LTV-O&M thema Veiligheid

Deelproject 1
VERBETERING HYDRODYNAMISCH NEVLA MODEL TEN BEHOEVE VAN SCENARIO-ANALYSE

756_05 WL Rapporten

www.watlab.be

LTV O&M thema Veiligheid

Deelproject 1: Verbetering hydrodynamisch NEVLA model ten behoeve van scenario-analyse

Maximova, T.; Ides, S. ; Vanlede, J.; De Mulder, T.; Mostaert, F.

November 2009

WL2009R756_05_rev2_0

This publication must be cited as follows:

Maximova, T.; Ides, S.; De Mulder, T.; Mostaert, F. (2009). LTV O&M thema Veiligheid - Deelproject 1: Verbetering hydrodynamisch NEVLA model ten behoeve van scenario-analyse. WL Rapporten, 756_05. Flanders Hydraulics Research & Deltares: Antwerp, Belgium

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.watlab.be

Document identification

Title:	LTV O&M thema Veiligheid : Deelproject 1: Verbetering hydrodynamisch NEVLA model ten behoeve van scenario-analyse		
Customer:	Ministerie van Verkeer en Waterstaat	Ref.:	WL2009R756_05_rev2_0
Keywords (3-5):	LTV Veiligheid, numerical model, Scheldt estuary		
Text (p.):	32	Tables (p.):	7
Appendices (p.):	/	Figures (p.):	69

Confidentiality:	☐ Yes	Exceptions	☐ Customer
			☐ Internal
			☐ Flemish government
		Released as from	
	☒ No		☒ Online available

Approval

Author	Reviser	Project leader	Division Head
ir. Tatiana Maximova	ir. Joris Vanlede	ir. Stefaan Ides	Dr. Frank Mostaert

Revisions

Nr.	Date	Description	Author
1_0	27/02/2009	Concept version	Maximova, T.
1_1	20/03/2009	Substantive revision	Ides, S.
1_2	28/09/2009	Revision customer	Kuijper, C.
2_0	23/11/2009	Final version	Maximova, T.

Abstract

In the framework of different projects, among which "LTV O&M thema Veiligheid - Deelproject 1" and "LTV O&M thema Toegankelijkheid - Ontwikkeling van een slibtransportmodel", a calibration of the existing hydrodynamic NEVLA model of the Scheldt estuary is executed. This report gives a summary of all the steps which are undertaken to improve the model.

The objective of the study "LTV O&M thema Veiligheid -- Deelproject 1" is to analyze the effect of different changes and their influence on the hydrodynamics of the estuary. Based on a literature review and data analysis some hypotheses concerning the change in tidal penetration in the estuary will be made. Afterwards these hypotheses will be verified with numerical models. In order to obtain reliable results, it is necessary that the numerical model performs well. Therefore a sensitivity analysis, a calibration and a validation of the NEVLA model, which will be used for 2D-3D hydrodynamic simulations, were carried out.

The objective of the sensitivity analysis was to understand the impact of different model parameters on the tidal penetration. The results of this analysis are described in (Ides et al., 2008) and (Vanlede et al., 2008a). In (Vanlede et al., 2008b) the calibration was performed for the calculated water levels and discharges, based on the phase and magnitude of the most important harmonic tidal components of these parameters. In (Maximova et al., 2009) the calibration of the NEVLA model was extended. The resulting model parameters from (Vanlede et al., 2008b) were used as the reference simulation. The methodology was based on the comparison of phase and magnitude of the calculated and measured high and low water levels. This extended calibration was mainly focused on the Upper Sea Scheldt and the tributaries Zenne and Dijle because in these regions the differences between calculated and measured water levels were the largest. As a result of the calibration, the accuracy of the model for high water levels and low water levels was improved for most stations along the Scheldt estuary.

The calibrated model was validated for a period with normal tide and for a period with an extreme high water. The calibrated model performs rather well for a period with normal tide. However, it does not simulate accurately a period with an extreme high water level. The reason for this and the possibilities to improve the model accuracy for such circumstances should be studied more in the future.

The roughness field used for the calibrated model is strongly related to the bathymetry that was used during calibration of the model. If we use a different bathymetry for the scenario analysis the roughness field might change as well. Therefore, a simple roughness field without variation in the transversal direction was found, which gives rather similar results as the calibrated model with the space varying roughness field.

Contents

List of tables

List of figures

1 Introduction

During the passed centuries the tidal regime of the Scheldt estuary has seriously changed. There are many factors that contributed to this evolution, such as land reclamation, enlargement of the navigation channel, permanent withdrawal of sand from the estuary for different purposes, changed tidal conditions in the North Sea, etc. The objective of the study “LTV O&M thema Veiligheid - Deelproject 1” is to analyze the effect of different changes and their influence on the hydrodynamics of the estuary. Based on a literature review and data analysis some hypotheses concerning the change in the tidal penetration in the estuary will be made. Afterwards these hypotheses will be verified with numerical models. In order to obtain reliable results, it is necessary that the numerical model performs well. Therefore a sensitivity analysis and a calibration of the NEVLA model, which will be used for 2D-3D hydrodynamic simulations, were carried out. The effort of this model calibration was carried out in the framework of different projects, among which “LTV O&M thema Veiligheid - Deelproject 1” and “LTV O&M thema Toegankelijkheid - Ontwikkeling van een slibtransportmodel”.

This report gives a summary of all the steps which are undertaken to improve the model. All different steps of the sensitivity analysis and the calibration process are described in detail in separate reports. The objective of the sensitivity analysis was to understand the impact of different model parameters on the tidal penetration. The results of this analysis are described in (Ides et al., 2008) and (Vanlede et al., 2008a). In (Vanlede et al., 2008b) the calibration was performed for the calculated water levels and discharges, based on the phase and magnitude of the most important harmonic tidal components of these parameters. The model was calibrated for the year 2006. In (Maximova et al., 2009) the calibration of the NEVLA model was extended. The resulting model parameters from (Vanlede et al., 2008b) were used as the reference simulation. However, the methodology of analysis was different in (Maximova et al., 2009). It was based on the comparison of the phase and magnitude of the calculated and measured high and low water levels. The tidal components of the water levels were not considered. This extended calibration was mainly focused on the Upper Sea Scheldt and the tributaries Zenne and Dijle because in these regions the differences between calculated and measured water levels were the largest.

2 Units and reference plane

Time is expressed in MET (Mean European Time).

Depth, height and water levels are expressed in meter NAP (Normaal Amsterdams Peil). A bathymetric depth is positive below the reference plane, water levels are positive above the reference plane.

The horizontal coordinate system used for the model is RD Parijs.

3 The numerical model

SIMONA (Simulatie Modellen Natte waterstaat) is a numerical model developed by Rijkswaterstaat the Netherlands. It describes hydrodynamic processes. SIMONA is a program for 2D and 3D modelling of water movement (Adema, 2006).

At Flanders Hydraulics Research the NEVLA model was developed for the Western Scheldt, the Sea Scheldt and connected Flemish rivers. The results of simulations of this model were used for analysis in this report. The model was developed in the SIMONA software and it includes a broad sea area and all Flemish tidal rivers, such as Schelde, Durme, Rupel, Nete (Beneden, Grote and Kleine), Dijle and Zenne. These rivers are represented until their tidal border.

The study area is shown on Figure 1. Figure 2 presents the grid of the NEVLA model.

4 Available data from measurements

Data from measurements had to be used for both sensitivity analysis and model calibration described in this report. A short description of the data used in this project is given here. More detailed description of the data can be found in (Vanlede et al., 2008a).

4.1 Boundary conditions

The NEVLA model has several upstream boundaries. At these upstream boundaries daily averaged discharges are measured at the following stations: Grobbendonk (Kleine Nete), Itegem (Grote Nete), Eppegem (Zenne), Haacht (Dijle), Dendermonde (Dender) and Merelbeke (Bovenschelde en Leie). These discharges are available from the Hydrometry department of Flanders Hydraulic Research. Furthermore, in (Ides et al., 2008) it was analyzed what is the effect of the use of more frequent time series of discharges at Merelbeke.

The downstream boundary of the NEVLA model as it is used in this study is defined by the line Westkapelle - Cadzand. As a consequence the measured water levels from Cadzand and Westkapelle can be used as boundary conditions. However, because of the orientation of the grid at the downstream boundary on the one hand and because of the fact that the downstream boundary needs to coincide with a grid line at the other hand, the used sea boundary does not coincide with the real boundary Cadzand - Westkapelle. The station Westkapelle is located on the boundary; however the model boundary at the left bank is located between Cadzand and Zeebrugge (Figure 3). At the boundary location between Cadzand and Zeebrugge the measured water level of Cadzand is used, with a phase shift related to the distance between these two locations. This phase shift was studied in (Maximova et al., 2009).

4.2 Topo-bathymetry

A topo-bathymetric survey of a river produces a field of points where the depth of each point is known. However, location of the topo-bathymetric measurement points can differ from the grid points of the numerical model. Therefore, it is necessary to use interpolation in order to calculate the depth for each grid point. Different interpolation techniques exist that can be used to change measured bathymetric data to the model bathymetry with a certain depth value per calculation point. These techniques were analyzed during the sensitivity analysis in (Vanlede et al., 2008a).

In the NEVLA model new bathymetric data are used. These are obtained on the basis of the most recent topo-bathymetric measurements of the modeled area:

- The Upper Sea Scheldt, Rupel and Durme: Single Beam measurements from 2001;
- The Lower Sea Scheldt: Single Beam measurements from 2004-2005;
- The Western Scheldt: Single Beam measurements from 2006, LIDAR survey of intertidal and supralitoral areas from 2003;
- The mouth area of the Western Scheldt: Single Beam measurements from 2003.

4.3 Wind

Wind is included in some model runs during the sensitivity analysis and calibration. Wind data are available from the Hydro Meteo Centrum Zeeland (HMCZ) database. The wind data measured at certain station are imposed in some simulations as a uniform wind field influencing the whole model area. This data consist of wind magnitude (10 minute average value) and direction (10 minute average value in degrees towards North). The sensitivity of the model to the use of wind was studied in (Vanlede et al., 2008a).

4.4 Water levels

For the model calibration it is necessary to compare the simulation results with the measurements. 10 minute time series of measured water levels (in m NAP) are available from the Hydro Meteo Centrum Zeeland (HMCZ) database for the stations on the Dutch territory and some Belgian stations. 1 minute time series of measured water levels (in m TAW) are available from the Hydrologic Information Centre (HIC) database for the Belgian stations.

Water levels measured in m TAW were converted to m NAP as follows: NAP = TAW - 2.33m. The time series from the HIC database were shifted by one hour in order to express all time series in MET. The measurement data from the HIC datasource are unvalidated data, as retrieved from the AOSO measurement stations in the Sea Scheldt. The HIC measurements can therefore have an (unknown) bias.

More detailed information about water level stations used for the calibration can be found in (Vanlede et al., 2008b) and (Maximova et al., 2009).

5 Sensitivity analysis

The sensitivity analysis of the NEVLA model was performed in order to understand the impact of different model parameters (bathymetry, boundary conditions, bed roughness, …) on the model results. The sensitivity analysis was performed in (Ides et al., 2008) and (Vanlede et al., 2008a).

The effect of the changes was analyzed based on the water levels, phase and magnitude of the most important harmonic components, discharges and distribution of the flow in the flood and ebb channels. The results of the reference simulation were compared with a simulation where only one of the parameters was changed. The results of the sensitivity analysis give necessary information for the model calibration. Furthermore, this information can be useful for other model applications in the Scheldt estuary.

The sensitivity analysis of the 2D NEVLA model was carried out for the overall model domain, however special attention went to the tidal area of the Scheldt estuary upstream Antwerp.

5.1 Grid

The model grid was adapted in the most upstream zone of the estuary, in order to improve the bathymetric schematization of the river in this area (i.e. grid lines with the same orientation of the thalweg). Afterwards, a sensitivity analysis was performed for the resolution of the grid in the upstream zone of the Scheldt estuary. For all simulations the model parameters were kept constant except the model grid. This allowed comparison of high and low waters calculated for different stations in different model runs.

5.1.1 Grid adaptations

The results of the model simulations with different grid schematizations in the upstream part of the Scheldt estuary were compared. This was done in order to find an optimal grid to reproduce correctly the tidal penetration in the estuary. Table 1 in Appendix shows an overview of the model runs with different grid schematizations.

The NEVLA model grid was adapted for the Rupel river with its tidal tributaries (run A02) and for the Upper Sea Scheldt between Temse and Melle (run A03c). The examples of grid adaptations are shown on Figures 4 – 6. This adaptation is a synthesis of the work that has been already previously done on the parts of the grid to improve the flow representation in the upstream parts of the estuary. Downstream Schelle the adapted grid is identical with the NEVLA grid.

After the grid adaptations in the Upper Sea Scheldt the changes in water levels downstream Antwerp were negligible. The largest changes were observed in the Scheldt estuary upstream Hemiksem and in the Rupel river. The grid adaptations (run A07) in the Upper Sea Scheldt, in the Rupel river and its tidal tributaries resulted in a better tidal penetration in the upstream part of the estuary (Ides et al., 2008; Vanlede et al, 2008a).

As a result of the new grid schematization the high and low waters changed significantly in the Rupel river, the tidal amplitude increased. In the Upper Sea Scheldt from Temse to Schoonaarde the high waters increased with order of 10 cm, while the low waters almost did not change. Upstream Schoonaarde the low waters decreased and the high waters increased (Figure 7). This increase of the tidal amplitude becomes more important upstream. It indicates a better penetration of the tidal wave in this part of the estuary.

A grid that has only a few cells, that transport flow, can cause obstacles to the flow when the axis of the river is not parallel to the axis of the grid. The adaptation of the grid so that it follows the axis of the river better can significantly improve modeling of the flow. For example, near Uitbergen the axis of the river is diagonal to the orientation of the original grid (run A00, A01b) (Figure 8), which creates an obstruction to the flow during low water periods. Near Kessel (Grote Nete) the original grid does not follow the shape of the river (run A00, A01b) (Figure 9). In the improved grid (runs A02, A03c, A07) these zones are schematized differently, the grid follows the shape of the river better (Figure 10, 11), which results in a better tidal penetration (Ides et al., 2008; Vanlede et al., 2008a).

At locations where the river strongly meanders, it can be chosen to let the grid of the river deviate from the reality (include less river bends in the model). This technique helps to avoid calculations with too fine grid, which describes all meanders upstream in detail. Thus, it helps to decrease calculation time. This technique was applied for the Rupel river and its tributaries (Vanlede et al., 2008a).

The original NEVLA grid (run A00) includes a large number of areas lying outside the dikes. These areas were studied in the framework of the actualized Sigmaplan to determine their potential as controlled inundation areas. The dikes that separate these areas from the river are in reality high enough to prevent flooding at this moment.

In the case the areas outside the dikes are presented in the grid, it is necessary to represent the dikes in the model bathymetry. However, the height of the dikes during the interpolation of the measured depth points becomes averaged because of lower surrounding depth measurements. This can result in unwanted flooding of the areas outside the dikes. Therefore, the areas that stay dry during the entire simulation were preventively deleted from the grid (Figure 12).

The removal of the areas outside the dikes (the so-called potential controlled inundation areas) from the model grid in the Sea Scheldt has, as expected, not significant or no effect on the water levels in the Western Scheldt. In the Sea Scheldt a clear effect is observed upstream Hemiksem. In Schoonaarde the high waters increase with about 10 cm (Figure 13). This is explained by the fact that the (unwanted) simulated flooding of the areas outside the dikes lower the high waters in the surrounding areas, comparable to the work of a controlled inundation area.

The low waters in the Sea Scheldt in the model run without the areas outside the dikes (run A07b) are lower in comparison to the run with these areas (run A07). A maximal decrease of 6 cm is observed at Temse. Probably this can be explained by the effect of delayed outwatering from the areas outside the dikes. In the Rupel and its tributaries the same effect is observed as in the Sea Scheldt concerning high waters. The effect of the decrease of low waters is observed only in the Rupel river itself (Ides et al., 2008).

The removal of the areas outside the dikes from the model improves the accuracy of the model. Furthermore, it results in a decrease of the number of calculation points and a decrease of calculation time.

The original NEVLA grid has 214.130 active cells with dimensions in M en N direction 340 and 2557 respectively (matrix is 24% full). The adapted grid has 219.426 active cells in the matrix of 340 by 2948. This is 5296 more active cells than in the NEVLA grid (increase of 2%).

5.1.2 Grid resolution

To study the effect of the grid resolution on the model results, a small detail model was used in (Ides et al., 2008). The attention was concentrated on the most upstream part of the estuary because grid resolution is rather rough there. Dendermonde was chosen as the downstream border, the upstream border was at Gentbrugge, Zwijnaarde and Merelbeke (the tidal border). Model runs with different grid resolutions were performed (Table 2).

The grid cells – which are about 50 m long and 18 m wide in the original model – were refined in the direction perpendicular and parallel to the thalweg. The results showed that minimal changes were observed at Dendermonde. It is located in the downstream part of the detail model and water levels at this station were determined to a large extent by the downstream boundary conditions. The differences between different runs became larger at Schoonaarde and Wetteren, at Melle they decreased again.

The use of the refined grid resulted in an increase of high waters and a decrease of low waters (Figure 14). With the use of 2x2 refining of the grid the tidal amplitude increased with about 25 cm; with the use of 4x4 refining this increase reached 45 cm. These changes in the tidal amplitude are important, they indicate a better tidal penetration. The grid resolution of the NEVLA model in the Upper Sea Scheldt seems to be too rough to represent the tidal evolution correctly. It was observed that a higher grid resolution results in a higher tidal amplitude.

Therefore, with the use of the refined grid the model results become closer to the measurements and the modeling of the tidal penetration in the estuary improves. However, the calculation time significantly increases. The grid adaptations described in this chapter resulted in the important changes of the tidal propagation. The tidal penetration in the upstream part of the estuary improved and the calculated tidal amplitude became closer to the measured one.

5.2 Topo-bathymetry

There are many interpolation methods that can be used to calculate the bathymetry for each grid cell from the measured bathymetric data. Table 3 presents an overview of the interpolation methods used for the analysis. It was analyzed how different interpolation methods affect the tidal storage and thus indirectly affect the tidal propagation in the estuary.

5.2.1 Comparison of Gridcell averaging, Maximum and Minimum value of near points algorithms

The analysis of the amplitude and phase of the important tidal components M2 and M4 showed that a deeper bathymetry (*Maximum value of near points*) and an undeeper bathymetry (*Minimum value of near points*) affect the amount of the tidal energy that can reach the end of the estuary (Figure 15). The use of the *Maximum of near points* algorithm resulted in an increase of the number of flow transporting cells (Figure 16), therefore the tidal flow could penetrate easier. The increase of depth in the case of *Maximum value of near points algorithm* resulted in a decrease up to 7 cm of the M4 amplitude in the upstream areas (Vanlede et al., 2008a).

As expected, the analysis of the phase M2 showed that the tidal wave was slower in the shallow bathymetry in comparison to the average bathymetry. The tidal wave became faster in the deeper bathymetry. This effect is noticeable in the Western Scheldt from the station Hoofdplaat and it becomes stronger more upstream. The effect of the different bathymetries on the water movement is the strongest in the upper parts of the estuary where the water depth is the smallest (Vanlede et al., 2008a).

The use of the deepest or the less deepest bathymetry affects high and low waters differently. In the deeper bathymetry high waters at Antwerp come on average 6.5 minutes faster than in the average bathymetry. In the undeeper bathymetry they come more than 12 minutes later. This asymmetry is less pronounced for low waters. In the deeper bathymetry low waters at Antwerp come 10.8 minutes faster. In the undeeper bathymetry they come 13.3 minutes later (Vanlede et al., 2008a).

The tidal penetration in the upstream areas could be improved by the use of the deepest bathymetry for these areas. In the Upper Sea Scheldt the best results were obtained using the *Maximum depth of near points* interpolation algorithm. This conclusion was made based on the analysis of the most important harmonic components composing the water level in this part of the estuary. For the rest of the estuary the average values of the depth give the best results.

The use of the *Maximum value of near points* and the *Minimum value of near points* interpolation methods resulted in a large change of the tidal storage in comparison to the use of the *Gridcell averaging* method. While the effect of the *Minimum value of near points* method on the tidal amplitude with larger tidal storage is limited to maximum of 40 cm, the effect of the smaller tidal storage with the *Maximum value of near points* method between Sint Amands and Schoonaarde is larger than 200 cm. In both cases the effect is the most pronounced upstream Temse (Ides et al., 2008).

5.2.2 Comparison of *Gridcell averaging, Closest value, Shepard and Inverse distance weighted mean* algorithms

The effect of the use of the *Closest* or *Shepard* interpolation techniques is rather not significant in comparison to the *Gridcell averaging* technique, for both amplitude and phase of M2, but also for other analyzed components (M4, M6, O1, K1, S2) (Figure 15). The magnitude of the high and low waters in Antwerp changed with less than 1 cm and the tidal phase changed with less than 1 min in the case of the use of the *Averaged, Schepard* or *Closest* algorithms (Vanlede et al., 2008a).

The algorithms that take into account the distance between the depth measurement point and the calculation grid point (the *Shepard* and the *Closest* algorithms) result in a little larger tidal storage in the deepest parts and in a little smaller tidal storage in the undeepest parts. This is explained by the concave shape of the deepest part and the convex shape of the undeepest parts of the estuary. Because of the concave shape of the deepest parts of the bottom, the *Closest* and *Shepard* algorithms result in a bathymetry in the deeper zones (under -3 m NAP) which is up to 0.3 % deeper than in the case of the use of the '"average" algorithm. Because of the convex shape of the undeep zones (above -3 m NAP) both algorithms give a bathymetry which is up to 0.2 % less deep than with the use of the "average" algorithm. However, the effect of these changes on the tidal storage is negligible (Vanlede et al., 2008a).

The comparison of the *Gridcell averaging*, the *Closest value* and the *Inverse distance weighted mean* methods showed that these methods give very similar results concerning the tidal propagation. The preference is given to the *Inverse distance weighted mean* method because it is most physically based. Nevertheless, the *Gridcell averaging* and *Closest value* methods can be used too because they produce results with limited differences (Ides et al., 2008).

5.2.3 Analysis of bathymetry for intertidal areas

After the analysis of the model sensitivity to the different interpolation techniques, it was analyzed how the use of a less accurate bathymetry for intertidal areas affect the model results. Bathymetry of the intertidal areas can not be measured with the single beam technique. The water depth in this zone is too small for the measuring vessel. The depth of these areas is measured with the LIDAR technique from an airplane. This technique has a smaller accuracy in comparison to the single beam technique. The effect of this smaller accuracy was schematically studied during the sensitivity analysis. The bathymetry for the intertidal areas was assigned 20 cm higher and 20 cm lower than the measured values. The effect of these changes on the model output was studied in order to analyze how the measurements with a lower accuracy affect the model results.

In the Western Scheldt there was almost no effect of these changes. In the Sea Scheldt only a small effect was observed during the high waters. From Bath to Wetteren there was an uniform decrease of the high waters of about 2 cm in run with a lower bathymetry of the intertidal areas. In the case of a higher bathymetry for the intertidal areas, the high waters increased with 2 cm upstream Bath (Ides et al., 2008). There was almost no effect during the low waters.

An increase or a decrease of the depth of the intertidal zones has a limited effect on the harmonic components (Figure 17). The effect on the component M4 is the strongest in comparison to other analyzed components (M2, M4, M6, O1, K1, S2). The increase of the bathymetry of the intertidal areas with 20 cm resulted in the increase of the M4 component with 1 cm and in the increase of the ratio of amplitudes M4/M2 with 1%.

5.3 Boundary conditions

5.3.1 Discharge at Merelbeke

The most important fresh water discharge comes into the Upper Sea Scheldt from the sluice complex near Merelbeke. Measured time series of discharges at Merelbeke are used in the model as one of the upstream boundaries. If more detailed measurements are not available, daily averaged discharges are used. The frequency of the discharge time series at Merelbeke can have an important effect on the model results.

On the basis of 5 minutes, hourly and daily discharge time series (Figure 18) it was analyzed what is the effect of the frequency of the measurements on the model results (Table 4). This analysis showed that the frequency of the discharge measurements at Merelbeke affects the model output upstream Hemiksem. The differences between the use of 5 minutes averaged discharges and hourly averaged discharges are not high (< 5 cm). However, there is a large difference in the case of the use of daily averaged discharges in comparison to 5 minutes averaged discharges (up to 80 cm for the low waters in Wetteren (Figure 19)). These differences are smaller during the periods with a quasi constant discharge (small differences in the water level) and they are the largest during the periods with a strongly varying discharge (Figure 20). This effect is significant (> 5cm for water level) until Temse. The variation of the discharge at Merelbeke has a stronger effect on low waters than on high waters.

In order to calculate the water levels in the Upper Sea Scheldt upstream Temse correctly, it is necessary to use at least hourly averaged discharges at Merelbeke. Daily averaged discharges can also give acceptable results but only during the periods with a constant upstream discharge. However, during the periods with large fluctuations of the discharge, deviations of water levels can be large (more than 50 cm between Wetteren and Schoonaarde).

Therefore, the sensitivity analysis showed that the discharge at Merelbeke has a significant effect on the model output. It is very important to have accurate and detailed time series of discharge for this location. At least 5 minutes or hourly averaged values should be used at Merelbeke. However, the detailed discharge data for Merelbeke are available only for a limited period. What is available with a higher frequency is a discharge measurement at Melle (Flanders Hydraulics – Hydrometry department). The possibility to shift the upstream model boundary to Melle and use the measurements of the ADM (10 minutes values or hourly values) was not analyzed in this report. In this case discharge can become negative because Melle is tidally affected. This is not clear yet what can be the effect of the use of negative discharges on the model stability. It should be investigated whether shifting the upstream boundary condition from daily discharges at Merelbeke to hourly fluxes (positive and negative) at Melle gives a similar improvement in the model results.

5.3.2 Wind

The importance of the wind implementation in model simulations was analyzed in (Vanlede et al., 2008a). The wind data measured at the station Vlissingen were imposed as a uniform wind field influencing the whole model area. For some periods wind velocity increased up to 12 m/s, which still can not be classified as a storm condition. Nevertheless, the wind implementation had a significant effect on the model results. The influence of the wind is included in the NEVLA model to a large extent via the imposed water level boundary Cadzand – Westkapelle. This can have an effect up to 20 cm on the water levels for the analyzed period. In the case of a storm this difference can become even higher and important differences in local flow velocities can occur. The relatively large surface of the Western Scheldt and the relatively small water depth result in an increase of the wind effect on the water levels.

Further studies are necessary to understand the importance of the wind direction and wind velocity in the total wind effect.

5.4 Bed roughness

The effect of the bed roughness on the water movement was studied (Table 6). It was analyzed how the roughness change in a certain area affects the results in and outside this area. This gave necessary knowledge for a more efficient approach for the model calibration. A special attention was paid to the effect of the roughness on the harmonic components M4 and M6, which have a strong effect on the maximal ebb and flood velocities. The output of all model runs was compared with the measured water levels and discharges. Furthermore, the harmonic analysis of the simulated water levels was performed and the results were compared with the harmonic components from the measured water levels.

First, it was checked how the use of different Manning coefficients affects the tidal penetration into the estuary. A tidal amplitude can be decreased by the use of the higher bed roughness or it can be increased by the use of the lower roughness (thus, lower resistance to the tidal wave). An uniform increase of the roughness results in a decrease of M2, M4, S2 and M6 parameters for the entire estuary (Figures 21, 22). The effect on the parameter M4 is stronger in the Western Scheldt and upstream Antwerp than between the Dutch – Belgian border and Kallo. A uniform higher roughness gives a larger phase shift 2M2-M4 (Figure 23), and thus more flood dominant character of the tidal wave. M4/M2 relation characterizes the tidal asymmetry. M4/M2 parameter increases with an increase of the roughness but only upstream Bath (Figure 23). Between the seaward boundary and Bath this effect is opposite (Vanlede et al., 2008a).

The simulations with the uniform bed roughness showed that it is necessary to define not constant roughness for different areas to represent the tidal movement in the estuary correctly (Ides et al., 2008). The Scheldt estuary was divided in 10 zones (Figure 24). The roughness of each zone was increased and decreased in order to analyze how these changes affect the model results. Where the roughness was adapted, the M2 and M4 amplitudes changed along the estuary (for example, Figure 25). Increase of the bottom roughness resulted in a smaller gradient; decrease of the bottom roughness resulted in a larger gradient. A local change of the bed roughness in a certain zone also affects the M2 amplitude in the zone upstream. Since the M2 component is the most important component for the tidal production, the change of the M2 parameter shows the change of the tidal amplitude.

By the analysis of the effect of the roughness in 10 parts of the estuary, the library describing the influence of the roughness change on the model results in a certain part of the estuary was composed in (Vanlede et al., 2008a). This library was later used for the model calibration.

Afterwards, the depth dependent roughness was used for the analysis in (Ides et al., 2008). The average depth decreases and thus roughness increases more upstream. This resulted in an increase of the tidal amplitude between Hoofdplaat and Boerenschans. Upstream Boerenschans the amplitude decreased.

The effect of the different roughness formulas on the model output was analyzed (Figure 26). SIMONA calculates internally with Chezy roughness coefficients. However, the user can specify different roughness coefficients in the input file. The effect of different roughness coefficients on the M2, M4 and

M6 amplitudes was studied. The higher amplitudes M2 were calculated downstream Temse in the case of the use of White Colebrook and Manning coefficients in comparison to the use of the constant Chezy value. The effect on M4 and M6 was not significant. This variation in amplitudes showed also in the tidal asymmetry.

The ratio M4/M2 amplitude was the lowest for the simulation with Chezy coefficients. Upstream Temse the differences between the use of White – Colebrook and Manning coefficients became larger. The phase shift 2M2-M4 was the largest for the simulation with Chezy coefficients; there were very small differences between the model runs with Manning and White – Colebrook coefficients (Vanlede et al., 2008a).

5.5 Conclusion

Sensitivity analysis in (Vanlede et al., 2008) and (Ides et al., 2008) was performed in order to analyze what is the effect of different numerical parameters on the model results.

The analysis showed that the model grid has an important effect on the model output, especially in the most upstream part of the Scheldt estuary. The grid adaptations in the Upper Sea Scheldt and Rupel resulted in the improvement of the tidal penetration in these parts of the estuary.

Different methods used to interpolate bathymetric measured data to the model grid were studied. This analysis showed that methods that use averaged depth give very similar results. Large differences in the tidal storage (and as a consequence in hydrodynamics) are observed when maximum and minimum values of the points are used.

At the upstream model boundary Merelbeke it was analyzed what is the effect of the use of discharge measurements with a higher frequency. The analysis showed that the difference between the use of 5 minutes or hourly averaged discharges is small. However, when daily averaged discharges are used, the effect of the natural fluctuation of the upper discharge is not modeled well. Differences in calculated water levels become high. This effect is observed in the Upper Sea Scheldt upstream Hemiksem. Therefore, the discharge at Merelbeke has a significant effect on the model output. It is very important to have accurate and detailed time series of discharge for this location. There is also a possibility to shift the upstream model boundary to Melle because 10 minutes discharge measurements are available for this location. However, this is not clear yet what can be the effect of this shift on the model results.

The model sensitivity to the use of different bottom roughness values was studied. First, an uniform roughness was analyzed and then different roughness values were assigned for different areas. Furthermore, different roughness formulas were compared. The results of the sensitivity analysis gave important information for the calibration and validation of the NEVLA model.

The model should be calibrated in order to produce the results close to the measurements. First, the model grid has to be adapted to improve the representation of the tidal penetration in the upstream part of the Scheldt estuary. Afterwards, the most recent bathymetric data has to be interpolated in order to get the bathymetry for the model. As an upstream boundary, at least hourly averaged discharges at Merelbeke should be used. For other upper tributaries daily averaged discharges can be used. Finally, the bed roughness field should be adapted to improve the accuracy of the model.

6 Calibration

The calibration is performed in order to improve the model accuracy. It is done by change of the model parameters. The results of the sensitivity analysis described in the previous chapters were used for the calibration. General calibration of the NEVLA model was done in (Vanlede et al., 2008b). Afterwards, calibration was extended in (Maximova et al., 2009), where attention was concentrated on the improvement of the model accuracy for the upstream parts of the estuary.

6.1 General calibration

For the model calibration different simulations were performed with different changes of the roughness and bathymetry. The result of the sensitivity analysis gave an important input for the calibration. In (Vanlede et al., 2008b) the NEVLA model was calibrated based on the phase and amplitude of the most important harmonic components composing the water levels at different locations along the Scheldt estuary. This model was calibrated for September 2006.

The objective of the calibration was to find optimal parameters for the numerical model that result in accurate modeling of the harmonic tidal parameters. If these tidal components are modeled correctly, it can be expected that tidal dynamics (and consequently water levels and discharges) is modeled accurately too. After the calibration on the basis of the harmonic components, the model results were compared with the measured discharges (so called MOVE transects) and the water levels in September 2006.

6.1.1 Methodology

For the model calibration different model simulations were performed with different parameters of the 2D hydrodynamic model. For each model simulation the following was analyzed:

- the amplitude and phase of astronomical components;

- the tidal evolution of water levels and discharges at different locations in the Scheldt and Rupel.

To distinguish the two most important harmonic components M2 and S2, it is necessary to use time series that are minimum two weeks long (spring – neap tidal cycle). Since a lot of measurement data are available for 2006, this year was chosen for the simulation. The simulation was performed for the period 29 August – 30 September 2006. Thus, two neap-spring tidal cycles are included and as a consequence the harmonic components are calculated accurately.

In total more than 30 runs were performed for the calibration. The following chapters of this report give an overview of the most important model runs.

6.1.2 Grid adaptation

The sensitivity analysis gave necessary information for the grid adaptation for the model calibration. More detailed information can be found in (Vanlede et al., 2008a). The grid used for the calibration is a combination of different grid optimizations. It is based of the NEVLA grid for the Western Scheldt and the coastal zone. The grid for the Sea Scheldt upstream Temse is taken from (Verelst et al., 2008). The grid for the Rupel and its tributaries is taken from (Adema, 2006). Furthermore, a number of areas outside the dikes was deleted from the grid. The effect of this grid on the model results was studied during the sensitivity analysis in (Vanlede et al., 2008a).

6.1.3 Simulation E01

After the sensitivity analysis (Vanlede et al., 2008a) some important conclusions were made:

- if the roughness of 0.022 $m^{-1/3}s$ is used, the M2 amplitude is modeled well between the seaward boundary and Breskens and between Hansweert and Antwerp. Between Breskens and Hansweert the increase of tidal amplitude was too strong and a higher roughness had to be used;

- to represent the tidal penetration in the Upper Sea Scheldt (upstream Schoonaarde) better, the *Maximum of near points* algorithm could be used.

These conclusions were used during the model calibration for run E01. Afterwards, different model parameters were changed in order to improve the accuracy of the model in comparison to the original NEVLA model. The calibration results were compared with the results of the original model E00. In run E01b only the bed roughness was increased without the change of the interpolation method for the upstream part of the Upper Sea Scheldt.

The evaluation of the calibration runs was done on the basis of the analysis of the harmonic components along the Scheldt estuary. These parameters do not give direct information about the absolute values of the water levels and discharges, but they give an idea about the tidal penetration into the estuary.

In the original E00 model run the bed roughness was defined as Chezy coefficients. Simulations E01 and E01b have very simple roughness field defined as Manning coefficients. The use of the Manning values has an advantage that the roughness is depth dependent; the effect of turbulence on the bottom becomes smaller with an increase of depth.

To represent the tidal propagation better in the Upper Sea Scheldt upstream Schoonaarde, the interpolation method that uses the deepest bathymetric value for the grid cell was chosen. This helped to improve the model accuracy for this part of the estuary. Upstream Temse the M2 parameter decreased and, as a result, the calculated amplitude became closer to the observations (Figure 27). Concerning the tidal asymmetry, the M4/M2 amplitude ratio improved upstream Schoonaarde and upstream Wetteren there was a good agreement with the observations (Figure 28).

The M2 amplitude changed; however, there was no significant improvement. M6 calculated in run E01 improved and became closer to the observations. The tidal asymmetry was modeled in E01 better than in E00 for the upstream sections of Hansweert – Walsoorden. The parameters M4/M2 and the phase difference 2M2-M4 show if the tidal penetration and the ebb-flood dominance are modeled accurately. These parameters were in a good agreement with the observations (Figure 29).

6.1.4 Simulation E19

After run E01 the harmonic parameters still required improvement. Therefore, the attention was concentrated on the adaptation of the bed roughness in the Western Scheldt, the Lower and Upper Sea

Scheldt. For the sections Breskens – Hansweert, Overloop van Valkenisse – Deurganckdok and Antwerp – Temse it was necessary to assign a higher roughness in comparison to the other parts of the estuary to model the tidal amplitude correctly. In general, the roughness decreases upstream Zandvliet. Adapted roughness field is shown on Figure 30.

The roughness field was optimized on the basis of the M2 component because it has the largest amplitude. M2 has to be modeled well in order to calculate correct water levels along the estuary. The adaptations of the roughness helped to improve the accuracy of the M2 amplitude (Figure 31).

The M4 amplitude was modeled well in run E19 for the entire estuary (Figure 32). There was very small difference between the calculated and observed M4 phase. The M6 amplitude calculated in run E19 is very similar to run E01. The amplitude ratio M4/M2 and the phase difference 2M2-M4 improved in run E19 for the Lower Sea Scheldt and the Western Scheldt.

Therefore, the harmonic components were significantly improved in run E19. However, this was also necessary to compare the calculated discharges and the water levels with the measurements. The analysis showed that both high and low waters were underestimated in the model. However, the calculated tidal amplitude was close to the observations, which is important for the velocities and discharges. Considering the tidal propagation, not only the amplitude is important but also the velocity of the tidal wave plays an important role. In the model the tidal wave was delayed in comparison to the reality.

6.1.5 Simulation E30

It was necessary to improve the accuracy of the model for the calculated low and high water levels. Different roughness values were used for the flood and ebb channels in order to increase both high and low waters that were underestimated in the model. The roughness for the ebb channel was increased and it was decreased for the flood channel. These changes were made only in the Western Scheldt and in the lower parts of the Lower Sea Scheldt (Figure 33).

The use of the bathymetry from run E01 (maximal depth per grid cell) has an advantage that the M2 amplitude is less dumped. But since too low S2 component is chosen in this zone for smaller dumping of the tidal wave, the amplitude becomes larger downstream. The same effect is observed for the M2 phase along the estuary.

Upstream Schelle the difference between the calculated and measured M2 amplitude is higher in run E30 than in run E19 (Figure 34). However, the results of run E30 were chosen as a final model run because correct representation of the S2 amplitude in run E30 compensates too large M2 amplitude. Therefore, the tidal amplitude is simulated accurately.

The use of the different roughness for the flood and ebb channels in the Western Scheldt results in a small increase of the M4 amplitude (Figure 35). It represents the reality better. Only between Temse and Schoonaarde this improvement is smaller. The amplitude and especially the phase of M6 in the Sea Scheldt improved in the comparison to run E19.

The tidal asymmetry (M4/M2 ratio) along the estuary is better simulated in run E30 than in E19. Between the Overloop van Hansweert and Walsoorden the phase difference 2M2-M4 is simulated better than in run E00, thus the ebb or flood dominance is better described by the model.

The high waters improved for most stations along the estuary in run E30. They are still underestimated at some stations, but results are better than in run E19. The low waters calculated in run E30 are lower than the measurements. The difference between the calculated and measured low waters increases upstream.

The model results show similar deviations of the high and low waters in the Western Scheldt and the Lower Sea Scheldt. This means that the tidal amplitude is modeled well. In the original model E00 the tidal amplitude was too large.

The differences in the calculated and measured phase of high water are very small in the Western Scheldt and the Lower Sea Scheldt. This difference increases more upstream. The maximal difference of about 30 min is observed at Melle (both for high and low waters). Similar to run E19, there is a positive difference in the phase of high and low waters. This means that tidal wave is delayed. Since the differences for high and low waters are similar, this means that durations of rising and falling water are modeled correctly.

Together with the analysis of the harmonic components and the water levels, the calculated and measured discharges were compared. Discharges through certain cross sections were analyzed. In final model run E30 the representation of discharges was improved in comparison to the original model. More detailed description of the results of this analysis can be found in (Vanlede et al., 2008b).

The model calibration resulted in an improvement of the model accuracy for the change of water level in time. This parameter, named also dh/dt, is very important for the representation of specific phenomena's that are related to the flow velocity.

6.1.6 Conclusions

In (Vanlede et al., 2008b) the model was calibrated for the year 2006 based on the phase and magnitude of the most important harmonic tidal components. During the calibration several model runs were performed in which some model parameters were changed. The main calibration parameters used in (Vanlede et al., 2008b) are bathymetry and bed roughness. Different bathymetric interpolation algorithms were analyzed. It was stated that the best results in the Upper Sea Scheldt were obtained using the maximum depth of near points interpolation algorithm. The roughness field of the Western Scheldt, Lower and Upper Sea Scheldt and tributaries was changed thoroughly. Different roughness values were defined for the flood and ebb channels in the Western Scheldt. Manning roughness coefficients were used instead of Chezy coefficients. The bed roughness of the Upper Sea Scheldt was decreased to ensure easier tidal penetration. This helped to improve M2 amplitude.

As a result of the calibration, the following elements were improved: simulation of the harmonic components (M2, S2, M4, M6) and simulation of the flood flow in the Rupel river and the Upper Sea Scheldt. Especially the M4 and M6 components were significantly improved which should result in a better modeling of the tidal asymmetry in the estuary. As a consequence, in a number of locations the shape of the discharge curve improved. A better shape of the tidal curve was obtained by the calculation of the first derivative of the tidal signal over time, so named 'dh/dt'. This parameter is significantly better represented by the calibrated model from this study.

6.2 Calibration of the model for the upstream part of the estuary

The general calibration of the NEVLA model that was done in (Vanlede et al. 2008b) is extended. The resulting model parameters from (Vanlede et al., 2008b) are used as the reference simulation. However, the methodology of the analysis is different. It is based on the comparison of the phase and magnitude of the calculated and measured high and low water levels. The tidal components of the water levels are not considered. This report describes the changes made to the model in order to improve its accuracy. This extended calibration is mainly focused on the Upper Sea Scheldt and the tributaries Zenne and Dijle because the calculated water levels differ the most from the measured ones in these regions. The calibration is performed for June – July 2002 because more detailed input data are available for this period.

6.2.1 Methodology

Several model runs were performed in order to improve the model results for June – July 2002. The calibration was especially focused on the comparison of the phase and magnitude of the calculated and measured high and low water levels at different stations along the estuary.

The phase and magnitude of the low and high water levels were found using Matlab, based on the sign of the first derivative of the water level time series. High and/or low waters for some locations were not found due to the limitations of the Matlab script: this is the case for the locations where the transition from rising water to falling water (or the opposite) is not very clear. On the other hand, the position of the measurement instrument in the river can also make it sometimes impossible to measure the exact low water (for example location Temse where the measurement instrument is located in a muddy environment, the level of the mud being approximately the level of the low water).

For this study, the following parameters were changed in order to improve the model results:

- Model bathymetry,
- Bed roughness,
- Boundary conditions,
- Implementation of a weir in the model.

6.2.2 Some general aspects

Location of discharge point at Merelbeke

In all runs except the first one new coordinates of the grid point for Merelbeke were defined. This was done, because after the first run it was found that the original grid point defined in the NEVLA model was off grid. Thus, the discharge defined in the input files for Merelbeke was not used in the calculations.

Bathymetric interpolation algorithm

In (Vanlede et al., 2008a) it was stated that the best results in the Upper Sea Scheldt were obtained using the maximum depth of near points interpolation algorithm. This conclusion was made based on the analysis of the most important harmonic components composing the water level in this part of the estuary. In (Maximova et al., 2009) again the effect of different bathymetric interpolation algorithms was studied, based on the water levels instead of on the harmonic components. The best results were obtained using the average bathymetry.

Location of water level point Cadzand

The downstream boundary of the NEVLA model as it is used in this study is defined by the line Westkapelle – Cadzand. As explained in the chapter 4.1 of this report, the used sea boundary does not coincide with the real boundary Cadzand – Westkapelle. The station Westkapelle is located on the boundary, however the model boundary at the left bank is located between Cadzand and Zeebrugge (Figure 3).

At the boundary location between Cadzand and Zeebrugge the measured water level of Cadzand is used, with a phase shift related to the distance between these 2 locations. In (Vanlede et al., 2008b) a time shift of 10 minutes was used. Since the tidal penetration in the model was different from the tidal penetration in nature for all stations, this 10 minute shift is studied again. The best results were obtained with the time shift of 20 minutes. This helped to improve both phase and magnitude of low and high waters for all stations.

Accuracy of the model

After the model adaptations described above, the accuracy of the model has increased. The model performs best in the Western Scheldt. The deviations between measured and calculated water levels increase more upstream.

For the Lower Sea Scheldt (from Liefkenshoek to Hemiksem) and for the Grote Nete (station Kessel) the calculated water levels do not deviate too much from the measurements (Figure 36). At Emblem located on the Kleine Nete the high waters are modelled better than the low waters (Figure 37). The largest deviations between the measured and modelled water levels occur in the Upper Sea Scheldt (from Temse to Melle) (Figure 38 run3) and tributaries Zenne and Dijle (stations Hombeek, Mechelen and Rijmenam) (Figures 39, 40, 41). The next paragraphs describe the changes made in the model in order to improve the model accuracy for these parts of the estuary.

6.2.3 Model calibration for the Upper Sea Scheldt

Both the high and low water levels for the Upper Sea Scheldt were too low in comparison to the measured ones. To improve the model accuracy different steps were taken during the process of the model calibration.

Adaptation of the bed roughness

To improve the model results, different roughness fields for the Upper Sea Scheldt were tested. The change of the roughness value affects tidal water movement and therefore affects low and high waters. On the one hand, a decreased roughness results in an easier tidal penetration. Therefore, high water levels increase. On the other hand, water can move faster in the seawards direction during ebb. Therefore, low water levels can decrease. An increased roughness has an opposite effect on high and low waters. It was necessary to find a roughness field that results in optimal calculated high and low waters which are close to the measurements for all stations. The original roughness field for the Lower and Upper Sea Scheldt is shown on Figures 42 and 43.

Discharge at Merelbeke

Another way to affect low waters is to change the upstream discharge. An increase of the discharge affects mainly low waters. It does not have strong influence on high waters because the flood flow is much larger than the upstream discharge. It was analysed how the model would react if the discharge at Merelbeke was increased. The analysis showed that an increase of the discharge at Merelbeke helped to improve the results of the model simulation. However, there is not a physical reason why the measured discharge would underestimate the real discharge at this location. Therefore, in all next model runs the original measured time series of the discharge at Merelbeke were used.

Flow barriers

To improve too low low waters a kind of a barrier, similar to a sill, was made in the river. An example of this barrier is shown on Figure 46. This barrier does not prevent the flood flow from flowing more upstream, while it hinders the water during ebb periods to flow back to the sea, especially around low water where the influence of such a barrier is maximal. From the physical point of view, such a barrier can be an undeeper part in the river which might not be included in the model because of the grid resolution or the interpolation process. This kind of a barrier was implemented by change of the local bathymetry. The effect of the barrier implementation in the different parts of the Upper Sea Scheldt was studied.

An influence of a flow barrier is limited only to a part of the Upper Sea Scheldt. It was necessary to increase low waters at all stations at the Upper Sea Scheldt. The implementation of the weir resulted in the improvement of the low waters only at some stations closest to the weir. The low waters at other locations were not influenced. Therefore, a flow barrier is not a global solution and it was not implemented in the Upper Sea Scheldt in the final calibrated model.

High water levels at Melle

The calculated high water levels for Melle were too low (on average 22 cm lower than the measured ones) (Figure 38). Different attempts were made to improve them.

First, the roughness between Wetteren and Melle was decreased. This improved the high waters but worsened the low water levels at Melle considerably. Then, different roughness values were assigned for the upper and lower parts of the river bottom between Wetteren and Melle. It was expected that a decrease of the roughness of the upper part of the bottom would affect only high waters. However, this did not result in significant changes. Afterwards, the roughness upstream Melle was increased. It was expected that the flood flow would be delayed at Melle due to the high roughness upstream and the high waters would increase. However, this did not give the expected result.

Therefore, the roughness field for the simultaneous improvement of both high and low waters at Melle was not found.

Final model run

The roughness field used in the final run is shown on Figures 44, 45. In the final model run (run 27) the high water levels improved for all stations located along the Scheldt estuary (Figures 50, 51). They increased in the Upper Sea Scheldt and came closer to the measurements. The calculated high water levels at Temse and Melle increased too. However, the model still underestimates the high waters at these stations.

The low water levels improved everywhere at the Scheldt estuary upstream Vlissingen except Hemiksem and Temse. The low water levels at Vlissingen were accurate and did not require improvement. At Hemiksem and Temse the low water levels worsened as a consequence of the improvement of the high water levels. As it was explained above, the low water levels at Temse are not very well measured and should not be considered as accurate.

After the calibration, the differences between the calculated and measured high and low waters in the Upper Sea Scheldt decreased. They do not exceed 11 cm for both high and low waters for all stations, except the high waters at Melle and Temse and the low waters at Temse. A limited period of the available measurements and not accurate measurements of the low waters at Temse could affect the analysis of the results for this station.

The phase of the calculated low and high waters was improved. The time delay observed in the model results was decreased.

6.2.4 Model calibration for Zenne

In this report the water levels at Hombeek located along the Zenne river were analysed. The calculated high water levels are close to the measurements and the calculated low water levels are much higher than the measurements (Figure 41). This means that water can not leave Zenne as fast as in reality during the ebb periods. Several attempts were made to decrease too high water levels by the adaptation of the bathymetry (Figure 47) and roughness. However, no successful change was found to improve the low waters at Hombeek. The difference between the model and measurements is not yet understood and has to be studied in the future.

6.2.5 Model calibration for Dijle

The water levels at two measurement stations at the Dijle river were analyzed. Before the calibration the calculated low water levels were too high for Mechelen and too low for Rijmenam (Figures 39, 40).

To improve the model accuracy for the Dijle river, a weir (which is a simplification of the real weir at Mechelen) was implemented in Mechelen. It was expected that this weir would be an obstacle for the water flow and would result in increased low waters at Rijmenam. At the same time, less water would be moving seawards during ebb at Mechelen. As a result of this, the low water levels at Mechelen would decrease. A weir at + 2 m NAP at Mechelen was implemented by the use of the weir structure in the SIMONA model. This improved the low water levels at Rijmenam (Figure 48). They increased and became close to the measurements. However, there was not any significant improvement in Mechelen (Figure 49).

Several attempts were made to improve the low waters at Mechelen by adaptation of the local bathymetry and the bed roughness up- and downstream Mechelen. However, this did not result in a decrease of too high low waters at this station.

6.2.6 Conclusions and recommendations

The calibration of the 2D SIMONA model was performed in this study for June – July 2002. The analysis was exclusively based on the comparison of both phase and magnitude of the calculated and measured high and low water levels. The objective of this study was to improve the model accuracy for the Upper Sea Scheldt estuary and tributaries Zenne and Dijle. The model was calibrated by changes of several parameters: bathymetry, bed roughness and boundary conditions. Furthermore, a weir was implemented at Mechelen.

The following changes were made in the final run:

- corrected coordinates of the discharge point for Merelbeke,
- bathymetry with averaged depth (grid cell averaging interpolation algorithm),
- time shift of 20 min of water level series at downstream boundary location Cadzand
- changed bathymetry of several cells for the river Zenne,
- changed roughness field for the Lower and Upper Sea Scheldt,
- changed roughness for the river Zenne,
- weir at Mechelen (at + 2 m NAP).

As a result of the calibration, the accuracy of the model for high water levels was improved for all stations along the Scheldt estuary. The difference between the calculated and measured high water levels for the Upper Sea Scheldt decreased. However, the high water levels at Melle are still too low. Different attempts were made to improve them. But they did not result in the simultaneous improvement of the model accuracy for both high and low water levels at Melle.

The high water levels were improved for the Rupel river and the Dijle river. However, the high water levels worsened at Kessel located at the Grote Nete.

The accuracy of the model for low water levels was improved everywhere for the Scheldt estuary upstream Vlissingen except Hemiksem and Temse. At Hemiksem and Temse the low water levels worsened as a consequence of the improvement of the high water levels. Due to not accurate measurements of the low waters at Temse, it is not possible to analyse the improvement of the results for this station.

The low water levels worsened a little at Boom and Walem located along the Rupel. The implementation of the weir structure at Mechelen resulted in the improvement of the low water levels at Rijmenam.

After the model calibration the time delay for both low and high waters decreased. Furthermore, for some stations (Vlissingen, Baalhoek, Schaar van de Noord, Bath and Kessel) the calculated high waters are observed earlier than the measured ones after the model calibration. It can be concluded that the changes made in the model in this study improved the accuracy of the model for most stations.

Figures 50 and 51 show the differences in time and magnitude – averaged values over the simulation period – for the calculated and measured high and low water levels for some stations. The differences between the model and measurements are presented for the initial NEVLA model as described by (Hartsuiker et al., 2004), the model as calibrated for September 2006 by (Vanlede et al, 2008b) and for the model calibrated for June – July 2002 by (Maximova et al., 2009). The model accuracy for high and low waters have clearly impoved through the three calibration steps.

However, further studies of the model are needed. The model accuracy should be improved for the high waters at Melle and Temse. The high waters at Melle are too low. The roughness field for the simultaneous improvement of both high and low waters at Melle still needs to be found.

The high and low waters at Temse are not accurate. It is necessary to analyse the water levels at Temse based on a longer period of measurements and more accurate measurements of low waters.

The low waters at Mechelen and Hombeek still require further improvement. A solution for the decrease of too high low waters at these stations was not found. The large difference in the low waters between the measurements and the model is not understood and should be studied in the future.

Furthermore, the model accuracy for the stations located on the Rupel river (Boom and Walem) and the Nete river (Emblem and Kessel) should be studied more in the future. The accuracy of the model for low waters at these stations still can be improved.

7 Validation

After calibration of the model it is necessary to check how the calibrated model performs for a different simulation period. A testing of the model performance on data that have not been used for the calibration is called model validation.

7.1 Validation for normal spring-neap tidal cycle

7.1.1 The simulation period

The model was calibrated for June – July 2002. The validation was performed for the period 29/08/2006 00:00 to 01/10/2006 00:00. Since this calibration period is approximately 4 weeks, the effect of the spring-neap tidal cycle is included in the mean water level values, as well as a broad range of the upstream discharges. New upstream and downstream boundary conditions are specified for this period. All other input parameters are left the same as in the calibrated model.

7.1.2 Boundary conditions

The water levels at Cadzand and Westkapelle (HMCZ database) are used as downstream boundary conditions. The NEVLA model has several upstream boundaries. The discharges at these upstream boundaries are available from the Hydrometry group of Flanders Hydraulics Research. The daily discharge series for a simulation period are available for Scheldt – Dendermonde, Zenne – Zemst, Dijle – Haacht, Grote Nete – Itegem and Kleine Nete – Grobbendonk. Zero discharge was specified for Durme – Waasmunster, Schelde – Gentbrugge and Bovenschelde – Zwijnaarde. 10 minutes discharge time series are available for the Bath canal.

The discharge at Merelbeke is the largest fresh water discharge coming to the Scheldt estuary. Thus, it has the most significant effect on the model output. Therefore, it is very important to have accurate and detailed time series of the discharge for this location. However, for the simulation period only daily discharge time series are available at Merelbeke.

Wind is included in the model run. Wind data are available from the Hydro Meteo Centrum Zeeland (HMCZ) database. The wind data measured at the station Hansweert are imposed as a uniform wind field influencing the whole model area. This data consist of wind magnitude (10 min average value) and direction (10 min average value in degrees towards North).

7.1.3 Results of the model validation

The results of the model validation are presented in Tables 7 and 8 and on Figures 52 - 55. The differences between the calculated and measured high water magnitude and phase and low water phase are not high. The differences in magnitude do not exceed 10 cm at any station except Melle (at Melle the difference is 15 cm). The differences in high and low water phase are small in the Western Scheldt and the Lower Sea Scheldt. Upstream Schoonaarde the differences in low water phase become a little larger (6 – 16 min). For most stations the modeled high waters for the year 2006 are even more accurate than for 2002.

However, the model accuracy for the low waters worsens considerably in 2006. The calculated low waters are lower than the measurements. The largest differences between the calculations and measurements are observed upstream Hemiksem and in the Rupel river. The average difference between the calculated and measured low waters at Melle is very small (- 3 mm). However, the actual differences in the low water at this station are much larger at some moments in time (Figure 56). They vary in time from plus 20 - 40 cm to minus 20 – 60 cm.

The large differences in the low waters upstream Hemiksem can be related to the fact that only daily discharge time series were available at Merelbeke. From the sensitivity analysis (Ides et al., 2008) it was found that the use of daily averaged discharges at this location worsens the calculated discharges in the Upper Sea Scheldt up to Hemiksem compared to hourly averaged discharges. When 5 min averaged discharges are used, the correspondence between the calculation and measurement is even better; however the difference between the 2 results is small.

The use of daily averaged discharges at Merelbeke affected mainly low waters because during the ebb period the upstream discharge is more important than during the flood.

There are large differences in the low waters at Boom and Walem because the accuracy of the calibrated model still needs to be improved for these stations to represent the low waters correctly.

The model validation showed that the calibrated model performs well for the stations downstream Hemiksem. Upstream Hemiksem the calculated low waters were not accurate in the validation run. The model accuracy upstream Hemiksem can be improved by the use of more accurate and detailed time series of discharge at Merelbeke.

7.2 Validation for storm period

In chapter 7.1 the calibrated model was validated for a period with a rather normal tide (September 2006). Besides this it is useful – in the framework of a project which is dealing with safety against flooding – to check how the model performs in extreme conditions. A period with an extreme high water was chosen for the model validation in this chapter.

7.2.1 The simulation period

The model was validated for the period from 15/10/2002 00:00 to 15/11/2002 23:30. On 26/10/2002, 27/10/2002 and 07/11/2002 the high waters at Antwerp were higher than 4.00 m NAP. A highest high water during the simulation period (4.30 m NAP) was observed at Antwerp on 07/11/2002 4:40. According to (Jeuken et al., 2007), the high water at Antwerp reaches 4.07 m NAP two times a year, a level of 4.22 m NAP once every year.

Since the simulation period is approximately 4 weeks, the effect of the spring-neap tidal cycle is included in the mean water level values, as well as a broad range of the upstream discharges. New upstream and downstream boundary conditions were specified for this period. All other input parameters were left the same as in the calibrated model.

7.2.2 Boundary conditions

The water levels at Cadzand and Westkapelle (HMCZ database) are used as downstream boundary conditions. The NEVLA model has several upstream boundaries. The discharges at these upstream boundaries are available from the Hydrometry group of Flanders Hydraulics Research. The daily discharge series for a simulation period are available for Zenne – Zemst, Dijle – Haacht, Grote Nete – Itegem, Kleine Nete – Grobbendonk and Scheldt - Merelbeke. 10 min discharge series are available for Scheldt – Dendermonde and for the Bath canal. Zero discharge is specified for Durme – Waasmunster, Schelde – Gentbrugge and Bovenschelde – Zwijnaarde.

Wind is included in the model run. Wind data are available from the Hydro Meteo Centrum Zeeland (HMCZ) database. The wind data measured at the station Hansweert are imposed as a uniform wind field influencing the whole model area. This data consist of wind magnitude (10 min average value) and direction (10 min average value in degrees towards North).

7.2.3 Results of the model validation

The analysis was based on a comparison of the measured and calculated magnitude and phase of the high and low waters. The high and low water values for the whole calculation period were determined and compared with the measured values in the same period. The average differences in the calculated and measured low and high waters were found for the whole simulation period (one month).

Furthermore, these differences were calculated for a short period with an extremely high water level (from 06/11/2002 10:00 to 08/11/2002 14:00). This was done in order to check if the model can simulate water levels correctly for a storm event.

Results for the entire simulation period

The results of the model validation for October – November 2002 are presented in Tables 7 and 8 and on Figures 52 - 55. The model performs well downstream Hemiksem. The average differences in magnitude and phase of high and low waters calculated for the entire simulation period are not high. The differences in magnitude do not exceed 8 cm, the differences in phase do not exceed 5 min. Upstream Hemiksem the model accuracy worsens. The high waters on average are lower than the measurements for all stations in the Upper Sea Scheldt, Rupel and its tributaries except Schoonaarde, Melle and Kessel. The low waters at all stations upstream Hemiksem are much lower than the measurements. The differences in some low waters at Wetteren and Melle exceed 50 cm (Figures 58 and 59). The differences in high water phase are small. The maximal differences of 16 min in low water phase are observed at Melle and Wetteren.

The average difference in high waters at Walem is smaller than 1 cm. However, the actual differences are larger than 20 cm at some moments (Figure 57). Nevertheless, the differences in most high waters at this station are not high. Opposite to this, the calculated low waters at Walem are constantly too low.

The average differences in high waters at Schoonaarde, Wetteren and Melle are small. However, the actual differences in high waters at these stations are much larger (Figures 58 and 59). They vary in time from positive to negative values and the average differences become close to zero. This is not the case for the stations downstream Hemiksem. The model accuracy is better there and the differences between the calculated and measured high and low waters are less than 5 to 10 cm for most high and low waters except the period with the storm event (Figures 60 and 61).

Therefore, the model validation showed that the calibrated model performs well downstream Hemiksem for a period with normal spring and neap tide. Upstream Hemiksem the differences between the calculations and measurements become larger. As explained in chapter 7.1, this can be related to the fact that only daily discharge time series were available at Merelbeke. From the sensitivity analysis (Ides et al., 2008) it was found that the use of daily averaged discharges at this location worsens the calculated discharges in the Upper Sea Scheldt up to Hemiksem compared to hourly averaged discharges.

Results for a short period with a storm event

The results of the analysis of the model accuracy for a short period with a storm event are presented in Tables 7 and 8 and Figures 52 - 55. The analysis shows that the calibrated model can not simulate a period with an extremely high spring tide very accurately. The differences between the calculations and measurements become high already at Baalhoek (11 cm). The calculated high and low waters are lower than the measurements for most stations. Only in the Upper Sea Scheldt and Kessel the calculated high waters are higher than the measurements. At Melle the calculated low waters are too high on average.

The high and low waters at most stations are delayed in the model. The maximal delay in the high water phase (16 min) is observed at Antwerp. The low waters in the Upper Sea Scheldt are delayed by 16 to 25 min.

The calibrated model does not simulate accurately a period with an extreme high water level. The accuracy of the model worsens in comparison to the period with normal tide. The reasons for this and the possibilities to improve the model accuracy for such circumstances should be studied more in the future. Some possible improvements are given here.

A first reason for the model not to reproduce extreme high waters in the Sea Scheldt correctly is the lack of controlled inundation areas in the model grid. These areas will be inundated only from a certain, relatively high water level on and their main goal is to decrease the extreme high water levels for a couple of centimetres, but they will also influence the level of the low waters. Since these areas are not included in the model, it is to be expected that the model will not be a reliable tool for these extreme water levels in the Sea Scheldt.

For the modelled high waters for example, the controlled inundation area of Paardeweide (located near Uitbergen) would have become active in reality. This controlled inundation area is inundated about once in a year during the period with the medium flood risk. The effect of the inundation of the Paardeweide area would have affected the measured high water levels in the upstream part of the estuary.

The extreme water levels that have been simulated in the model are events which happen once to twice a year. If a stronger storm is simulated in the model, the differences between the model results and measurements will be even larger since more controlled inundation areas will be flooded in reality and this effect will not be taken into account in the calculations. However, the high water levels in the model are reproduced too low compared to reality for the Western Scheldt and the Lower Sea Scheldt. The effect of including the inundation area would even decrease the calculated high water levels, and thus worsen the results of the model. In the Upper Sea Scheldt, the high water levels are calculated too high. As a consequence the introduction of inundation areas in this zone might improve the model results.

Another reason for the rather poor model accuracy in the Upper Sea Scheldt may be the use of the daily discharges at Merelbeke. The averaging of some important peak discharges throughout a day can worsen the model accuracy. The use of the 10 minute time series can significantly improve the model accuracy for the Upper Sea Scheldt area.

The low waters in the Upper Sea Scheldt during the extremely high water events are lower than the measurements for all stations except Melle during the storm period. On the contrary the high waters are higher than the measurements. It was analyzed how the model would react if the discharge at Merelbeke was increased by 20% respectively by 100%. It is expected that an increase of the discharge would affect the low waters more than the high waters because the flood flow is much larger than the upstream discharge.

The increase of the discharge at Merelbeke resulted in an increase of the high and low waters in the Upper Sea Scheldt (Figures 62 – 63). The high waters increased and became too high. Some low waters at Wetteren improved when the discharge was increased by 20%. However, some of them became too high. When the discharge was increased by 100%, the high and low waters in the Upper Sea Scheldt became too high. At stations located more downstream the changes were smaller because the discharge at Merelbeke is much smaller than the flood discharge at these stations. The analysis showed that the increase of the discharge did not help to improve the model accuracy.

A possible approach to improve the model accuracy during extreme storm events is to adapt the wind drag coefficient. This coefficient is used for the computation of the force on the water surface due to wind. If the coefficient increases than the wind effect on the water levels increases too. The wind direction is about 300 degrees during the period with extreme high water. This means that wind blows into the estuary and pushes the water. This can result in an increase of the high waters. However, the wind is not strong during the analyzed storm period (always less than 13 m/s). Thus, the increase of the wind drag coefficient in the model will probably not have an important effect on the results.

Finally it is mentioned that the model is not calibrated yet for the intertidal (and subtidal) areas. They are inundated during the flood period and can have an important effect on the water level during storm events. In the current model no distinction is made between the bed roughness of the channels and the roughness of the intertidal areas.

8 Suitable roughness field for scenario analysis

8.1 Introduction

The roughness field used for the final calibration run varies in space along the estuary as well as in the transversal direction (the bed roughness used for the ebb and flood channel is different). Possibly this roughness field is very strongly related to the bathymetry that is used in the model and it is valid only for this bathymetry used during the calibration. If we use a different bathymetry for the scenario analysis the roughness field to be used might change as well since because of its space varying character it is coupled with the morphological evolutions (for example if the ebb channel is on a slightly different location, the roughness field assigned to this ebb channel should be shifted as well).

Therefore, it is necessary to analyse if it is sufficient to use a uniform bed roughness field for the scenario analysis. Different roughness fields – with a rather small space varying distribution – were implemented and the accuracy of the model was compared with the measurements. The analysis was based on a comparison of the evolution of the water levels in time, measured versus calculated values. The high and low water values for the whole calculation period were determined and compared with the measured values in the same period. The average differences in the calculated and measured low and high waters were found (Tables 9 and 10, Figures 66 - 69). These differences for the new model runs with changed roughness were compared with the calibrated NEVLA model.

8.2 The calibration process

First, two uniform bed roughness fields were implemented in the model (run 1 and run 2). The analysis showed that the use of a uniform bed roughness value is not sufficient to obtain accurate results for the entire estuary. When a uniform roughness of 0.022 $m^{1-/3}s$ was used (run 1), the differences between the calculations and measurements became large already at Terneuzen for the low waters and at Hansweert for the high waters. The high waters were too high at all stations except Melle. The low waters were too low at most stations. Furthermore, at most stations both high and low waters were observed earlier in the model than in reality. In the Upper Sea Scheldt the low waters were observed later than in reality.

The model run 2 with a uniform roughness of 0.025 $m^{1-/3}s$ resulted in more accurate water levels than run 1. The magnitude and phase of the high and low waters were accurate downstream Hemiksem. Upstream Hemiksem the differences became larger. The high waters were lower than the measurements; the low waters were higher than the measurements in the Upper Sea Scheldt. The low waters at Boom and Walem were accurate; however, the high waters at these stations were too low. Therefore, runs 1 and 2 showed that it is not sufficient to use a uniform roughness field for the entire estuary. In all next model runs a uniform roughness of 0.025 $m^{1-/3}s$ was used only downstream Schelle. Upstream Schelle the bed roughness field was adapted.

In run 3 the roughness was decreased to 0.022 $m^{1-/3}s$ upstream Schelle and to 0.024 $m^{1-/3}s$ in the Rupel and its tributaries. This was done in order to increase too low high waters and decrease too high low waters in the Upper Sea Scheldt. However, the results of run 3 showed that this decrease of the roughness was not enough to improve the model results.

Therefore, in run 4 the roughness was decreased even more. It was assigned to 0.020 $m^{1-/3}s$ upstream Schelle and 0.022 $m^{1-/3}s$ for the Rupel and its tributaries. This helped to improve the high waters in the Upper Sea Scheldt. However, the low waters at Wetteren and Melle became too low. The high waters in the Rupel and its tributaries improved just a little, while the low waters decreased.

In run 5 the roughness of 0.018 $m^{1-/3}s$ was used between Schelle and Temse and for the Zenne river; 0.02 $m^{1-/3}s$ upstream Temse and for the rivers Rupel, Dijle and Nete; 0.024 $m^{1-/3}s$ for the Durme. This helped to improve (increase) a little the high waters in the Rupel and the Upper Sea Scheldt. The low waters in the Upper Sea Scheldt almost did not change and they decreased and became too low in the Rupel.

The roughness field used upstream Schelle in run 6 is shown on Figure 65. Downstream Schelle a uniform roughness of 0.025 $m^{1-/3}s$ was used (Figure 64). This roughness field resulted in the smallest differences between the model output and measurements for the most stations in comparison to the previous runs with simple roughness fields (Tables 9 and 10, Figures 66 - 69).

8.3 Conclusion

The bed roughness field from run 6 can be used for the scenario analysis. It is uniform downstream Schelle and varies in space upstream Schelle. This roughness field is rather simple: it does not vary in the transversal direction (there is no different roughness for ebb and flood channel). We can expect that it is valid for different bathymetries.

However, if the same bathymetry as for the calibrated model is used, it is better to use the roughness field from the calibrated model. This roughness field produces the best results for this bathymetry.

9 References

Adema, J., (2006). Evaluatie van hydraulische modellen voor operationele voorspellingen. Deelopdracht 3: Afregelen van Vlaamse rivieren in het Kustzuid model en vergelijking Kalman sturing. Rapport Alkyon A1401R3r2, in opdracht van WL Borgerhout (M.729-09).

Hartsuiker, G., van Banning G., (2004). 2Dh NEVLA-Scheldemodel. Bouw en afregeling stromingsmodel.

Ides, S.; Vanlede, J.; De Mulder, T.; Mostaert, F., (2008). Vervolgstudie inventarisatie en historische analyse van slikken en schorren langs de Zeeschelde – Gevoeligheidsonderzoek 2D modellen. Ref. WL2008R713_21_2rev2_0.

Jeuken, C.; Hordijk, D.; Ides, S.; Kuijper, C.; Peeters, P.; de Sonneville, B.; Vanlede, J., (2007). Koploperproject LTV O&M – Thema Veiligheid – Deelproject 1. Inventarisatie historische ontwikkeling van de hoogwaterstanden in het Schelde estuarium. WL Rapporten, 756_03. Flanders Hydraulics Research & WL Delft Hydraulics, Antwerp, Belgium.

Maximova, T.; Ides, S.; Vanlede, J.; De Mulder, T.; Mostaert, F., (2009). Verbetering 2D randvoorwaardenmodel. Deelrapport 3: Calibratie bovenlopen. WL Rapporten, 753_09. Flanders Hydraulics Research, Antwerp, Belgium.

Vanlede, J., Decrop, B., De Clercq, B., Ides, S., De Mulder, T. en Mostaert, F., (2008a). Permanente verbetering modelinstrumentarium: verbetering randvoorwaardenmodel. Deel 1: gevoeligheidsonderzoek. Ref. WL2008R753_09rev1.

Vanlede, J., Decrop, B., De Clercq, B., Ides, S., De Mulder, T. en Mostaert, F., (2008b). Permanente verbetering modelinstrumentarium: verbetering randvoorwaardenmodel. Deel 2: afregelen van het Scheldemodel. Ref. WL2008R753_09rev1.

Verelst K.; De Mulder T.; Mostaert F., (2008). Zeeschelde tussen Gentbrugge en Melle. Verbetering hydrodynamisch-numeriek modelinstrumentarium. WL Rapporten, 800/1. Waterbouwkundig Laboratorium: Borgerhout, België.

Tables

Table 1. Overview of runs with grid adaptations in (Vanlede et al., 2008a)

Name	Grid description
A00	NEVLA (M 753-01)
A01b	Rough schematization of Rupel and its tributaries (M756-01 LTV slib)
A02	Rupel and its tributaries accordingly to KUSTZUID v5 (M729-09)
A03c	Grid adaptation for the Sea Scheldt (M800/1)
A07	NEVLA until Schelle. The Upper Sea Scheldt from M800/1, Rupelbekken accordingly to KUSTZUID v5 (M729-09)
A07b	A07, without flood areas

Table 2. Overview of runs with different grid resolution in (Ides et al., 2008)

Name	Grid description
Run110	Basis grid run 105
Run111	Basis grid 1x2 refined
Run112	Basis grid 2x2 refined
Run113	Basis grid 4x4 refined

Table 3. Overview of runs with different bathymetries in (Vanlede et al., 2008a)

Name	Bathymetry	Interpolation method
B01	Available samples for 2006	Gridcell Averaging
B02	Available samples for 2006	Closest
B03	Available samples for 2006	Max of near points
B04	Available samples for 2006	Min of near points
B05	Available samples for 2006	Shepard
B06	The same as B01, but Sea Scheldt based on ungrided measured samples	Gridcell Averaging
B07	Intertidal areas 20cm deeper	Gridcell Averaging
B08	Intertidal areas 20cm undeeper	Gridcell Averaging

Table 4. Overview of runs with different boundary conditions in (Ides et al., 2008)

Name	Boundary condition	Period
Run 301	5 min averaged discharges at Merelebeke	26jun – 9jul 2002
Run 302	Hourly averaged discharges at Merelbeke	26jun – 9jul 2002
Run 303	Daily averaged discharges at Merelbeke	26jun – 9jul 2002

Table 5. Overview of runs with different boundary conditions in (Vanlede et al., 2008a)

Name	Downstream boundary (discharge)	Downstream boundary (water level)	Wind	Simulation period
C00	Day (Melle)	CZ-WK	No	Jun 2002
C01	Day (Merelbeke)	CZ-WK	No	Jun 2002
C02	5 min (Merelbeke)	CZ-WK	No	Jun 2002
C03	Hour (Merelbeke)	CZ-WK	No	Jun 2002
B01	Day	CZ-WK	No	1-30 sept 2006
C05	Day	ZUNO	No	1-30 sept 2006
C06	Day	CZ-WK	Yes	1-30 sept 2006
C07	Day	ZUNO	Yes	1-30 sept 2006

Table 6. Overview of runs with different bed roughness in (Vanlede et al., 2008a)

Name	Formula	Block nr	Bed roughness
B01	Manning	Manning	0.022
D00	Manning	Uniform	0.025
D01	Manning	1	0.020
D02	Manning	2	0.020
D03	Manning	3	0.020
D04	Manning	4	0.020
D05	Manning	5	0.020
D06	Manning	6	0.020
D07	Manning	7	0.020
D08	Manning	8	0.020
D09	Manning	9	0.020
D10	Manning	10	0.020
D11	Manning	1	0.030
D12	Manning	2	0.030
D13	Manning	3	0.030
D14	Manning	4	0.030
D15	Manning	5	0.030
D16	Manning	6	0.030
D17	Manning	7	0.030
D18	Manning	8	0.030
D19	Manning	9	0.030
D20	Manning	10	0.030
D21	Chézy	Uniform	equivalent n=0.025
D22	White-Colebrook	Uniform	equivalent n=0.025
D23	Manning	-	n=f1(D)
D24	Manning	-	n=f2(D)
D25	Manning	-	Intertidal areas: 0.030; other areas 0.025
D26	Manning	Uniform	0.028
D003D	Manning (**3D** model)	Uniform	0.025

Parameter	Value	Simulation
Manning coefficiënt	0.025 $m^{-1/3}s^{-1}$	D00
Chézy coefficiënt	57 $m^{1/2}s^{-1}$	D21
Nikuradse roughness length	0.0685 m	D22

Table 7. Differences in magnitude of high and low waters for model calibration and validation (NV = water level could not be determined based on the used algorithm)

Station	Difference (calculation - measurement)							
	high water (cm)				low water (cm)			
	final calibration (June-July 2002)	validation (year 2006)	validation (Oct-Nov 2002)	validation for storm period (06-08/11/2002)	final calibration (June-July 2002)	validation (year 2006)	validation (Oct-Nov 2002)	validation for storm period (06-08/11/2002)
Vlissingen	2.4	4.5	3.4	2.4	1.0	-1.6	0.4	1.5
Terneuzen	-6.0	-1.7	-3.1	-6.5	0.6	-2.4	-1.7	-1.8
Hansweert	-4.3	2.5	-0.4	-6.4	-0.2	-4.8	-1.9	-2.5
Baalhoek	-7.2	-0.8	-3.0	-11.2	-4.8	-7.6	-7.3	-10.3
Schaar van de Noord	-7.4	-1.6	-2.0	-9.6	-4.0	-7.7	-5.7	-8.6
Bath	-1.2	-0.2	0.3	-11.0	-3.1	-7.0	-5.4	-8.8
Liefkenshoek	-6.9	-0.5	-2.8	-15.8	-0.3	-3.8	-4.1	-4.9
Antwerp	-6.7	2.0	-2.4	-17.9	1.5	-5.6	-2.9	-3.2
Hemiksem	-3.0	-8.9	-13.9	-20.9	-7.0	-28.1	-22.5	-23.3
Temse[1]	-11.9	-1.0	-7.1	-13.1	-21.1	-42.2	-32.2	-48.4
Schoonaarde	1.1	8.0	1.4	8.5	-9.1	-27.3	-26.5	-23.5
Wetteren	-3.5	-2.5	-1.1	10.8	-9.5	-9.2	-14.0	-25.7
Melle	-22.3	-15.0	4.3	23.4	-11.0	-0.3	-5.3	11.3
Boom	-6.6	-3.5	-7.4	-12.2	-15.0	-31.9	-25.1	-27.8
Walem	-10.5	5.1	-0.4	-2.1	-29.1	-34.8	-31.2	-32.3
Mechelen	-2.0	-0.6	-6.5	-9.7	NV			
Kessel	14.3	8.9	11.4	26.2	NV			

[1] The low waters at Temse are not accurate. The measurement instrument is located in a muddy environment, the level of the mud being approximately the level of the low water

Table 8. Differences in phase of high and low waters for model calibration and validation (NV = water level could not be determined based on the used algorithm)

Station	Difference (calculation - measurement)							
	phase of high water (min)				phase of low water (min)			
	final calibration (June-July 2002)	validation (year 2006)	validation (Oct-Nov 2002)	validation for storm period (06-08/11/2002)	final calibration (June-July 2002)	validation (year 2006)	validation (Oct-Nov 2002)	validation for storm period (06-08/11/2002)
Vlissingen	0	-2	-2	-1	3	3	1	3
Terneuzen	1	-2	0	3	5	6	3	6
Hansweert	4	2	2	1	7	6	6	8
Baalhoek	-1	-3	-1	5	3	1	1	-1
Schaar van de Noord	-1	-6	-2	5	3	1	0	-2
Bath	-1	-3	2	0	4	2	0	1
Liefkenshoek	4	3	2	5	6	3	3	8
Antwerp	8	6	5	16	6	4	2	8
Hemiksem	3	0	0	5	4	1	3	4
Temse[1]	3	1	0	0	2	2	4	25
Schoonaarde	3	1	-2	2	9	6	10	16
Wetteren	3	-2	0	11	12	9	16	25
Melle	10	3	0	1	15	16	17	17
Boom	7	2	1	2	5	3	1	6
Walem	5	2	0	2	2	0	1	2
Mechelen	13	2	3	3	NV			
Kessel	-3	-3	3	11	NV			

[1] The low waters at Temse are not accurate. The measurement instrument is located in a muddy environment, the level of the mud being approximately the level of the low water

Table 9. Differences in magnitude of high and low waters compared to measurements for the model runs with simple roughness fields (NV = water level could not be determined based on the used algorithm)

Station	difference in high water (calculation - measurement) (cm)							difference in low water (calculation - measurement) (cm)						
	calibrated model	run 1	run 2	run 3	run 4	run 5	run 6	calibrated model	run 1	run 2	run 3	run 4	run 5	run 6
Vlissingen	2.4	1.9	-3.1	-3.1	-3.2	-3.2	-3.1	1.0	-2.7	0.4	0.4	0.5	0.5	0.5
Terneuzen	-6.0	2.9	-5.9	-5.9	-5.9	-6.0	-6.1	0.6	-10.0	-4.2	-4.1	-4.0	-3.9	-3.9
Hansweert	-4.3	10.8	-1.2	-1.4	-1.6	-1.6	-1.7	-0.2	-13.7	-6.2	-6.0	-5.8	-5.7	-5.6
Baalhoek	-7.2	8.5	-5.8	-6.0	-6.2	-6.4	-6.4	-4.8	-18.7	-9.9	-9.6	-9.4	-9.3	-9.2
Schaar van de Noord	-7.4	9.4	-5.2	-5.5	-5.7	-5.9	-5.9	-4.0	-19.1	-9.3	-9.0	-8.7	-8.6	-8.5
Bath	-1.2	17.3	2.0	1.8	1.6	1.5	1.4	-3.1	-18.9	-9.2	-8.8	-8.5	-8.3	-8.3
Liefkenshoek	-6.9	16.4	-0.5	-0.9	-1.2	-1.5	-1.5	-0.3	-18.6	-7.8	-7.3	-6.9	-6.7	-6.7
Antwerp	-6.7	18.2	-0.8	-2.2	-3.1	-3.9	-4.0	1.5	-15.9	-2.3	-1.3	-0.6	-0.4	-0.5
Hemiksem	-3.0	20.0	-1.9	-3.8	-5.2	-5.5	-5.6	-7.0	-23.3	-6.6	-5.4	-4.5	-4.7	-5.0
Temse[1]	-11.9	10.2	-15.6	-15.4	-15.6	-14.5	-14.4	-21.1	-25.4	-12.0	-13.8	-15.0	-17.6	-18.2
Schoonaarde	1.1	10.0	-19.5	-10.9	-4.9	-3.5	2.6	-9.1	19.1	27.7	14.8	4.8	4.5	1.5
Wetteren	-3.5	7.0	-23.6	-12.0	-3.2	-1.8	-0.9	-9.5	6.1	17.7	0.6	-12.6	-12.5	-1.0
Melle	-22.3	-12.4	-46.5	-31.6	-20.2	-18.7	-25.3	-11.0	-7.6	4.9	-14.1	-28.6	-28.4	-7.4
Boom	-6.6	15.2	-9.7	-10.7	-10.8	-9.5	-9.5	-15.0	-20.7	-1.6	-2.7	-5.9	-10.3	-10.6
Walem	-10.5	9.4	-17.2	-17.5	-16.3	-13.6	-13.6	-29.1	-23.0	-4.6	-7.6	-14.4	-22.4	-22.6
Mechelen	-2.0	10.7	-16.4	-16.2	-14.7	-10.9	-10.9	NV						
Kessel	14.3	21.4	-5.5	-2.8	2.1	10.2	10.4	NV						

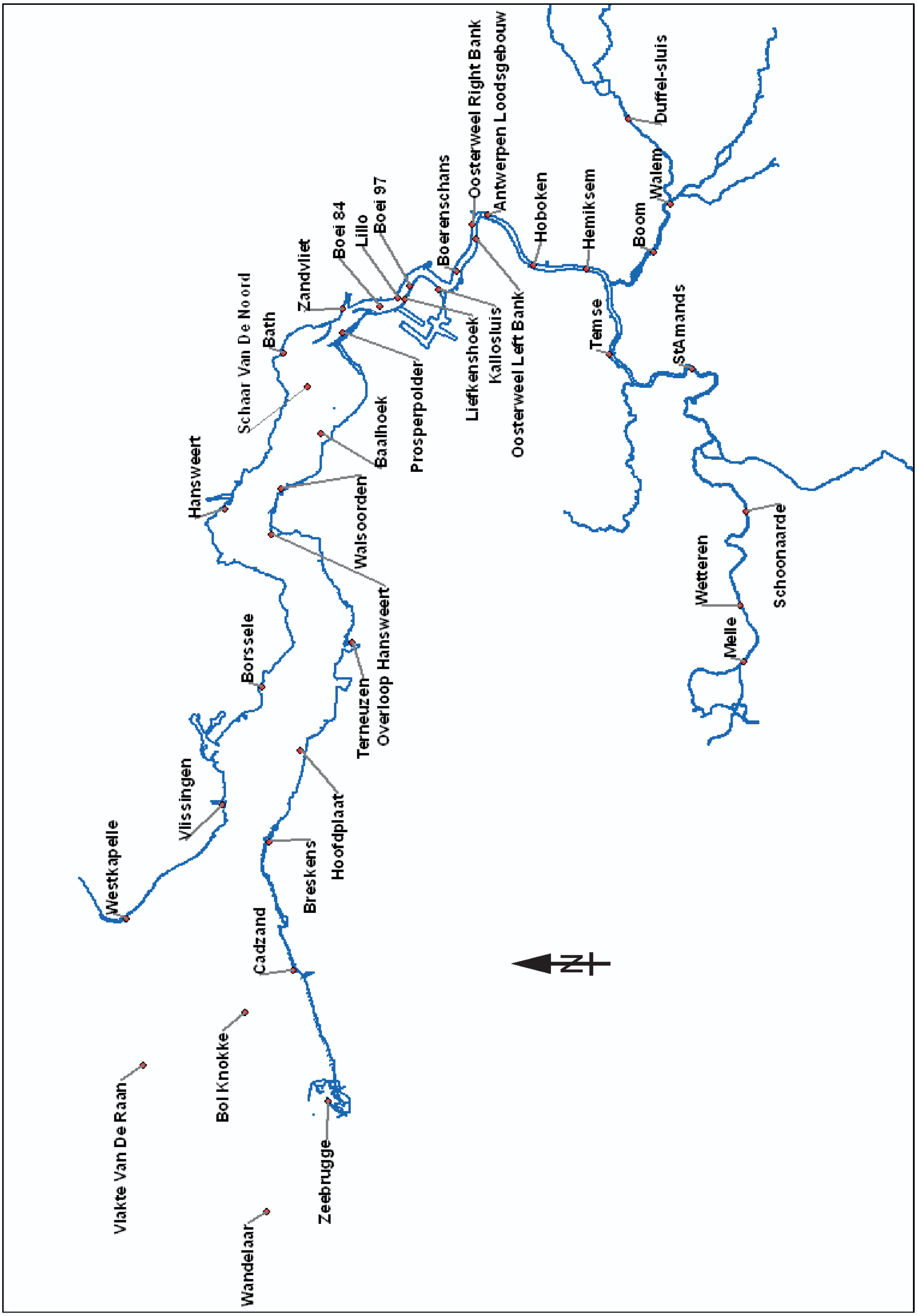
[1] The low waters at Temse are not accurate. The measurement instrument is located in a muddy environment, the level of the mud being approximately the level of the low water

Table 10. Differences in phase of high and low waters compared to measurements for the model runs with simple roughness fields (NV = water level could not be determined based on the used algorithm)

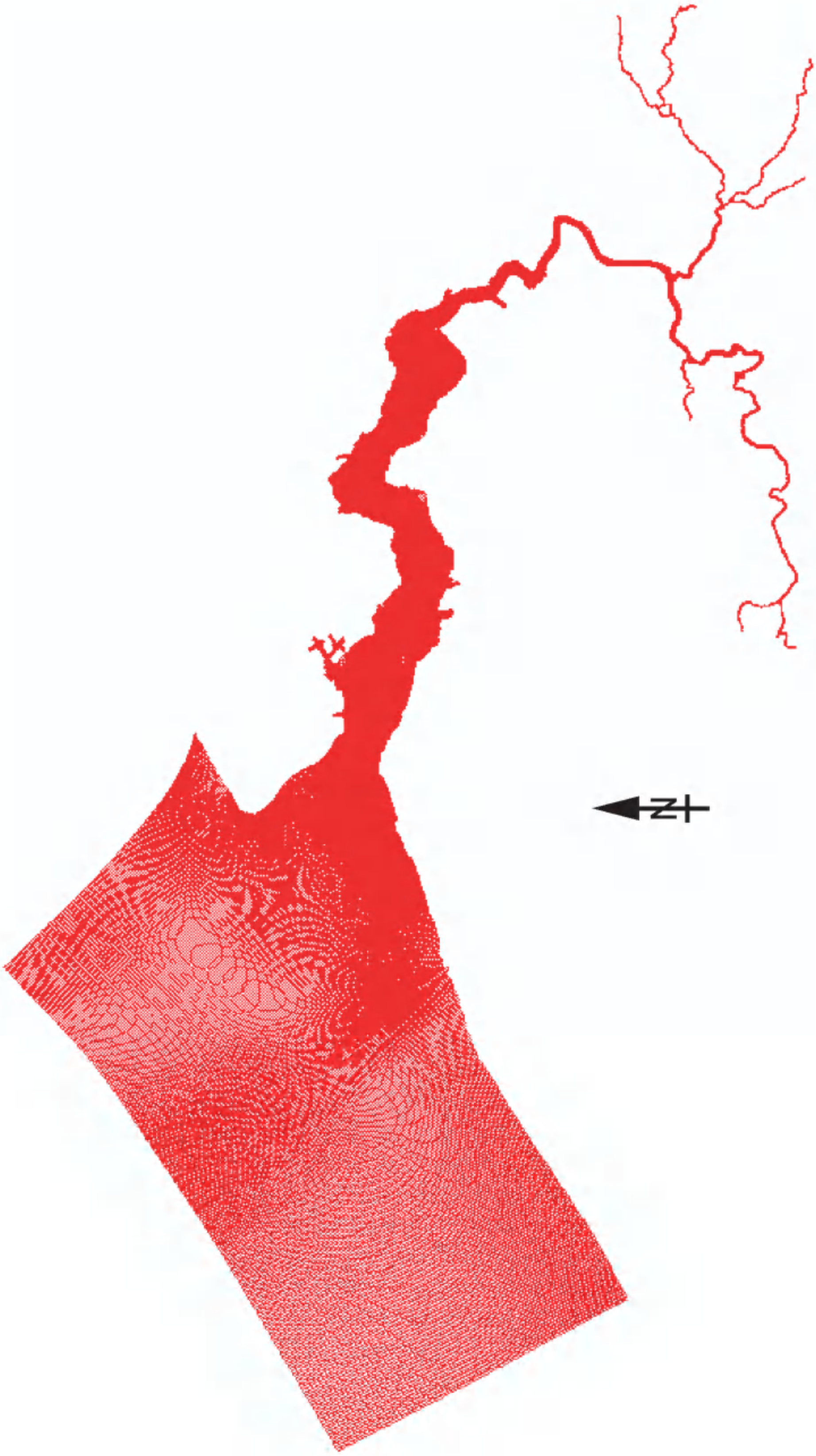
Station	difference in time of high water (min)							difference in time of low water (min)						
	calibrated model	run 1	run 2	run 3	run 4	run 5	run 6	calibrated model	run 1	run 2	run 3	run 4	run 5	run 6
Vlissingen	0	3	7	6	6	7	6	3	3	7	7	7	7	7
Terneuzen	1	1	5	4	5	5	4	5	-2	2	2	2	2	2
Hansweert	4	-4	0	0	0	0	0	7	-5	2	2	2	2	2
Baalhoek	-1	-4	0	0	1	0	1	3	8	1	1	1	1	1
Schaar van de Noord	-1	-5	1	1	2	1	1	3	-9	0	0	0	0	0
Bath	-1	-5	0	0	0	0	0	4	-11	-1	-1	-1	0	-1
Liefkenshoek	4	-5	1	1	1	1	1	6	-10	0	0	0	0	0
Antwerp	8	-2	6	4	5	5	5	6	-10	0	1	1	2	2
Hemiksem	3	-7	0	1	2	3	3	4	-12	0	1	2	2	2
Temse[1]	3	-6	1	2	3	2	2	2	-15	1	1	1	1	0
Schoonaarde	3	-6	6	2	0	0	-1	9	5	19	14	13	12	11
Wetteren	3	-6	6	2	0	0	-1	12	10	29	22	15	15	17
Melle	10	-3	9	5	1	1	2	15	10	30	19	17	16	23
Boom	7	-4	4	6	6	7	7	5	-7	5	5	5	4	4
Walem	5	-4	4	4	4	5	5	2	-6	5	6	4	3	3
Mechelen	13	-2	6	7	7	6	7	NV						
Kessel	-3	-9	4	5	2	-1	-1	NV						

[1] The low waters at Temse are not accurate. The measurement instrument is located in a muddy environment, the level of the mud being approximately the level of the low water

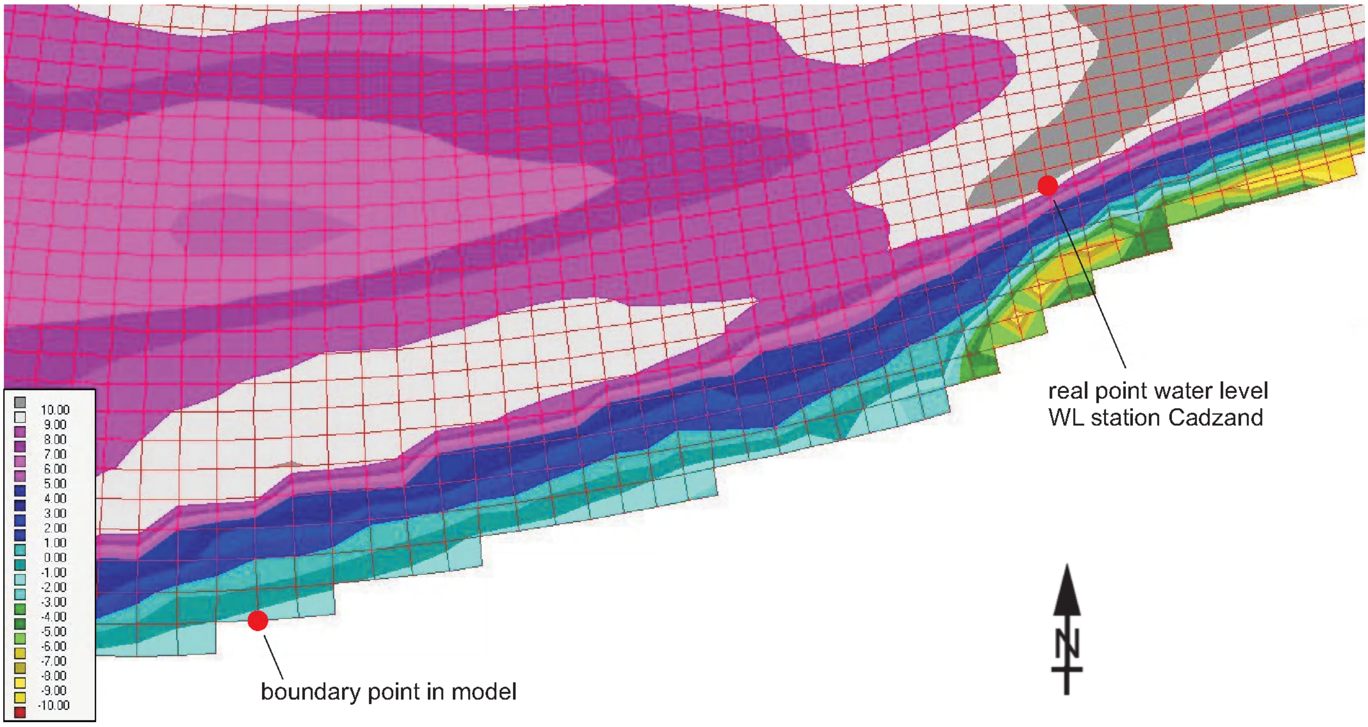
Figures



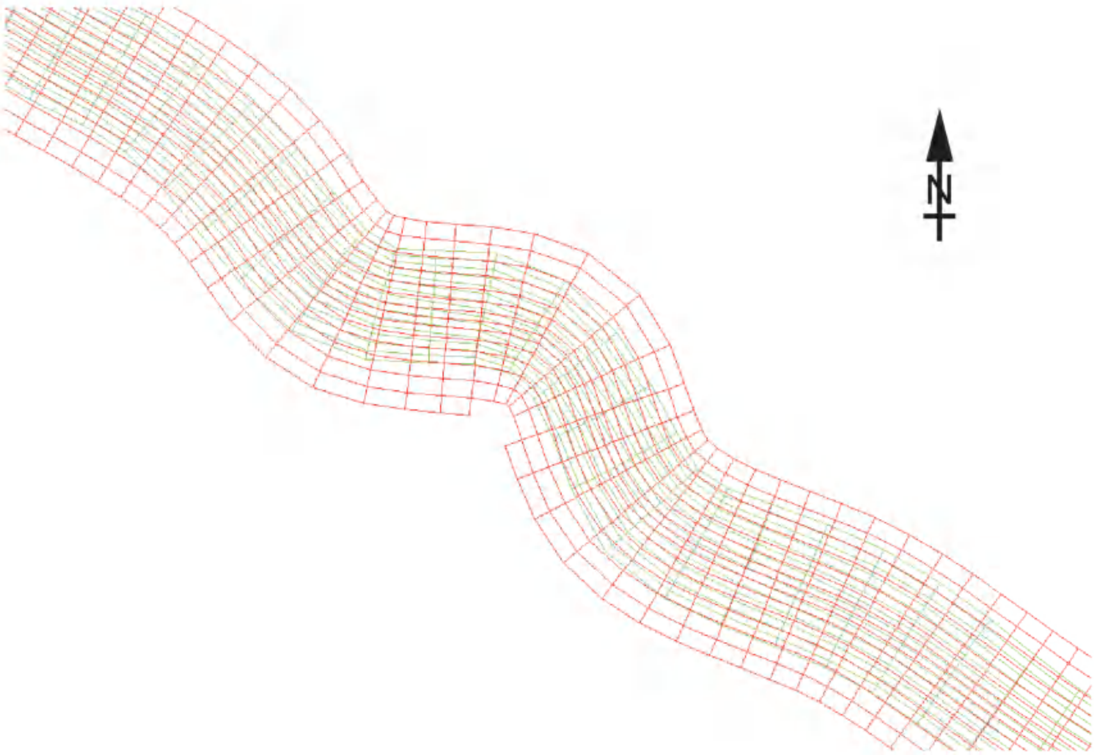
The Scheldt estuary - Water level measurement stations

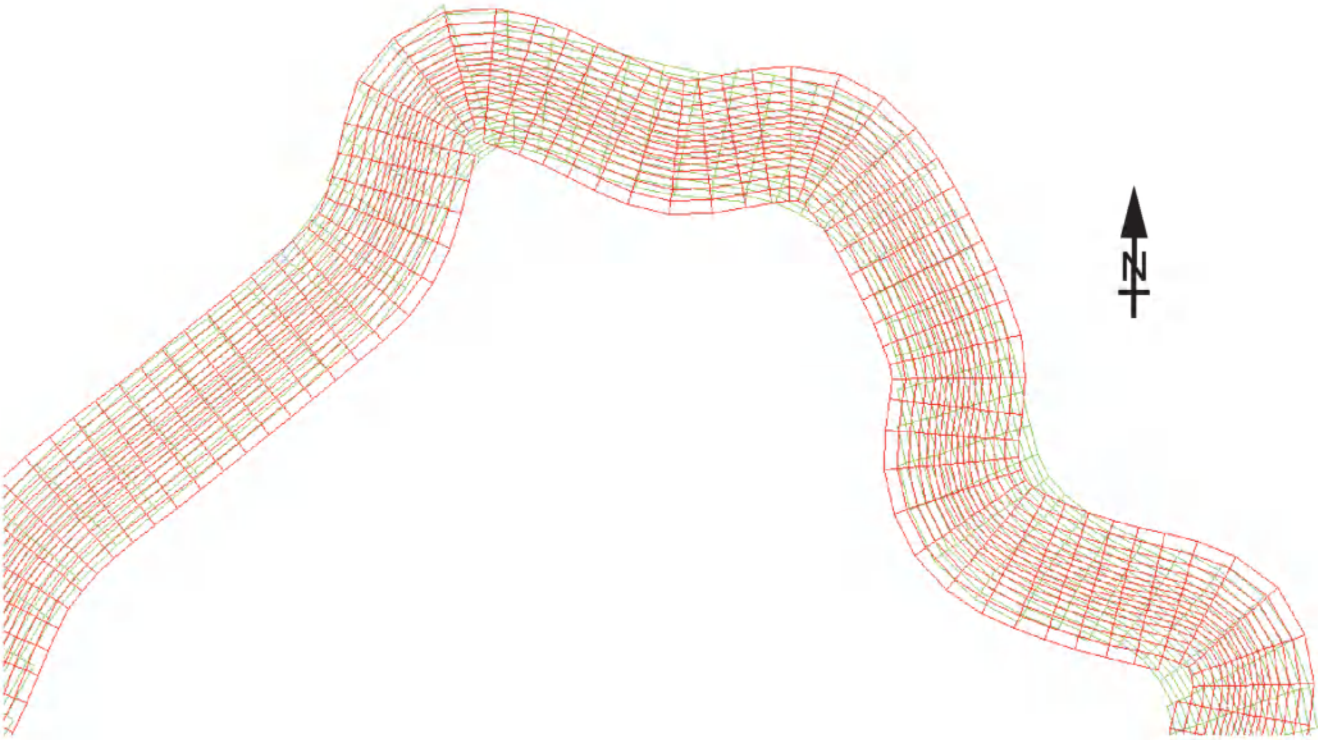


Grid of NEVLA model



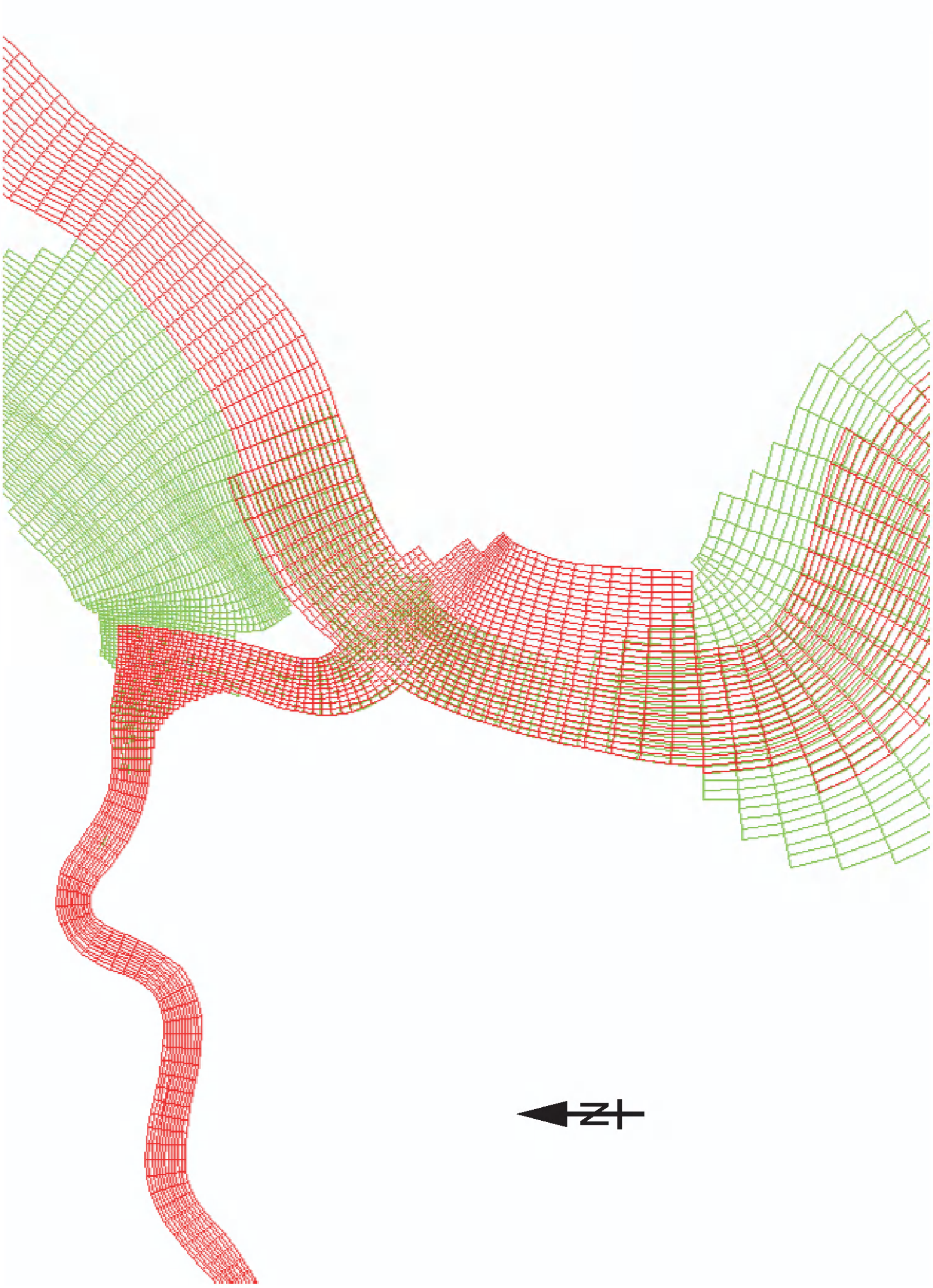
Location of the boundary point in model, located between Zeebrugge and Cadzand	bathymetry : m NAP



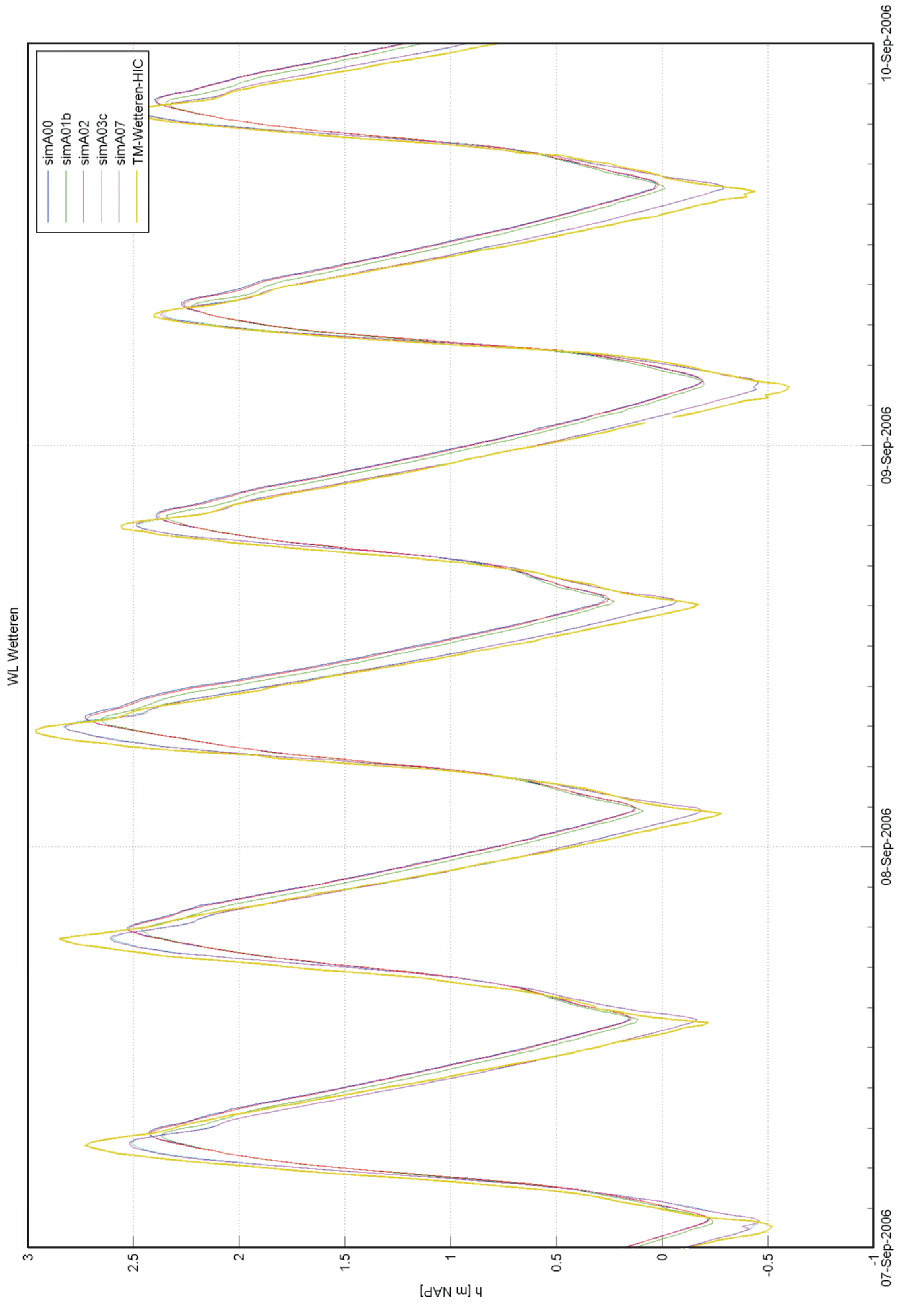


Grid adaptations in the tributaries of the Rupel river.
Grid A02 (red) and grid A00 (green)

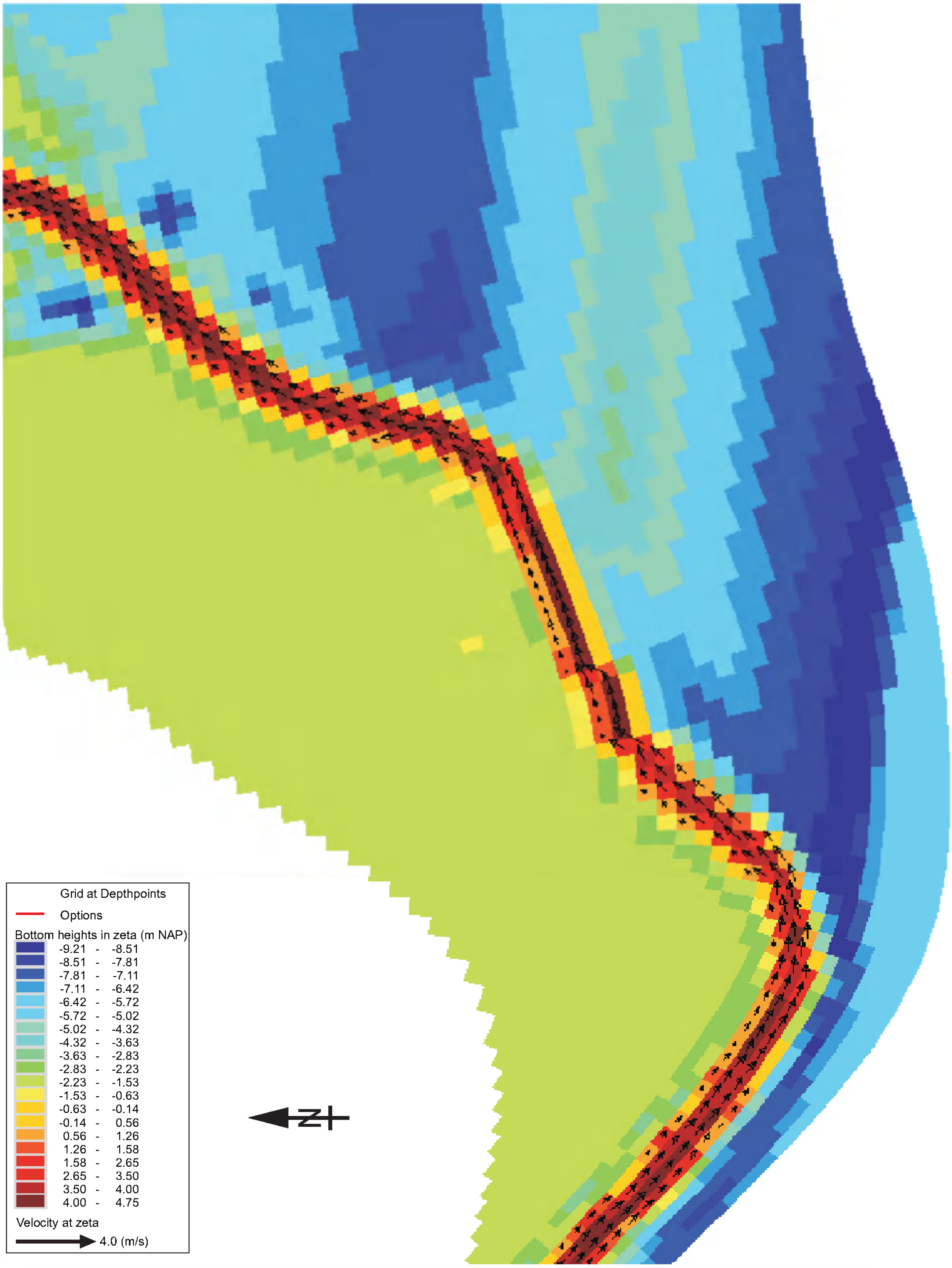
Grid adaptations in the Upper Sea Scheldt.
Grid A03 (red) and grid A00 (green)



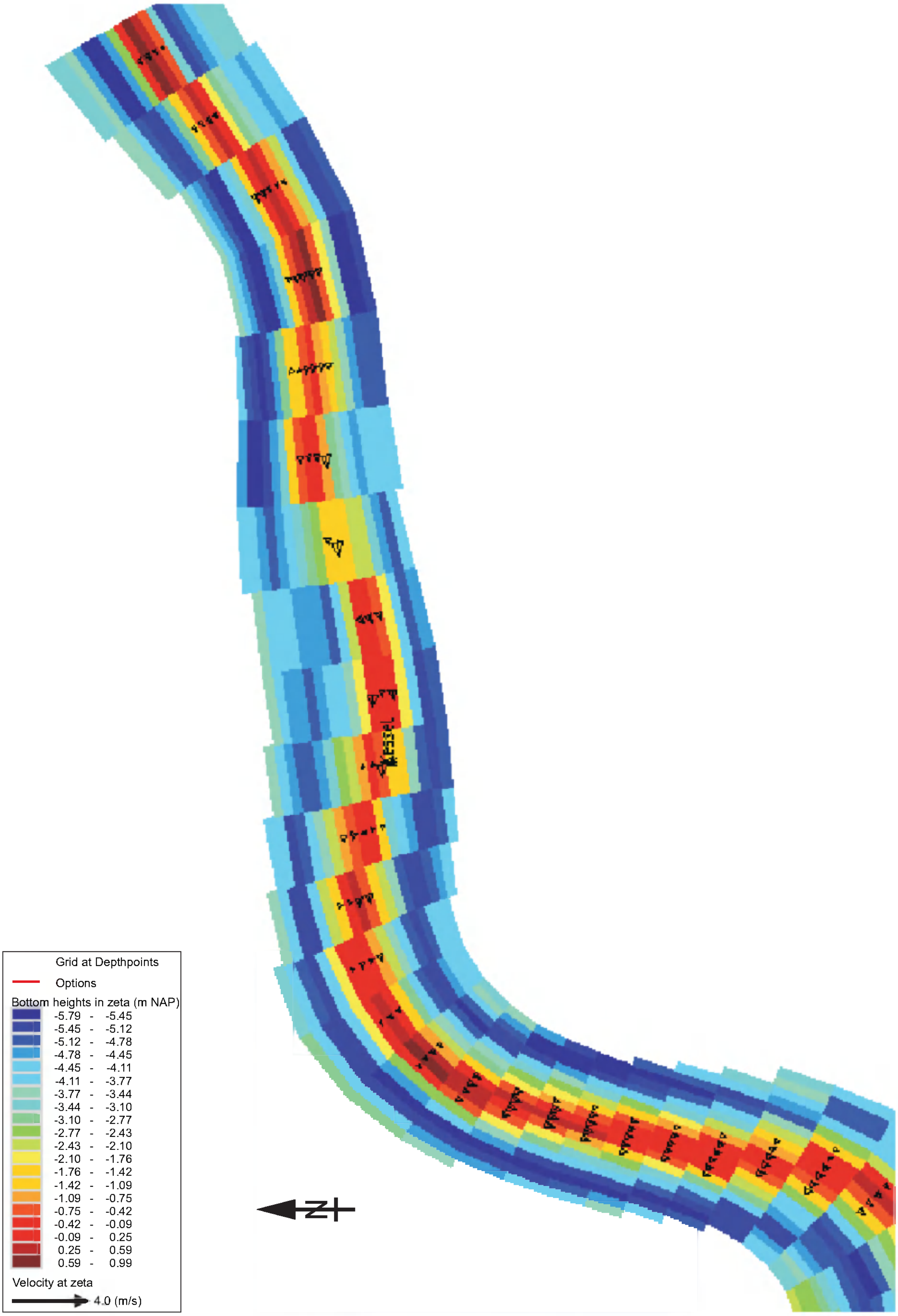
Grid adaptations in the Upper Sea Scheldt near Rupelmonde.
Grid A03 (red) and grid A00 (green)



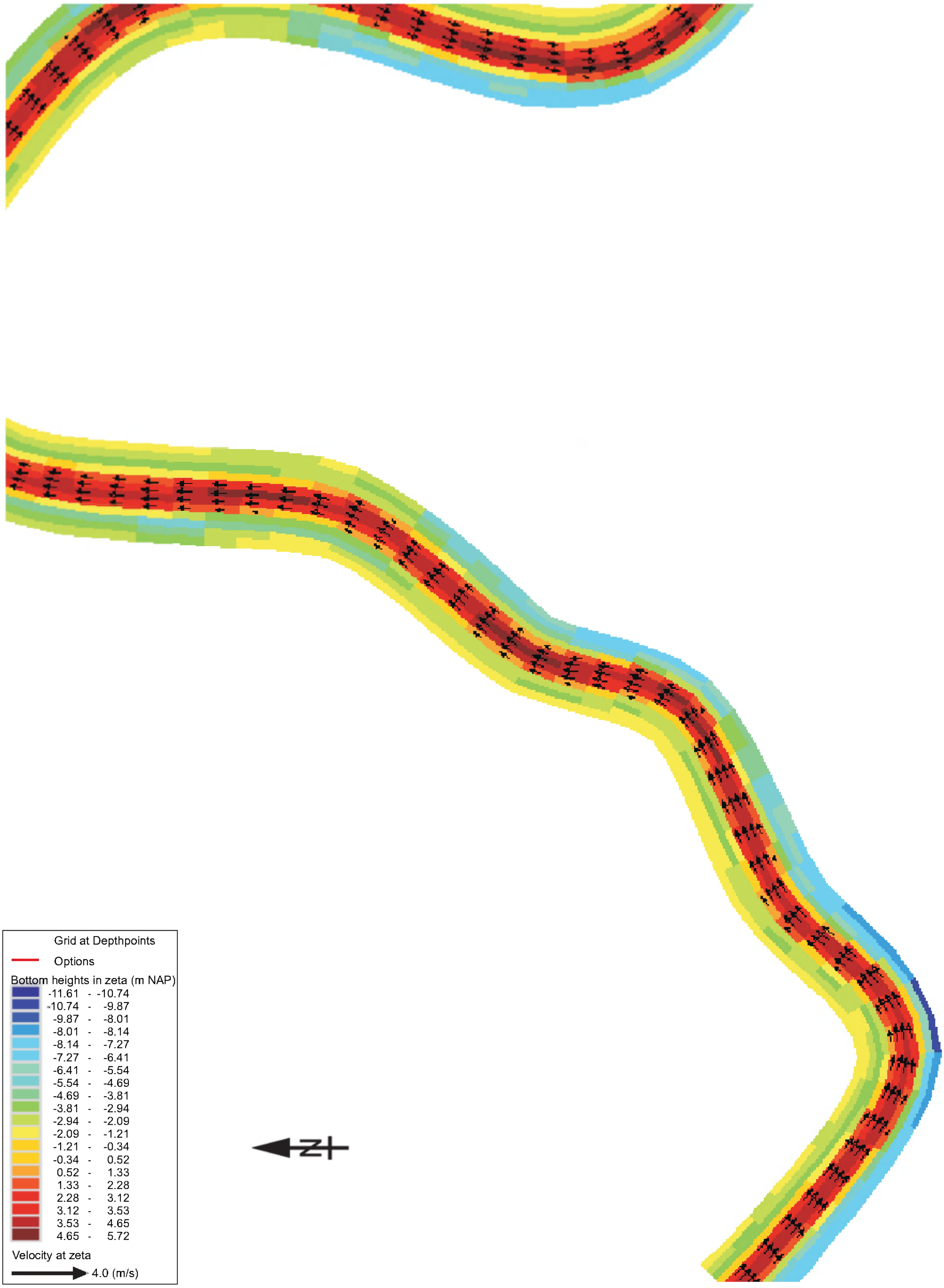
Measured and calculated water levels at Wetteren for model runs with different grids



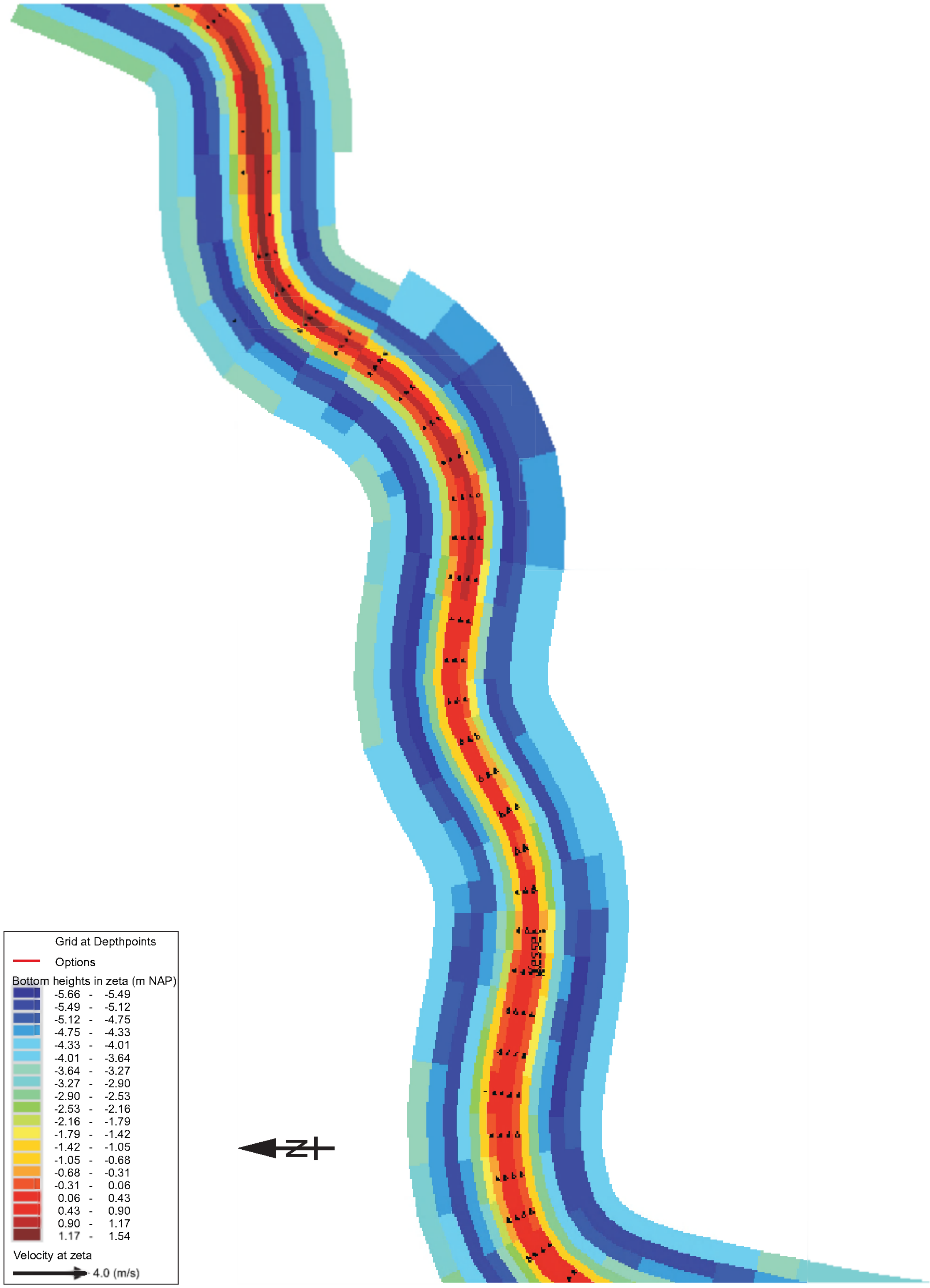
Model bathymetry and velocity near Uitbergen
(Original schematization in NEVLA)



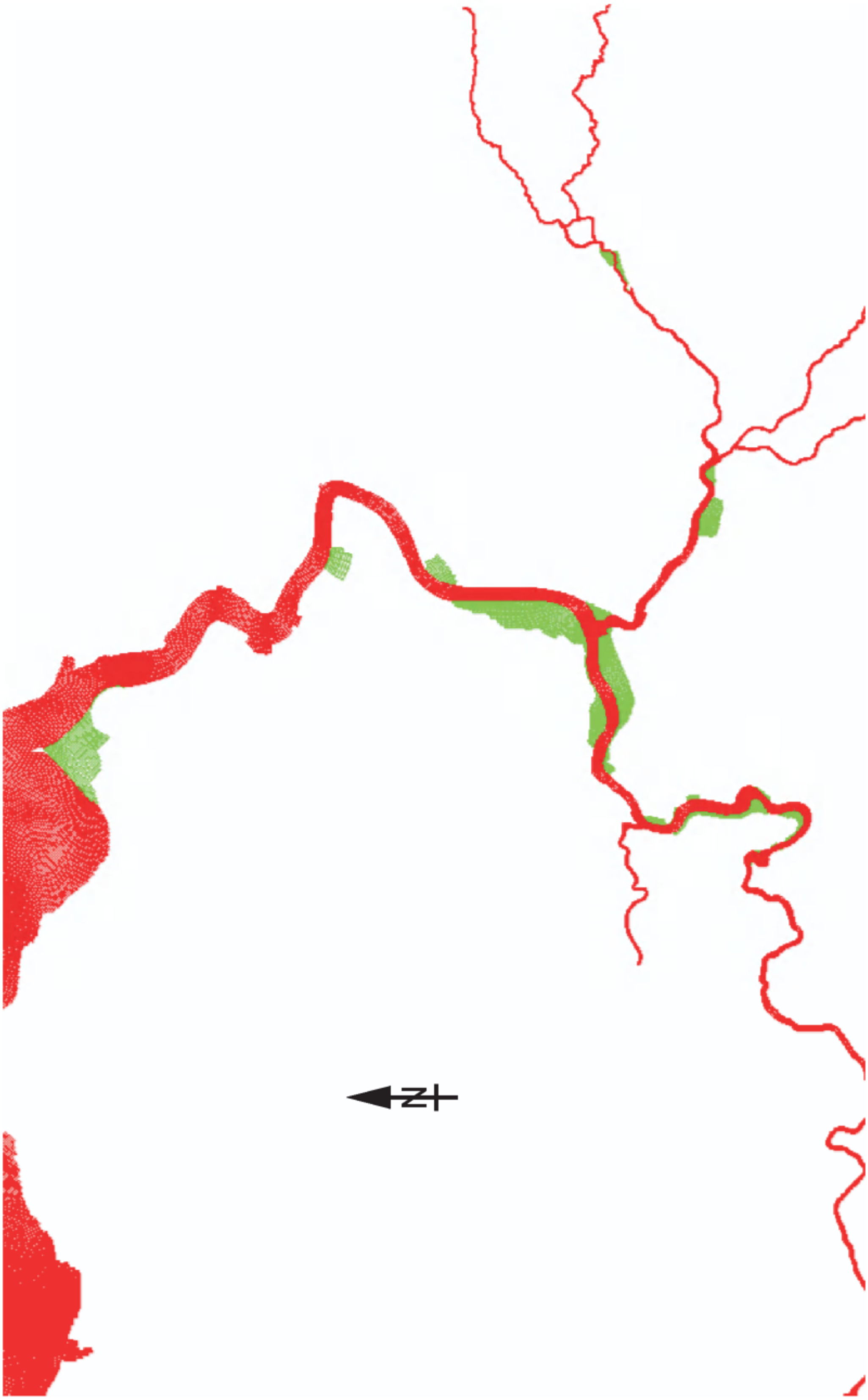
Model bathymetry and velocity near Kessel
(Original schematization in NEVLA)



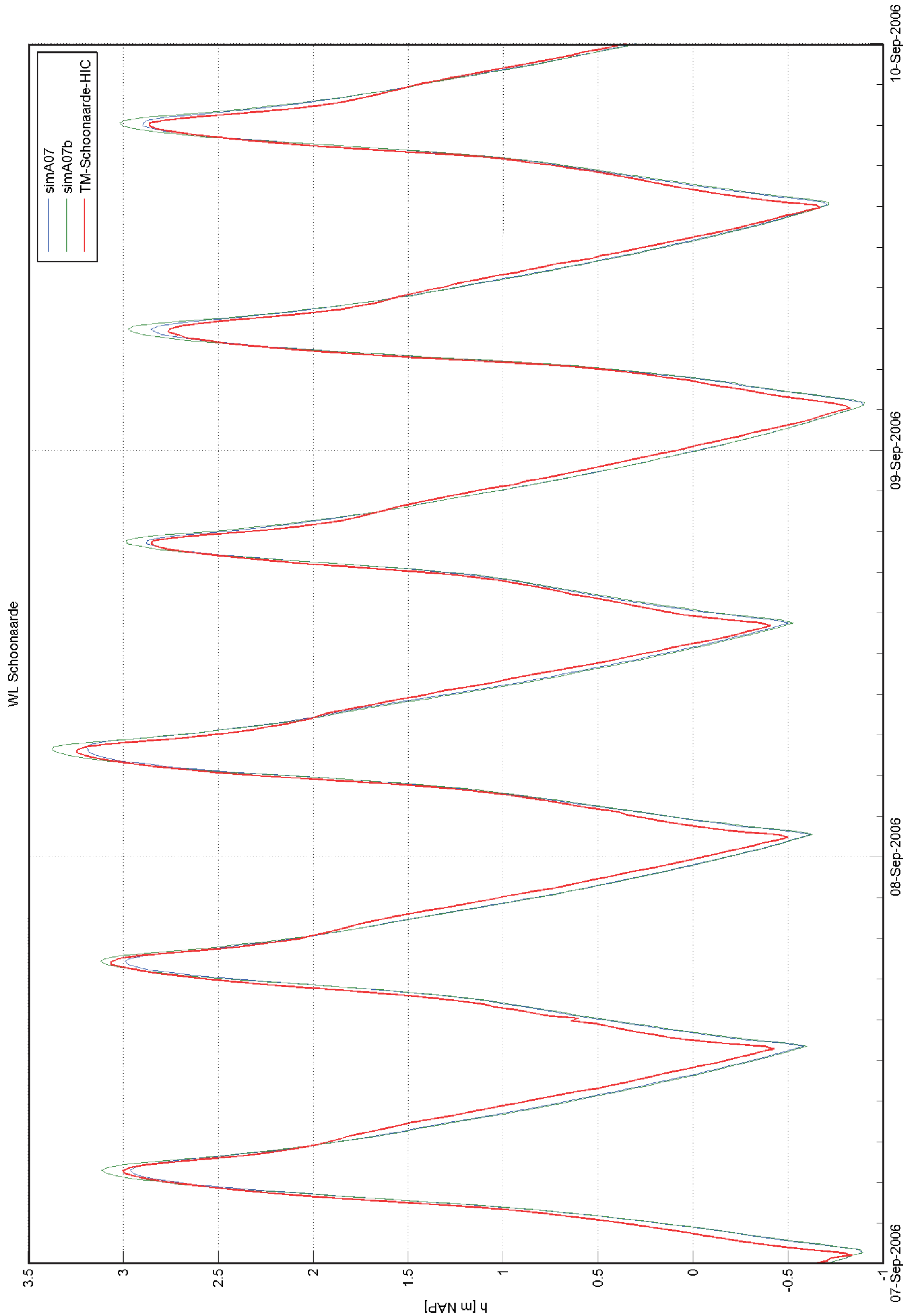
Model bathymetry and velocity near Uitbergen (improved schematization)



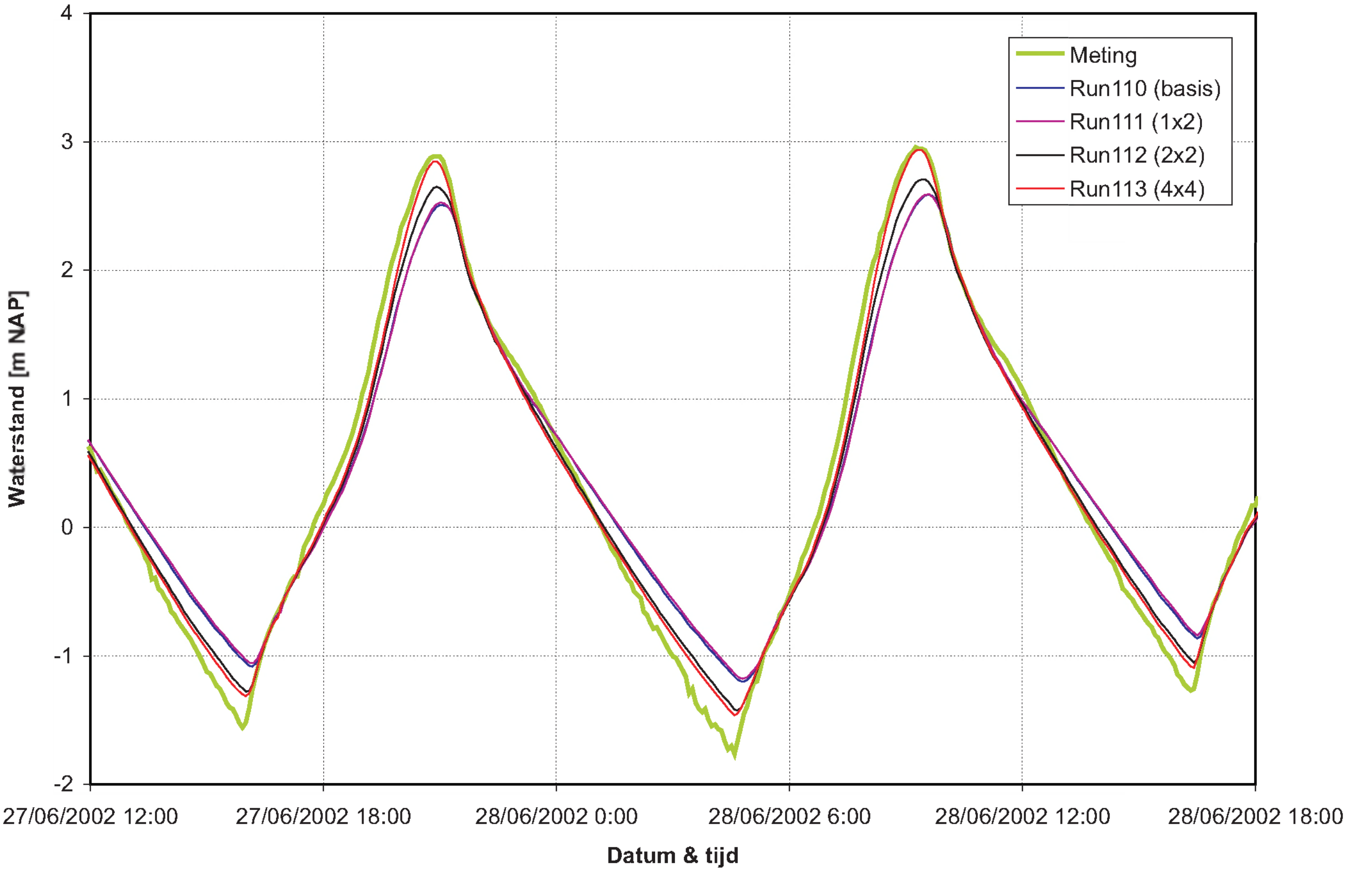
Model bathymetry and velocity near Kessel (improved schematization)

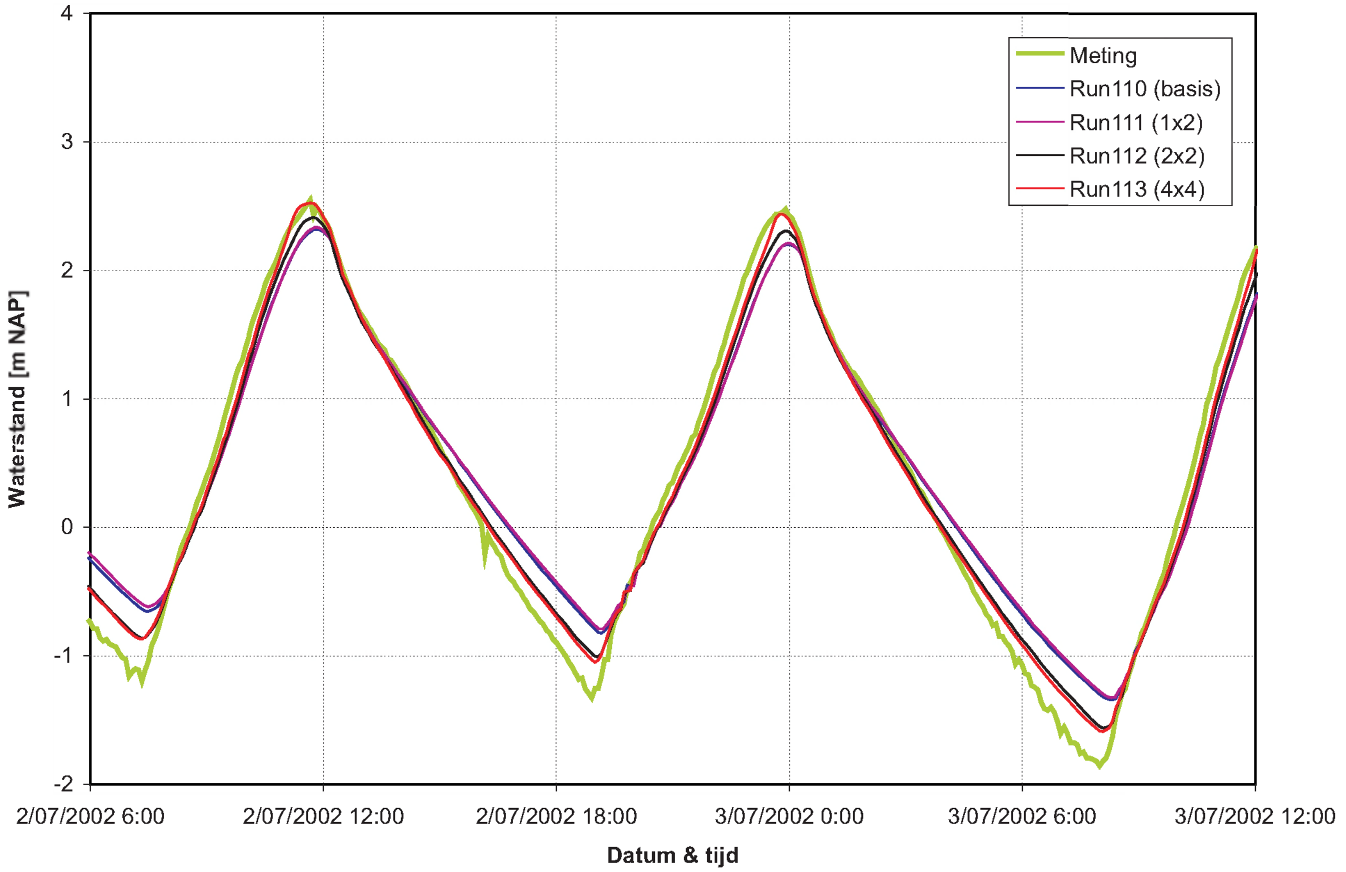


Areas outside dikes removed from the grid.
Grid A07 (green) and grid A07b (red)

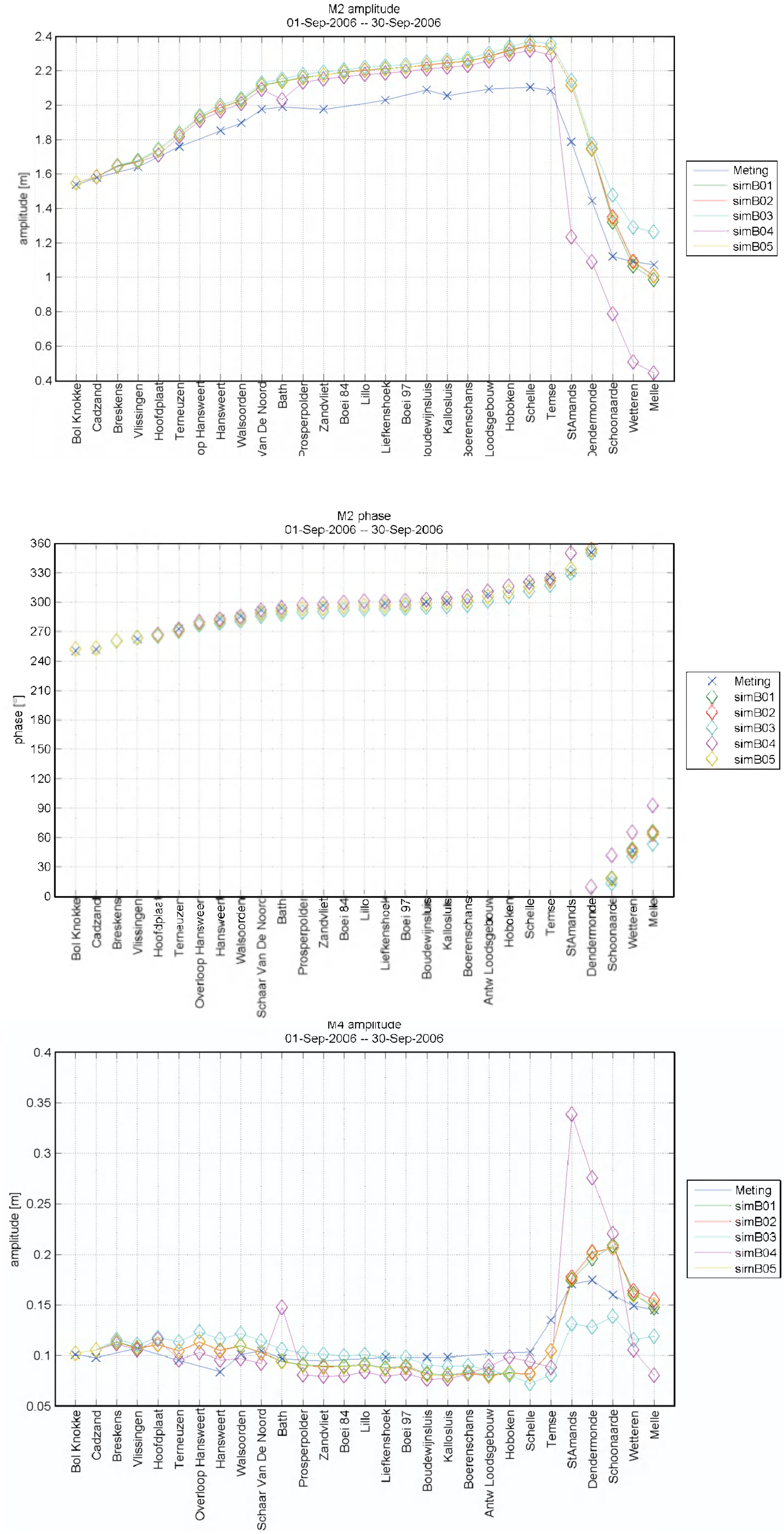


Effect of the removal of areas outside dikes from grid on the water levels at Schoonaarde

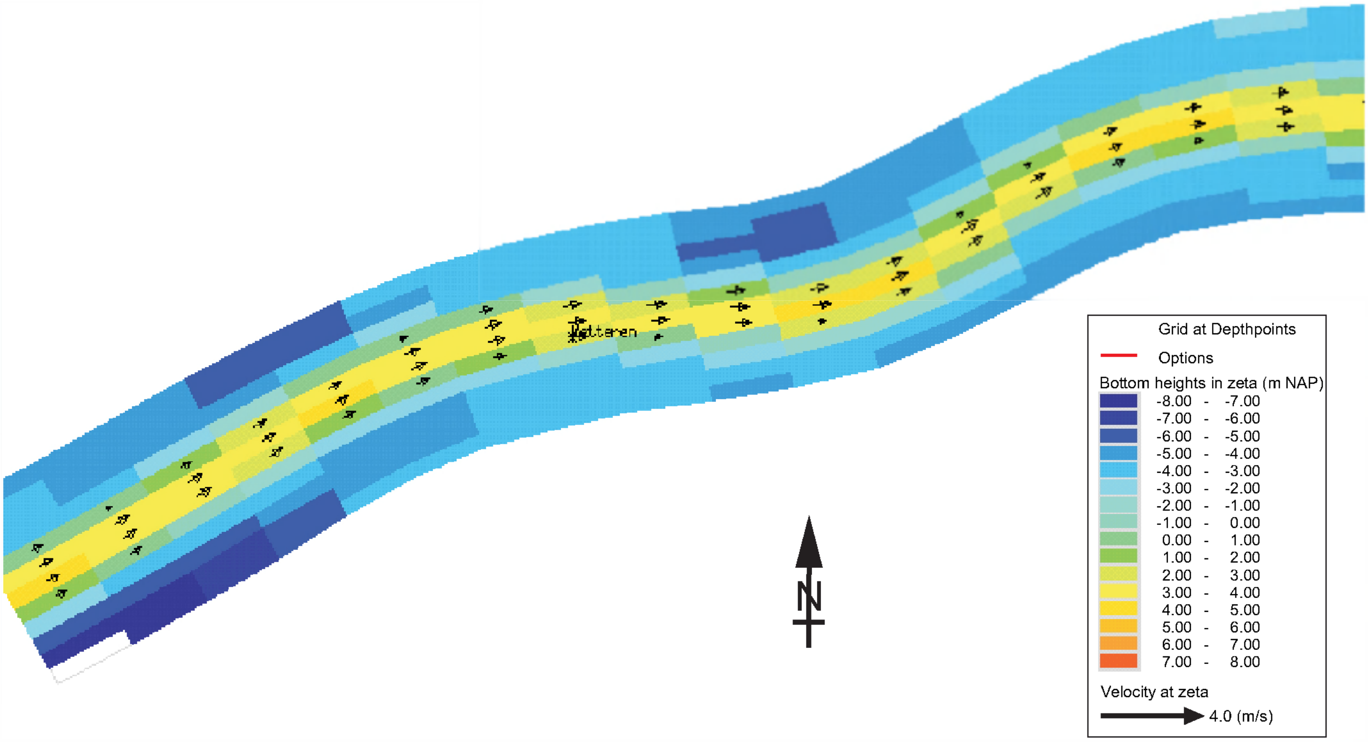


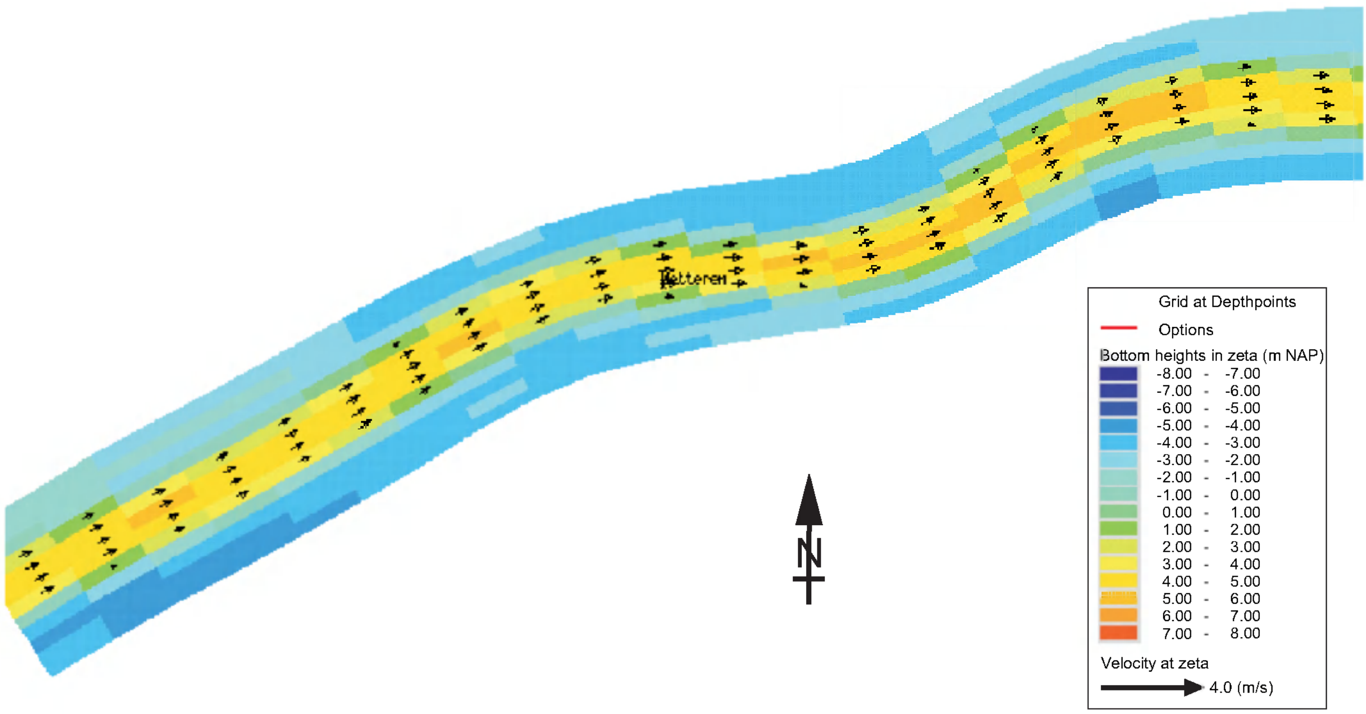


Influence of the grid resolution on water levels. Measured and calculated water levels at Schoonaarde

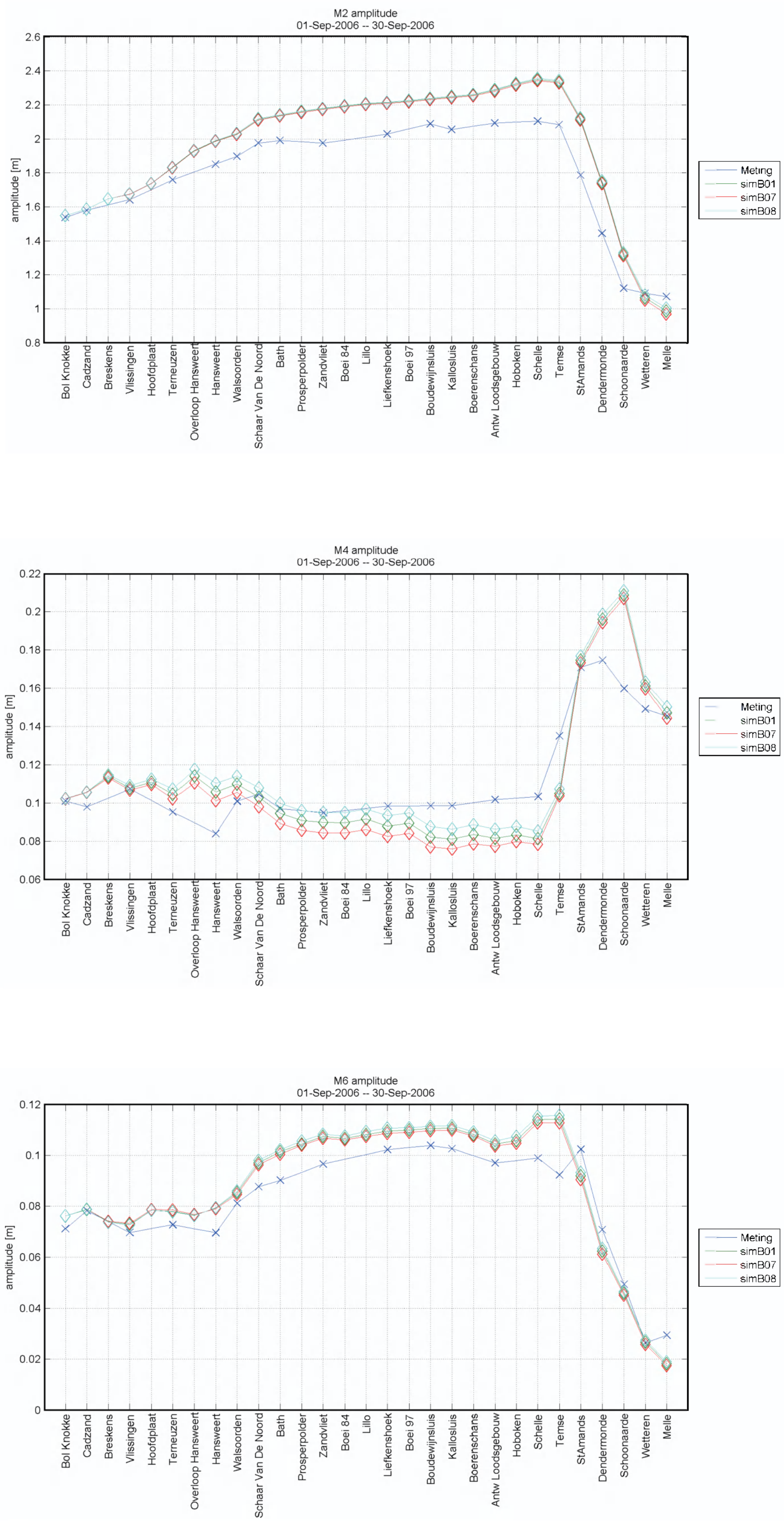


M2 amplitude and phase and M4 amplitude for runs B01 – B05

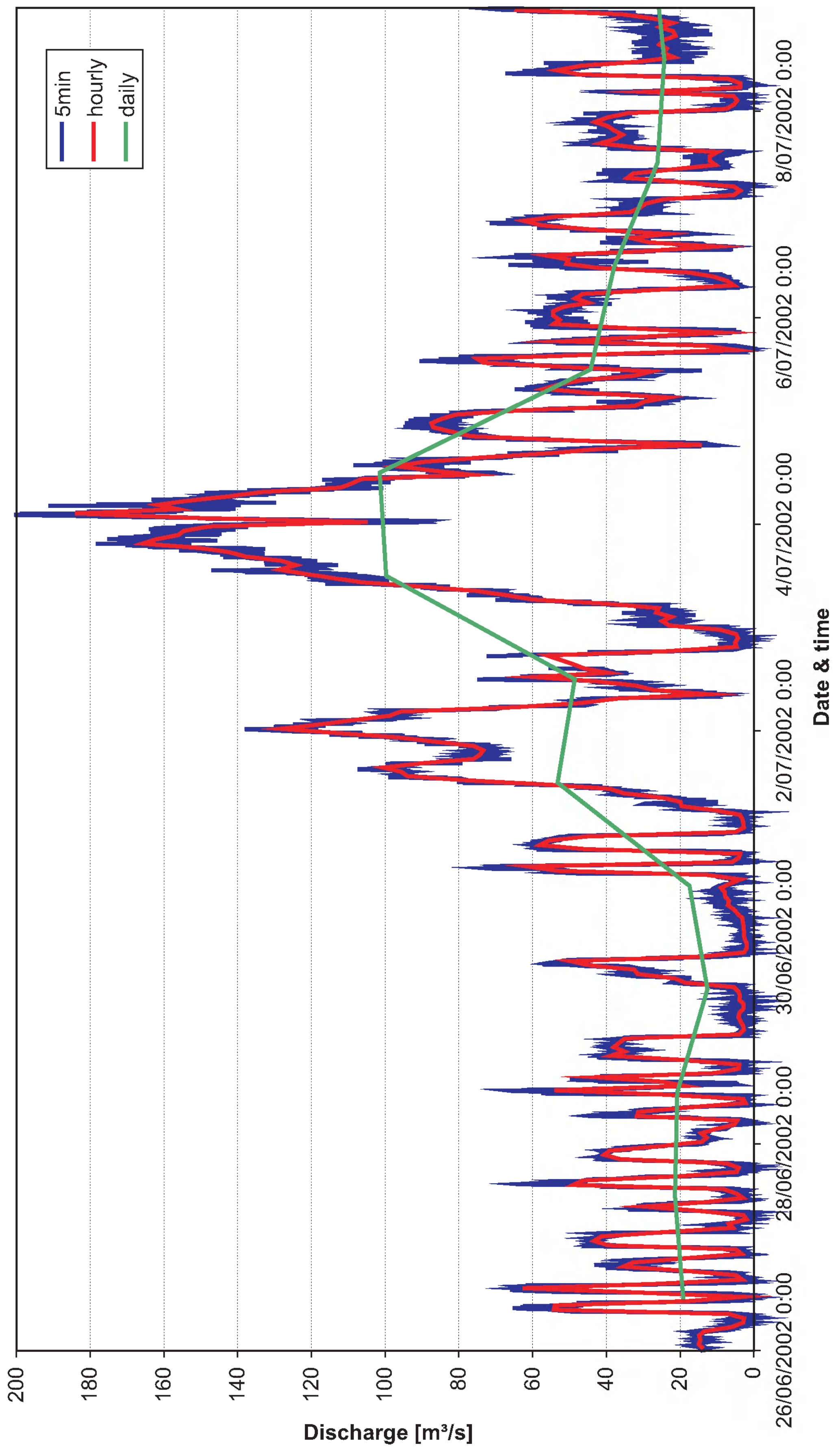




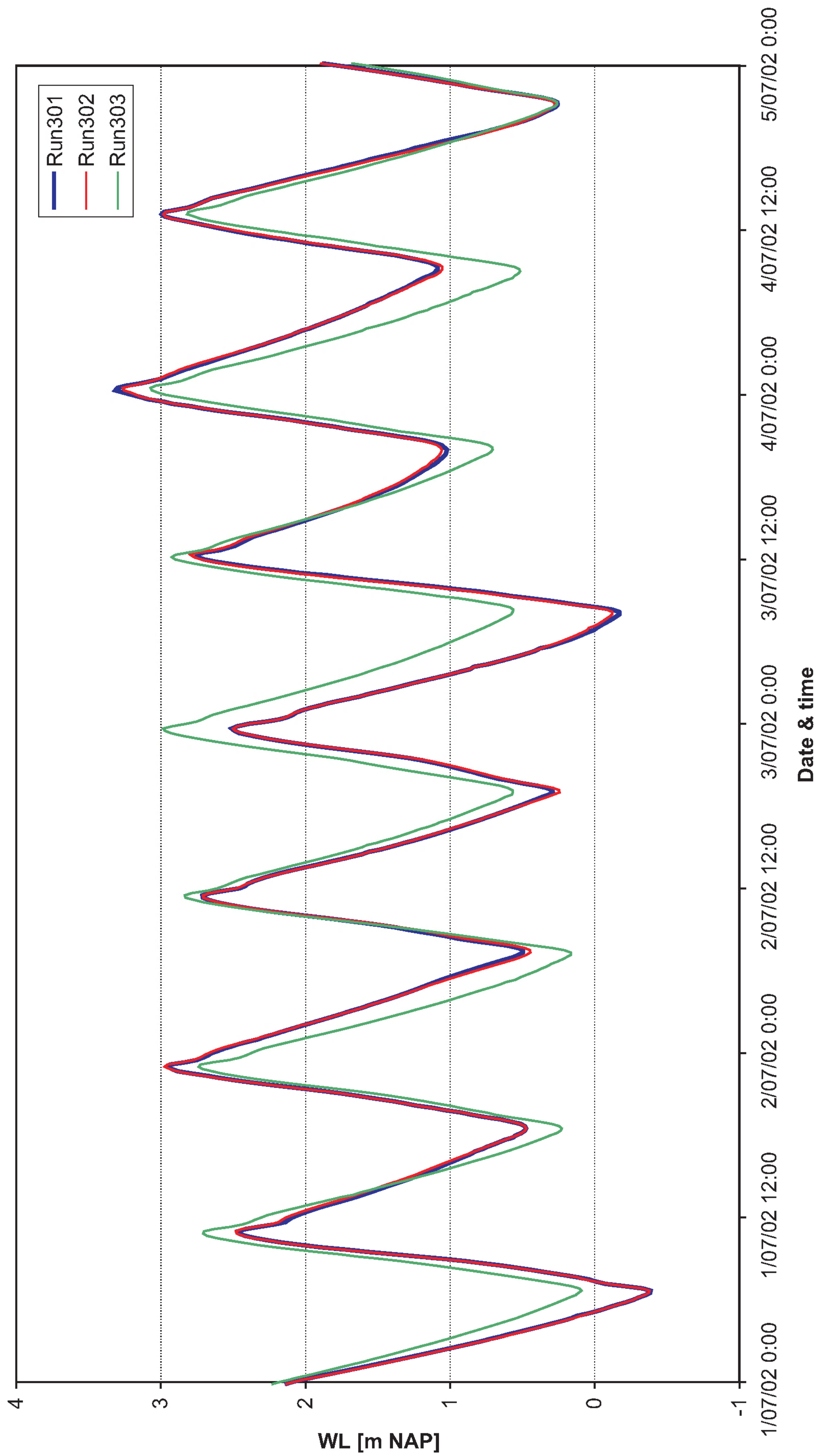
Bathymetry and velocity for runs B01 (above) and B03 (below)



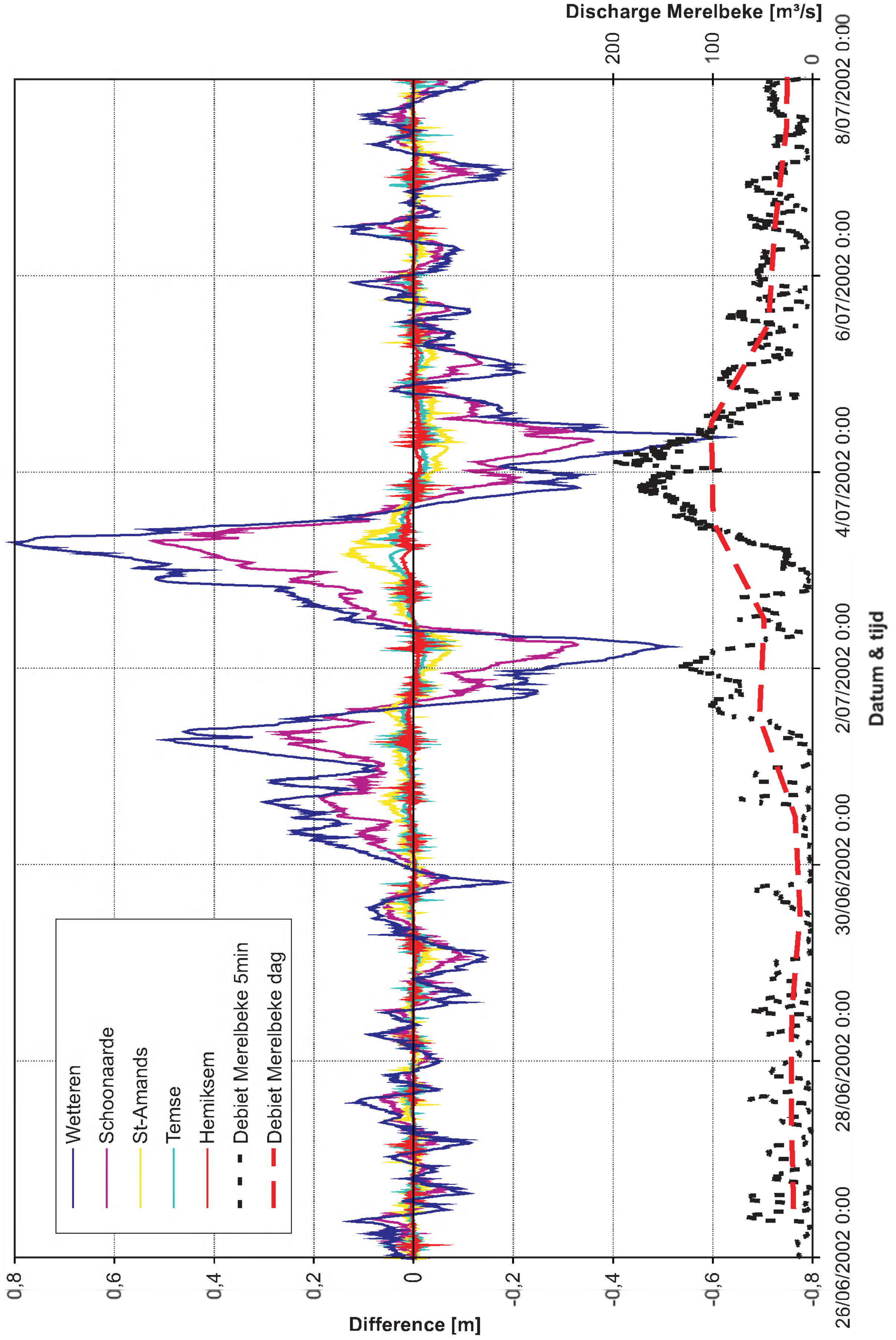
M2, M4 and M6 amplitude for runs B01, B07 (deeper tidal areas) and B08 (undeeper tidal areas)



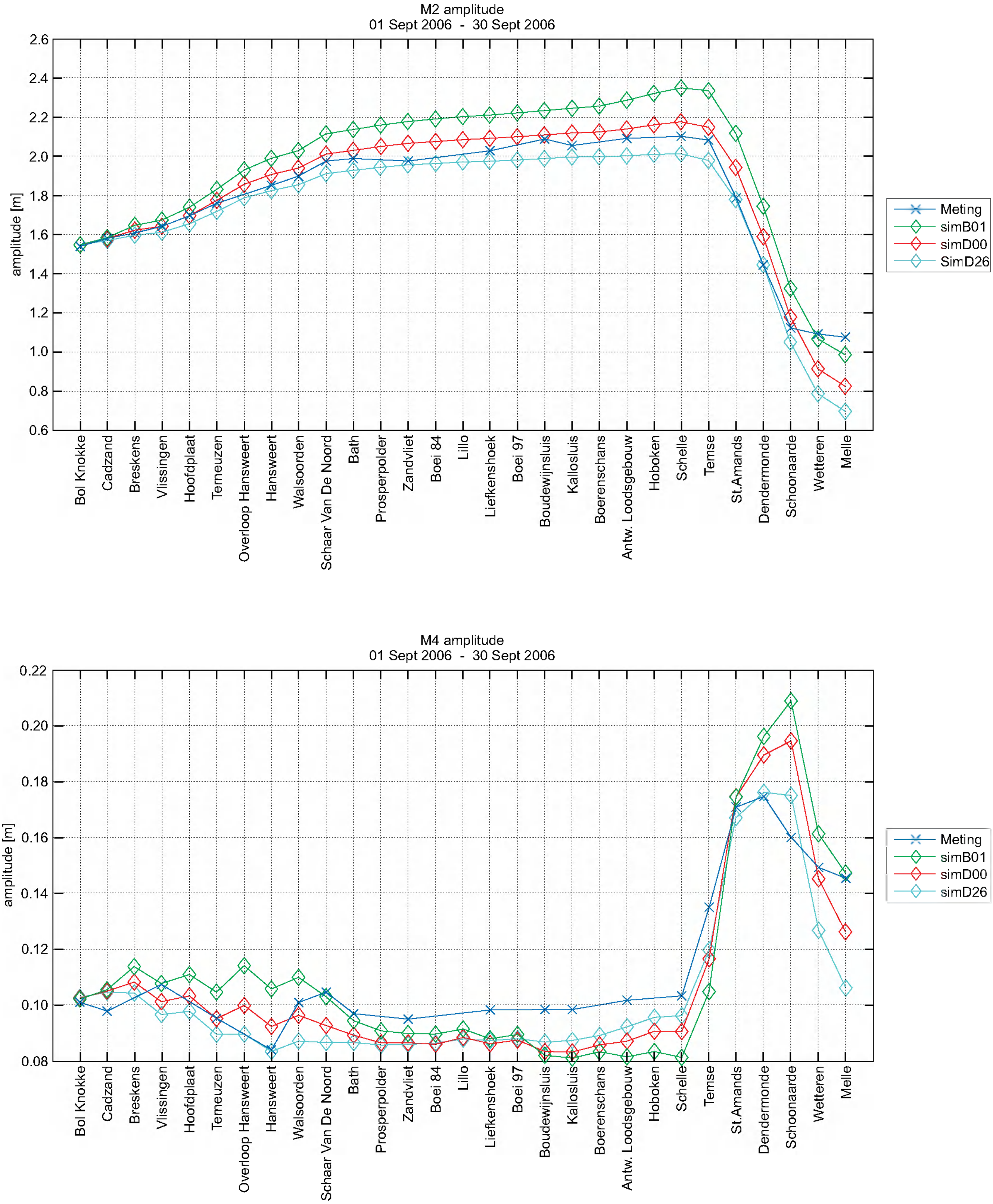
Measured discharges at Merelbeke
Comparison of 5 minutes, hourly and daily averaged discharges



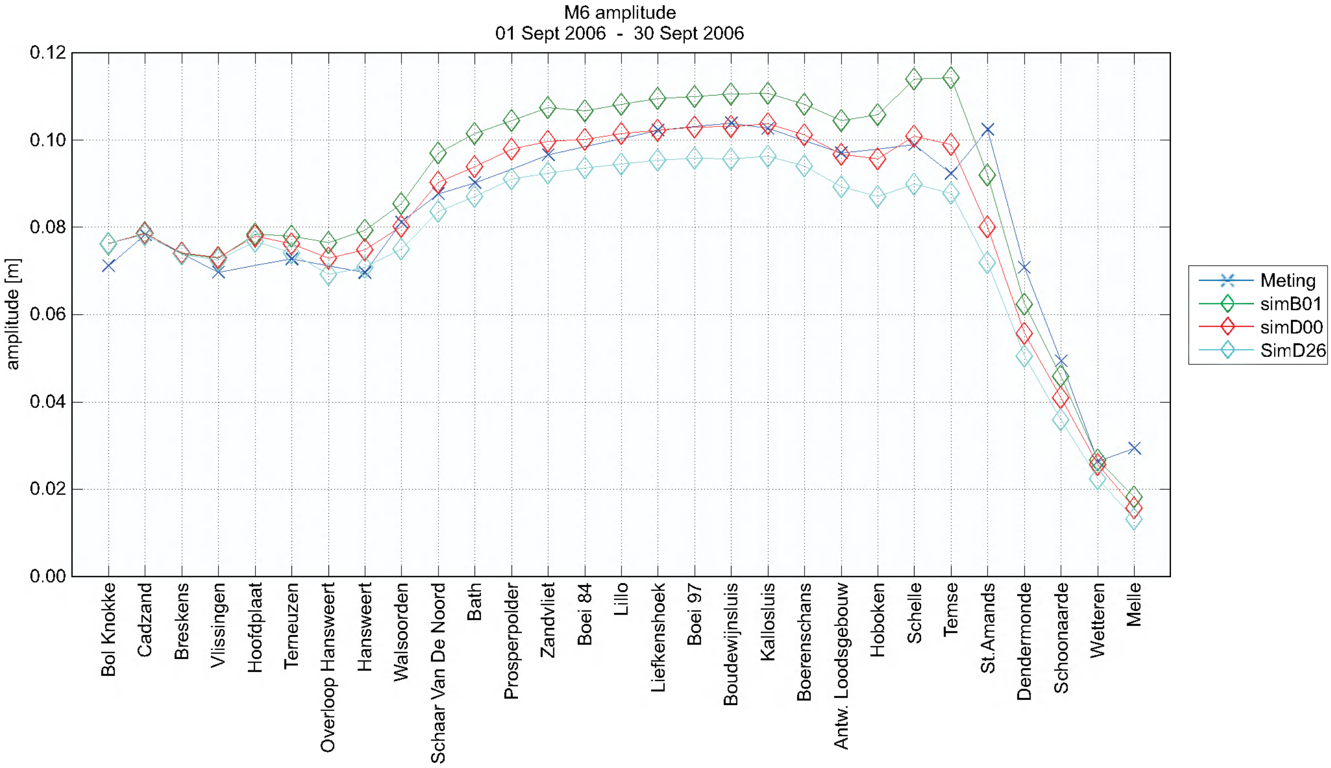
Calculated water levels at Wetteren



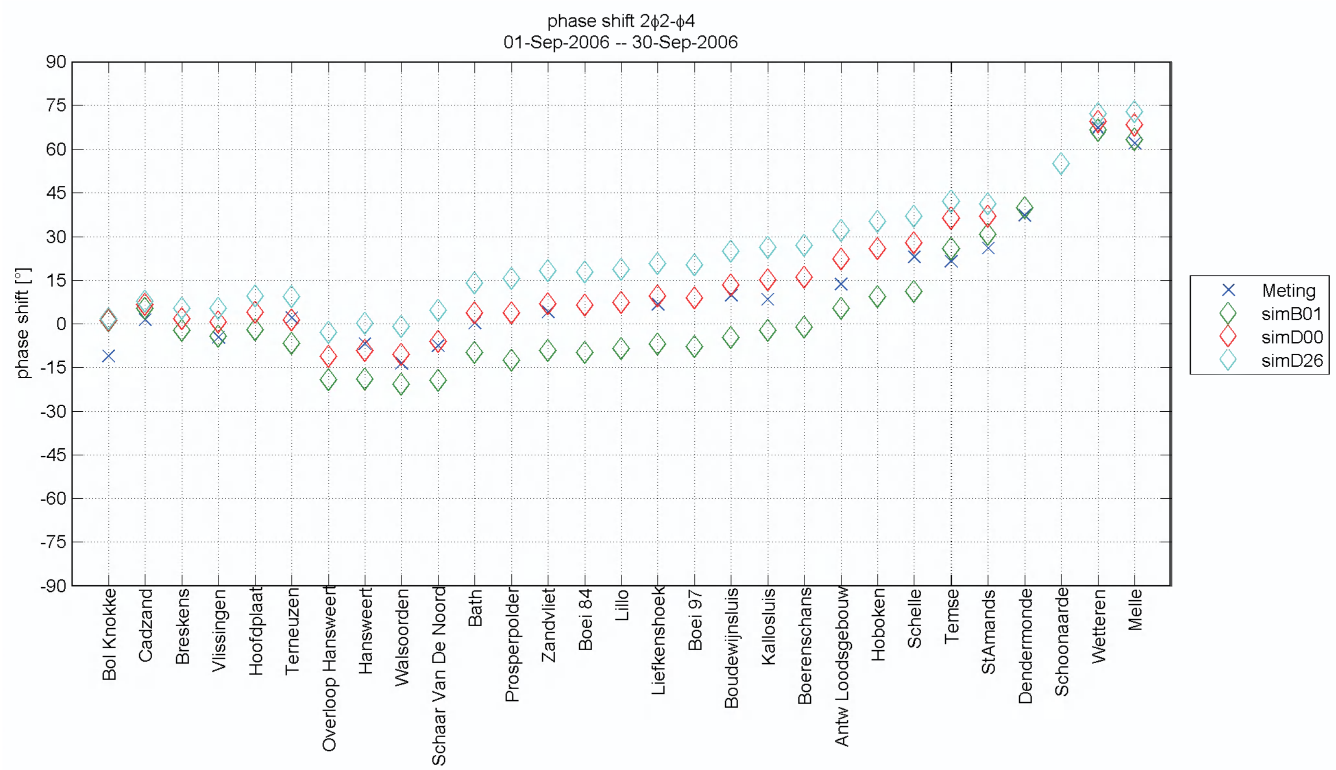
Difference in calculated water levels in the case of use of 5 minutes and daily averaged discharges

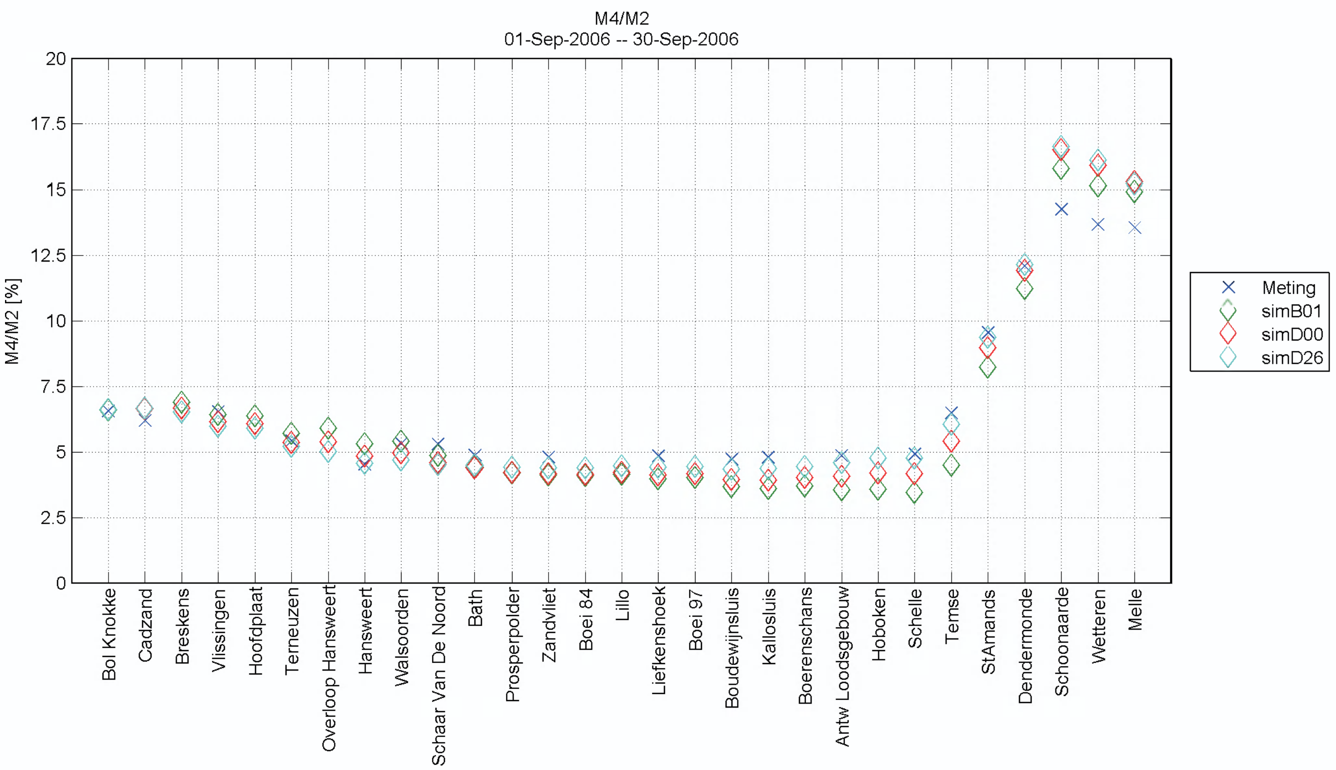


Comparison of the M2 and M4 amplitude for different uniform Manning roughness coefficients

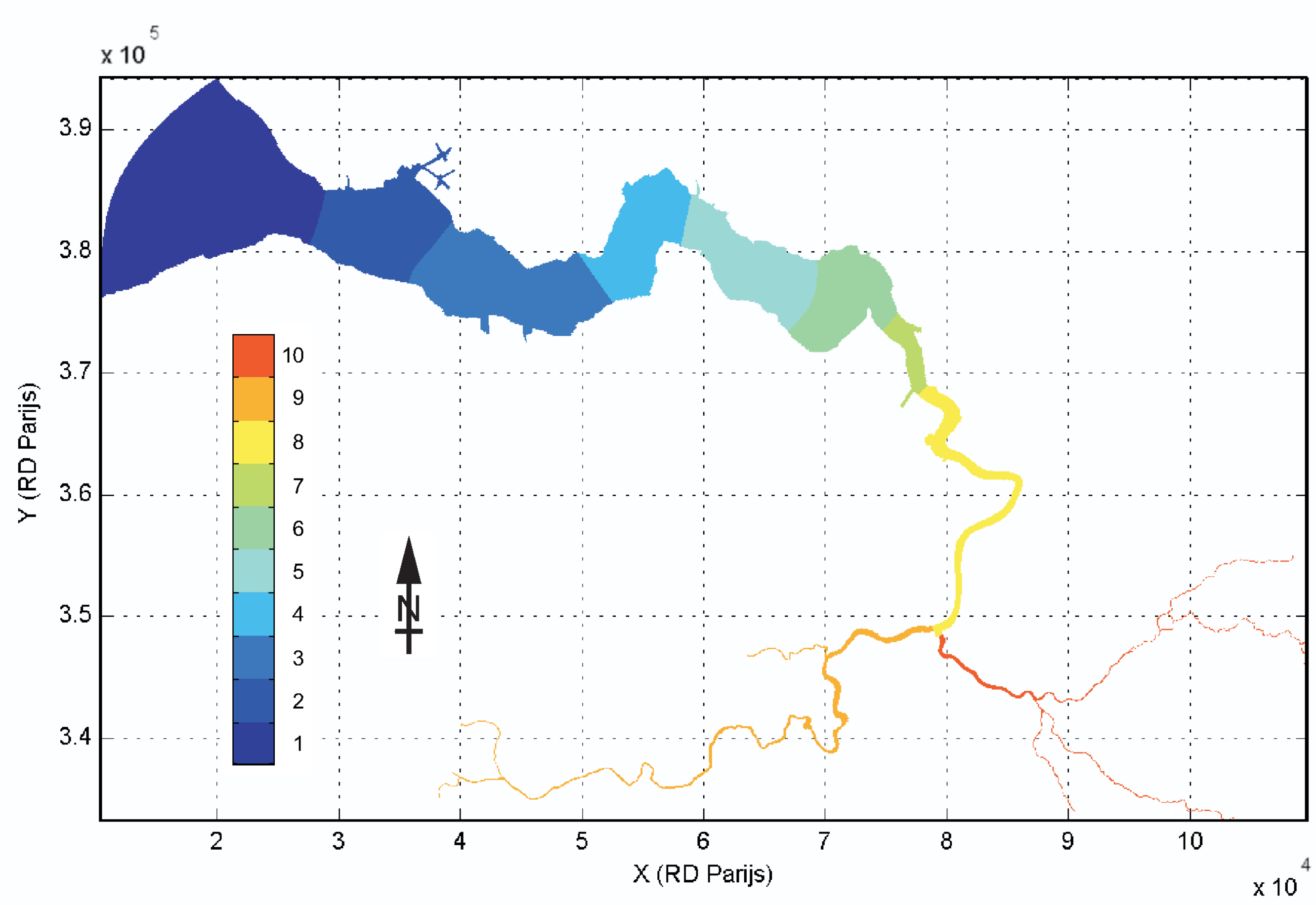


Comparison of the M6 amplitude for different uniform Manning roughness coefficients

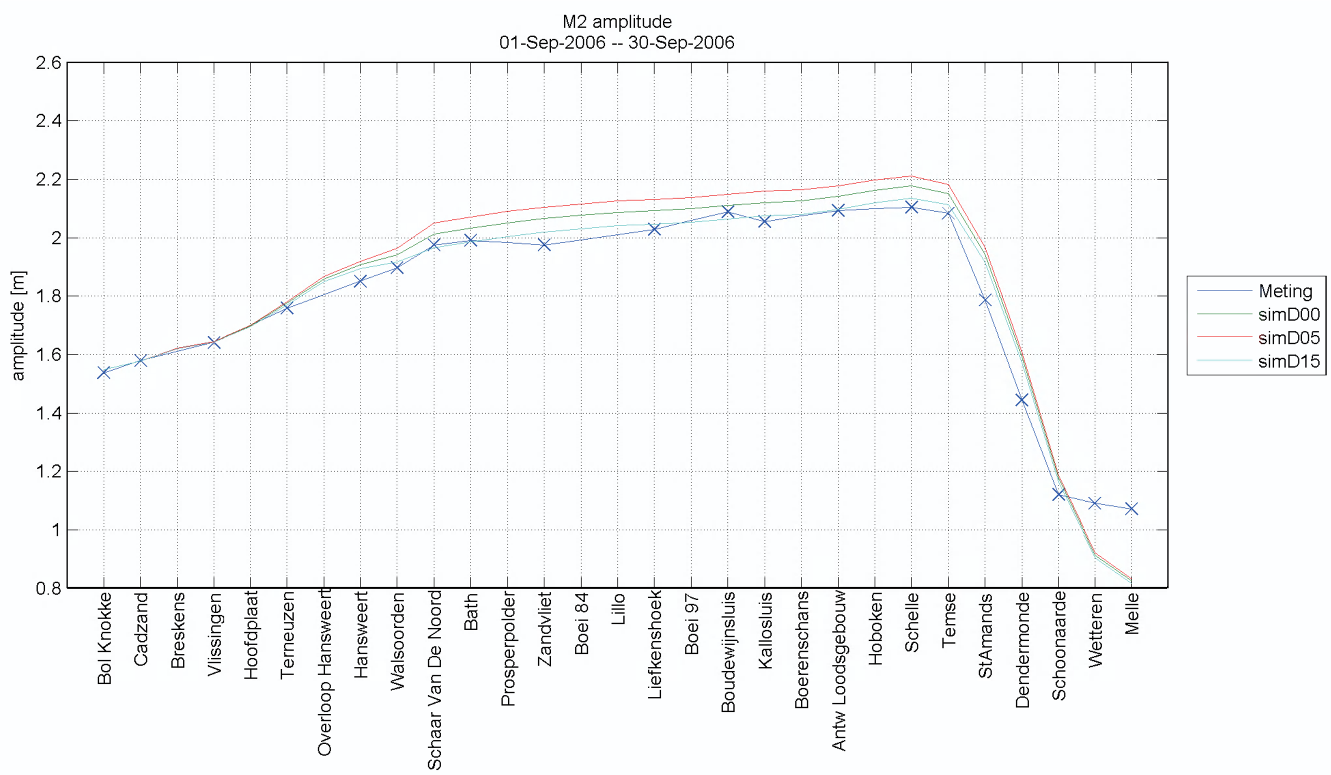


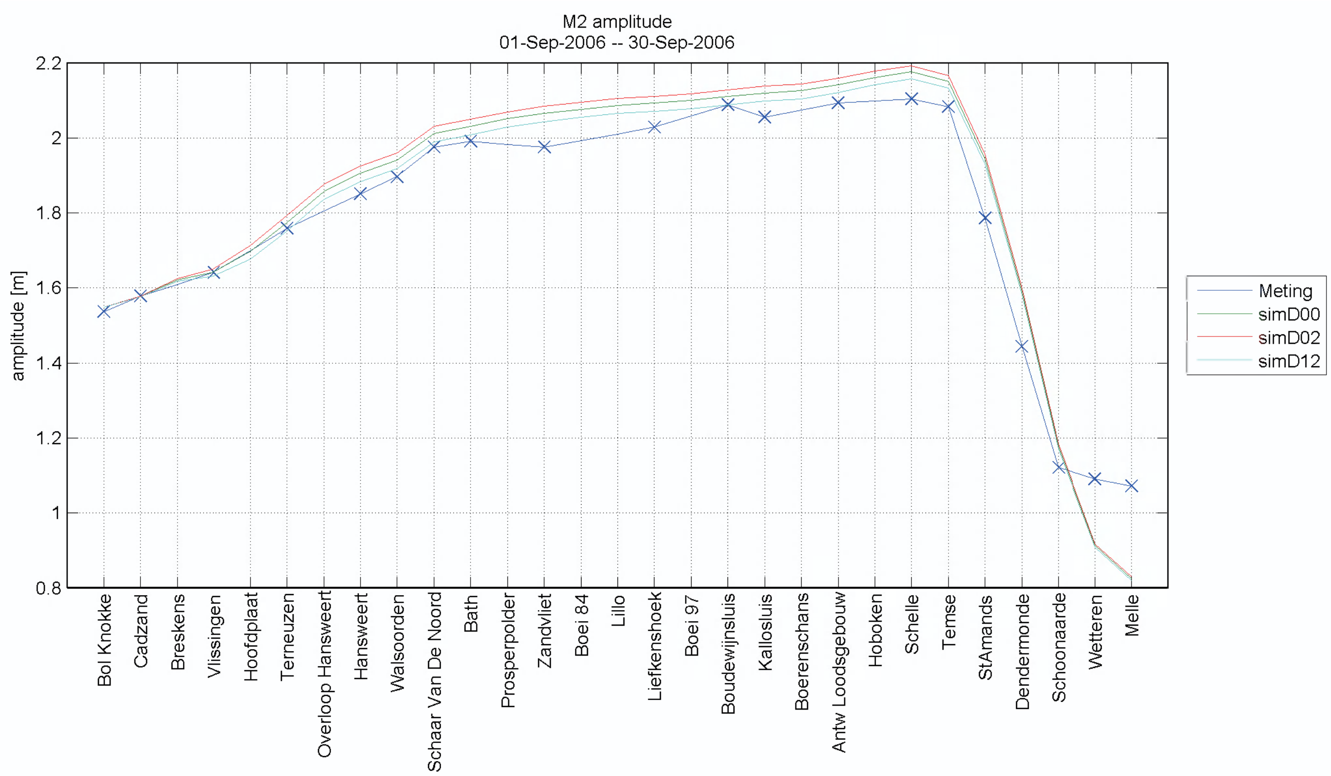


Phase shift between M2 and M4 and M4/M2 relation for different uniform Manning roughness coefficients

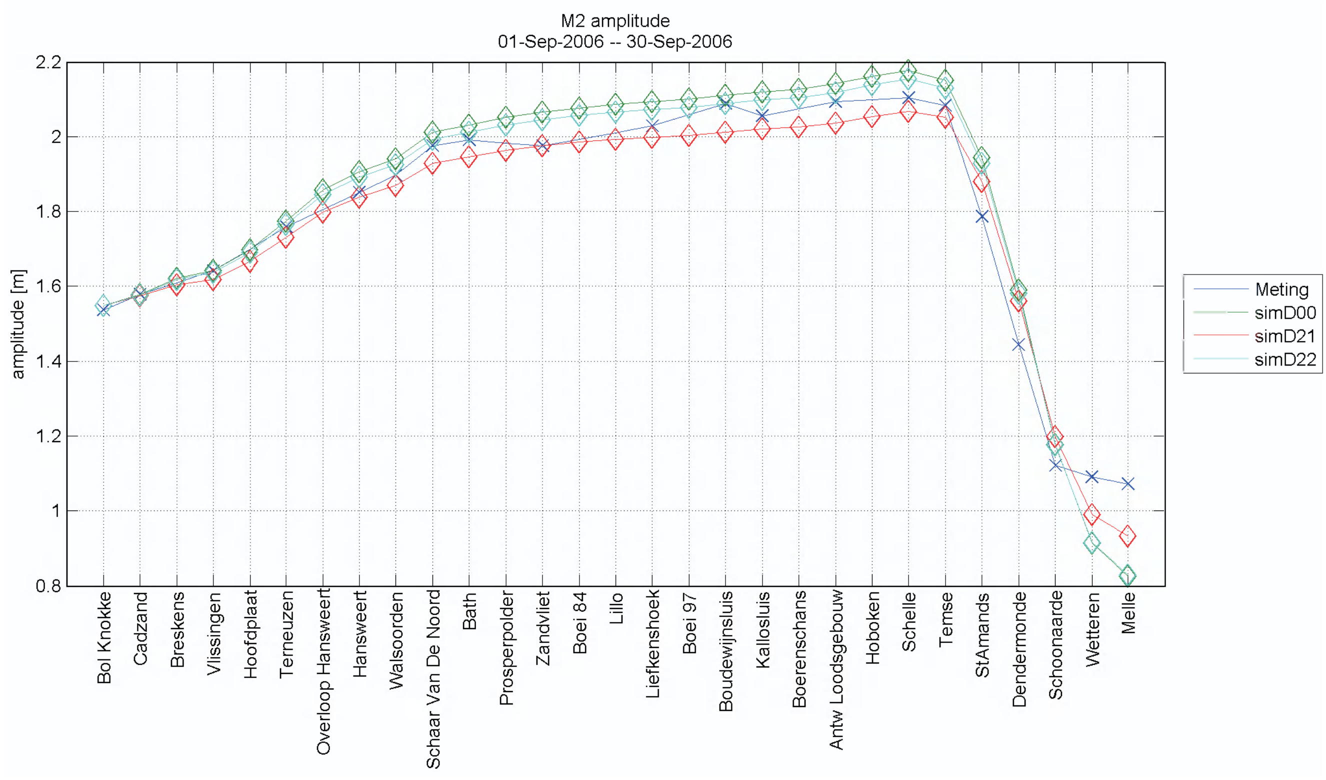


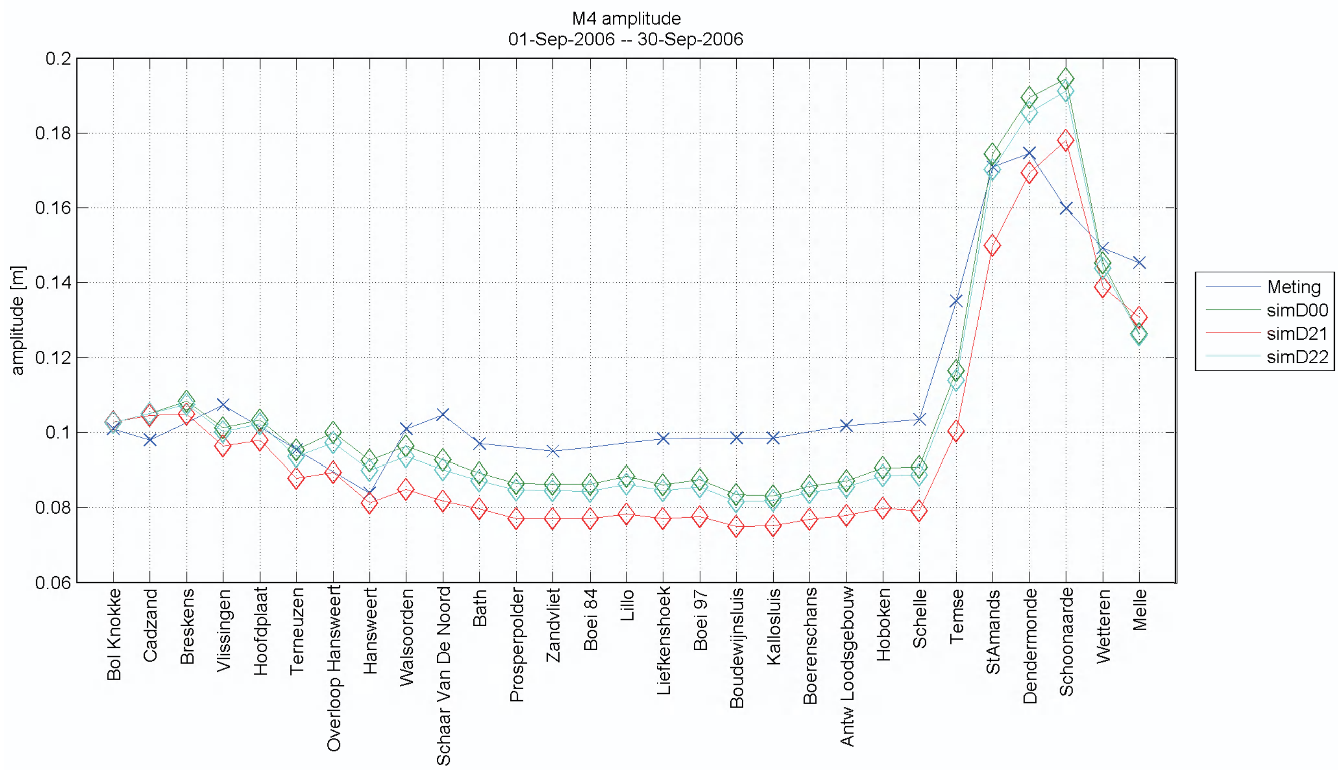
The Scheldt estuary divided in 10 parts for the sensitivity analysis



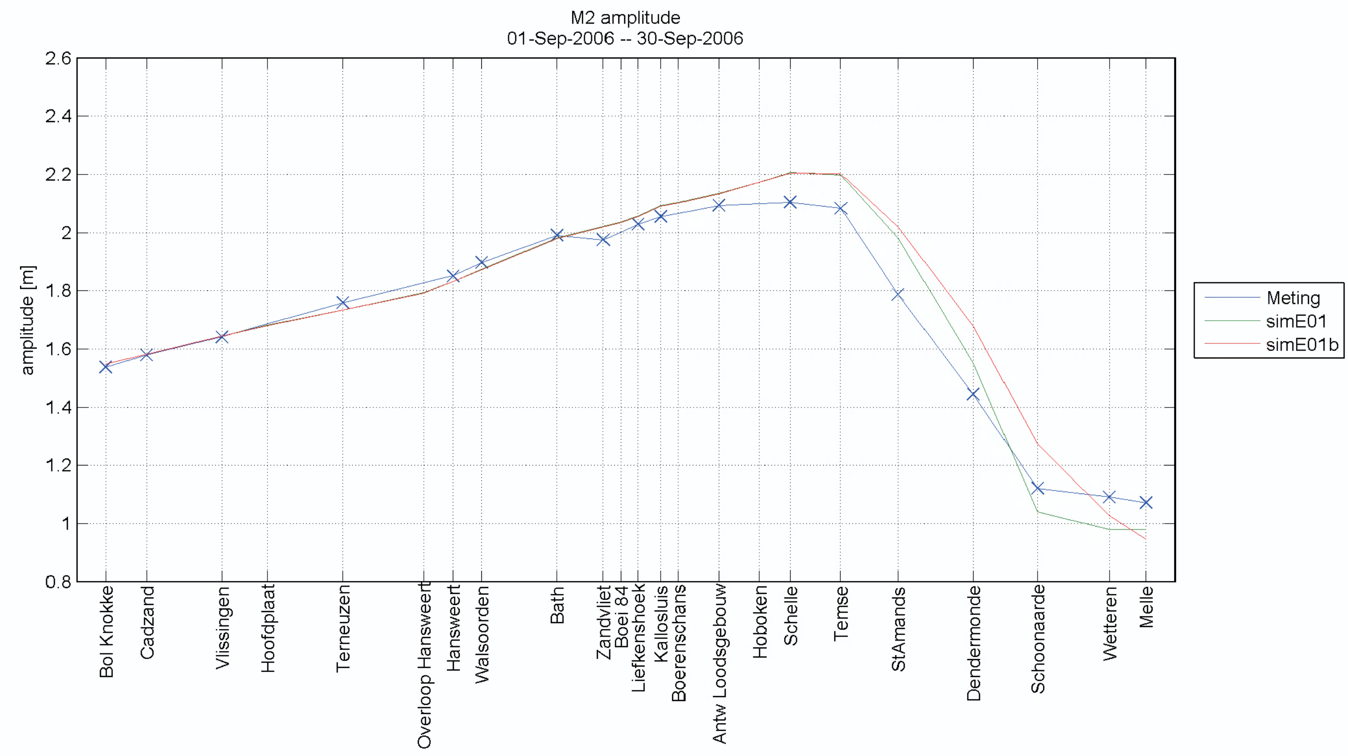


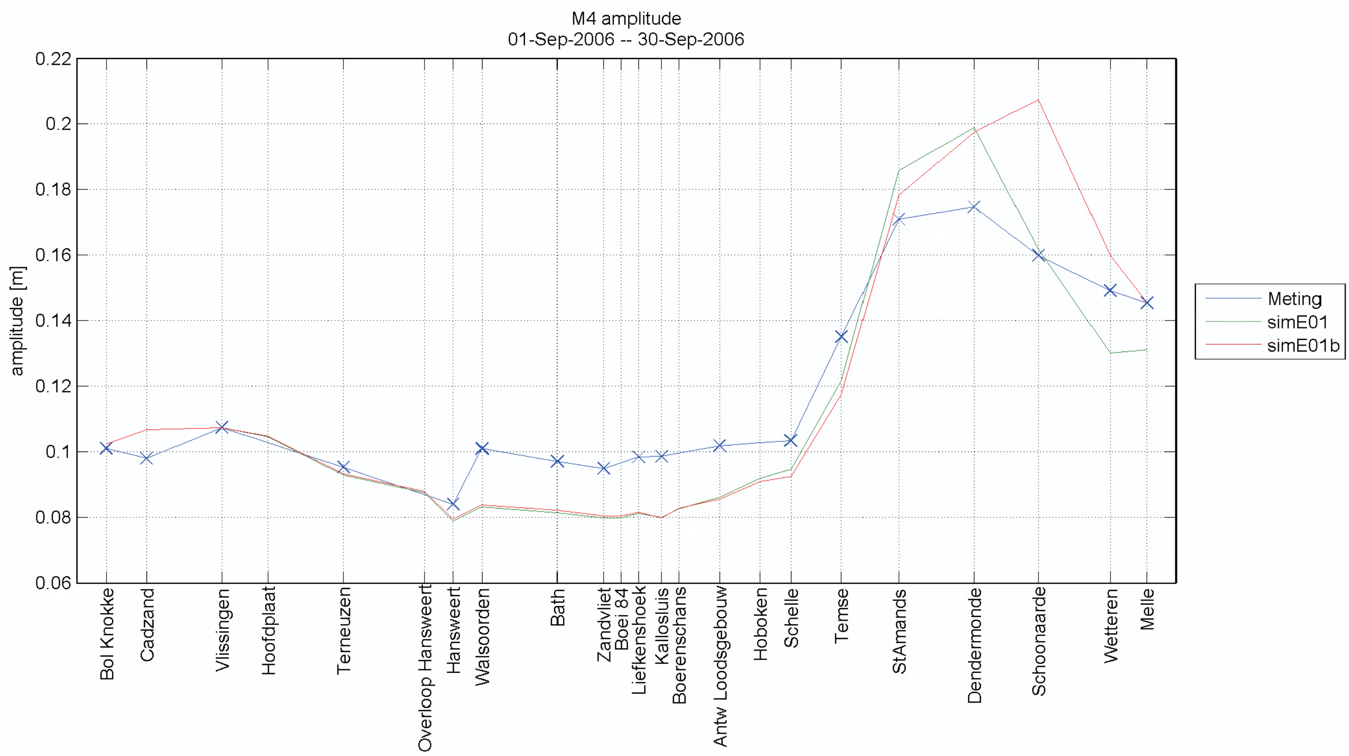
Comparison of the M2 amplitude for different roughness values in the area from Hansweert to Schaar van de Noord (above) and between Vlissingen and Hoofdplaat (below)



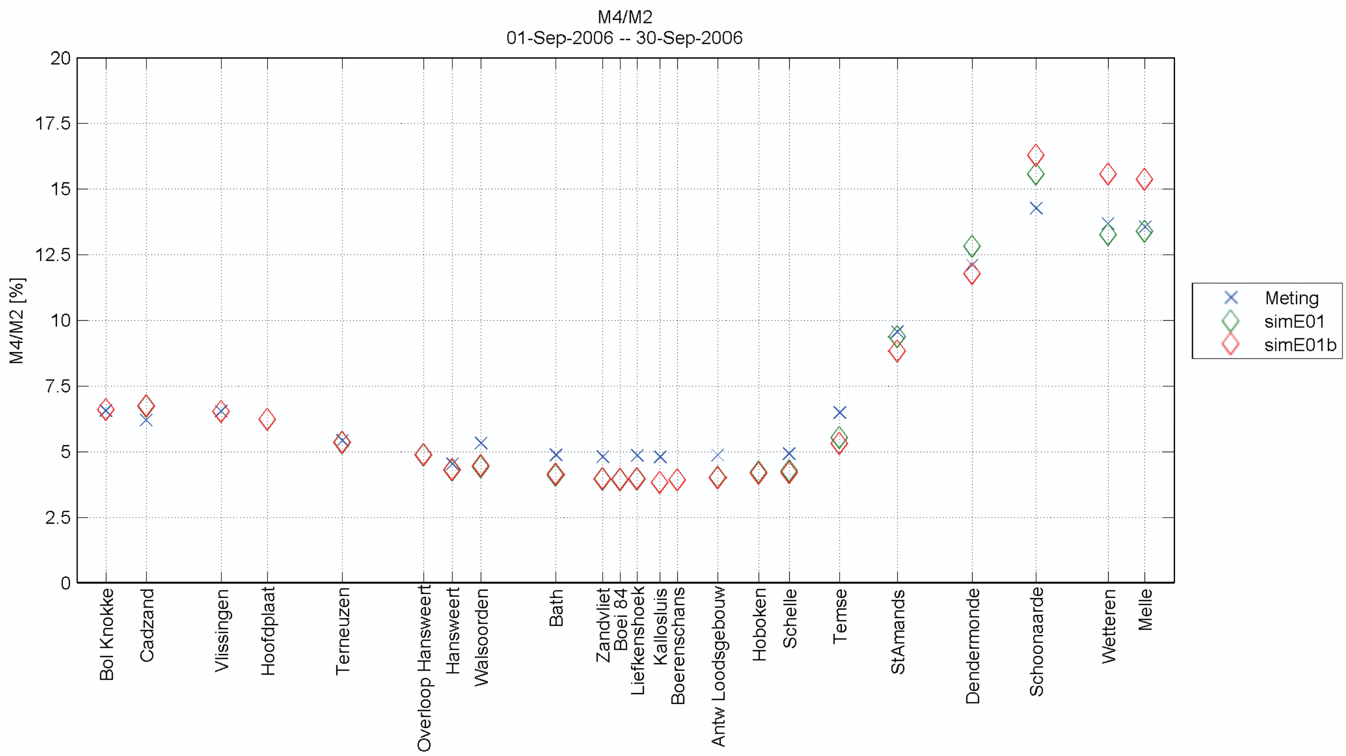


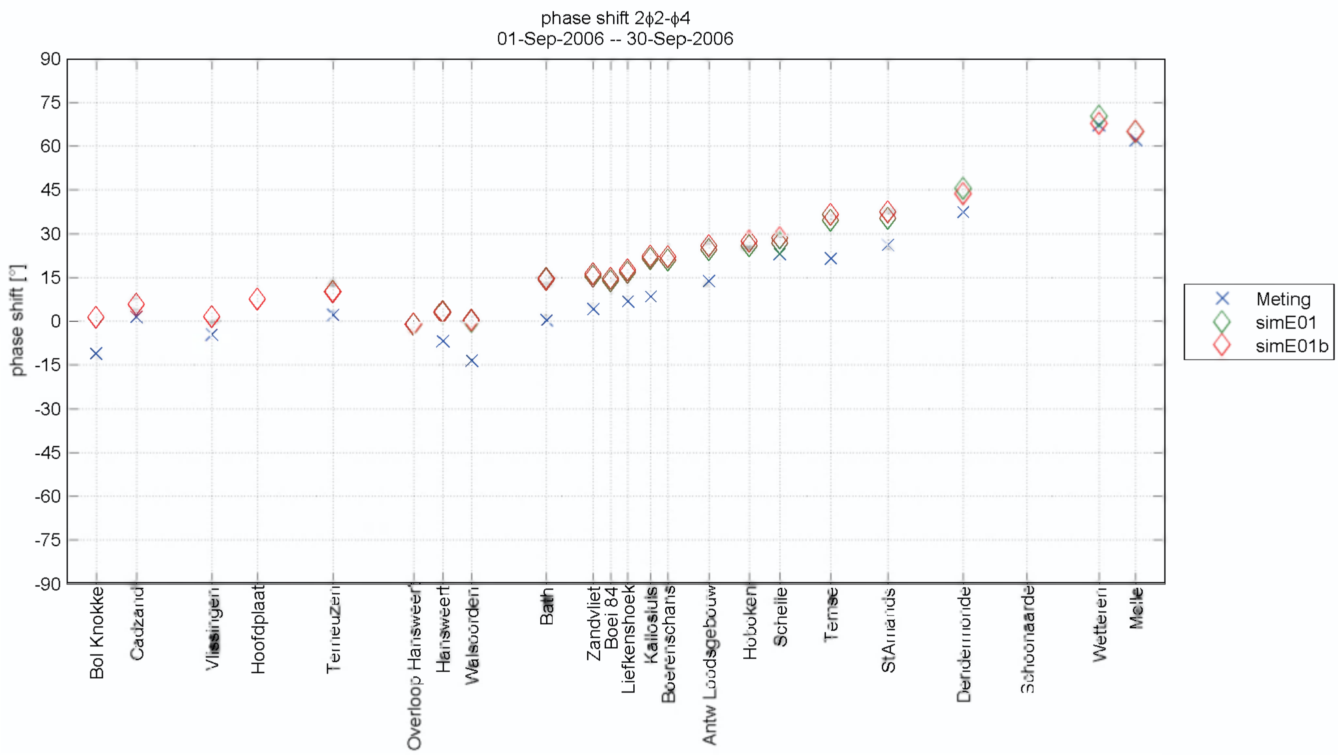
Comparison of M2 and M4 amplitude for 3 roughness coefficients: Chezy, Manning and White-Colebrook



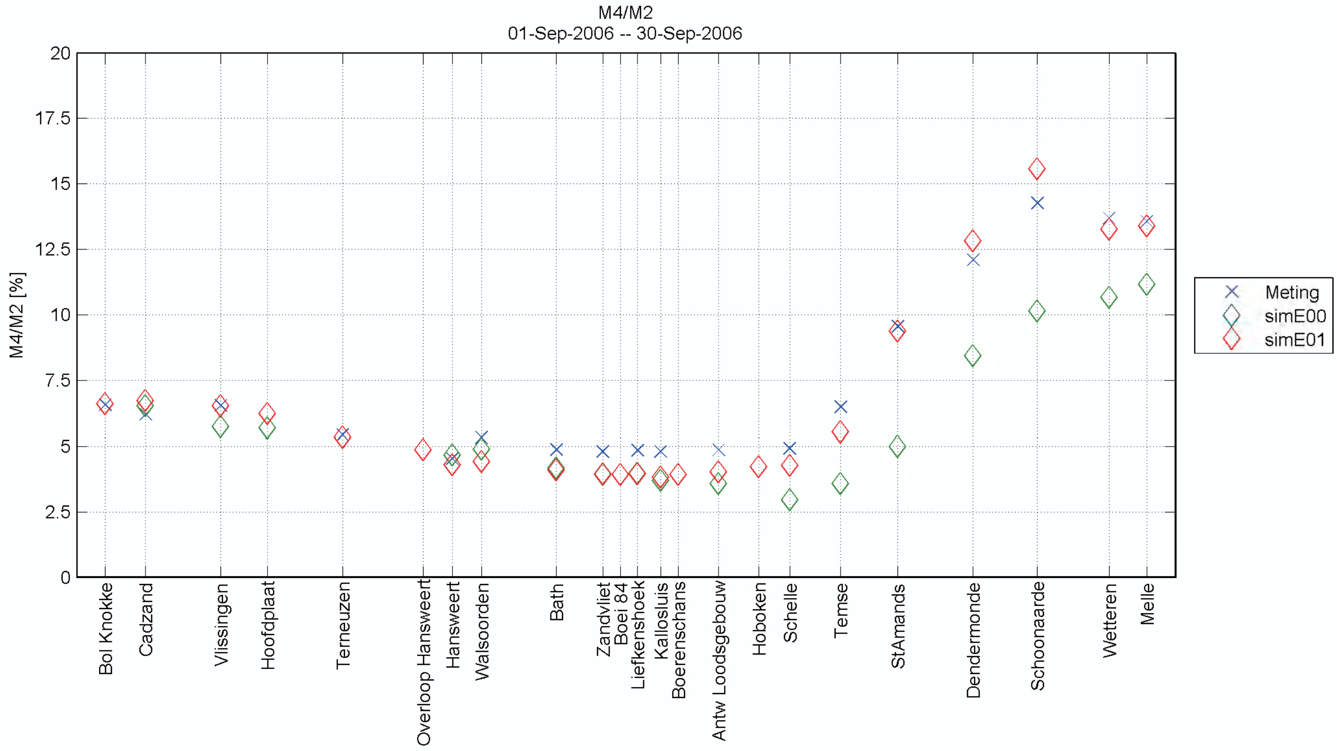


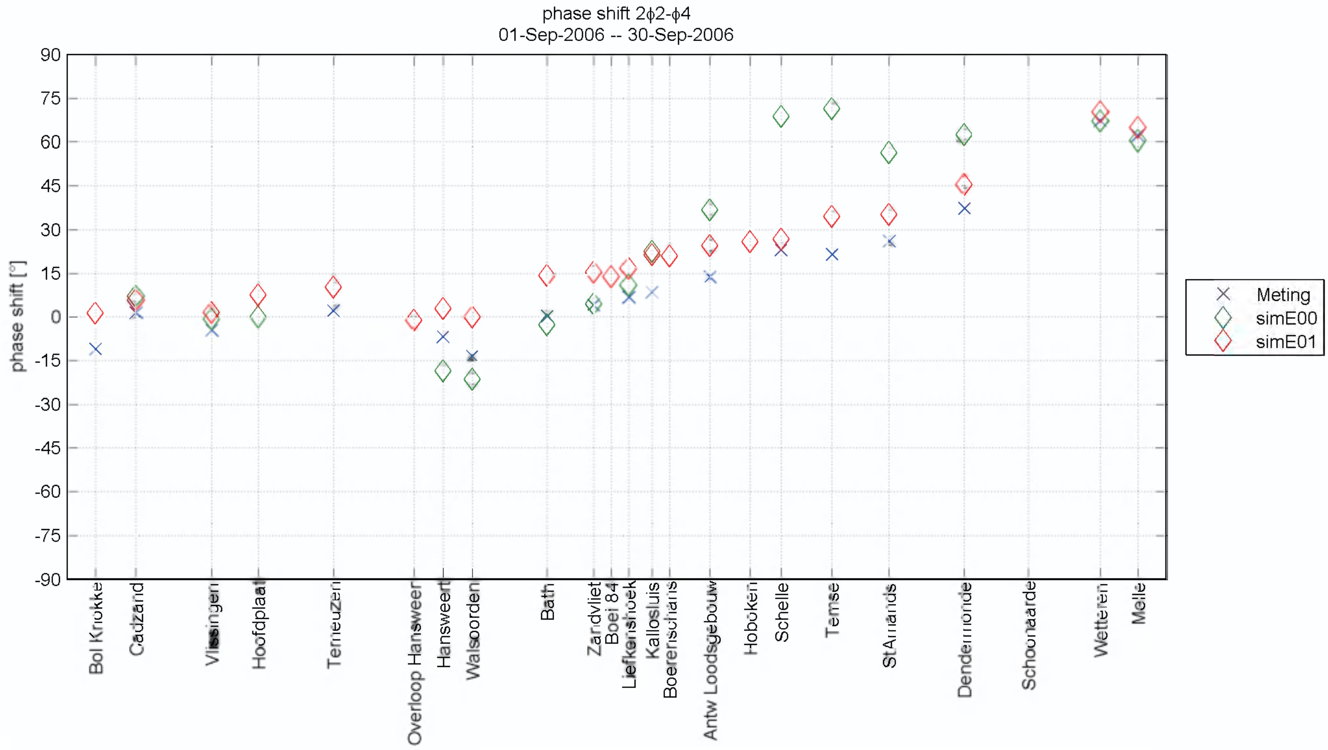
M2 en M4 amplitudes for the calibration runs E01 and E01b



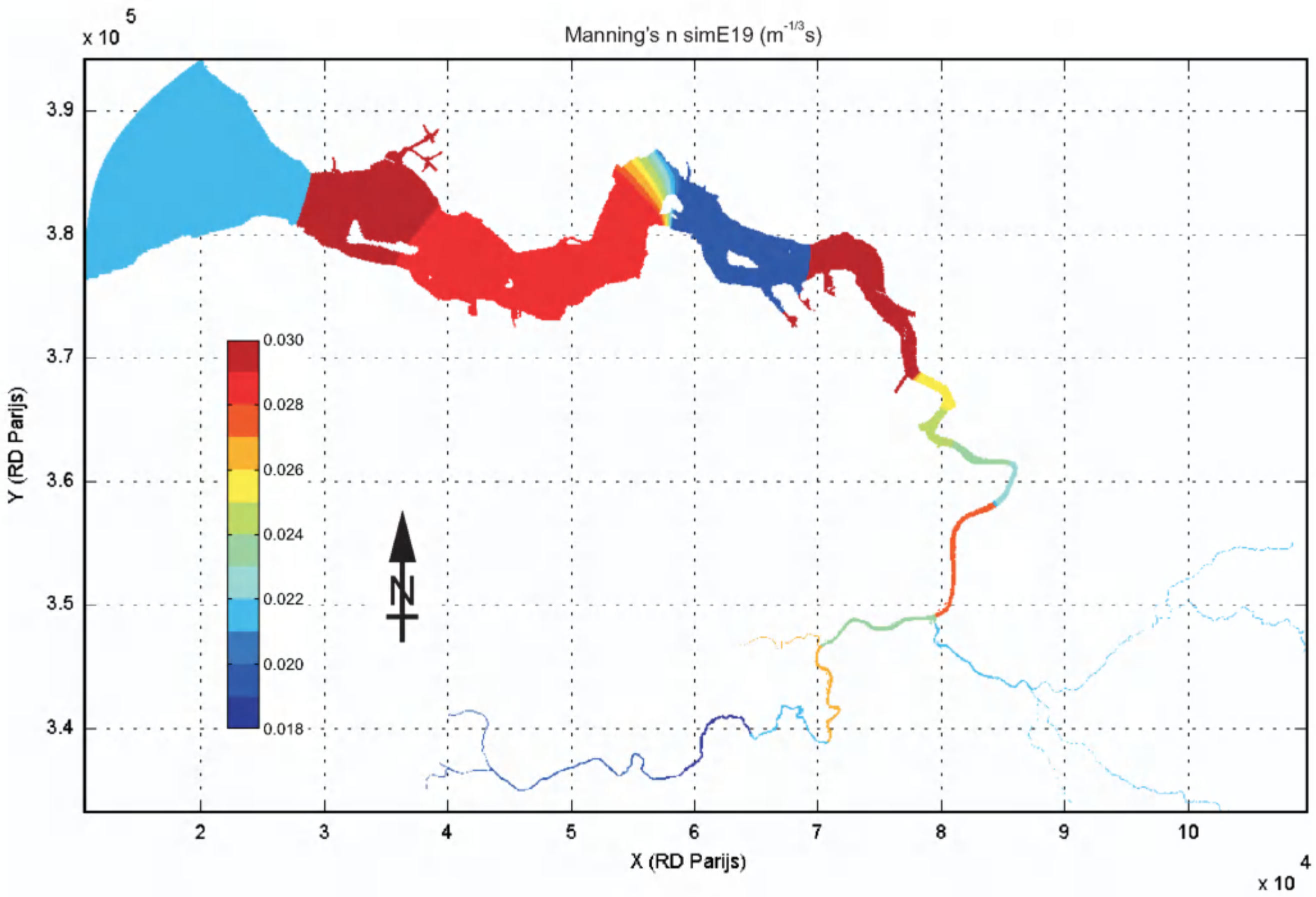


M4/M2 amplitude and 2M2-M4 phase difference for the calibration runs E01 and E01b

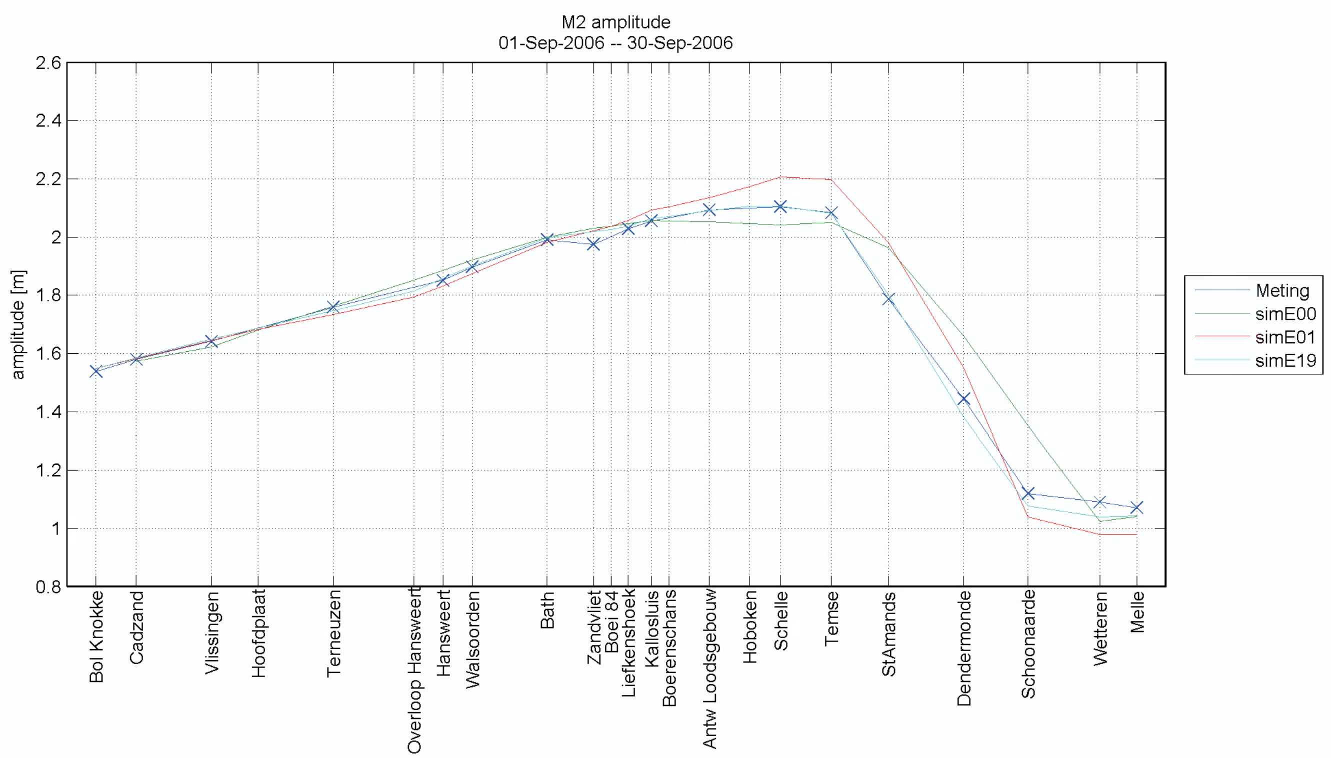


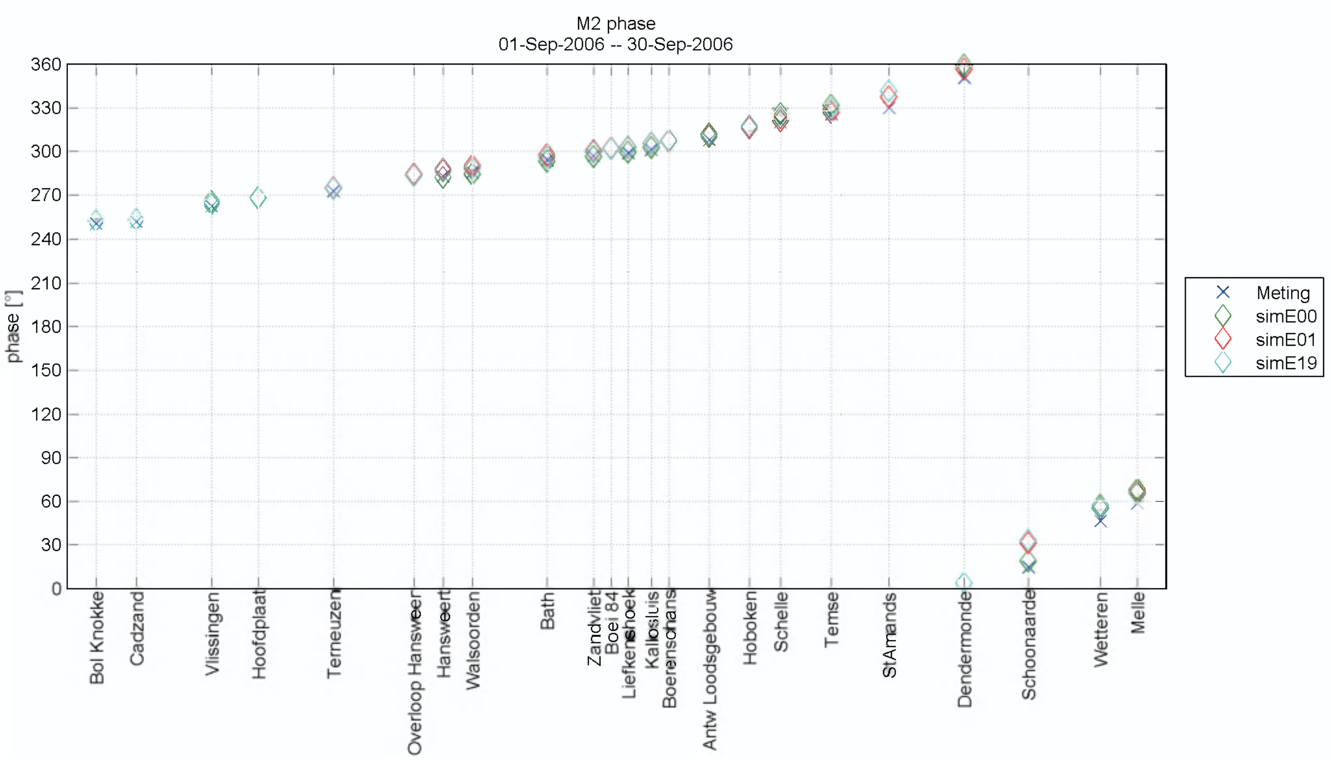


M4/M2 amplitude and 2M2-M4 phase for original NEVLA model (E00) and calibration run E01

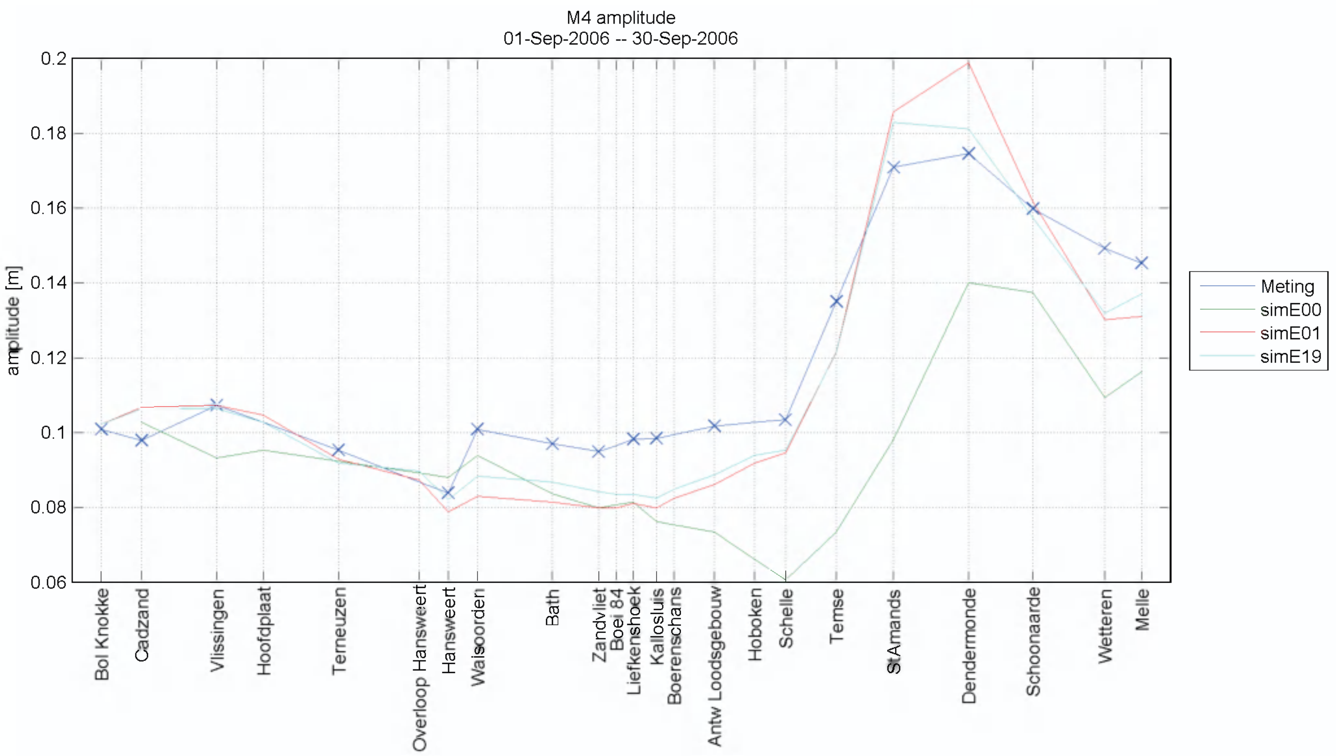


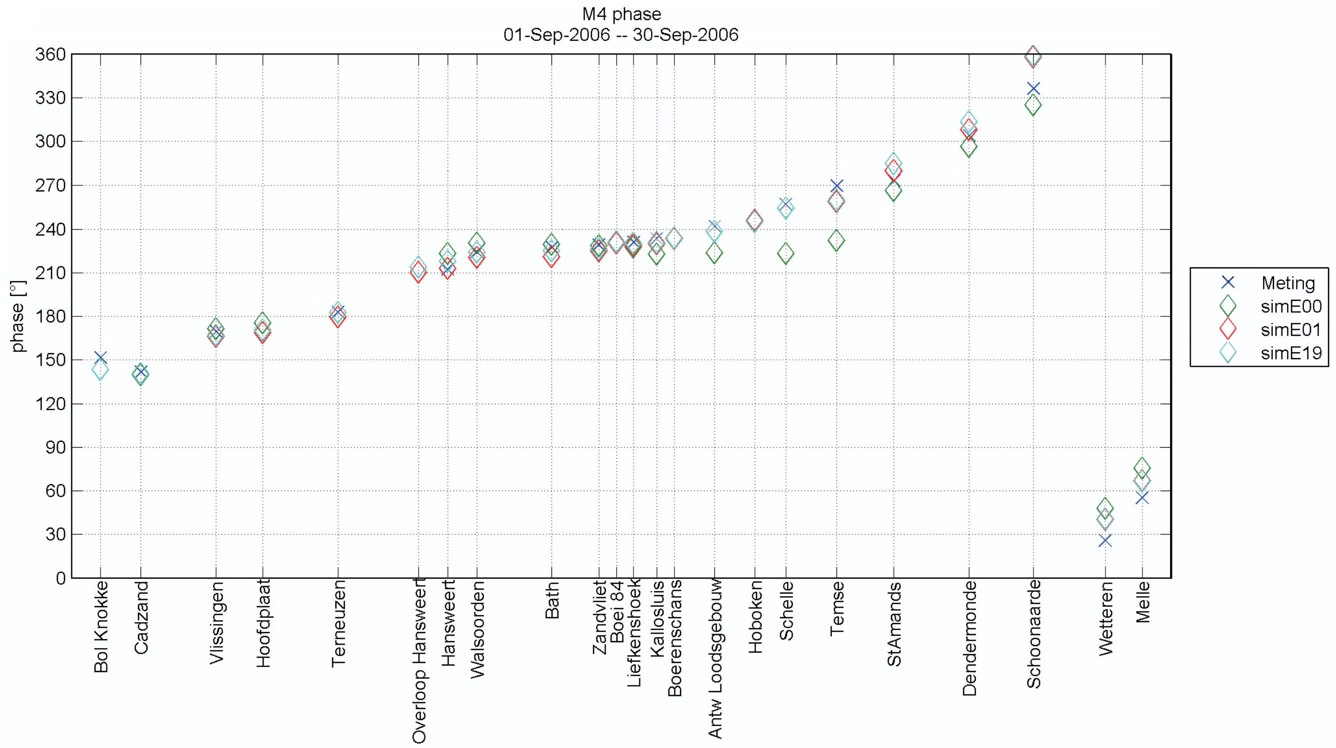
Roughness field for the Scheldt estuary for run E19



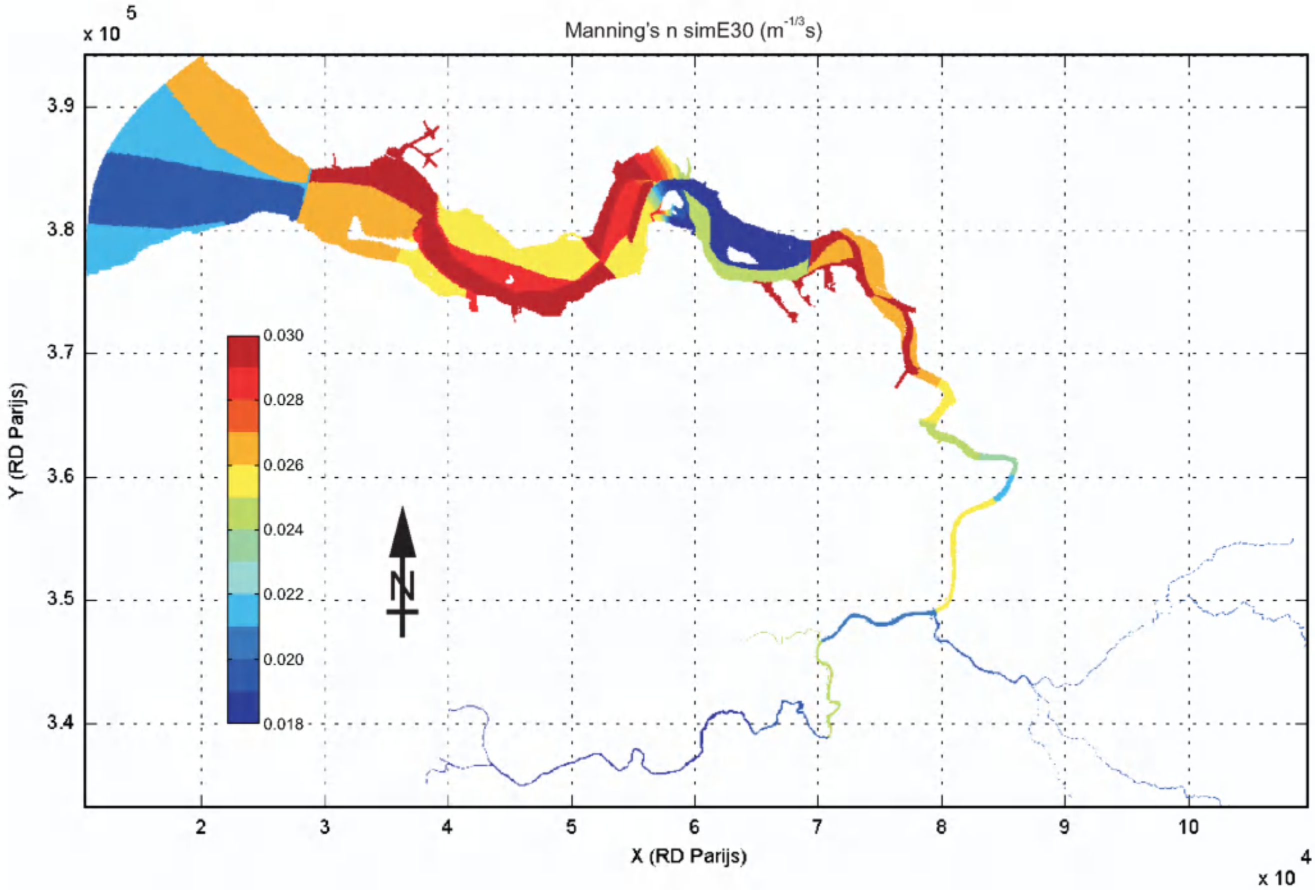


M2 amplitude and phase for the original NEVLA model (E00) and runs E01 and E19

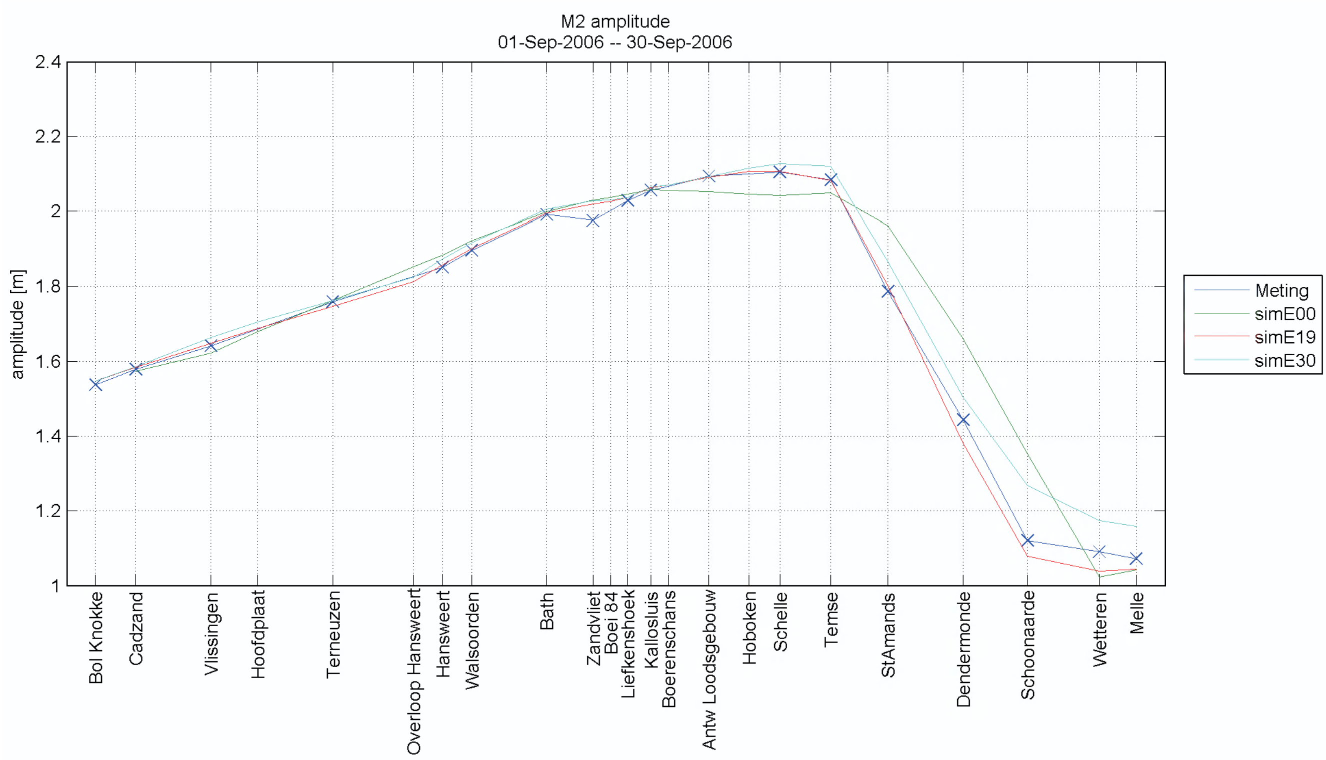


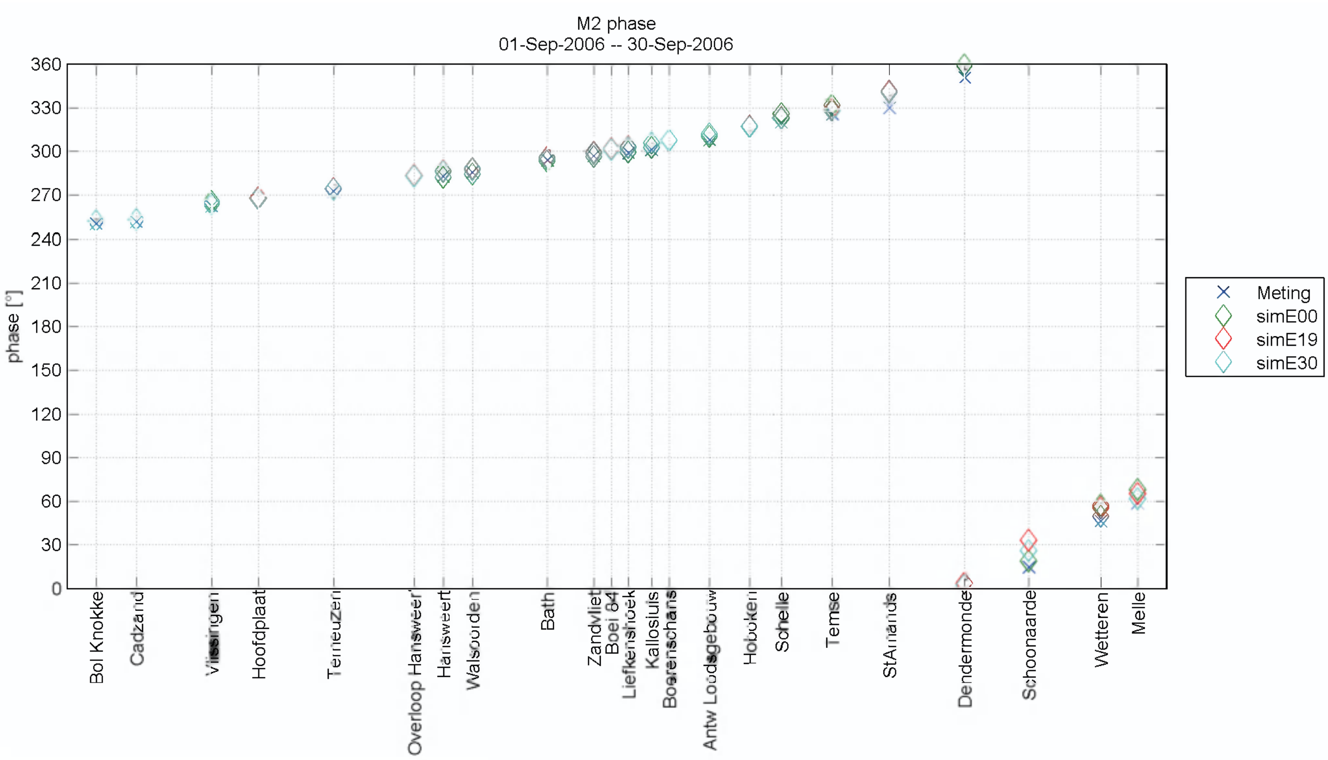


M4 amplitude and phase for the original NEVLA model (E00) and runs E01 and E19

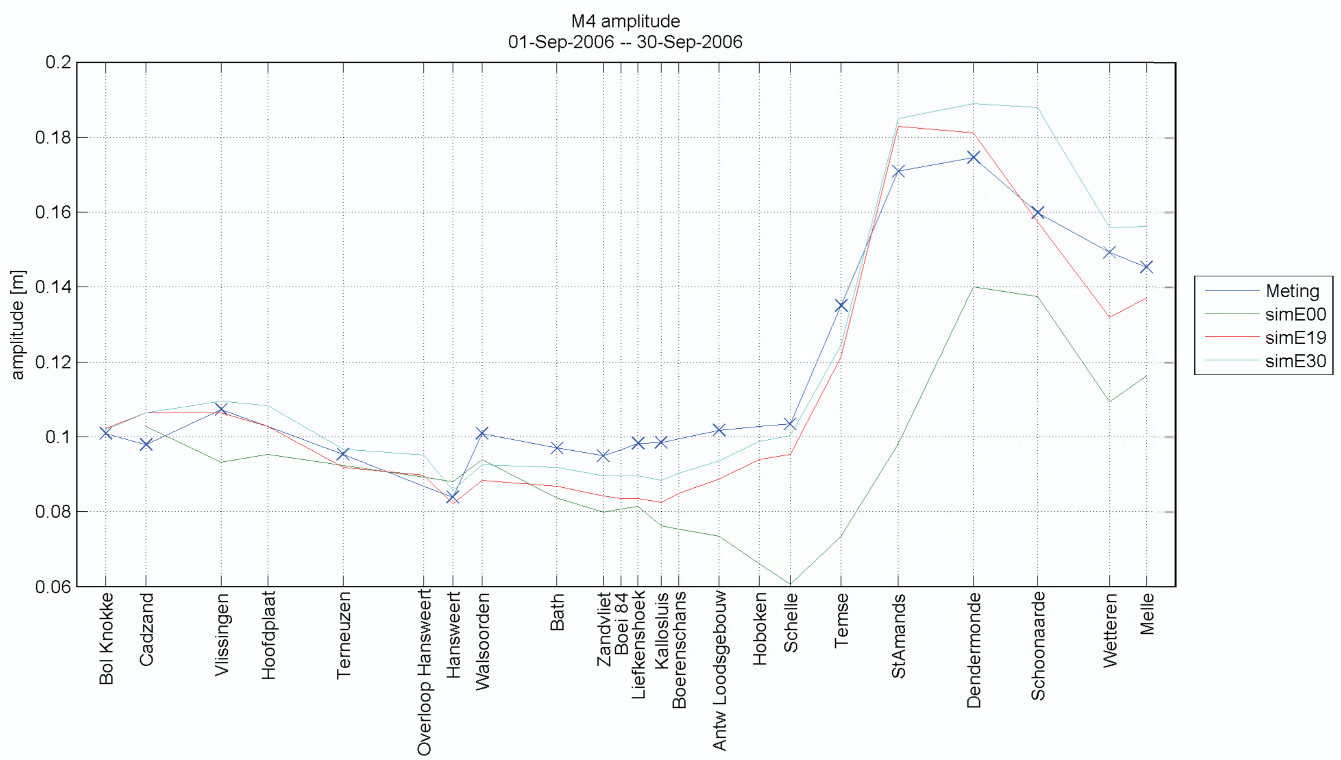


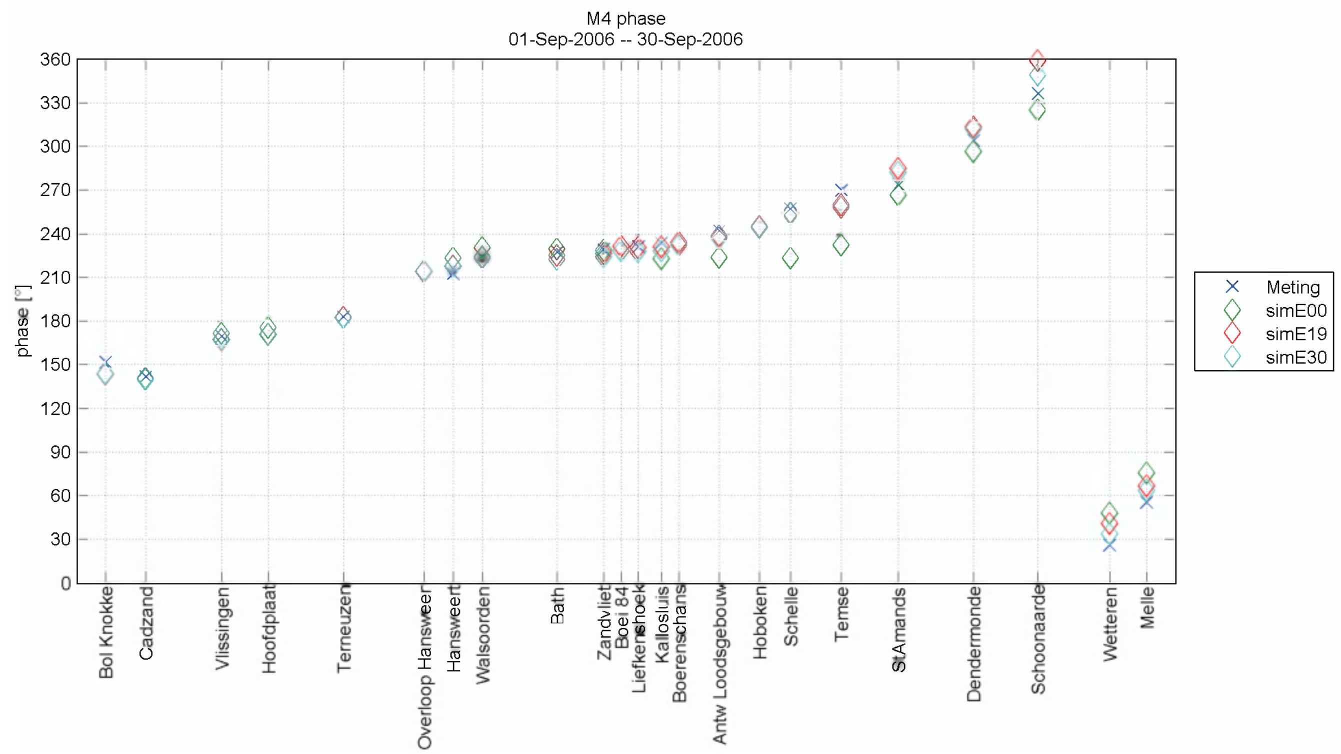
Roughness field for the Scheldt estuary for run E30



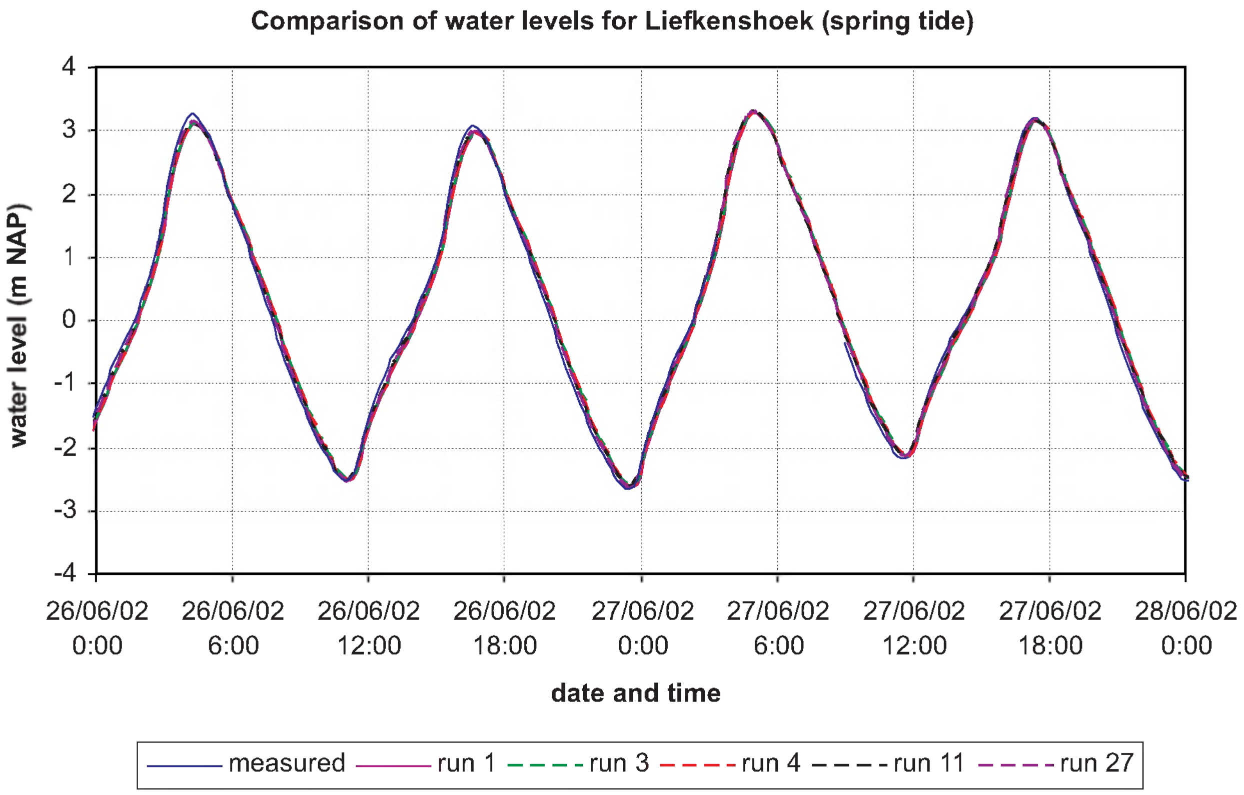


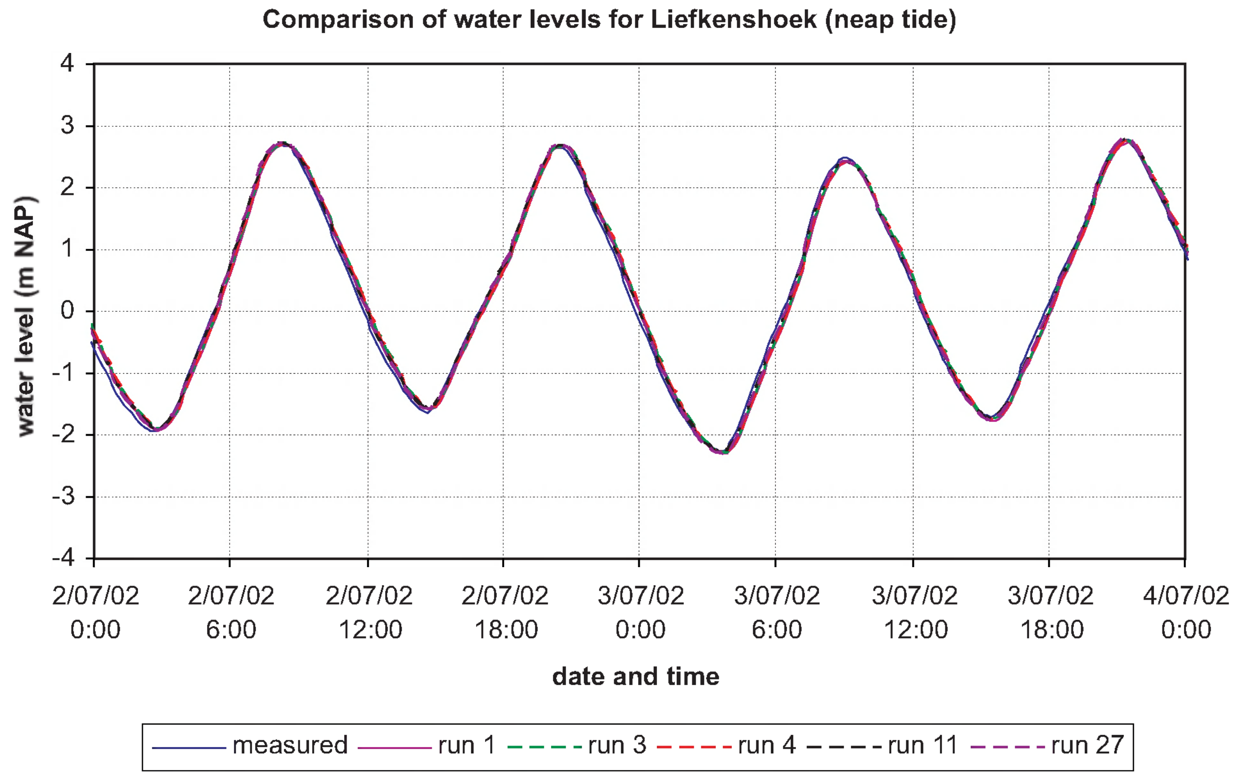
M2 amplitude and phase difference for the original NEVLA model (E00) and runs E19 en E30



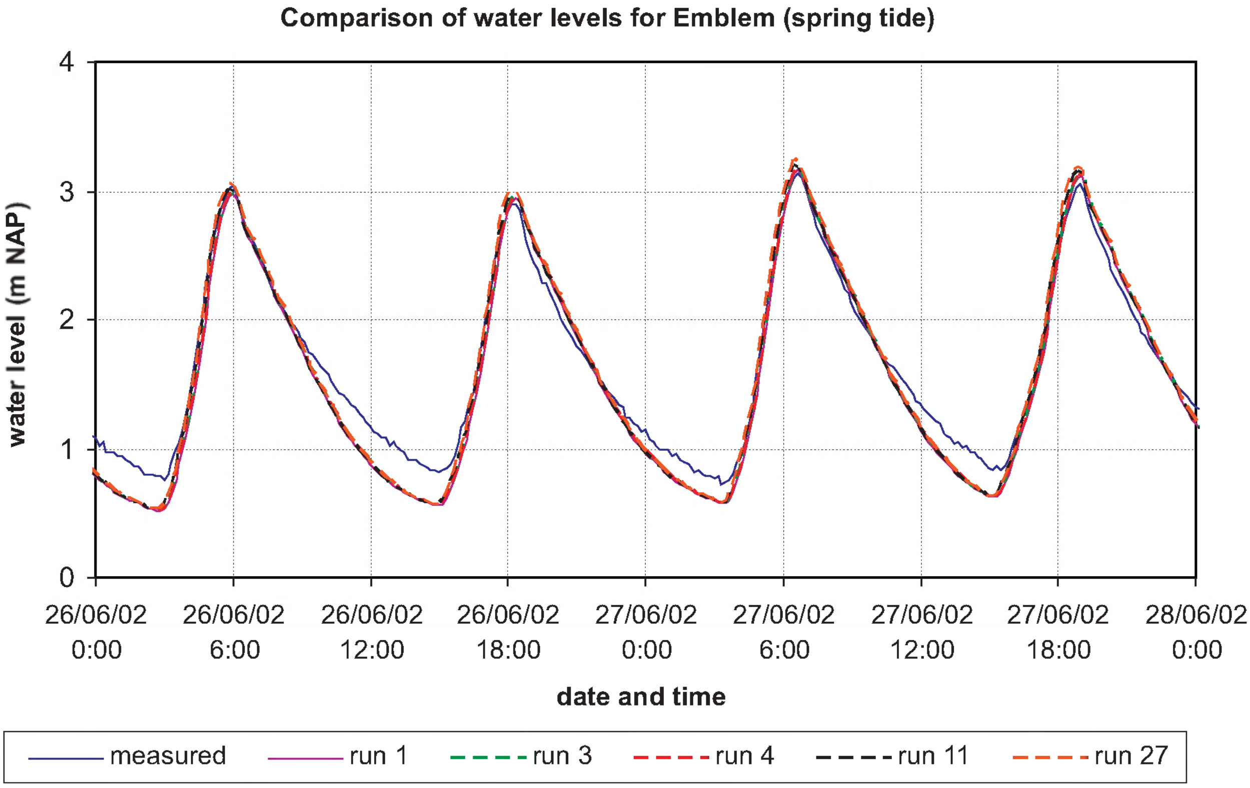


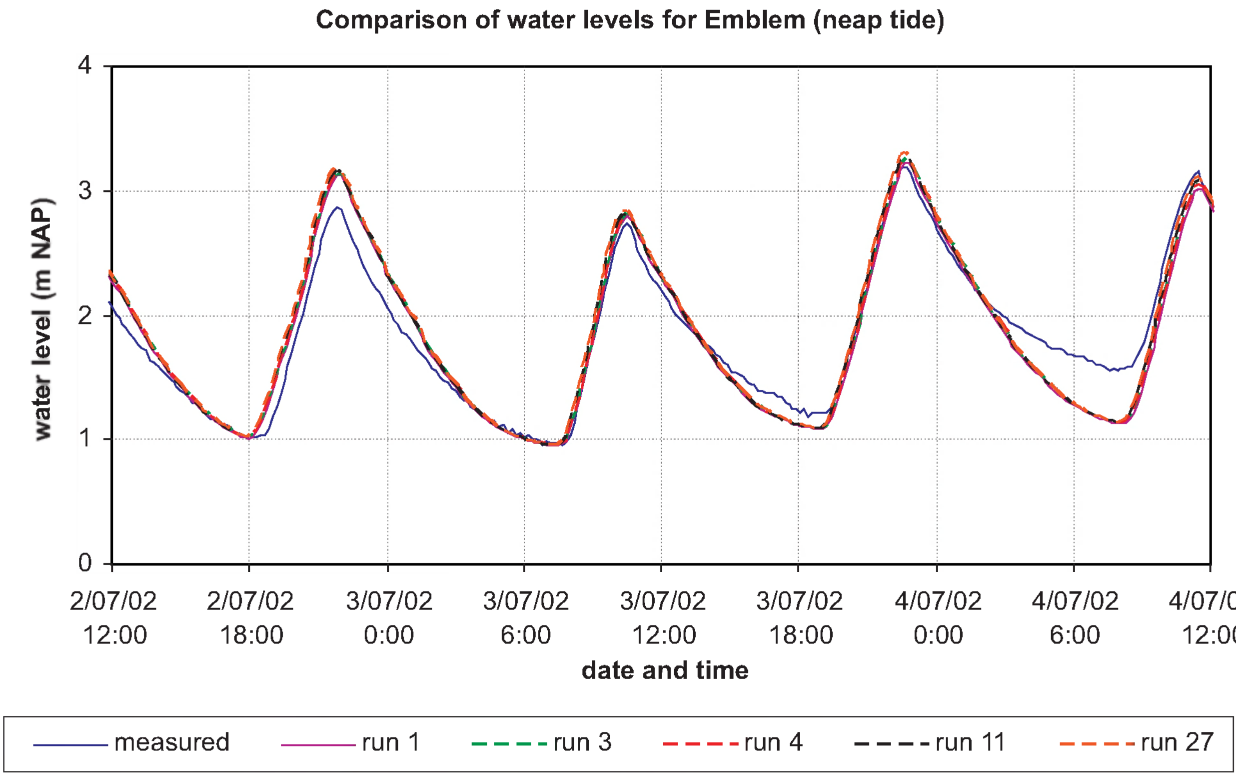
M4 amplitude and phase difference for the original NEVLA-model (E00), and runs E19 en E30



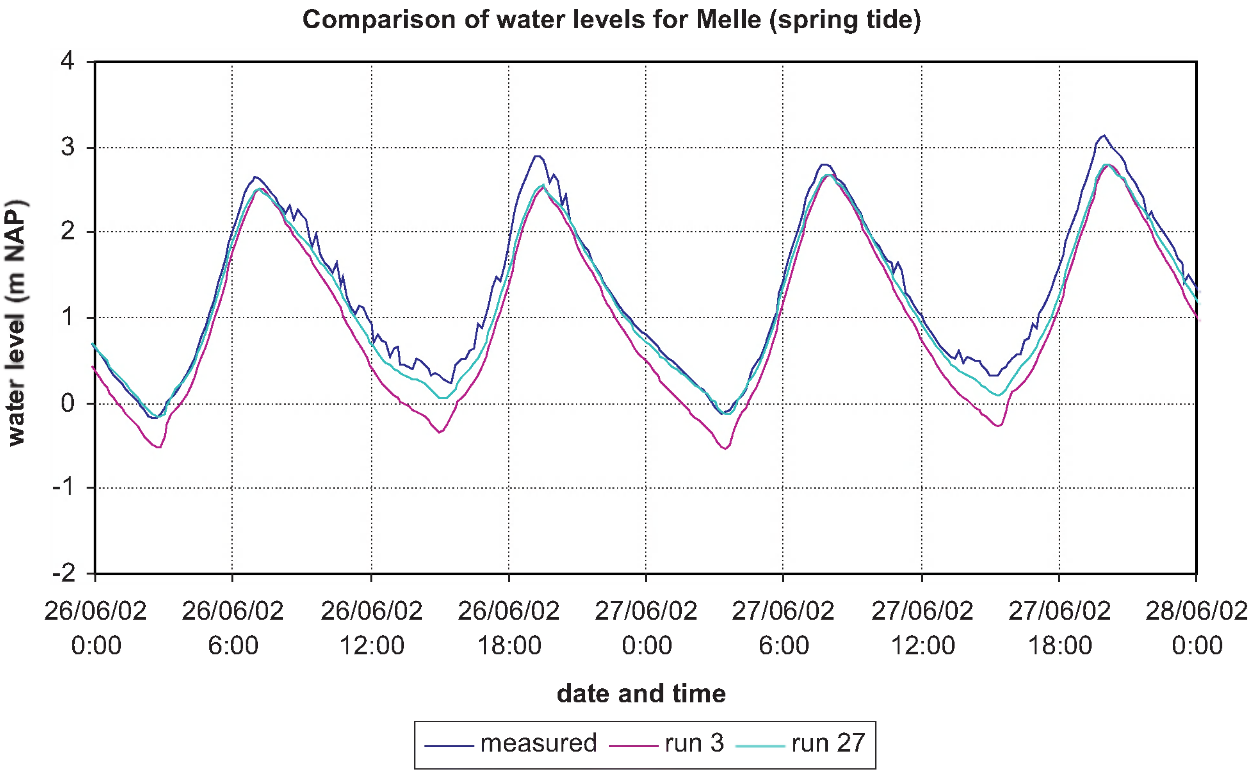


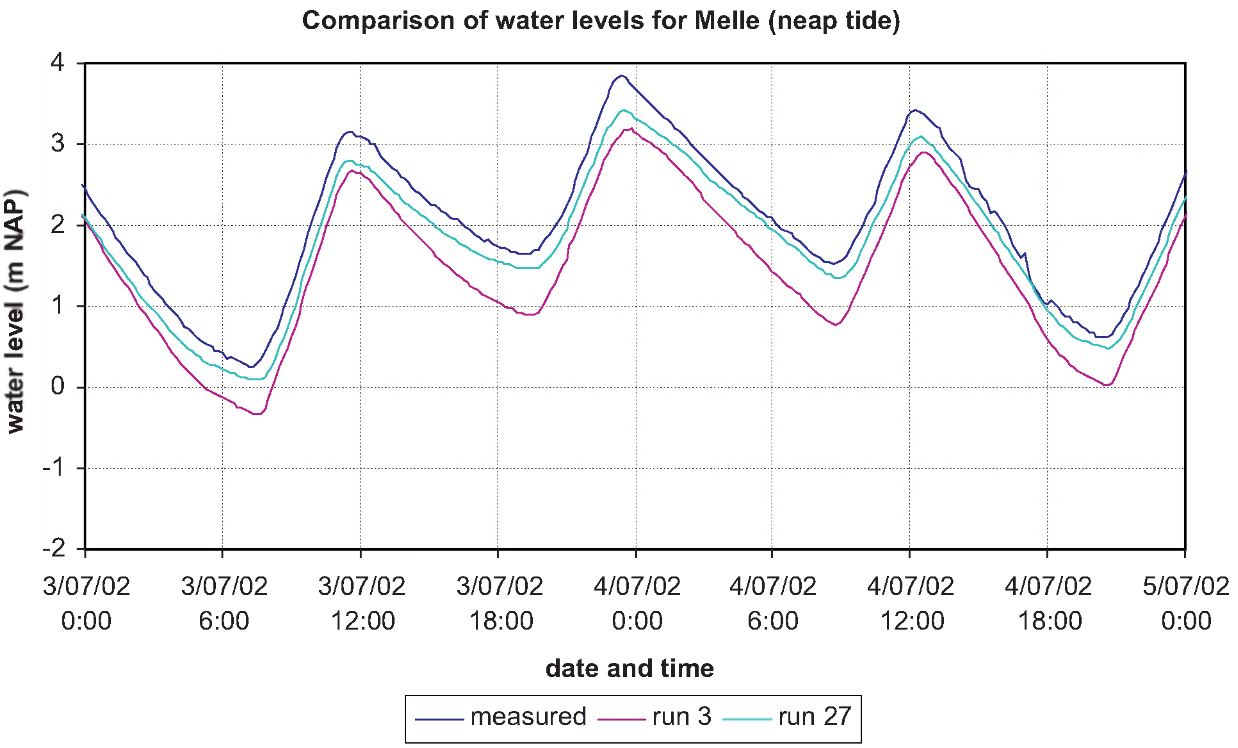
Water levels at Liefkenshoek for spring and neap tide



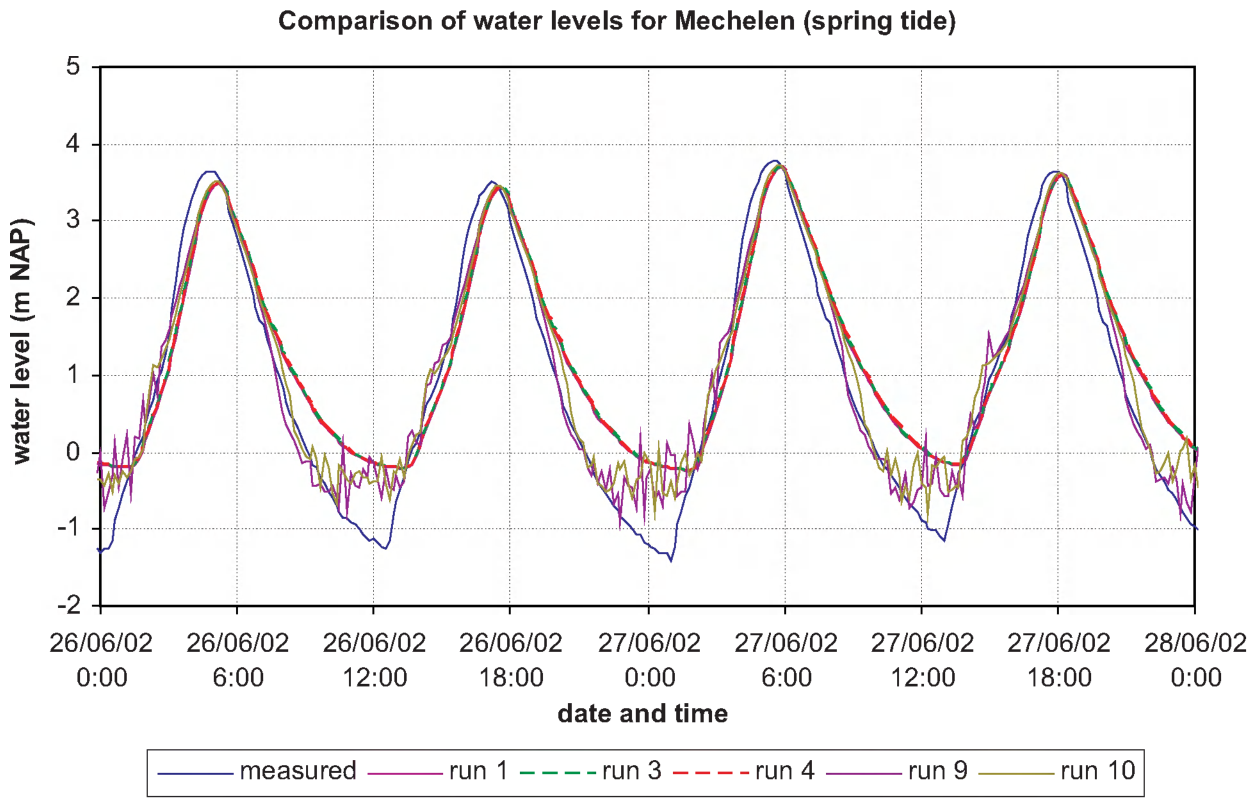


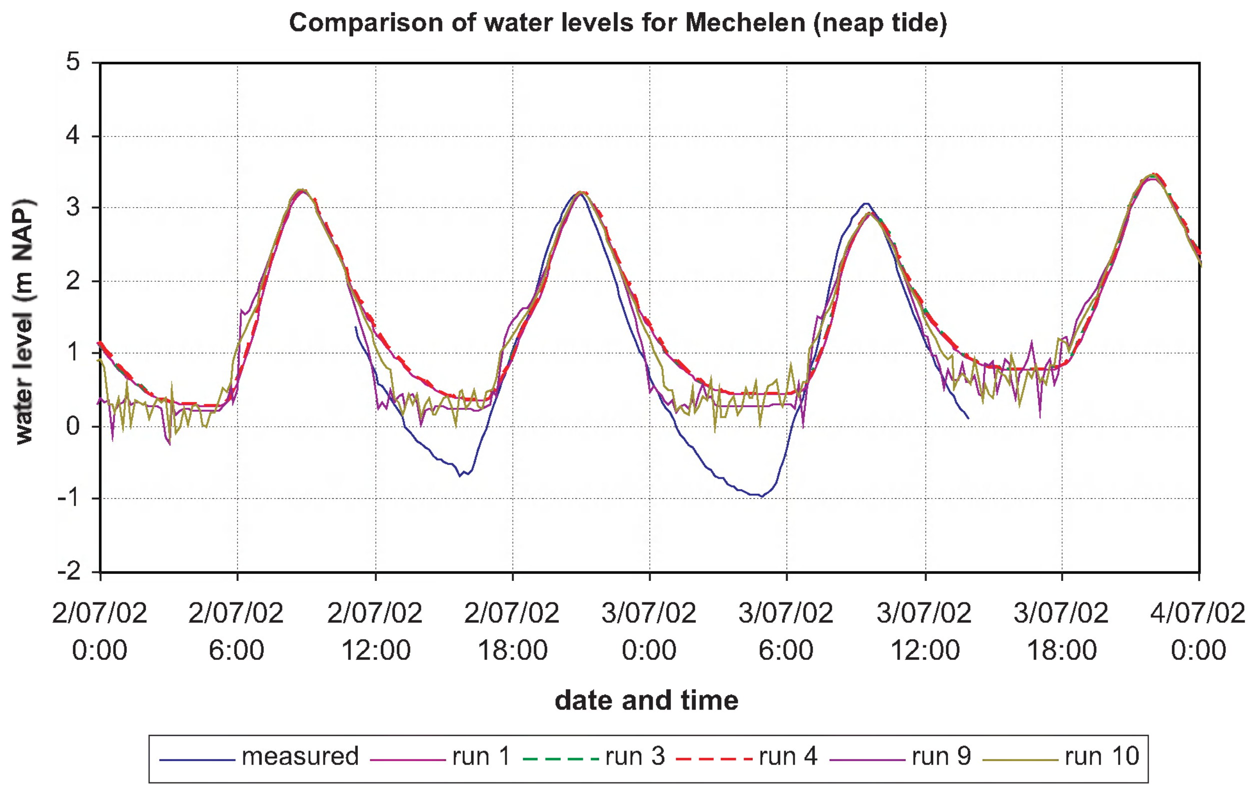
Water levels at Emblem for spring and neap tide



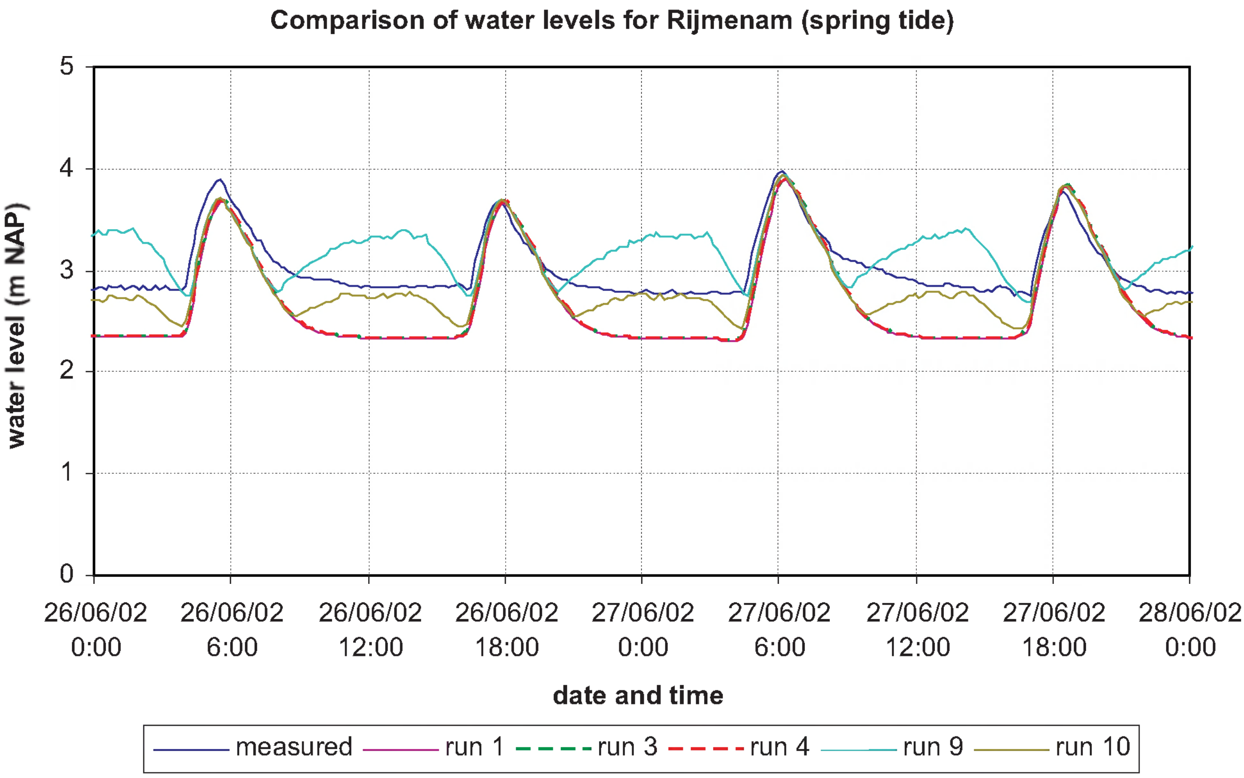


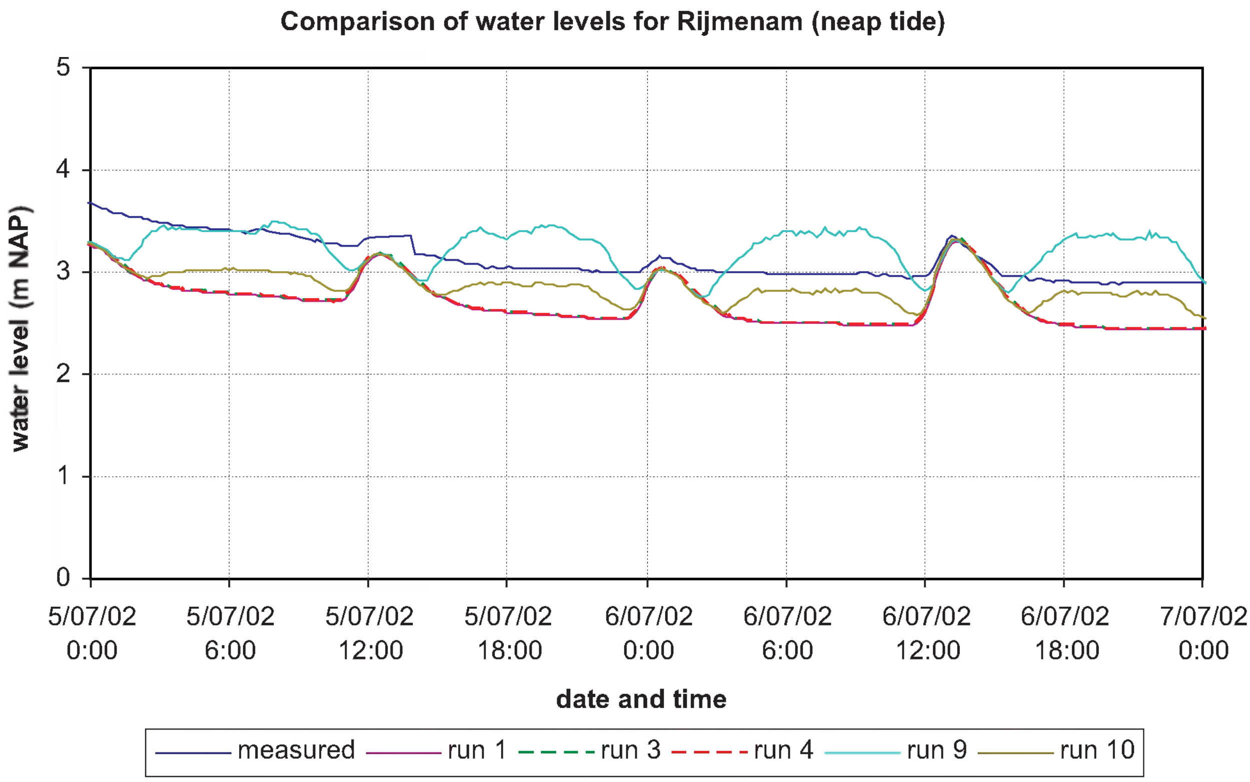
Comparison of the results of initial run and final run 27 for Melle



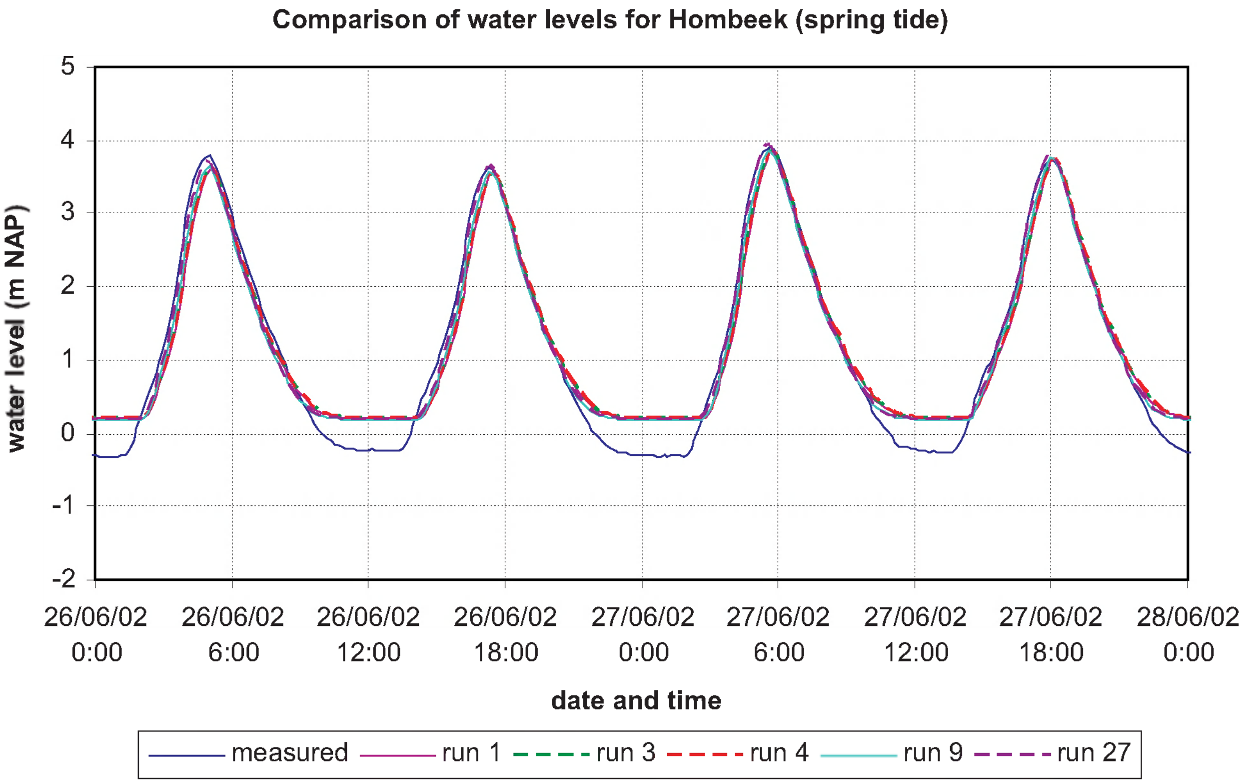


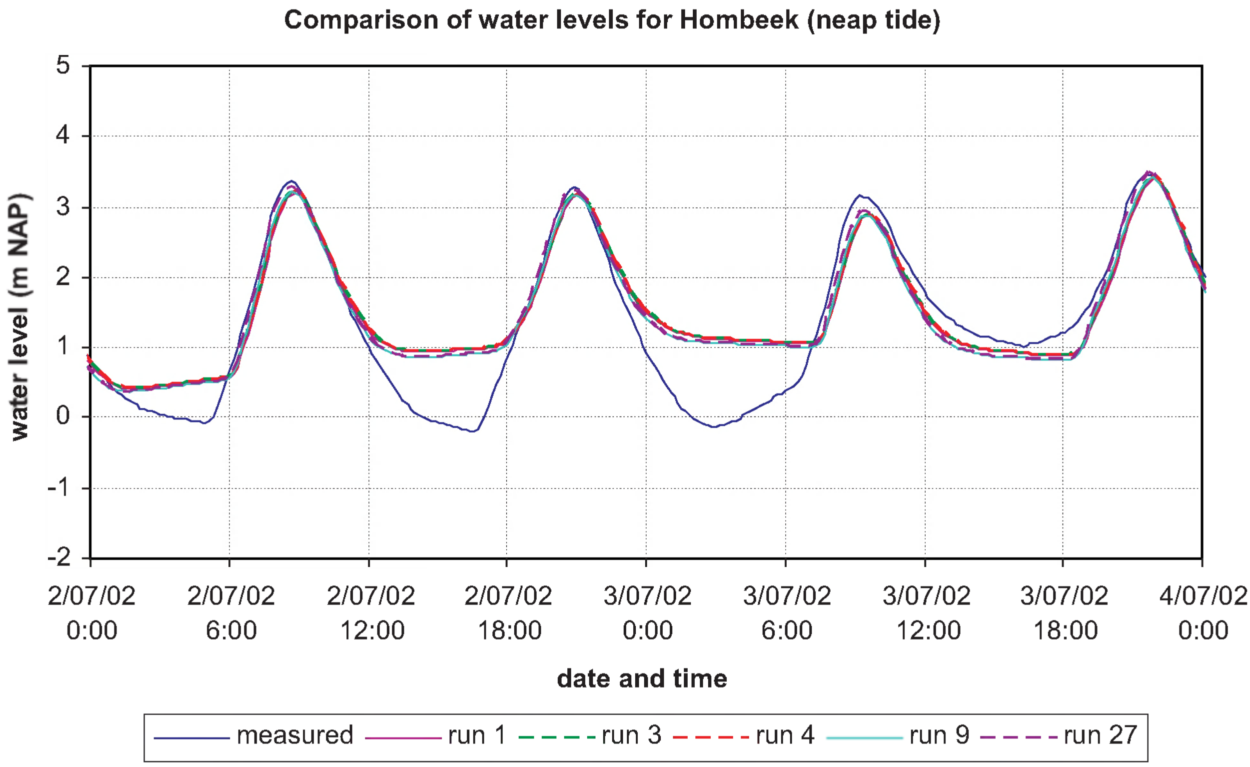
Water levels at Mechelen for spring and neap tide



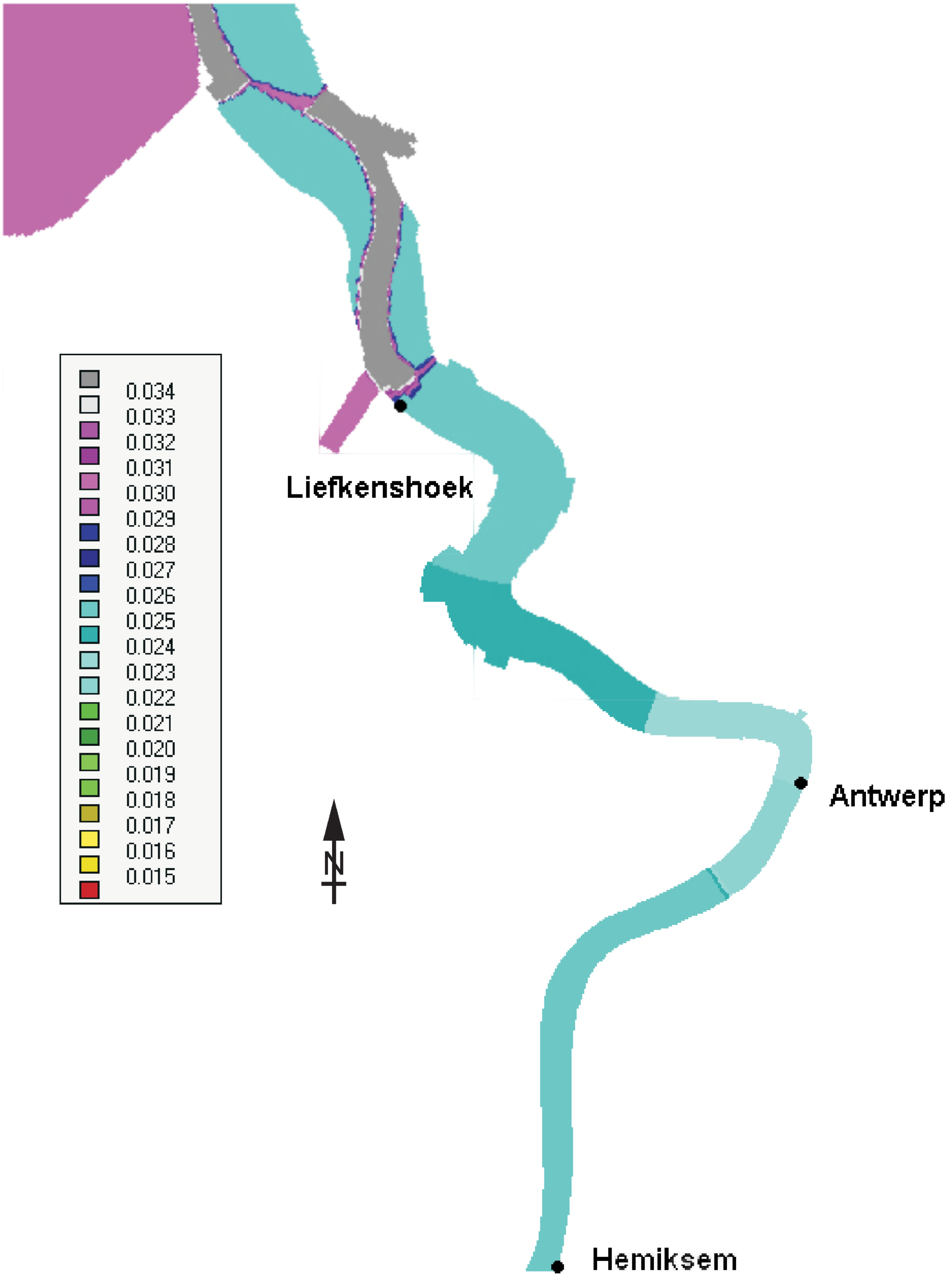


Water levels at Rijmenam for spring and neap tide

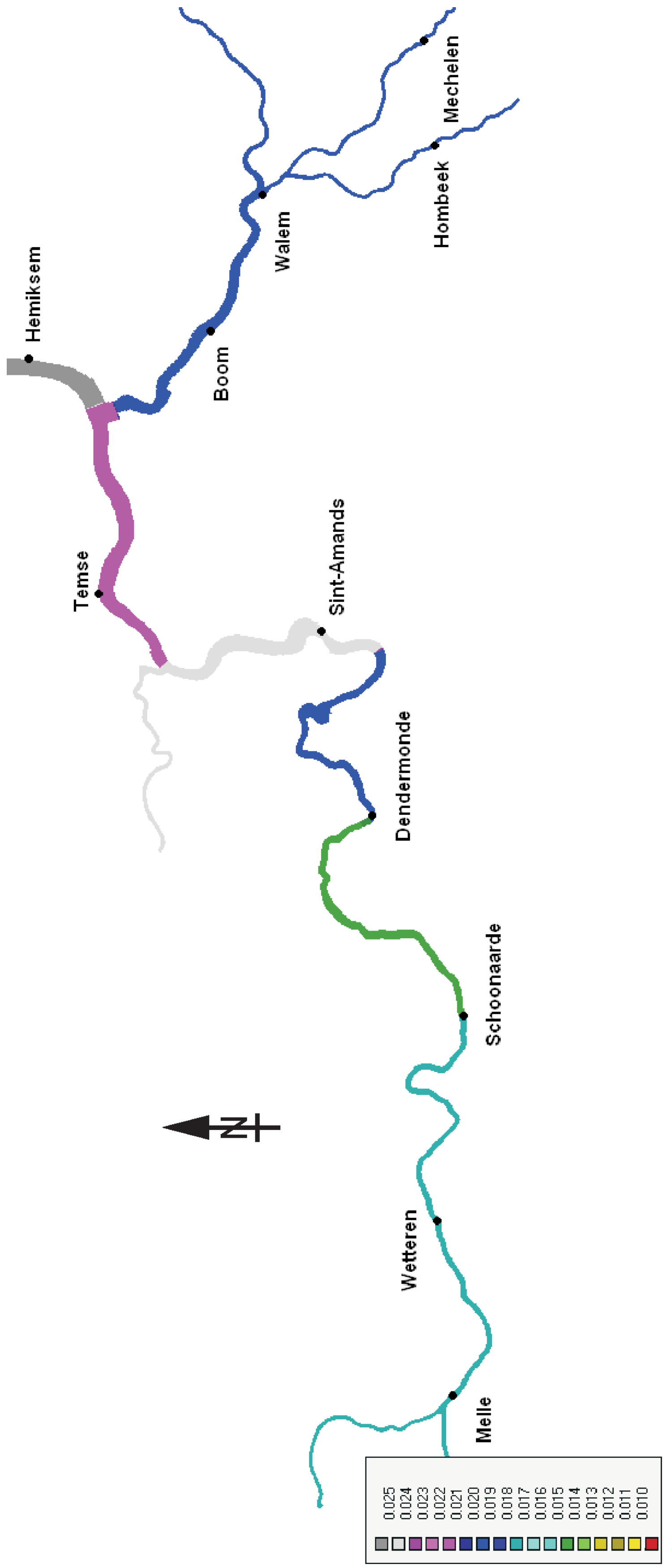




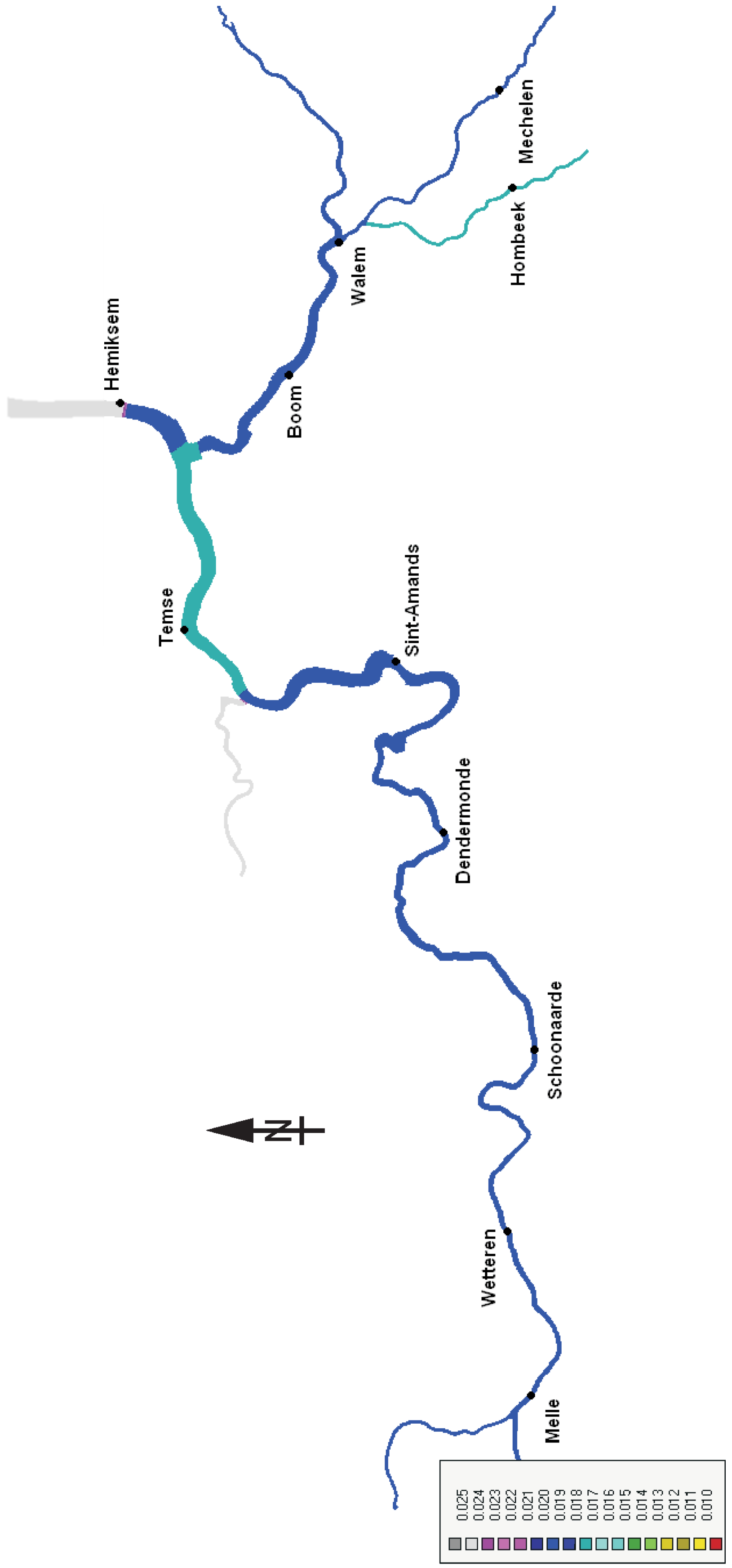
Water levels at Hombeek for spring and neap tide



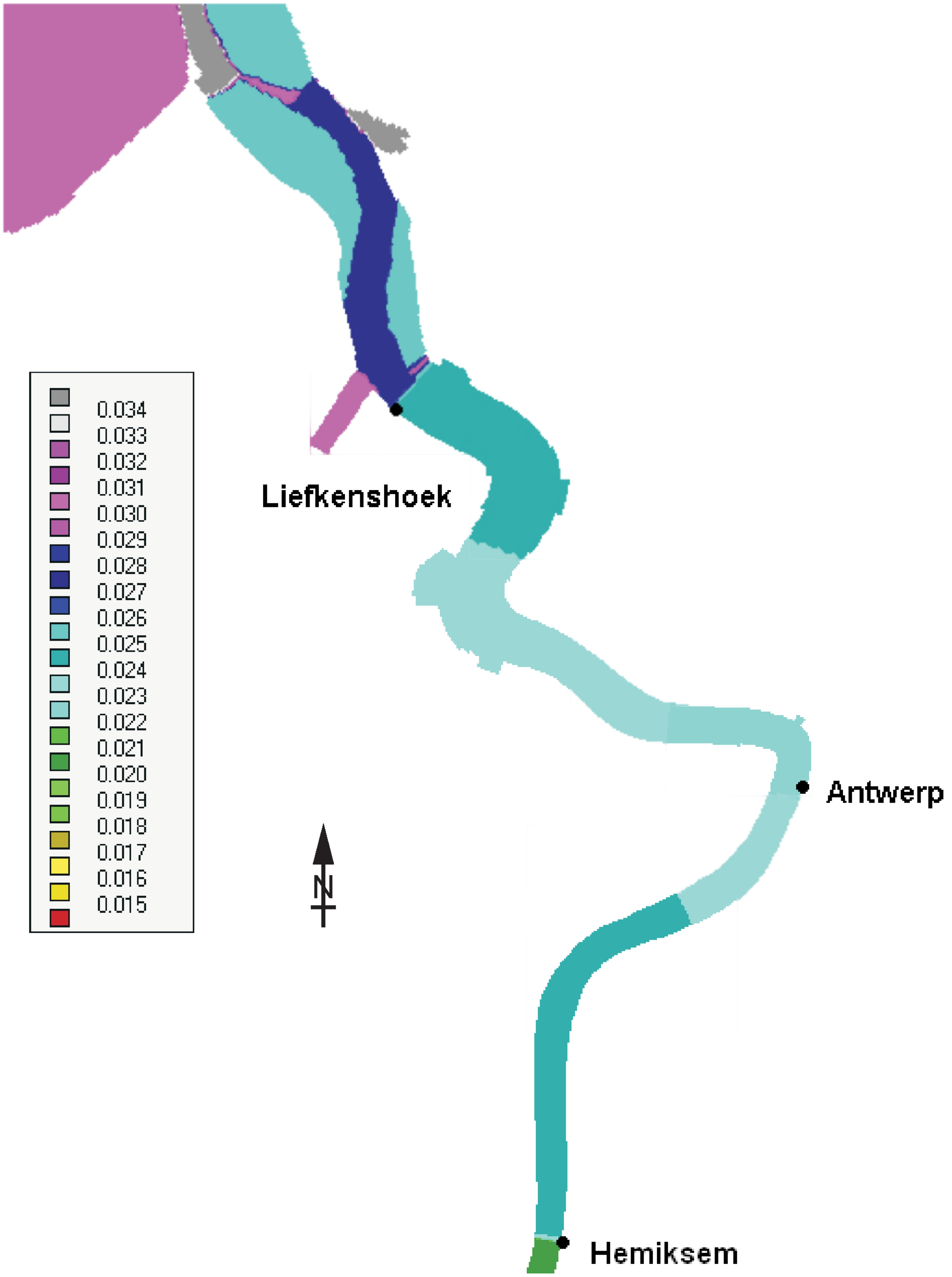
Original roughness field for the Lower Sea Scheldt
Roughness values expressed as Manning value ($m^{-1/3}s$)



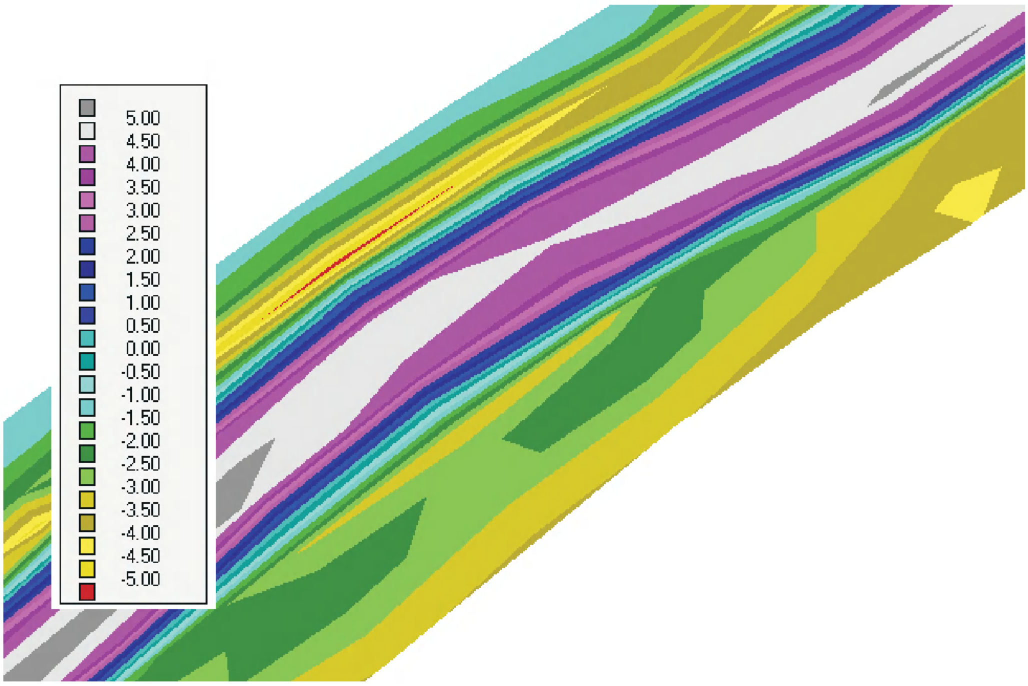
Original roughness field for the Upper Sea Scheldt
Roughness values expressed as Manning value ($m^{-1/3}s$)

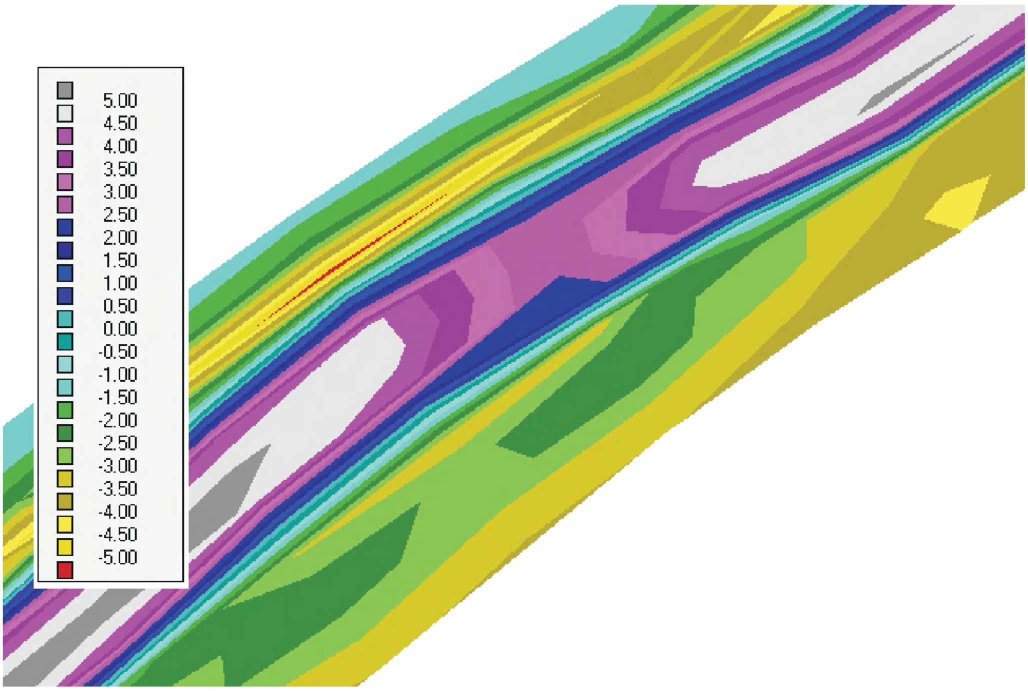


Roughness field for the Upper Sea Scheldt for run 27
Roughness values expressed as Manning value ($m^{-1/3}s$)

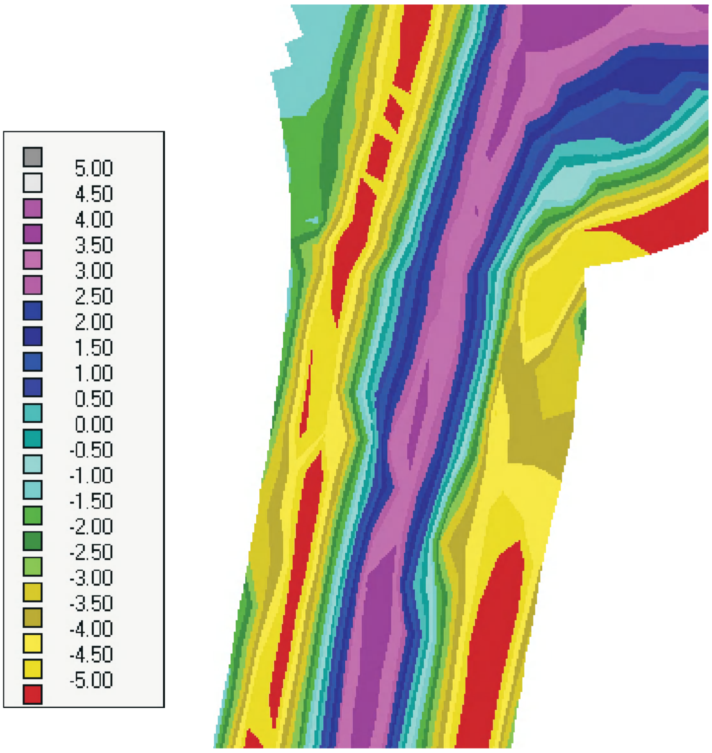


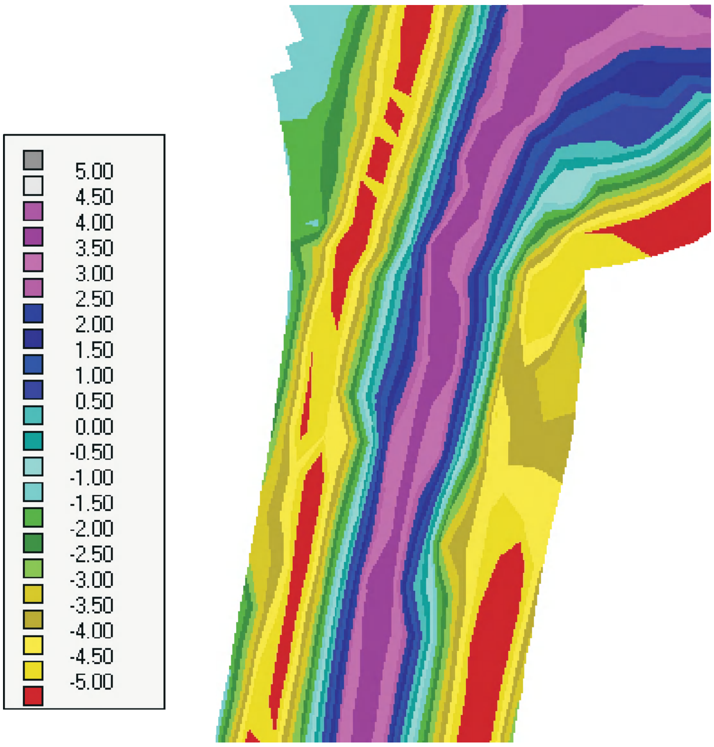
Roughness field for the Lower Sea Scheldt for run 27
Roughness values expressed as Manning value ($m^{-1/3}s$)



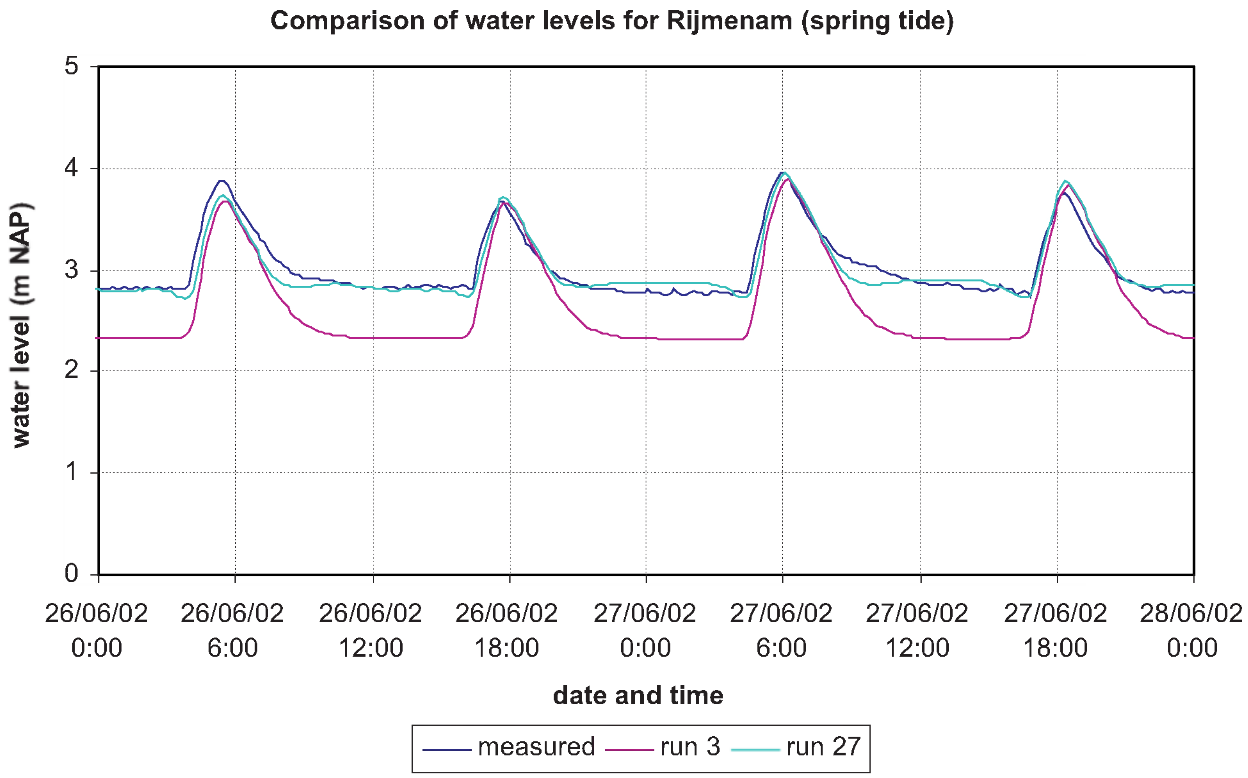


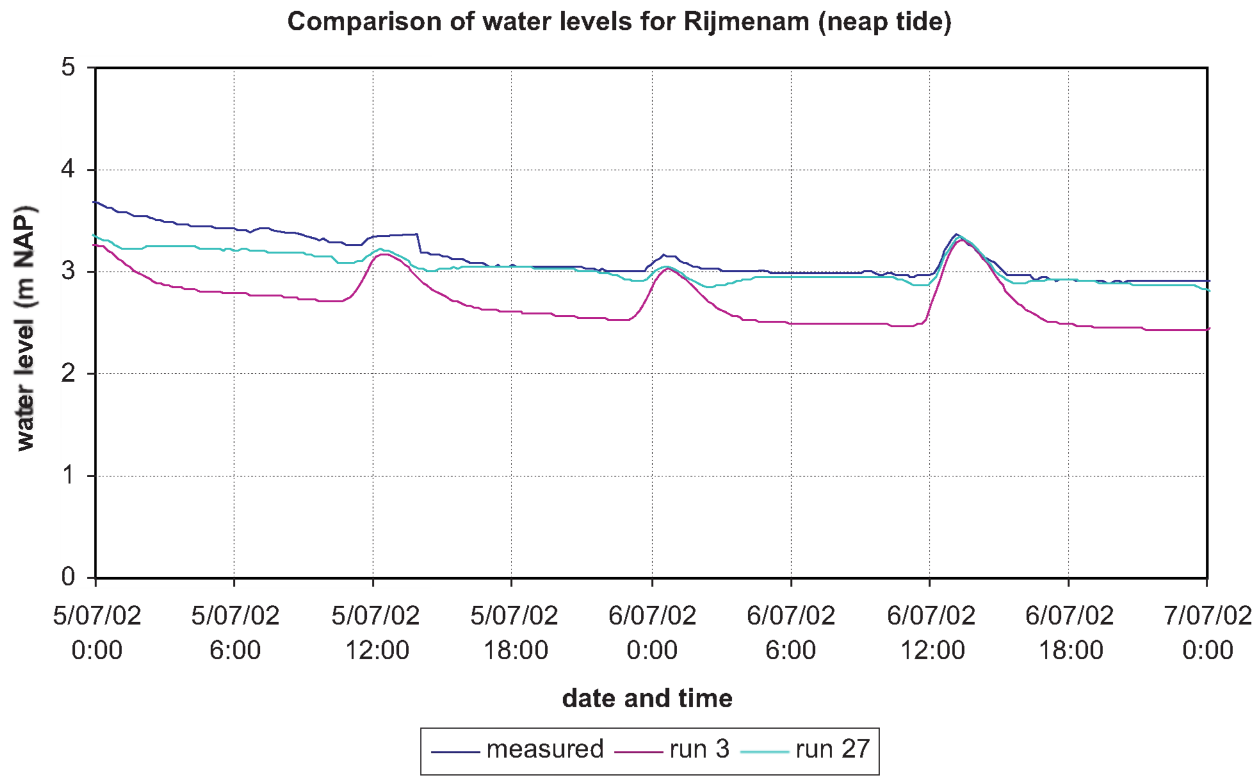
Bathymetry downstream Schoonaarde before implementation of the weir (above) and after implementation of the weir (below)	bathymetry : below NAP (m)



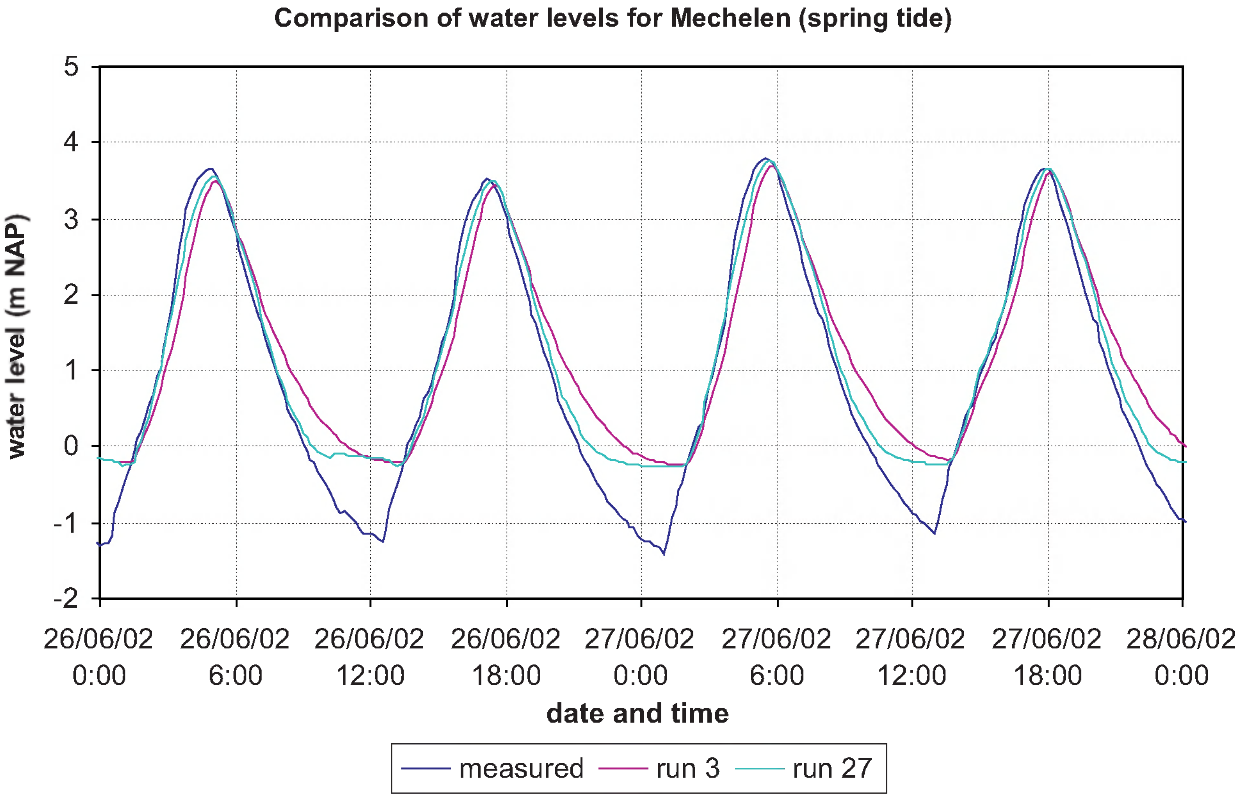


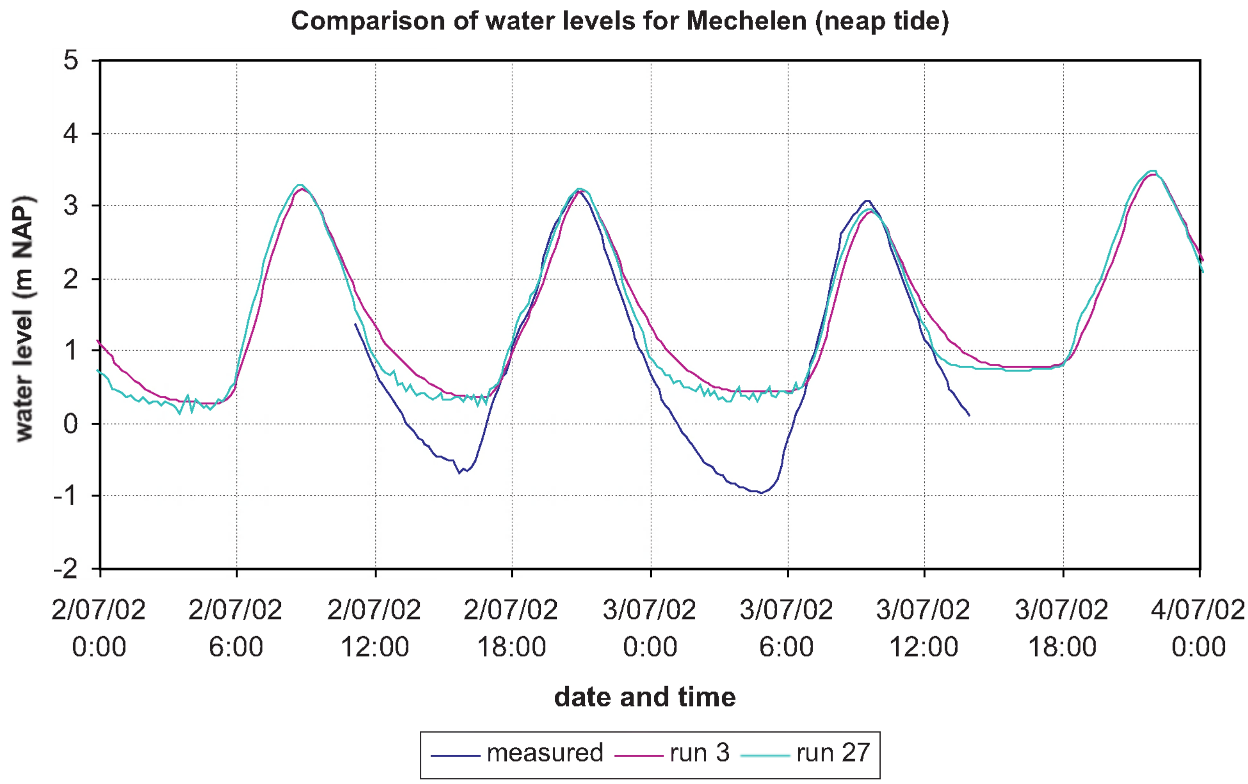
Original bathymetry for Zenne (above) and bathymetry after changes (below)	bathymetry : below NAP (m)



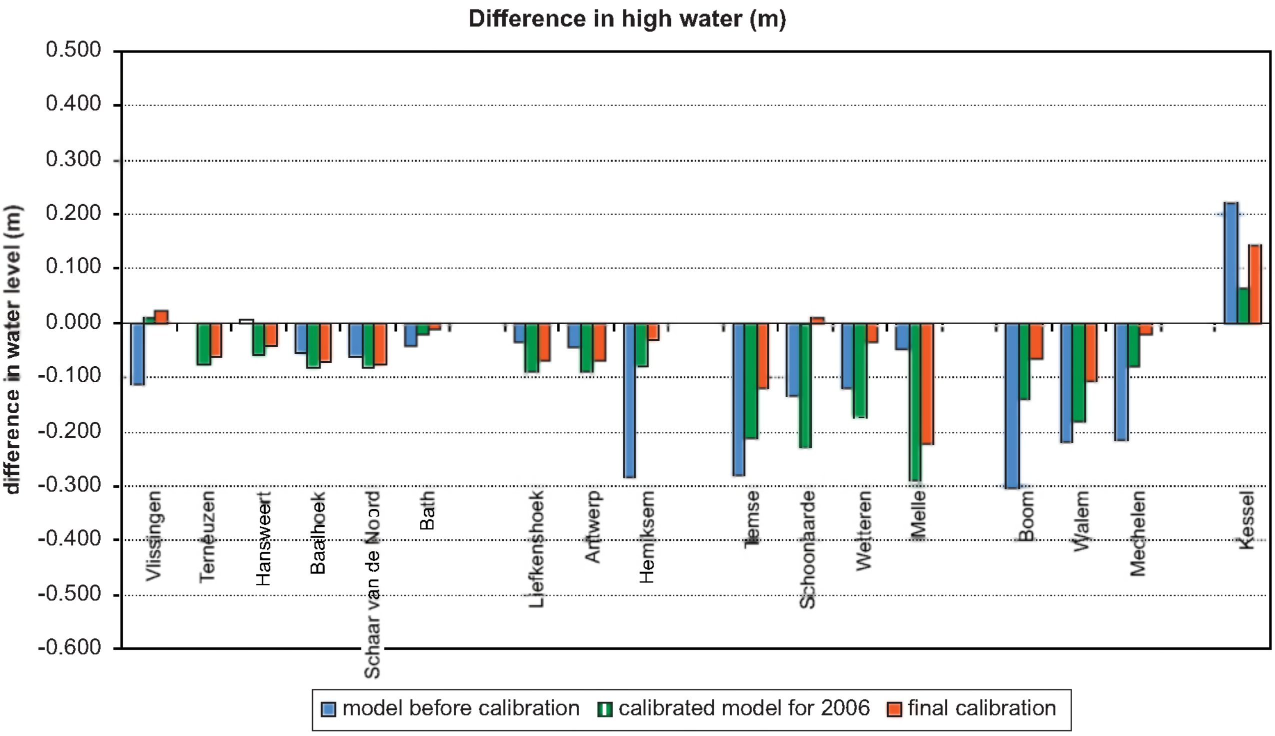


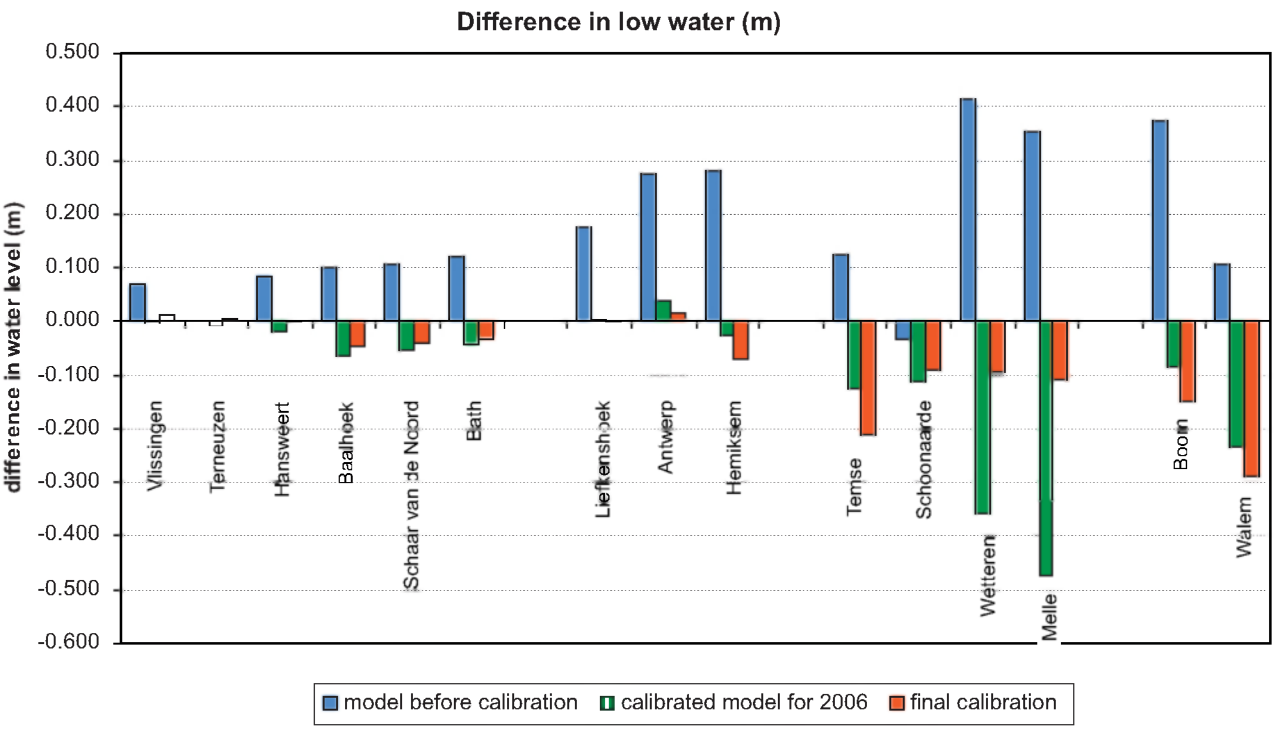
Comparison of the results of initial run and final run 27 for Rijmenam



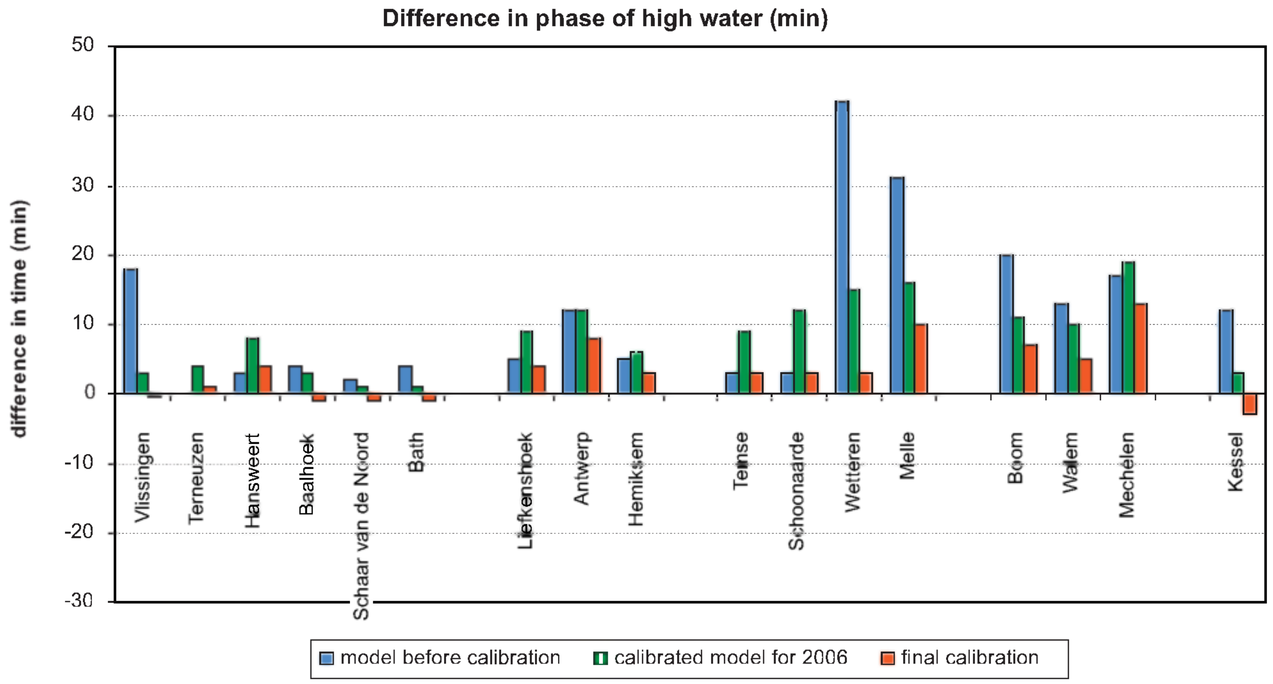


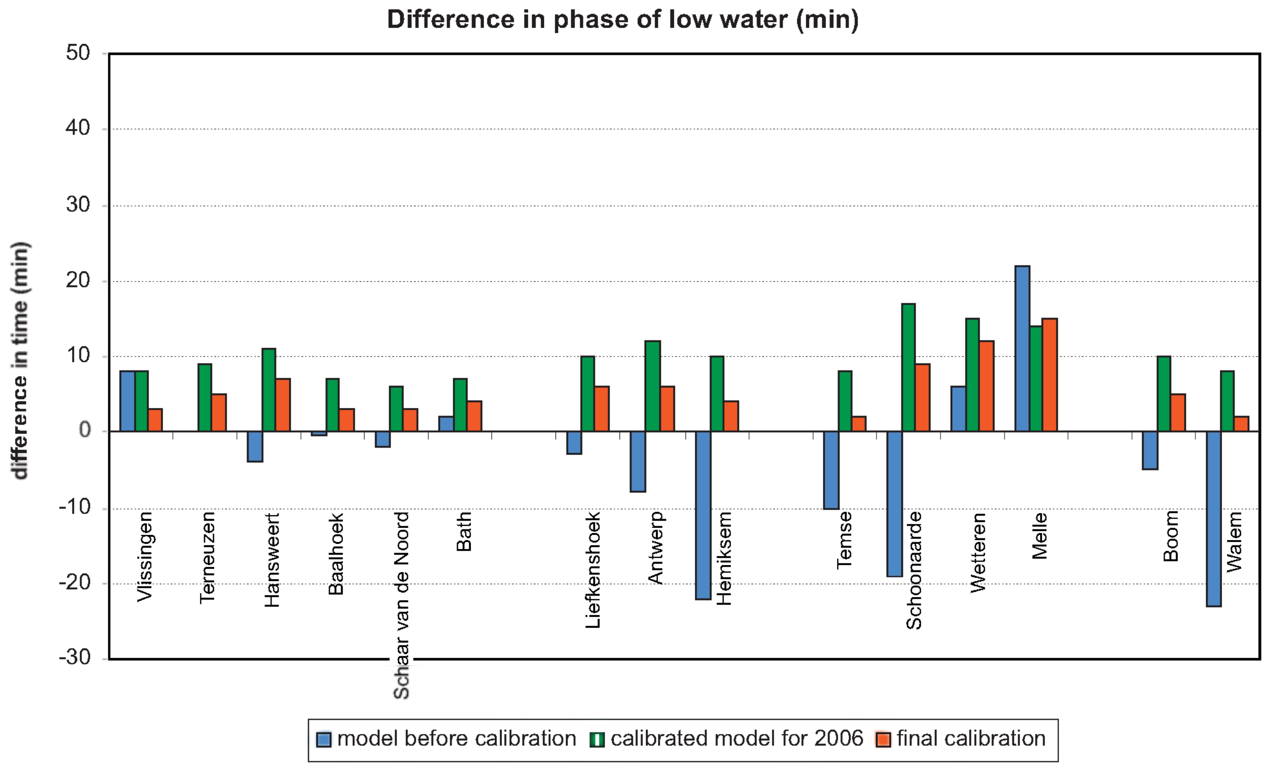
Comparison of the results of initial run and final run 27 for Mechelen



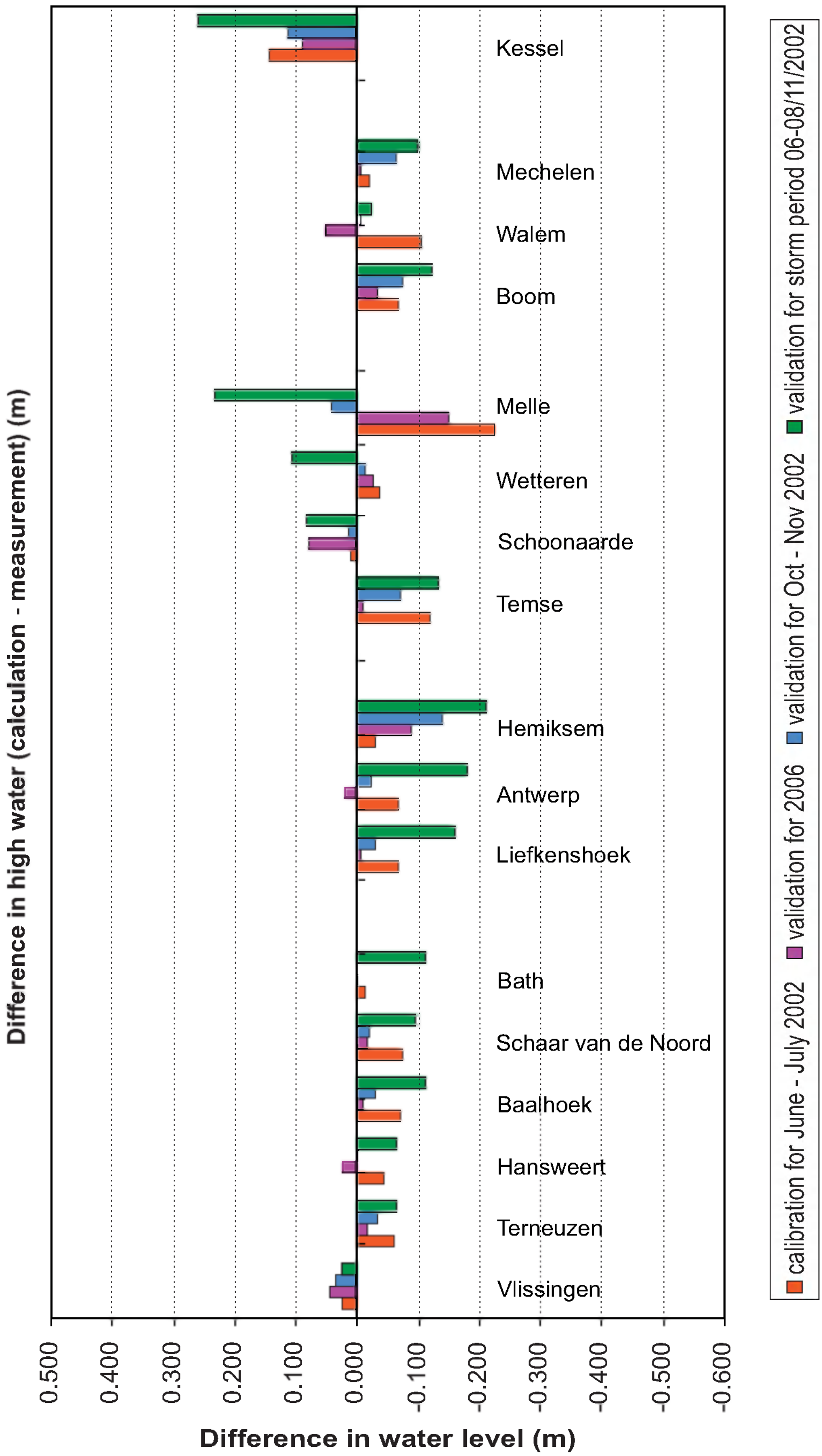


Difference between calculated and measured water levels before and after calibration (calculation – measurement)

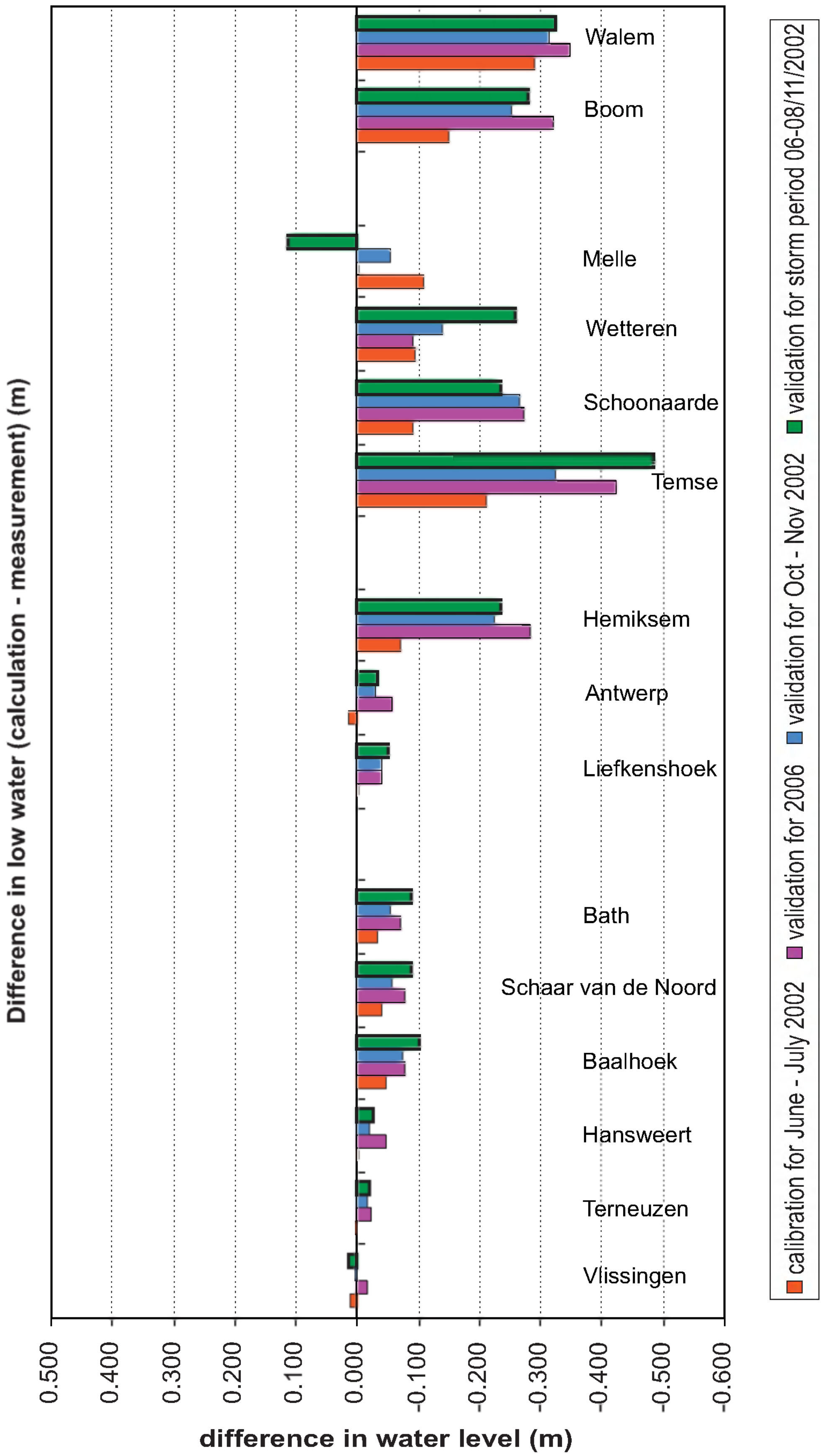




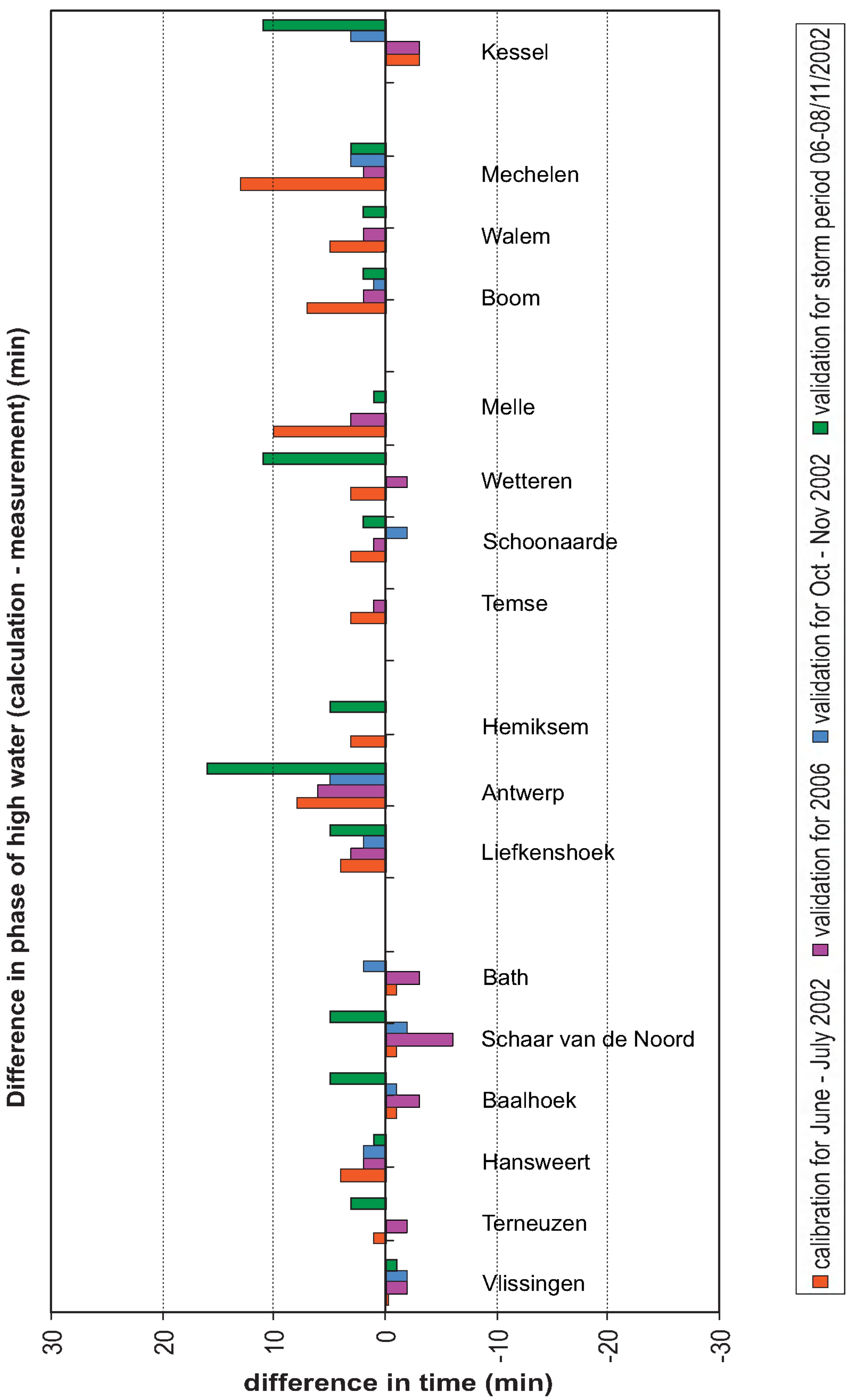
Difference between calculated and measured phase of low and high waters before and after calibration (calculation – measurement)



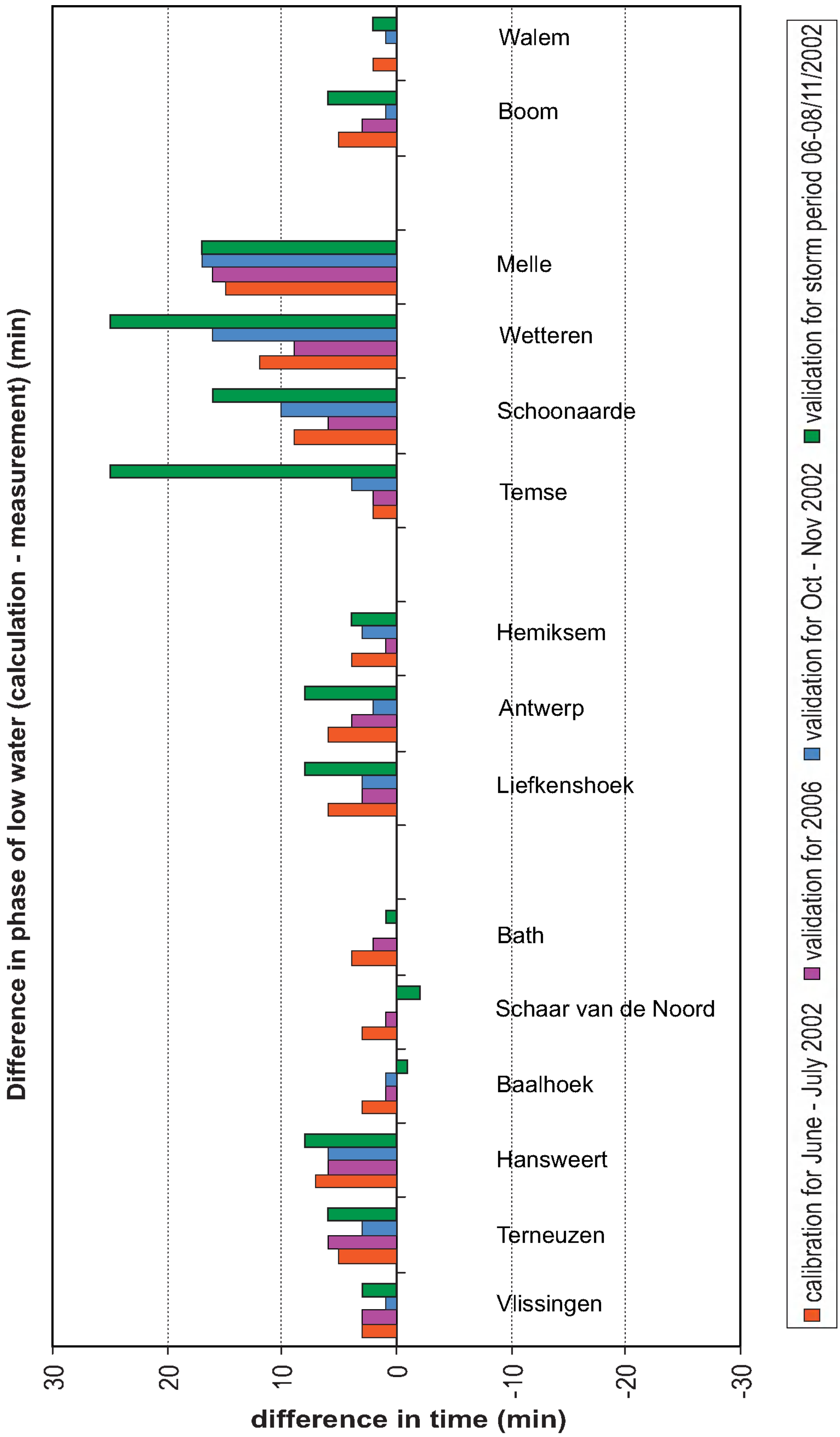
Difference between calculated and measured magnitude of high waters for calibration and validation



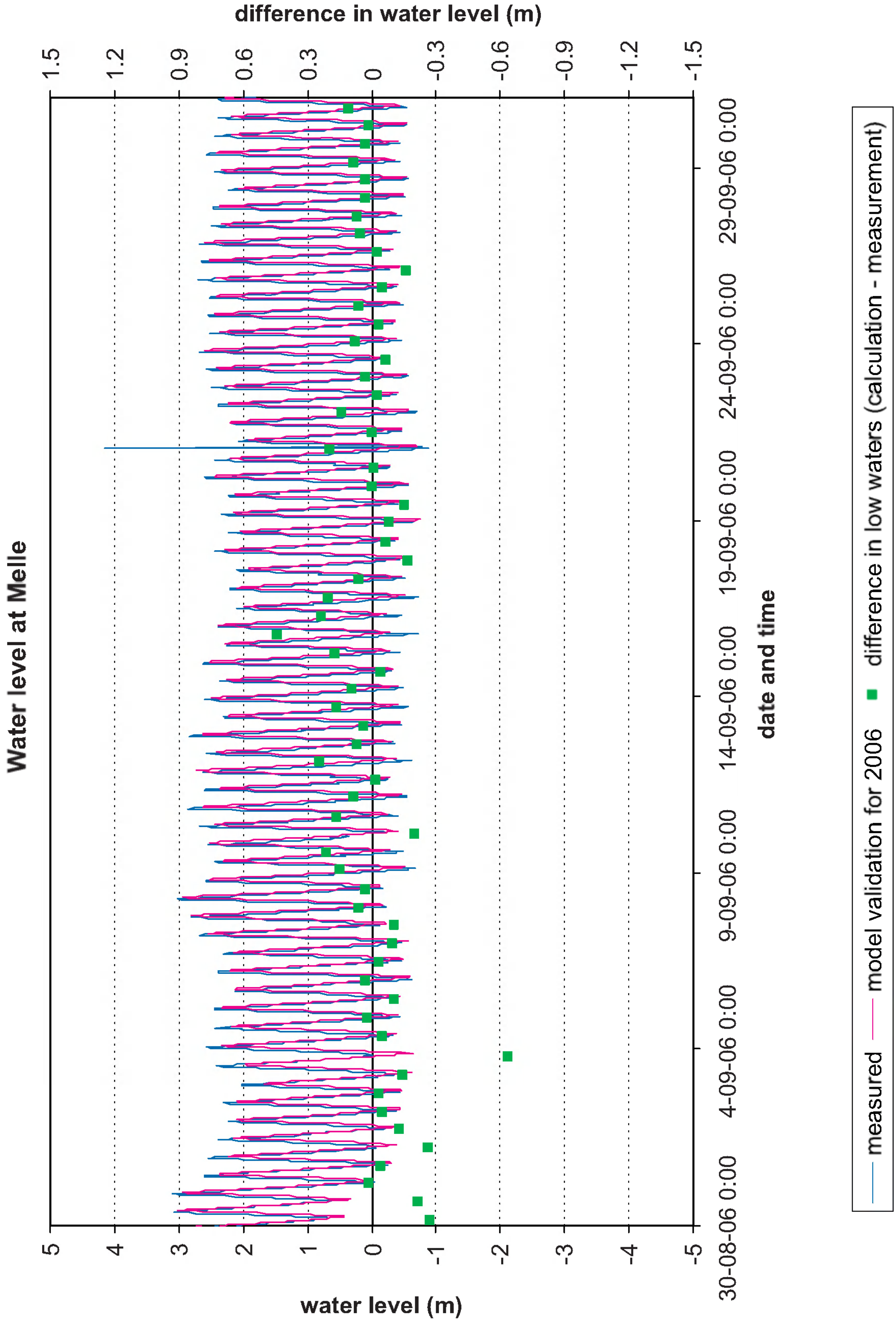
Difference between calculated and measured magnitude of low waters for calibration and validation



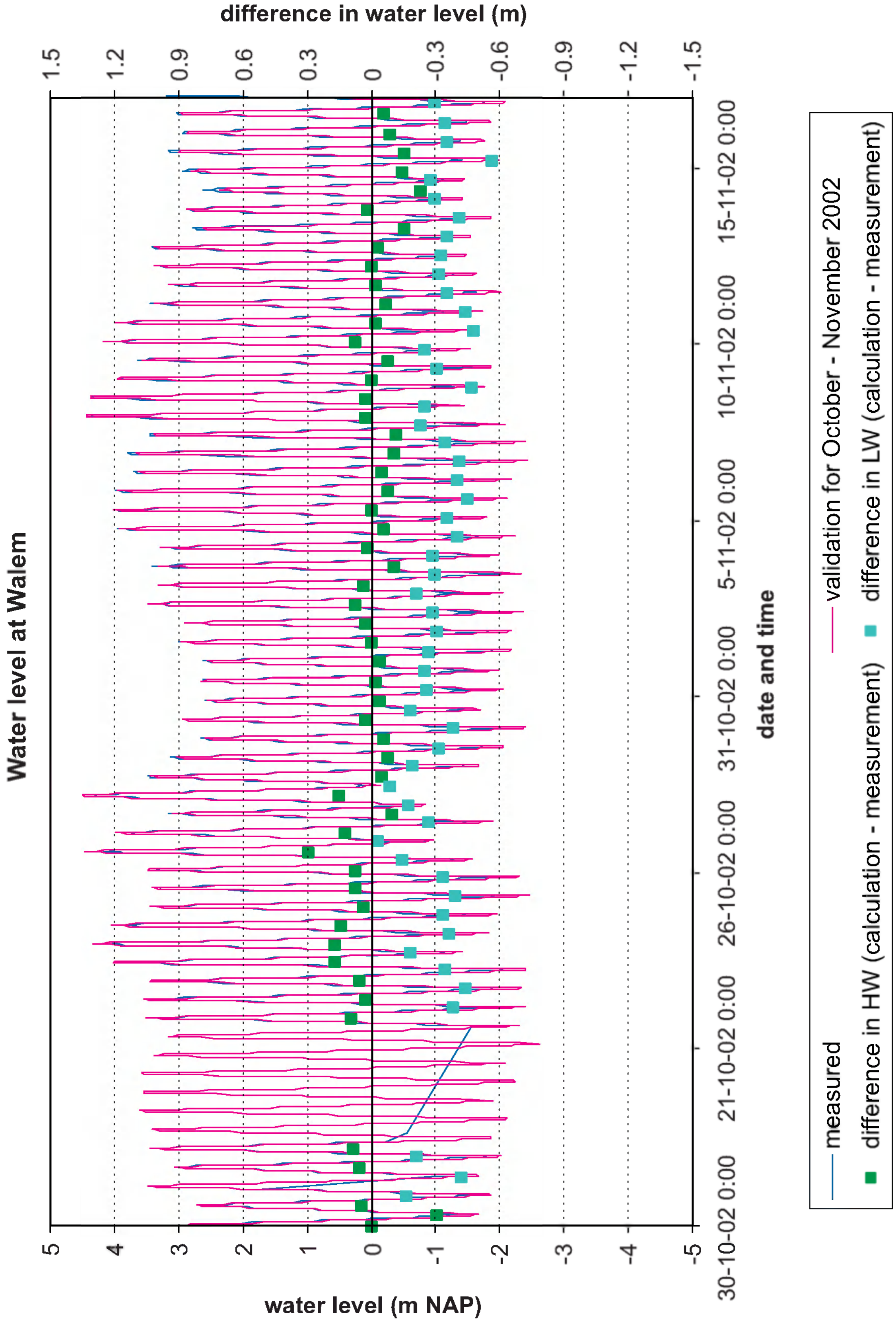
Difference between calculated and measured phase of high waters for calibration and validation



Difference between calculated and measured phase of low waters for calibration and calibration and validation

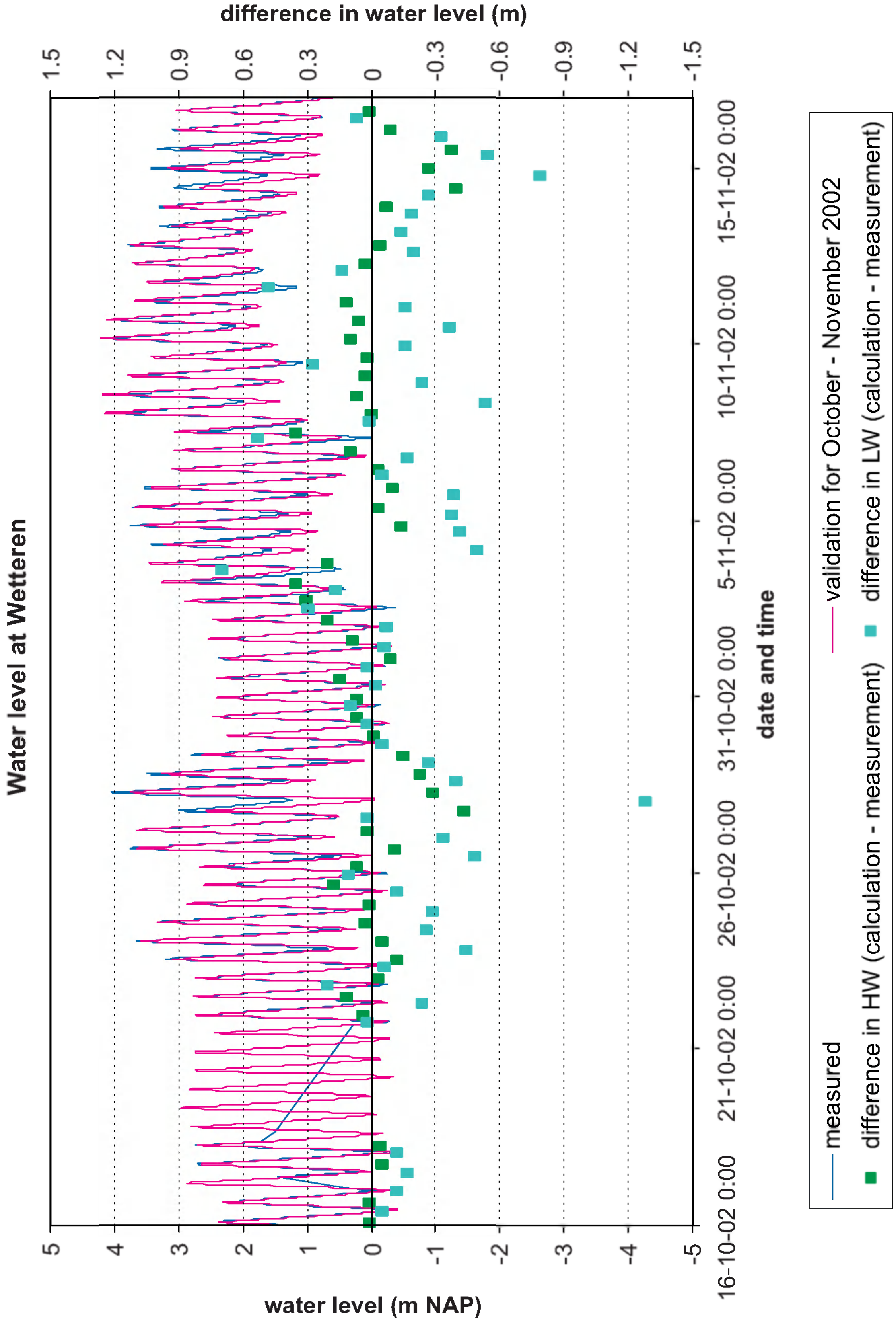


Measured and calculated water level at Melle in 2006

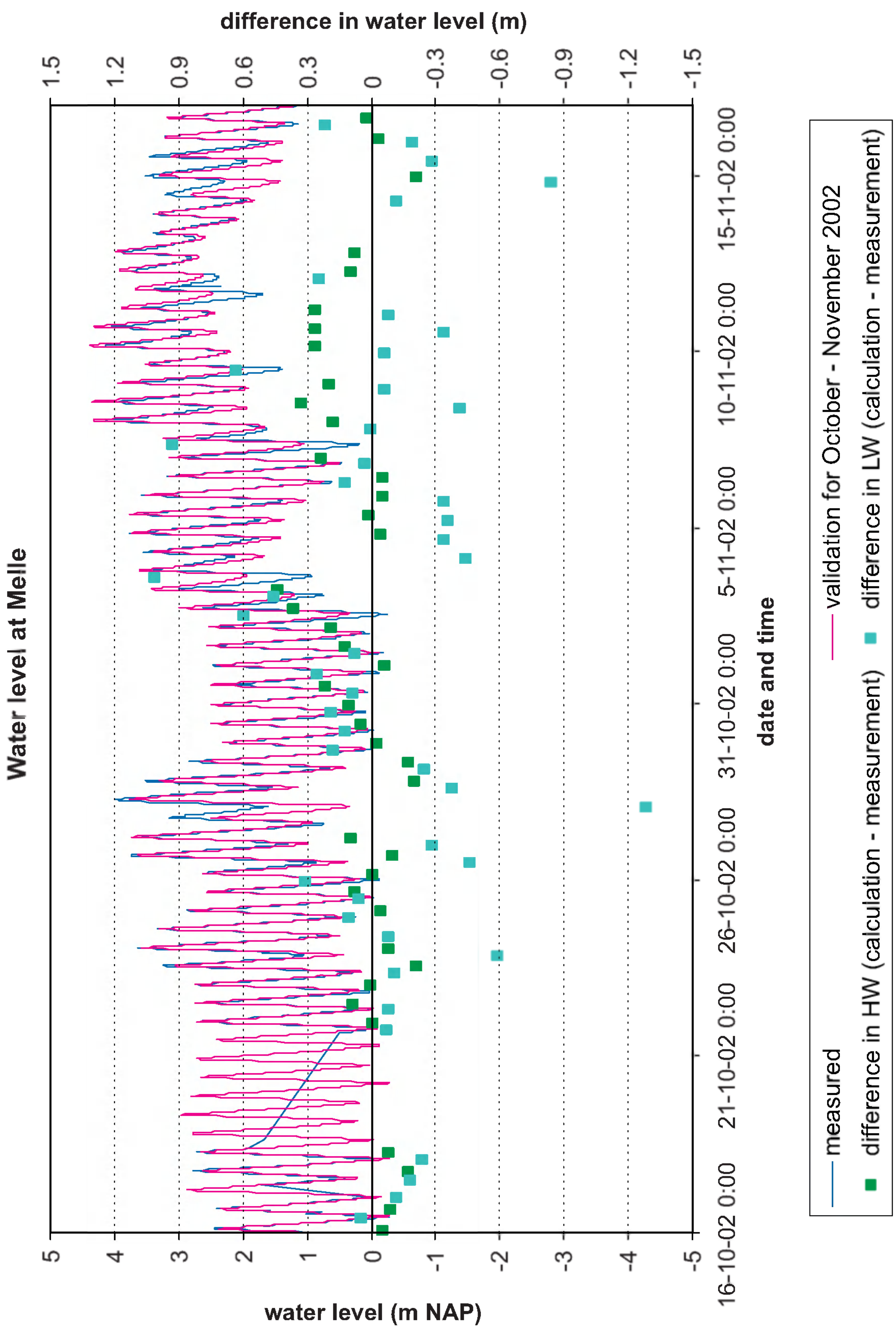


Measured and calculated water level at Walem in 2002

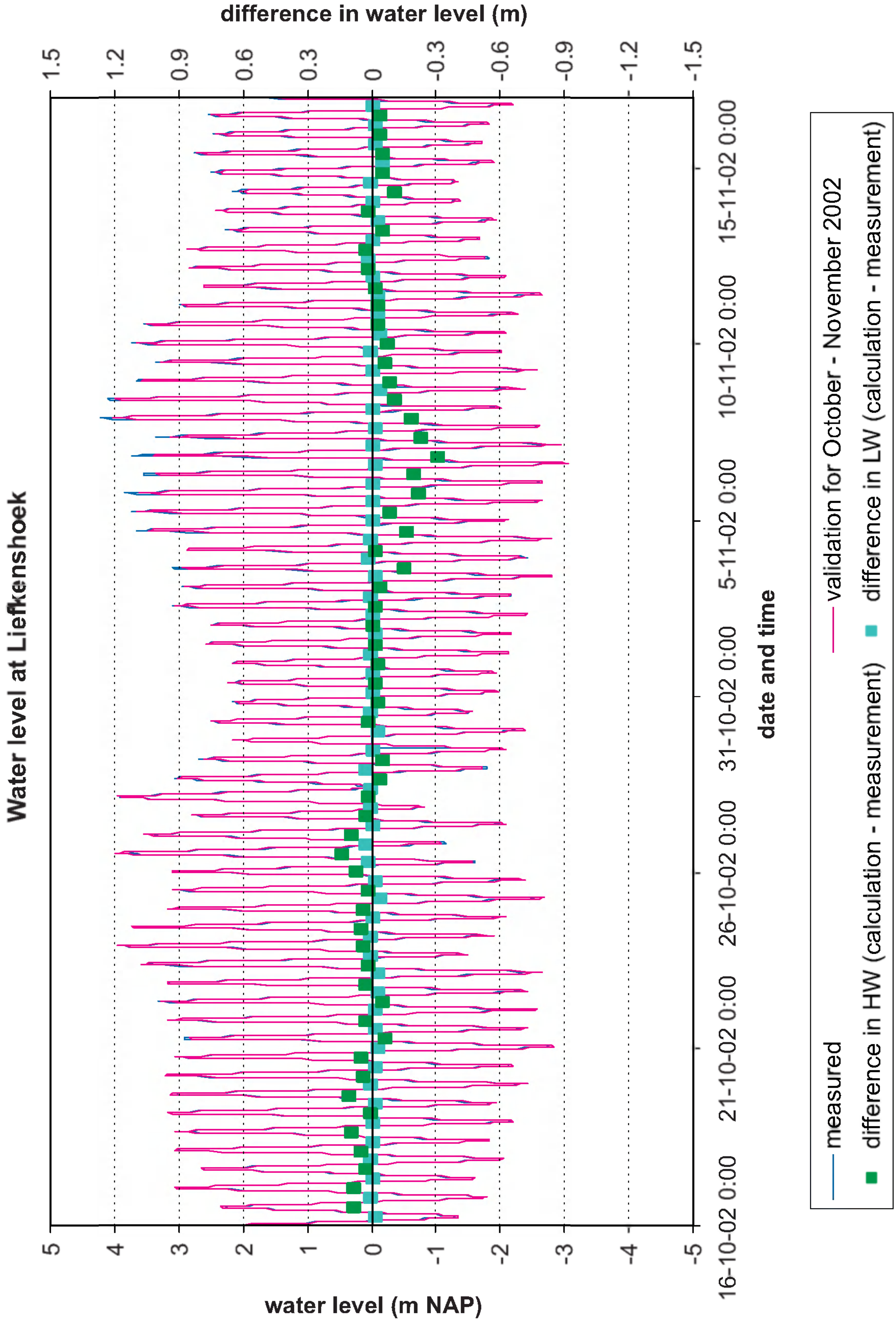
bathymetry : m NAP



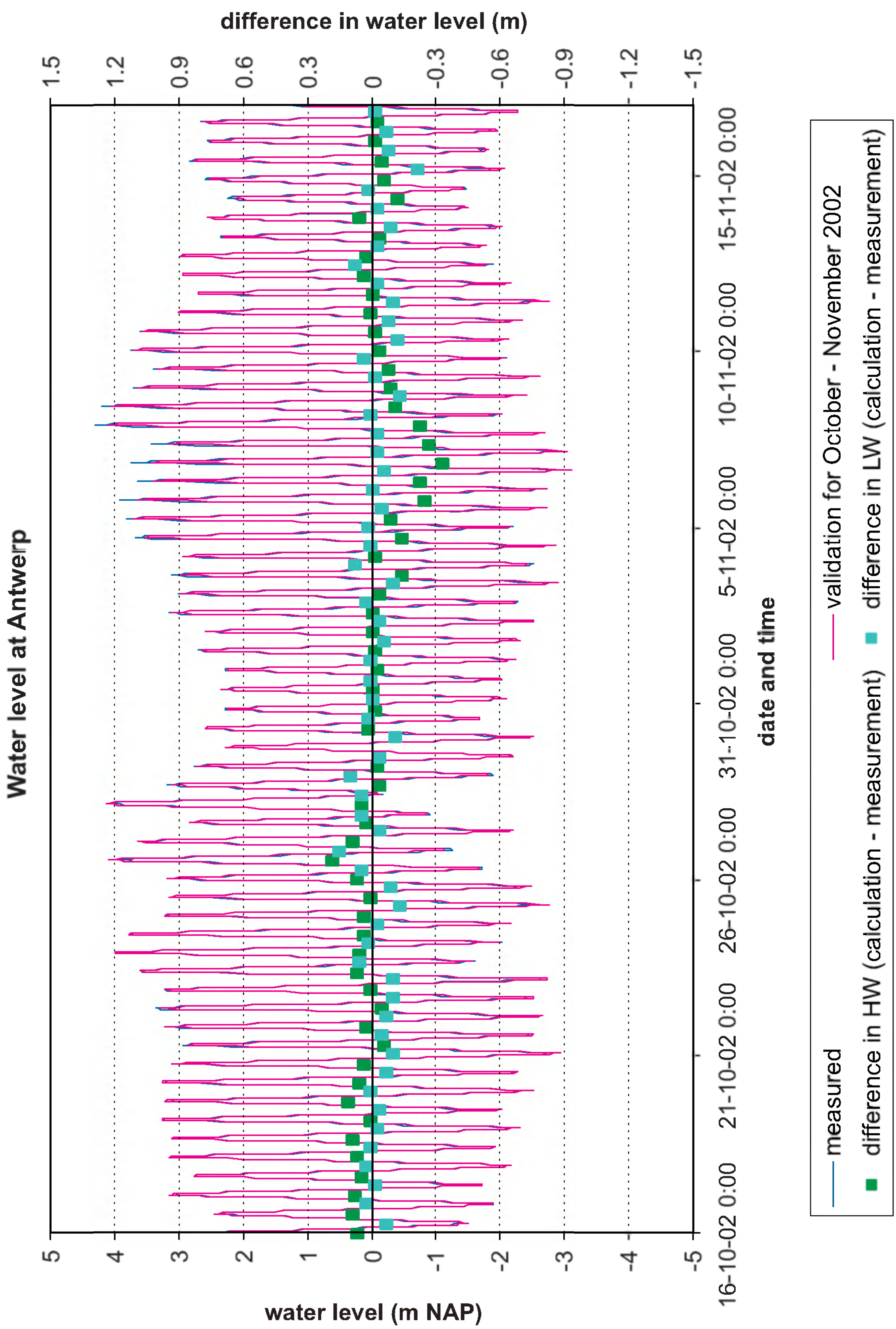
Measured and calculated water level at Wetteren in 2002 | bathymetry : m NAP



Measured and calculated water level at Melle in 2002

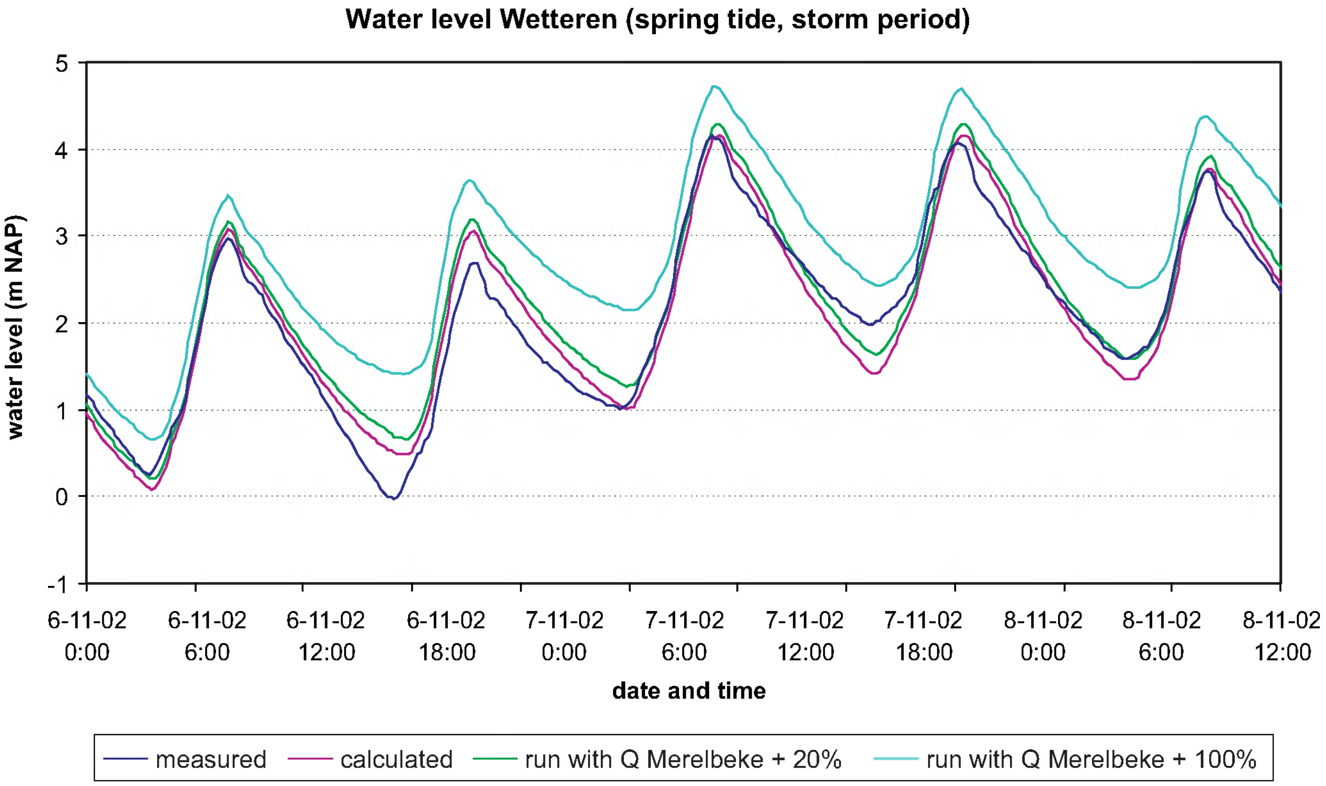


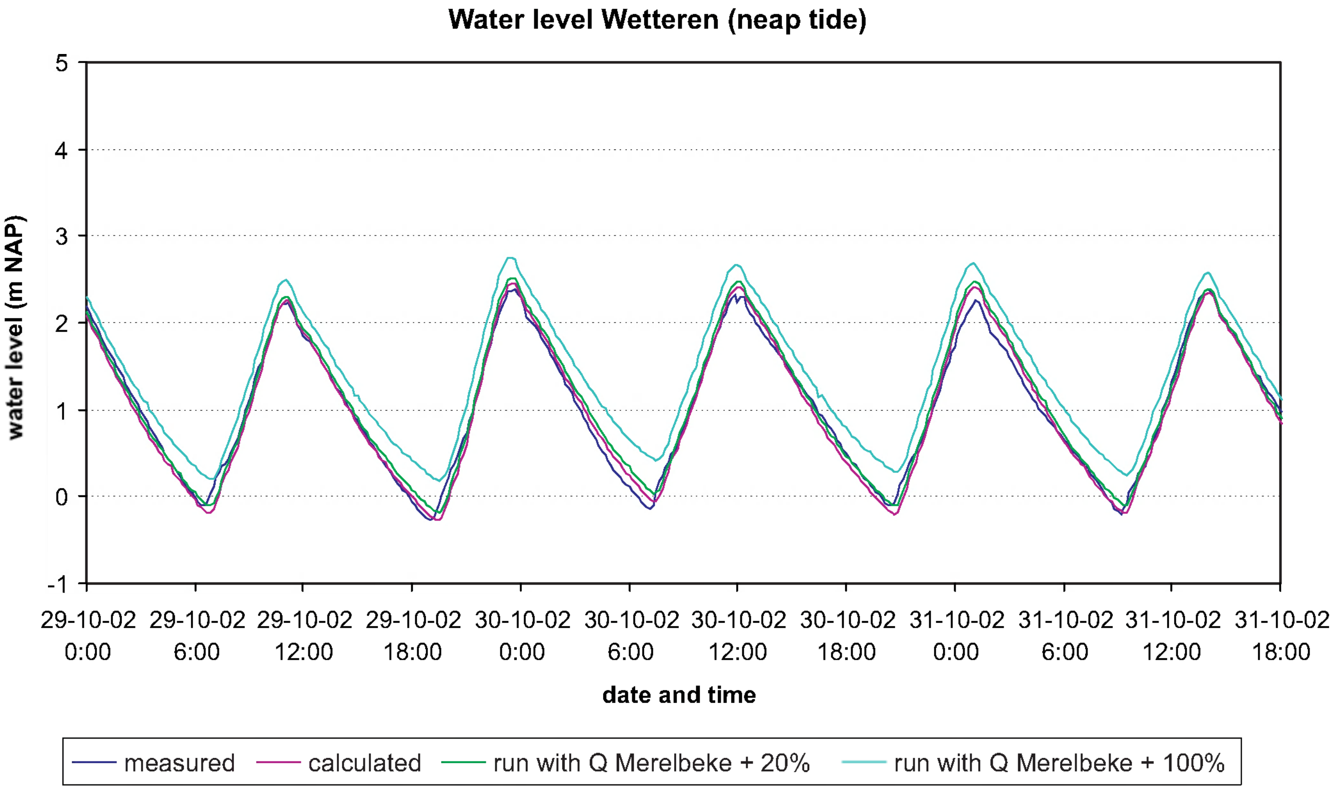
Measured and calculated water level at Liefkenshoek in 2002



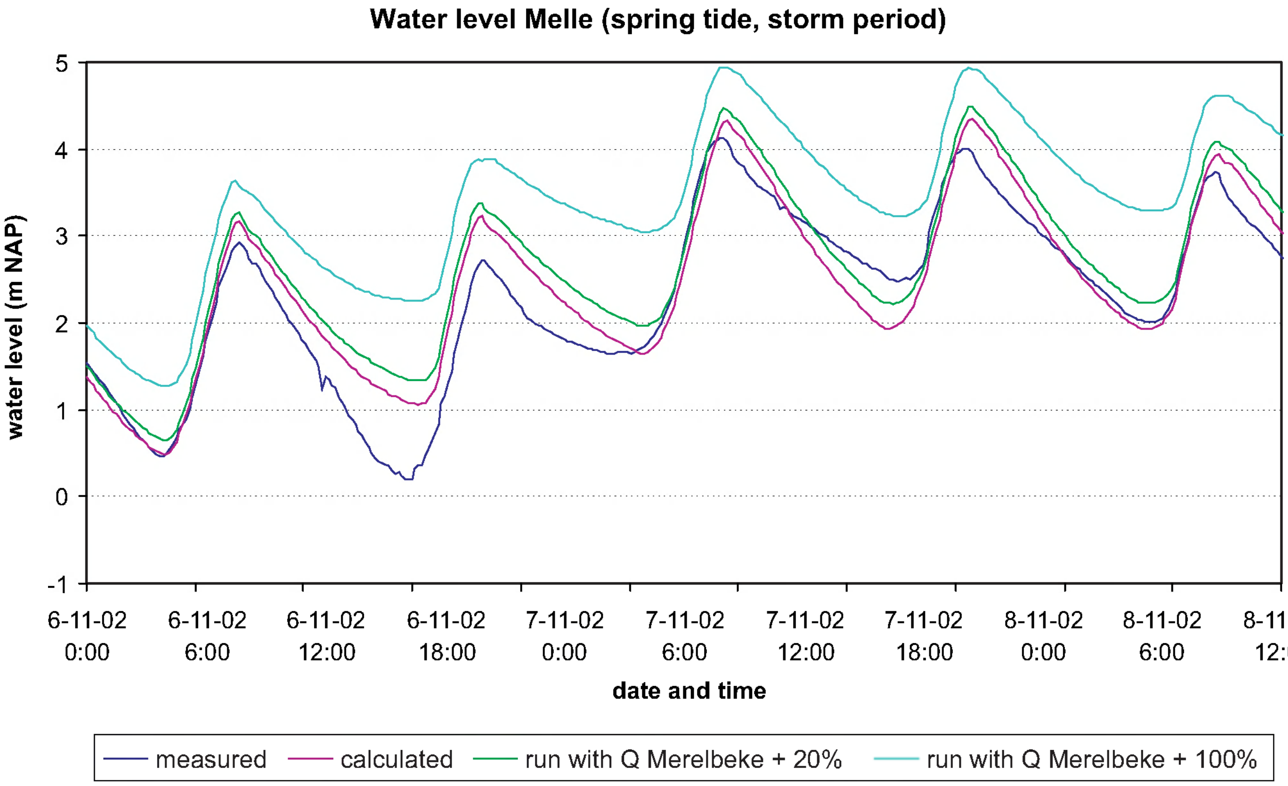
Measured and calculated water level at Antwerp in 2002

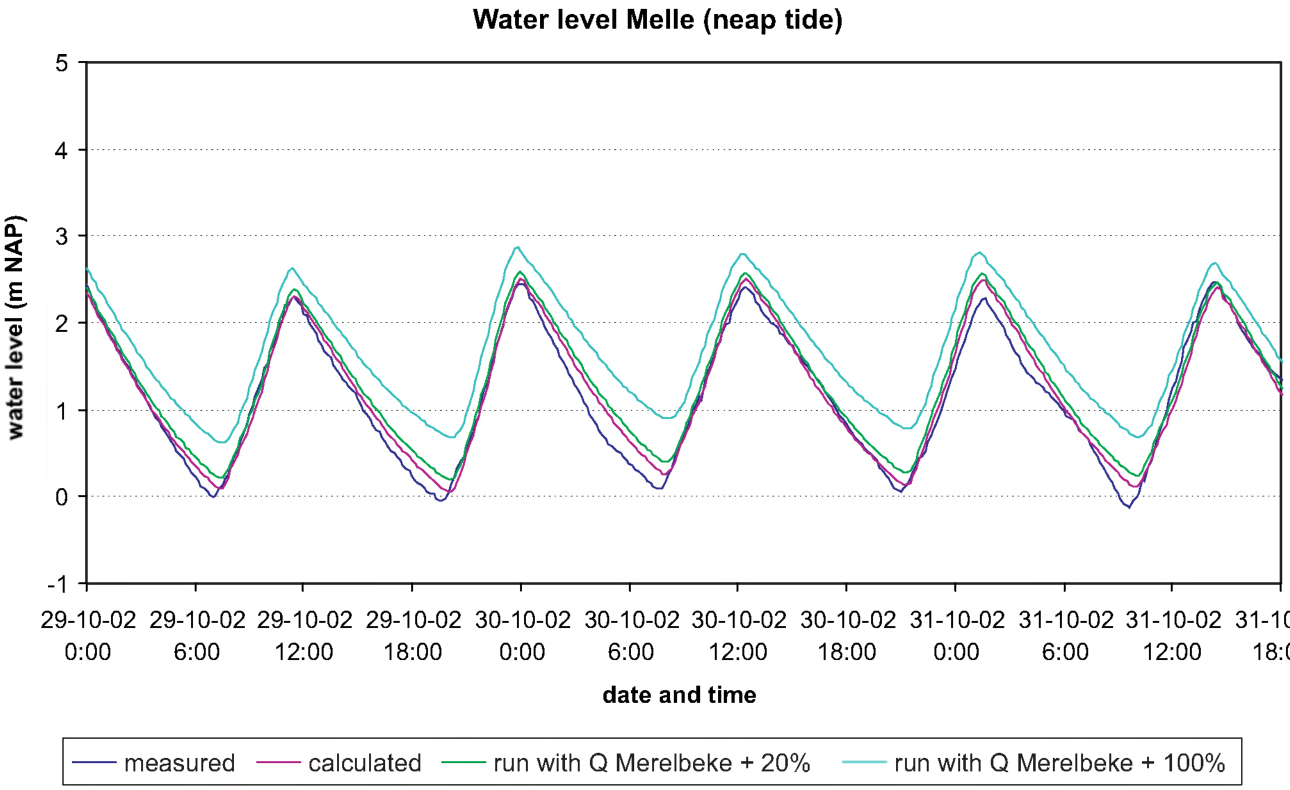
Water level Wetteren (spring tide, storm period)



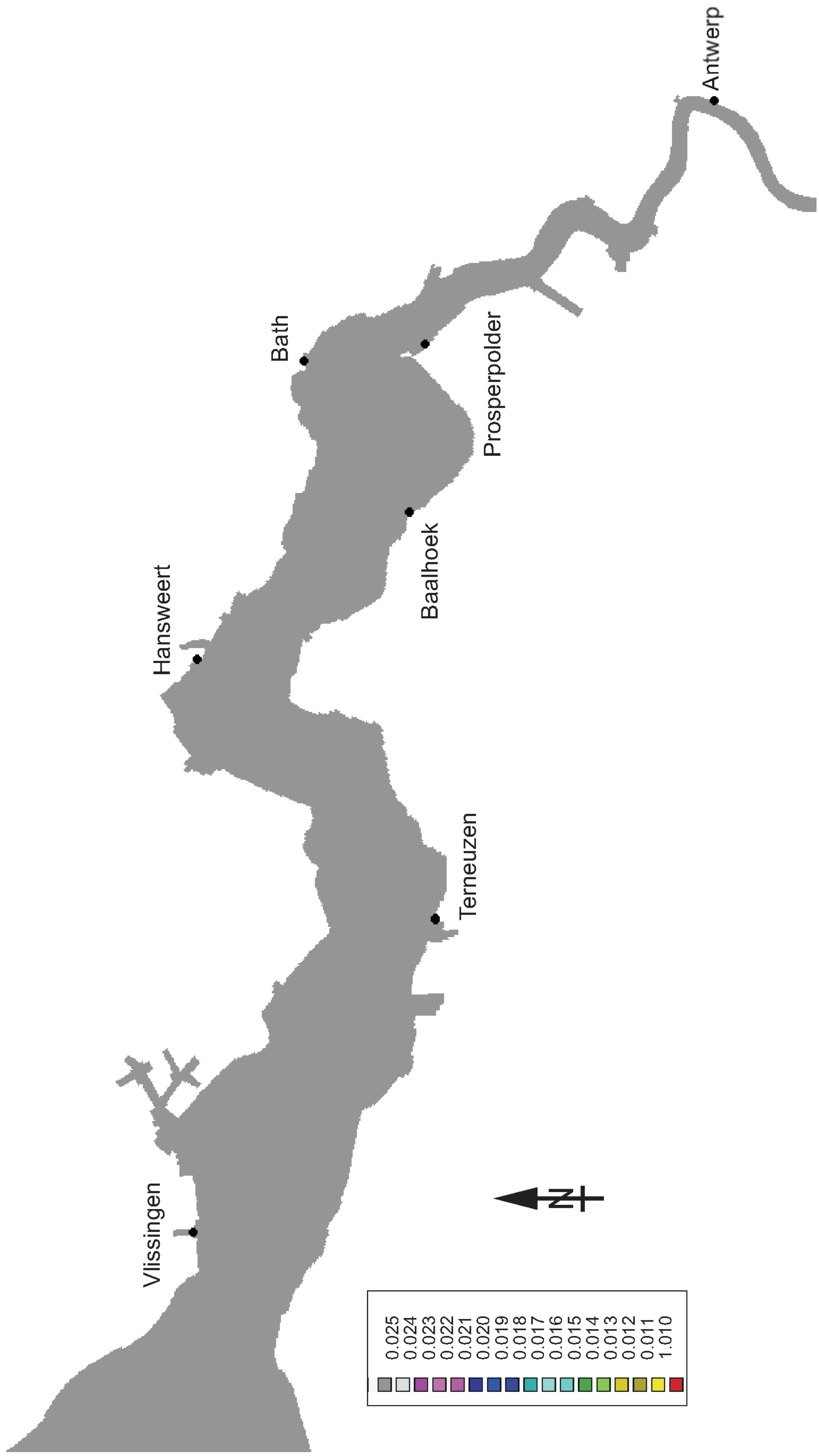


Measured and calculated water level at Wetteren for the runs with increased discharge at Merelbeke

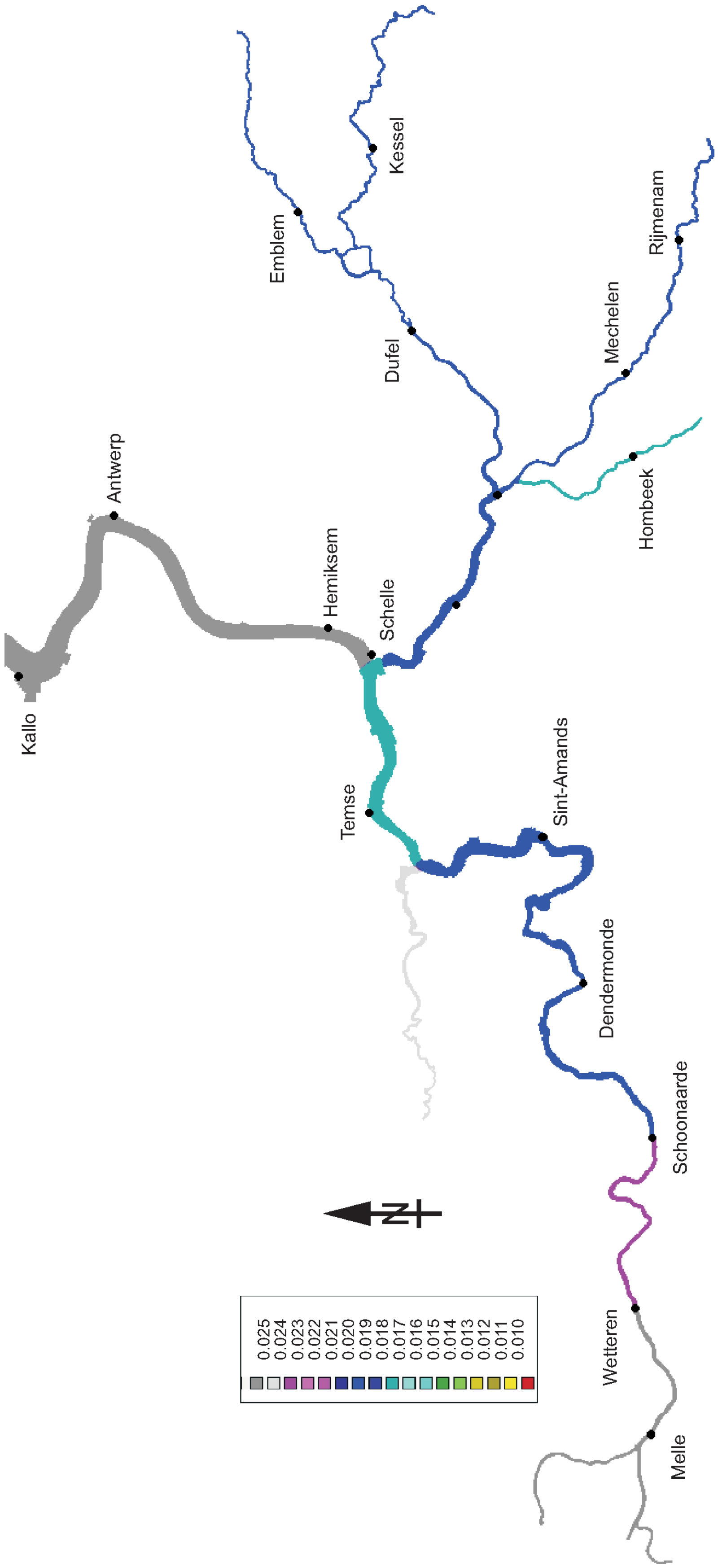




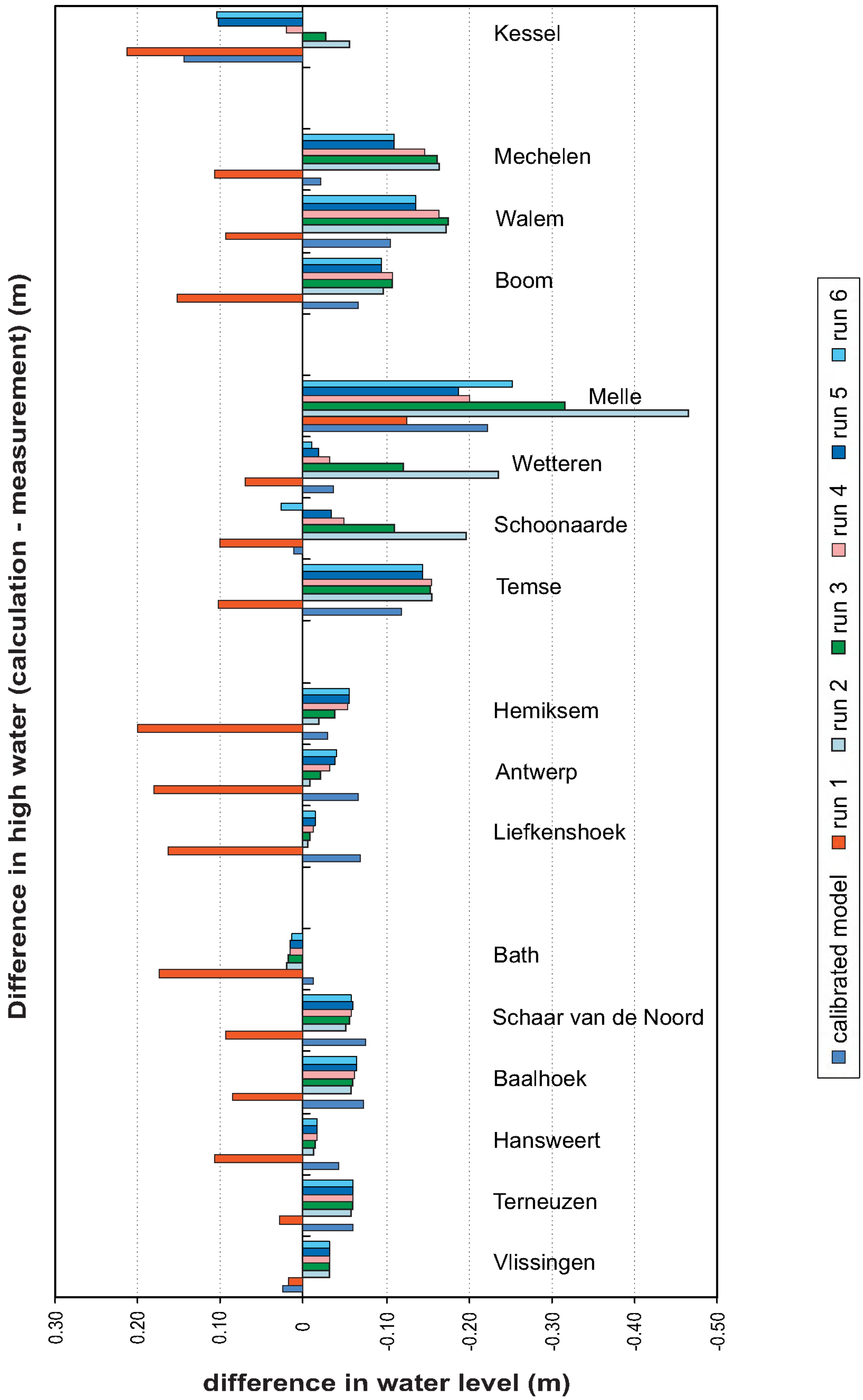
Measured and calculated water level at Melle for the runs with increased discharge at Merelbeke



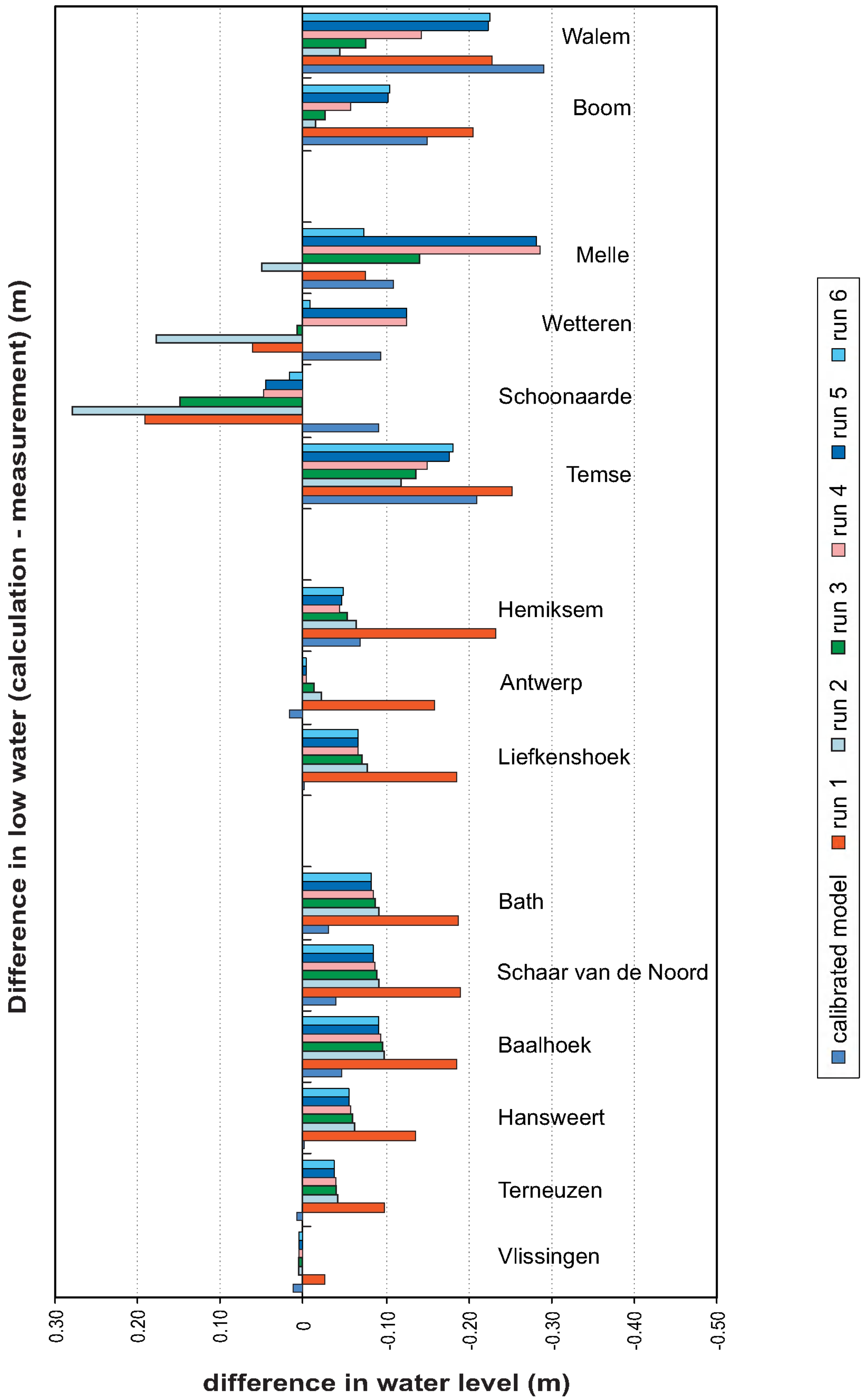
Uniform bed roughness field for the Western Scheldt for run 6
Roughness values expressed as Manning value ($m^{-1/3}s$)



Bed roughness field for the Sea Scheldt for run 6
Roughness values expressed as Manning value ($m^{-1/3}s$)

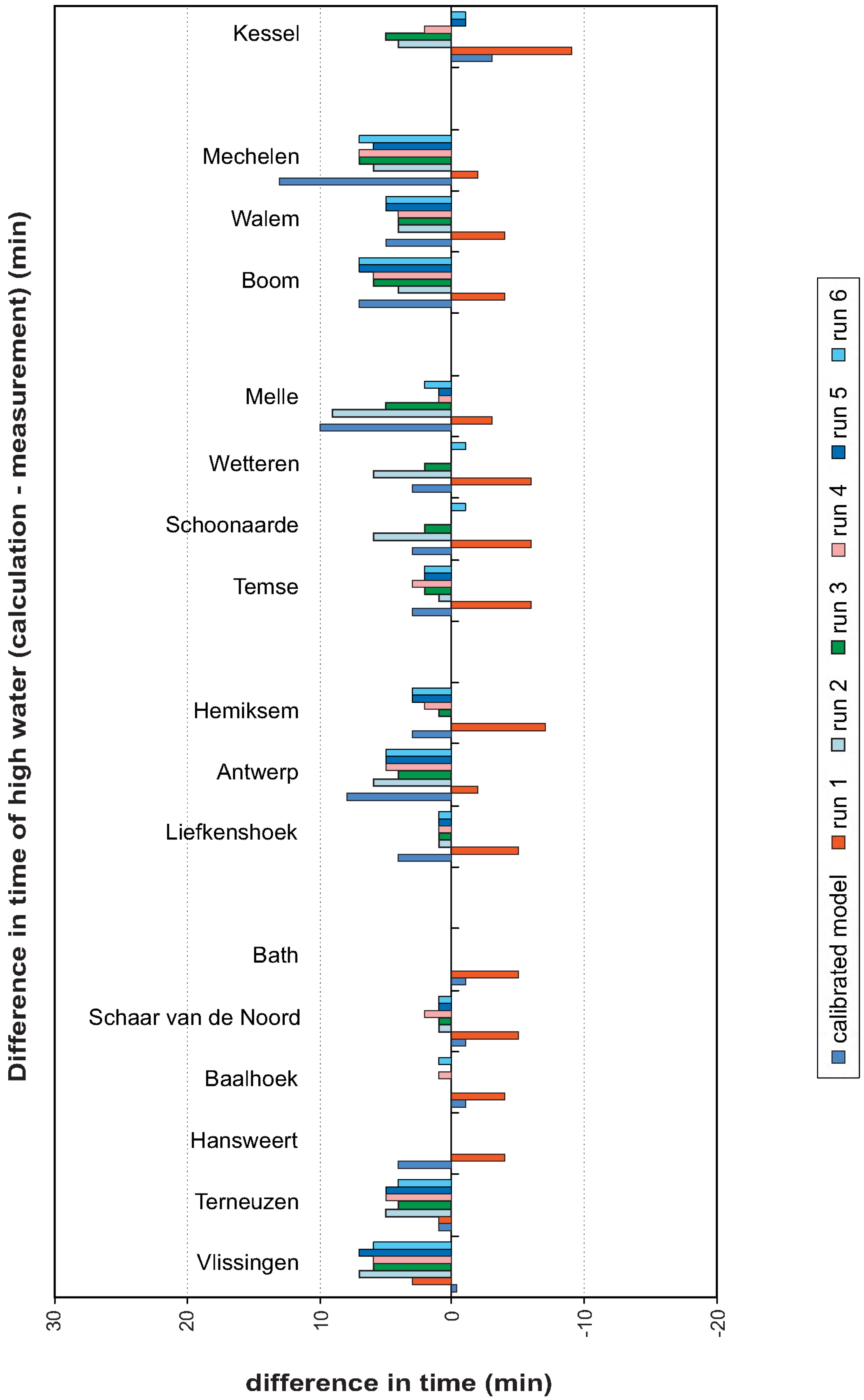


Differences in magnitude of high waters for the model runs with simple roughness fields	bathymetry : m NAP

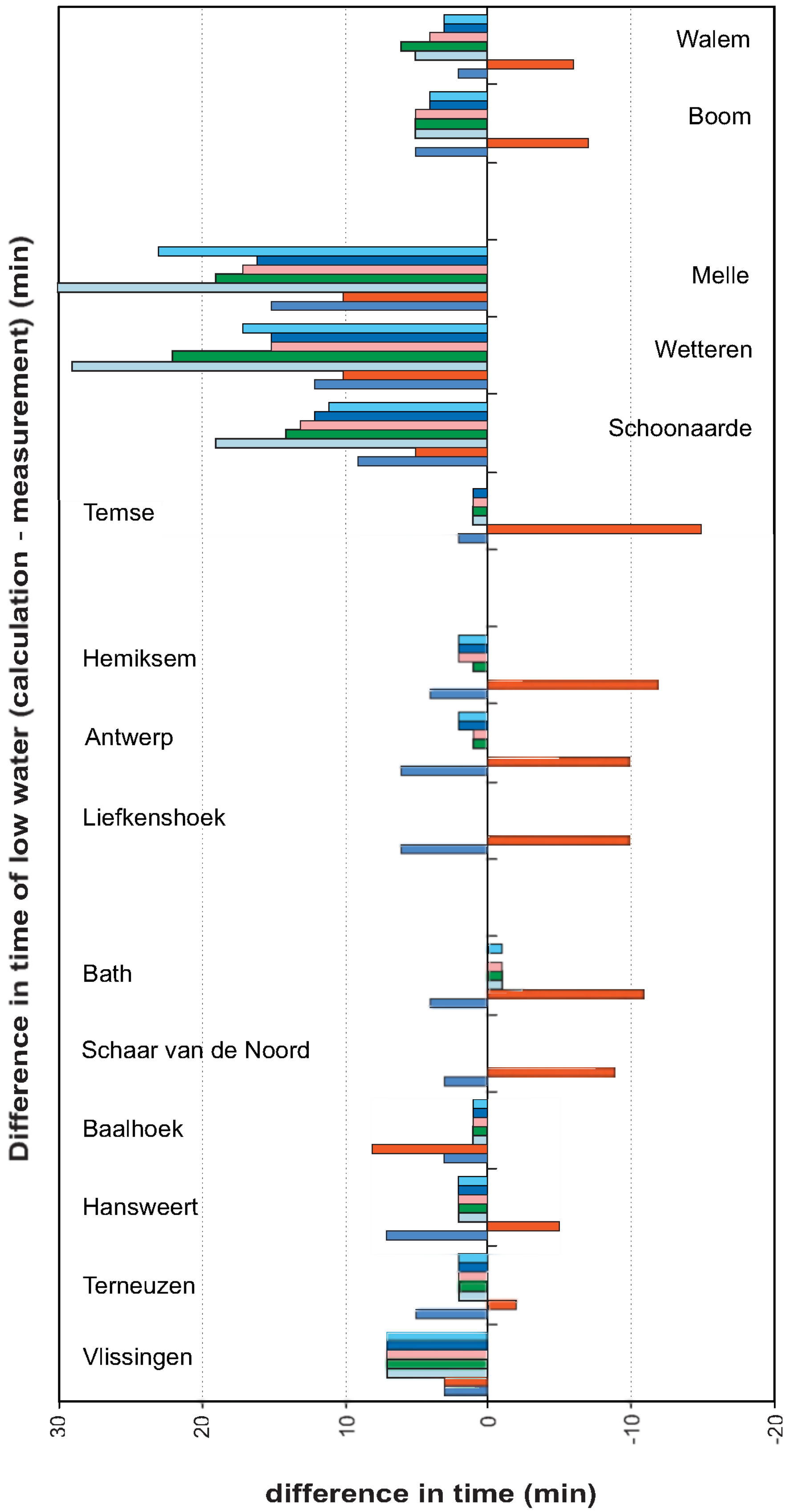


Differences in magnitude of low waters for the model runs with simple roughness fields

bathymetry : m NAP



Differences in phase of high waters for the model runs with simple roughness fields



Differences in phase of low waters for the model runs with simple roughness fields

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.watlab.be