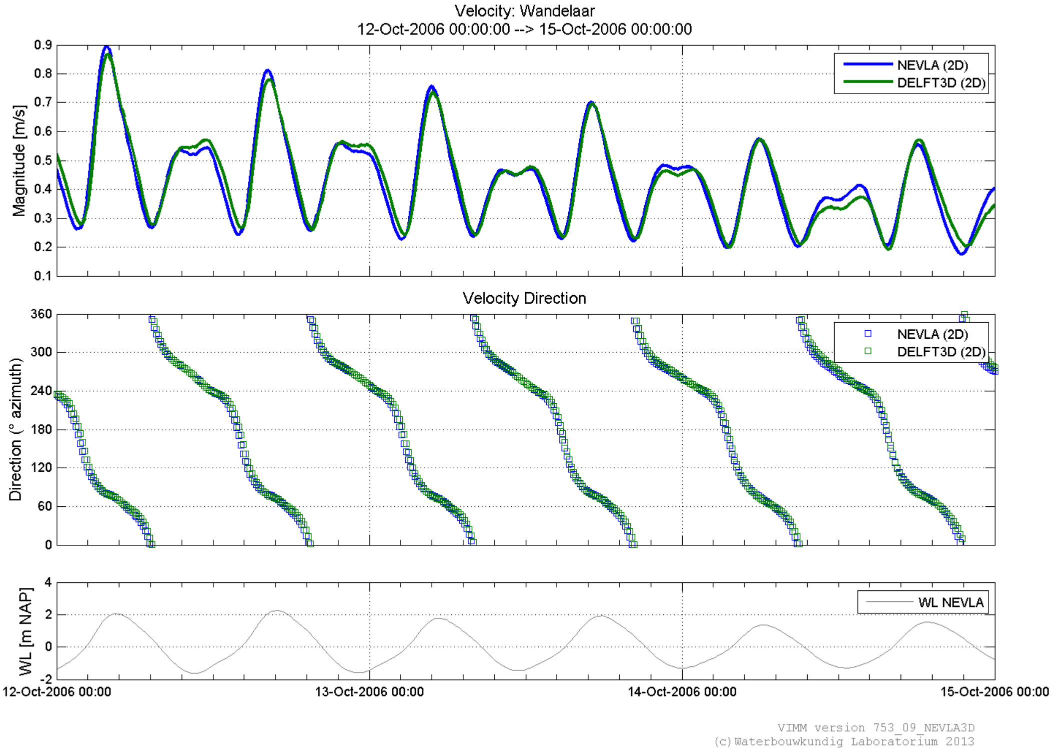

Figure 2-4: Time series of modeled current velocity and current direction in the NEVLA model (blue) and in the present model (green) in Wandelaar.

The morphodynamic results show a qualitatively and quantitatively reasonable agreement with expectations and have not been calibrated further (Zimmermann et al., 2013b, Annex C). A detailed comparison with data is presented in chapter 3.

2.4. Input reduction

The input reduction consists in simplifying the forcing conditions to simulate a longer period without the entire time series. The input reduction is a very time-consuming process which aims to verify that the reduced conditions yield a similar result as the full time series of the forcing conditions. It is distinct from the calibration, it aims to conserve the calibrated results while simplifying the input.

The input reduction for the N2V model has been made based on the previous work done within the OKNO model (Zimmermann et al., 2012 ; also described again in Zimmermann et al., 2013b).

The representative tide has been derived by simulating a neap-spring tidal cycle, then selecting two consecutive tidal cycles which yield the same net and gross alongshore transport pattern than the full neap-spring cycle (Zimmermann et al., 2012). The excellent correlation obtained gives confidence in these results in the entire OKNO model, from Oostende to Knokke.

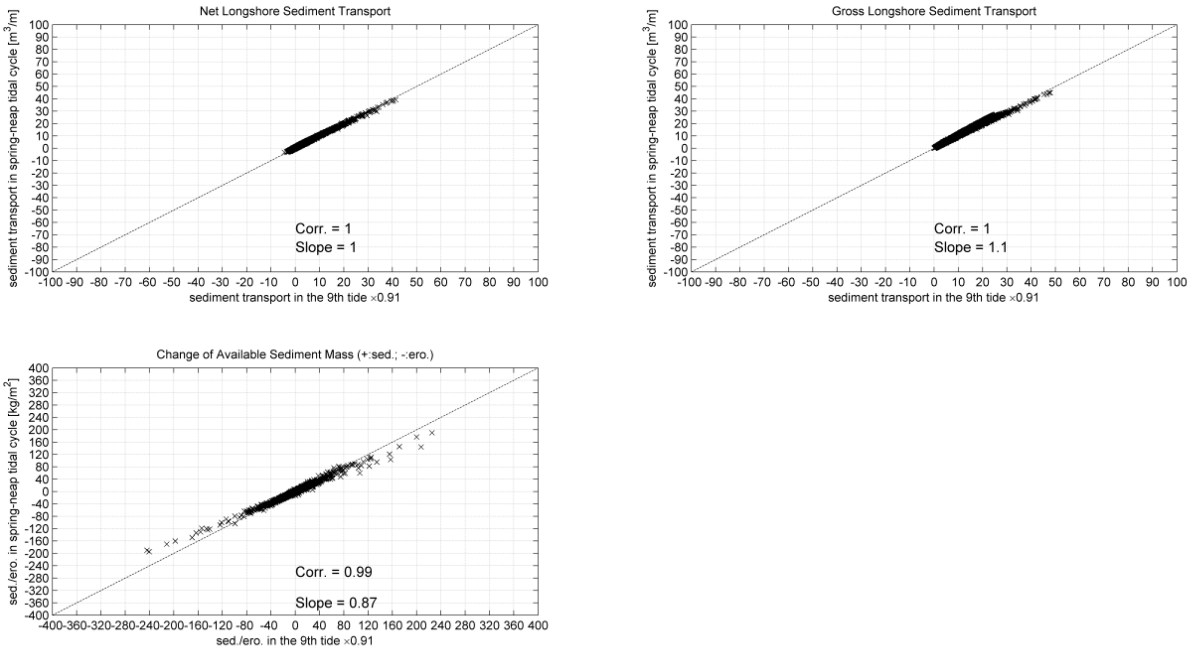

Figure 2-5: Correlation and regression line of net longshore sediment transport, gross longshore sediment transport and sedimentation/erosion between representative and spring-neap tides in the OKNO model.

For the larger N2V model, boundary conditions are obtained from the NEVLA model instead of the Zuno model. The validity of the representative tide therefore needs to be verified again. To avoid repeating the work, the two consecutive tidal cycles of the NEVLA model most similar to the representative tide of the OKNO model have been chosen (Zimmermann et al., 2013b). Current velocities with this new tidal cycle are very similar to those of the original representative tide throughout the model domain (Figure 2-6 to Figure 2-9). The similarity of model settings (bathymetry, roughness) give further confidence in the validity of this tide reduction for the N2V model. The validity of the tide reduction outside of the original OKNO model extent is not known (West of Oostende and East of Knokke). It can be reasonably assumed that it remains at least qualitatively correct there.

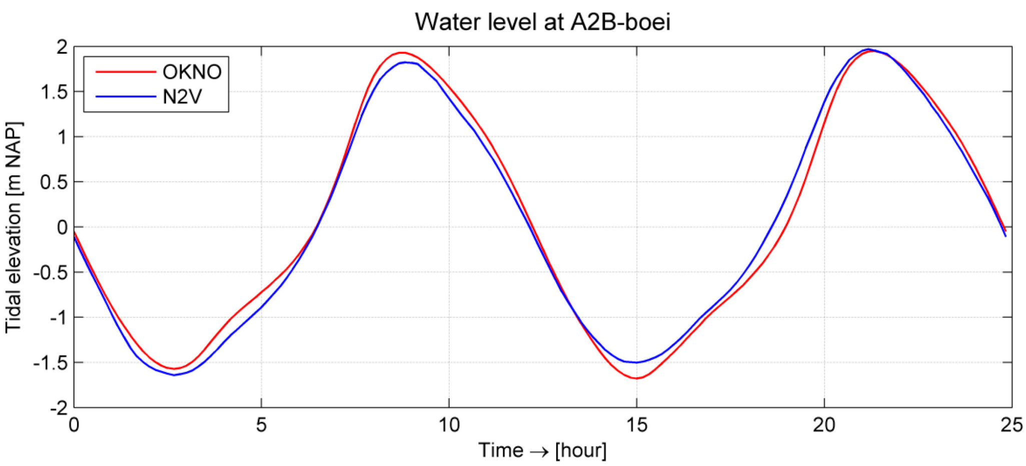

Figure 2-6: Water level of a representative tide at A2B-boei in the OKNO and N2V models.

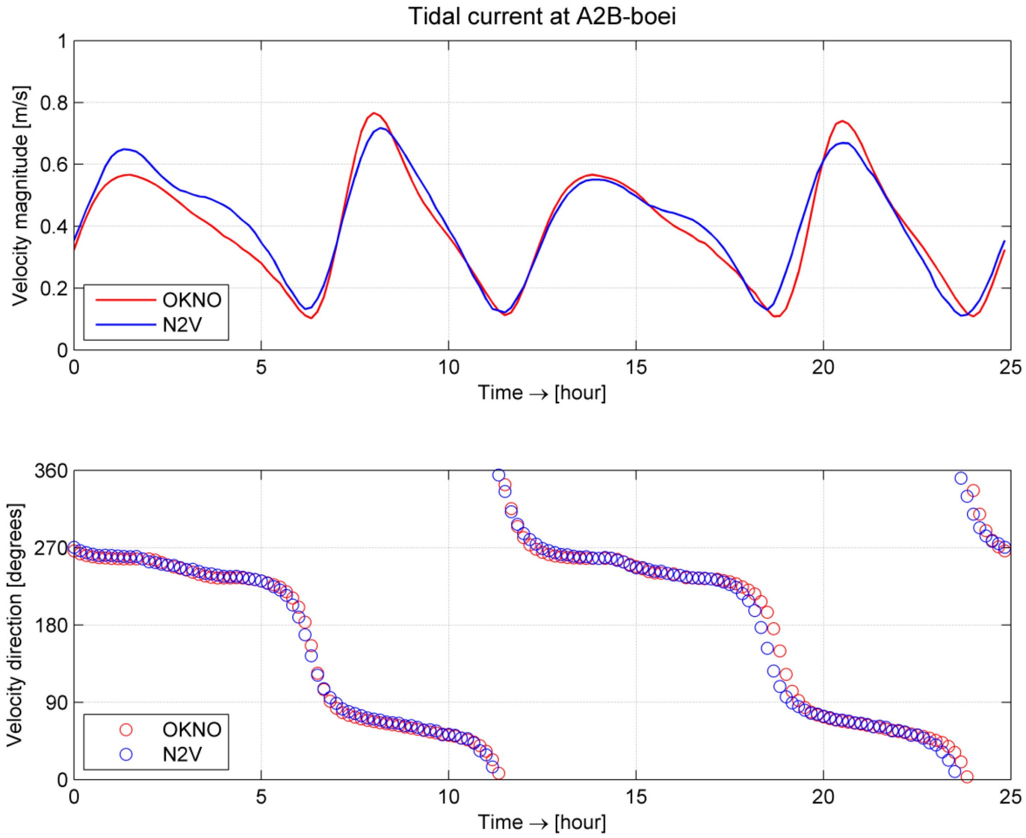

Figure 2-7: Current velocity of a representative tide at A2B-boei in the OKNO and N2V models.

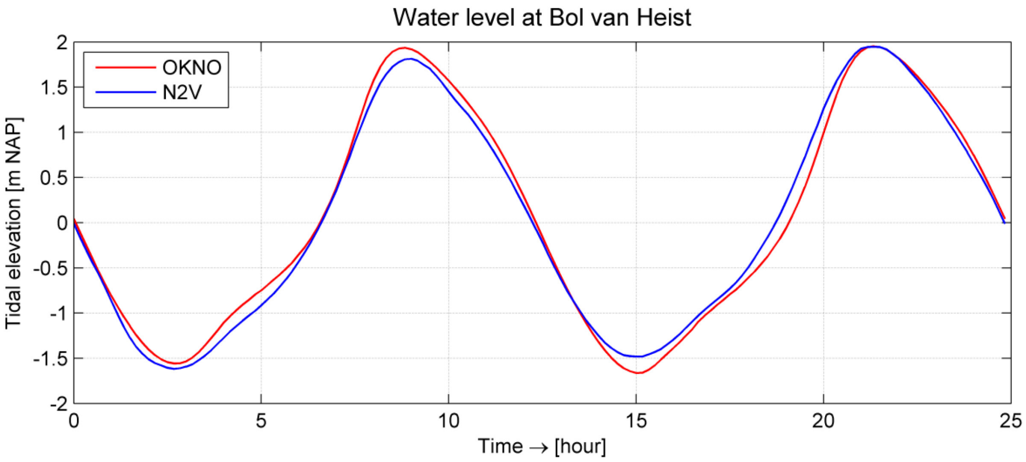

Figure 2-8: Water level of a representative tide at Bol van Heist in the OKNO and N2V models.

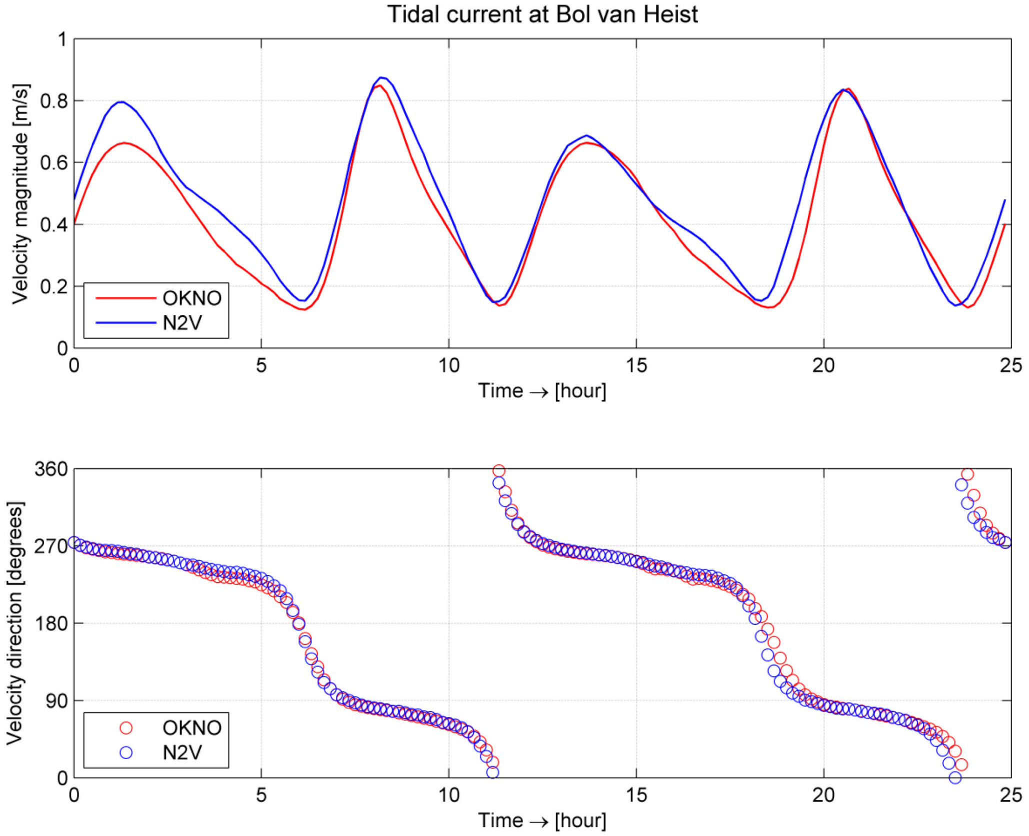

Figure 2-9: Current velocity of a representative tide at Bol van Heist in the OKNO and N2V models.

The representative wave climate has been derived by simulating each individual wave condition of the yearly wave climate with a correlated wind condition and the representative tide, and by using the statistical OPTI tool to derive a subset of conditions which yield the same net and gross longshore transport pattern (Zimmermann et al., 2012). The excellent correlation obtained gives confidence in these results in the entire OKNO model, from Oostende to Knokke (Figure 2-10 and Figure 2-11).

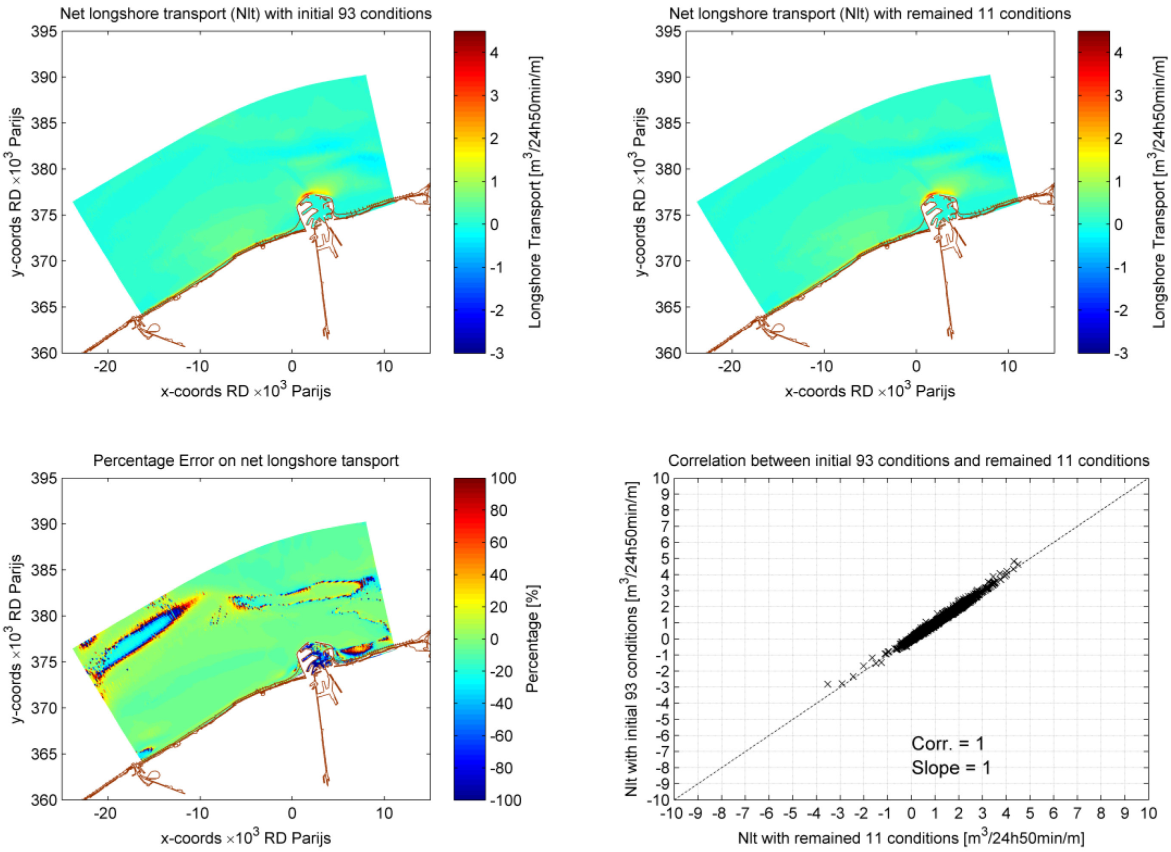

Figure 2-10: upper right: net longshore transport produced by full 93 wave conditions;
upper left: net longshore transport produced by reduced 11 wave conditions;
lower left: percentage error of reduced 11 wave conditions compared to full 93 wave conditions;
lower right: correlation of net longshore transport between full 93 wave conditions and reduced 11 wave conditions.

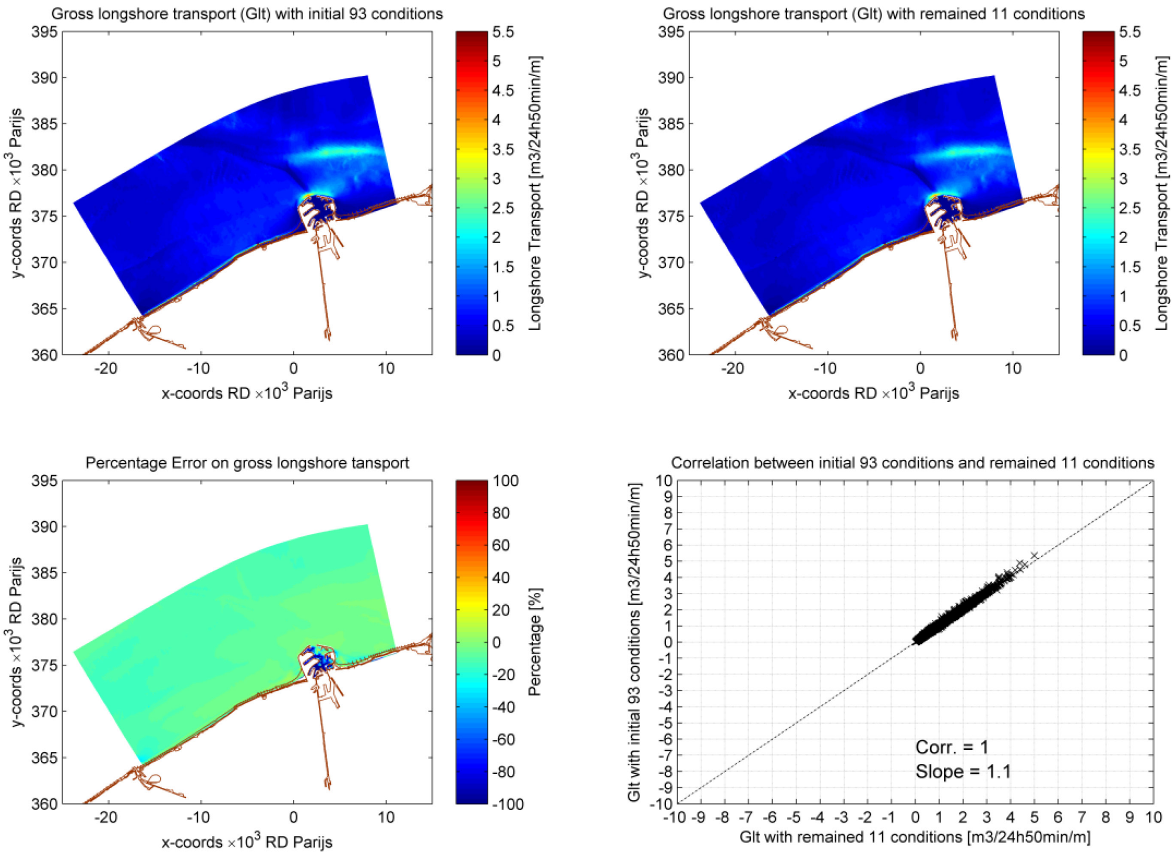

Figure 2-11: upper right: gross longshore transport produced by full 93 wave conditions;
upper left: gross longshore transport produced by reduced 11 wave conditions;
lower left: percentage error of reduced 11 wave conditions compared to full 93 wave conditions;
lower right: correlation of gross longshore transport between full 93 wave conditions and
reduced 11 wave conditions.

In order to increase the time horizon of the morphological computations, the number of wave conditions has then been further reduced from 11 to 4 conditions. This has been done with the same OPTI routine and the same results as those used for the initial wave climate reduction. The reduced wave climate of the N2V model is presented in Table 2-2.

Table 2-2: Representative wave conditions and their weighting factors

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

Figure 2-12 shows that using 4 wave conditions yields very similar results to those using 11 wave conditions (N2V model with long term morphology settings).

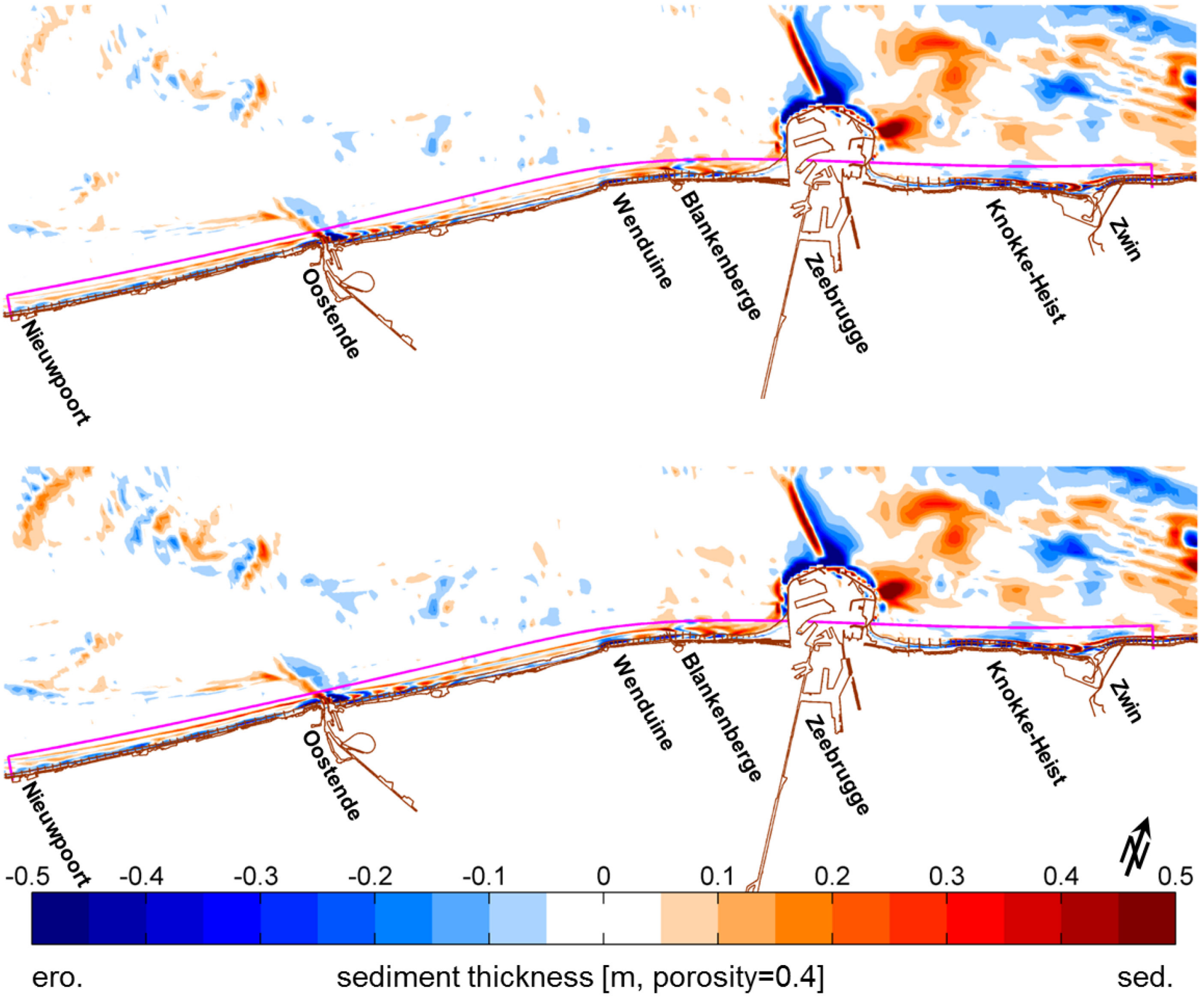

Figure 2-12: Erosion-sedimentation [m] in the N2V model after one year with 4 wave conditions (top) and 11 wave conditions (bottom), with bathymetry of 2010.

3. Model results

3.1. Data sources

This chapter presents and discusses the modelled long term morphology based on observations. Two data sources are available to evaluate the morphology: the Quest4D project and the yearly measurement of coastal profiles and sand volumes done by the Coastal Division.

The Quest4D project uses topography and bathymetry data over the period 1997-2010 to visualize the observed long term morphological evolution of the Belgian coast and shelf (Houthuys, 2012). The modelled erosion-sedimentation pattern is compared to this data.

The analyses of yearly coastal profiles along the coast allows to measure changes in sand volumes on the dry beach, the wet beach and the sea floor, and to correct measured values for human impacts such as nourishments to estimate the natural erosion-sedimentation trend. The modelled erosion-sedimentation volumes along the coast are compared to this data.

3.2. Comparison with data

On the shelf, the agreement between the modelled and the observed erosion-sedimentation patterns is qualitative to poor (Figure 3-1). Modelled dune fields flatten because the local resolution is too coarse and because their growth would involve 3D effects which are not modelled.

Near the coast it could be found that most main patterns are well reproduced by the model: sedimentation at Oostende, erosion at Wenduine, sedimentation near the western dam of the Zeebrugge port and erosion at Knokke-Heist. However the sedimentation in the Baai van Heist (next to the eastern dam of the Zeebrugge port) is not captured by the model, and the reason for which will be interpreted and specifically investigated in a later chapter. To validate the morphology model in a quantitative way, a comparison between modelled results and measured data is made section by section (Figure 3-2 and Table 3-1). The modelling sedimentation/erosion is obtained from gradients of the net longshore transport shown in Figure 3-2, which has been already integrated over cross-shore profiles within the magenta box marked in Figure 2-12.

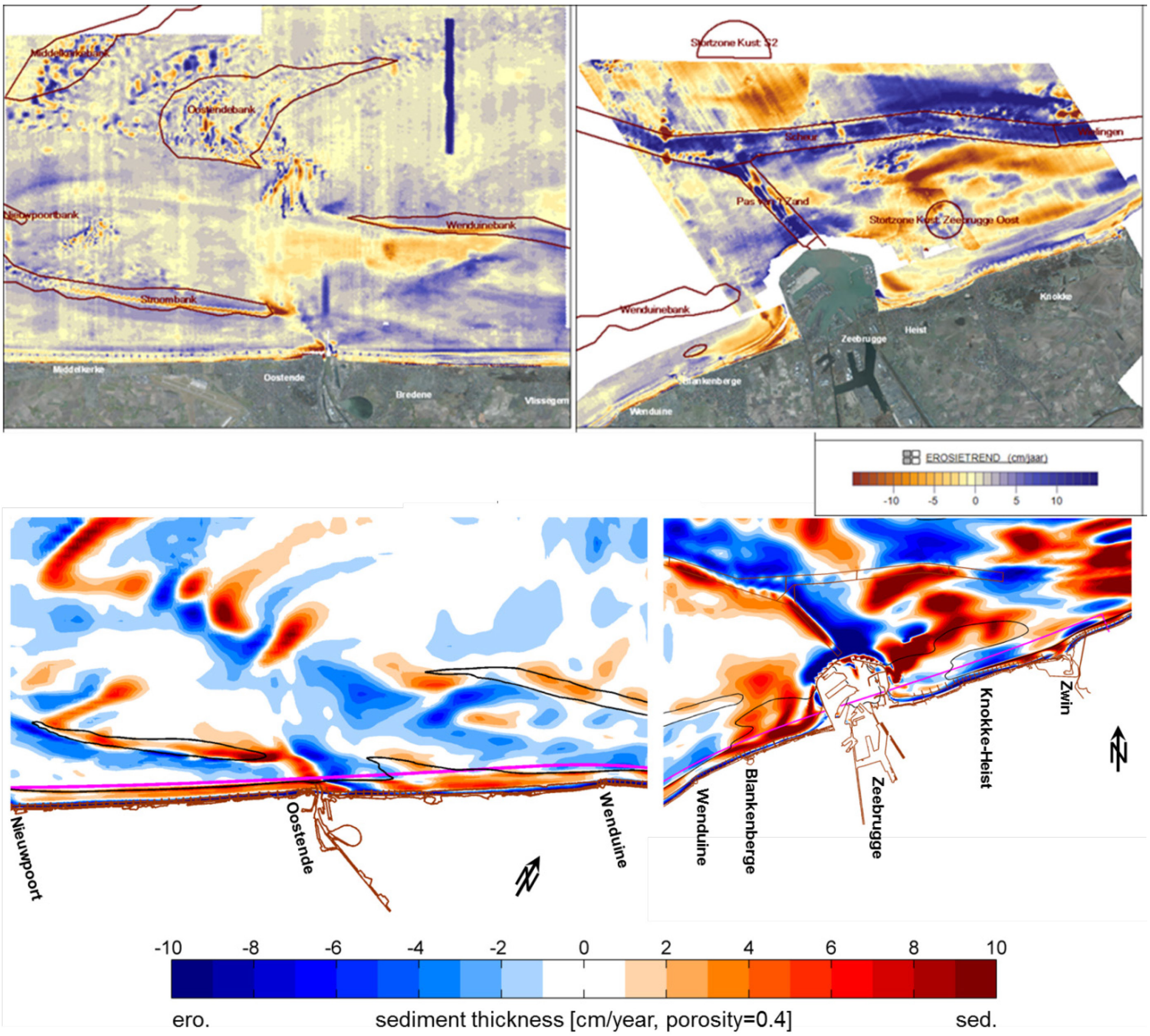

Figure 3-1: Observed (upper) and modelled (lower) sedimentation/erosion within the whole Belgian coast.

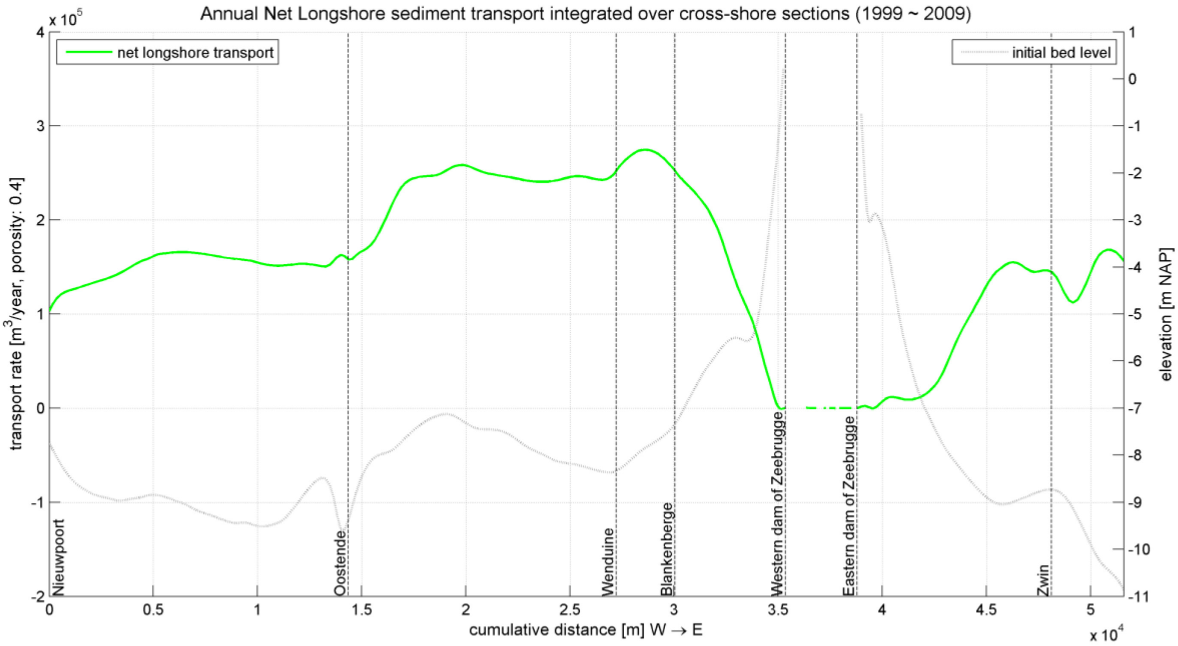

Figure 3-2: Modelled annual net longshore sediment transport integrated over cross-sections (in the magenta box of lower panel, Figure 3-1) during the period from 1999 to 2009.

Table 3-1: Modelled and observed sedimentation/erosion rates along the Belgian coast

Sections	Modelling (unit: m^3/year)	Observation (unit: m^3/year)
Kp 0 ~ Kp 6	erosion 62,000	accretion 80,000
Kp 6 ~ Kp 12	accretion 12,000	accretion 20,000
Kp 12 ~ Kp 14	erosion 10,000	/
Kp 15 ~ Kp 20	erosion 90,000	erosion 30,000
Kp 20 ~ Kp 25	accretion 12,000	erosion 20,000
Kp 25 ~ Kp 28	erosion 24,000	erosion 65,000
Kp 30.5 ~ Kp 35	accretion 240,000	accretion 280,000
Kp 39 ~ Kp 41	erosion 8,000	accretion 180,000 to Kp 43
Kp 41 ~ Kp 47	erosion 140,000	erosion 70,000 and accretion 50,000

Between Nieuwpoort and Middelkerke (kp 0 and kp 6)

The model shows a beach erosion of about 62,000m^3/year. The data shows for this area an accretion of 80,000m^3/year. The difference is probably associated with boundary effects and poor bathymetric data of offshore sand banks. Between De Panne and Middelkerke, the observed beach accretion is considerable (400,000m^3/year), which might be due to cross shore transport, with the Flemish Banks as sediment source. This might also explain the difference.

Between Middelkerke and Raversijde (kp 6 and kp 12)

A stable situation is given in the model (12,000m^3/year accretion). The data show an accretion of 20,000m^3/year, which is relatively small. Most of the sedimentation is situated below -4m TAW.

In Ostend (kp 12 and kp 14)

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

Between Ostend and Bredene (kp 15 and kp 20)

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

Between Bredene and just East of De Haan (kp 20 and kp 25)

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

For Wenuine (between kp 25 and kp 28)

The model gives an increase in net longshore sediment transport of 100,000m^3/year (or a beach erosion) in the zone starting 400m West of the Rotonde up to 400m East of the Rotonde of Wenduine. The data show over the same area an erosion of 50,000m^3/year. In the next 1200m the model predicts a sedimentation of 60,000m^3/year, while the data show an erosion of 15.000m^3/year. Integrated over the whole area, the model gives an erosion of 24,000m^3/year to 60,000 m^3/year (10 vs. 1 year), while the data show an erosion of 65,000m^3. The large difference between 1 and 10 years is related to the beach extent: in reality, nourishments keep the contour lines more offshore, causing more erosion. It can be concluded that the model represents the data well, but the distribution over the area is somewhat different.

East of harbour entrance Blankenberge – harbour Zeebrugge (Between kp 30.5 and kp 35)

The model gives 24,000m^3 erosion just East of the harbour of Blankenberge and 240,000m^3 accretion in the next sections, while the data show 110,000m^3 erosion just East of the harbour of Blankenberge, 280,000m^3 accretion in the next sections. The result is acceptable, considering that the harbour of Blankenberge is not incorporated in detail in the numerical model.

First 3km East of harbour of Zeebrugge (between kp 39 and kp 41)

The model gives stable situation with a small erosion about 8,000m^3/year.

The data show a net sedimentation of 180,000m^3/year is observed (over the first 4km, so the sedimentation zone is 1km longer). The reason for the difference is the input of sand coming around the harbour of Zeebrugge. This quantity is estimated at 200,000m^3/year and is eroded near the NE-breakwater of Zeebrugge. The eroded and transported sand is very fine (grain size around 100µm) and settles down at the Baai van Heist. In the numerical model the sand is uniform (200µm). Also in the model, the erosion near the NE-breakwater is visible, but the sand settles down much more offshore due to the much higher settling velocity.

Knokke-Zoute - Zwin (between kp 40 and kp 47)

The model shows that the net longshore sediment transport increases with 140,000m^3/year (beach erosion) ignoring the peak in sediment transport near the Zwin.

The data show an erosion of 70,000m^3/year for Knokke-Zoute and Lekkerbek and an accretion of 50.000m^3/year in front of the Zwin. The difference and the behavior near the Zwin is probably due to the absence of the groynes in the numerical model.

3.3. Comparison 1986-1996 and 1999-2009

Figure 3-3 and Figure 3-4 compare the modelled erosion-sedimentation pattern after one and ten years respectively when starting the simulation with the bathymetries of 1986 and 1999 (for the zone East of Zeebrugge). In 1986 the extension of the port of Zeebrugge has just been completed, therefore the scour hole and the sedimentation in the Baai van Heist are absent. The system is more out of equilibrium than in 1999, therefore stronger adjustments of the morphology are expected.

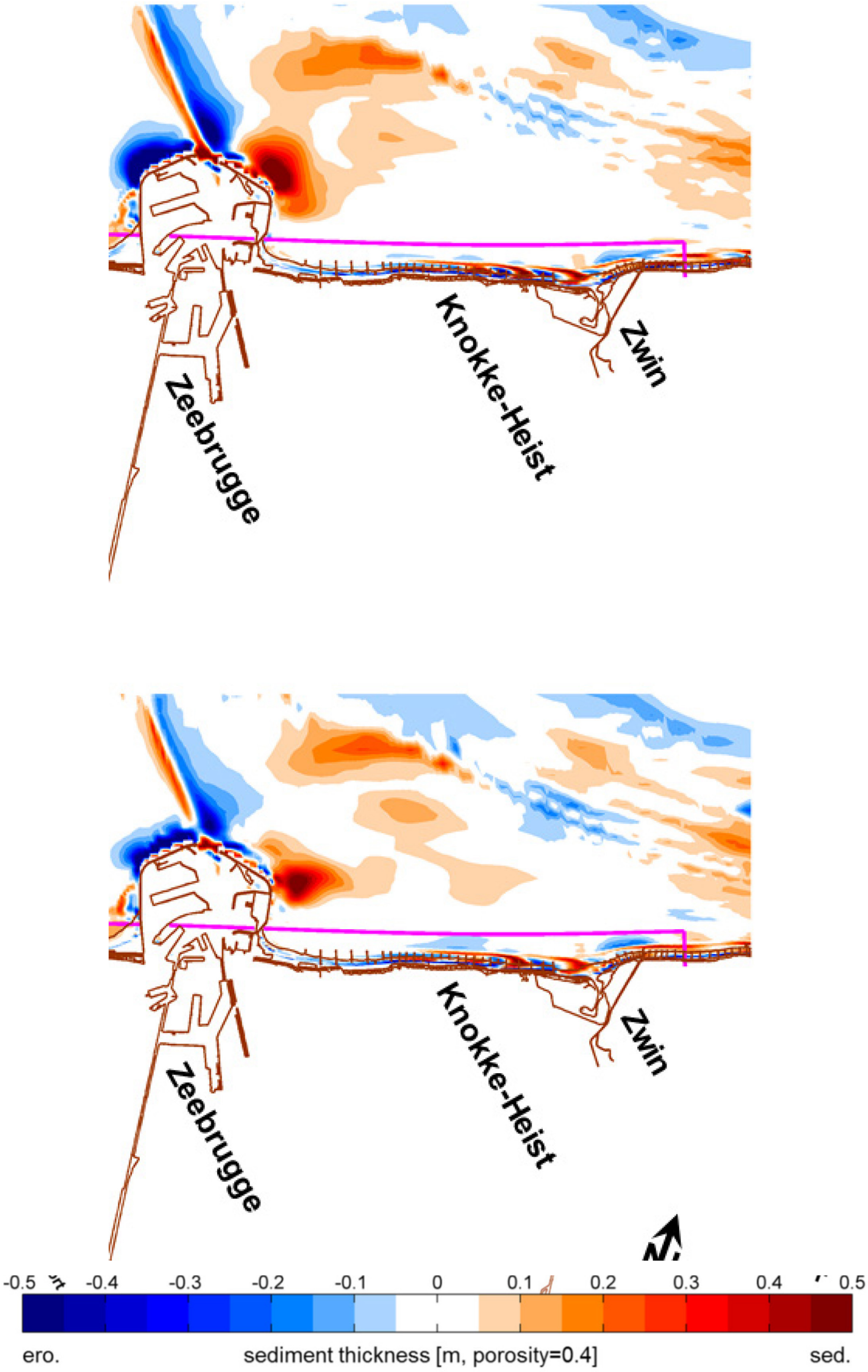

Figure 3-3: Erosion-sedimentation [m] in the N2V model after one year with the bathymetries of 1986 (top) and 1999 (bottom).

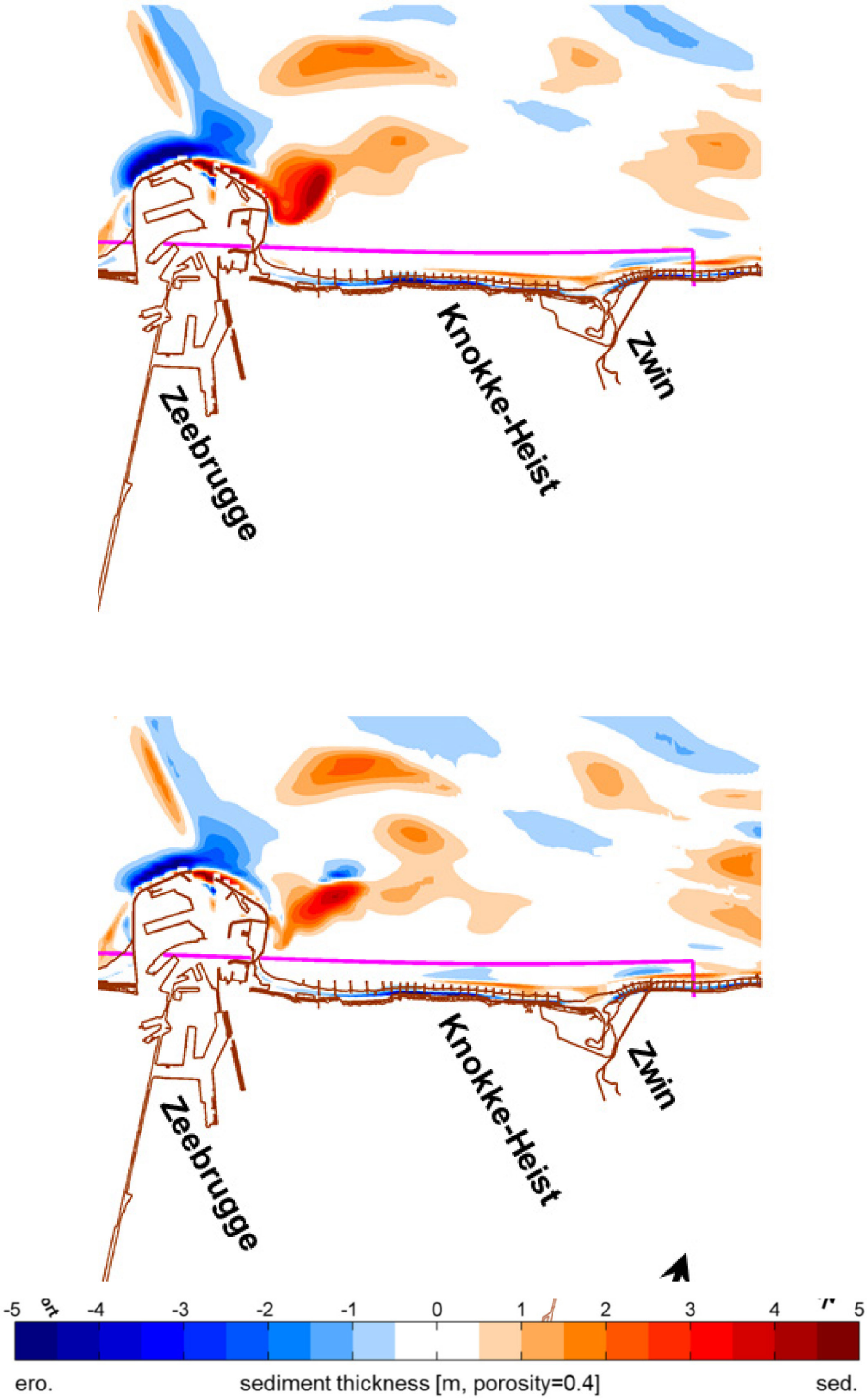

Figure 3-4: Erosion-sedimentation [m] in the N2V model after ten years with the bathymetries of 1986 (top) and 1999 (bottom).

3.4. Model prediction

Figure 3-5 and Figure 3-6 compare the modelled erosion-sedimentation pattern after one year and ten years respectively when starting the simulation with the bathymetries of 2010 instead of 1999. This approximately corresponds to the present state of the system, it allows to compare the expected future behaviour from 2010 on to the one observed during the last decade since 1999.

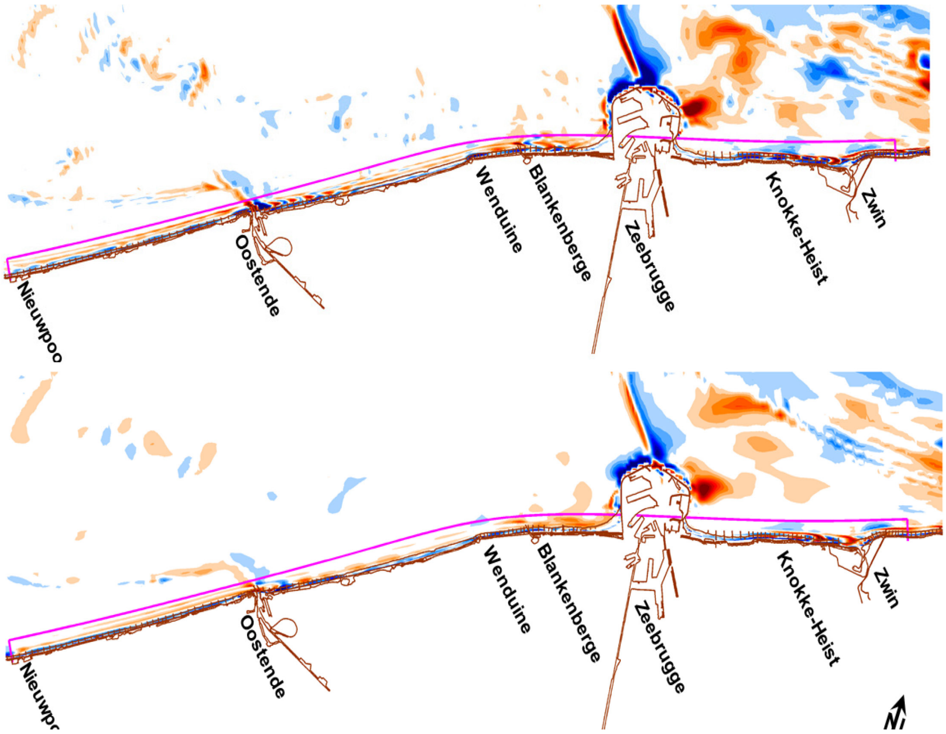

Figure 3-5: Erosion-sedimentation [m] in the N2V model after one year with the bathymetries of 2010 (top) and 1999 (bottom).

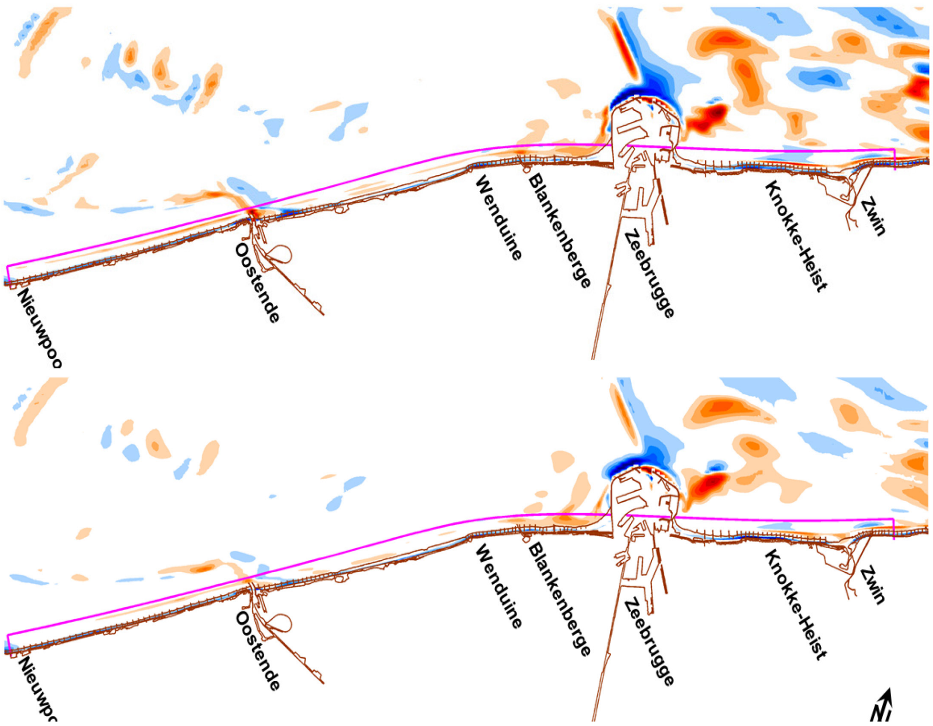

Figure 3-6: Erosion-sedimentation [m] in the N2V model after ten years with the bathymetries of 2010 (top) and 1999 (bottom).

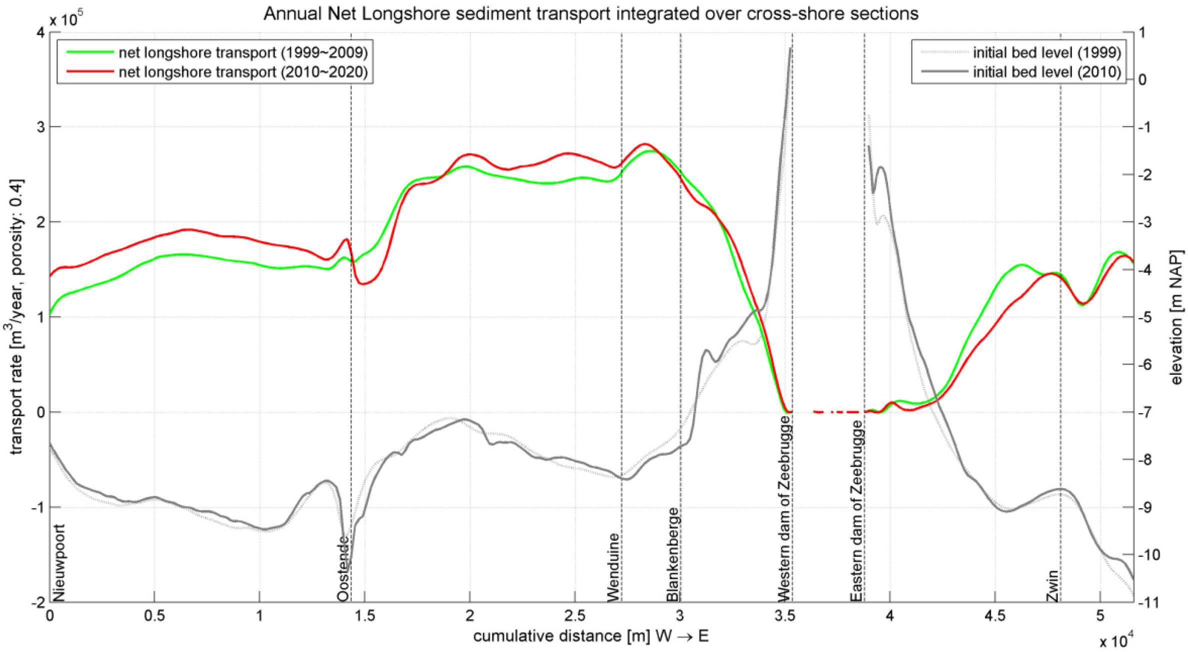

Figure 3-7: Modelled annual net longshore sediment transport integrated over cross-sections (in the magenta box, Figure 3-5) during the periods from 1999 to 2009 and from 2010 to 2020.

Table 3-2: Modelled sedimentation/erosion rates along the Belgian coast with initial bathymetries of 1999 and 2010

Sections	Modelling (unit: m^3/year) 1999 ~ 2009 vs. 2010 ~ 2020		Observation (unit: m^3/year)
Kp 0 ~ Kp 6	erosion 62,000	erosion 47,000	accretion 80,000
Kp 6 ~ Kp 12	accretion 12,000	accretion 19,000	accretion 20,000
Kp 12 ~ Kp 14	erosion 10,000	erosion 10,000	/
Kp 15 ~ Kp 20	erosion 90,000	erosion 140,000	erosion 30,000
Kp 20 ~ Kp 25	accretion 12,000	erosion 100	erosion 20,000
Kp 25 ~ Kp 28	erosion 24,000	erosion 8,000	erosion 65,000
Kp 30.5 ~ Kp 35	accretion 240,000	accretion 225,000	accretion 280,000
Kp 39 ~ Kp 41	erosion 8,000	erosion 1,000	accretion 180,000 to Kp 43
Kp 41 ~ Kp 47	erosion 140,000	erosion 140,000	erosion 70,000 and accretion 50,000

3.5. Conclusion

These results show that the morphological model is, aside from local deviations, sufficiently well calibrated to be used in practical applications. The model reproduces major longshore transport trends in the coastal zone, both qualitatively and quantitatively, with the exception of uncertainties at the Western model boundary (Nieuwpoort and Oostende) and related to the sedimentation in the Baai van Heist.

Remind that cross shore transports are not modelled. Therefore the model is not applicable for those zones or scenarios where strong cross-shore transports are believed to play a significant role. The morphology on the shelf is not validated. Moreover, due to poor grid resolution and missing 3D effects, it was not possible to model bar mitigation properly. The missing sedimentation at Baai van Heist is further discussed in the next section.

4. Improvement of the modelled sedimentation in the Baai van Heist

4.1. Overview

In order to investigate the model shortcomings concerning the sedimentation in the Baai van Heist, results from several models have been used.

- The OKNO model (the legacy model), with boundary conditions from the larger Zuno model (paragraph 2.2.1).
- The N2V model (this model), with boundary conditions from the larger Nevla model (paragraph 2.2.1).
- The Zeebrugge model (a 2D version of the 3D sediment transport model, De Maerschalck 2015), with boundary conditions from the larger Zuno model.

4.2. Comparison of grain sizes

In the previous chapter, it has been found that the long-term morphology model failed to capture the sedimentation in the Baai van Heist, which is present in the measured data. The grain size used in the model is thought to be too large to be transported into the Baai van Heist. Therefore a grain size 100µm is used to specifically investigate formation of the sedimentation in the Baai van Heist. The 100µm-grain-size sediment seems to be transported further than the 200µm-grain-size one (Figure 4-1). To better investigate this related issue, three models are employed and inter-compared running with the 100µm-grain-size sediment.

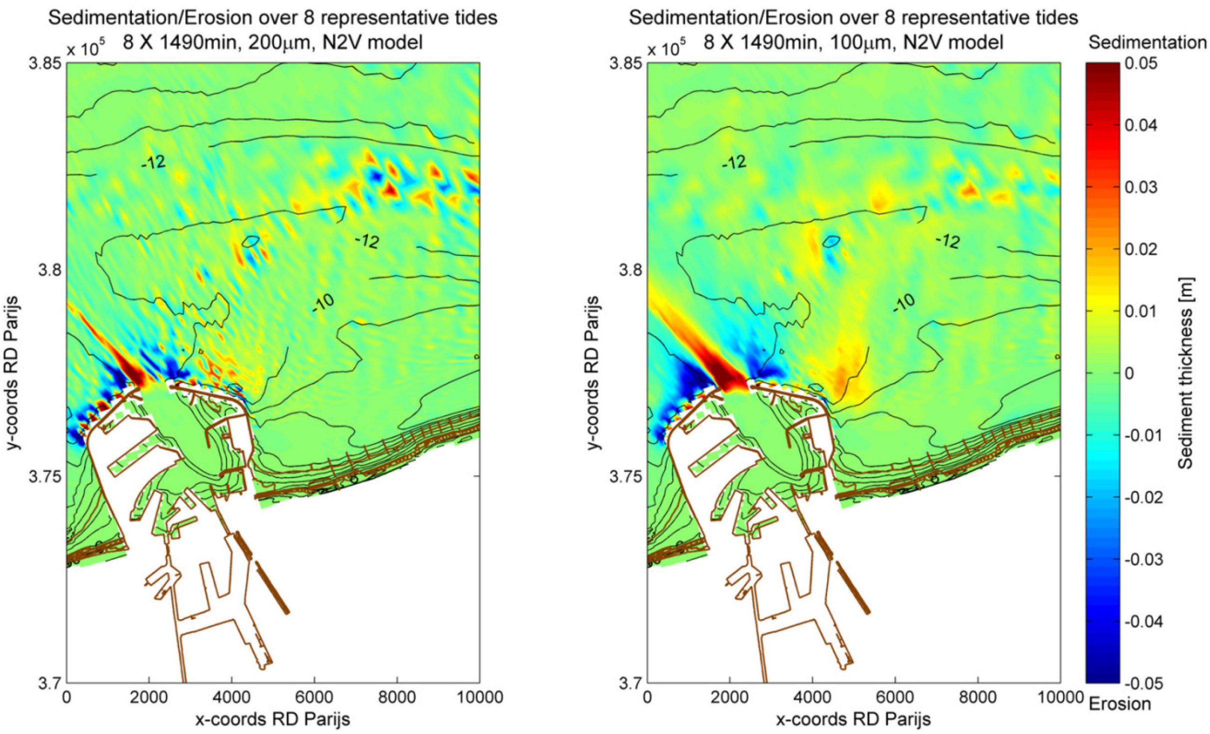

Figure 4-1: Sedimentation/erosion of 200µm (left) and 100µm (right) sediment with 8 representative tides in the N2V model.

4.3. Comparison of model settings

Table 2-1 shows exactly same values for the parameters applied in the three models except the time step which is related to the size of the model grids. From Figure 4-2 it could be found that Zeebrugge model has the highest resolution of grids around the Zeebrugge port. In consideration for a better modelling of wave breaking, the grids in the surf zone are specifically refined in the OKNO and N2V models. Figure 4-3 gives more direct information for the grid resolution in the three models.

Table 4-1: Comparison of relevant model settings

Parameter	OKNO	N2V	Zeebrugge
Bathymetry dataset (year)	1986	1986	1986
Time step (s)	20	12	6
Bottom roughness (Manning, $s/m^{1/3}$)	0.022	0.022	0.022
Grain size (µm)	100	100	100
MorFac (Morphological factor)	1	1	1
Wall roughness (Partial, m)	0.15	0.15	0.15
Water density (kg/m^3)	1023	1023	1023
Horizontal eddy viscosity (m^2/s)	1	1	1
Horizontal eddy diffusivity (m^2/s)	1	1	1

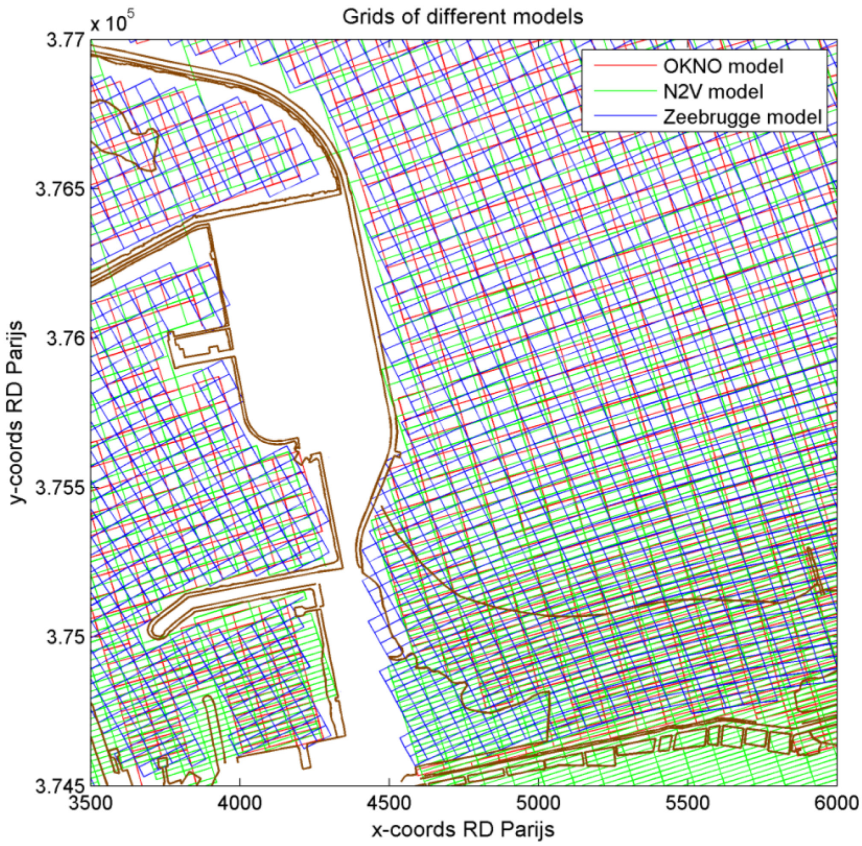

Figure 4-2: Model grids at the Baai van Heist
(red: OKNO model, green: N2V model, blue: Zeebrugge model).

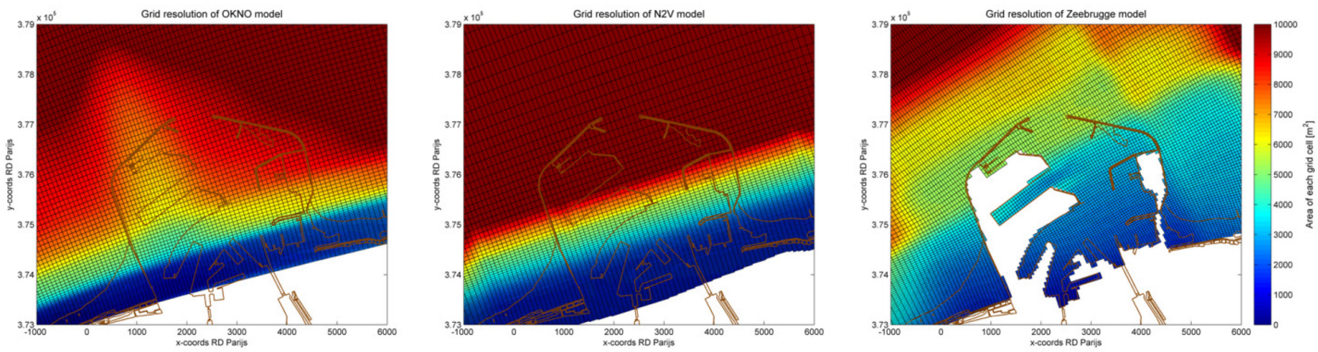

Figure 4-3: Resolution of the model grids around the Zeebrugge port
(left: OKNO model, middle: N2V model, right: Zeebrugge model).

4.4. Comparison of hydrodynamics

The hydrodynamics at two locations A2B-boei and Bol van Heist are shown from Figure 4-4 to Figure 4-7. The discrepancy of the hydrodynamics among the three models could be mainly ascribed to the different boundary conditions. The original representative tide is selected by the OKNO model. In this study the N2V model which covers a larger domain of the Belgian Coast was developed. To avoid repeating the work to select the representative tide, from the NEVLA model two consecutive tidal cycles most similar to the original representative tide were chosen, and then the NEVLA model provided the boundary conditions to the N2V model. The originale Zeebrugge model was calibrated for a different time span than the OKNO and N2V model. It was decided to use the model within the period it was calibrated for. Therefore, two consecutive tidal cycles closest to the representative tide were chosen.

Figure 4-8 and Figure 4-9 exhibit the maps of momentary current around the Zeebrugge port at maximum flood and ebb respectively in the three models. In the comparison among the three model, it could be observed that the Zeebrugge model gives the largest maximum flood current (ca. 1.5m/s) but the lowest maximum ebb current (ca. 0.9m/s). While the N2V model shows the lowest maximum flood current (ca. 1.3m/s) but the largest ebb current (ca. 1.0m/s). Therefore the Zeebrugge model produces the strongest tidal asymmetry around the Zeebrugge port with the selected representative tide.

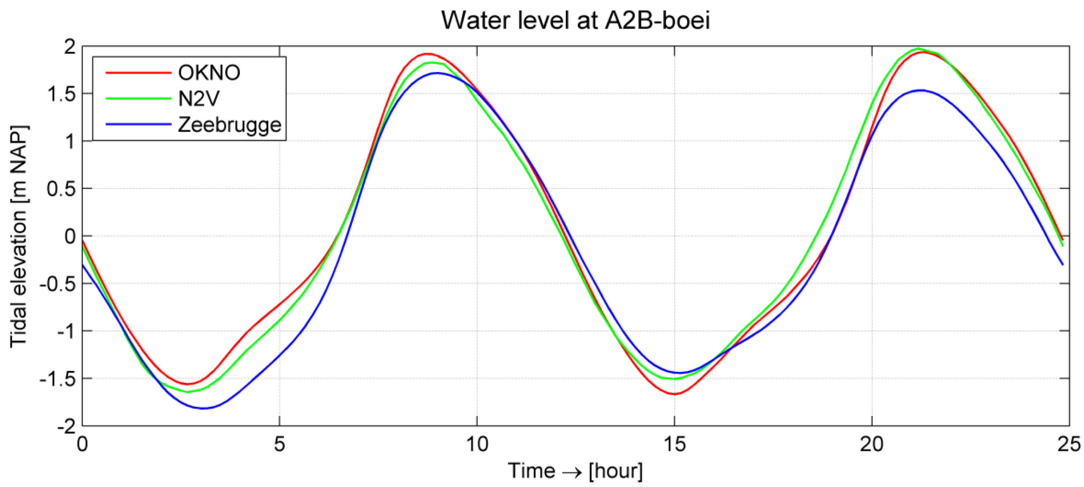

Figure 4-4: Water level of a representative tide at A2B-boei in the OKNO, N2V and Zeebrugge models.

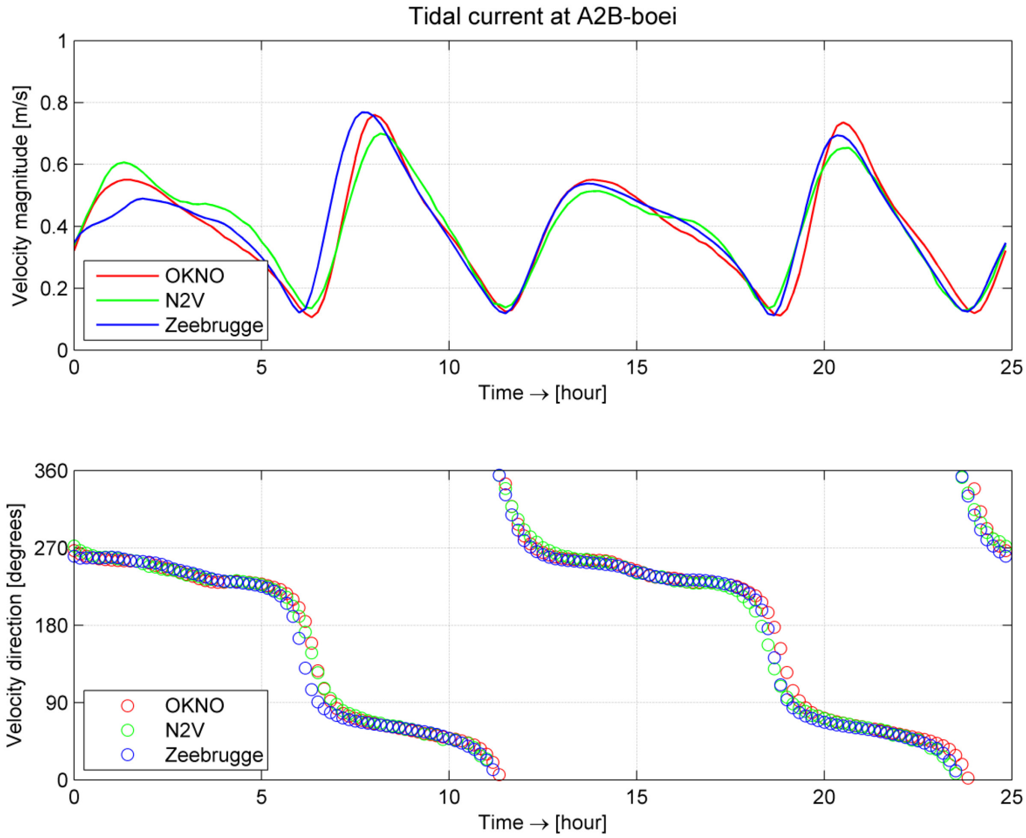

Figure 4-5: Current velocity of a representative tide at A2B-boei in the OKNO, N2V and Zeebrugge models.

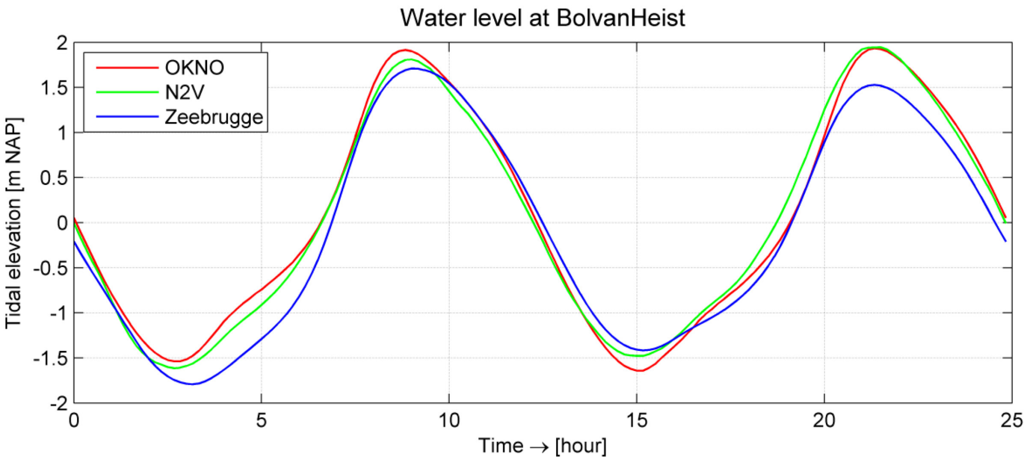

Figure 4-6: Water level of a representative tide at Bol van Heist in the OKNO, N2V and Zeebrugge models.

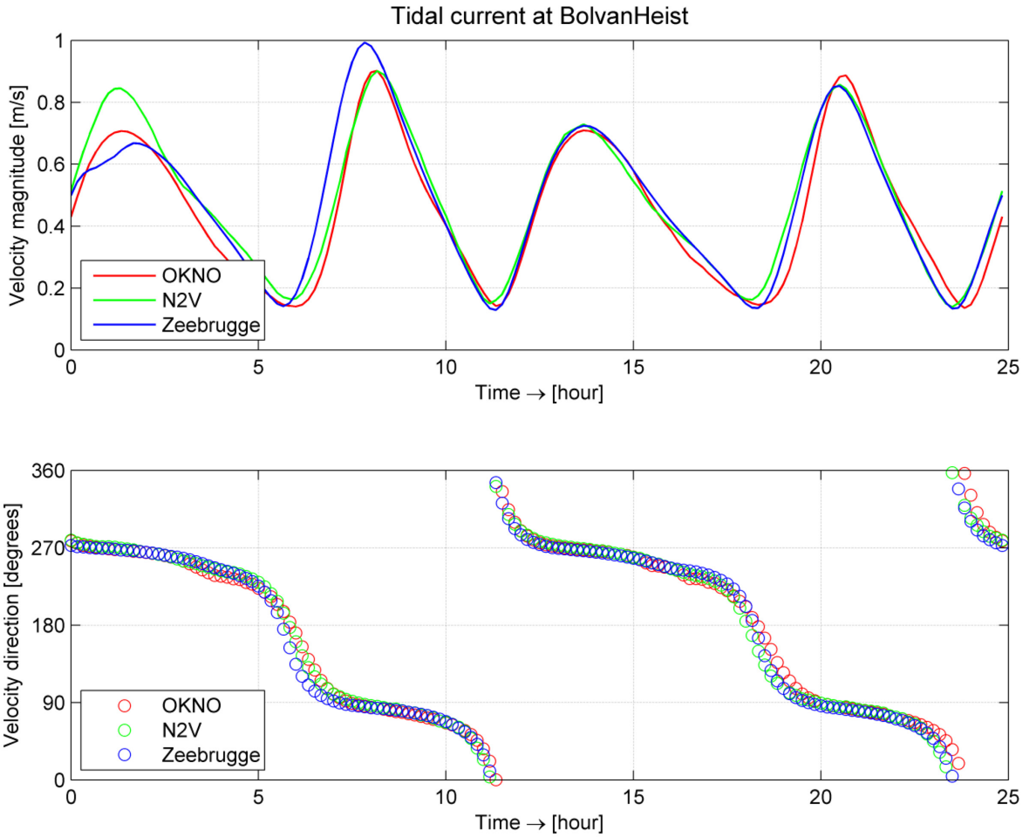

Figure 4-7: Current velocity of a representative tide at Bol van Heist in the OKNO, N2V and Zeebrugge models.

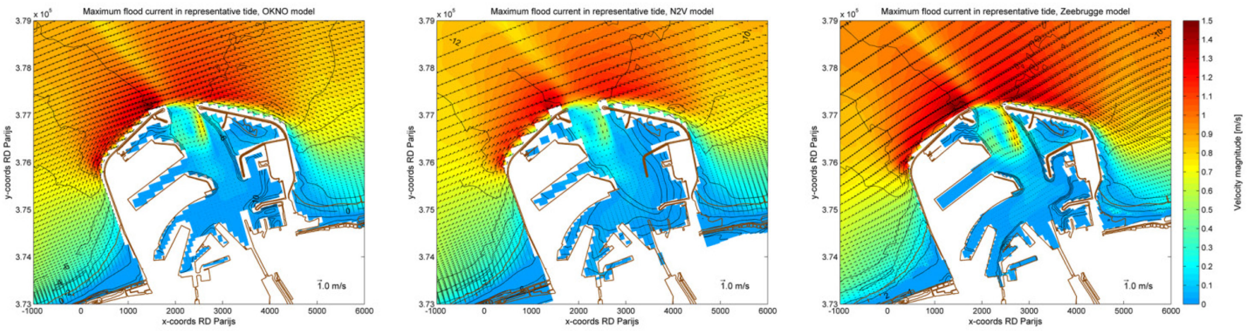

Figure 4-8: Maximum flood current (between 0 and 10 hour, Figure 4-7) around the Zeebrugge port in the OKNO (left), N2V (middle) and Zeebrugge (right) models.

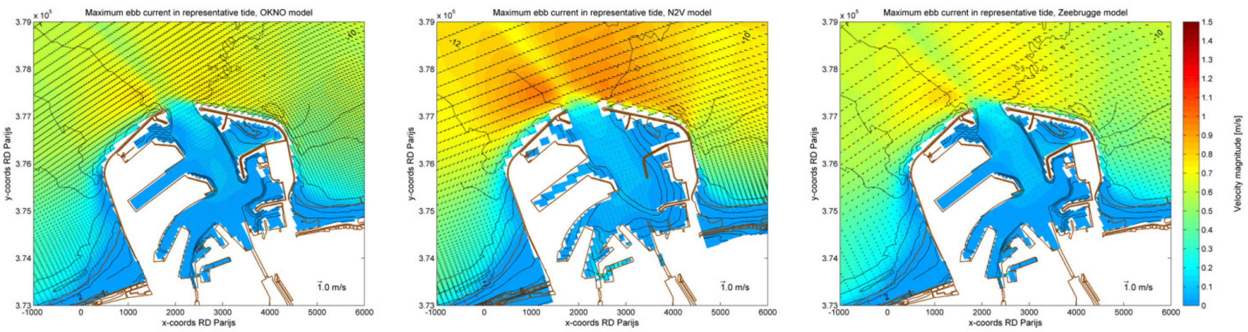

Figure 4-9: Maximum ebb current (between 0 and 10 hour, Figure 4-7) around the Zeebrugge port in the OKNO (left), N2V (middle) and Zeebrugge (right) models.

4.5. Comparison of morphodynamics

Due to the discrepancy of the hydrodynamics, different morphology changes could be anticipated as shown as in Figure 4-10. Like the results modelled with 200µm sediment, the OKNO and N2V models still produce quite consistent morphology changes with 100µm sediment. The Zeebrugge model also gives a similar pattern of morphology change, but the erosion around the breakwaters and sedimentation near the eastern breakwater appear to be slightly higher than those in the OKNO and N2V models, which could be strongly related to the higher peak-flood current between 5 and 10 hours at the location Bol van Heist. Apart from that the peak-flood current is around 0.1m/s higher, it is noticeable that at Bol van Heist the peak-ebb current between 0 and 5 hours is around 0.18m/s lower in the Zeebrugge model than that in the N2V model.

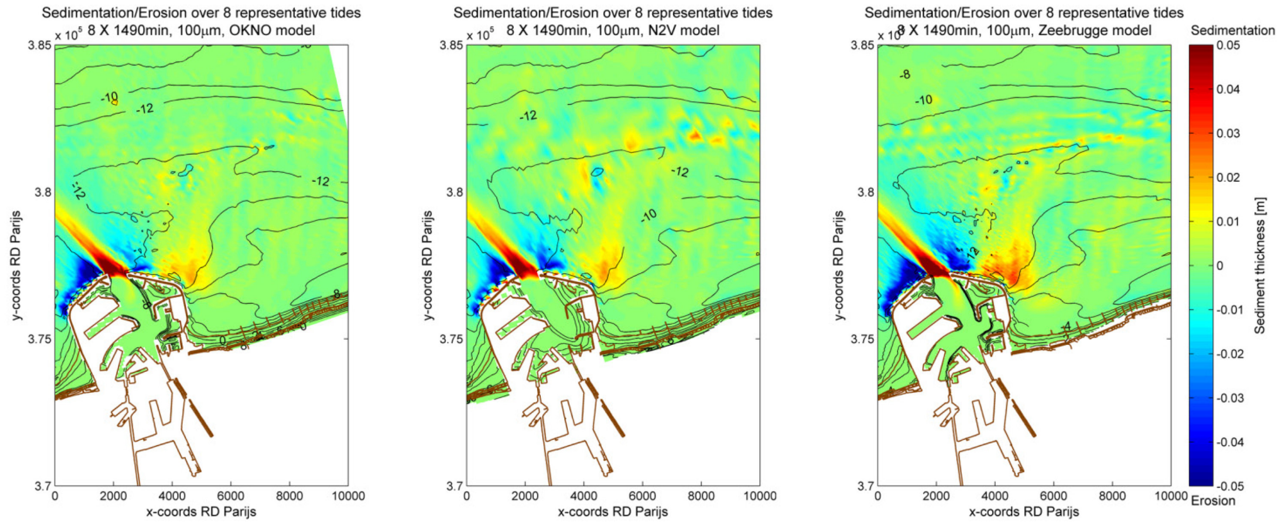

Figure 4-10: Sedimentation/erosion of 100µm sediment with 8 representative tides in the OKNO (left), N2V (middle) and Zeebrugge (right) models.

4.6. MU-HEIST model

In addition to the three internal models (OKNO, N2V and Zeebrugge), results from an external model MU-HEIST are introduced to better understand the sedimentation in the Baai van Heist. The MU-HEIST model was developed in the Coherens code at BMM (Van den Eynde et al., 2007).

This model was firstly calibrated against measurement data in terms of hydrodynamics, which was sampled at five locations shown as Figure 4-11.

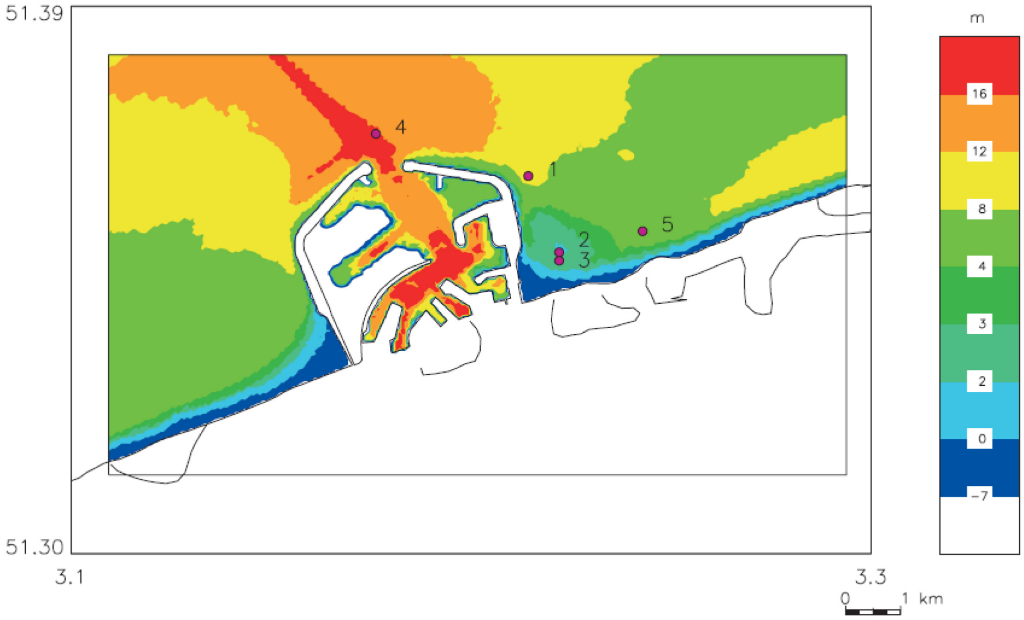

Figure 4-11: Measurement locations and bathymetry of the MU-HEIST model.

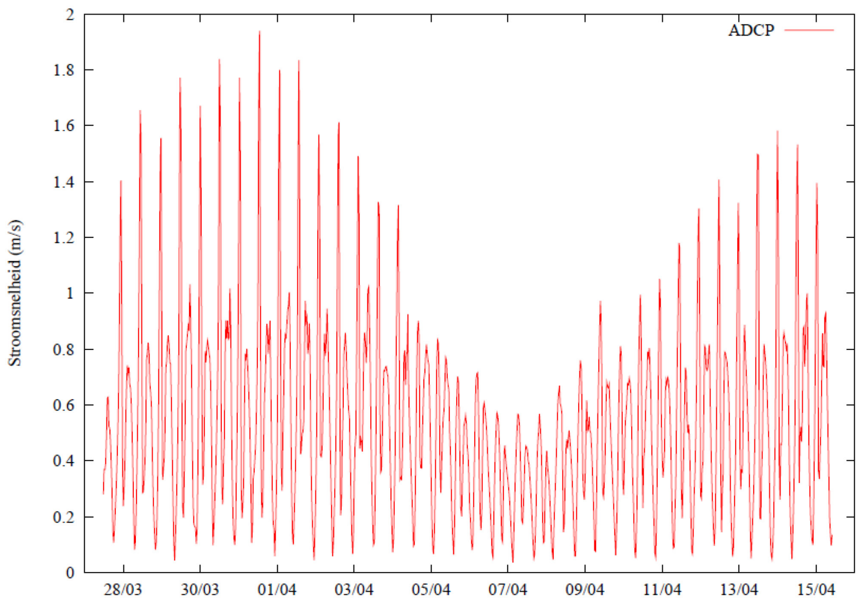

Figure 4-12: Time-series depth-averaged velocity magnitude sampled at location 1 (in Figure 4-11) for the whole measurement campaign from March 27 to April 15, 2006.

Figure 4-12 shows that the measurement campaign covers more than 18 days and a complete spring-neap-spring tidal cycle was recorded. It is found that the measured current velocity close to the eastern dam of the Zeebrugge port peaks at nearly 2.0m/s at the spring tide.

The comparison between measurement and modelling results shows that the measured currents could reach nearly 2.0m/s and 1.6m/s (Figure 4-12) at flood of spring tides while the modelled ones are only limited to 1.2m/s (Figure 4-13) and 1.0m/s (Figure 4-14). This large difference between the measurement and model was attributed to insufficient accuracy of the bathymetry on a small scale in the study (Van den Eynde et al., 2007). Moreover, in the Zeebrugge model which gives the largest maximum flood current around the breakwaters of the Zeebrugge port in the three models as discussed in section 4.4, the maximum flood current at the same measurement location is also limited to 1.2m/s at a spring tide and to 0.9m/s at the selected representative tide.

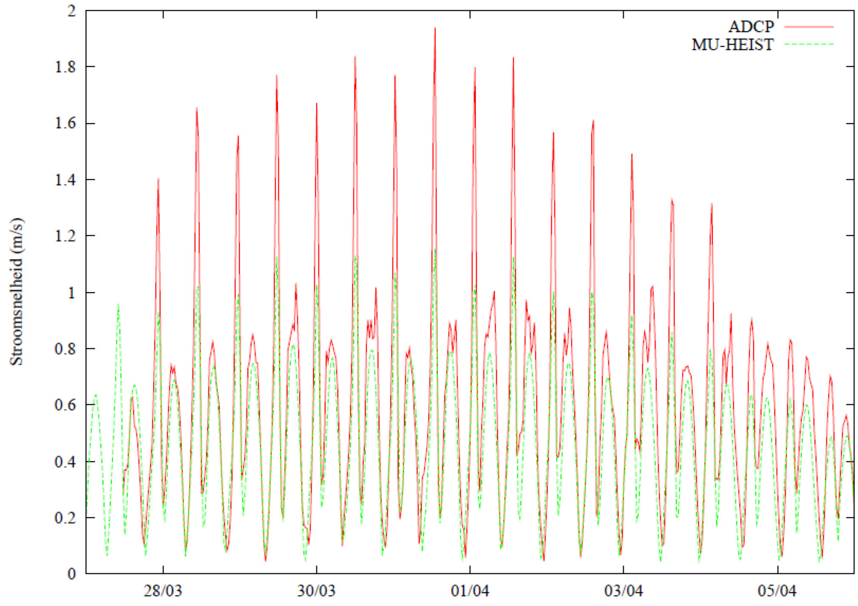

Figure 4-13: Comparison of depth-averaged velocity magnitude between measurement (red) and modelling (green) results at location 1 (in Figure 4-11) during the period from March 27 to April 6, 2006.

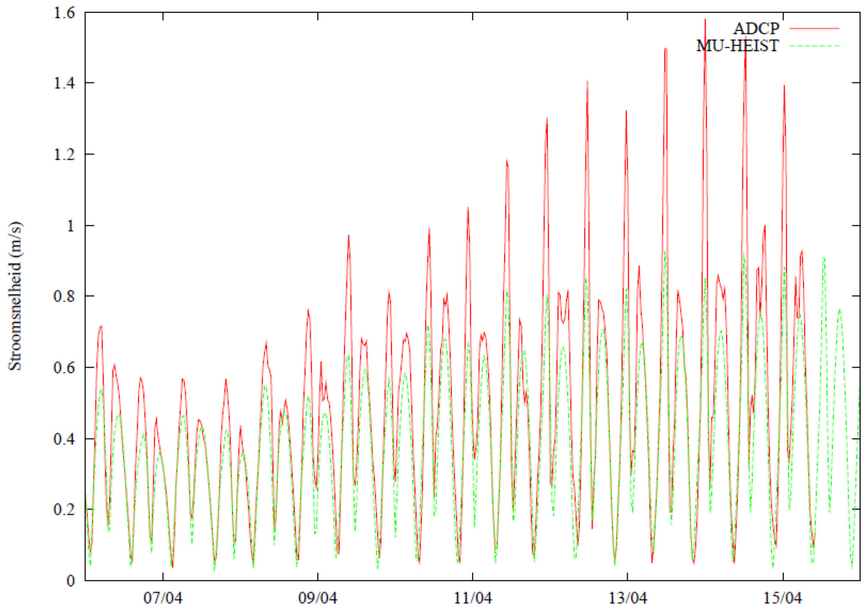

Figure 4-14: Comparison of depth-averaged velocity magnitude between measurement (red) and modelling (green) results at location 1 (in Figure 4-11) during the period from April 6 to April 16, 2006.

A more comprehensive comparison between the MU-HEIST and Zeebrugge models was carried out in Annex B, from which the current vectors around the Zeebrugge port produced by the two models are compared hourly at comparable time points of the spring tides. Because the MU-HEIST model gives bathymetry in contour as background instead of velocity magnitude, it is hard to compare the velocity magnitude between the two models. But the current vectors still indicate that the two models produced quite consistent eddies formed during the transition from flood to ebb. In addition, because a more recent bathymetry data is used in the MU-HEIST model and the Baai van Heist has significantly silted up since 1986, it is shown that the Baai becomes dry during the ebb phase rather than that any eddy is formed. While the bathymetry data of 1986 is used in the Zeebrugge model, thus during the whole ebb phase there is always some flow visible in the Baai which has not silted up yet.

In the study of sediment transport with the MU-HEIST model, it is addressed that the sand transport formula of Ackers and White (1973) is not suitable to be applied in the area around the Zeebrugge port. Then the mud transport formula of Ariathurai-Partheniades (Ariathurai, 1976 and Krone 1962) is employed in the MU-HEIST model to study the sediment transport:

$$E = M\frac{(\tau - \tau_e)}{2\tau_e}\ if\ \tau > \tau_e$$

$$D = wC\frac{(\tau_d - \tau)}{2\tau_d}\ if\ \tau < \tau_d$$

where M = 0.00012kg/m^2/s, τ_e = 0.5Pa and τ_d = 0.5Pa, and settling velocity of particles w is an parameter for sensitivity tests. In addition, the sediment transport within the MU-HEIST model is only driven by tidal currents without any effect of waves.

Two sedimentation/erosion maps are produced with two different settling velocities 0.01m/s and 0.0001m/s (Figure 4-15 and Figure 4-16). It could be observed that the settling velocity plays a quite significant role on the sedimentation/erosion. Due to the larger settling velocity, higher sedimentation is produced at both sides of the Zeebrugge port. With the lower settling velocity, the sedimentation seems to be extended further into the sheltering area next to the eastern dam of the Zeebrugge port, however the model might be strongly flawed by the setup in which the whole domain is consider to be covered by the mud with such a small settling velocity.

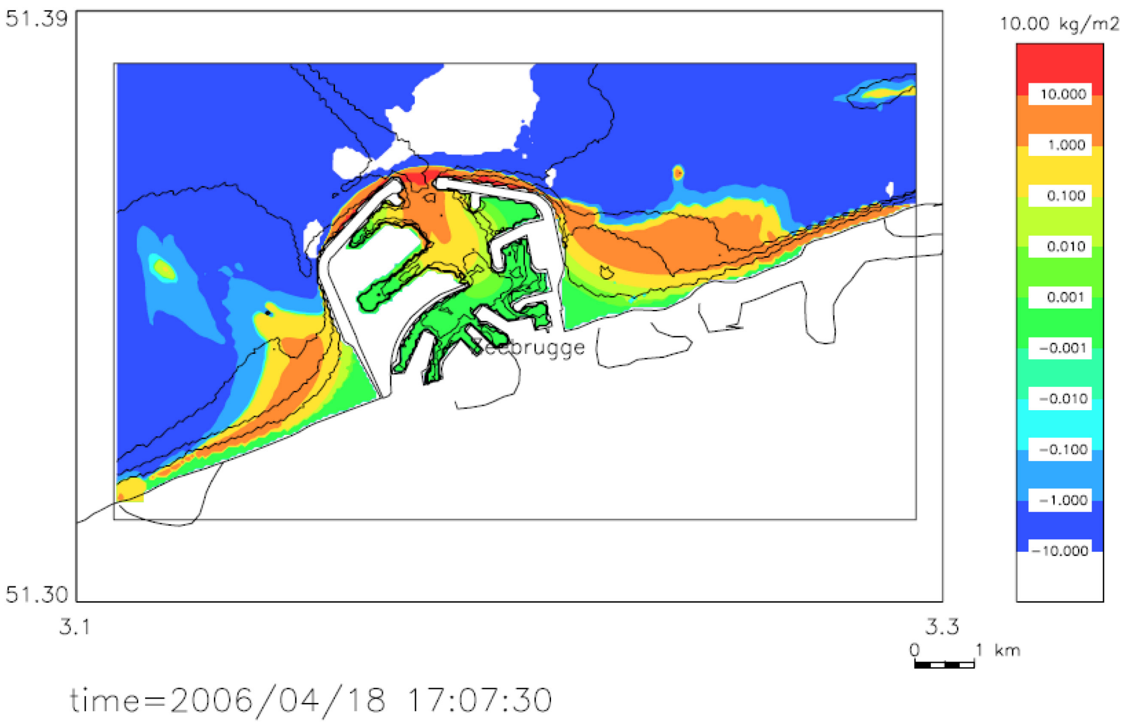

Figure 4-15: Tidal averaged sedimentation/erosion with (w = 0.01m/s) within a tide centered at 18/04/2006 12:07:30.

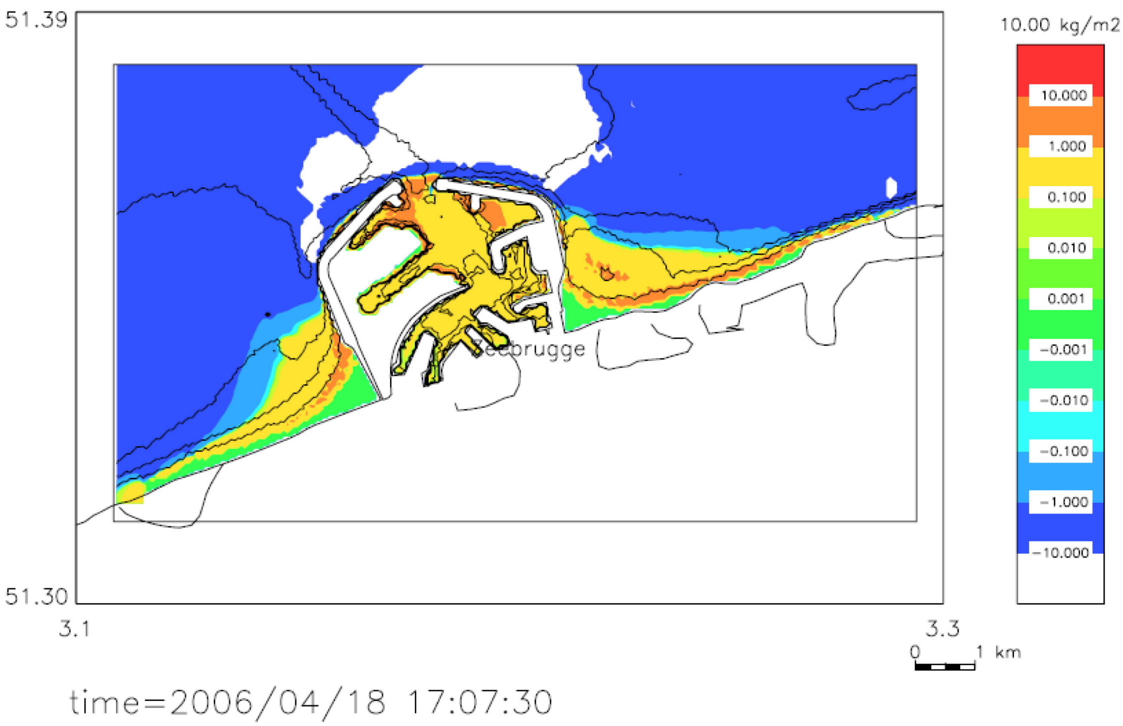

Figure 4-16: Tidal averaged sedimentation/erosion with (w = 0.0001m/s) within a tide centered at 18/04/2006 12:07:30.

4.7. Sensitivity study with Zeebrugge model

For the specific investigation on the sedimentation at the Baai van Heist, the Zeebrugge model is employed to do sensitivity study in consideration of its better grid resolution around the Zeebrugge port. After the sensitivity study, a reasonable parameter set will be applied to the N2V model.

A basic set-up for the Zeebrugge model is:

- bathymetry dataset of 1986;
- 8 tidal cycles (8 X 1490min);
- 100µm grain size;
- no wind and wave;
- no morphological acceleration.

Table 4-2: Overview of sensitivity tests

Run / Parameter	R00	R01	R02	R03	R04	R05	R06
HLES	Off	On	Off	Off	Off	Off	Off
2D/3D	2D	2D	3D	2D	2D	2D	2D
Tide	Rep.	Rep.	Rep.	Spr.	Rep.	Rep.	Rep.
Horizontal eddy viscosity (m^2/s)	1	1	1	1	0.1	1	1
Horizontal eddy diffusivity (m^2/s)	1	1	1	1	1	10	1
Bottom roughness (Manning, $s/m^{1/3}$)	0.022	0.022	0.022	0.022	0.022	0.022	map

* HLES: horizontal large eddy simulation; R00: reference case; Rep.: representative; Spr.: spring; map: Figure 4-17.

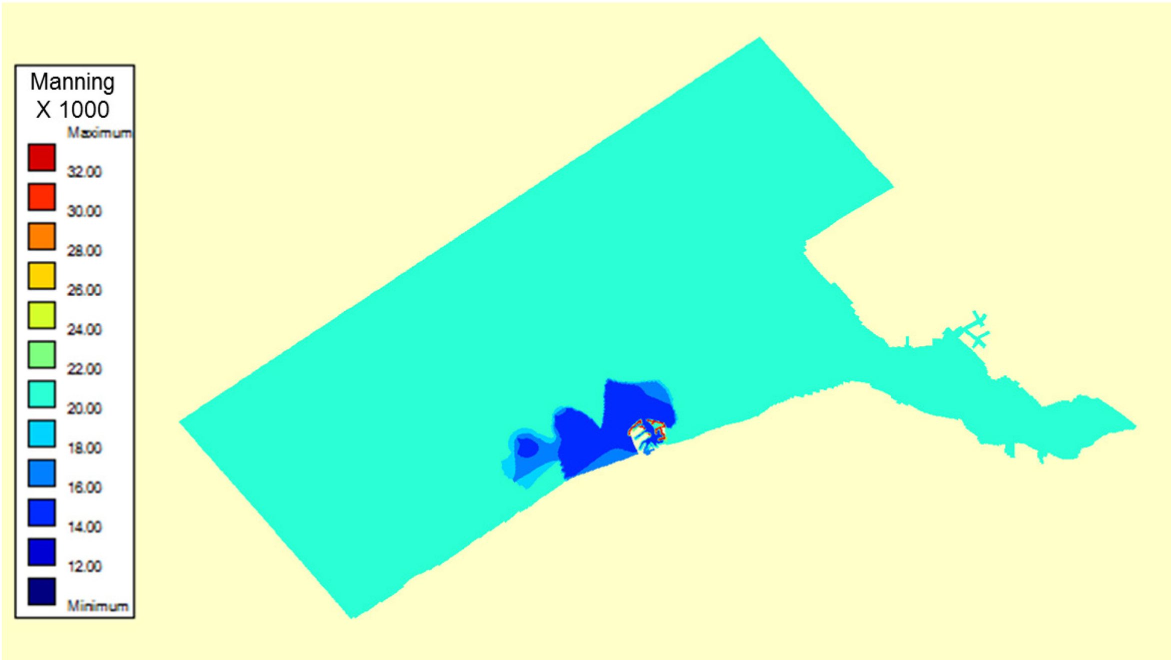

Figure 4-17: Roughness map applied in R06.

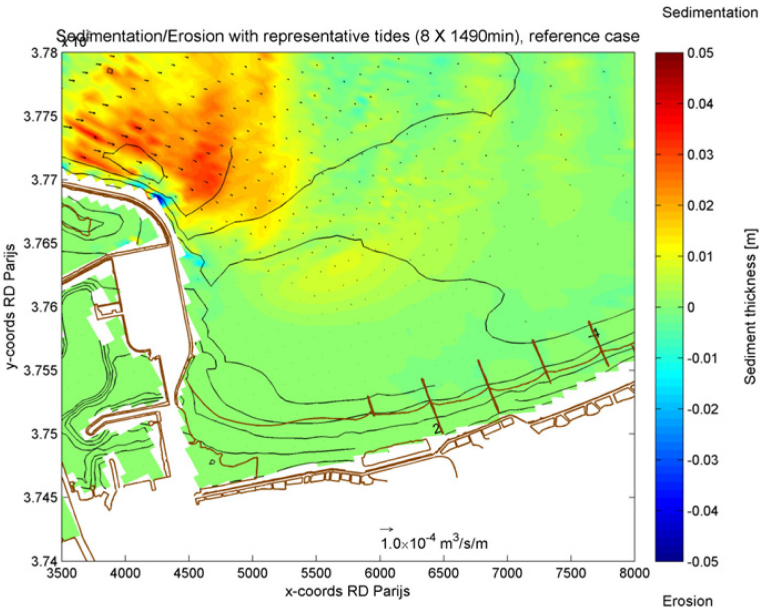

Figure 4-18: Sedimentation/erosion map of reference case.

Figure 4-18 indicates the sedimentation/erosion after 8 tidal cycles (8 X 1490min) in the reference case. The results of the sensitivity tests are subsequently displayed from Figure 4-19 to Figure 4-24. It could be found that the cases R02, R03 and R06 are potentially able to produce stronger sedimentation at the Baai van Heist compared with the reference case. However, 8 consecutive spring tides do not exist in reality and with the 3D mode the computation time would be largely increased (roughly estimated at least by a factor 5 of 6 vertical layers). It indicates that the selected representative tide is poorly representative for the Bai van Heist since some important processes are missing duringthe representative tide. Thus the roughness map becomes the only pragmatic way to improve the modelling results at the Baai van Heist. In order to see effects of the roughness map on the long-term morphology, one more sensitivity test based on the morphological acceleration technique is carried out.

The set-up for the long-term morphology model is:

- bathymetry dataset of 1986;
- 28 representative tidal cycles (28 X 1490min);
- 100µm grain size;
- with morphological acceleration (MorFac=125, ca. 10 years);
- no wind and wave.

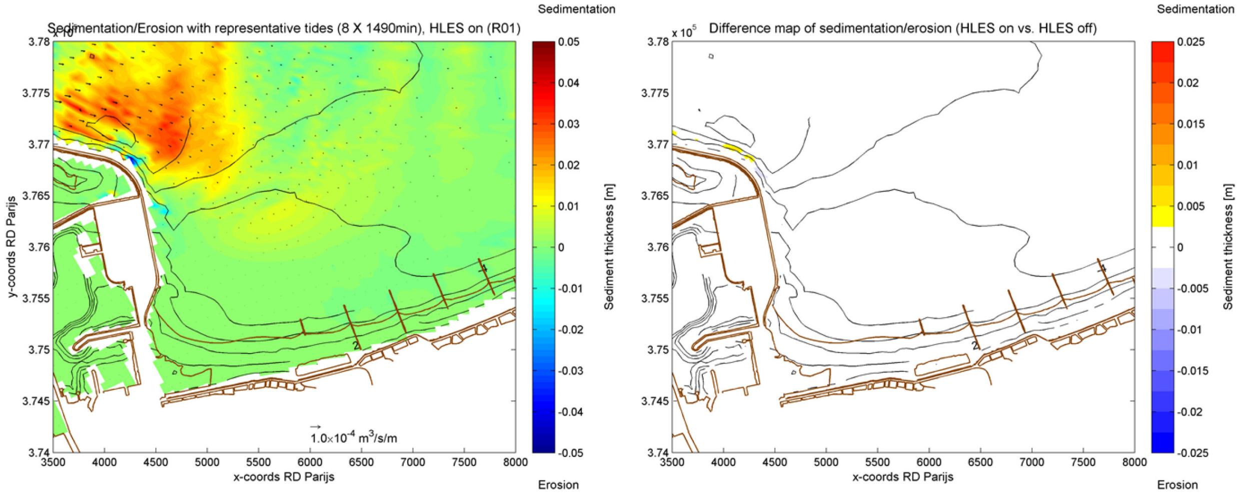

Figure 4-19: left: Sedimentation/erosion map of R01 case;
right: Sedimentation/erosion of R01 relative to reference case.

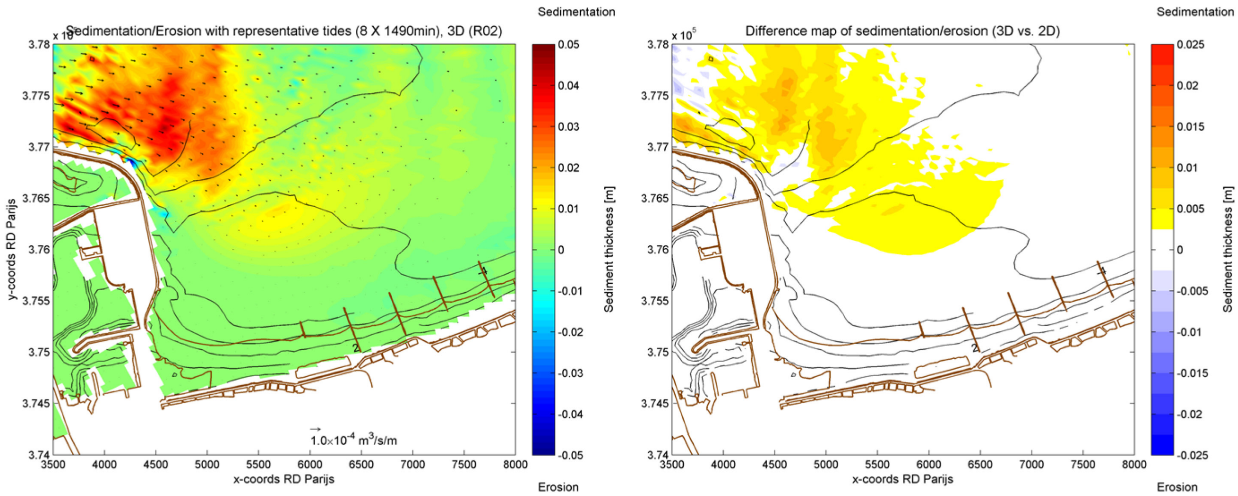

Figure 4-20: left: Sedimentation/erosion map of R02 case;
right: Sedimentation/erosion of R02 relative to reference case.

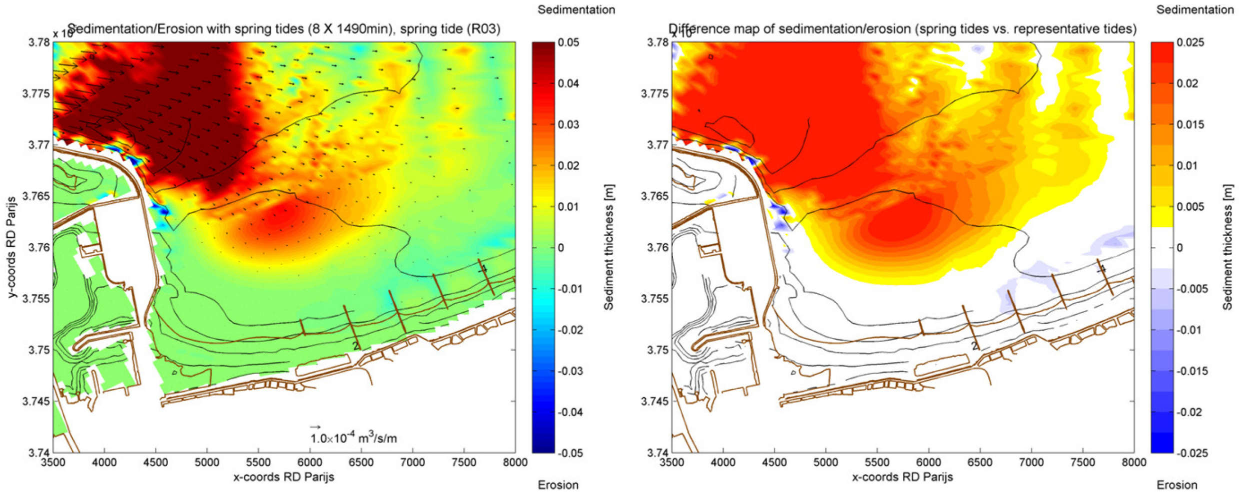

Figure 4-21: left: Sedimentation/erosion map of R03 case;
right: Sedimentation/erosion of R03 relative to reference case.

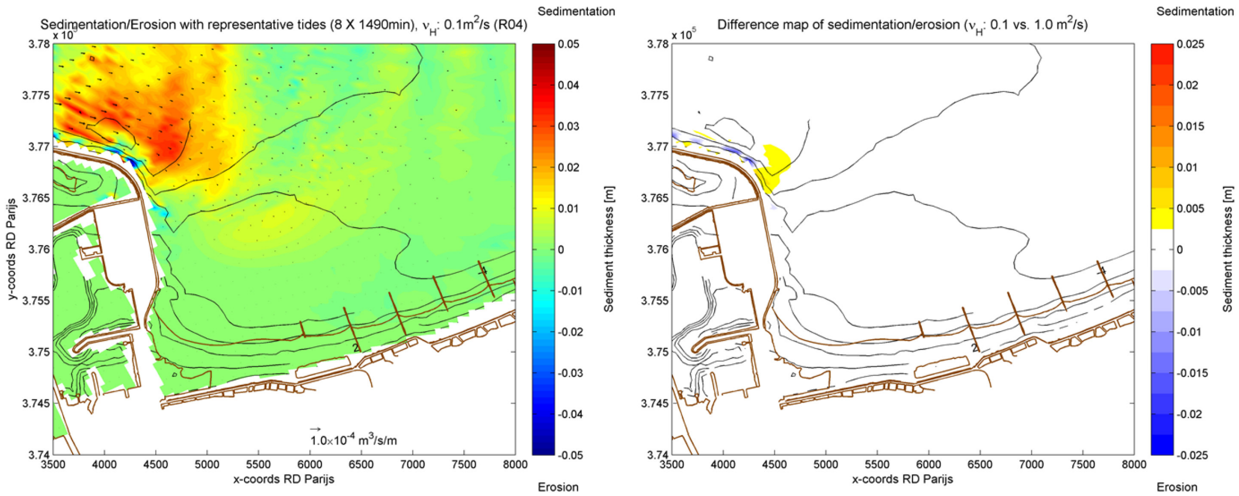

Figure 4-22: left: Sedimentation/erosion map of R04 case;
right: Sedimentation/erosion of R04 relative to reference case.

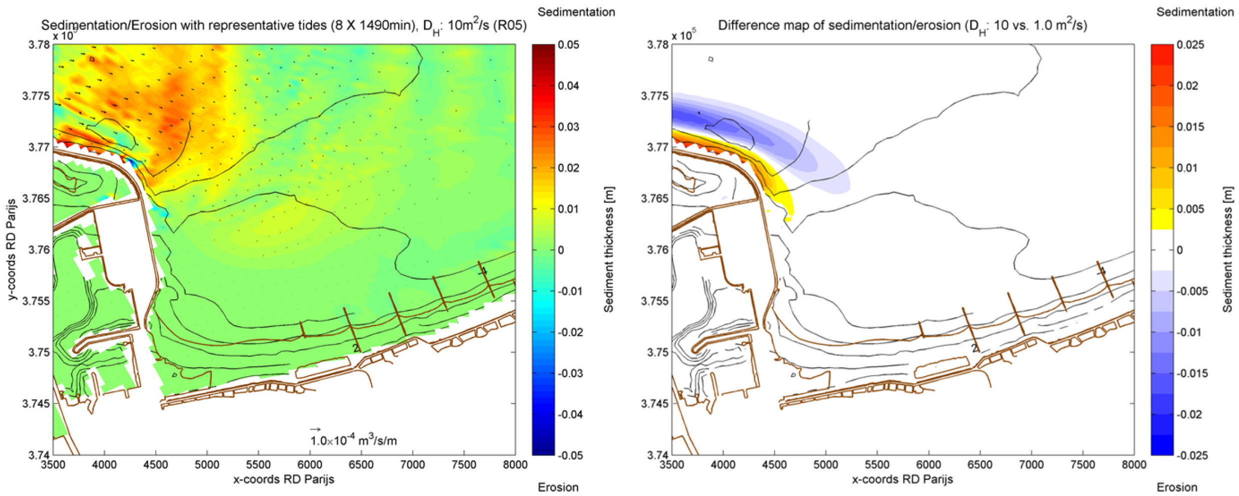

Figure 4-23: left: Sedimentation/erosion map of R05 case;
right: Sedimentation/erosion of R05 relative to reference case.

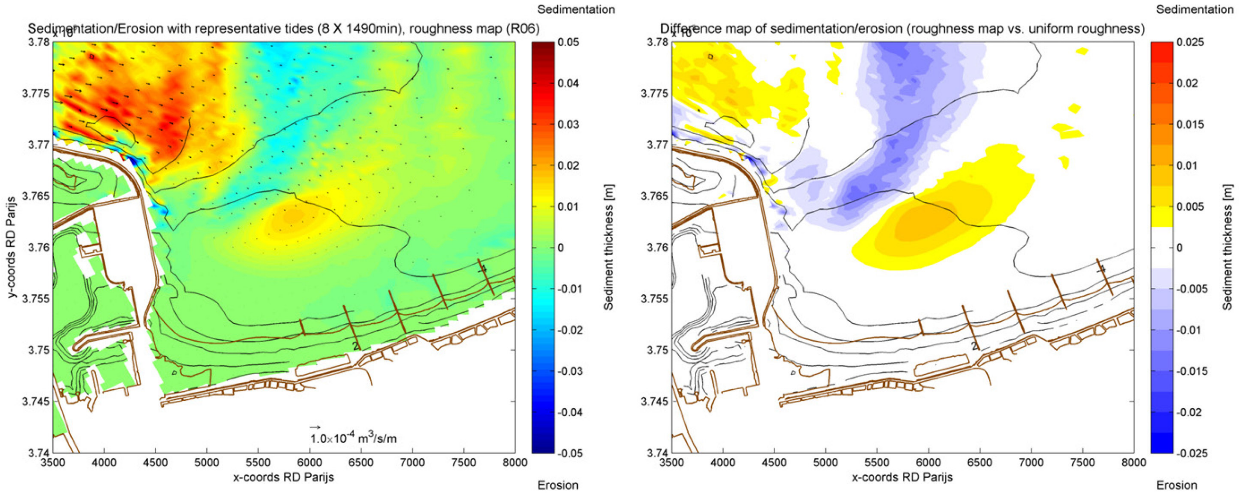

Figure 4-24: left: Sedimentation/erosion map of R06 case;
right: Sedimentation/erosion of R06 relative to reference case.

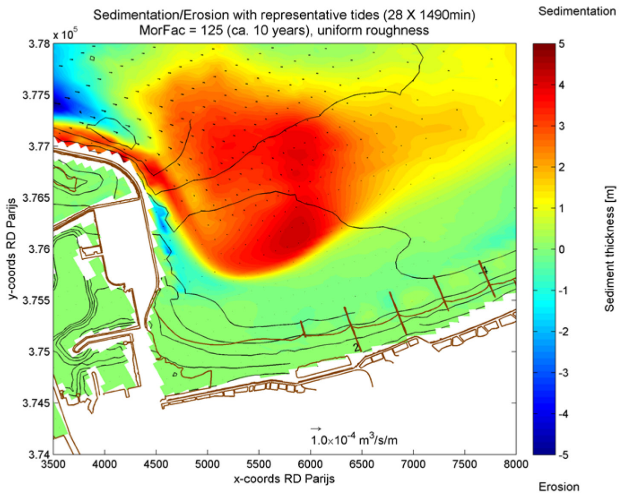

Figure 4-25: 10-year sedimentation/erosion with uniform roughness.

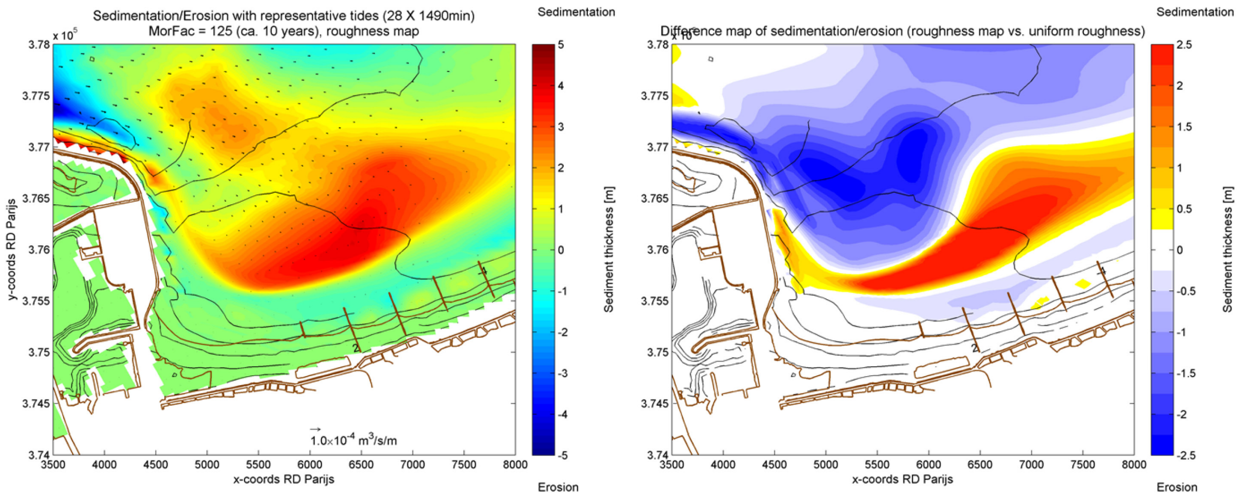

Figure 4-26: left: 10-year sedimentation/erosion with roughness map;
right: 10-year sedimentation/erosion with roughness map relative to the case with uniform roughness.

From Figure 4-25 and Figure 4-26 it could be observed that the roughness map plays a quite visible role on the long-term morphology change. The sediment after bypassing the breakwater of the Zeebrugge port could be transported further and the sedimentation is produced more landwards.

4.8. Updated N2V model

In the sensitivity study, the Zeebrugge model was employed in view of its better grid resolution around the Zeebrugge port. While in the whole study one of the major objectives is to evaluate the morphodynamics in the surf zone along the coast, then the Zeebrugge model is not fit anymore for this objective due to its insufficient grid resolution in the surf zone. Based on results of the sensitivity study, the roughness map is applied to the N2V model which is able to describe the longshore sediment transport due to tide-, wind- and wave-driven currents in the surf zone.

4.8.1. Model settings

In the previous study time series of the representative wave climate during 8 representative tidal cycles was created to simulate 1 year of morphology change (Zimmermann et al., 2013). In order to simulate 10-year morphology change, these time series were repeated twice. In addition to the roughness map and three times of the time-series representative wind/wave climate, the three bathymetries of 1986, 1999 and 2010 were all applied to the N2V model, which was run with a larger MorFac for 24 representative tidal cycles to achieve the 10-year morphology simulation.

The scenarios and relevant parameters set-up have been summarized in Table 4-3.

Table 4-3: Overview of scenarios for the 10-year morphology simulation

Bathymetry dataset / Parameter	1986	1999	2010
Simulation period (min)	24 X 1490	24 X 1490	24 X 1490
MorFac (Morphological factor)	121.67	121.67	121.67
Bottom roughness (Manning, $s/m^{1/3}$)	Roughness map	Roughness map	Roughness map
Grain size (μm)	100	100	100
Wave communication interval (min)	10	10	10
Number of wave conditions (-)	11	11	11
Time step (s)	12	12	12
Wall roughness (Partial, m)	0.15	0.15	0.15
Water density (kg/m^3)	1023	1023	1023
Horizontal eddy viscosity (m^2/s)	1	1	1
Horizontal eddy diffusivity (m^2/s)	1	1	1

4.8.2. Model results

The three scenarios based on the different bathymetry datasets show an approximately similar sedimentation/erosion pattern. It could be observed that there is a little sediment which has been transported into the sheltered area next to the eastern dam of the Zeebrugge port. But the sedimentation seems to be still much lower compared with the measurement data (Figure 4-27), and the location of the sedimentation is not reproduced properly by the model in view of the closed isobath in the right panel of Figure 4-28. Moreover, apart from the strong erosion nearshore caused by longshore sediment transport in the surf zone, the wave-induced erosion in the magenta ellipse between the sedimentation areas is also quite remarkable, since measurements show sedimentation there. Due to insufficient resolution of the model, the groins were not modelled. This explains partly the strong erosion in the nearshore.

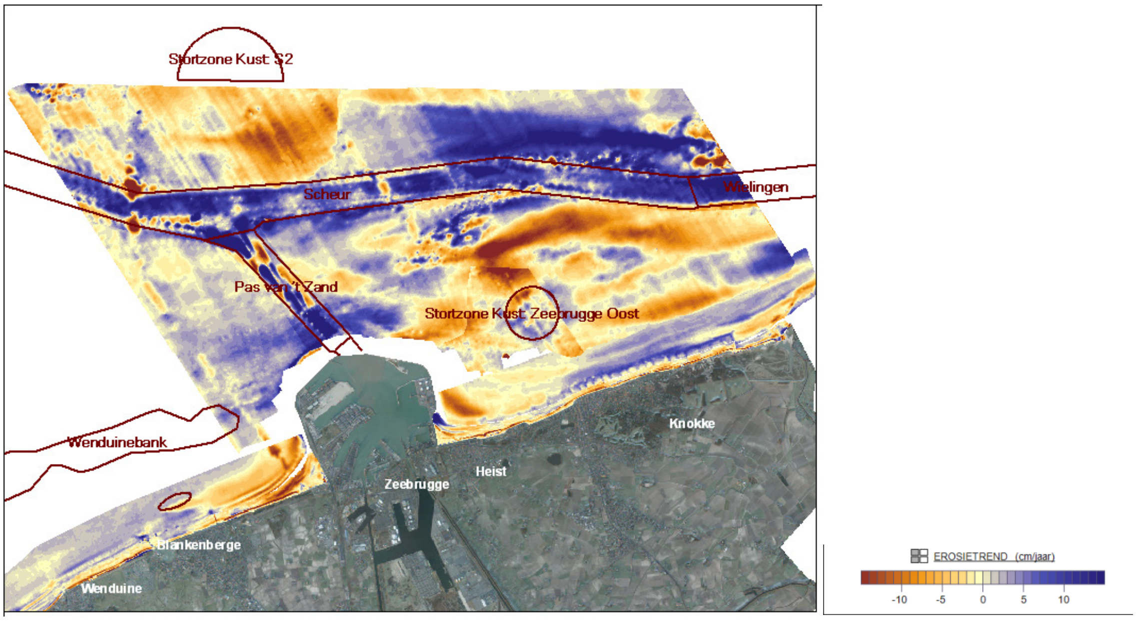

Figure 4-27: Measured erosion and sedimentation between 1999 and 2009 – large area.

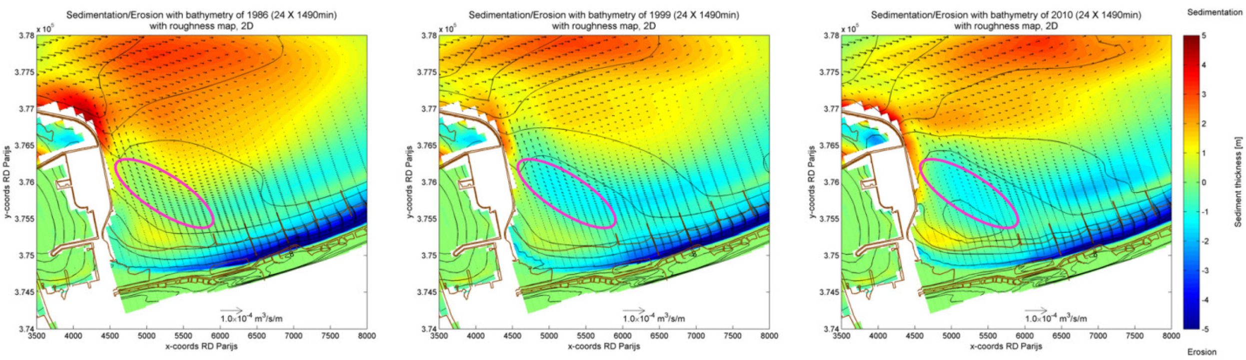

Figure 4-28: 10-year sedimentation/erosion at the Baai van Heist with bathymetries of 1986 (left), 1999 (middle) and 2010 (right).

Figure 4-29 shows the morphology change in the absence of waves. It suggests that waves are instrumental in causing the sedimentation in the Baai van Heist, and the erosion just offshore of it. If the erosion due to the role of waves does exist in reality, more sediment has to be transported here to compensate for it, but the amount of sediment transported here seems to be still far underestimated by the model.

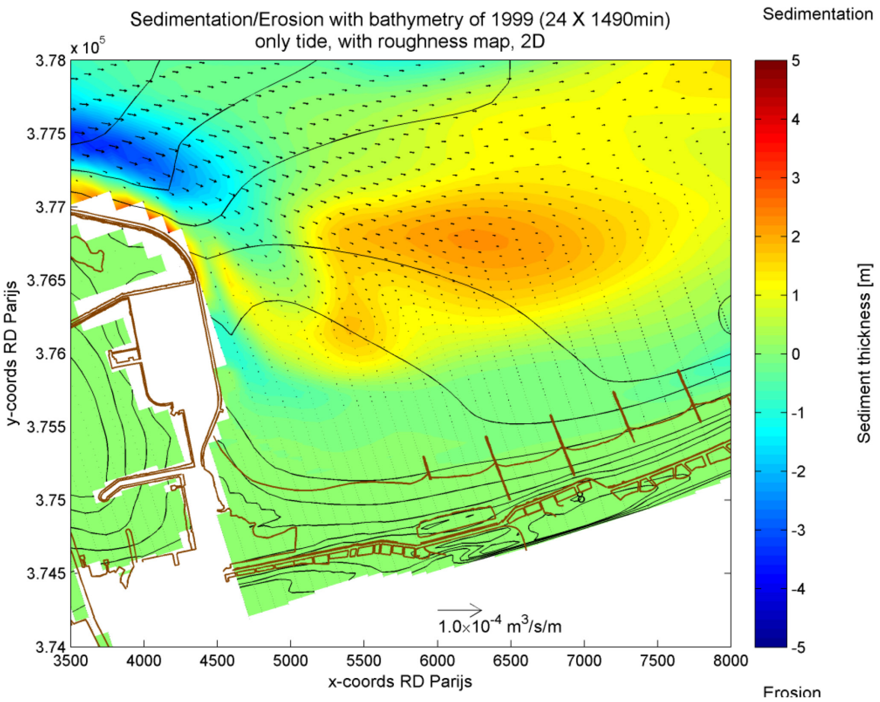

Figure 4-29: 10-year sedimentation/erosion produced by only tide at the Baai van Heist with bathymetry of 1986.

Figures below compare the measured erosion/sedimentation during 10 years, resp. starting from autumn 1986 and spring 1999 with the modelled result for the same period. For both intervals, the same time series of the wave climate are used (the previous analysis concluded that in reality the gross longshore sediment transport was about 10% higher for the first decade compared to the second decade).

For each decade, the modelled erosion-sedimentation is shown for a large extent and a reduced extent, and on the third picture the measured bed changes are shown at the same extent.

In the period 1986-1997 some works have been done in the Baai van Heist:

- For the first 400m East of the harbour mole, following works were done (Houthuys, 2012):
    - Sand mining near the LW line between 1986 and 1993 and between November 1992 and April 1993 (for the land fall works of “Zeepipe”) : a total volume estimated at 50.000 m³ was removed.
    - At this location, a layer of unconsolidated mud was observed. This layer was removed and replaced by 60.000 m³ of sand in July 1993.
    - This was repeated in October 1994 using 105.000 m³ of sand
- In the next 600m, 70.000 m³ of sand was added in 1994.
- The total artificial increase of sand is 180.000 m³, compared to a natural increase in volume of 1.8 million m³.
- Between 1997 and 2007 the artificial volume change in this area is negligible. The large nourishment of 1999 starts at about 4km from the harbour mole.

Non-modelled human activities should therefore not have a meaningful impact on the results.

From the figures, it can be concluded that:

- For the period 1986-1997:
    - The formation of an “island” is predicted by the model but smaller and more southwards than observed
    - The model indicates large areas that erode, which is not observed. This might partly be explained by the lack of cross shore transport in the model and missing groins in the model.

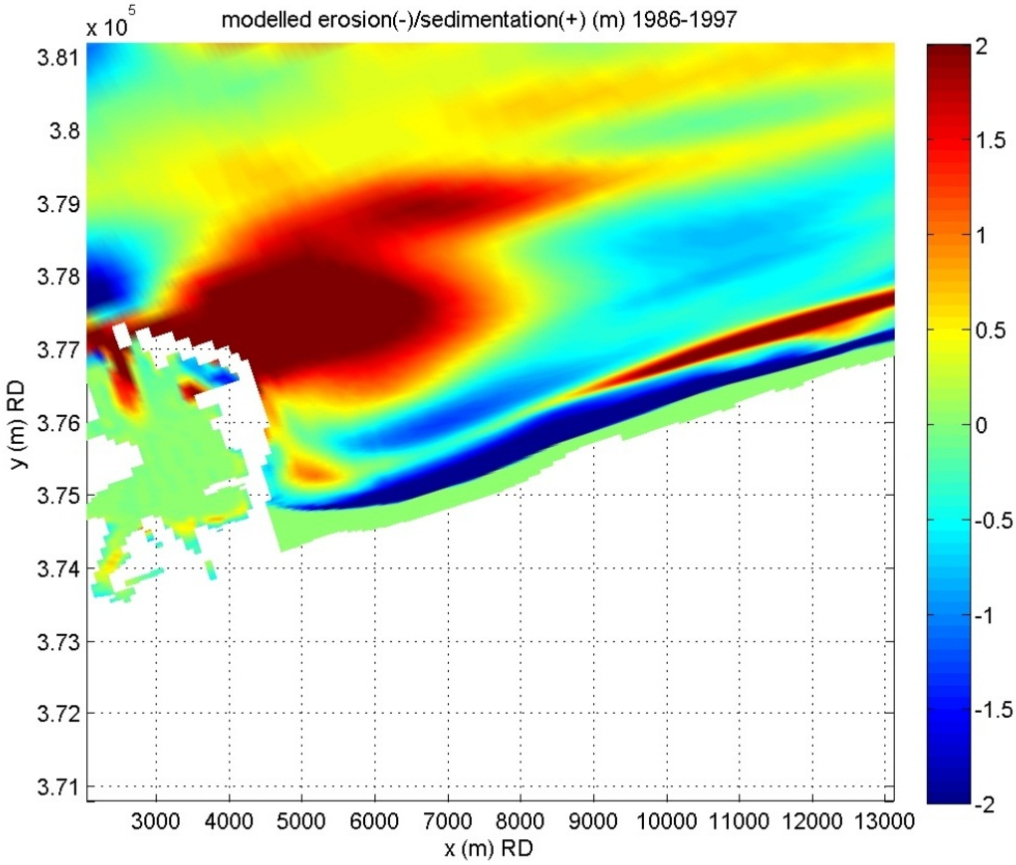

Figure 4-30: Modelled erosion and sedimentation between 1986 and 1997 – large area.

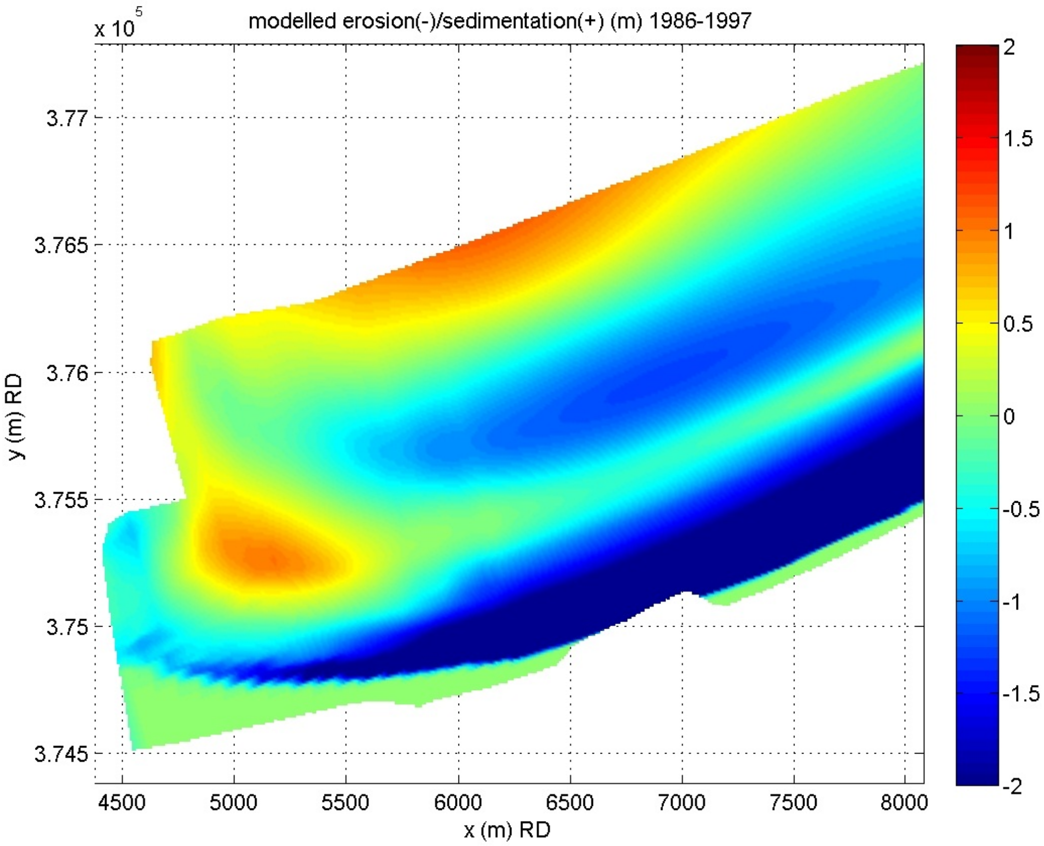

Figure 4-31: Modelled erosion and sedimentation between 1986 and 1997 – area of measurements.

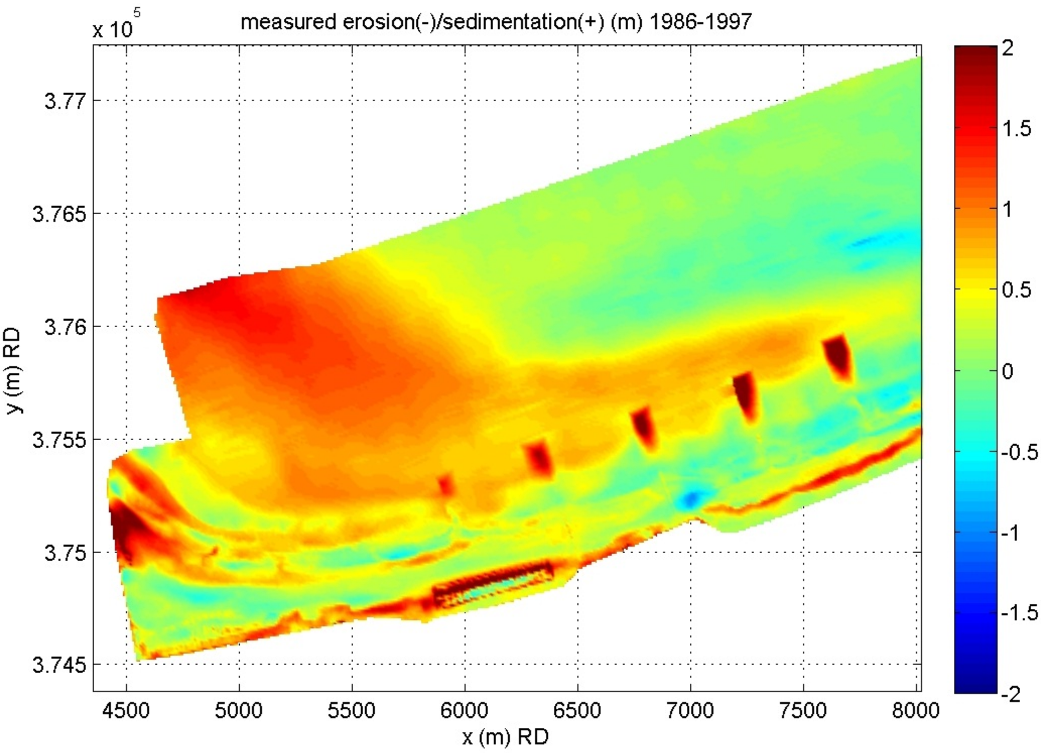

Figure 4-32: Measured erosion and sedimentation between 1986 and 1997 – area of measurements.

- For the period 1999-2009:
  - An important area with sedimentation in the SW is correctly reproduced by the model (values somewhat smaller than observed)
  - Large erosion areas NE of this area are modelled, but not observed. The sedimentation to the N of this area is also observed (but more northwards)

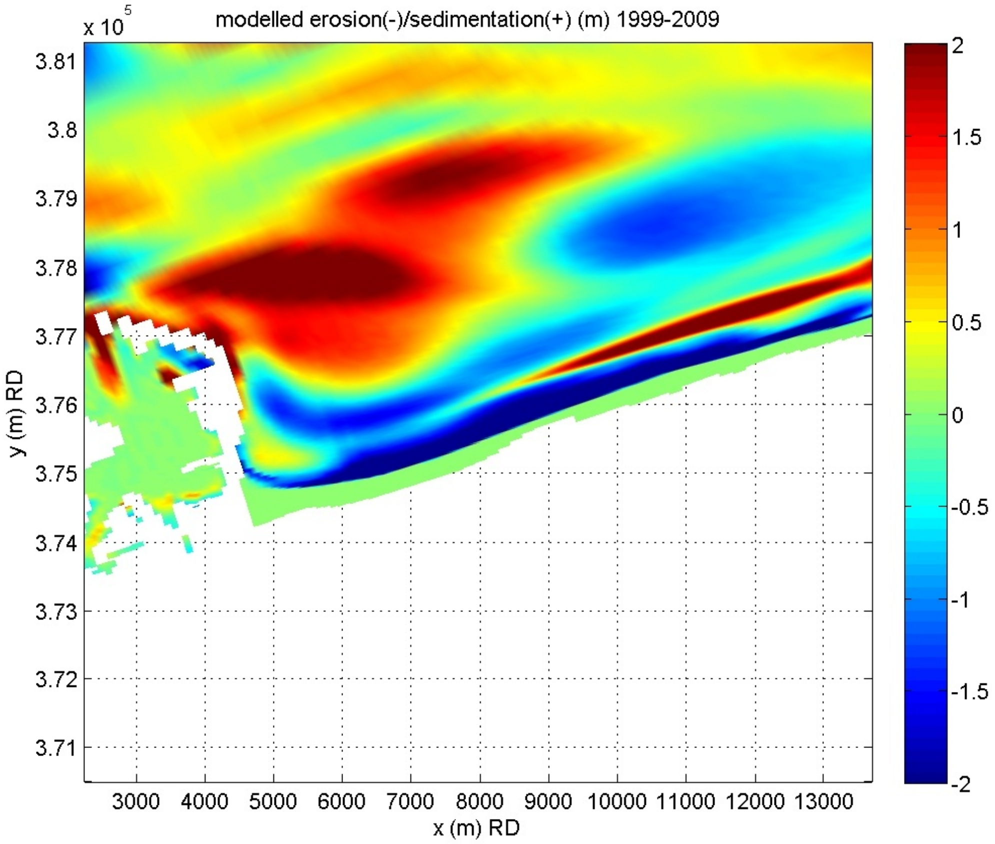

Figure 4-33: Modelled erosion and sedimentation between 1999 and 2009 – large area.

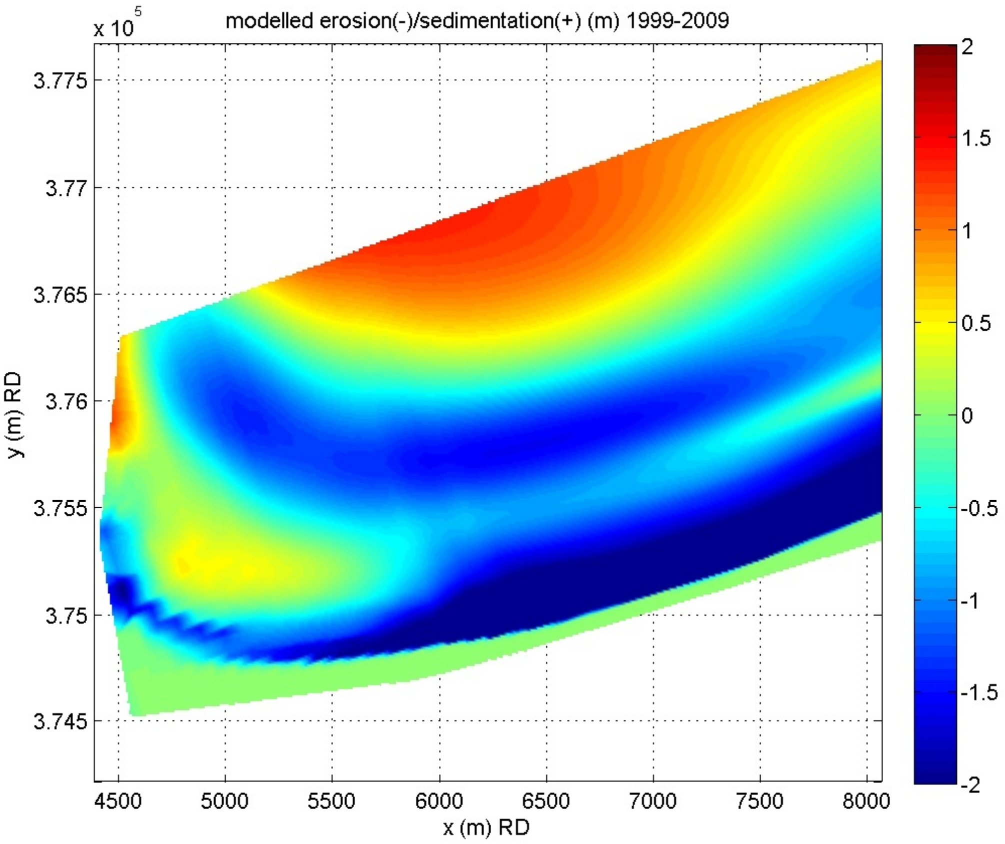

Figure 4-34: Modelled erosion and sedimentation between 1999 and 2009 – area of measurements.

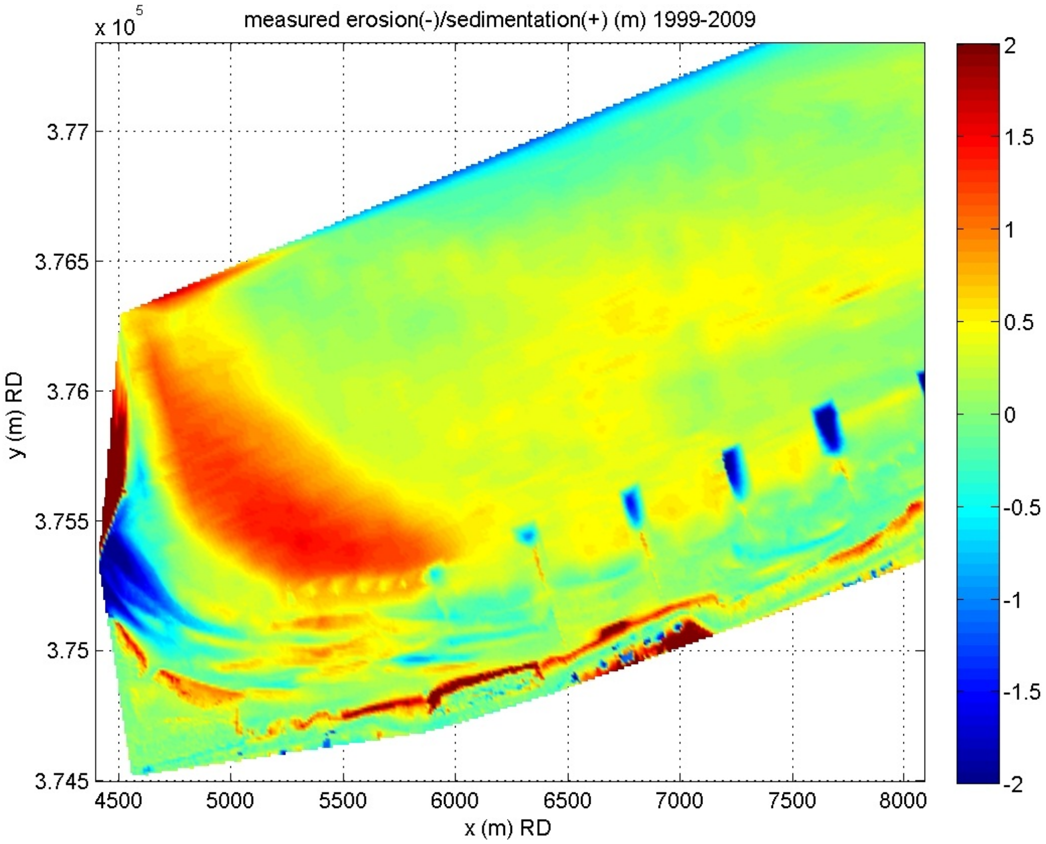

Figure 4-35: Measured erosion and sedimentation between 1999 and 2009 – area of measurements.

4.9. 3D N2V model driven by spring-neap tide

4.9.1. Purpose

The 2D N2V model driven by a representative tide and wave climate appears to still not be able to reproduce the sedimentation in the Baai van Heist satisfactorily, even though the roughness map is applied in the model. Due to the way that suspended transport is treated in 2D (the Galappatti relaxation time scale), the transport of fine sediment like 100µm cannot be modelled to an extent close to real 3D effect. Therefore the N2V model is extended to 3D for a better modelling of the suspended transport.

In addition, the influence of the spatial variability of sediment size is studied by including multiple fractions.

4.9.2. Representative tide in 3D

According to the Delft3D FLOW User Manual, the thickness of bottom and surface layers is chosen to be 2% of the total water depth in order to resolve the logarithmic profile of the horizontal velocity components in the vertical, and wind effects on the water surface. In addition, the increasing/decreasing rate of thickness of the layers between the bottom and surface is limited to 1.5. Then 13 layers are obtained in total and distributed as the figure shown below:

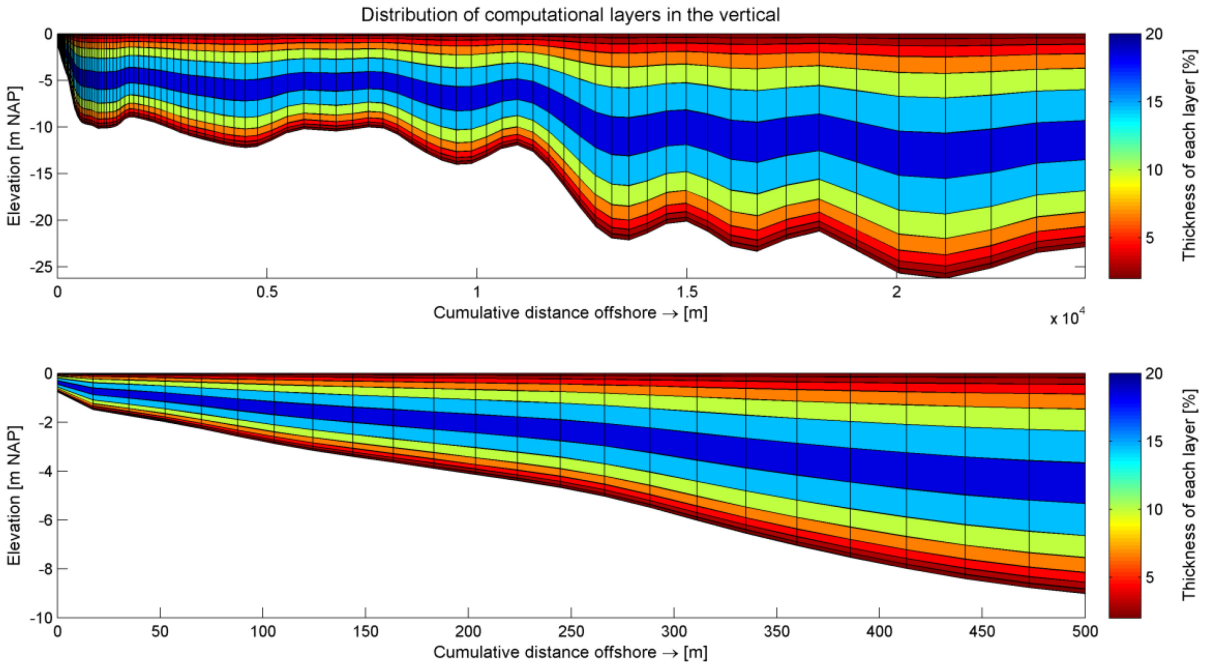

Figure 4-36: Vertical distribution of computational layers in the 3D N2V model
(bottom figure is a zoom of the top figure).

At the beginning of this study, the tidal reduction was performed with the OKNO model in which an uniform grain size 200µm was used. To verify validity of the representative tide selected in the former 2D mode for the current 3D mode, firstly the transport of 100µm sand is simulated in the 2D OKNO model, and afterwards the OKNO model is changed to 3D mode. Each of these models is separately run with a spring-neap tidal cycle (14 x 1490min), and with 14 representative tidal cycles.

Compared to the former 2D model which gave a slope near to 1 between the spring-neap and representative tides with the 200µm sand (Figure 4-37), the new 2D model with 100µm sand also gives a slope near to 1 (Figure 4-38), whereas the new 3D model with the 100µm sand produces a slope near to 2 (Figure 4-39), which indicates that the representative tide largely underestimates the sediment transport during the spring-neap tidal cycle. Therefore it is clearly shown that the "representative" tide is not representative anymore for the 100µm sand in the 3D model.

In order to save time, the tidal reduction for the selection of the representative tide is not redone for the 3D mode. Instead new hydraulic boundaries for a full spring-neap tidal cycle were generated by the NEVLA model, and imposed to the 3D N2V model together with the reduced wave climate presented in Table 2-2.

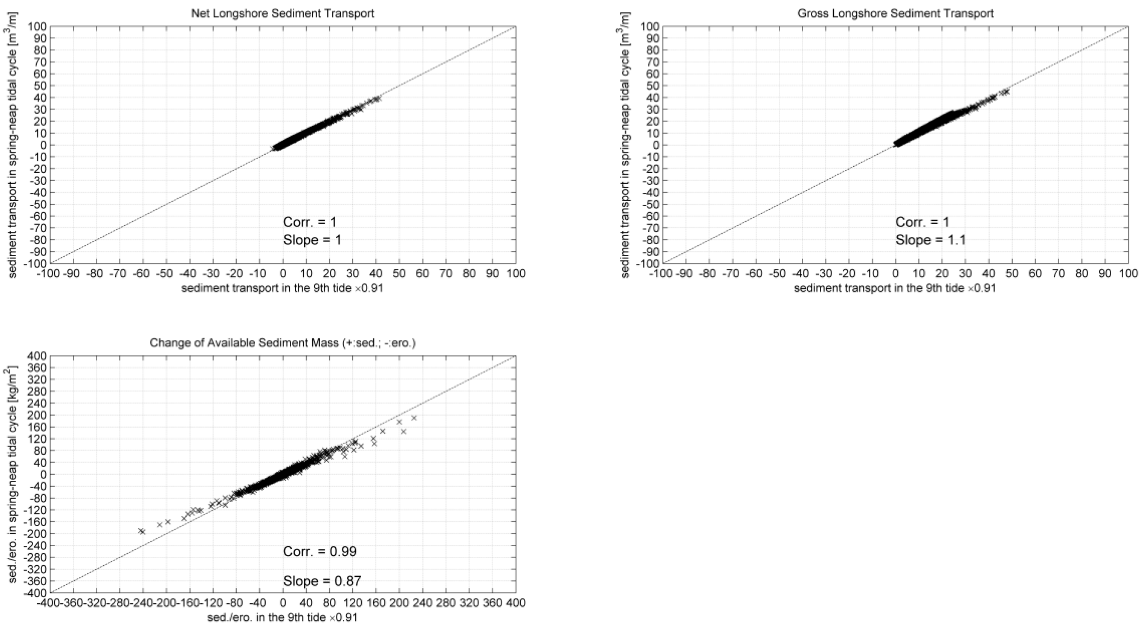

Figure 4-37: Comparison of net alongshore sediment transport (upper left),
gross alongshore transport (upper right) and initial erosion-sedimentation (lower left) between 14 representative tides (x axis) and the full neap-spring cycle (y axis), 200µm sand in the 2D OKNO model.

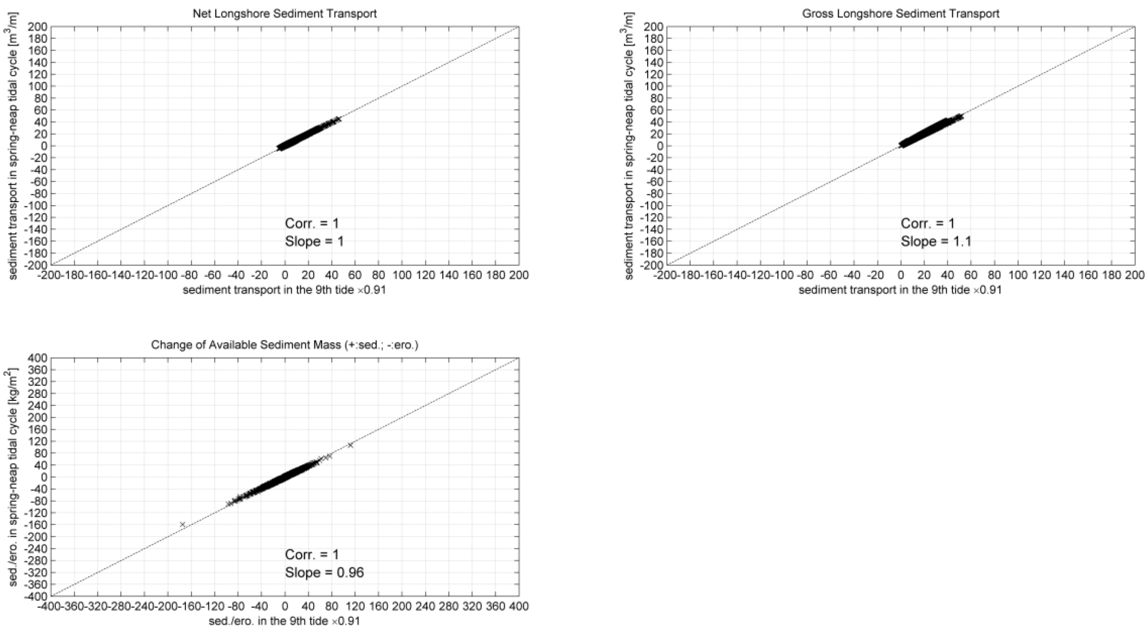

Figure 4-38: Comparison of net alongshore sediment transport (upper left),
gross alongshore transport (upper right) and initial erosion-sedimentation (lower left) between 14 representative tides (x axis) and the full neap-spring cycle (y axis), 100µm sand in the 2D OKNO model.

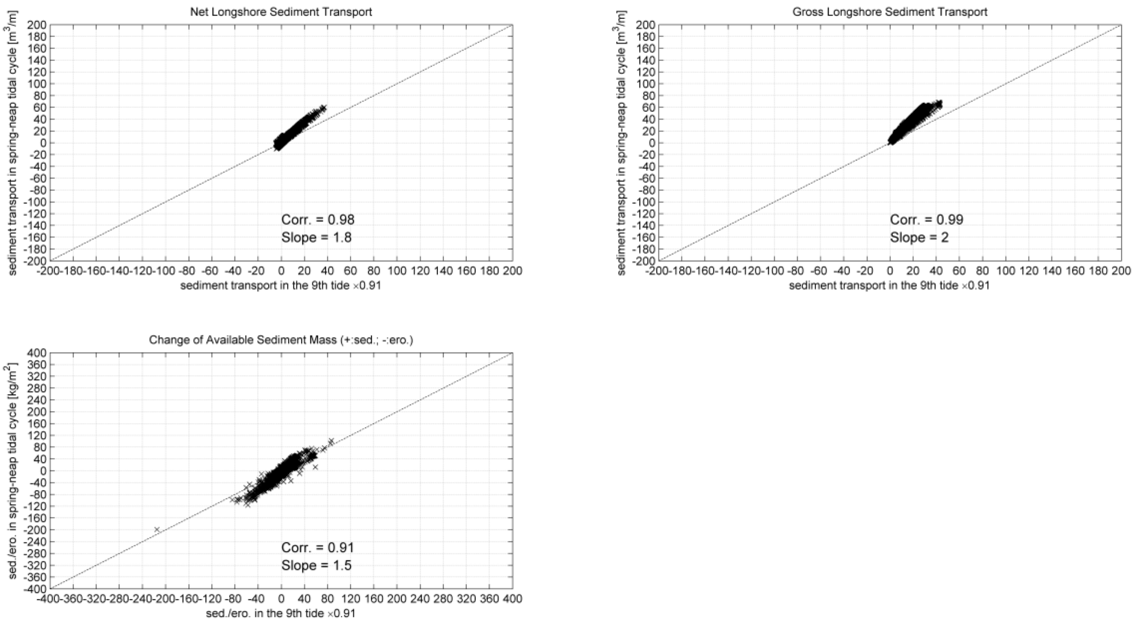

Figure 4-39: Comparison of net alongshore sediment transport (upper left), gross alongshore transport (upper right) and initial erosion-sedimentation (lower left) between 14 representative tides (x axis) and the full neap-spring cycle (y axis), 100µm sand in the 3D OKNO model.

4.9.3. Model settings

In the new 3D N2V model, three sediment fractions including 100, 200 and 350µm sands are employed for a better description of the variable natural condition. In order to simulate 10-year morphology change, the time-varying MorFac technique is applied. The whole simulation period consists of four spring-neap tidal cycles (4 x 14 x 1490min) in accordance with the four representative wave/wind conditions. Each wave/wind condition is imposed on one spring-neap tidal cycle (14 x 1490min) with a constant MorFac which is determined by the weighting factor of each wave/wind condition. Relevant model parameters set-up could be found in Table 4-4.

In addition, the 3D N2V model starts with an initial bed composition in which the three sediment fractions are uniformly distributed with an equal proportion of 1/3. The four wave/wind conditions SW125, N175, W175 and W275 are imposed on the four spring-neap tidal cycles sequentially.

Table 4-4: Summary of model parameters set-up

Parameter	Selected value
Time step	0.2 minute (12sec)
Vertical distribution of computational layers from surface to bottom	2%, 3%, 4.5%, 6.75%, 10%, 14.5%, 18.5%, 14.5%, 10%, 6.75%, 4.5%, 3%, 2%
Horizontal eddy viscosity	1 m^2/s
Horizontal eddy diffusivity	1 m^2/s
Background vertical eddy viscosity	0.000001 m^2/s
Background vertical eddy diffusivity	0.000001 m^2/s
Turbulence model	*k-epsilon*
Roughness-formulation	Manning

Manning-coefficient	0.022 $m^{-1/3}s$
Grain size	100µm, 200µm and 350µm
Transport formula	Van Rijn TRANSPOR2000
Morphological acceleration factor (MorFac)	107.2 (SW125), 48.7 (N175), 17.2 (W175), 5.5 (W275)
Spin-up time	1440 minutes
Threshold sediment thickness	0.2m
Factor for erosion of adjacent dry cells	1
Wave-related suspended transport factor	0.2
Wave-related bed-load transport factor	1
Maximum number of underlayers	10
Thickness of transport layer	0.1m
Thickness of stratigraphy layers	5.0m

4.9.4. Model results

Compared to the previous 2D N2V model with roughness map and uniform grain size of 100µm, the 3D N2V model appears to be more capable of producing the sedimentation at the Baai van Heist (Figure 4-40). In order to reveal the main mechanism producing such a sedimentation, the sedimentation/erosion maps in four wave/wind conditions are generated separately (Figure 4-41). It could be observed that the sedimentation at the Baai van Heist is completely formed in the N175 condition. Moreover, the frequent wave/wind conditions SW125 and N175 are shown to play a much more significant role in the morphology change than the less frequent conditions W175 and W275. It should particularly be mentioned that the morphology change in the W275 condition does not cover the full spring-neap tidal cycle (14 X 1490min) due to a crash of computation possibly from numerical instability, and only covers a half of the spring-neap tidal cycle (7 X 1490min). In view of the relatively small morphology change produced in the half of the spring-neap tidal cycle, the total morphology change produced in the full one would not make a considerable contribution to the 10-year morphology change.

In addition, the remarkable erosion observed in the surf zone and between the sedimentation areas in the 2D model seems to be effectively reduced in the 3D model. However, this is only a test run with a single set of parameters in 3D mode, thus it is still very hard to clarify the dominant processes which result in such a reduction.

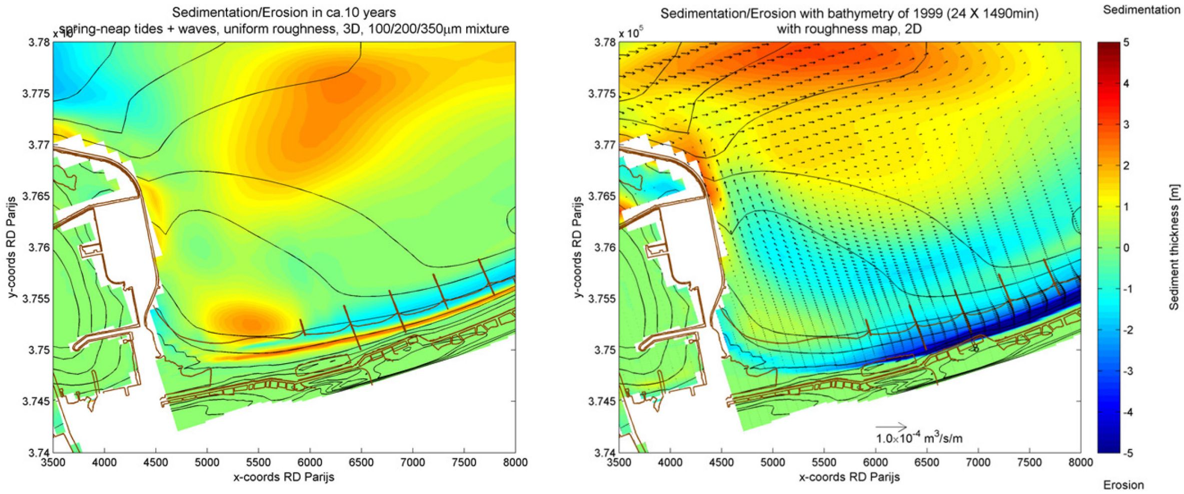

Figure 4-40: Comparison of 10-year sedimentation/erosion at the Baai van Heist between the 3D (left) and 2D (right) N2V model.

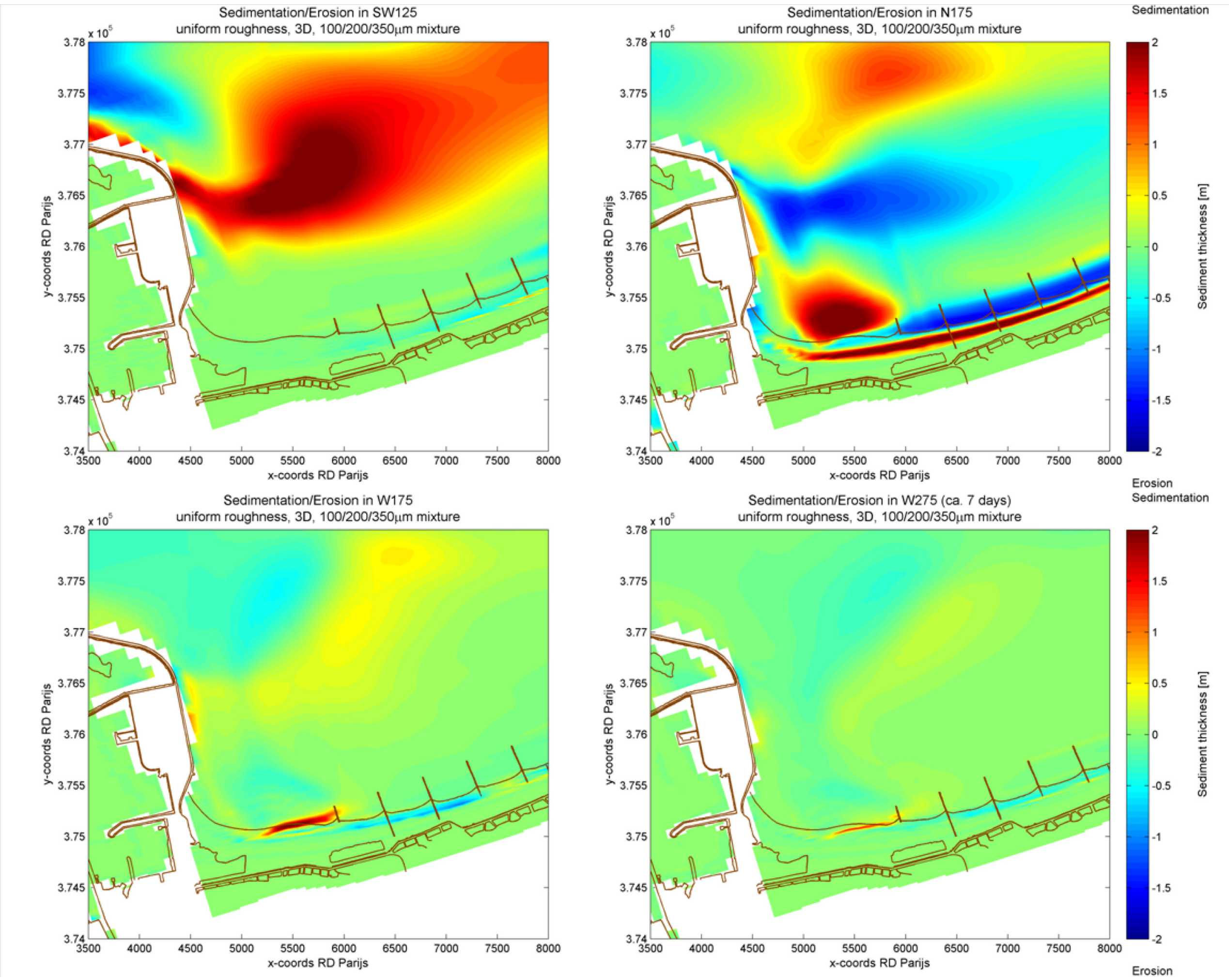

Figure 4-41: Sedimentation/erosion at the Baai van Heist in SW125 (upper left), N175 (upper right), W175 (lower left) and W275 (lower right).

The erosion and sedimentation volumes modelled over a period of 10 years (starting with the 1999-bathymetry) are shown in Table 4-5. Also the contribution of the 4 different wave conditions and the measured trend over the same period is shown. The results are given per coastal section, as shown in Figure 4-42.

Table 4-5: Modelled and measured erosion/sedimentation trends (in 1000 m^3/year)

	Baai van Heist	Duinbergen	Albertstrand	Knokke-Zoute	Knokke-Lekkerbek	Zwin
N175	57	-38	-49	-82	-34	-7
SW125	8	72	35	-62	-28	43
W175	1	14	-4	-28	-19	11
W275	-3	8	2	-7	-8	1
per year	63	56	-17	-179	-89	48
Measured trend	52.5	97	45	-54	-6	43

Figure 4-42 Defintion of coastal sections

From this table, it can be concluded that:

- The sedimention in Baai van Heist is predicted well.
- The erosion in Knokke (Zoute and Lekkerbek) is overestimated.(might be partly explained by the absence of groins in the model).
- The main contribution to the sedimentation is coming from the wave condition N175. (the only direction resulting in Eastward transport)

4.10. Conclusion

In this chapter four numerical models (OKNO, N2V, Zeebrugge and MU-HEIST) were introduced to investigate the specific issue regarding the sedimentation in the Baai van Heist. It is shown that satisfactory modelling results are unachievable in various trials of 2D mode, while the new 3D N2V model exhibits a promising result. A few conclusions are drawn below to give a valuable insight into this issue.

1. In general, the three internal models (OKNO, N2V and Zeebrugge) gave quite comparable results. The discrepancy is mainly caused by their boundary conditions selected from different time periods.
2. The hourly comparison shows that there is a quite good agreement of current velocities between the external model MU-HEIST and the internal model Zeebrugge. However compared with the measurement data presented in the report of the MU-HEIST model (Van den Eynde et al., 2007), the flood current next to the eastern dam of the Zeebrugge port is largely underestimated by both

models. If the measurement data is reliable, the sediment transported into Baai van Heist is also largely underestimated by the models.

3. In the study of the MU-HEIST model, it is addressed that the mud transport formula of Ariathurai-Partheniades is more suitable for the area around the Zeebrugge port than the sand transport formula. Then the sediment is only transported in suspension. Athough 0.0001m/s is not a realistic value for the fall velocity of the local sediment in sensitivity tests, the sedimentation produced at the Baai van Heist seems to be closer to the measurement data. However this model is only driven by tidal currents without taking any of wave effects into account, and additionally could be strongly flawed by the setup in which the whole domain is assumed to be covered by the mud with such a small settling velocity.
4. In the sensitivity tests with the Zeebrugge model the roughness map appears to be a simple and pragmatic way to produce more sedimentation in the Baai van Heist because the current velocity around the Zeebrugge port is increased and more sediment could be transported into the bay. However with the roughness map the 10-year flow-wave-morphology coupled 2D N2V model is still unable to reproduce sedimentation in the Baai van Heist properly.
5. Due to the fact that the representative tide is not representative anymore in 3D mode, the 3D N2V model is run with the full spring-neap tidal cycle (14 X 1490min). With the technique of time-varying MorFac and multiple sediment fractions, the flow-wave-morphology coupled 3D N2V model shows a quite good potential to reproduce the sedimentation in the Baai van Heist. In particular the N175 wave/wind condition is shown to play a dominant role in the formation of the sedimentation.

4.11. Outlook

Because of limited time, there has been only one test run with a single set of parameters in 3D mode. The 3D test run shows a strong potential to reproduce the sedimentation in the Baai van Heist. However, a deep and complete investigation requires further investigations in the future:

1. The wave climate applied in the 3D N2V model is actually from the existing representative wave climate, which is selected based on the runs driven by the representative tide. Firstly the 3D mode would give a different representative tide than the 2D one, and secondly based on the different representative tide, the wave reduction work has to be redone following the OPTI procedures. Considering the laborious work to reselect the representative wave climate for the 3D model with the OPTI method , the representative wave climate could be selected following the reduction method introduced in the study of Walstra et al. (2013).
2. By changing the N2V model from 2D to 3D mode, the undertow process can be simulated in the model, and accordingly the onshore transport should be also switched on in the 3D model. The parameters used for the wave-related onshore transport in the 3D N2V model are empirical values and not calibrated and validated at all. In order to have optimal cross-shore profiles in modelling of the long-term morphology change, the calibration of these parameters has to be carried out.
3. With the new reduced representative wave/wind conditions and calibrated parameters for the wave-related onshore transport, before starting modelling of the long-term morphology change an initial bed composition map would be created instead of the current one in which the 3 fractions of sediment (100, 200 and 350µm sand) are distributed uniformly.
4. The test run of the 3D N2V model demonstrates that the wave/wind condition N175 plays a quite significant role in the formation of sedimentation at the Baai van Heist. However, the information about grain size distribution in the Baai van Heist is very scarce and uncertain. In contrast with the sand transport driven by the combined forces of tides and waves in this study, the mud transport only driven by the tidal force was applied in some of other studies for this zone (Fettweis and Van den Eynde, 2003; Van den Eynde et al., 2007; Bi and Toorman, 2015). To obtain a correct understanding of the main natural processes, it is of great importance to find out the stratigraphic history of the sedimentation in the past 20 years through in-situ cores.

Conclusions

This reports describes the calibration of the Newport to Vlissingen morphodynamic model (N2V). The N2V model is an extended version of the OKNO model (Oostende to Knokke), it has the same objective of focusing on longshore transport in the surf zone. The same input reduction for waves and tide as for the OKNO model is applied. The model is validated against measured alongshore sand transport trends in the littoral zone.

In general the model is capable to reproduce at most beaches these trends fairly well. However, since Delft3D is not capable of modelling cross-shore transport in a 2DH mode, the model results should be considered with care in those zones or scenarios where strong cross-shore transports are believed to play a significant role, such as in the Baai van Heist and Knokke, and for bar migration. Also the morphology on the shelf is not validated.

The model shows poor behaviour at Baai van Heist as well. Different parameters and model settings were intensively tested in order to improve sedimentation properties near Baai van Heist. The model was compared to other similar models with high resolution for this region. However, it was concluded that none of the 2D models was capable of reproducing the sedimentation at Baai van Heist in a satisfying way. In addition, it was concluded that sedimentation is also strongly influenced by Northern wind- and wave conditions and spring tides. Therefore the representative tide seemed to be insufficient. A first attempt of a 3D version of the model showed strong potential to reproduce the sedimentation. However, setting up a full 3D model requires recalibration of the model in combination with a new input reduction procedure. Unfortunately, in combination with the fact that switching to 3D enlarges the CPU times severely, it was beyond the scope of the project to set up a fully calibrated 3D version of the model.

References

Bi, Q., Toorman, E.A. (2015). Mixed-sediment transport modelling in Scheldt estuary with a physics-based bottom friction law. Ocean Dynamics 65: 555-587.

De Maerschalck, B.; Vanlede, J.; Dujardin, A.; Verwaest, T.; Mostaert, F. (2015). Sediment Transport Model for the Port of Zeebrugge: Model set-up, Calibration, Validation. Version 1_0. WL Rapporten, 00_067. Flanders Hydraulics Research: Antwerp, Belgium

Fettweis M., Van den Eynde D. (2003). The mud deposits and the high turbidity in the Belgian–Dutch coastal zone, southern bight of the North Sea. Continental Shelf Research 23 (7): 669–691.

IMDC (2009). Afstemming Vlaamse en Nederlandse voorspelling golfklimaat op ondiep water – Deelopdracht 4: Technisch Wetenschappelijke Bijstand – Eindrapport (Dutch). Report number 09030, IMDC, Antwerp, Belgium.

Houthuys, R. 2012. Morfologische trends van de Vlaamse Kust in 2011 (in Dutch), Agentschap Maritieme dienstverlening en Kust, Afdeling Kust: Oostende, 150 pp.

Van den Eynde, D.; Kerckhof, F.; Francken, F.; Haelters, J.; Lauwaert, B. (2007). Ontwikkeling van de zandbank ter hoogte van Heist: Eindrapport. Management Unit of the North Sea Mathematical Models: Brussels, Belgium. Ref. ZAHE/1/DVDE/200710/NL/ER.

Verheyen, B.; Vanlede, J.; Decrop, B.; Verwaest, T.; Mostaert, F. (2013). Verbetering randvoorwaarden-model: Deelrapport 5 – Actualisatie van het 3D Scheldemodel. Version 2_0. WL Rapporten, 00_018. Flanders Hydraulics Research & IMDC: Antwerp, Belgium.

Walstra, D.J.R., Hoekstra, R., Tonnon, P.K., Ruessink, B.G. (2013). Input reduction for long-term morphodynamic simulations in wave-dominated coastal settings. Coastal Engineering 77: 57–70.

Zimmermann, N.; Wang, L.; Mathys, M.; Trouw, K.; Delgado, R.; Toro, F.; Verwaest, T.; Mostaert, F. (2012). Scientific support regarding hydrodynamics and sand transport in the coastal zone: Calibration of the Oostende-Knokke hydrodynamic and sediment transport model (OKNO). Version 1_0. WL Rapporten, 744_30. Flanders Hydraulics Research & IMDC: Antwerp, Belgium. Ref. IMDC I/RA/11355/12.098/NZI.

Zimmermann, N.; Wang, L.; Trouw, K.; Vanlede, J.; De Maerschalck, B.; Verwaest, T.; Mostaert, F. (2013a). Toegankelijkheid haven Blankenberge: Optimalisatie van de haveningang. Versie 4.0. WL Rapporten, 00_063. Waterbouwkundig Laboratorium & IMDC: Antwerp, Belgium. Ref. IMDC I/RA/11355/13.221/NZI/NZI.

Zimmermann, N.; Wang, L.; Delecluyse, K.; Suzuki, T.; Trouw, K.; De Maerschalck, B.; Vanlede, J.; Verwaest, T.; Mostaert, F. (2013b). Energy atolls along the Belgian coast: Effects on currents, coastal morphology and coastal protection. Version 5.0. WL Rapporten, 13_105. Flanders Hydraulics Research & IMDC: Antwerp, Belgium. Ref. IMDC: I/RA/11355/13.222/LWA/NZI.

Zimmermann, N.; Trouw, K.; De Maerschalck, B.; Toro, F.; Verwaest, T.; Mostaert, F. (2014). Scientific support regarding hydrodynamics and sand transport in the coastal zone: Evaluation of XBeach for long term cross-shore modelling. Version 1_0. WL Rapporten, 744_30. Flanders Hydraulics Research & IMDC: Antwerp, Belgium. Ref. IMDC: I/RA/11355/12.050/MIM/NZI.

Annex A – Model grids and bathymetry

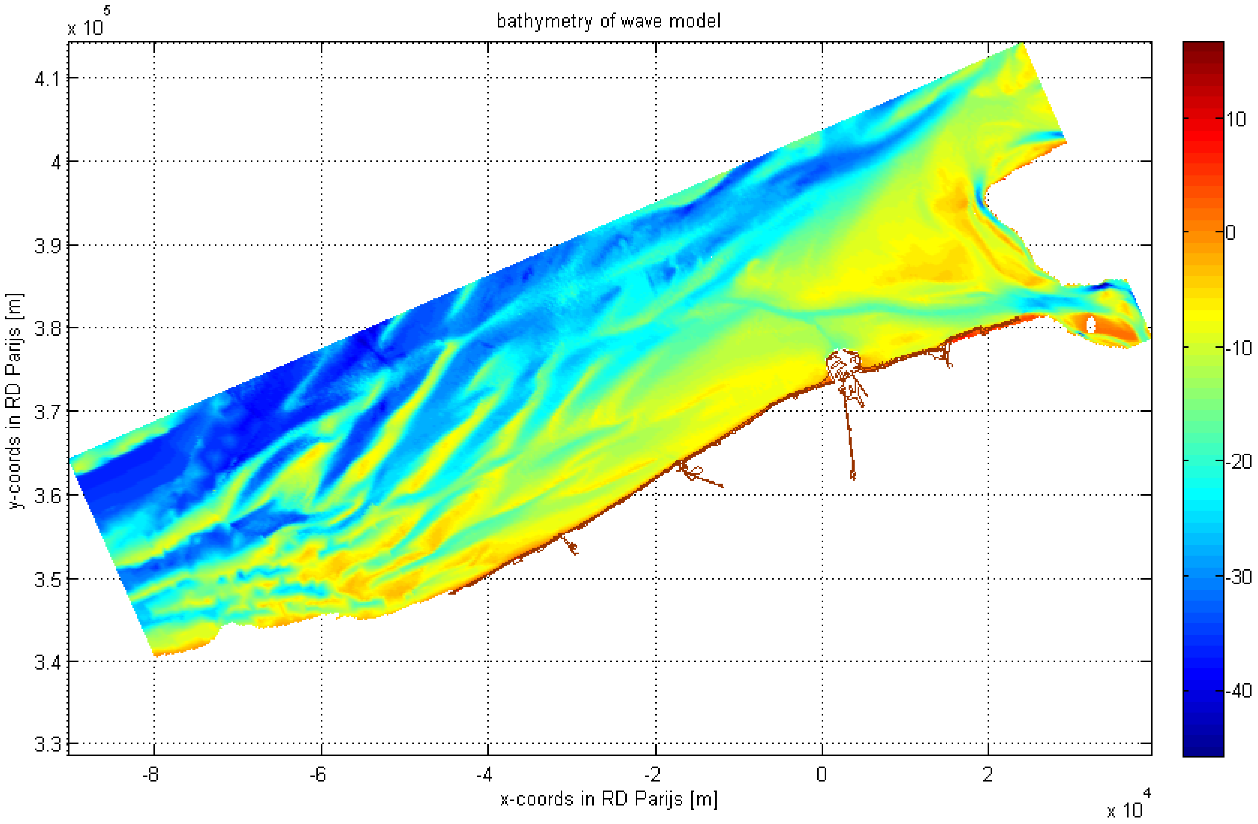

Figure A-1: Bathymetry of the model used for the wave calculations, covering the entire Belgian coast (IMDC, 2009).

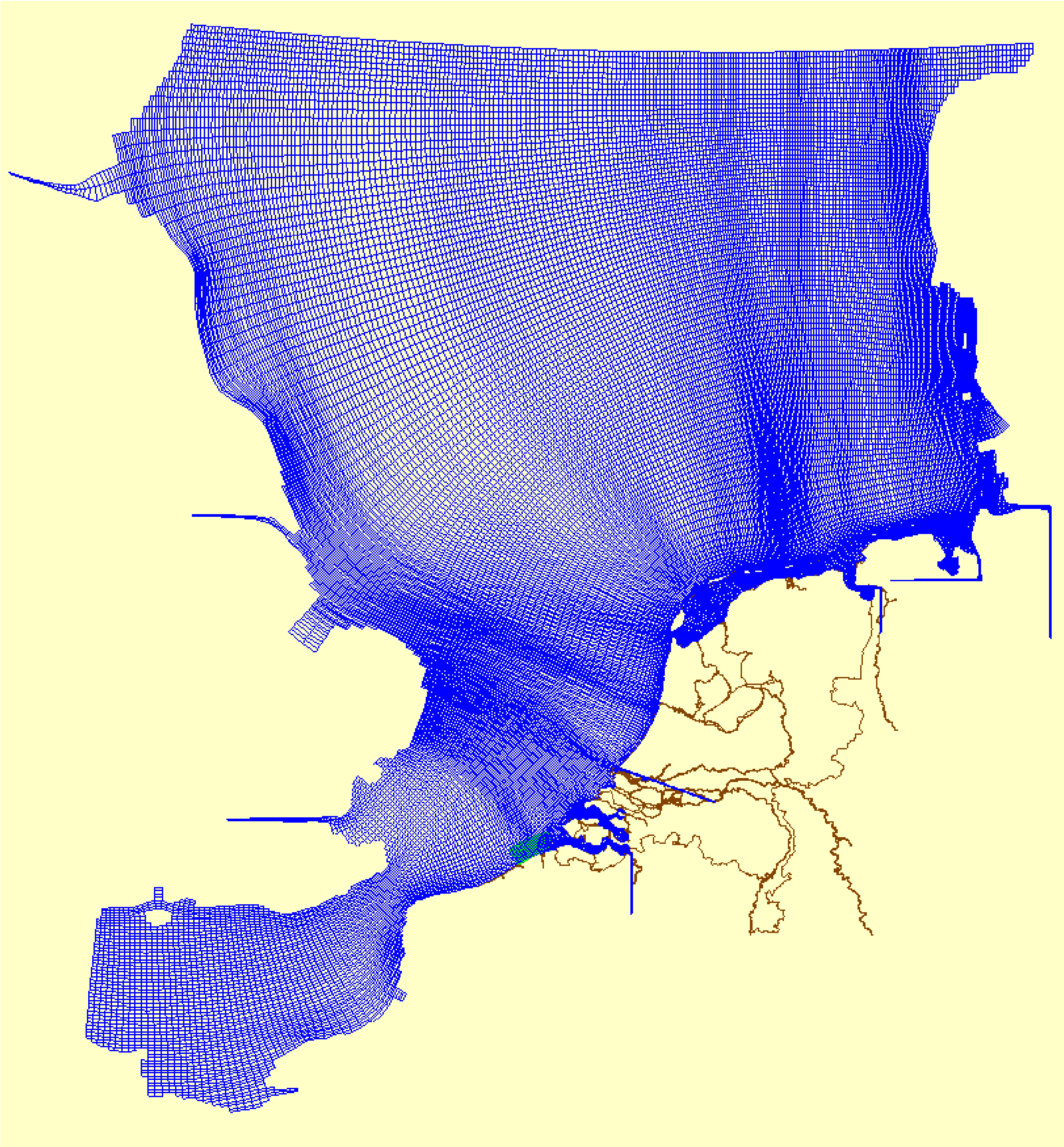

Figure A-2: Extent of the Zuno model (blue) used to generate flow boundary conditions for the OKNO model (green).

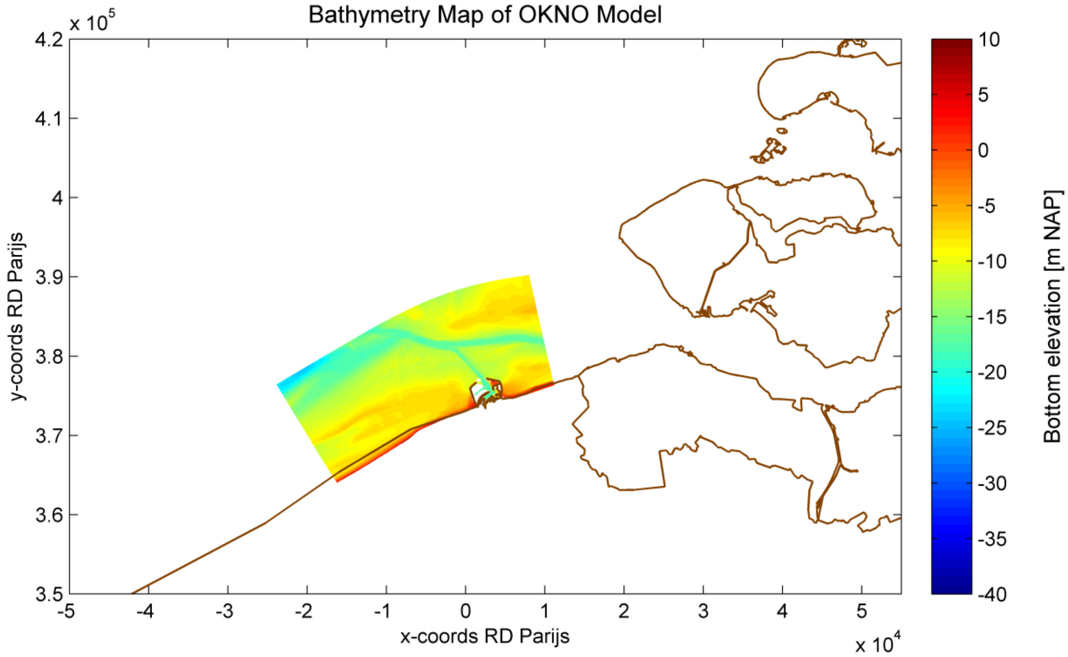

Figure A-3: Extent and bathymetry of the OKNO model.

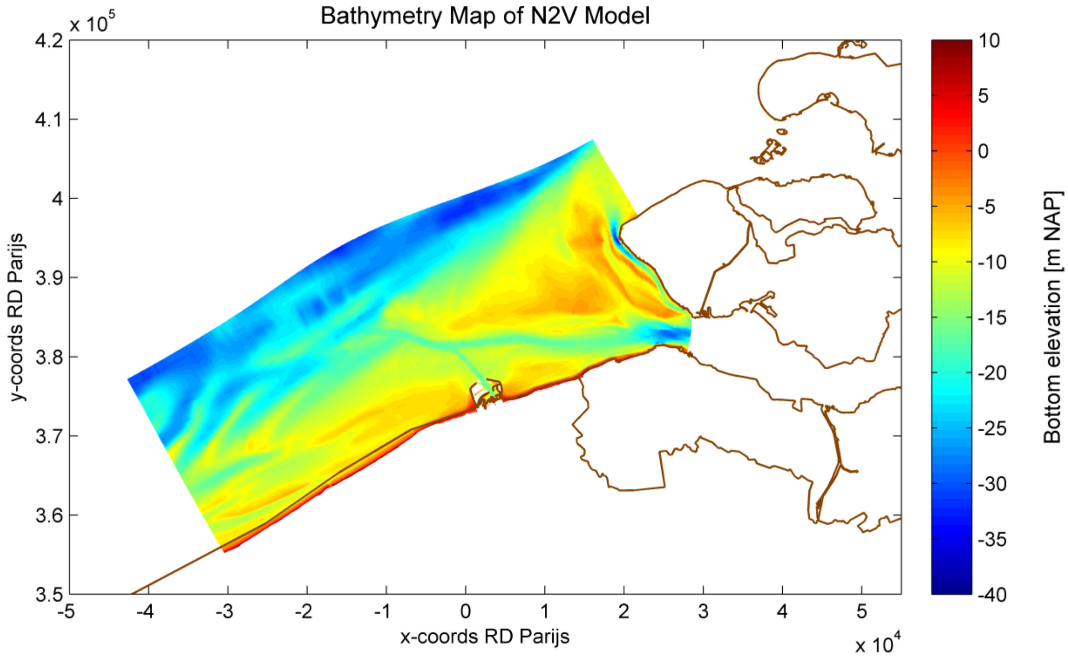

Figure A-4: Extent and bathymetry of the N2V model.

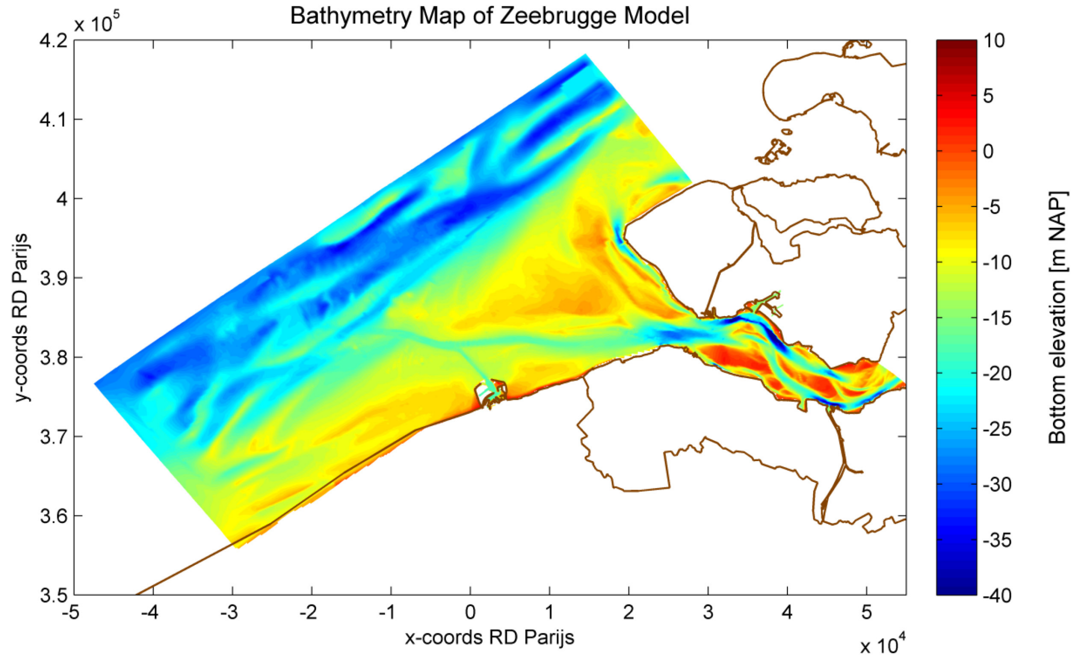

Figure A-5: Extent and bathymetry of the Zeebrugge model.

Annex B – Hourly comparison of velocity vectors between the MU-HEIST model and the Zeebrugge model

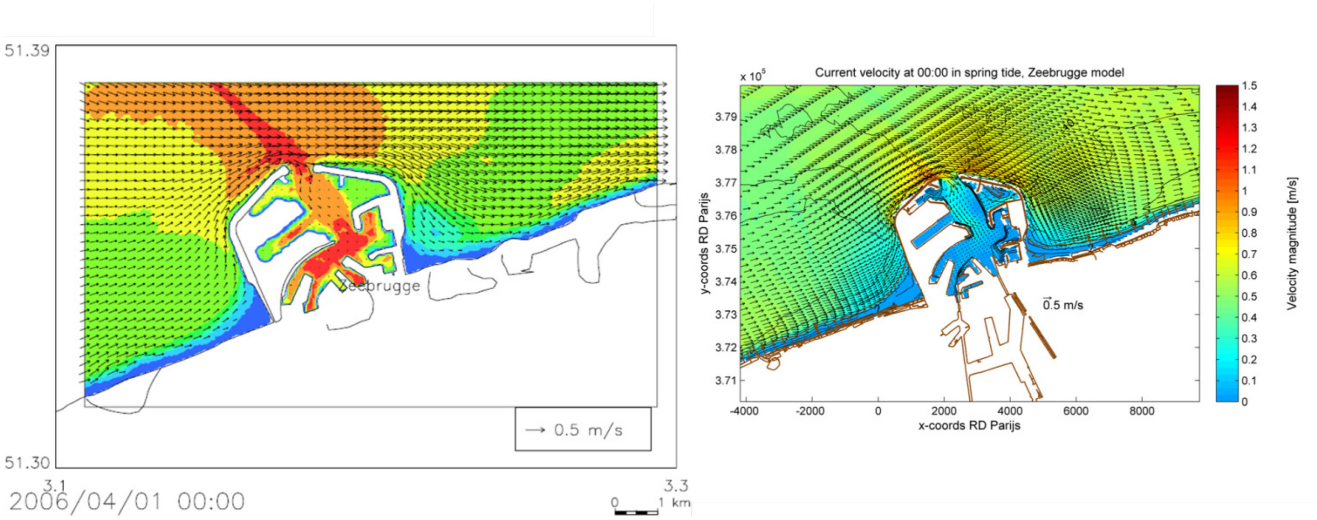

Figure B-1: Current velocity at 00:00 (left: MU-HEIST*; right: Zeebrugge).

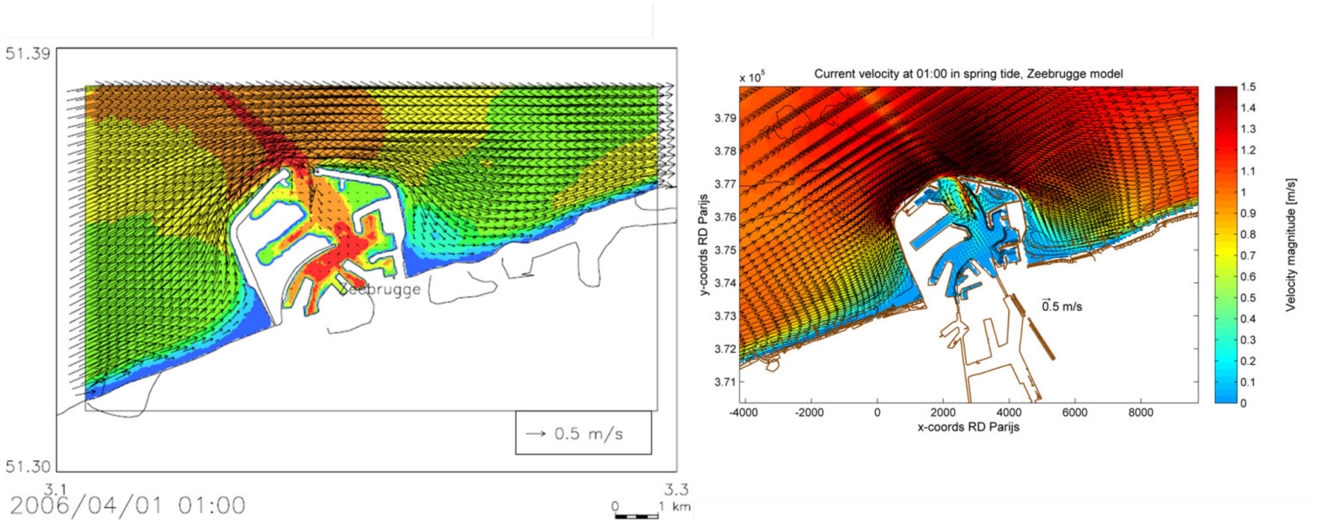

Figure B-2: Current velocity at 01:00 (left: MU-HEIST*; right: Zeebrugge).

*: in the MU-HEIST model the contour as background represents bathymetry rather than magnitude of the velocity, whereas in the Zeebrugge model the contour represents magnitude of the velocity.

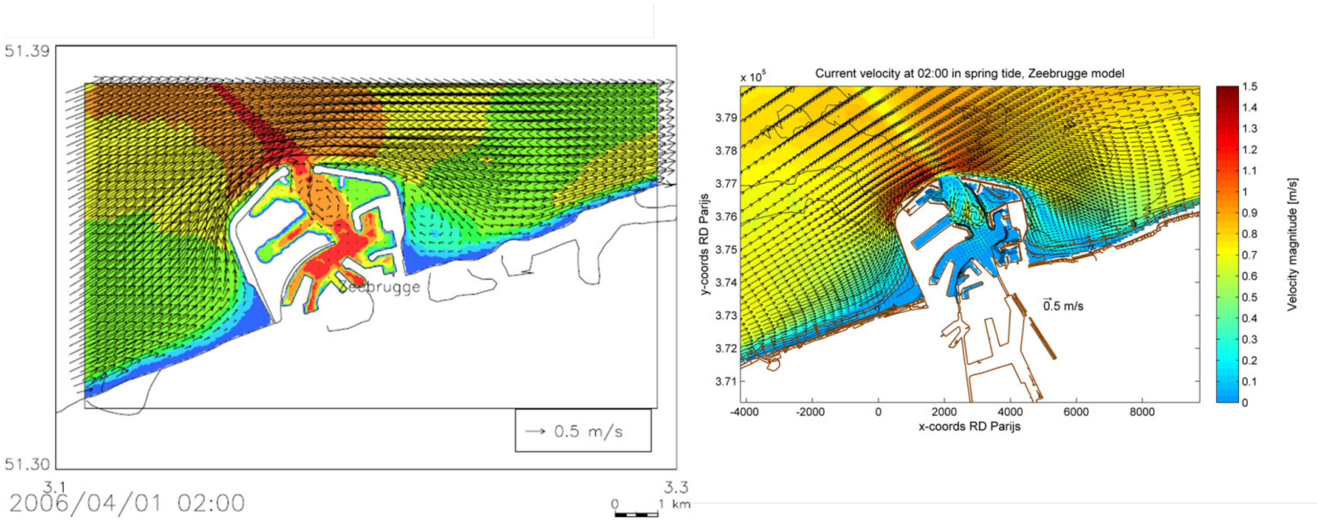

Figure B-3: Current velocity at 02:00 (left: MU-HEIST*; right: Zeebrugge).

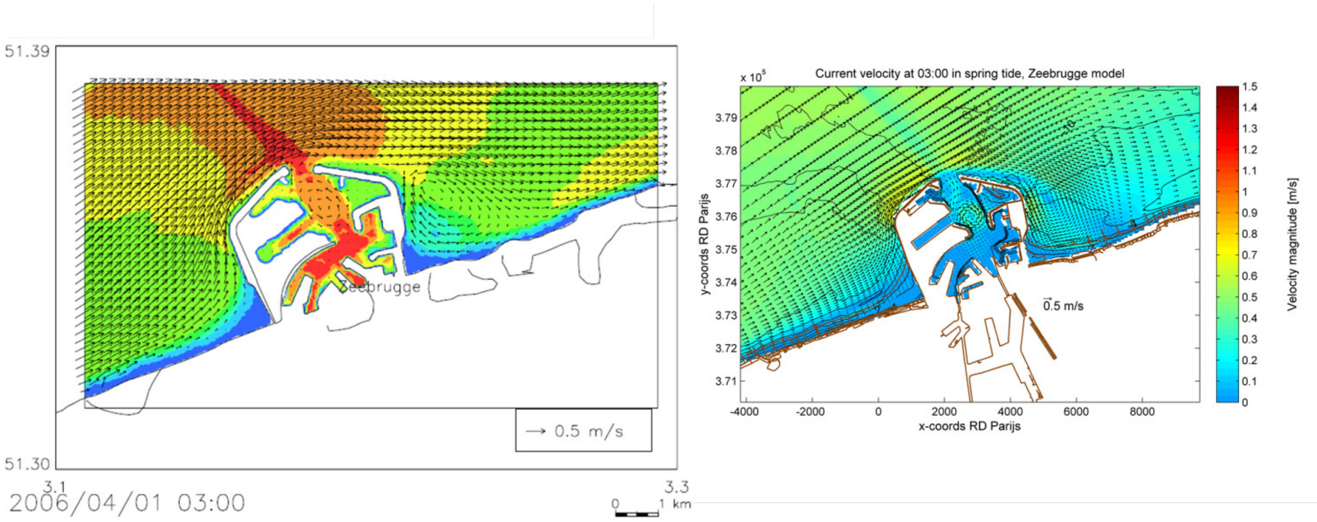

Figure B-4: Current velocity at 03:00 (left: MU-HEIST*; right: Zeebrugge).

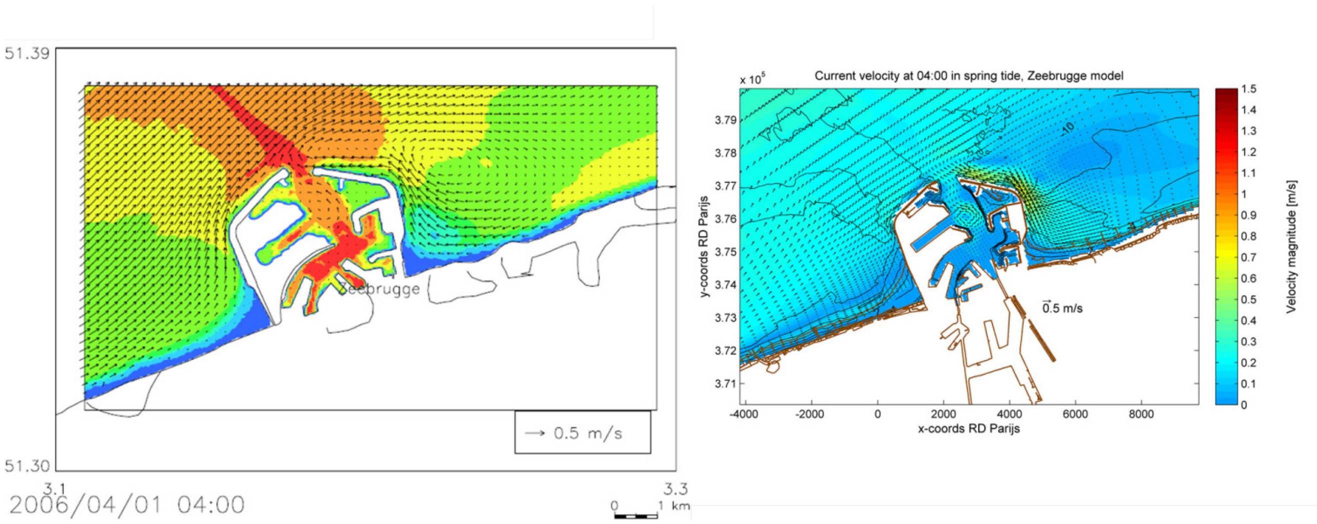

Figure B-5: Current velocity at 04:00 (left: MU-HEIST*; right: Zeebrugge).

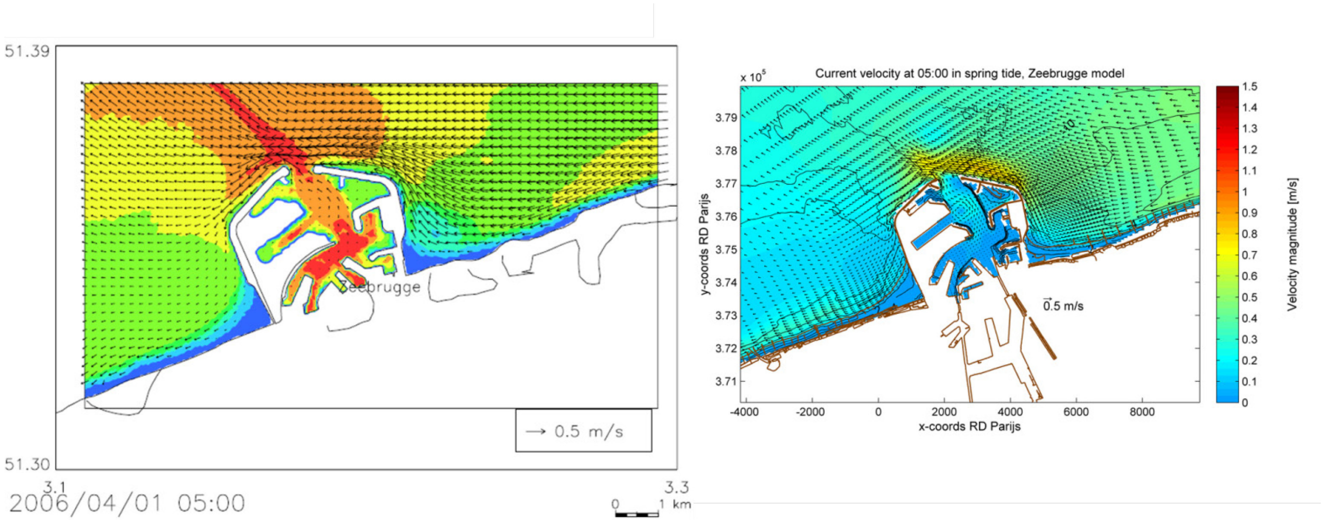

Figure B-6: Current velocity at 05:00 (left: MU-HEIST*; right: Zeebrugge).

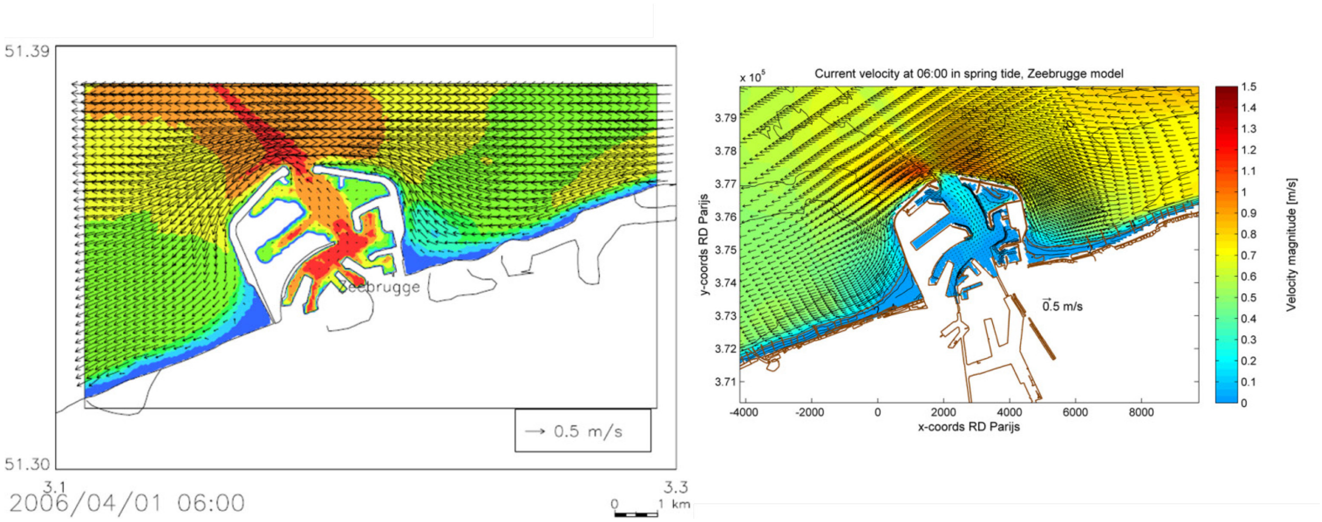

Figure B-7: Current velocity at 06:00 (left: MU-HEIST*; right: Zeebrugge).

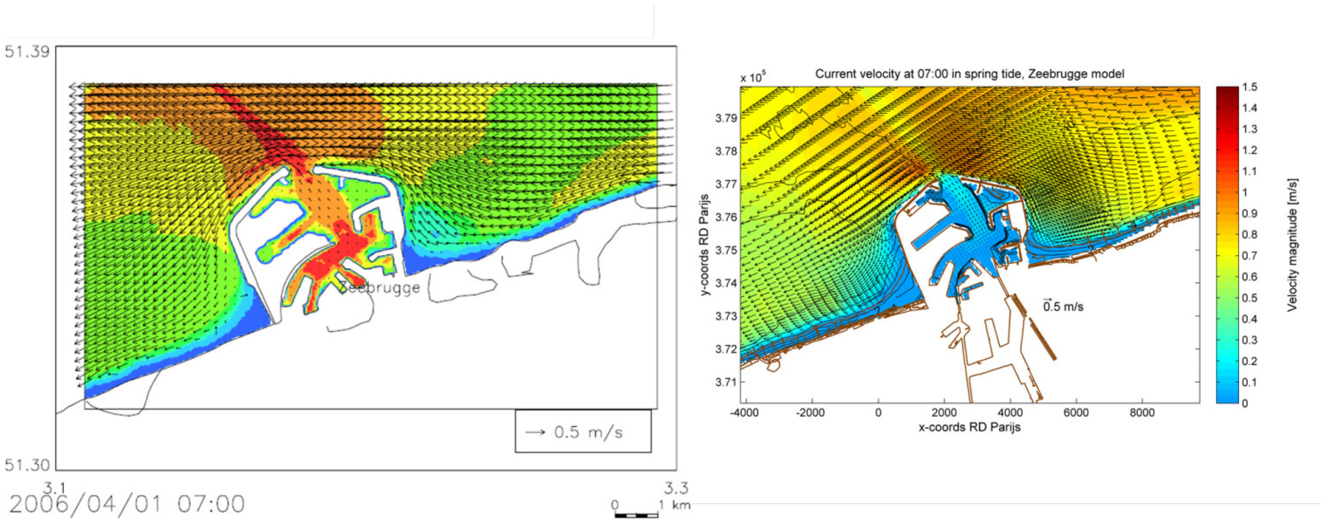

Figure B-8: Current velocity at 07:00 (left: MU-HEIST*; right: Zeebrugge).

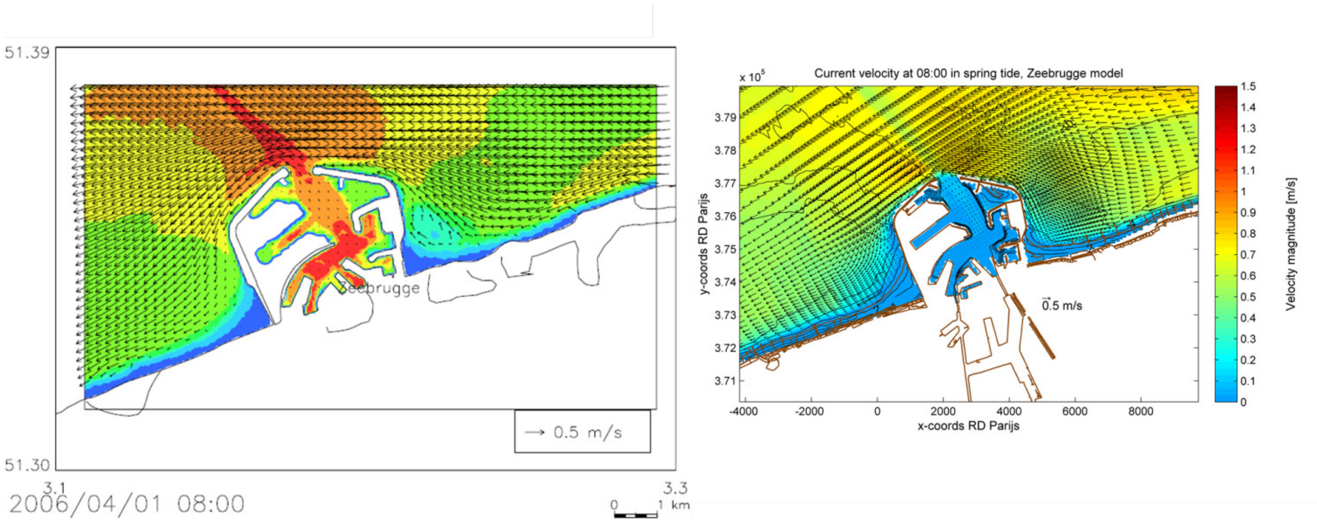

Figure B-9: Current velocity at 08:00 (left: MU-HEIST*; right: Zeebrugge).

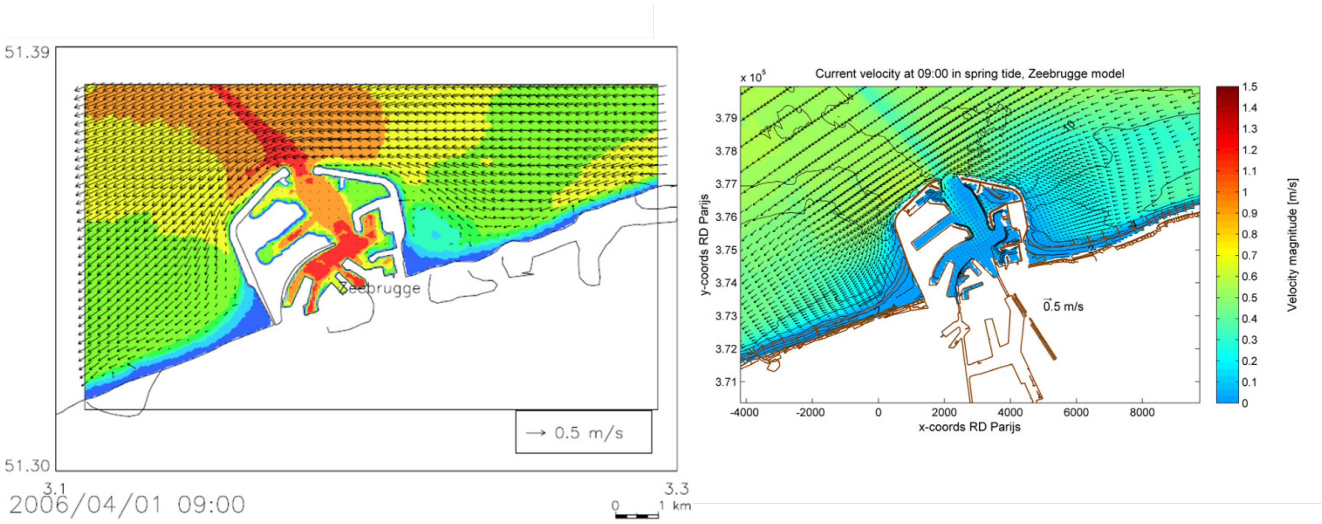

Figure B-10: Current velocity at 09:00 (left: MU-HEIST*; right: Zeebrugge).

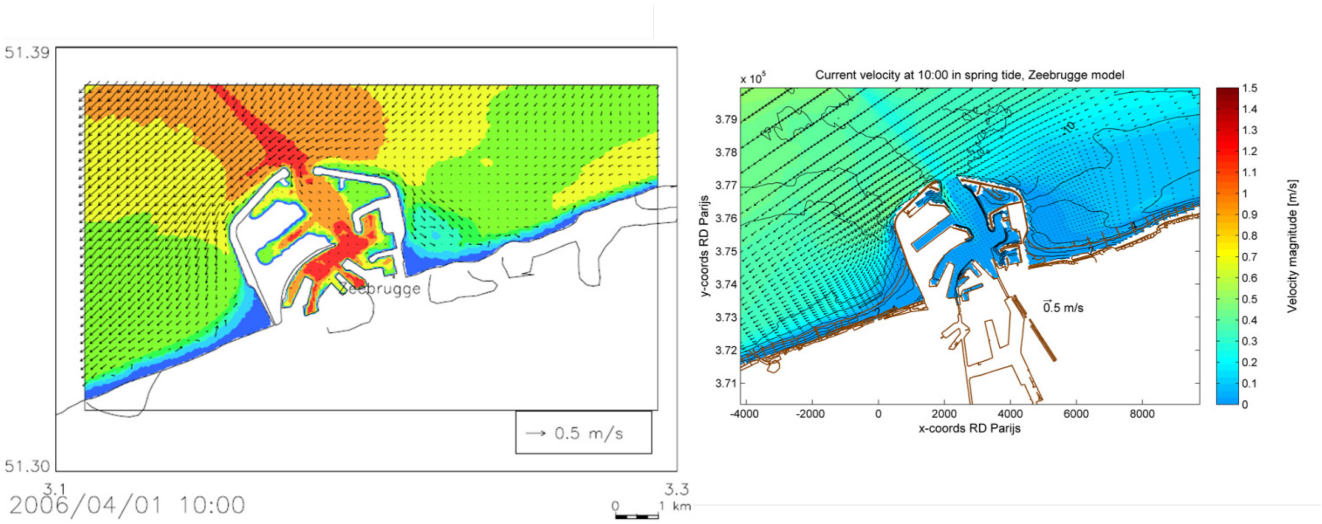

Figure B-11: Current velocity at 10:00 (left: MU-HEIST*; right: Zeebrugge).

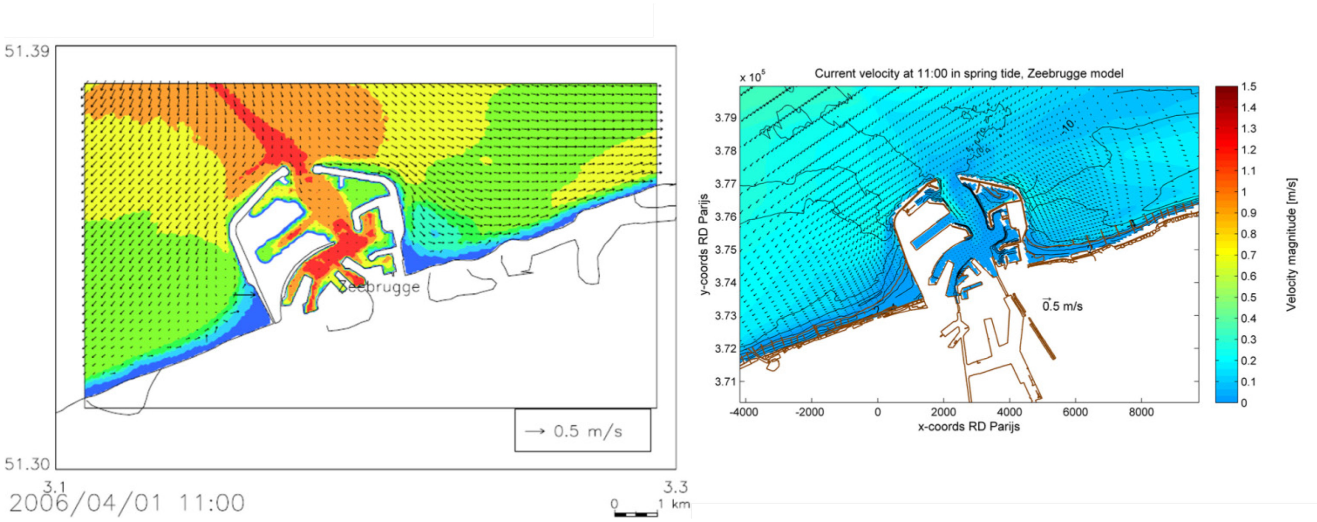

Figure B-12: Current velocity at 11:00 (left: MU-HEIST*; right: Zeebrugge).

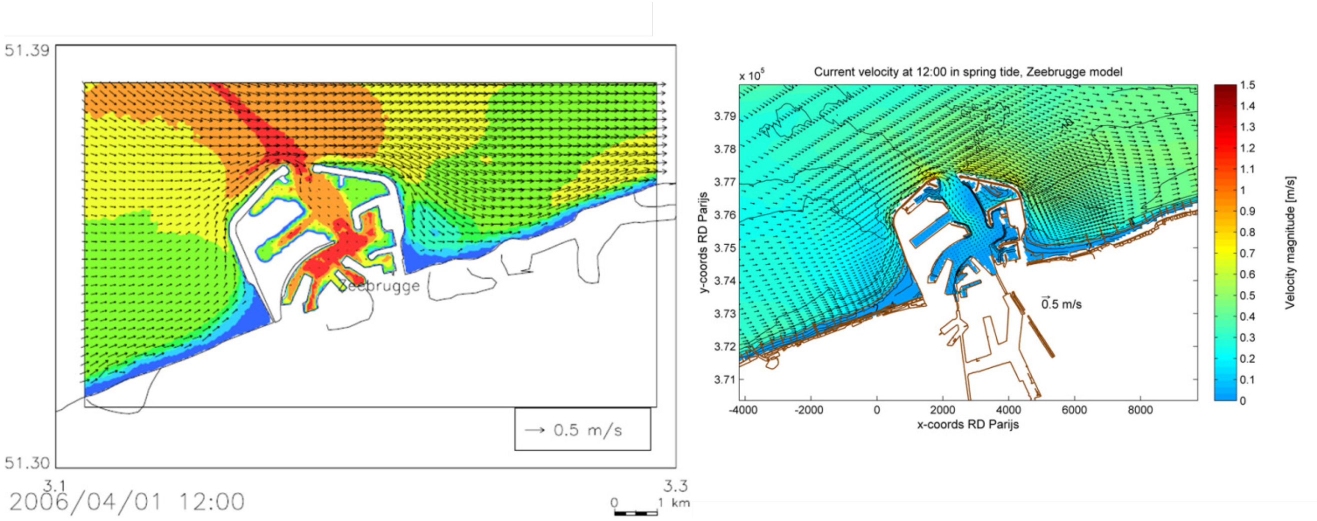

Figure B-13: Current velocity at 12:00 (left: MU-HEIST*; right: Zeebrugge).

Waterbouwkundig Laboratorium

Flanders Hydraulics Research

Berchemlei 115
B-2140 Antwerp
Tel. +32 (0)3 224 60 35
Fax +32 (0)3 224 60 36
E-mail: waterbouwkundiglabo@vlaanderen.be
www.waterbouwkundiglaboratorium.be