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Habitatmapping ondiep water Zeeschelde

Deelrapport 2 : NUMERIEK 2D MODEL

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Habitatmapping ondiep water Zeeschelde

Deelrapport 2 - Numeriek 2D model

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Abstract

Shallow subtidal areas and intertidal zones are very important for the ecology of the estuary. These areas are characterized by low dynamics, which results in a silty and nutrient-rich environment. They form habitats for large bird polpulations and benthic species.

The objective of the project “00_028 Habitatmapping ondiep water Zeeschelde” is to study the relations between the physical, sedimentological and ecological characteristics in the Sea Scheldt and to classify the shallow subtidal areas according to their ecological value (in collaboration with INBO).

This report describes the calibration and validation of a numerical model. The model accuracy is analyzed based on comparison of the model results and measured water levels, discharges, stationary velocities and sailed ADCP measurements. The calibrated model will be used to analyse the hydrodynamic characteristics of the study areas.

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List of abbreviations

ADCP	Acoustic Doppler Current Profiler
FHR	Flanders Hydraulics Research
HIC	Hydrologic Information Centre
HMCZ	Hydro Meteo Centrum Zeeland
HW	High Water
INBO	Instituut voor Natuur- en Bosonderzoek
LIDAR	Laser Imaging Detection And Ranging
LW	Low Water
MAE	Mean Absolute Error
MET	Middle European Time
NAP	Normaal Amsterdams Peil
NEVLA	NEderlands-VLAams waterbewegingsmodel
RD Parijs	Rijksdriehoekscoördinaten Parijs (horizontal reference system)
RMAE	Relative Mean Absolute Error
RMSE	Root Mean Square Error
TAW	Tweede Algemene Waterpassing
TS	Time Series
UTC	Coordinated Universal Time

1 Introduction

Shallow subtidal areas and intertidal zones are very important for the ecology of the estuary. These areas are characterized by low dynamics, which results in a silty and nutrient-rich environment. They form habitats for large bird populations and benthic species.

The objective of the project “00_028 Habitatmapping ondiep water Zeeschelde” is to study the relations between the physical, sedimentological and ecological characteristics in the Sea Scheldt and to classify the shallow subtidal areas accordingly to their ecological value (in collaboration with INBO).

This report describes the calibration and validation of a numerical model. These calibration and validation were performed for different study areas where data on flow velocities were available (table 1). Based on the results of the model calibration a parameter-setup was chosen and flow velocity data for the entire Sea Scheldt were generated. These results will be used in the further research phases of this project.

Table 1. Study areas

Study area	Type of area	Location on figure 1
Schaar van Ouden Doel (left bank)	Mesohaline	1
Galgenschoor (right bank)		
Notelaer (right bank)	Oligohaline	2
Ballooi (left bank)		
Branst (left bank and right bank)	Fresh water long residence time	3
Appels (left bank and right bank)	Fresh water short residence time	4

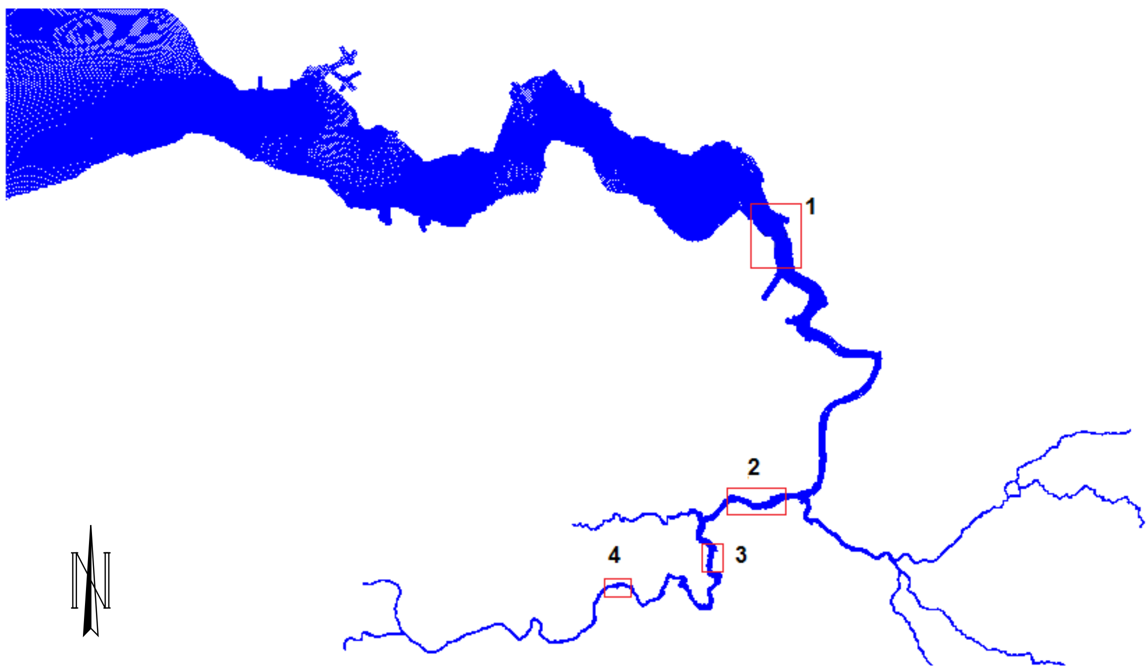

Figure 1 - Location of the study areas

2 Units and reference plane

Time is expressed in MET (Middle European Time).

Depth, height and water levels are expressed in meter TAW (Tweede Algemene Waterpassing). A bathymetric depth is positive below the reference plane, water levels are positive above the reference plane.

The horizontal coordinate system is RD Parijs.

3 The numerical model

3.1 Introduction

The NEVLA model (*Maximova et al.,* 2009; *Verheyen et al.,* 2012) was developed at Flanders Hydraulics Research for the Western Scheldt, the Sea Scheldt and connected Flemish rivers. The grid resolution of the NEVLA model is too coarse to accurately represent the flow velocities in the study areas in the Sea Scheldt.

In the framework of this project a Delft3D model with refined grid resolution is developed. The grid of the NEVLA3D model (*Verheyen et al.,* 2012) is 3x3 refined. The Delft3D model will be calibrated and validated based on the comparison of the calculated and measured water levels, velocities (sailed ADCP and stationary velocities) and discharges.

The downstream boundary of the model is located at Walsoorden; the upstream boundary is located at the tidal border (figure 2). The North Sea and the Western Scheldt downstream Walsoorden are not included in the model to decrease computational time and size of the output files. Parallel computing is used.

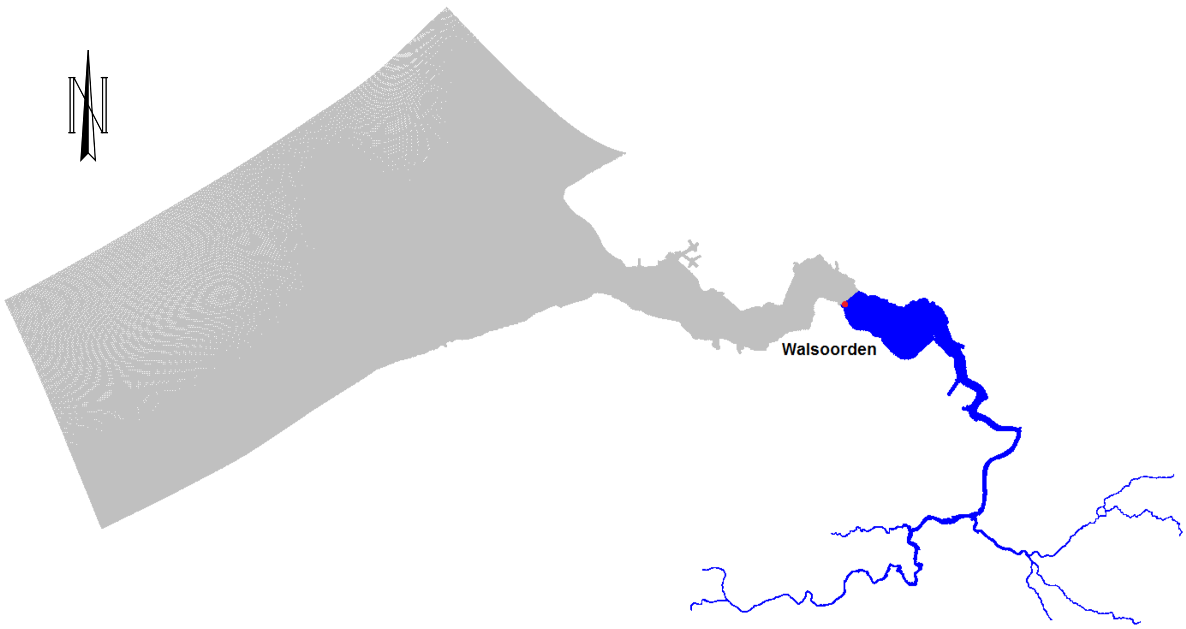

Figure 2 - Model grid of the Delft3D model (with the downstream boundary at Walsoorden)

3.2 Model grid

The model grid is 3 times finer than the NEVLA grid. This means that the grid size is about 26 x 18 m (length x width) at Schaar van Ouden Doel. At Galgenschoor it is 25 x 11 m.

At Notelaer and Ballooi the grid resolution varies from 36 x 14 m to 32 x 11 m. The model grid is extended at this location (in comparison to the NEVLA 3D) to completely include the Ballooi intertidal area.

At Branst the grid resolution varies from 35 x 13 m to 25 x 10 m. At Appels it changes between 32 x 6 m and 29 x 5 m.

Figure 21 to figure 28 show the model grid in the study areas and in the upstream part of the Scheldt. The brown line in these figures is the boundary between tidal marshes and dry area.

3.3 Topo-bathymetry

3.3.1 The river channel and intertidal areas

The bathymetry for the Western Scheldt and Lower Sea Scheldt is defined based on the samples from 2011 provided by Rijkswaterstaat and Vlaamse Hydrografie respectively. Measurements from 2009, 2010 and 2011 are used for the Upper Sea Scheldt and Rupel. The bathymetry for the intertidal areas is defined based on the LIDAR measurements from 2011. When LIDAR and bathymetric data overlapped, the preference was given to the bathymetry. TAW is used as a vertical reference. The bathymetric data are converted from a 1 by 1 m grid to a 5 by 5 m grid.

Shepard averaging method was used for the grid cell averaging of samples. For the locations, where resolution of the samples was not sufficient to use averaging, triangular interpolation and internal diffusion were used.

Recent bathymetric measurements are not available for the upstream part of the Rupel tributaries and Zwijnaarde. The same bathymetry was used at Zwijnaarde as in the 3D NEVLA model (*Verheyen et al*., 2012). The bathymetry used for the Rupel and its tributaries is described in figure 29. Samples from the 1D model were interpolated to define the bathymetry for Zenne, Kleine Nete, Grote Nete and upstream part of Dijle (triangular interpolation was used).

The model grid includes a number of areas lying outside the dikes. Special care was taken to inspect the height of the dikes in the model bathymetry. During the interpolation from bathymetric samples to a model bathymetry, the height of the dikes can get averaged because of lower surrounding depth measurements. This can result in unwanted flooding of some areas outside the dikes.

3.3.2 Schematization of the flow guiding structures in the Sea Scheldt

The flow guiding structures of Ballastplaat and Ouden Doel ("leidam en strekdam" in Dutch) in the Lower Sea Scheldt are defined in the model bathymetry (figure 30). During the interpolation from bathymetric samples to a model bathymetry, the height of the structures can be averaged. This can result in an artificially low bathymetry of some parts of the structures. The samples of the crests of the structures were used to manually correct the bathymetry.

It was opted not to define the structures of Ballastplaat and Ouden Doel as "thin dams" in the model. If a "thin dam" is defined in the model, water can not flow over this dam. However, in reality flow over the leidam and strekdam is possible, as the level of the crest is near half-tide height.

3.3.3 Deurganckdok

The bathymetry of the Deurganckdok was defined based on the values of the target depth: 19 m below TAW in the middle of the dock and 17 m below TAW near the quay walls (100m from the walls) (figure 31).

3.4 Boundary conditions

Measured water levels at Walsoorden (HMCZ database) are used as a downstream boundary condition. They are specified for a period from 19/06/2009 00:00 to 01/07/2009 00:00 (figure 34). TAW is used as a vertical reference.

The bathymetry at the downstream boundary of the model was deepened (figure 32) in order to increase the model stability (*WL/Delft Hydraulics*, 2007). The bathymetry of the deepened grid cells was smoothly connected with the adjacent cells. A higher viscosity (30 m²/s) was defined at the downstream boundary (figure 33). These measures helped to decrease excessive flow velocities at the downstream boundary.

Measured discharges are used as an upstream boundary condition (figure 35) (see § 4.4.1).

3.5 Time step

The time step used for the model simulations is 3s. It is chosen based on the analysis of the Courant number and based on the resuts of the sensitivity analysis (see § 6.1.1). The Courant number should be smaller than 10 in the interest zone of the model (*Deltares*, 2011).

The Courant number in the study areas for a time step of 3 s is shown in figure 36 to figure 38. The Courant number is smaller than 10 in the largest part of the study areas. Only at Appels it slightly exceeds 10 in some parts of the river channel. However, the sensitivity analysis (§ 6.1.1) showed that this does not have an effect on the model results.

3.6 Model settings

The applied model settings are described in table 2.

Table 2. Applied model settings for the detailed model

Parameter	**Value**
Time step	3 s
Secondary flow	Off
Initial condition water level	+1.5 m TAW
Horizontal eddy viscosity	0.3 m²/s (30 m²/s at the downstream boundary) (see § 3.4)
HLES	Off
Number of layers in the vertical	1 (2D model)
Version Delft3D Flow	5.00.00.1234 (Linux)
Salt transport	Off
Wind	On
Computational time	3 days 19:30 (12 CPU's) (modeling period of 7.5 days) 2 times faster than reality
Roughness formula	Manning
Bed roughness value	varying roughness field (figure 53)

3.7 Simulation period

The simulation period for the model calibration and validation in this study is chosen from 22/06/2009 00:00 to 29/06/2009 06:00. The spin-up period is 1 day (from 22/06/2009 00:00 to 23/06/2009 00:00). The simulation period is chosen based on the analysis of comparable tides for the ADCP sailed measurements.

The analyzed period includes spring and average tides with tidal factors from 1.03 to 1.18 (see Appendix 3 for an explanation of tidal coefficients).

3.8 Weir at Mechelen

In reality there is a weir near Mechelen which is controlled automatically or by hand (figure 39). In the case of low discharges the weir is controlled automatically. If the discharges are high (the difference between water level upstream and downstream is less than 80 cm), the weir is manually controlled (*Adema*, 2006). Analysis of the measured water levels at Mechelen upstream the weir and Rijmenam (figure 40, figure 41) shows that the weir was open in the beginning of the simulation period and closed in the second half of the period.

Since realistic control of a weir is not possible in the model due to the limitations of Delft3D, it was decided not to include the weir in the simulations. This does not have an effect on water levels and flow velocities in the study areas.

3.9 Discharge point Merelbeke

Figure 42 shows the location of the discharge point Merelbeke in the model. It is defined in the lock instead of the channel near the lock in order to avoid too high velocities in this channel and to guarantee a smooth inflow. This has only a very local effect on the modeled velocities. The model results downstream the lock of Merelbeke are not affected.

4 Available measurement data

4.1 Water levels

4.1.1 Available water levels

For the simulation period, the measured water levels in 26 different stations were gathered. Table 3 shows the list of the stations for which measured water levels are available. Figure 19 shows the location of the measurement stations.

10 min time series of the water level measurements (m NAP, MET) were retrieved from the Hydro Meteo Centrum Zeeland database (HMCZ, www.hmcz.nl) for the stations on the Dutch territory and some Belgian stations. These data were converted to the TAW reference plane**. Measured water levels for the Belgian stations were available from** the Hydrologic Information Centre (HIC) (YAKU database, http://waterstanden.vlaanderen.be/). The measurements from the HIC database are stored as one-minute time series in UTC (Coordinated Universal **Time), and were converted to 10 minute time series in MET (Middle European Time).**

The measurement data from the HIC data source are unvalidated data, as retrieved from the AOSO measurement stations in the Sea Scheldt. The HIC measurements can therefore have an (unknown) bias.

Table 3. Water level stations used for the model calibration

	Station	**Data source**
	Scheldt	
1	Baalhoek	HMCZ
2	Schaar van de Noord	HMCZ
3	Bath	HMCZ
4	Zandvliet	YAKU
5	Liefkenshoek	HMCZ
6	Boudewijn lock	YAKU
7	Kallo lock	HMCZ
8	Antwerp	HMCZ
9	Schelle	YAKU
10	Temse	
11	Tielrode	
12	Sint Amands	
13	Dendermonde	
14	Schoonaarde	
15	Wetteren	
16	Melle	
	Rupel and tributaries	
17	Boom	YAKU
18	Walem	
19	Duffel	
20	Lier Maasfort	
21	Lier Molbrug	
22	Emblem	
23	Kessel	
24	Mechelen sluis	
25	Hombeek	
26	Zemst	

4.1.2 Quality of water level measurements

High and low waters at some stations are not analyzed. There is a problem with the measurement of low waters at Temse. The measurement instrument at this station is located in a muddy environment, measuring the level of the mud instead of the water level around low water.

High waters at Kessel and Emblem are not found due to the limitations of the VIMM software.

The transition from falling to rising water is not very clear at Hombeek and Zemst. The curve of the measured water level at Hombeek has a very flat shape around low water and the software considers a different moment as a moment of low water (figure 84). The measured water level at Zemst oscillates around low water making it difficult to find the exact location of the low water (figure 85).

4.2 ADCP measurements

4.2.1 ADCP sailed in the study areas

Available ADCP velocity measurements are described in table 4. Measurements at Galgenschoor, Branst and Appels were performed by FHR in the framework of this project (00_028). Velocities at Notelaer and Ballooi were measured in the framework of the project 713_21 'Vervolgstudie inventarisatie en historische analyse van slikken en schorren langs Zeeschelde' (*Aqua Vision,* 2010e). The data for Schaar van Ouden Doel are described in (*Aqua Vision*, 2006).

Table 4. Available ADCP measurements

Location	**Measurement instrument**	**Figure**	**Measurement period (MET)**		**Tidal coefficient Antwerp**
			Start	**end**	
Schaar van Ouden Doel	Workhorse 600 kHz	figure 3	12/09/2006 06:03	12/09/2006 18:00	1.10
Galgenschoor	RioGrande*	figure 4	02/09/2011 07:12	02/09/2011 19:07	1.15
	StreamPro		02/09/2011 07:56	02/09/2011 19:57	
Branst 1	StreamPro	figure 5	04/08/2011 9:38	04/08/2011 19:47	1.13
Branst2	RioGrande**	figure 6	05/08/2011 06:47	05/08/2011 19:01	1.07
	StreamPro	figure 7	05/08/2011 07:31	05/08/2011 19:17	
Ballooi (dwars)	Workhorse	figure 8	10/06/2009 06:42	10/06/2009 19:22	1.02
Notelaer (dwars)	Workhorse 600 kHz		11/06/2009 07:15	11/06/2009 19:53	0.99***
Notelaer (langs)	RioGrande 1200 kHz		10/06/2009 07:00	10/06/2009 19:42	1.02
Appels	StreamPro	figure 9	01/08/2011 06:59	01/08/2011 19:18	1.14

*RioGrande can measure flow velocities in both deep and shallow areas; StreamPro ADCP can be used only for the measurements in shallow areas (max depth is 3 m). Therefore, the RioGrande measurement at Galgenschoor will be used for the analysis because it is more complete.
** this measurement should be regarded as a measurement in one point(figure 6)
*** spring tide with a relatively small tidal amplitude was observed on 10/06 and 11/06/2009

Figure 3 - ADCP measurements at Schaar van Ouden Doel (12/09/2009)

Figure 4 - ADCP measurements at Galgenschoor (RioGrande) (02/09/2011)

Figure 5 - ADCP measurements at Branst 1 (04/08/2011)

Figure 6 - ADCP measurements at Branst 2 (RioGrande) (05/08/2011)

Figure 7 - ADCP measurements at Branst 2 (StreamPro) (05/08/2011)

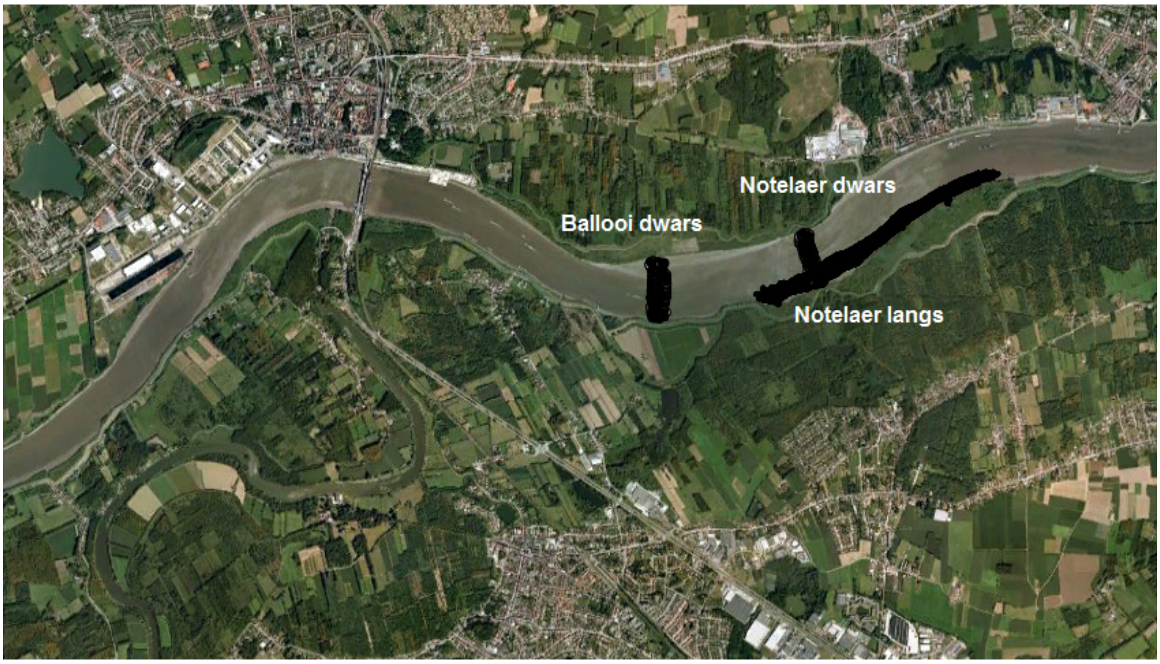

Figure 8 - ADCP measurements at Notelaer and Ballooi (10/06 and 11/06/2009)

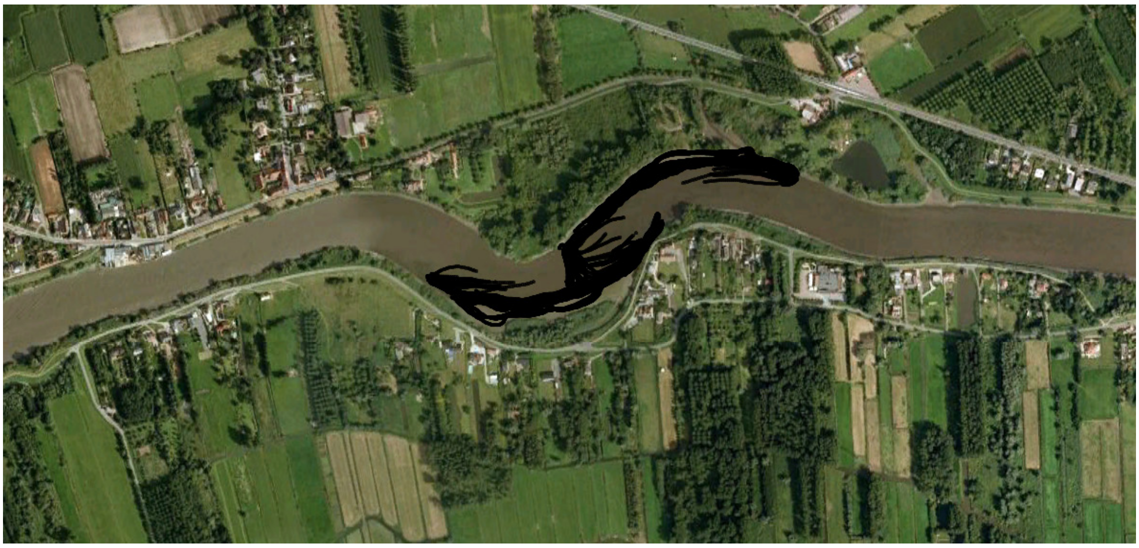

Figure 9 - ADCP measurements at Appels (01/08/2011)

4.2.2 ADCP sailed near the study areas

Since the final output of this phase of the project is the flow velocity field for the entire Sea Scheldt, additional measurements were used for the analysis. Within the scope of the MONEOS (*Plancke et al.,* 2012) several cross sections are measured annually. The following measurements were used for the calibration and validation of the model (table 5).

Table 5. Available ADCP measurements near the study areas

Location	Figure	Measurement period (MET)		Tidal coefficient Antwerp	Reference
		start	end		
Liefkenshoek	figure 10	27/05/2009 05:27	27/05/2009 18:31	1.11	*AquaVision*, 2010a
Oosterweel	figure 11	29/04/2010 05:07	29/04/2010 17:50	1.20	*AquaVision*, 2010b
Driegoten	figure 12	23/06/2009 07:24	23/06/2009 20:14	1.11	*AquaVision*, 2010c
Schoonaarde	figure 13	25/06/2009 07:13	25/06/2009 20:02	1.12	*AquaVision*, 2010d

Figure 10 - ADCP measurements at Liefkenshoek (27/05/2009)

Figure 11 - ADCP measurements at Oosterweel (29/04/2010)

Figure 12 - ADCP measurements at Driegoten (23/06/2009)

Figure 13 - ADCP measurements at Schoonaarde (25/06/2009)

4.3 Stationary velocity

Stationary velocity measurements are available in two locations: Buoy 84 and Oosterweel. These locations are situated near the study areas in the Lower Sea Scheldt (figure 20) and they can be used for the model calibration. Velocities are measured continuously in these locations and, therefore, the measurements are available for the entire year 2009.

4.4 Discharges

4.4.1 Discharges at the model boundary

Timeseries of fresh water inflow are made available by the Hydrometry group of Flanders Hydraulics Research. The daily discharge series for a period of 1 year from 01/01/2009 to 31/12/2009 are defined for Zenne – Zemst, Dijle – Haacht, Grote Nete – Itegem, Kleine Nete – Grobbendonk and Dender – Appels. The daily discharges for Bath canal (Spuikanaal Bath) are received from Rijkswaterstaat Zeeland and defined in the model from 01/01/2009 to 01/01/2010 (*Verheyen et al.,* 2012). The discharge time series are visualized in figure 35. Zero discharge is specified for Durme – Waasmunster, Upper Sea Scheldt – Gentbrugge, Upper Sea Scheldt – Zwijnaarde because there was no or negligible discharge during the period of the analysis.

The most important fresh water inflow is the Upper Sea Scheldt via the lock complex near Merelbeke. The discharge measurements at Merelbeke are not available for the analyzed period. Daily discharges from the nearby station Melle are specified instead at Merelbeke (figure 35). From a sensitivity analysis *(Vanlede et al.*, 2008) it was found that the use of daily averaged discharges at Merelbeke worsens the model results from Merelbeke to Dendermonde when compared to hourly discharges.

4.4.2 Discharges for the model calibration/validation

Table 6 gives an overview of the 13 hours discharge measurements that can be used for the model calibration and validation.

Table 6. Available discharge data

Name of cross section	Date
R1 Vaarwater boven Bath	30/03/2010
R1 Ballastplaat	01/04/2010
R2 Total	11/04/2012
Liefkenshoek	27/05/2009
	30/04/2010
Oosterweel	29/05/2009
	29/04/2010
Kruibeke	26/05/2009
	14/04/2010
Boom	22/06/2009
	27/04/2010
Driegoten	23/06/2009
	15/04/2010
Schoonaarde	25/06/2009
	14/04/2010

4.5 Wind

Wind is included in the model. Wind data are available from the HMCZ database. The wind data measured at Hansweert are presented in figure 43. The measured wind is imposed uniformly in the model domain.

5 Methodology

5.1 Model calibration

The main objective of the model calibration in this project is to improve the model accuracy for the velocities in shallow subtidal and intertidal areas. For the model calibration different simulations are performed with different parameters of the 2D hydrodynamic model. Bed roughness and horizontal eddy viscosity are used as the calibration parameters. The results of model simulations are compared with the measured water levels, stationary velocities, sailed ADCP measurements and discharges.

Model results and measurements are analyzed using the MATLAB tool VIMM developed within FHR. This software does the statistical analysis of the model maps and histories and helps to evaluate the model accuracy. The description of the output generated with the VIMM is given in the chapter Methodology of (*Verheyen et al*., 2012).

The available ADCP measurement data are split in the calibration and validation datasets so that different types of areas (mesohaline, oligohaline, etc.) are represented in both sets.

The water levels and stationary velocity measurements are compared with the model results for the periods described in table 7. Harmonic analysis of the tide is performed and statistical parameters (bias, RMSE, $RMSE_0$) are calculated for high and low waters and for the time series of water levels (more information is given in Appendix 4). The magnitude and direction of the stationary velocities are analyzed. Also an analysis of the components of the currents is performed based on (*Sutherland et al.,* 2003) (Appendix 4). This results in a MAE (mean absolute error), combining magnitude and direction and RMAE (relative mean absolute error).

Table 7. Continuous measurements used for the model calibration

Type of measurement	Location	Analyzed period
Water levels	WL stations from HMCZ and HIC databases	23/06/2009 00:00 – 29/06/2009 06:00
Stationary velocity measurements	Oosterweel	23/06/2009 00:00 – 29/06/2009 06:00
	Buoy 84	23/06//2009 00:00 – 29/06/2009 06:00

The ADCP measurements and discharges are compared with the model results for the tides similar to the tides observed during the measurements (table 8, table 9). More information about the tidal coefficients k is given in Appendix 3. For each measurement a comparable tide is found inside the simulation period based on the smallest RMSE value between the observed tides during the measurement and during the modeling period. This is done in order to obtain a better representation of the velocities and discharges in the model. Differences between the measurements and model results can be expected when comparable tides have a big RMSE. The model accuracy is evaluated based on the vector plots of velocities, statistical parameters and plots of the discharge histories.

Table 8. ADCP sailed measurements used for the model calibration

Measurement	**Tref of measured tide**	$k_{Antwerp}$	**Tref of comparable tide**	$k_{Antwerp}$	**RMSE**
ADCP sailed in the Lower Sea Scheldt					
Galgenschoor RioGrande	02/09/2011 13:00	1.15	26/06/2009 12:50	1.12	0.08
Liefkenshoek	27/05/2009 11:50	1.11	27/06/2009 13:20	1.08	0.11
ADCP sailed in the Upper Sea Scheldt					
Branst2 StreamPro	05/08/2011 15:50	1.07	26/06/2009 14:40	1.12	0.09
Branst2 RioGrande*	05/08/2011 15:50	1.07	26/06/2009 14:40	1.12	0.09
Ballooi dwars	10/06/2009 12:30	1.02	28/06/2009 15:20	1.03	0.07
Driegoten	23/06/2009 12:00	1.11	23/06/2009 12:00	1.11	0
Schoonaarde	25/06/2009 15:10	1.12	25/06/2009 15:10	1.12	0

* this measurement is regarded as a measurement in one point (figure 6)

Table 9. Discharge data used for the model calibration

Measurement	**Tref of measured tide**	$k_{Antwerp}$	**Tref of comparable tide**	$k_{Antwerp}$	**RMSE**
Liefkenshoek	27/05/2009 12:00	1.11	27/06/2009 13:30	1.08	0.11
Liefkenshoek	30/04/2010 11:20	1.15	26/06/2009 12:50	1.12	0.15
Oosterweel	29/05/2009 14:00	1.07	23/06/2009 10:30	1.11	0.18
Oosterweel	29/04/2010 11:00	1.20	26/06/2009 13:10	1.12	0.20
Kruibeke	26/05/2009 11:30	1.15	26/06/2009 13:10	1.12	0.23
Kruibeke	14/04/2010 10:30	1.13	23/06/2009 23:00	1.15	0.10
Boom	22/06/2009 10:30	1.09	23/06/2009 11:30	1.11	0.08
Boom	27/04/2010 10:40	1.16	24/06/2009 00:20	1.15	0.10
Driegoten	23/06/2009 12:00	1.11	23/06/2009 12:00	1.11	0
Driegoten	15/04/2010 12:30	1.14	24/06/2009 00:30	1.15	0.07
Schoonaarde	25/06/2009 15:10	1.12	25/06/2009 15:10	1.12	0
Schoonaarde	14/04/2010 13:40	1.13	24/06/2009 02:20	1.15	0.11

The ADCP measurement at Branst (RioGrande) is regarded as a measurement in one point (figure 6). It is compared with the model results for a comparable tide.

5.2 Model validation

Based on the results of the calibration the final model parameters were chosen and a validation was performed. For the model validation an independent set of ADCP measurements (that was not used for the model calibration) was compared with the model results for the comparable tides described in table 10.

Table 10. ADCP sailed measurements used for the model validation

Measurement	Tref of measured tide	$k_{Antwerp}$	Tref of comparable tide	$k_{Antwerp}$	RMSE
ADCP sailed in the Lower Sea Scheldt					
Schaar van Ouden Doel	12/09/2006 12:50	1.10	26/06/2009 12:30	1.12	0.16
Oosterweel	29/04/2010 11:00	1.20	27/06/2009 01:50	1.18	0.16
ADCP sailed in the Upper Sea Scheldt					
Branst 1	04/08/2011 15:10	1.13	26/06/2009 14:50	1.12	0.08
Notelaer langs	10/06/2009 12:30	1.02	28/06/2009 15:20	1.03	0.07
Notelaer dwars	11/06/2009 13:10	0.99	28/06/2009 15:20	1.03	0.18
Appels	01/08/2011 13:40	1.14	24/06/2009 13:40	1.13	0.11

The recent discharge measurements for the cross sections R1 and R2 became available in the end of the project (table 11). They are not used for the model calibration and are analyzed only for the model validation.

Table 11. Discharge data used for the model validation

Measurement	Tref of measured tide	$k_{Antwerp}$	Tref of comparable tide	$k_{Antwerp}$	RMSE
R1 Vaarwater boven Bath	30/03/2010 10:00	1.25	27/06/2009 01:00	1.18	0.13
R1 Ballastplaat1*	01/04/2010 16:50	1.22	26/06/2009 05:40	1.18	0.10
R1 Ballastplaat2*	01/04/2010 16:50	1.22	26/06/2009 05:40	1.18	0.10
R2 Total	11/04/2012 13:00	1.13	26/06/2009 12:30	1.12	0.17

*The cross section R1 Ballastplaat 1 (from 0 to 800 m) is longer than R1 Ballastplaat 2 (from 0 to 700 m)

5.3 Cost function

In order to select the best calibration run, a cost function is calculated for each simulation. The cost function is defined to get one objective factor that represents improvement or deterioration of the model performance. The cost function is expressed in function of the reference run, so a value lower than 1 indicates an improvement (*Verheyen et al.*, 2012).

$$Cost = \sum \frac{Factor_i}{Factor_{i,ref}} * Weight_i$$

7 parameters are selected as factors for the calculation of the cost function (table 12). The RMSE of the water level time series and discharge RMSE are calculated as a weighted average of RMSE's for all measurement locations. The MAE of stationary velocity is an average of MAE's for the top and bottom velocities at Buoy 84 and Oosterweel. Velocities at Branst measured with RioGrande are analyzed separately from other stationary velocities because only the measured velocity magnitude is reliable in this location. Therefore, the MAE of velocity components can not be found. The RMSE of velocity magnitude is analyzed instead.

The RMSE of the model for each location with measured ADCP velocities (Galgenschoor, Liefkenshoek, Branst, etc.) is calculated as a weighted average of RMSE's for each transect in this location. The total RMSE of the model (vs. ADCP measurements) is calculated as average (*not weighted*) of the RMSE's for different locations. This is done in order to avoid giving more weight to the locations with a larger number of measurements. All study areas are equally important for the model calibration and they should have the same weight in the calculation of the total RMSE.

Velocity directions at Branst and Appels measured with the ADCP are wrong and they are excluded from the analysis.

In the cost function more weight is given to velocities than to water levels because the main objective of this project is to improve the model accuracy for the velocities in the shallow and intertidal areas. A low weight (5%) is given to the stationary velocities in Branst because this measurement is available only for a short period (13 hours), while stationary velocities at Buoy 84 and Oosterweel are available for the entire period of analysis.

Table 12. Factors for the calculation of the cost function

Factor	Weight
Water level RMSE (Time series)	10%
Harmonic analysis (Vector comparison)	10%
Stationary velocity MAE (Buoy 84, Oosterweel)	15%
Stationary velocity RMSE mag (Branst RioGrande)	5%
Discharge RMSE	20%
ADCP transect velocity RMSE magnitude	20%
ADCP transect velocity RMSE direction	20%
Sum	**100%**

5.4 Observation points in the intertidal areas

A number of observation points is defined in the study areas for different depth zones: moderately deep subtidal, shallow subtidal, low mudflats ('laag slik' in Dutch), medium mudflats ('midden slik') and high mudflats ('hoog slik') (table 18). These points are defined in the model based on the coordinates and depth values provided by INBO.

Due to the grid resolution it is not always possible to define an observation point in the model exactly in the measurement location. The history points in the model are defined as close as possible to the measurement points provided by INBO. Attention was given to select model output points with a similar depth as the measurement points. The model output points are always in the same depth zones as the measurements (see table 19).

6 Sensitivity analysis

6.1.1 Time step

Model runs used for the sensitivity analysis for a time step are described in table 13. The tested time steps were chosen based on the analysis of the Courant number which should be smaller than 10 in the interest zone of the model.

A shorter simulation period was used for the sensitivity analysis than for the model calibration and validation in order to decrease the computational time.

Table 13. Model runs for the sensitivity analysis to a time step

Model run	Time step (s)	Number of CPU's	Simulation period	Computational time
simWSenZS_12	2.4	12 (hexa)	3.5 days	2 days 8:47
simWSenZS_13	3	12 (hexa)		1 day 18:13
simWSenZS_14	1.5	8 (quad)*		3 days 9:15

*8 quad processors were used for simWSenZS_14 because hexa node was not available at that moment. However, 8 quad processors calculate faster than 12 hexa processors (if the same time step and the same simulation period are analyzed).

Stability and accuracy of the model runs with different time steps were analyzed. Maps of differences in velocity magnitude and direction (simWSenZS_13 vs. simWSenZS12 and vs. simWSenZS_14) were found (these maps are presented on the CD which is included with this report). The analysis showed that the results of all three simulations are very similar to each other. The RMSE of velocity magnitude is smaller than 1 cm/s, the RMSE of velocity direction is 0.5 to 3 degrees (table 20). Therefore, it was chosen to use a time step of 3 s for this study.

6.1.2 Grid resolution

The effect of the grid resolution on the model results was studied in (*Maximova et al.,* 2010). The analysis of water levels and velocities showed that model runs with the grid refinement 3x3 and 4x4 (in comparison to NEVLA) produce similar results for most periods of the tide. Therefore, it is sufficient to use the model grid with 3x3 refinement for the model calibration and validation.

6.1.3 Bed roughness and viscosity

The bed roughness and horizontal eddy viscosity are important calibration parameters. The model sensitivity to these parameters was tested in the simulations described in table 14. A short literature review on the bed roughness is given in Appendix 6.

Table 14. Model runs for the sensitivity analysis to the bed roughness and viscosity

Model run	Bed roughness ($m^{-1/3}s$)	Viscosity (m²/s)
simWSenZS_15	0.022	1
simWSenZS_21	0.022	0.5
simWSenZS_25	0.027	0.5

Considering energy dissipation, changes in the bed roughness and viscosity have similar effect on the model results. A decrease of these parameters results in an increase of the tidal amplitude and velocity (a lower energy dissipation). It is necessary to find an optimal combination of the bed roughness and viscosity that results in the smallest differences between the calculated and measured velocities and water levels.

A change of the horizontal eddy viscosity affects the velocity profile along the cross section. When viscosity increases, the velocity profile becomes less convex and the horizontal velocity gradients decrease.

7 Calibration

The model was calibrated by varying the roughness and viscosity parameters. Overview of the most important simulations used for the model calibration is presented in table 15. The complete list of the model runs used for the model calibration is given in table 21. The bed roughness is represented in color for each zone (the color scale is shown in the lower part of the table).

Table 15. The most important model runs used for the model calibration

Model run	viscosity (m^2/s)	Walsoorden		Antwerp		St Amands		Schoonaarde		Melle	Durme	Rupel	Zenne	Dijle	Beneden Nede	Grote Nete	Kleine Nete
simWSenZS_19a	1																
simWSenZS_22	1																
simWSenZS_29	0.5																
simWSenZS_32	0.5																
simWSenZS_34	0.3																
simWSenZS_36	0.3	idem simWSenZS_34 but rgh slik = rgh river - 15%, rgh schor = rgh river + 10%															
simWSenZS_37	0.3	idem simWSenZS_34 but rgh slik = rgh river – 25%, rgh schor = rgh river + 10%															

color scale	roughness ($m^{-1/3}s$)	color scale	roughness ($m^{-1/3}s$)	color scale	roughness ($m^{-1/3}s$)	color scale	roughness ($m^{-1/3}s$)	color scale	roughness ($m^{-1/3}s$)
	0.014		0.017		0.020		0.023		0.026
	0.015		0.018		0.021		0.024		0.027
	0.016		0.019		0.022		0.025		0.028

First, it was necessary to improve the propagation of the tidal wave in the model. This was done based on the analysis of the water levels and discharges at different locations along the estuary. Afterwards, an attempt was made to improve the velocities in shallow and intertidal areas by implementation of the varying roughness field of the tidal flats and marshes.

The model bias for high and low waters and M2 amplitude are presented in figure 14 to figure 16 for several model runs used for the model calibration. The analysis of the results of the reference run simWSenZS_19a showed that the tidal energy dissipation is too high upstream Schoonaarde. The accuracy of the simulations with uniform roughness fields was not sufficient. Therefore, a varying roughness field had to be used. Different combinations of the bed roughness and viscosity were tested in order to find optimal model parameters that would provide a sufficient model accuracy for the water levels and velocities. The bias of low and high waters and M2 amplitude were improved at most stations during the calibration process (figure 14 to figure 16). The most significant improvements are observed upstream Schoonaarde.

As explained in chapter 5.3, a cost function was used to give an objective estimation of the model performance. The model run with the best accuracy has the lowest score. Figure 17 and table 16 show the scores of several model runs. The cost function significantly decreases in simWSenZS_34 (mostly as a result of improvement of the modeled water levels). In further simulations the horizontal eddy viscosity and roughness of the river channel were kept the same as in simWSenZS_34. Only the roughness of the tidal flats and marshes was adapted in order to improve the calculated velocities in these areas (table 15, table 21).

Table 17 presents the RMSE values for the different ADCP campaigns. The model accuracy at Galgenschoor was improved in simWSenZS_36 and simWSenZS_37. This is not seen in the cost function, which stayed constant after simWSenZS_34. Adaptation of the roughness of the intertidal areas also helped to improve slightly the modeled velocities at Liefkenshoek, Ballooi (dwars) and Driegoten. Velocities at Branst and Schoonaarde stayed the same as in simWSenZS_34. The results of the calibrated model run simWSenZS_37 are described in chapter 8.

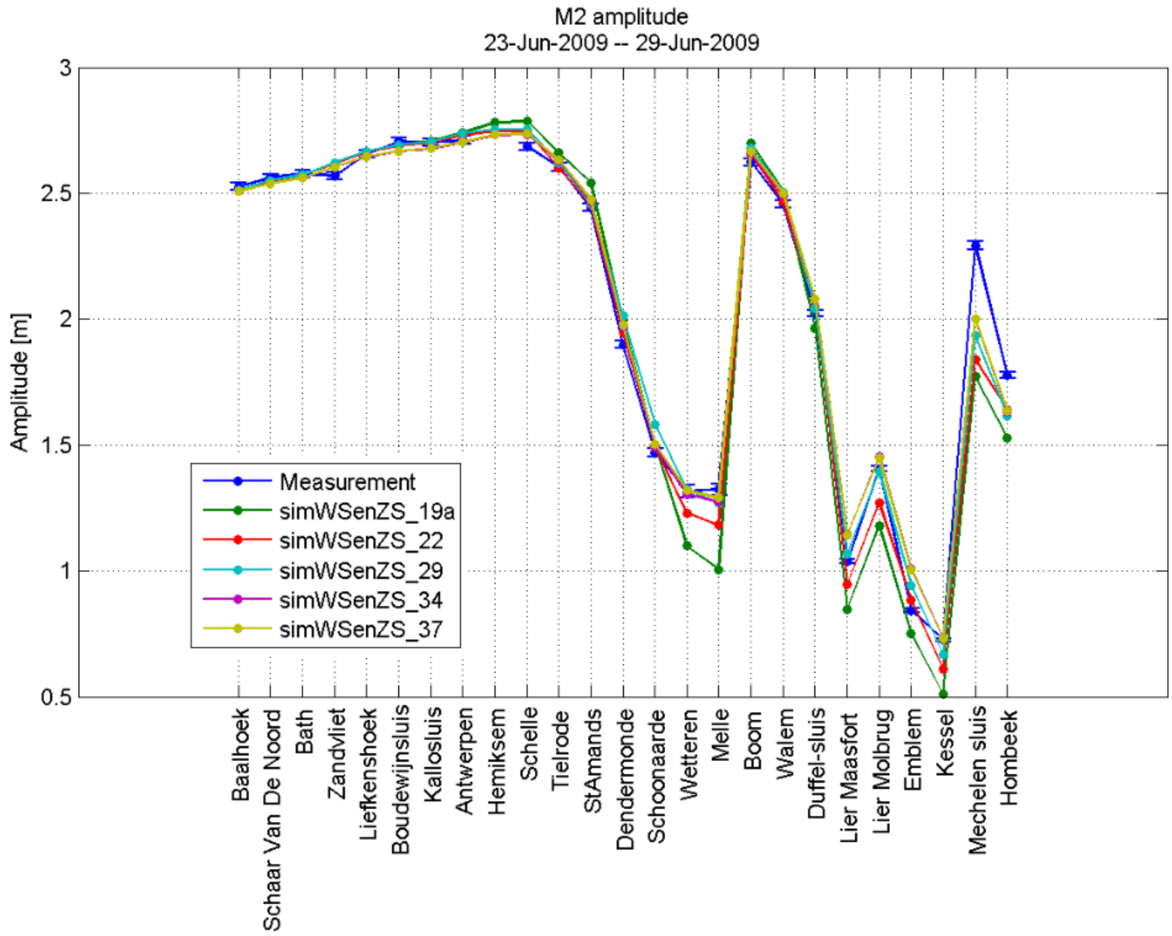

Figure 14 - M2 amplitude in some model runs used for the model calibration

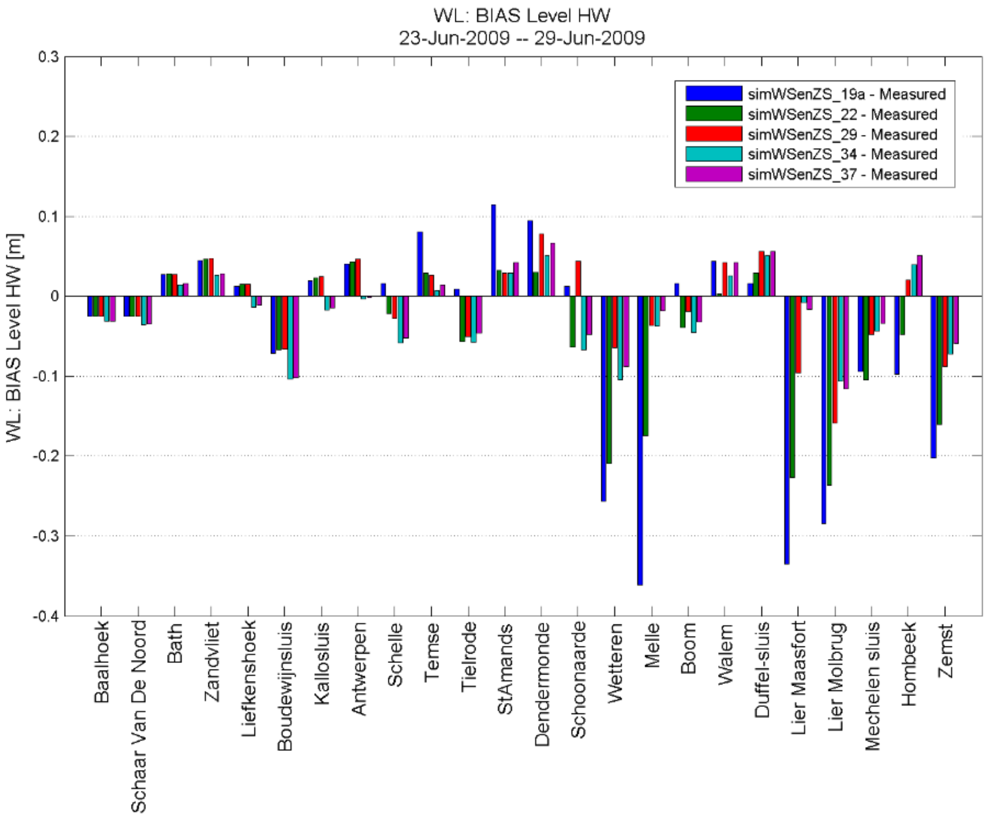

Figure 15 - Bias of high waters in some model runs used for the model calibration

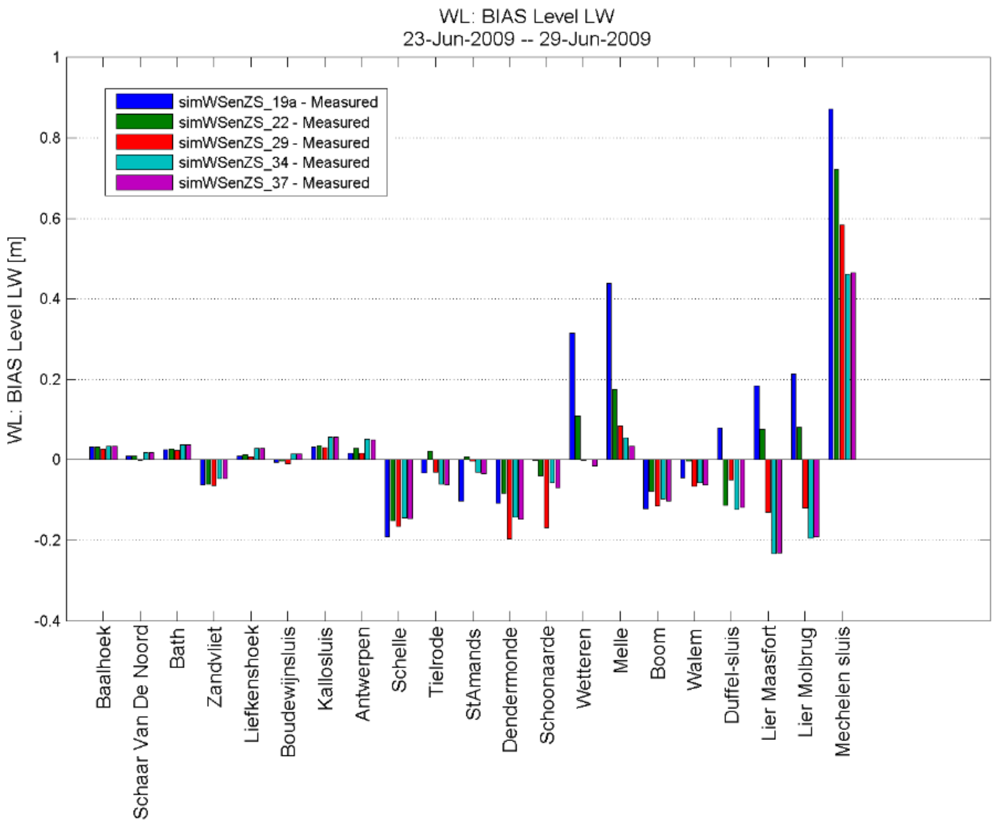

Figure 16 - Bias of low waters in some model runs used for the model calibration

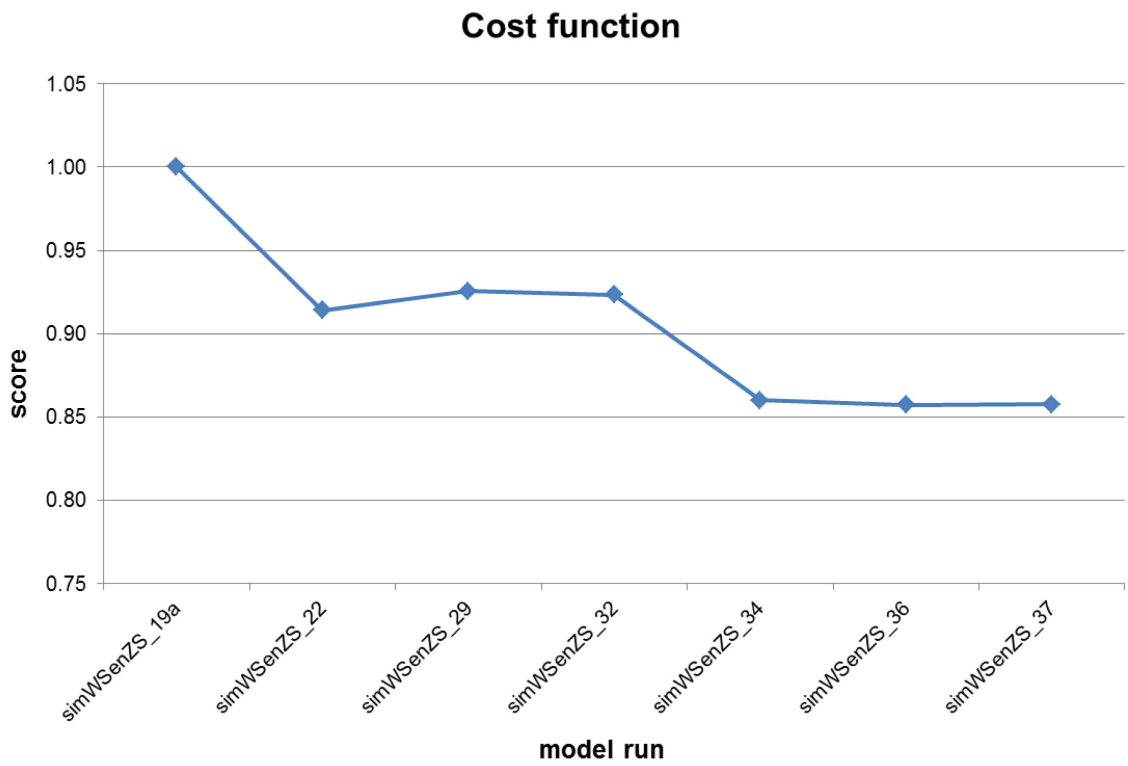

Figure 17 - Cost function

Table 16. Cost function of some model runs used for the model calibration

Model run	Water level		Harmonic analysis		Stationary velocity (Buoy84, Oosterweel)		ADCP measurement in one point (Branst RioGrande)		Discharge		ADCP velocity				Total score
	RMSE of time series (m)	Score	Vector difference (m)	Score	MAE (m/s)	Score	RMSE mag (m/s)	Score	RMSE (m³/s)	Score	RMSE magnitude (m/s)	Score	RMSE direction (degrees)	Score	
weight	*0.1*		*0.1*		*0.15*		*0.05*		*0.2*		*0.2*		*0.2*		
simWSenZS_19a	0.21	1.00	0.38	1.00	0.19	1.00	0.14	1.00	440	1.00	0.18	1.00	39	1.00	**1.00**
simWSenZS_22	0.17	0.81	0.30	0.79	0.19	0.98	0.11	0.75	409	0.93	0.17	0.96	37	0.96	**0.91**
simWSenZS_29	0.15	0.75	0.29	0.75	0.20	1.02	0.12	0.81	421	0.96	0.17	0.96	38	1.00	**0.93**
simWSenZS_32	0.15	0.74	0.29	0.74	0.20	1.02	0.12	0.80	421	0.96	0.17	0.96	38	1.00	**0.92**
simWSenZS_34	0.13	0.63	0.24	0.64	0.19	0.99	0.10	0.72	402	0.91	0.17	0.93	35	0.90	**0.86**
simWSenZS_36	0.13	0.64	0.25	0.64	0.19	0.99	0.11	0.73	404	0.92	0.16	0.90	35	0.90	**0.86**
simWSenZS_37	0.13	0.64	0.25	0.65	0.19	0.99	0.11	0.73	407	0.92	0.16	0.89	35	0.90	**0.86**

Table 17. RMSE of velocity magnitude and direction for different transects used for the model calibration

Model run	ADCP velocity												Average RMSE	
	RMSE mag (m/s)*						RMSE dir (degrees)*							
	Galgenschoor	Liefkenshoek	Ballooi dwars	Driegoten	Branst StreamPro	Schoonaarde	Galgenschoor	Liefkenshoek	Ballooi dwars	Driegoten	Branst StreamPro	Schoonaarde	RMSE mag	RMSE dir
simWSenZS_19a	0.18	0.17	0.18	0.18	0.13	0.22	55	32	32	37	wrong measurement	36	0.18	39
simWSenZS_22	0.18	0.17	0.16	0.17	0.14	0.20	55	32	32	29		36	0.17	37
simWSenZS_29	0.18	0.17	0.16	0.18	0.14	0.19	64	32	32	28		36	0.17	38
simWSenZS_32	0.18	0.17	0.16	0.18	0.14	0.19	64	32	32	28		36	0.17	38
simWSenZS_34	0.19	0.18	0.15	0.17	0.14	0.17	53	31	32	21		36	0.17	35
simWSenZS_36	0.16	0.17	0.14	0.16	0.14	0.17	53	31	33	22		36	0.16	35
simWSenZS_37	0.15	0.17	0.14	0.16	0.14	0.17	53	31	33	22		36	0.16	35

*The RMSE's of velocity magnitude and direction (model vs. ADCP measurement) are average values for all transects inclusive slack periods (the model accuracy around the slack periods worsens significantly). Figure 103 to figure 114 give a better idea about the model performance during different periods.

The model accuracy for the velocity direction is good in the deeper part of the river for the most transects. It worsens in the shallower areas where the velocity magnitude is very small (an example for one of the transects is shown in figure 18). This results in an ancrease of the RMSE value of the entire transect (there is a peak of the RMSE of velocity direction between -4 and -3 hours relative to the reference time in figure 104).

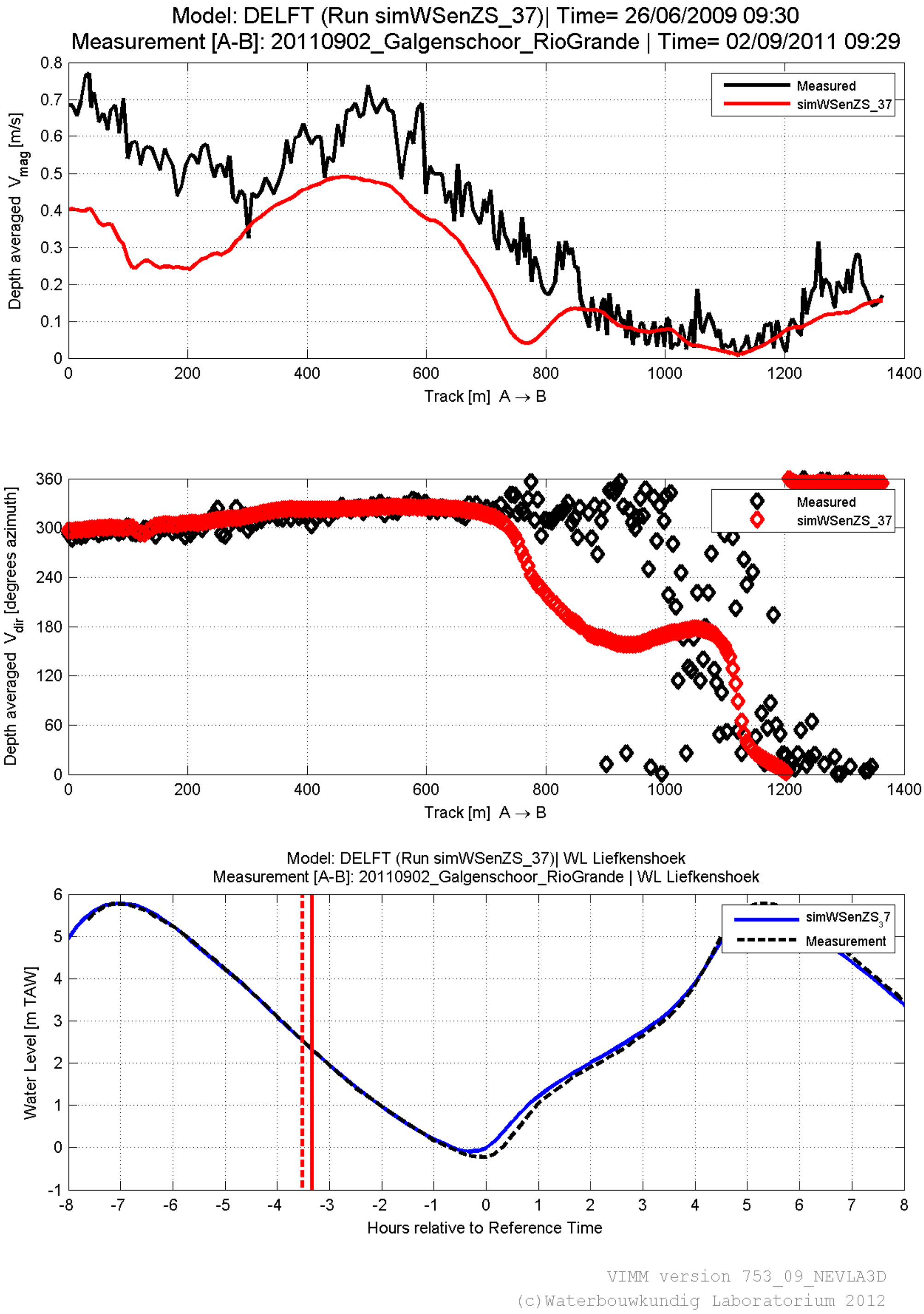

Figure 18 - Example of the modeled and measured velocity magnitude and direction at Galgenschoor

8 Discussion of the calibrated model

8.1.1 Introduction

The analysis of the statistical parameters and histories of water levels, discharges and velocities shows that run simWSenZS_37 produces the best results. A varying roughness field is used in this simulation (figure 44 to figure 49). The roughness of the tidal marshes ('schorren') is 10% higher than the roughness of the river channel. The roughness of the tidal flats ('slikken') is 25% lower than the roughness of the river channel. This is similar to the conclusions in (*Maximova et al.,* 2010) for Notelaer and Ballooi. The roughness of the tidal flats in that study was 26% lower than the roughness of the river channel. This can be explained by the fact that the tidal flats are composed of muddy sediment and are not vegetated.

A lower horizontal eddy viscosity of 0.3 m²/s is defined in simWSenZS_37 than in the NEVLA model. The horizontal eddy viscosity defined in the model is linked with the grid resolution. The viscosity should decrease if the grid becomes finer because the eddy viscosity also parameterizes the mixing due to the subgrid part of the horizontal eddies.

The figures and tables describing the results of the calibrated model are presented in Appendix 1. The used statistical parameters are described in Appendix 4.

8.1.2 Water levels

Analysis of the high and low waters and time series

Figure 50 to figure 55 present the plots of bias and RMSE for high and low waters and for the complete time series. Figure 60 to figure 85 show the history plots of calculated and measured water levels. The values of the statistical parameters calculated for the water levels are given in table 22 to table 24.

The bias of high waters does not exceed 10 to 11 cm at all stations. At most stations it is lower than 5 cm. The bias of low waters is smaller than 7 cm at most stations in the Scheldt. At Schelle and Dendermonde the bias of low waters is -15 cm. The calculated low waters are not accurate at Lier and Mechelen. This may be related to the fact that the model bathymetry of the Rupel tributaries is defined based on the old cross sections from the 1D model and, thus, is not very reliable.

The RMSE of the water level time series varies between 5 and 17 cm in the Scheldt. The highest RMSE is calculated at Schelle (17 cm) and Melle (16 cm). In the Rupel and its tributaries the RMSE varies between 10 and 14 cm. A very high RMSE at Mechelen (32 cm) may be related to the uncertainties in the model bathymetry.

The model accuracy upstream Dendermonde is affected by the use of the daily time series of the discharge at Merelbeke (*Vanlede et al.,* 2008). This discharge is the largest fresh water discharge coming to the Scheldt estuary. It has the most significant effect on the model output. The model accuracy in the upstream part of the Upper Sea Scheldt will improve if an accurate and detailed time series of the discharge at Merelbeke is defined.

Harmonic analysis

The harmonic analysis of the water levels is presented in table 25 to table 33. The amplitude and phase of different harmonic components (M2, M4, M6 and K1) are calculated for different stations along the estuary. The M2 component is the most important because it has the highest amplitude. The tidal amplitude depends to a large extent on the amplitude of M2.

The calculated M2 amplitude and phase are close to the measurements at most stations in the Scheldt (figure 56, figure 57). The differences are larger in the tributaries of the Rupel river. The calculated M2 amplitude is lower than the measurement at Mechelen sluis and Hombeek. At Emblem the model result is higher than the measurement. As explained above it can be related to the uncertainties in the bathymetry.

M4, M6 and K1 components are presented in table 27 to table 32. They are less important for the model calibration than M2.

M4/M2 ratio and phase difference 2M2-M4 are calculated for each station. These parameters are related to the assymetry of the vertical tide (*Wang et al.,* 2002). These components are presented in figure 58 to figure 59.

8.1.3 Stationary velocities

Figure 86 to figure 89 show the time series of the calculated and measured velocities at Buoy 84 and Oosterweel. Stationary velocities at these locations are measured at the top level (3.3 m at Buoy 84; 4.5 m at Oosterweel) and bottom level (0.8 m at Buoy 84, 1 m at Oosterweel). The results of the 2D model are depth average. Therefore, it is expected that the modeled velocities would overestimate the bottom velocities and underestimate the top velocities. The statistical parameters are given in table 34.

As expected, the modeled depth average velocities overestimate the measured bottom velocities at **Buoy84** (bias is 15 cm/s, RMSE is 19 cm/s) (figure 86). The measured top velocities are also slightly overestimated in the model (bias is 10 cm/s, RMSE is 13 cm/s) (figure 87). The differences are higher during ebb than during flood. The RMAE of velocity components is 0.45 for the bottom velocities (reasonable/fair model performance accordingly to (*Sutherland et al.,* 2003)) and 0.35 for the top velocities (good model performance) (Appendix 4).

The calculated ebb velocities at **Oosterweel** are lower than the measurements in the top level (figure 89). The flood velocities are modeled better. The model results are close to the measured bottom velocities (bias is 7 cm/s, RMSE is 16 cm/s) (figure 88). The RMAE of velocity components is similar for the top and bottom levels: 0.26 and 0.27 (good model performance).

The model results are very sensitive to the location of the observation points in the model. These points were defined as close as possible to the real coordinates of measurement locations Buoy84 and Oosterweel. Due to the grid resolution it is not always possible to define a point in the model in exactly the same location as required. In shallow areas it can have a significant effect on the model results.

The comparison of the measured and modeled velocities at **Branst** is shown in figure 90. Velocities at Branst were measured with the RioGrande ADCP, which stayed in approximately the same location (figure 6) This ADCP data are regarded as a stationary velocity measurement in one point. Average measured coordinates are found and the measured velocities are compared with the model results in the same point. The velocity direction is measured erroneously in this location and it is excluded from the analysis. Only the velocity magnitude is analyzed. The bias of the modeled velocity at Branst is 4 cm/s; the RMSE is 11 cm/s.

8.1.4 Discharges

Figure 91 to figure 102 show the comparison of the modeled and measured discharges. The statistical parameters are presented in table 35. The model results and measurements are analyzed for the comparable tides. Differences between the calculations and measurements are expected when the agreement between the measured and modeled tides is not sufficient.

Measured discharges in the Lower and Upper Sea Scheldt are available for the years 2009 and 2010. There is a good agreement between the model results and measurements for most locations. The shape of the discharges is well represented in the model. The RMSE of the discharge time series is 4 to 9% of the maximum discharge at a certain location (table 35).

The flood discharge at Oosterweel is overestimated in the model compared to the measurement from 2009 and it is slightly underestimated compared to the measurement from 2010. This is related to the differences between the observed and simulated tides. There is a phase difference between the calculated and measured discharges at Kruibeke from 2009. It is related to the phase difference between the comparable tides. The modeled discharges at Kruibeke are higher than the measurements from 2010. The calculated flood discharge at Schoonaarde is higher than the measurements from 2009 and 2010; the ebb discharge is modeled better.

8.1.5 ADCP velocities

The vector plots of the modeled and measured velocities for all transects are presented on the CD which is included with this report. The plots of statistical parameters are shown in figure 103 to figure 114. Each point on these plots represents an average bias or RMSE for a certain transect. Table 36 shows the values of bias and RMSE for different ADCP transects.

The absolute value of the bias of the modeled velocities at **Galgenschoor** is smaller than 10 cm/s for most transects (figure 103), the RMSE is 5 to 15 cm/s (figure 104). The bias of velocity direction is smaller than 10 degrees for most transects. The RMSE of velocity direction varies between 4 and 79 degrees (the slack period is not taken into account). The model accuracy for the velocity direction is good in the deeper part of the river for the most transects. It worsens in the shallower areas where the velocity magnitude is very small (figure 18). This results in an ancrease of the RMSE value of the entire transect.

Velocities at Galgenschoor are underestimated in the model during ebb. The model accuracy was improved during the calibration process but it is still not sufficient for a few transects in the beginning of ebb (the bias is -25 to -29 cm/s, the RMSE is 26 to 32 cm/s). The flood period is modeled better. The underestimation of the modeled velocities at Galgenschoor may be related to the vicinity of the strekdam. It is very important to have an accurate and detailed bathymetry of this dam in the model. The strekdam and leidam were defined based on the samples of the crests of the dams (chapter 3.3.2). The differences in velocity may be related to the uncertainties in the model bathymetry.

The absolute value of bias of the velocity magnitude at **Liefkenshoek** is smaller than 10 cm/s for most transects (figure 105). The maximum bias is calculated around the slack period. The RMSE of velocity magnitude varies from 7 to 20 cm/s (figure 106). The bias of velocity direction is smaller than 10 degrees, the RMSE of velocity direction is 5 to 25 degrees (not taking slacks into account).

The absolute value of bias of velocity magnitude is smaller than 10 cm/s and the bias of velocity direction is smaller than 10 degrees for most transects measured at **Ballooi (dwars) (**figure 107**)**. The RMSE of magnitude is about 7 to 13 cm/s at this location. The RMSE of direction is smaller than 15 degrees (figure 108). Peaks of the bias and RMSE are found around the slack.

The bias of the modeled velocities at **Driegoten** is smaller than 10 cm/s and the RMSE is about 6 to 15 cm/s for all transects except the slack moments and one transect measured in the end of flood (figure 109, figure 110). The RMSE increases to 25 cm/s for the transect in the end of the flood period (moment of the maximum velocity); the model overestimates the measurements. The absolute value of bias of velocity direction is smaller than 5 degrees, the RMSE of velocity direction is smaller than 10 degrees.

The absolute value of bias at **Branst (Bijboot StreamPro)** varies between 3 and 15 cm/s for all transects (except the slack moment) (figure 111). The RMSE changes from 8 to 18 cm/s (figure 112). It is important to keep in mind that some of the velocity magnitudes in this location were measured erroneously. High peaks were observed in the measured transects. Most of these peaks were filtered during the preprocessing. However, some of the measured velocity magnitudes are still not reliable. The velocity direction at Branst is measured erroneously and excluded from the analysis.

The absolute value of velocity bias at **Schoonaarde** is smaller than 10 cm/s for most periods (figure 113). The RMSE varies between 8 and 18 cm/s (figure 114). The RMSE of velocity direction is smaller than 20 degrees for most transects.

9 Validation

The model validation is performed for the same period as the model calibration. Different ADCP measurements and discharges are used for the analysis (table 10 and table 11 in §0). The results of the model validation are presented in Appendix 2.

9.1 Discharges

Figure 115 to figure 118 show the comparison of the modeled and measured discharges for the cross sections R1 and R2. The statistical parameters are presented in table 37.

Discharges through the cross section R1 Vaarwater boven Bath have an RMSE of about 1000 m³/s, which is about 5.6% of the maximum discharge in this location. The RMSE for the cross section R2_total is 6.6% of the maximum discharge there.

Discharges through the cross section R1 Ballastplaat are not accurate in the model. The RMSE is about 15% of the maximum discharge. This is probably related to the uncertainties in the bathymetry of the Ballastplaat dam ('leidam'). Analysis of the measured discharges shows that the flow through R1 Ballastplaat is observed when the water level is higher than 3 mTAW (figure 116). In the model the flow through this cross section is calculated significantly earlier, when the water level is only 1.5 mTAW. More recent and accurate bathymetric samples of the dam are needed to improve the model performance.

9.2 ADCP velocities

The vector plots of the measured and modeled velocities are presented on the CD which is included with this report. The plots of statistical parameters for different transects are shown in figure 119 to figure 130. The values of bias and RMSE are given in table 38.

The model bias of the velocity magnitude at **Doelpolder** is maximum (more than 20 cm/s) around the slack periods and in the middle of flood. For most transects the absolute value of bias is about 10 to 15 cm/s or smaller (figure 119). The RMSE is minimum during ebb (8 to 15 cm/s). During flood the RMSE varies between 5 cm/s and almost 25 cm/s (for the transect in the middle of flood) (figure 120). Velocities at Doelpolder are strongly affected by the vicinity of the strekdam and leidam (especially the strekdam). Therefore, it is very important to have an accurate bathymetry of these dams in the model to simulate the velocities in this location correctly. The differences in velocity may be related to the uncertainties in the model bathymetry.

The absolute value of bias of velocity direction at Doelpolder is smaller than 10 degrees for most transects; the RMSE is smaller than 15 degrees. The differences are higher during slacks.

The bias of the velocities at **Oosterweel** lies between -5 and 20 cm/s (not taking the slack periods into account). It is smaller than 10 cm/s for most transects (figure 121). The bias increases at the end of the flood period. The maximum flood velocity is overestimated in the model at Oosterweel. The RMSE varies between 10 and 23 cm/s (the RMSE is maximum in the end of flood) (figure 122). The bias of velocity direction at Oosterweel is smaller than 5 degrees for most periods; the RMSE is smaller than 10 degrees.

The bias of the velocity at **Notelaer ('langs'** – longitudinal profile**)** varies between 0 and -15 cm/s for most periods (figure 123). The RMSE varies from 7 to more than 15 cm/s for some transects (figure 124). The absolute value of bias of the velocity direction is smaller than 5 degrees, the RMSE does not exceed 20 degrees (if slacks are not taken into account).

The absolute value of the model bias of the transverse velocity profiles at **Notelaer ('dwars' –** transverse profile) is smaller than 10 cm/s (except slacks) (figure 125). The RMSE is 8 to 17 cm/s (figure 126). The RMSE of velocity direction is smaller than 15 degrees for most transects.

The velocity measurements at **Branst** used for the model validation are located at the outer side of the bend. The measurements at the inner side of the bend were used for the model calibration. The analysis shows that the model accuracy at the inner side of the bend (calibration) is better than the accuracy at the outer side (validation). Velocities at the outer bend are underestimated in the model during ebb (the bias is -8 to -24 cm/s, the RMSE is 12 to 30 cm/s) (figure 127, figure 128). The model accuracy during flood is better: the absolute value of bias is smaller than 10 cm/s, the RMSE is 4 to 15 cm/s for most transects during flood. The use of the 3D model can improve the calculated velocities in the river bend (*Maximova et al*., 2011).

The velocity direction at Branst and Appels is measured erroneously and excluded from the analysis.

The bias of velocity magnitude at **Appels** varies between -16 and 6 cm/s for most transects (figure 129). Most of the calculated velocities are underestimated in the model. The RMSE of velocity magnitude at Appels changes from 7 to 35 cm/s (figure 130). High peaks were observed in the measured velocities in this location. Most of these peaks were filtered during the preprocessing. However, some of the measured velocity magnitudes are still not reliable.

10 Conclusions

In this study a Delft3D model with refined grid resolution (3 times finer than the NEVLA grid) was developed for the Scheldt estuary upstream Walsoorden. It will be used to calculate the hydrodynamic characteristics of the study areas and the entire Sea Scheldt. This model was calibrated and validated based on the available water levels, velocity and discharge measurements. The horizontal eddy viscosity and bed roughness were used as calibration parameters.

A varying roughness field was defined in the calibrated model (run simWSenZS_37). The roughness of the tidal flats (‘slikken’) is 25% lower than the roughness of the river channel. This can be explained by the fact that tidal flats are composed of muddy sediment and are not vegetated. Furthermore, the hydraulic smoothness of these zones can be increased due to the existence of biological films (*Maximova et al.,* 2010). The roughness of the tidal marshes (‘schorren’) is 10% higher than the roughness of the river channel. Tidal marshes are vegetated and it is expected that they have a higher roughness than a deeper part of the river.

The model accuracy for high and low waters and harmonic components of the tidal wave was improved at most stations in the Scheldt. The modeled and measured discharges have the same shape; discharges are well represented in the model at most locations.

The calculated velocities were compared with the measured stationary velocities at Buoy84, Oosterweel and Branst (RioGrande measurement). The analysis of the RMAE of velocity components shows that the model performance is good at most locations and it is reasonable for the bottom velocities at Buoy84 (accordingly to (*Sutherland et al.,* 2003)).

The modeled velocities were compared with transverse and longitudinal ADCP measurements. The model performs well at most locations of available ADCP measurements. During the calibration process the model accuracy significantly improved at Galgenschoor and Schoonaarde. Also the modeled velocities at Ballooi and Driegoten improved. The model accuracy at Liefkenshoek was good and it did not change during the calibration process.

The use of a lower roughness of the tidal flats helped to improve the modeled velocities in the shallow zones. However, this effect was rather limited and the calculated velocities at Galgenschoor and Notelaer (longitudinal profile) are still underestimated in the model during some periods of the tide. (*Dekker*, 2010) also noticed that the flow velocities in the intertidal areas were underestimated by the SCALWEST model. This underestimation can be related to the use of Manning roughness coefficients, which can result in an overestimation of the effect of roughness in shallow areas. Further research of this problem will be carried out in the framework of the project ‘00_018 Verbetering randvoorwaardenmodel’. More velocity measurements on the tidal flats and marshes are needed to improve the model performance there.

11 Recommendations

11.1 Bathymetry

The bathymetric measurements for the upstream part of Zenne, Nete and Dijle are not available. The model bathymetry was defined there based on the old cross sections from the 1D model. More recent bathymetric measurements of the Rupel tributaries are needed to improve the model performance there.

The structures of Ballastplaat and Ouden Doel ("leidam en strekdam" in Dutch) in the Lower Sea Scheldt were defined in the model bathymetry based on the samples of the crests of the dams. These samples were made in 2009 based on the bathymetry available at that period. More recent detailed measurements of the structures are needed to improve the velocities in the vicinity of these structures.

11.2 Time of model and measurements

Velocity maps are calculated in the model every 30 minutes. For the comparison of the model results with the ADCP measurements, the closest in time transect of the ADCP measurements was found for each model map. It takes some time to measure a transect. Therefore, each measurement file contains data for some period of the time while each model map represents only one certain moment during tide. Therefore, a better agreement between the model results and measurements is expected if the sailed transects are limited in length (and therefore, in time).

11.3 Discharge

The model accuracy upstream Dendermonde is affected by the use of the daily time series of the discharge at Merelbeke (*Vanlede et al.,* 2008). This discharge has a significant effect on the model output. The model accuracy in the upstream part of the Upper Sea Scheldt will improve if an accurate and detailed time series of the discharge at Merelbeke is defined.

11.4 Numerical aspects

The model accuracy in the river bends can be improved by the use of a 3D model. (*Maximova et al.,* 2011) concluded that a 3D model with 2 layers produces more accurate results in the river bends than a 2D model.

11.5 Velocity measurements

Some of the longitudinal ADCP transects used in this project were measured on the tidal flats (during high water). However, most measurements were performed in the subtidal zones. Measurements on the tidal marshes ('schorren') are not available for this project. More velocity data in the intertidal zones are needed to improve the model performance there.

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Tables

Table 18. Observation points in the study areas

Code*	Ecozone	Reality			Model					
		X	Y	Z (mTAW)	X	Y	M	N	Z (mTAW)	Z in WL point** (mTAW)
OD_Z_6	supralitoraal	75984	372246	-4.67	75973	372251	361	598	-4.66	-4.5
OD_Z_5	hoog slik	76086	372353	-4.06	76110	372323	355	600	-4.30	-3.9
OD_Z_4	midden slik	76192	372425	-2.83	76186	372430	350	598	-2.87	-2.67
OD_Z_3	laag slik	76320	372509	-0.46	76316	372513	344	599	-0.35	-0.07
OD_Z_2	ondiep water	76371	372540	0.86	76366	372530	342	600	0.77	1.15
OD_Z_1	matig diep subtidaal	76495	372606	4.16	76500	372613	336	601	4.23	4.64
OD_N_5	hoog slik	75654	372821	-4.07	75665	372822	354	565	-4.09	-3.97
OD_N_4	midden slik	75759	372905	-2.96	75775	372900	349	566	-2.83	-2.55
OD_N_3	laag slik	75860	372997	-0.62	75854	373008	344	565	-0.46	-0.27
OD_N_2	ondiep water	75906	373037	0.69	75907	373028	342	566	0.70	1.21
OD_N_1	matig diep subtidaal	75943	373062	3.32	75944	373065	340	566	3.51	4.24
GS_Z_5	hoog slik	78051	369475	-4.72	78051	369477	311	774	-4.87	-4.32
GS_Z_4	midden slik	77987	369450	-2.54	77990	369450	314	774	-2.59	-2.35
GS_Z_3	laag slik	77916	369420	-0.89	77909	369414	318	774	-0.38	-0.05
GS_Z_2	ondiep water	77875	369405	0.68	77885	369416	319	773	0.42	0.91
GS_Z_1	matig diep subtidaal	77701	369360	4.25	77700	369357	328	771	4.30	4.44
GS_N_5	hoog slik	77993	370457	-4.85	77992	370437	303	708	-4.53	-3.65
GS_N_4	midden slik	77947	370461	-1.57	77943	370449	305	707	-1.57	-1.3
GS_N_3	laag slik	77863	370469	-0.54	77866	370478	308	705	-0.52	-0.22
GS_N_2	ondiep water	77775	370477	0.86	77774	370464	312	705	0.93	1.16
GS_N_1	matig diep subtidaal	77676	370485	3.72	77676	370492	316	703	3.78	4.67
AP_5	hoog slik	62668	340704	-4.91	62684	340707	347	3441	-4.89	-4.16
AP_4	midden slik	62660	340728	-3.11	62649	340720	351	3442	-3.32	-2.3
AP_3	laag slik	62657	340739	-1.96	62646	340736	354	3442	-1.79	-1.18
AP_2	ondiep water	62655	340744	-0.65	62644	340742	355	3442	-0.58	0.46
AP_1	matig diep subtidaal	62653	340750	1.81	62671	340758	356	3441	1.65	2.88
ZL_5	hoog slik	62763	340950	-4.24	62765	340947	380	3436	-3.98	-2.75
ZL_4	midden slik	62767	340940	-2.65	62768	340937	378	3436	-2.48	-2.03
ZL_3	laag slik	62770	340932	-1.50	62800	340941	377	3435	-1.64	-1.26
ZL_2	ondiep water	62772	340924	-0.13	62772	340923	375	3436	-0.25	0.56
ZL_1	matig diep subtidaal	62775	340915	2.70	62775	340912	373	3436	2.20	3.11

Code*	Ecozone	Reality			Model					
		X	Y	Z (mTAW)	X	Y	M	N	Z (mTAW)	Z in WL point (mTAW)
BR_N_5	hoog slik	70691	344882	-4.66	70680	344875	331	2124	-4.58	-4.46
BR_N_4	midden slik	70678	344856	-3.85	70670	344856	333	2124	-3.48	-2.51
BR_N_3	laag slik	70665	344829	-0.41	70687	344820	335	2125	-1.08	-0.31
BR_N_2	ondiep water	70661	344821	1.24	70649	344819	337	2124	1.53	2.45
BR_N_1	matig diep subtidaal	70646	344792	4.00	70638	344801	339	2124	3.70	4
BR_Z_4	midden slik	70975	344614	-2.16	70978	344611	333	2136	-2.42	-1.34
BR_Z_3	laag slik	70969	344607	-0.36	70988	344576	334	2137	-0.33	1.04
BR_Z_2	ondiep water	70964	344604	0.77	70978	344569	335	2137	1.69	2.63
BR_Z_1	matig diep subtidaal	70951	344593	3.03	70948	344587	336	2136	3.29	4.31
PL_5	hoog slik	70813	344394	-4.22	70825	344388	355	2139	-4.38	-3.4
PL_4	midden slik	70790	344445	-2.80	70780	344452	355	2136	-3.00	-1.68
PL_3	laag slik	70811	344467	-1.12	70821	344451	352	2137	-1.15	-0.94
PL_2	ondiep water	70838	344492	0.40	70831	344493	349	2136	0.31	0.79
PL_1	matig diep subtidaal	70853	344506	2.05	70848	344507	347	2136	2.24	2.84
BAL_5	hoog slik	75096	348132	-3.66	75094	348129	350	1794	-4.03	-3.29
BAL_4	midden slik	75095	348111	-2.47	75096	348106	348	1794	-2.15	-1.87
BAL_3	laag slik	75096	348050	-0.96	75100	348049	343	1794	-0.98	-0.91
BAL_2	ondiep water	75100	347967	1.79	75105	347968	336	1794	1.52	2.17
BAL_1	matig diep subtidaal	75102	347932	4.58	75107	347933	333	1794	4.38	5.04
NOT_W_5	hoog slik	76275	347953	-4.28	76268	347948	319	1764	-4.55	-3.23
NOT_W_4	midden slik	76265	347974	-2.45	76297	347978	320	1763	-2.64	-2.09
NOT_W_3	laag slik	76249	348006	-0.91	76216	347975	322	1765	-1.12	-0.56
NOT_W_2	ondiep water	76237	348031	0.64	76233	348032	325	1764	0.86	1.49
NOT_W_1	matig diep subtidaal	76221	348058	3.57	76221	348060	327	1764	3.58	4.42
NOT_O_5	hoog slik	76725	348263	-4.11	76725	348259	321	1749	-4.56	-3.72
NOT_O_4	midden slik	76715	348284	-2.55	76709	348282	323	1749	-2.28	-1.71
NOT_O_3	laag slik	76692	348312	-0.48	76665	348286	325	1750	-0.67	-0.14
NOT_O_2	ondiep water	76685	348322	1.01	76658	348297	326	1750	0.76	2.23
NOT_O_1	matig diep subtidaal	76664	348349	5.09	76664	348351	329	1749	5.01	5.54

*OD – Schaar van Ouden Doel; GS – Galgenschoor; AP – Appels; ZL – Zele; BR – Branst; PL – plaat (left bank at Branst) ; BAL – Ballooi; NOT – Notelaer

**depth in the water level points is found as a maximum value of the four surrounding depth points (depth is positive in Delft3D) (Appendix 5)

Table 19. Depth limits of different zones

Zone	Mesohaline		Oligohaline		Fresh water long residence time		Fresh water short residence time	
Distance (km)	5		43.5		53		74	
Code	OD	GS	BAL	NOT	BR	PL	ZL	AP
Moderately deep subtidal								
Depth limit (mTAW)*	2.1		2.109		1.88		0.87	
Shallow subtidal								
Depth limit (mTAW)*	0.1		0.1		-0.12		-1.13	
Low mudflats (laag slik)								
Depth limit (mTAW)*	-1		-1.32		-1.5		-2.09	
Medium mudflats (midden slik)								
Depth limit (mTAW)*	-3.98		-4		-4.1		-4.09	
High mudflats (high slik)								

*Depth is positive in Delft3D

Table 20. RMSE of velocity magnitude and direction for runs with different time steps

Study area	simWSenZS_13 vs. simWSenZS_14		simWSenZS_13 vs. simWSenZS_12	
	RMSE mag (m/s)	RMSE dir (degrees)	RMSE mag (m/s)	RMSE dir (degrees)
Schaar van Ouden Doel	0.002	3	0.002	2
Galgenschoor	0.001	1	0.001	1
Notelaer and Balloi	0.002	0.5	0.001	0.5
Branst	0.002	1	0.001	0.5
Appels	0.008	1	0.005	1

Table 21. Model runs used for the model calibration

Model run	viscosity (m²/s)	Walsoorden		Antwerp		St Amands		Schoonaarde		Melle	Durme	Rupel	Zenne	Dijle	Beneden Nede	Grote Nete	Kleine Nete
simWSenZS_15/ 19a/ 23*	1																
simWSenZS_16	1																
simWSenZS_18	1																
simWSenZS_20	1																
simWSenZS_22	1																
simWSenZS_21	0.5																
simWSenZS_25	0.5																
simWSenZS_26	0.5																
simWSenZS_29	0.5																
simWSenZS_32	0.5																
simWSenZS_33	0.5	idem simWSenZS_29 but rgh slik = rgh river + 5%, rgh schor = rgh river + 10%															
simWSenZS_35	0.5	idem simWSenZS_29 but rgh slik = rgh river - 5%, rgh schor = rgh river + 10%															
simWSenZS_27	0.3																
simWSenZS_28	0.3																
simWSenZS_30	0.3																
simWSenZS_31	0.3																
simWSenZS_34	0.3																
simWSenZS_36	0.3	idem simWSenZS_34 but rgh slik = rgh river - 15%, rgh schor = rgh river + 10%															
simWSenZS_37	0.3	idem simWSenZS_34 but rgh slik = rgh river – 25%, rgh schor = rgh river + 10%															
simWSenZS_38	0.3	idem simWSenZS_34 but rgh slik is uniform (0.016 $m^{-1/3}s$), rgh schor = rgh river + 10%															

*These model runs have small differences in bathymetry

color scale	roughness ($m^{-1/3}s$)	color scale	roughness ($m^{-1/3}s$)	color scale	roughness ($m^{-1/3}s$)	color scale	roughness ($m^{-1/3}s$)	color scale	roughness ($m^{-1/3}s$)
	0.014		0.017		0.020		0.023		0.026
	0.015		0.018		0.021		0.024		0.027
	0.016		0.019		0.022		0.025		0.028

Figures

Figure 19 – The Scheldt estuary

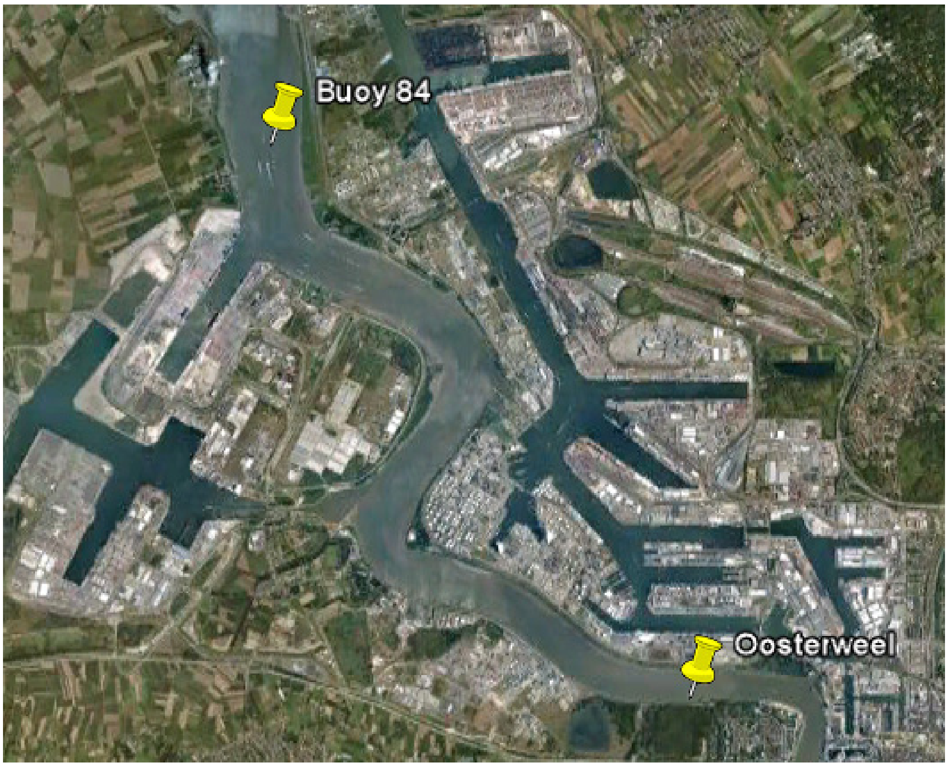


Figure 20 - Location of stations Oosterweel and Buoy 84

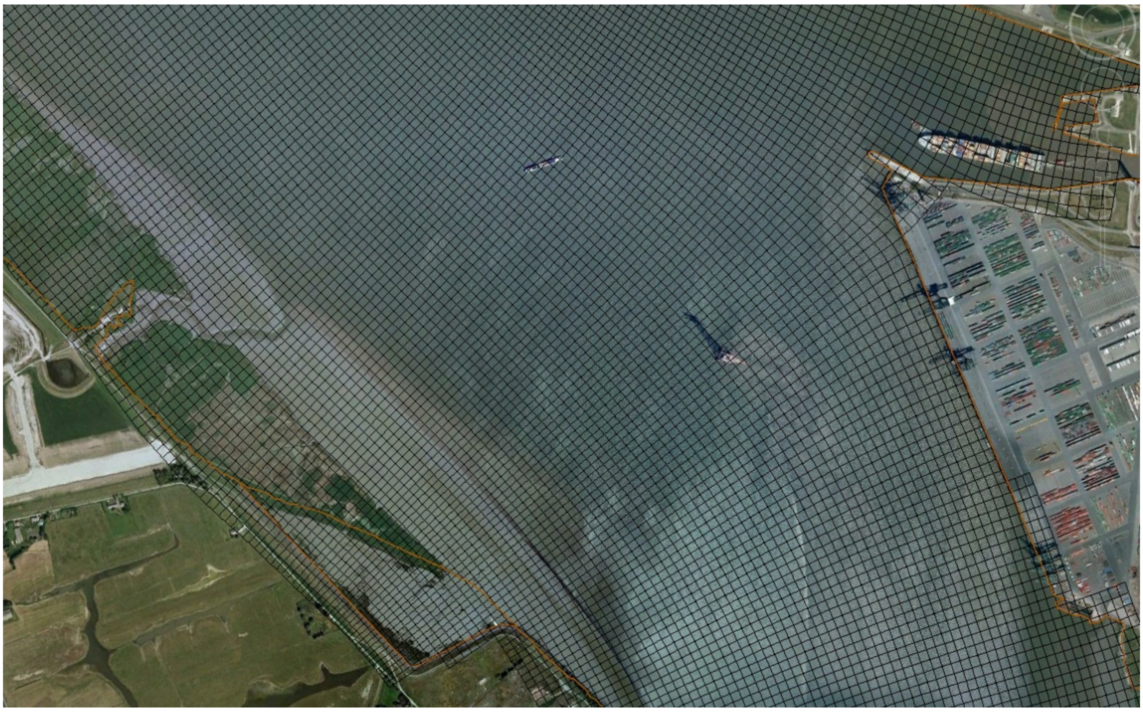


Figure 21 - Model grid at Schaar van Ouden Doel

Figure 22 - Model grid at Galgenschoor

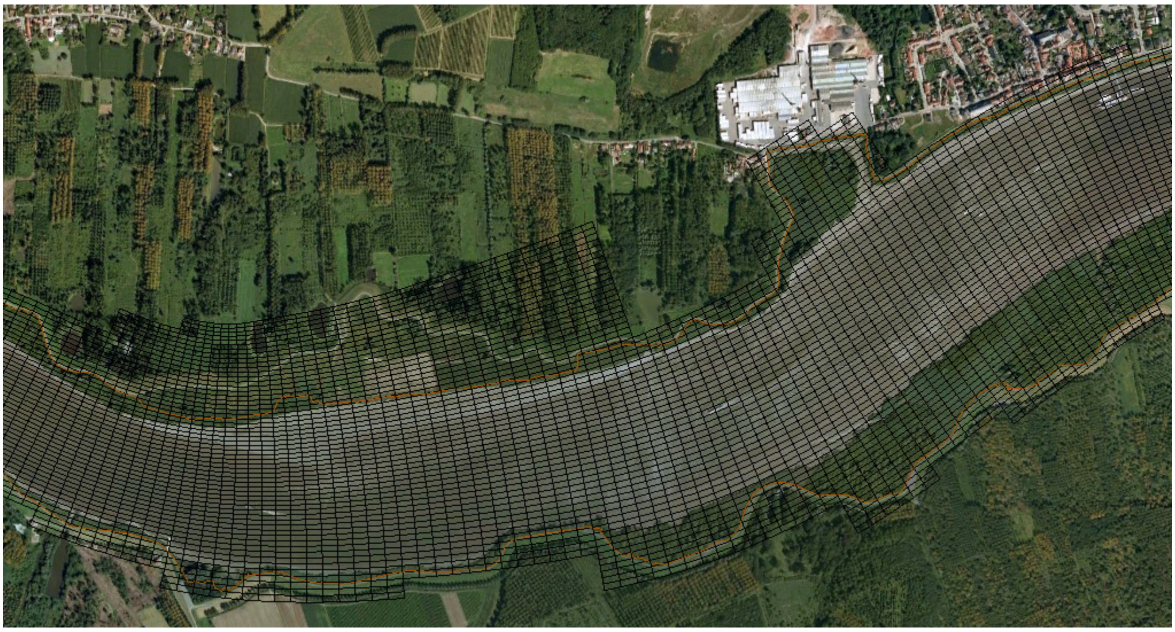


Figure 23 - Model grid at Notelaer and Ballooi

Figure 24 - Model grid at Branst

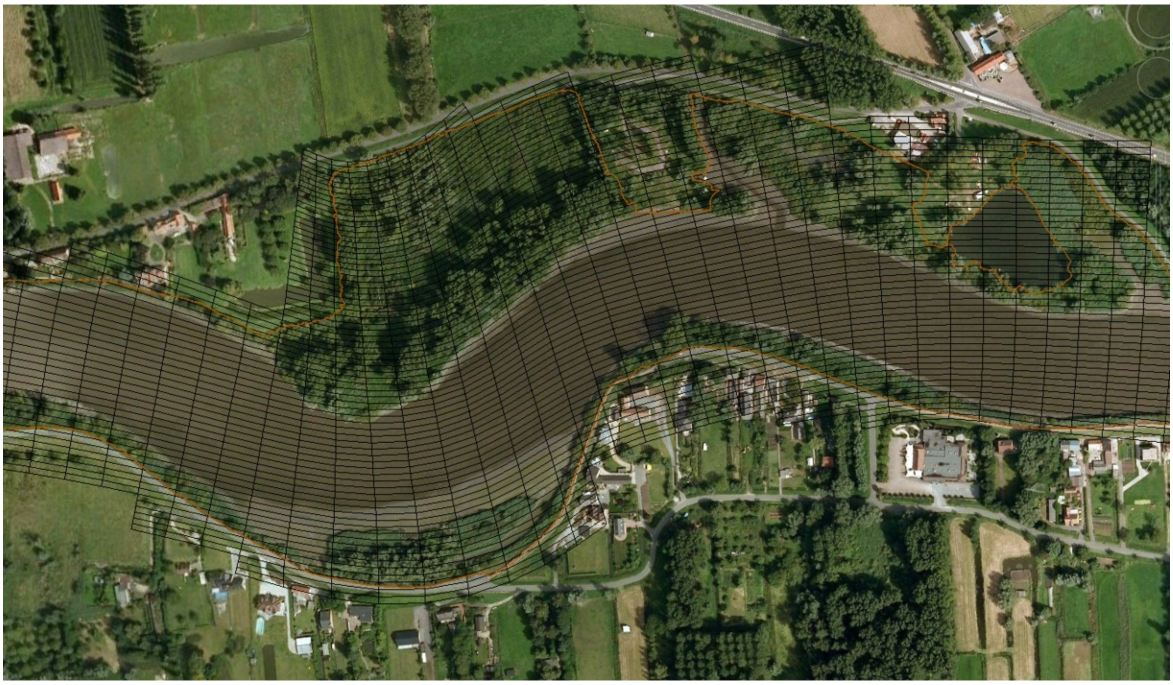


Figure 25 - Model grid at Appels

Figure 26 - Model grid at Uitbergen

Figure 27 - Model grid at Wetteren

Figure 28 - Model grid at Melle

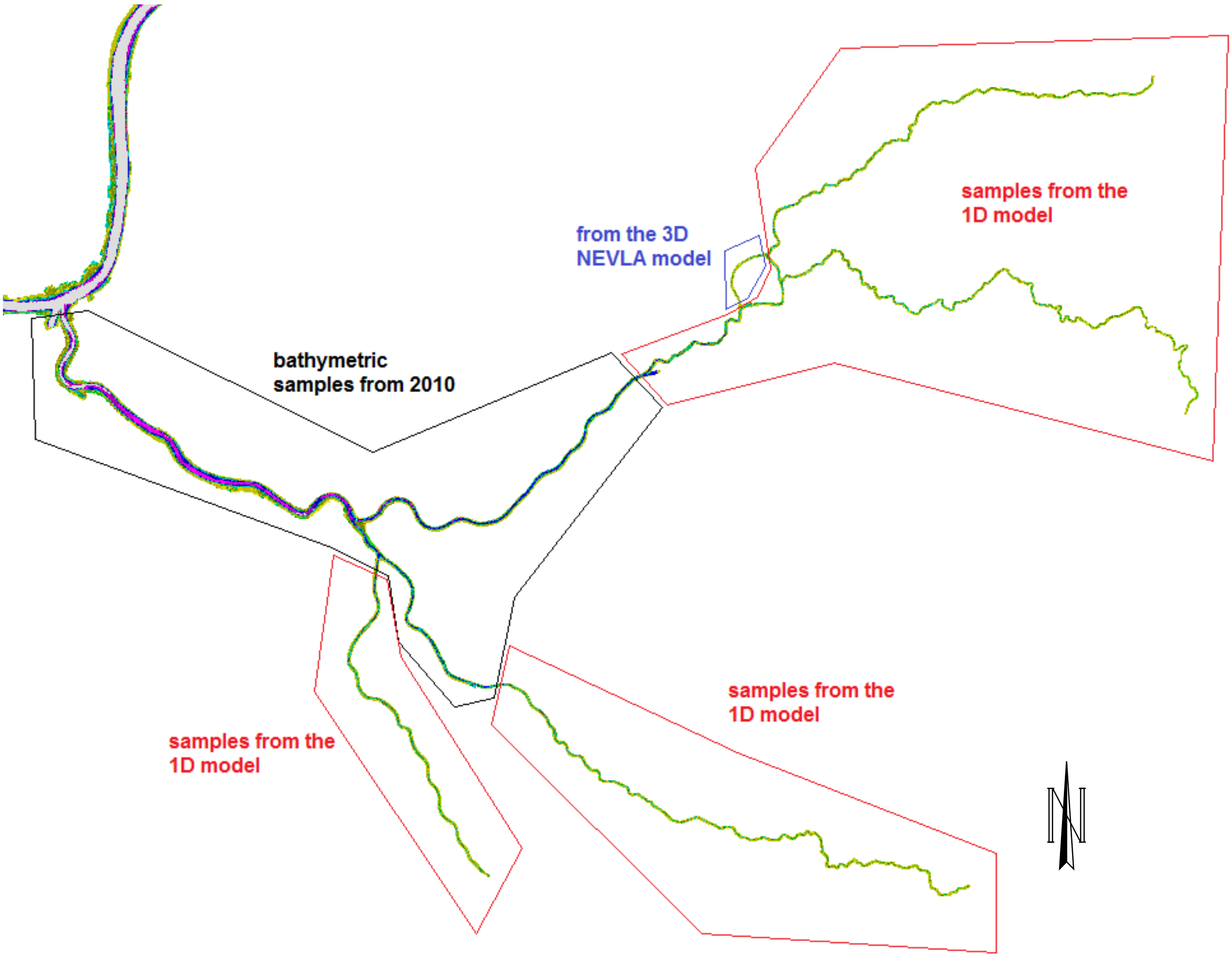


Figure 29 - Bathymetric measurements for the Rupel and tributaries

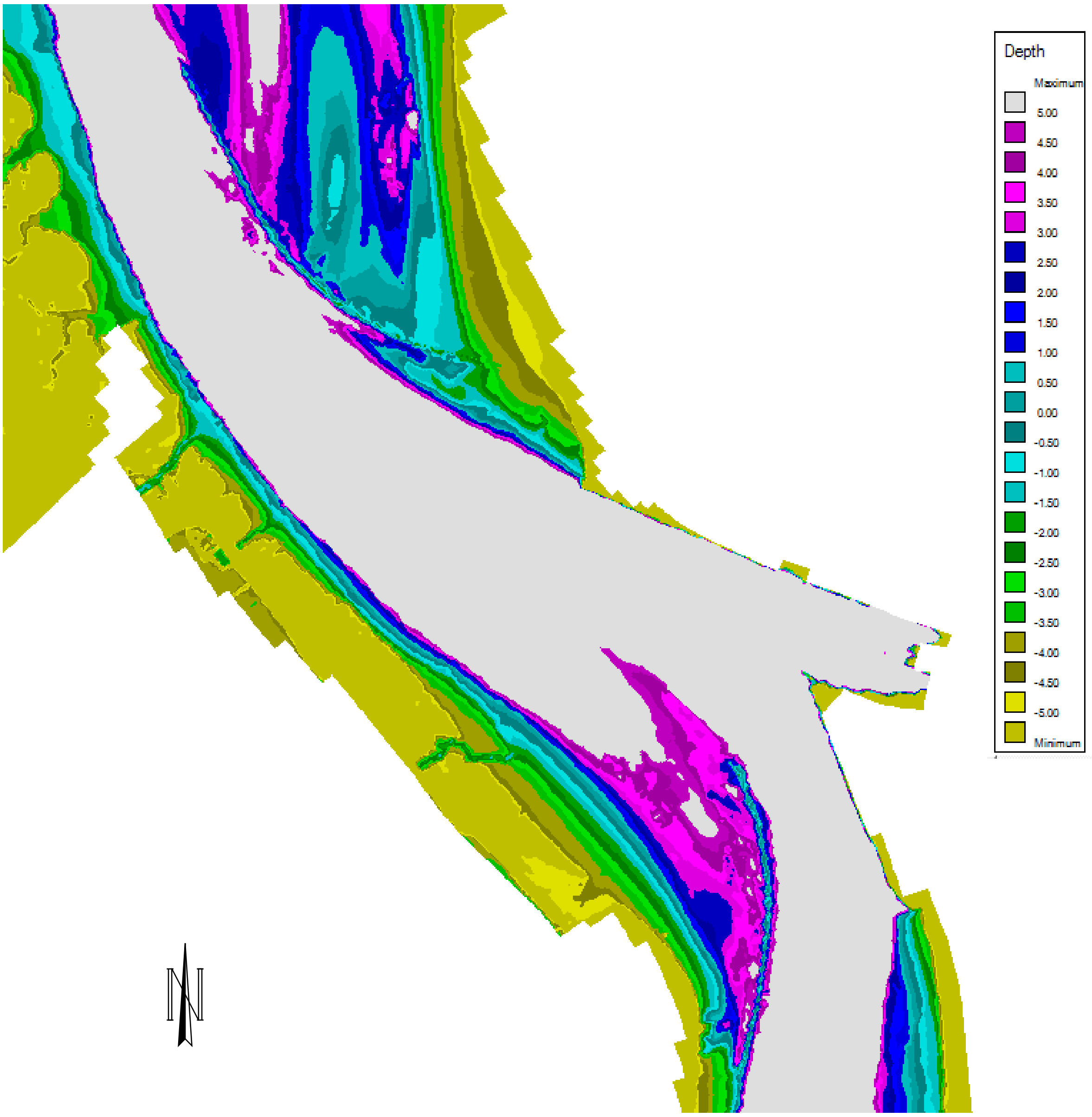


Figure 30 - Implementation of the leidam and strekdam in bathymetry (mTAW)

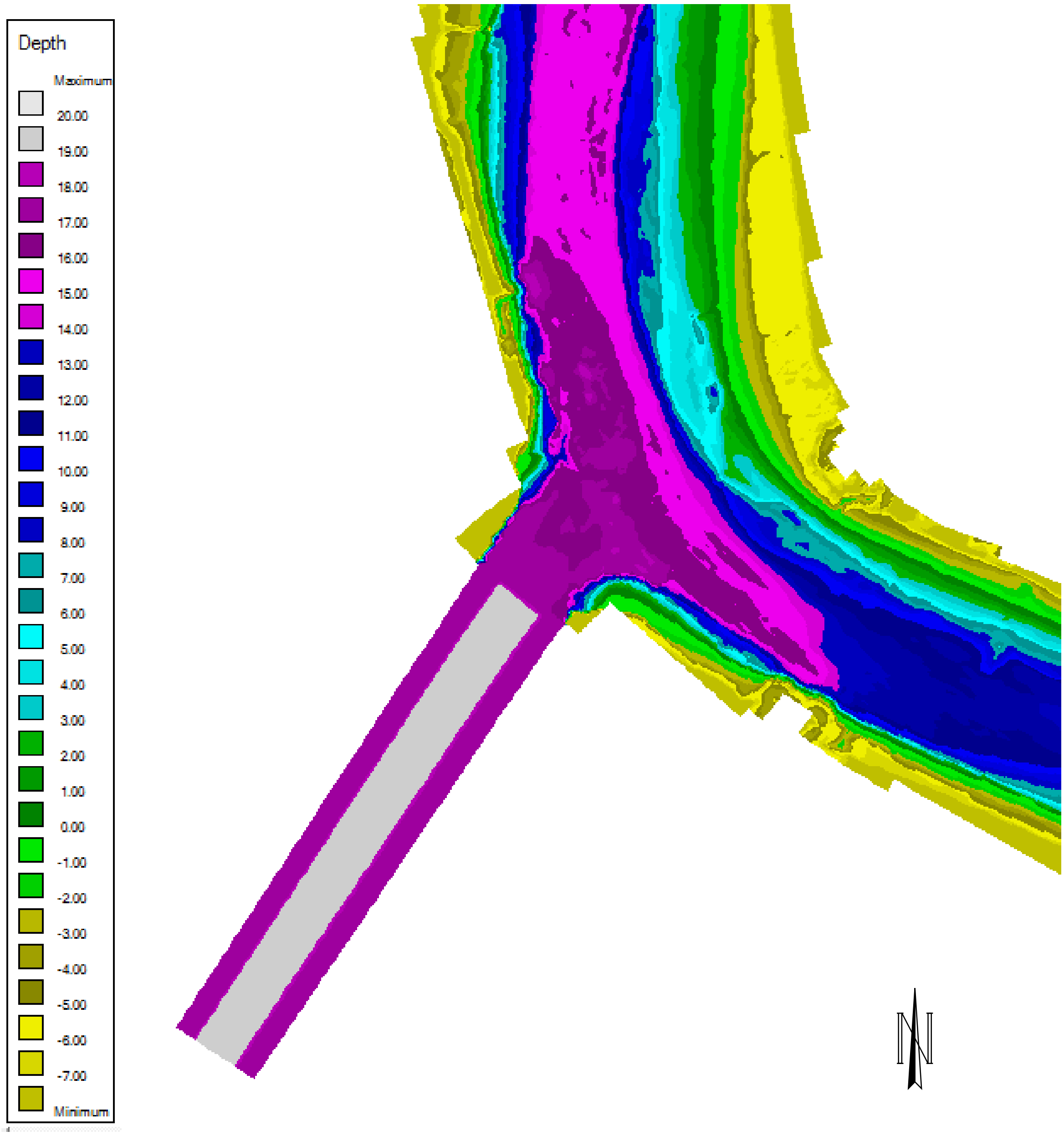


Figure 31 - Bathymetry of the Deurganckdok (mTAW)

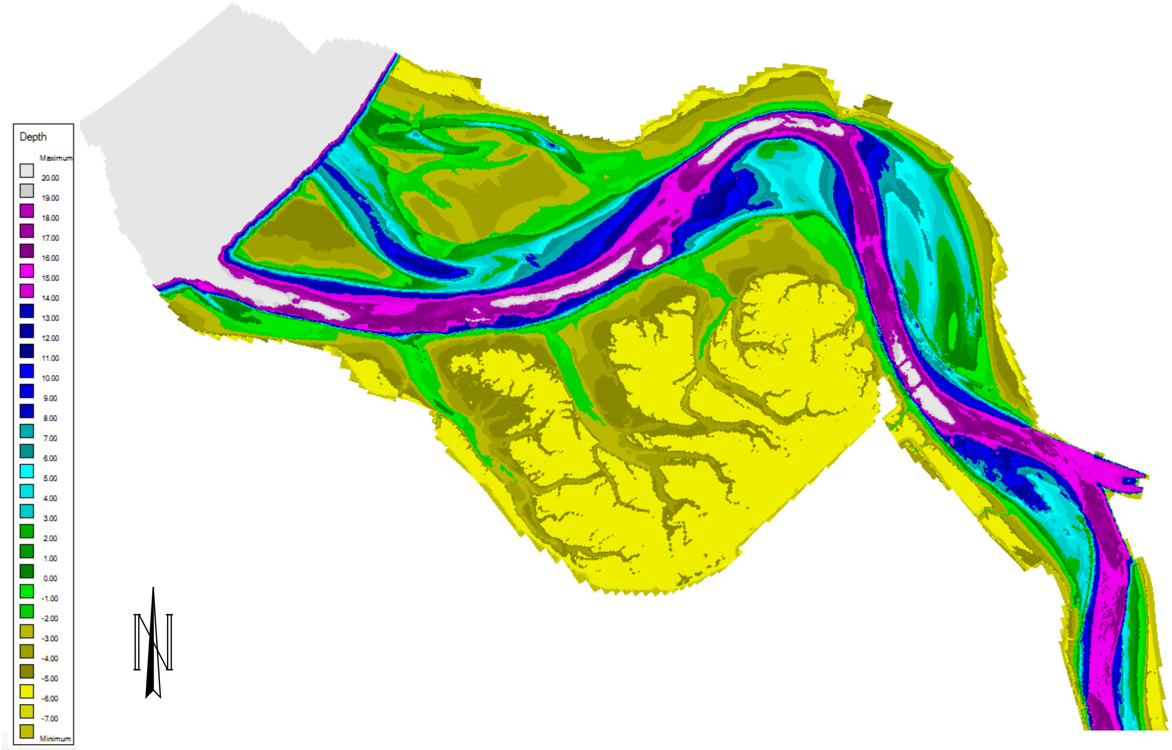


Figure 32 - Model bathymetry at the downstream boundary (mTAW)

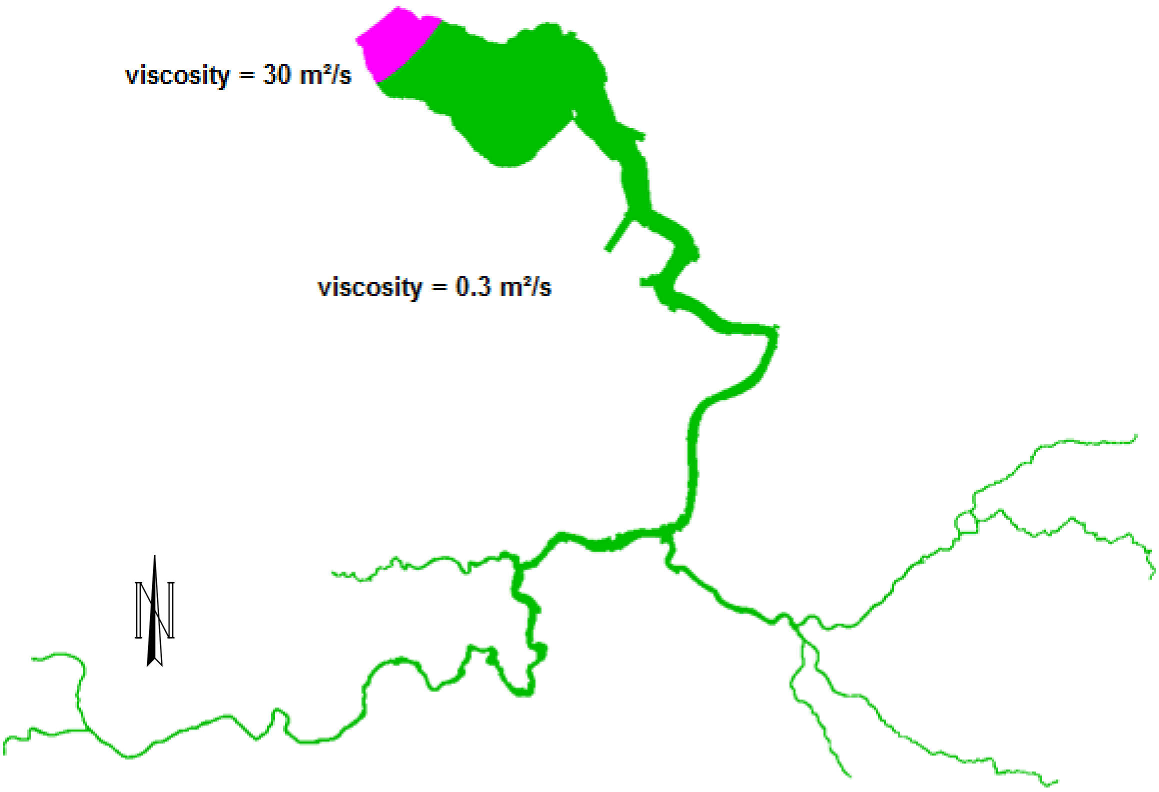


Figure 33 - Viscosity in the calibrated model

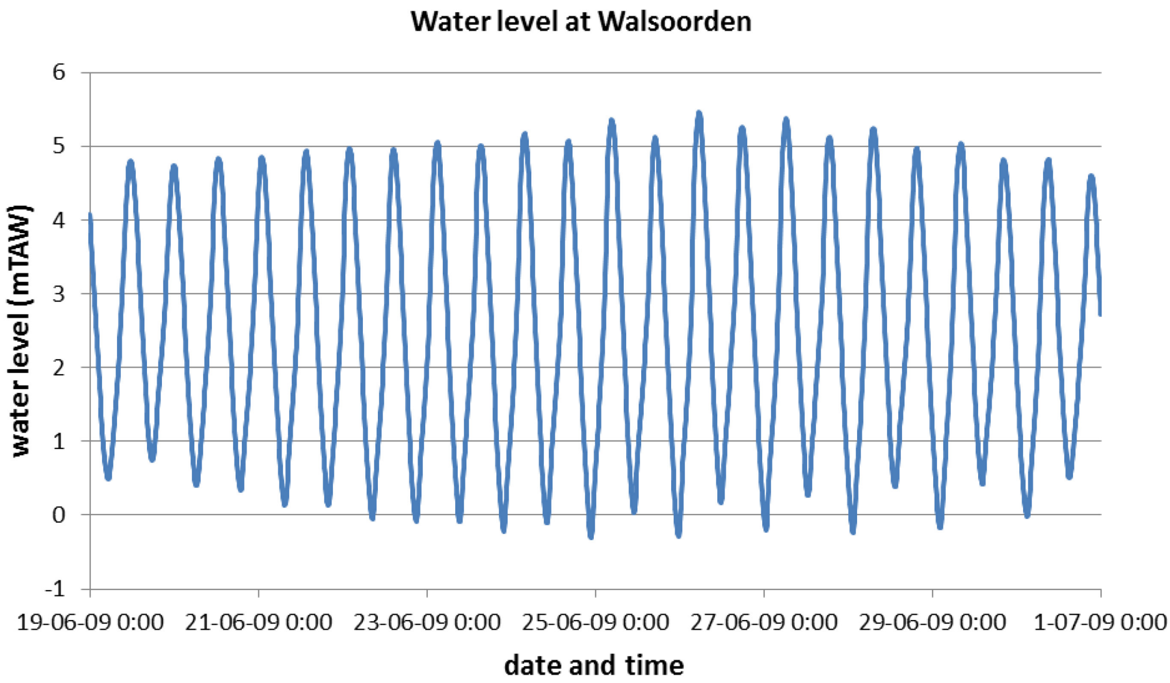


Figure 34 - Water level at Walsoorden

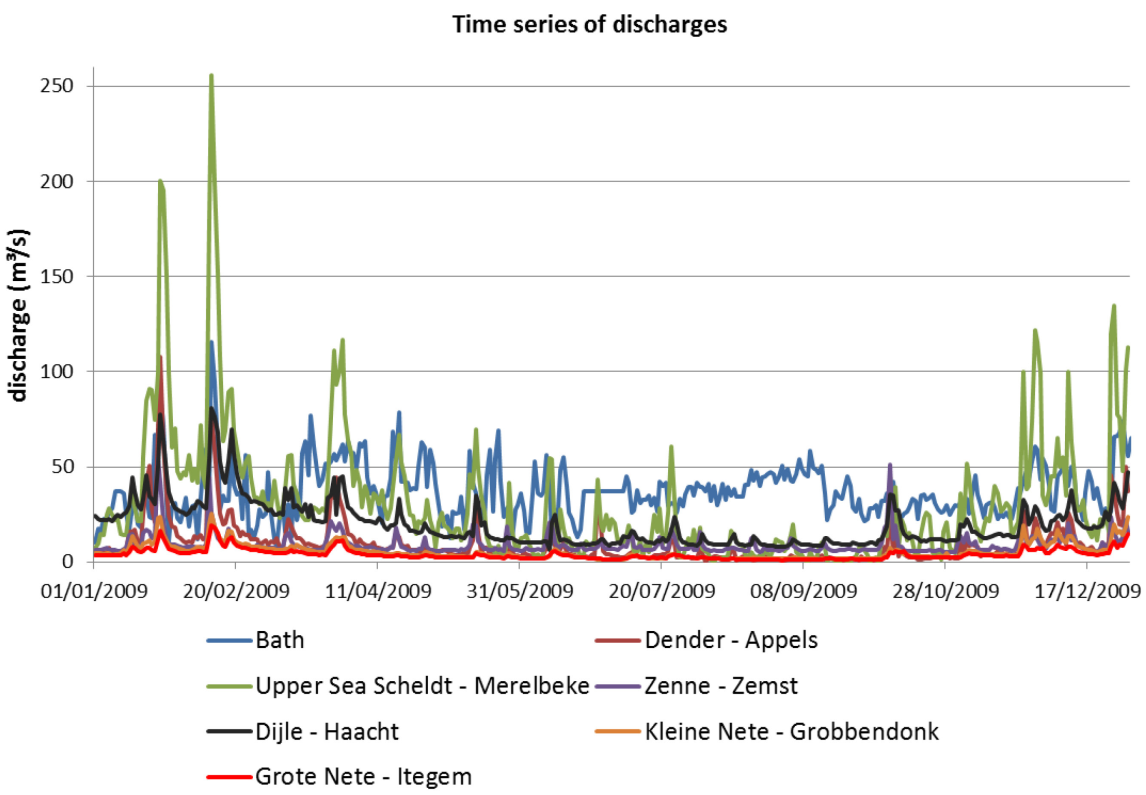


Figure 35 - Discharges defined in the model

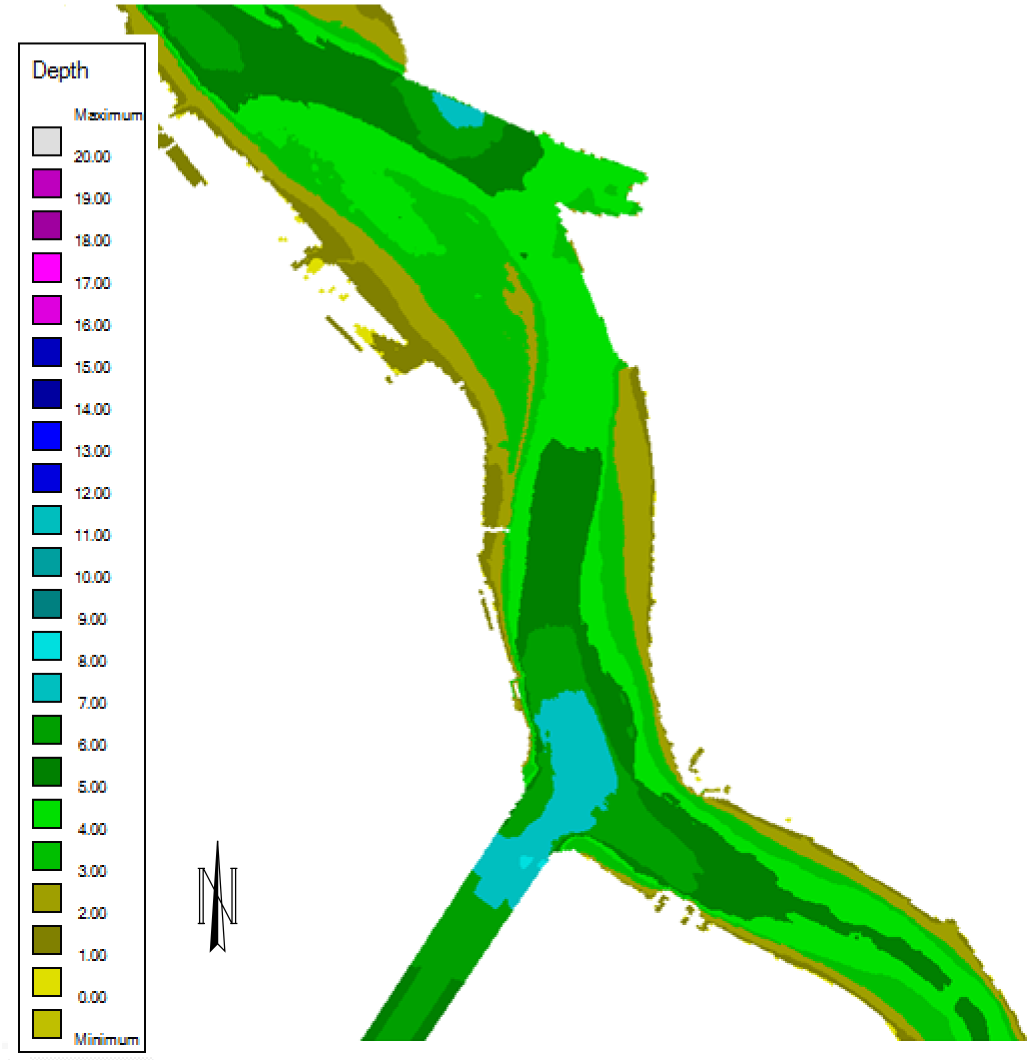


Figure 36 - Courant number at Schaar van Ouden Doel and Galgenschoor (time step = 3 s, Zref = 5.5 mTAW)

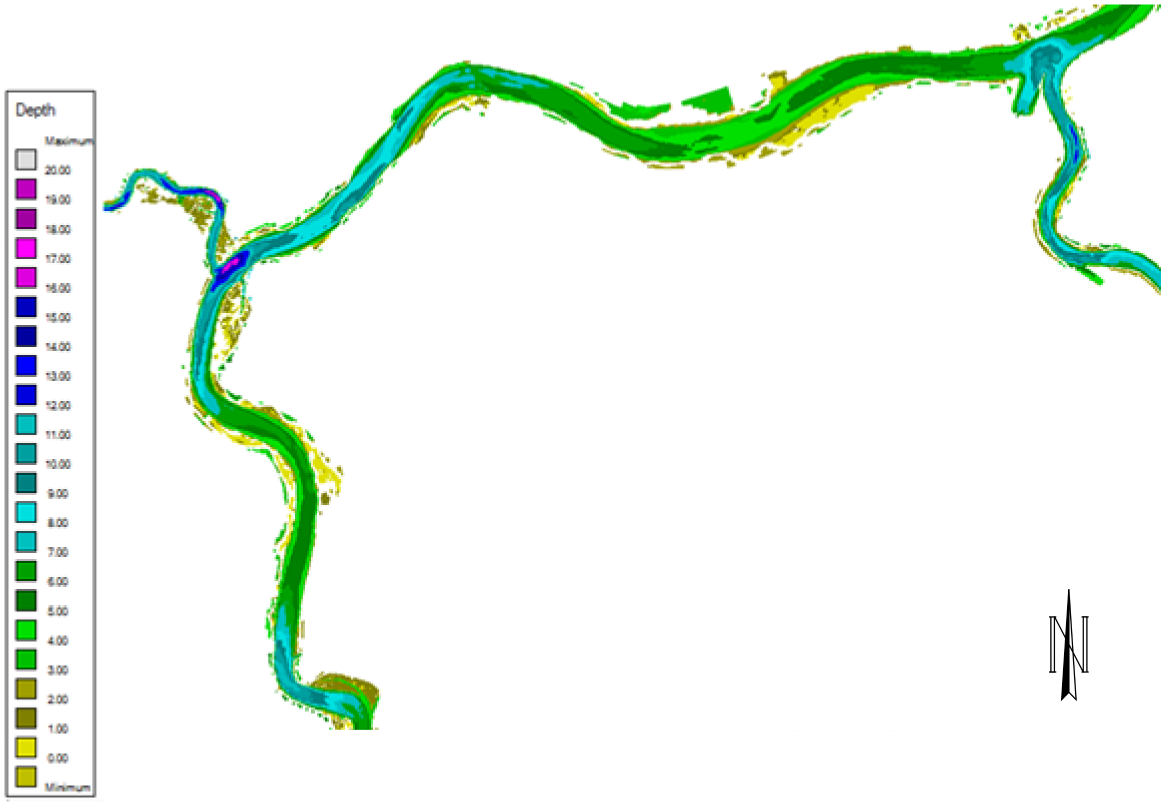


Figure 37 - Courant number at Ballooi, Notelaer and Branst (time step = 3 s, Zref = 6 mTAW)

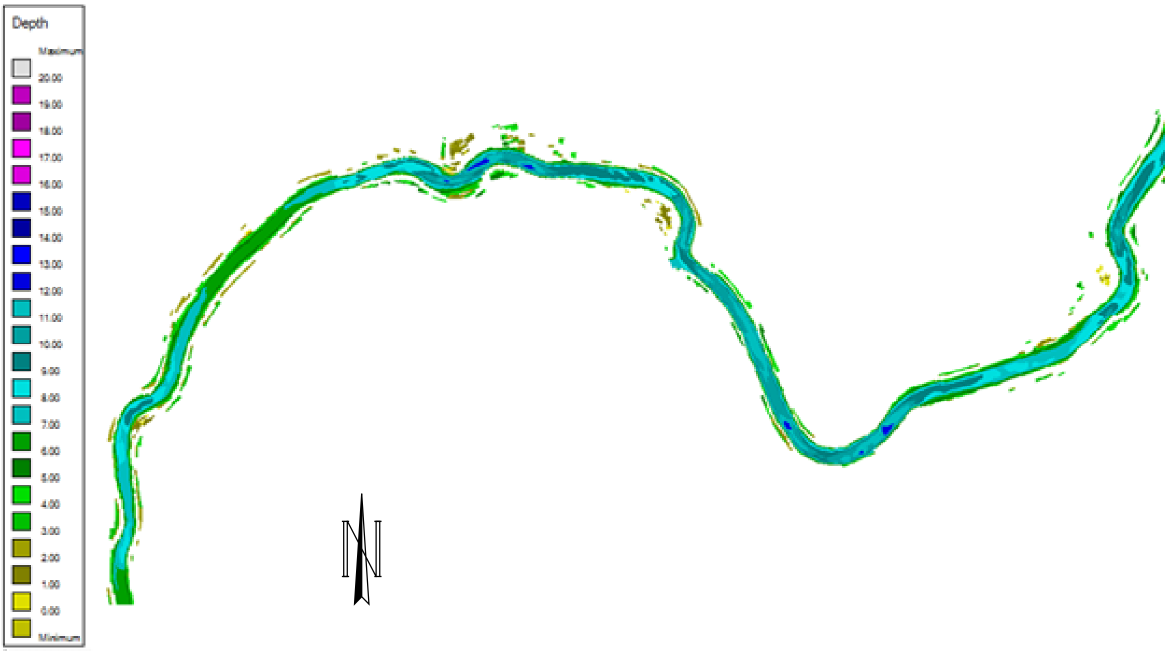


Figure 38 - Courant number at Appels (time step = 3 s, Zref = 5.5 mTAW)

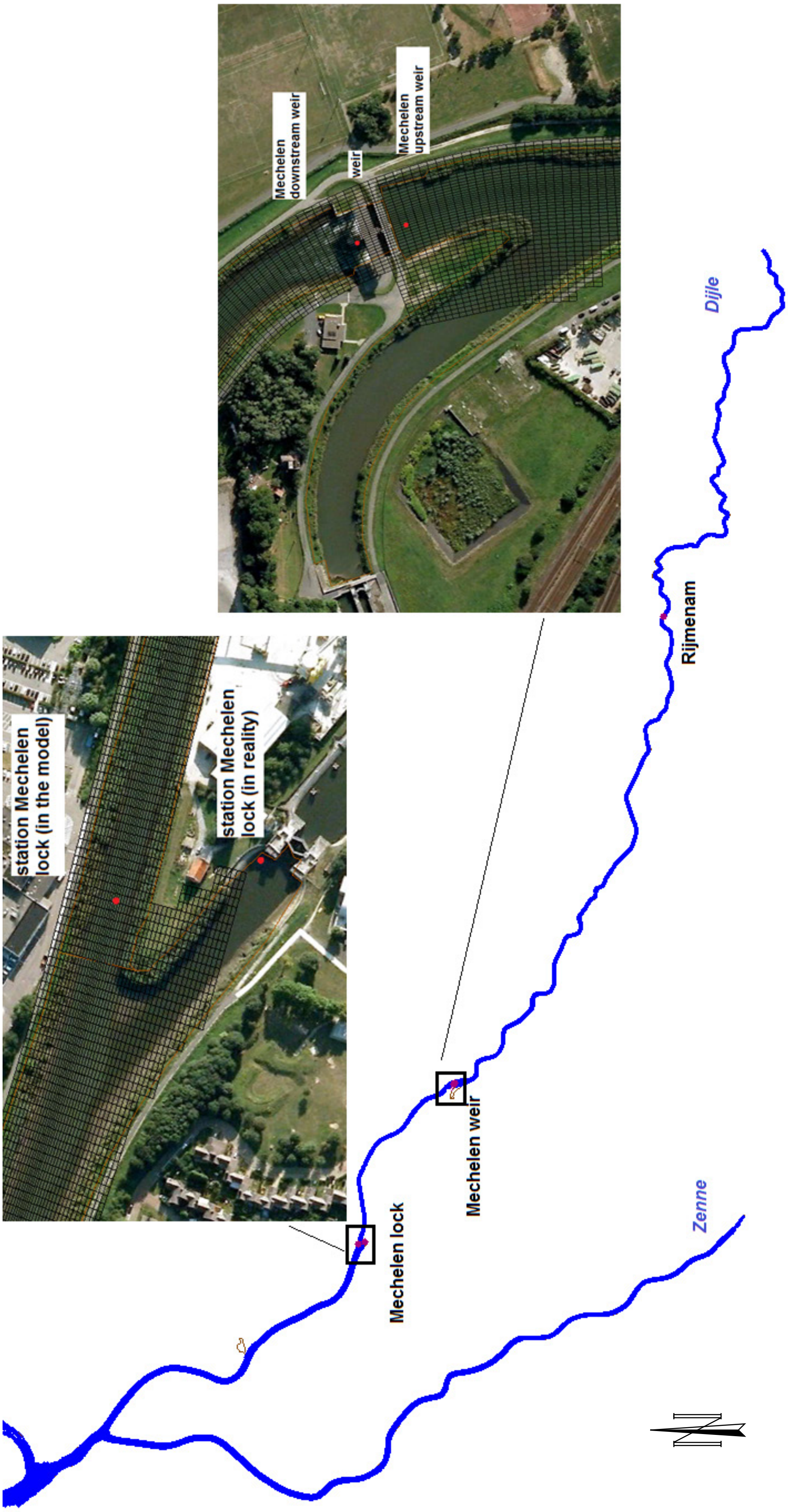


Figure 39 - Location of stations Mechelen and Rijmenam

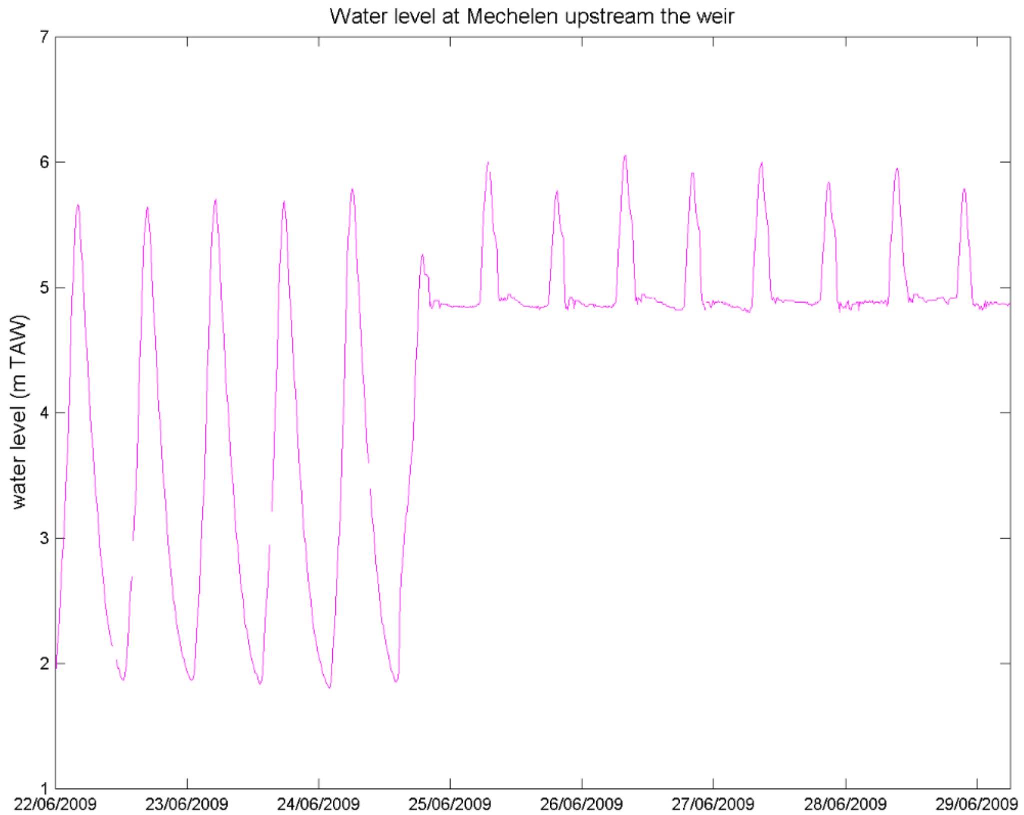


Figure 40 - Water level at Mechelen upstream the weir

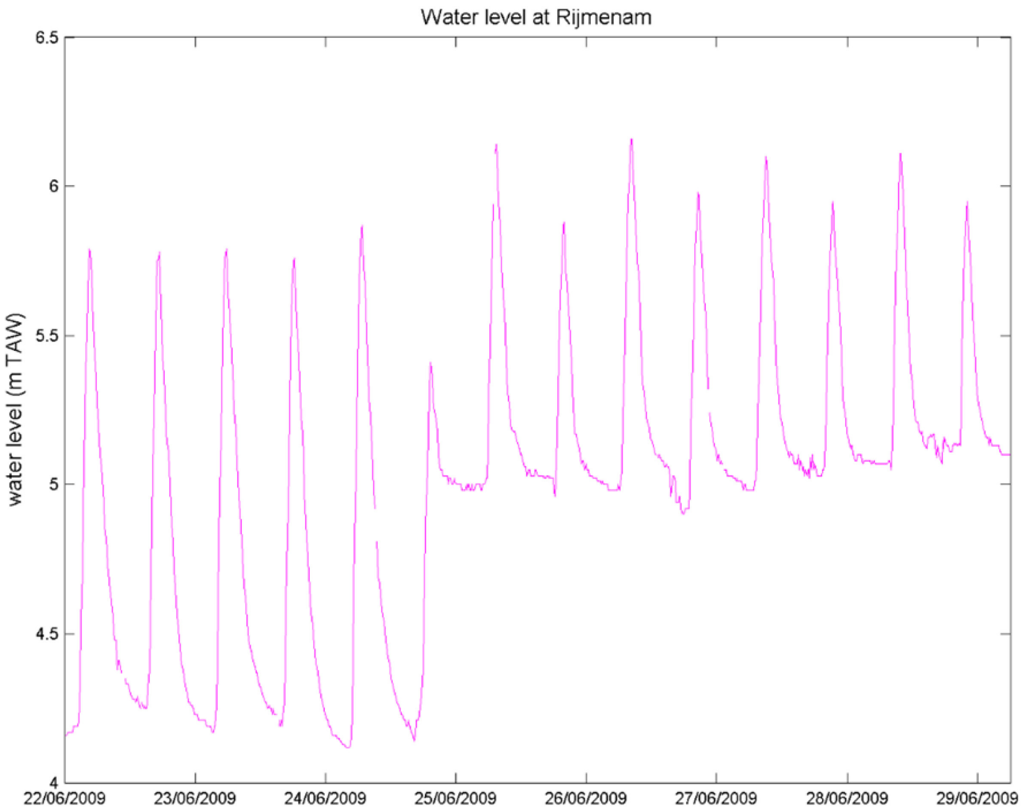


Figure 41 - Water level at Rijmenam

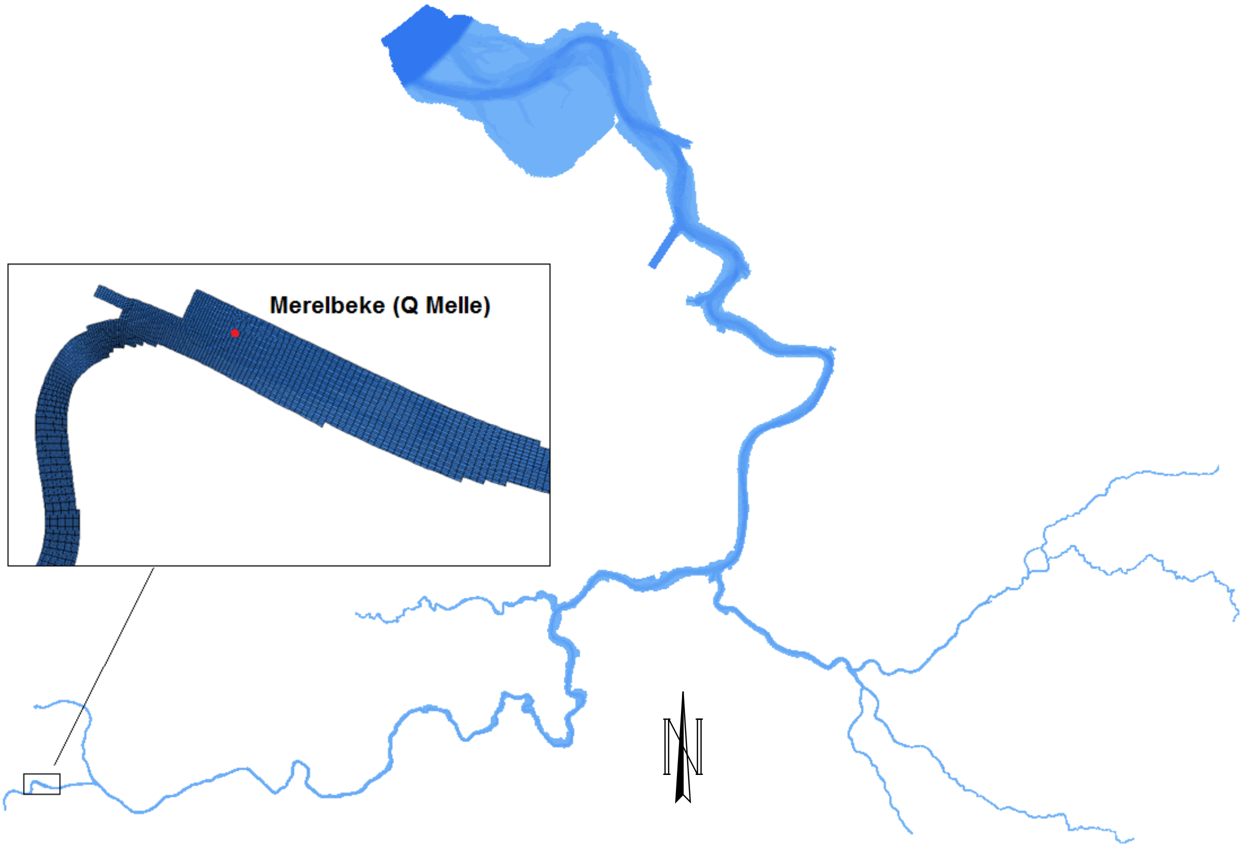


Figure 42 - Location of the discharge point Merelbeke in the model

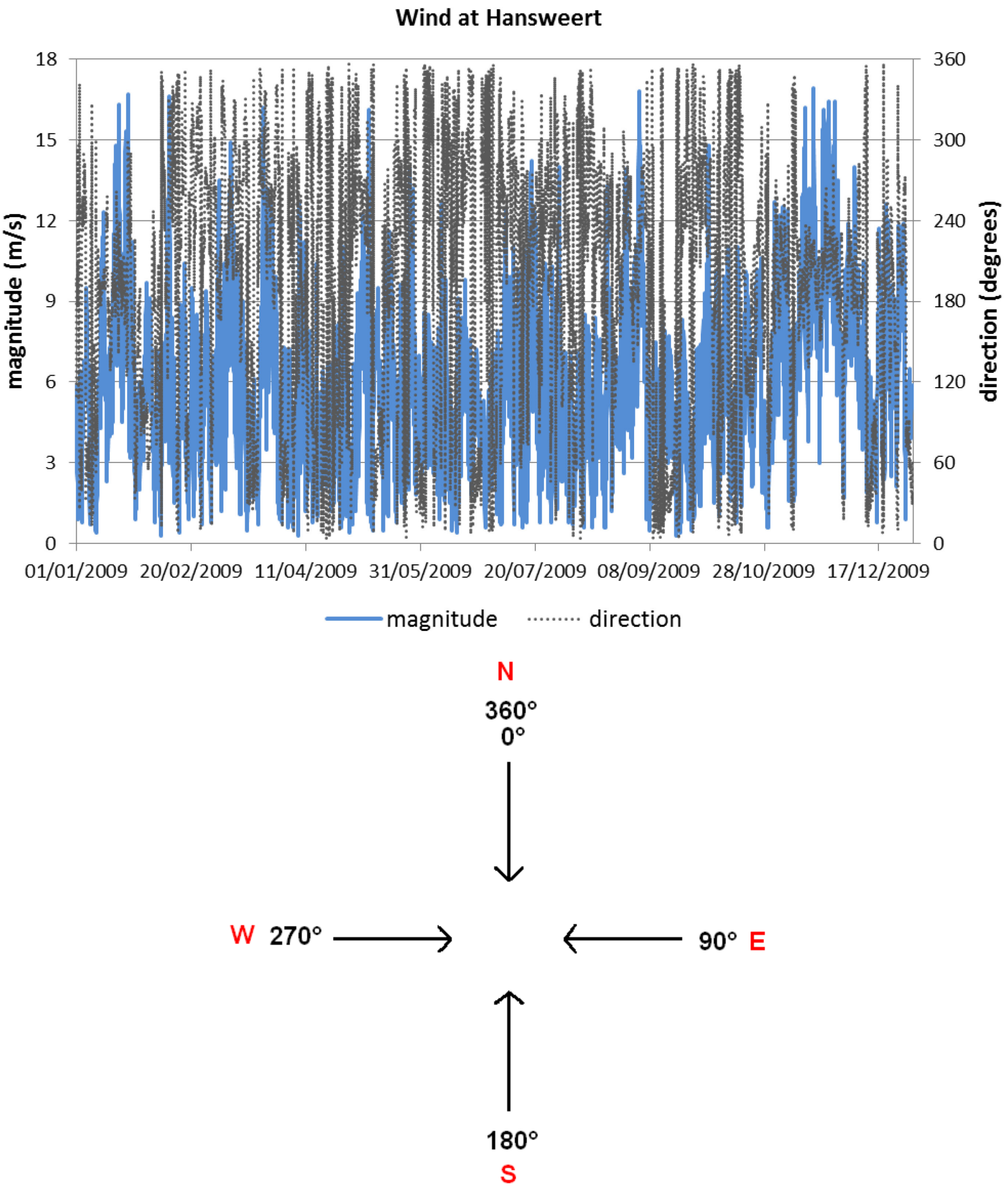


Figure 43 - Wind at Hansweert

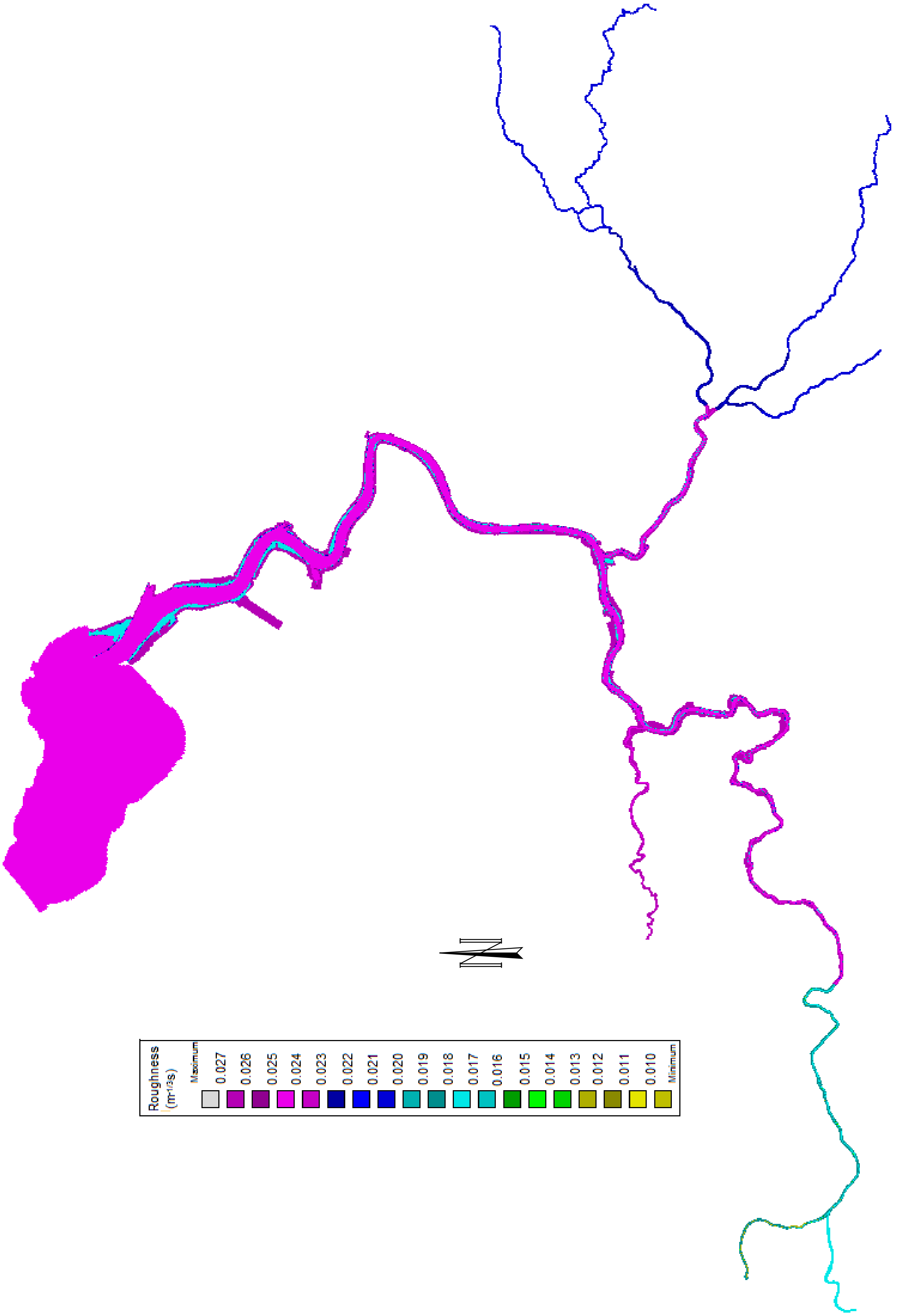


Figure 44 - Roughness field (Manning) used in run simWSenZS_37

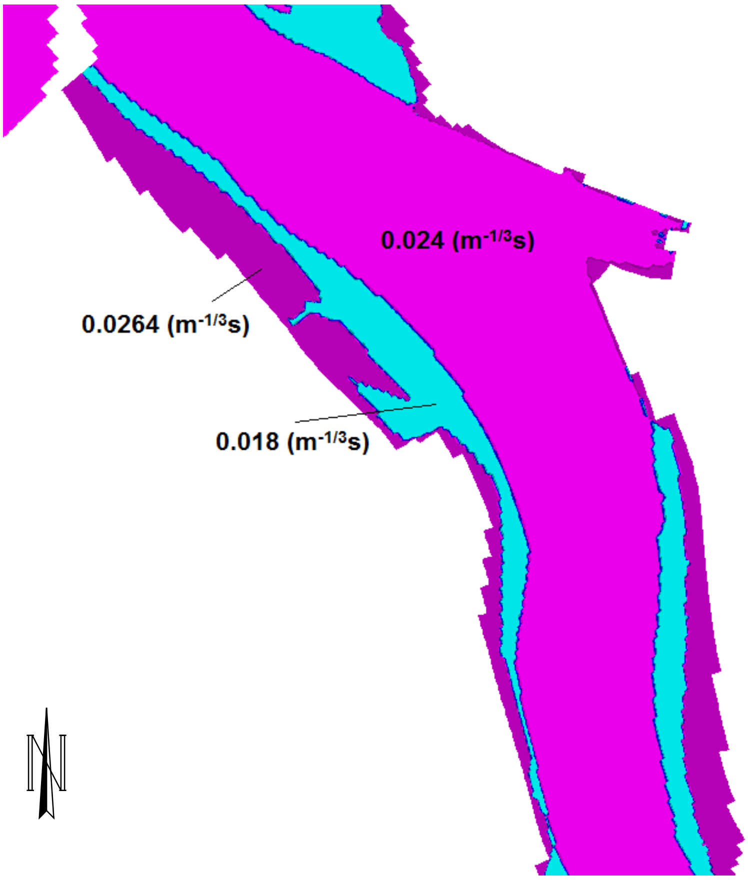


Figure 45 - Roughness field (Manning) at Schaar van Ouden Doel and Galgenschoor

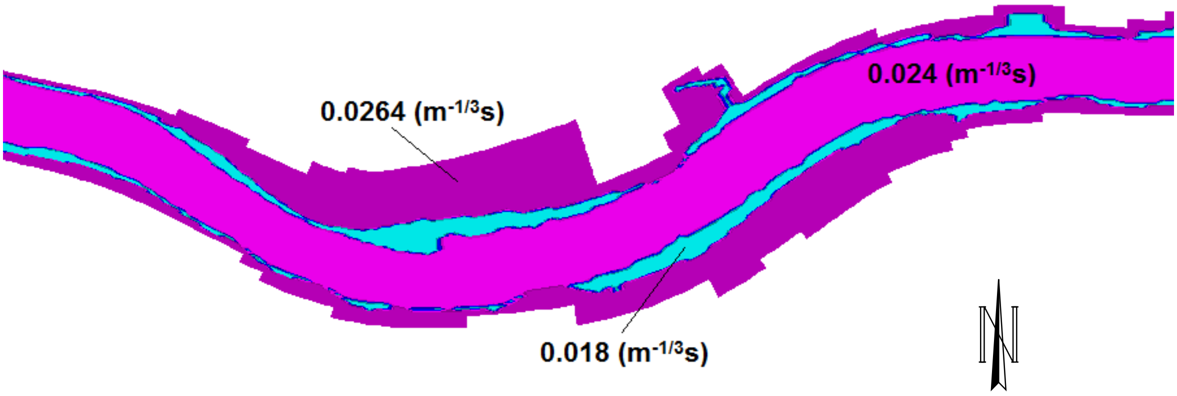


Figure 46 - Roughness field (Manning) at Notelaer and Ballooi

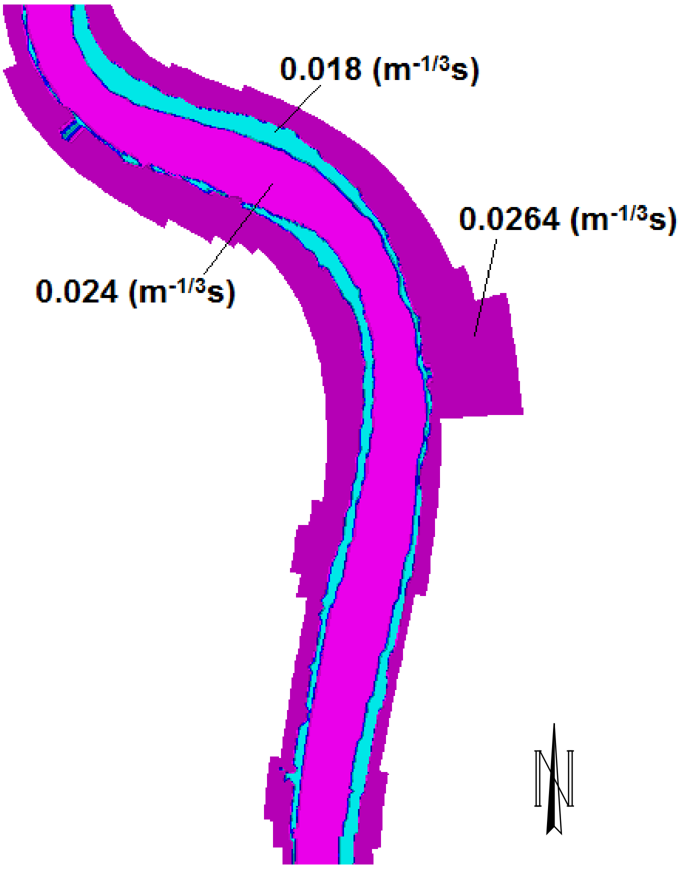


Figure 47 - Roughness field (Manning) at Branst

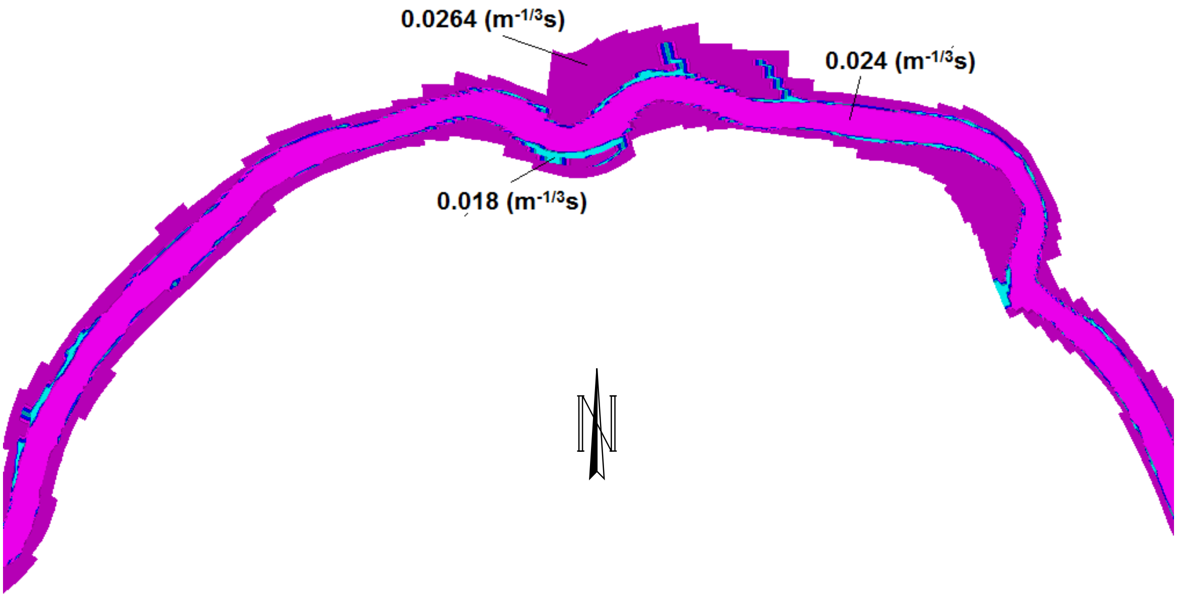


Figure 48 - Roughness field (Manning) at Appels

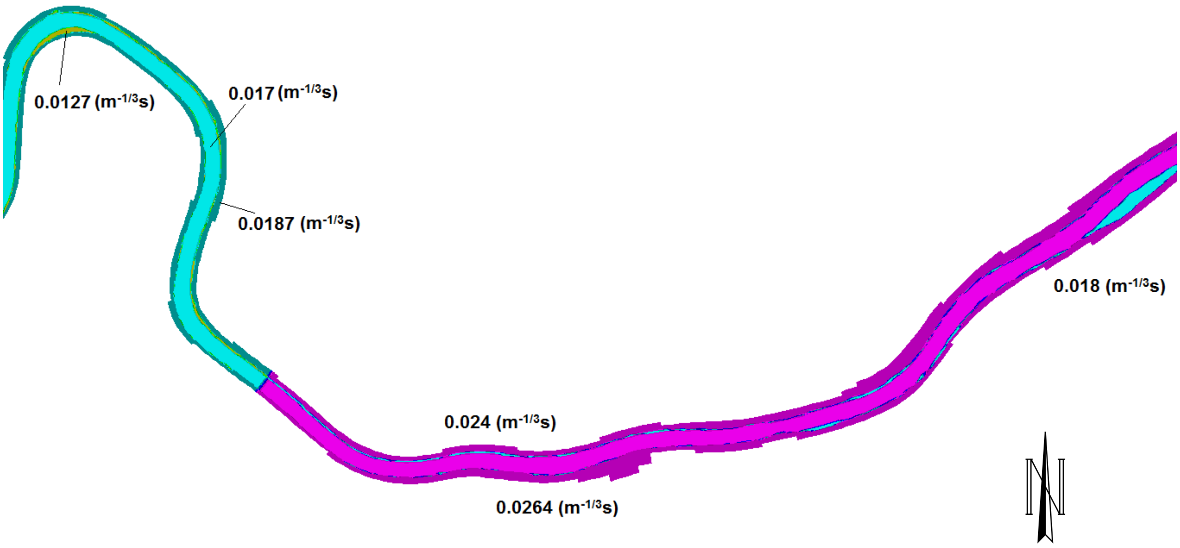


Figure 49 - Roughness field (Manning) at Schoonaarde

Appendix 1. Results of the model calibration

Water levels

Table 22. Statistical parameters for the water level time series (simWSenZS_37 vs. measurements)

Station	Complete Time Series		
	BIAS TS	RMSE TS	RMSE_0 TS
	[m]	[m]	[m]
Baalhoek	0.00	0.05	0.05
Schaar Van De Noord	0.00	0.06	0.06
Bath	0.02	0.06	0.06
Zandvliet	-0.02	0.12	0.12
Liefkenshoek	0.00	0.06	0.06
Boudewijnsluis	-0.04	0.12	0.12
Kallosluis	0.04	0.06	0.05
Antwerpen	0.03	0.06	0.05
Schelle	-0.12	0.17	0.12
Tielrode	-0.09	0.13	0.10
StAmands	-0.01	0.11	0.11
Dendermonde	-0.07	0.15	0.13
Schoonaarde	-0.09	0.13	0.09
Wetteren	-0.06	0.13	0.12
Melle	-0.02	0.16	0.16
Boom	-0.07	0.14	0.12
Walem	-0.05	0.10	0.09
Duffel-sluis	-0.08	0.12	0.09
Lier Maasfort	-0.11	0.14	0.09
Lier Molbrug	-0.12	0.14	0.06
Mechelen sluis	0.14	0.32	0.29
Hombeek	0.08	0.14	0.12
Total	-0.03	0.13	0.11

Table 23. Statistical parameters for high waters (simWSenZS_37 vs. measurements)

Station	HW					
	BIAS HW	RMSE HW	RMSE_0 HW	BIAS HW	RMSE HW	RMSE_0 HW
	[m]	[m]	[m]	[min]	[min]	[min]
Baalhoek	-0.03	0.03	0.01	-0.8	2.9	2.8
Schaar Van De Noord	-0.03	0.04	0.01	-1.2	4.3	4.1
Bath	0.02	0.03	0.02	-0.8	6.5	6.4
Zandvliet	0.03	0.03	0.02	-5.4	7.2	4.8
Liefkenshoek	-0.01	0.02	0.02	-0.4	6.3	6.3
Boudewijnsluis	-0.10	0.10	0.02	-2.1	6.6	6.3
Kallosluis	-0.01	0.05	0.05	1.4	5.0	4.8
Antwerpen	0.00	0.02	0.02	5.0	8.4	6.7
Schelle	-0.05	0.06	0.02	-9.1	10.0	4.2
Temse	0.01	0.02	0.02	-7.5	8.9	4.8
Tielrode	-0.05	0.05	0.03	-4.2	6.5	4.9
StAmands	0.04	0.05	0.02	-8.3	10.6	6.6
Dendermonde	0.07	0.07	0.03	-16.2	16.8	4.1
Schoonaarde	-0.05	0.07	0.05	-12.1	12.7	3.8
Wetteren	-0.09	0.12	0.08	-7.9	9.0	4.3
Melle	-0.02	0.10	0.09	-4.5	6.4	4.5
Boom	-0.03	0.04	0.02	-5.8	8.2	5.7
Walem	0.04	0.05	0.03	-2.1	4.8	4.3
Duffel-sluis	0.06	0.07	0.03	-11.2	12.0	4.1
Lier Maasfort	-0.02	0.02	0.01	-10.9	11.5	3.6
Lier Molbrug	-0.12	0.12	0.02	-10.4	10.9	3.2
Mechelen sluis	-0.03	0.04	0.03	-5.9	7.5	4.7
Hombeek	0.05	0.06	0.02	-1.8	4.3	3.9
Zemst	-0.06	0.06	0.03	-2.1	4.2	3.6
Total	-0.02	0.06	0.03	-5.3	8.7	4.8

Table 24. Statistical parameters for low waters (simWSenZS_37 vs. measurements)

Station	LW					
	BIAS LW	RMSE LW	RMSE_0 LW	BIAS LW	RMSE LW	RMSE_0 LW
	[m]	[m]	[m]	[min]	[min]	[min]
Baalhoek	0.03	0.03	0.01	-3.3	6.8	5.9
Schaar Van De Noord	0.02	0.02	0.01	-5.4	7.2	4.8
Bath	0.04	0.04	0.01	-4.2	6.5	4.9
Zandvliet	-0.05	0.05	0.02	-10.9	11.9	4.7
Liefkenshoek	0.03	0.03	0.01	-5.8	7.4	4.5
Boudewijnsluis	0.01	0.03	0.03	-12.7	13.8	5.4
Kallosluis	0.06	0.06	0.01	-5.0	6.6	4.3
Antwerpen	0.05	0.05	0.01	-4.5	6.7	5.0
Schelle	-0.15	0.15	0.01	-10.9	11.1	1.9
Tielrode	-0.06	0.07	0.03	-3.6	6.0	4.8
StAmands	-0.03	0.05	0.03	-8.6	9.2	3.1
Dendermonde	-0.15	0.15	0.05	-5.0	7.1	5.0
Schoonaarde	-0.07	0.09	0.05	-3.3	7.1	6.2
Wetteren	-0.02	0.12	0.11	-0.9	6.0	6.0
Melle	0.03	0.20	0.20	4.6	10.3	9.2
Boom	-0.10	0.10	0.02	-8.6	9.2	3.1
Walem	-0.06	0.07	0.03	-6.8	8.1	4.4
Duffel-sluis	-0.12	0.12	0.03	-7.1	8.3	4.3
Lier Maasfort	-0.23	0.23	0.03	-5.0	6.5	4.1
Lier Molbrug	-0.19	0.19	0.03	-5.8	9.8	7.9
Mechelen sluis	0.46	0.48	0.14	2.3	4.0	3.3
Total	-0.02	0.15	0.06	-5.2	8.3	5.2

Table 25. Harmonic analysis: Amplitude M2

Amplitude M2	Measurement		simWSenZS_37	
WL Station	Value	Error	Value	Error
Baalhoek	2.53	0.01	2.51	0.01
Schaar Van De Noord	2.56	0.01	2.54	0.01
Bath	2.58	0.01	2.56	0.01
Zandvliet	2.57	0.01	2.61	0.01
Liefkenshoek	2.66	0.01	2.65	0.01
Boudewijnsluis	2.71	0.01	2.67	0.01
Kallosluis	2.70	0.01	2.68	0.01
Antwerpen	2.71	0.01	2.70	0.02
Schelle	2.69	0.01	2.74	0.02
Tielrode	2.60	0.02	2.63	0.01
StAmands	2.44	0.01	2.47	0.02
Dendermonde	1.90	0.02	1.98	0.01
Schoonaarde	1.47	0.02	1.50	0.01
Wetteren	1.32	0.02	1.32	0.02
Melle	1.32	0.02	1.29	0.02
Boom	2.62	0.01	2.67	0.01
Walem	2.46	0.01	2.50	0.01
Duffel-sluis	2.02	0.01	2.08	0.01
Lier Maasfort	1.04	0.01	1.14	0.01
Lier Molbrug	1.40	0.01	1.45	0.01
Emblem	0.84	0.01	1.00	0.01
Kessel	0.73	0.01	0.73	0.01
Mechelen sluis	2.29	0.02	2.00	0.01
Hombeek	1.78	0.01	1.64	0.01

Table 26. Harmonic analysis: Phase M2

Phase M2	Measurement		simWSenZS_37	
WL Station	Value	Error	Value	Error
Baalhoek	91.0	0.3	89.7	0.3
Schaar Van De Noord	93.7	0.3	92.3	0.3
Bath	95.9	0.3	94.4	0.3
Zandvliet	100.7	0.3	97.4	0.3
Liefkenshoek	101.1	0.3	99.7	0.3
Boudewijnsluis	104.3	0.3	101.4	0.3
Kallosluis	103.3	0.3	102.8	0.3
Antwerpen	110.1	0.3	109.3	0.3
Schelle	124.6	0.4	121.5	0.3
Tielrode	134.9	0.3	132.4	0.3
StAmands	140.9	0.3	138.4	0.4
Dendermonde	161.9	0.5	158.5	0.4
Schoonaarde	186.8	0.6	185.1	0.6
Wetteren	212.6	1.0	212.8	0.7
Melle	225.0	1.0	224.5	0.8
Boom	132.8	0.4	129.8	0.3
Walem	140.3	0.3	138.1	0.3
Duffel-sluis	158.7	0.3	156.9	0.3
Lier Maasfort	190.1	0.5	190.4	0.5
Lier Molbrug	174.7	0.4	174.2	0.4
Emblem	201.9	0.5	203.6	0.4
Kessel	215.0	0.5	221.2	0.6
Mechelen sluis	149.4	0.3	155.5	0.3
Hombeek	155.5	0.4	157.5	0.4

Table 27. Harmonic analysis: Amplitude M4

Amplitude M4	Measurement		simWSenZS_37	
WL Station	Value	Error	Value	Error
Baalhoek	0.20	0.01	0.20	0.01
Schaar Van De Noord	0.20	0.01	0.19	0.01
Bath	0.19	0.01	0.19	0.01
Zandvliet	0.19	0.01	0.18	0.02
Liefkenshoek	0.19	0.01	0.19	0.01
Boudewijnsluis	0.20	0.01	0.18	0.01
Kallosluis	0.20	0.01	0.18	0.02
Antwerpen	0.20	0.02	0.19	0.01
Schelle	0.21	0.01	0.20	0.01
Tielrode	0.32	0.02	0.33	0.02
StAmands	0.38	0.02	0.38	0.02
Dendermonde	0.36	0.02	0.41	0.02
Schoonaarde	0.34	0.02	0.36	0.02
Wetteren	0.29	0.02	0.32	0.02
Melle	0.29	0.02	0.34	0.02
Boom	0.28	0.01	0.27	0.01
Walem	0.35	0.01	0.35	0.01
Duffel-sluis	0.49	0.01	0.53	0.01
Lier Maasfort	0.40	0.01	0.44	0.01
Lier Molbrug	0.50	0.01	0.51	0.01
Emblem	0.35	0.01	0.40	0.01
Kessel	0.31	0.01	0.30	0.01
Mechelen sluis	0.45	0.02	0.53	0.01
Hombeek	0.57	0.01	0.62	0.01

Table 28. Harmonic analysis: Phase M4

Phase M4	Measurement		simWSenZS_37	
WL Station	Value	Error	Value	Error
Baalhoek	181.3	3.5	180.9	3.6
Schaar Van De Noord	183.3	3.9	185.7	3.8
Bath	179.1	4.2	182.0	4.4
Zandvliet	183.6	4.2	182.6	3.8
Liefkenshoek	182.5	4.3	185.5	4.2
Boudewijnsluis	184.3	4.2	184.5	5.3
Kallosluis	186.5	3.9	184.4	4.1
Antwerpen	194.8	4.2	195.1	4.3
Schelle	212.2	4.0	209.3	4.4
Tielrode	223.9	3.0	220.3	2.5
StAmands	235.6	2.6	229.4	2.2
Dendermonde	264.4	2.5	258.0	2.2
Schoonaarde	299.4	2.6	299.3	2.5
Wetteren	347.9	4.2	350.9	3.1
Melle	17.9	4.7	16.2	3.1
Boom	219.0	3.1	215.0	3.1
Walem	230.9	2.4	229.6	2.3
Duffel-sluis	263.5	1.5	260.3	1.2
Lier Maasfort	321.5	1.3	317.2	1.2
Lier Molbrug	298.3	1.2	294.0	1.1
Emblem	344.7	1.1	343.2	1.3
Kessel	11.1	1.3	13.9	1.5
Mechelen sluis	254.4	2.2	259.7	1.4
Hombeek	288.6	1.2	289.5	1.1

Table 29. Harmonic analysis: Amplitude M6

Amplitude M6	Measurement		simWSenZS_37	
WL Station	Value	Error	Value	Error
Baalhoek	0.24	0.01	0.24	0.02
Schaar Van De Noord	0.26	0.01	0.26	0.01
Bath	0.26	0.01	0.27	0.01
Zandvliet	0.28	0.01	0.29	0.01
Liefkenshoek	0.31	0.01	0.30	0.01
Boudewijnsluis	0.31	0.02	0.30	0.01
Kallosluis	0.31	0.01	0.30	0.02
Antwerpen	0.30	0.01	0.28	0.01
Schelle	0.31	0.02	0.30	0.02
Tielrode	0.31	0.02	0.28	0.02
StAmands	0.27	0.02	0.26	0.01
Dendermonde	0.20	0.02	0.19	0.01
Schoonaarde	0.12	0.02	0.13	0.01
Wetteren	0.07	0.02	0.09	0.02
Melle	0.08	0.02	0.10	0.02
Boom	0.28	0.02	0.27	0.02
Walem	0.23	0.02	0.23	0.01
Duffel-sluis	0.15	0.01	0.15	0.01
Lier Maasfort	0.16	0.01	0.18	0.01
Lier Molbrug	0.17	0.01	0.17	0.01
Emblem	0.17	0.01	0.19	0.01
Kessel	0.14	0.01	0.15	0.01
Mechelen sluis	0.14	0.02	0.18	0.01
Hombeek	0.22	0.01	0.25	0.01

Table 30. Harmonic analysis: Phase M6

Phase M6	Measurement		simWSenZS_37	
WL Station	Value	Error	Value	Error
Baalhoek	243.0	3.2	238.1	3.1
Schaar Van De Noord	254.3	3.1	249.5	2.9
Bath	258.9	2.8	255.6	2.7
Zandvliet	278.9	3.1	268.1	2.9
Liefkenshoek	285.2	2.7	279.0	2.9
Boudewijnsluis	294.6	2.8	283.8	3.1
Kallosluis	295.3	2.6	289.0	2.9
Antwerpen	321.7	2.9	316.4	2.9
Schelle	16.1	2.7	6.1	2.9
Tielrode	48.2	2.9	39.6	2.8
StAmands	62.0	3.7	53.5	3.5
Dendermonde	105.5	4.8	87.8	4.9
Schoonaarde	133.5	8.2	114.5	5.9
Wetteren	189.8	20.0	171.4	10.4
Melle	236.5	18.0	211.0	10.4
Boom	39.1	3.1	30.4	3.2
Walem	56.8	3.7	51.6	3.2
Duffel-sluis	74.2	5.3	56.7	5.4
Lier Maasfort	96.1	3.2	87.5	3.0
Lier Molbrug	67.3	3.6	58.5	3.9
Emblem	126.2	2.6	119.2	2.5
Kessel	163.1	2.8	160.8	3.2
Mechelen sluis	63.6	6.8	41.1	4.2
Hombeek	43.1	3.5	46.1	2.8

Table 31. Harmonic analysis: Amplitude K1

Amplitude K1	Measurement		simWSenZS_37	
WL Station	Value	Error	Value	Error
Baalhoek	0.13	0.01	0.13	0.01
Schaar Van De Noord	0.13	0.01	0.13	0.01
Bath	0.13	0.01	0.13	0.01
Zandvliet	0.13	0.01	0.13	0.01
Liefkenshoek	0.13	0.01	0.14	0.01
Boudewijnsluis	0.13	0.01	0.14	0.01
Kallosluis	0.14	0.01	0.14	0.01
Antwerpen	0.14	0.01	0.14	0.01
Schelle	0.13	0.01	0.14	0.01
Tielrode	0.12	0.01	0.12	0.01
StAmands	0.11	0.01	0.12	0.01
Dendermonde	0.12	0.01	0.10	0.01
Schoonaarde	0.11	0.01	0.08	0.01
Wetteren	0.13	0.02	0.08	0.01
Melle	0.12	0.02	0.08	0.02
Boom	0.13	0.01	0.13	0.01
Walem	0.12	0.01	0.12	0.01
Duffel-sluis	0.11	0.01	0.10	0.01
Lier Maasfort	0.07	0.01	0.05	0.01
Lier Molbrug	0.10	0.01	0.06	0.01
Emblem	0.04	0.01	0.04	0.01
Kessel	0.06	0.01	0.03	0.01
Mechelen sluis	0.15	0.01	0.08	0.01
Hombeek	0.07	0.01	0.04	0.01

Table 32. Harmonic analysis: Phase K1

Phase K1	Measurement		simWSenZS_37	
WL Station	Value	Error	Value	Error
Baalhoek	6.3	5.7	6.3	5.5
Schaar Van De Noord	7.9	5.5	8.7	4.9
Bath	8.4	4.9	9.4	5.3
Zandvliet	14.8	5.6	12.8	4.5
Liefkenshoek	15.9	5.4	15.2	4.9
Boudewijnsluis	17.7	5.8	16.1	5.3
Kallosluis	18.7	6.2	17.2	5.7
Antwerpen	25.4	5.7	23.6	5.4
Schelle	37.4	5.2	32.9	5.0
Tielrode	47.1	6.9	40.9	5.8
StAmands	51.4	6.9	44.9	6.8
Dendermonde	49.7	6.1	57.4	7.7
Schoonaarde	78.9	8.1	73.5	9.5
Wetteren	93.2	8.3	88.7	10.7
Melle	85.0	9.5	94.9	13.3
Boom	42.5	7.2	38.4	5.7
Walem	47.1	7.1	43.8	5.5
Duffel-sluis	56.5	5.8	52.7	7.7
Lier Maasfort	42.4	5.9	51.3	9.8
Lier Molbrug	44.6	4.8	50.2	9.5
Emblem	47.7	8.9	52.3	11.4
Kessel	32.0	5.0	49.7	12.5
Mechelen sluis	41.0	5.5	48.6	7.7
Hombeek	19.1	9.4	35.0	16.2

Table 33. Vector differences of model results vs. measurements

Vector differences of model results vs measurements	simWSenZS_37
WL Station	Vector difference [m]
Baalhoek	0.09
Schaar Van De Noord	0.11
Bath	0.12
Zandvliet	0.24
Liefkenshoek	0.12
Boudewijnsluis	0.26
Kallosluis	0.13
Antwerpen	0.12
Schelle	0.35
Tielrode	0.29
StAmands	0.22
Dendermonde	0.36
Schoonaarde	0.24
Wetteren	0.18
Melle	0.20
Boom	0.29
Walem	0.19
Duffel-sluis	0.27
Lier Maasfort	0.31
Lier Molbrug	0.28
Emblem	0.40
Kessel	0.18
Mechelen sluis	0.73
Hombeek	0.34
Total vector difference of model results vs. measurements	0.25

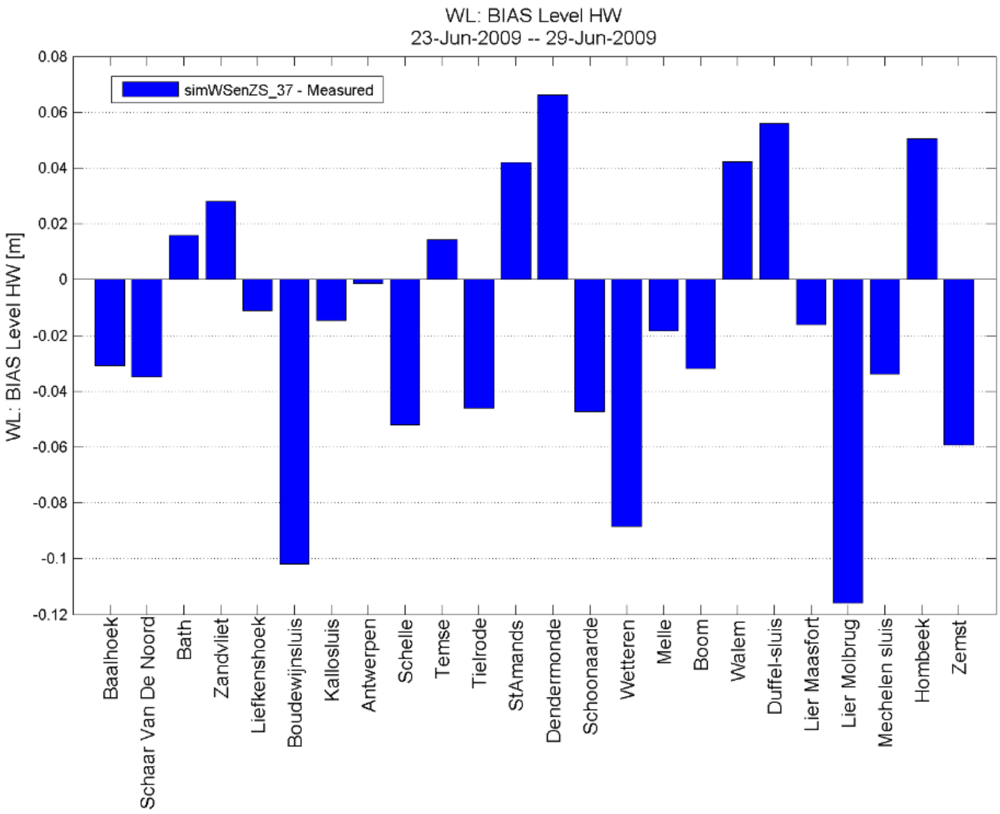


Figure 50 - Bias of high water magnitude (model – measurement)

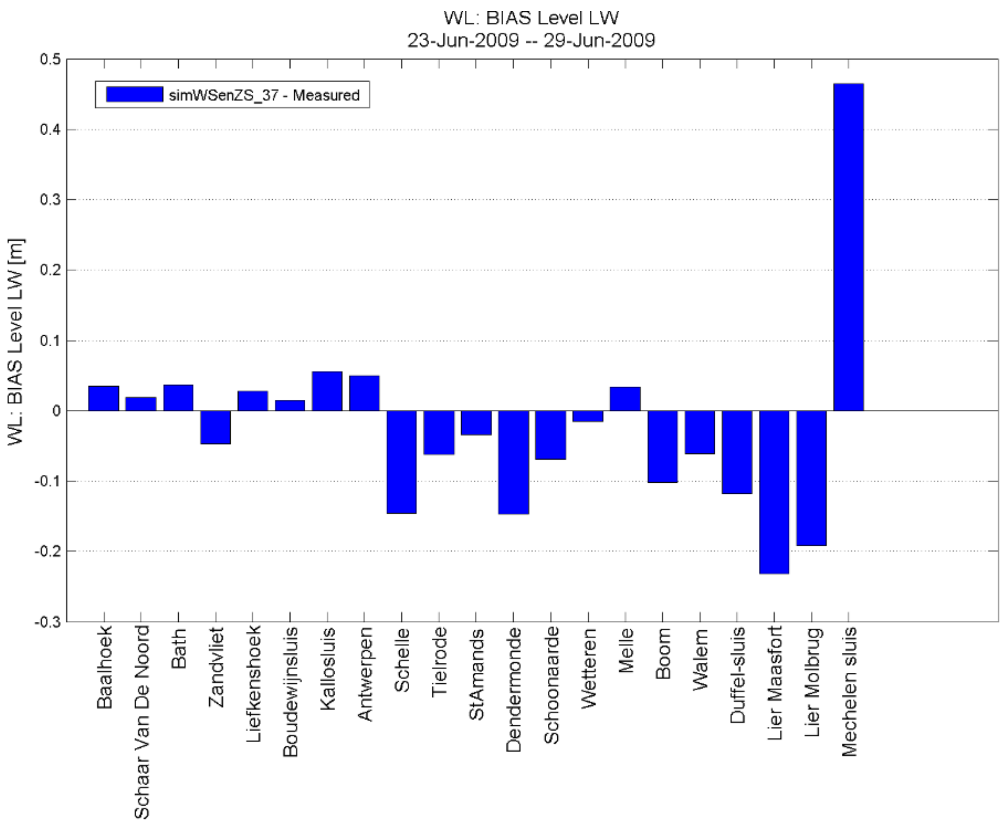


Figure 51 - Bias of low water magnitude (model – measurement)

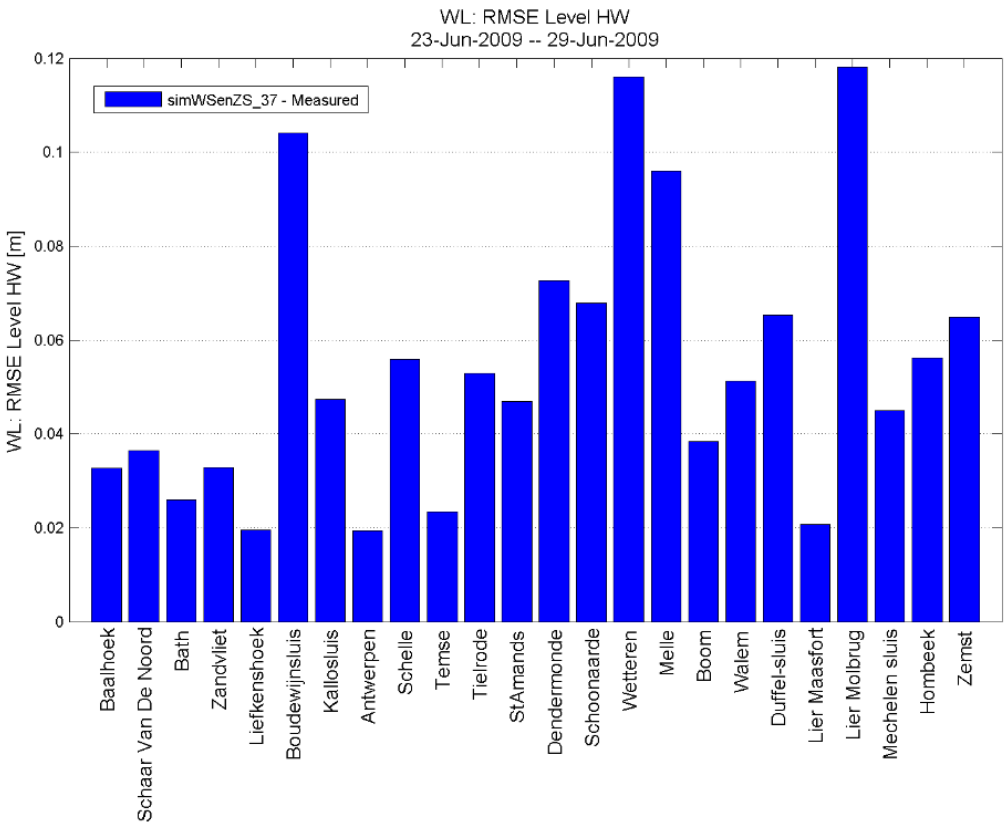


Figure 52 - RMSE of high water magnitude (model vs. measurement)

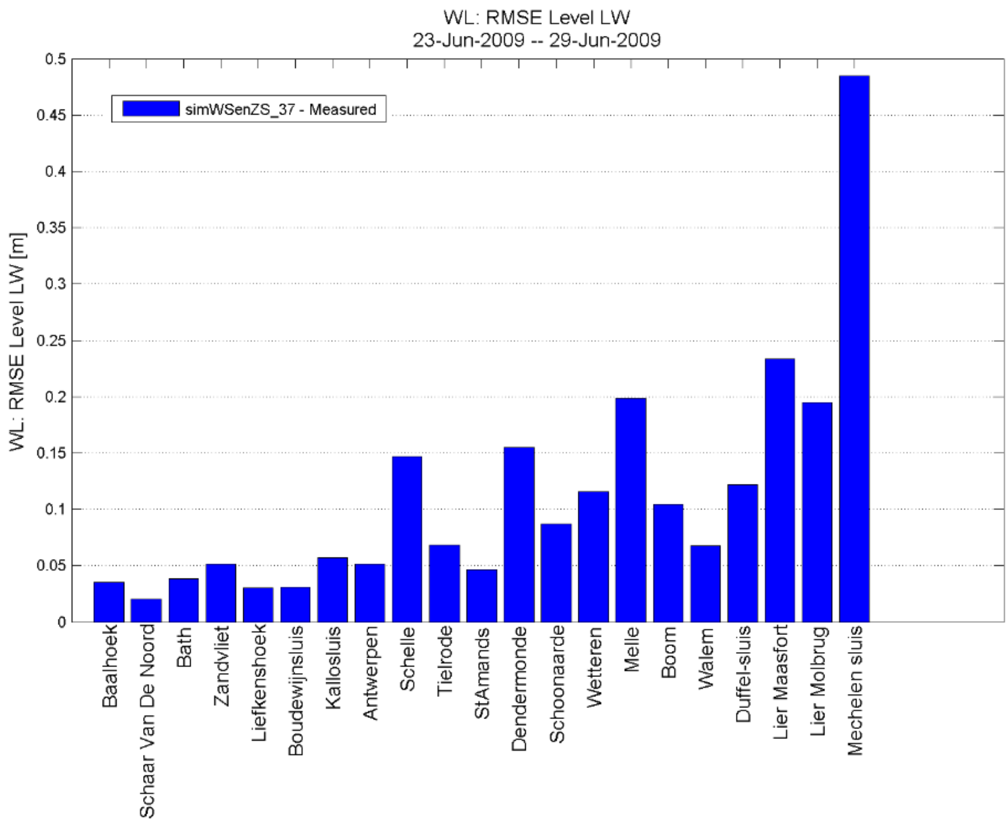


Figure 53 - RMSE of low water magnitude (model vs. measurement)

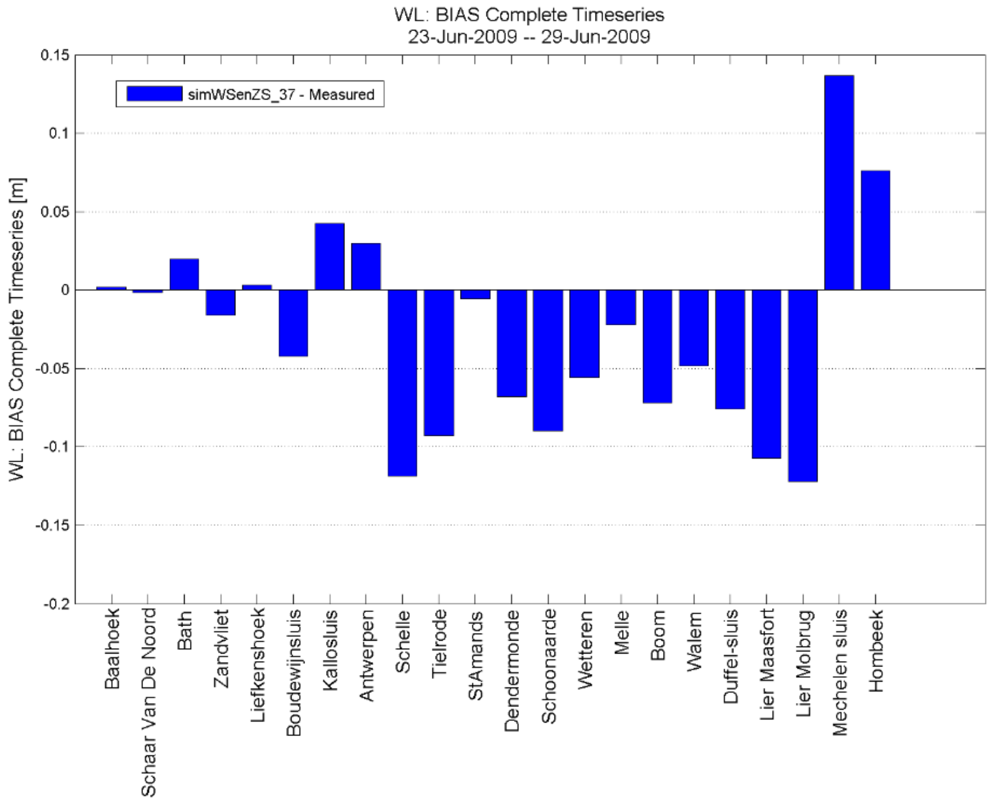


Figure 54 - Bias of the water level time series

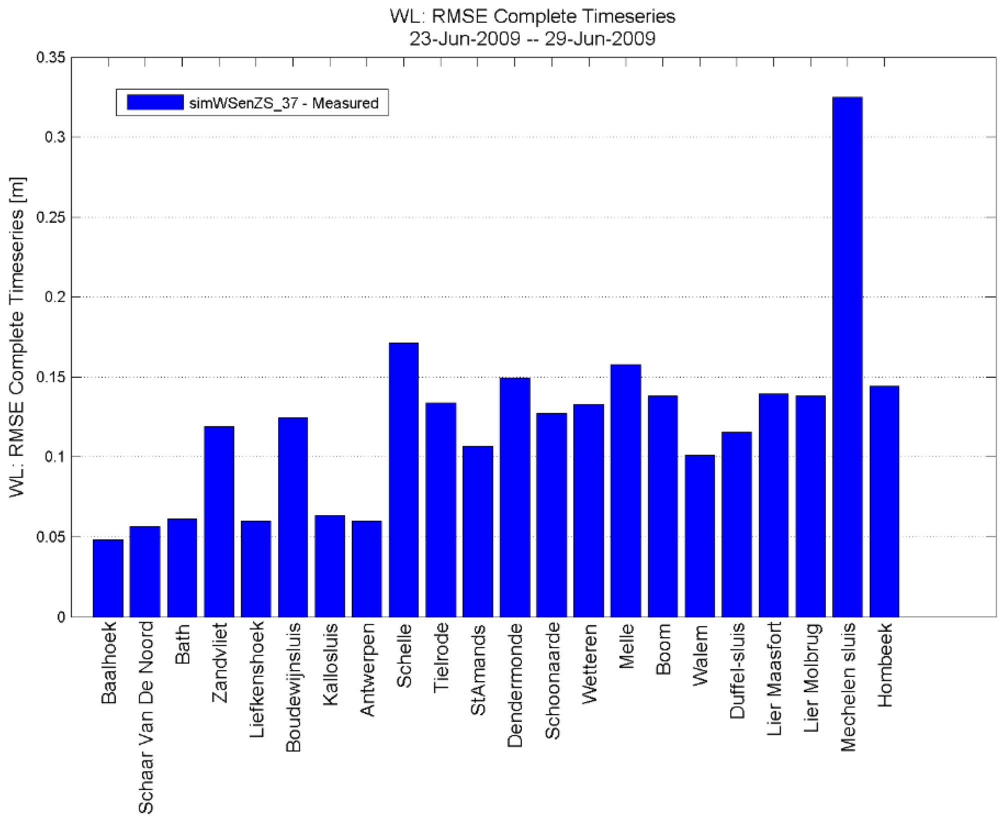


Figure 55 - RMSE of the water level time series

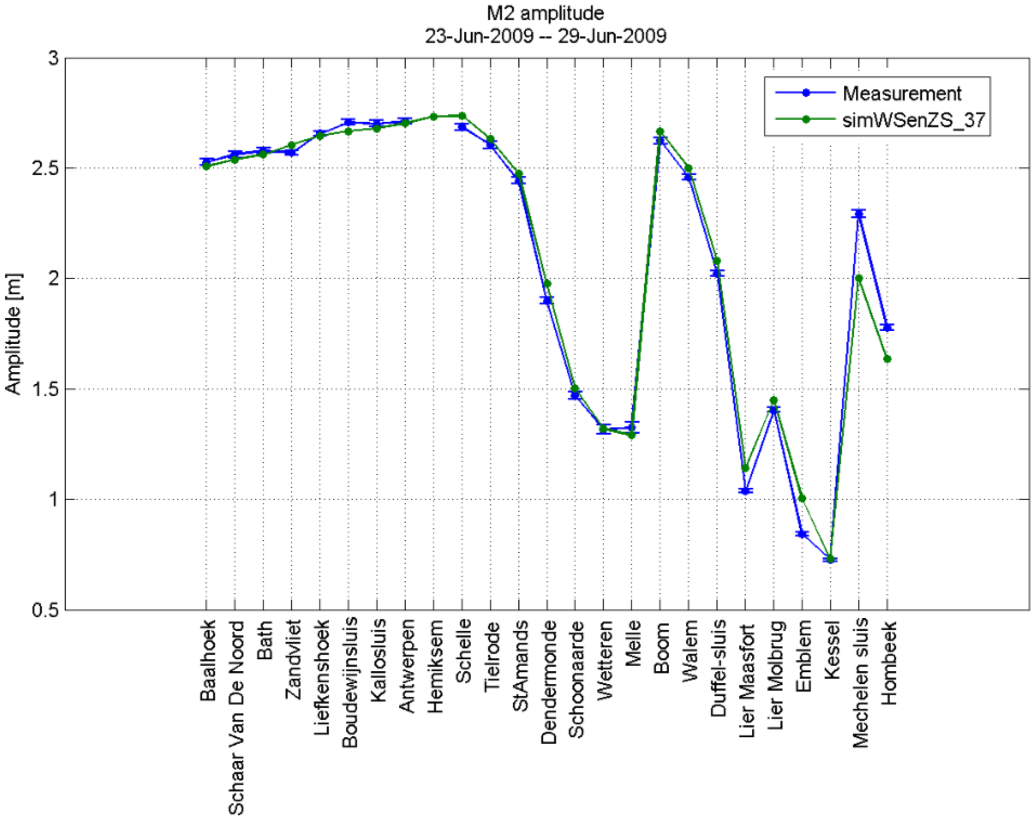


Figure 56 - M2 amplitude

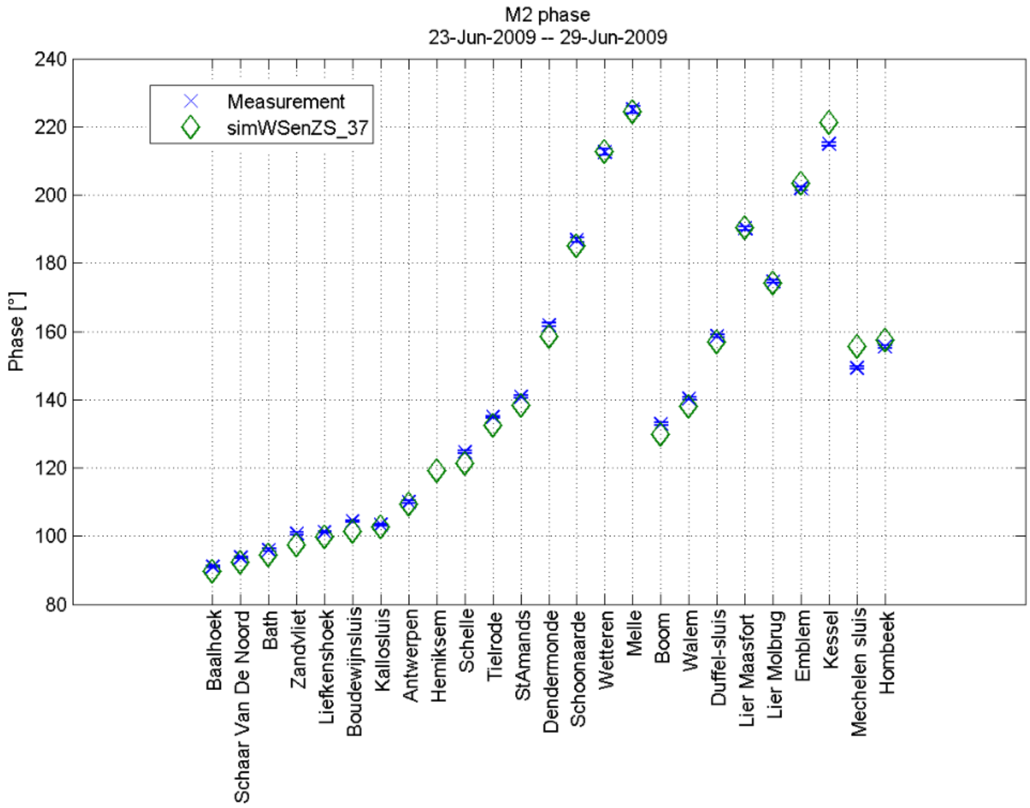


Figure 57 - M2 phase

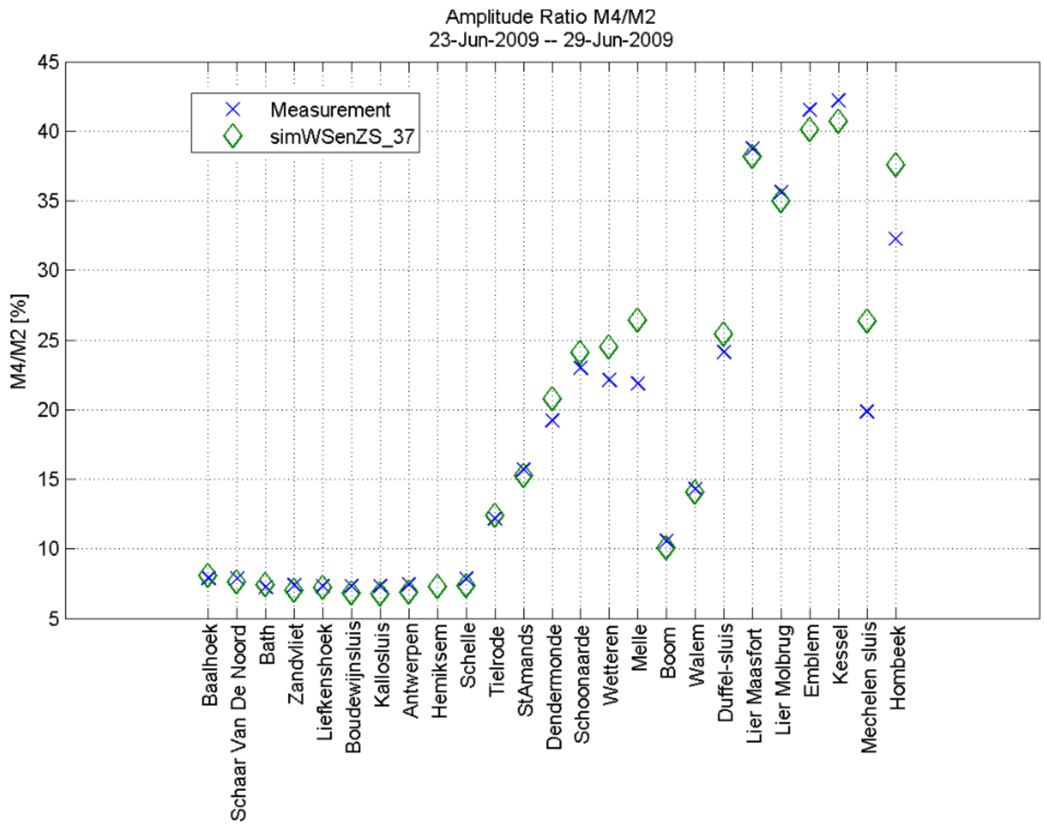


Figure 58 – Amplitude ratio M4/M2

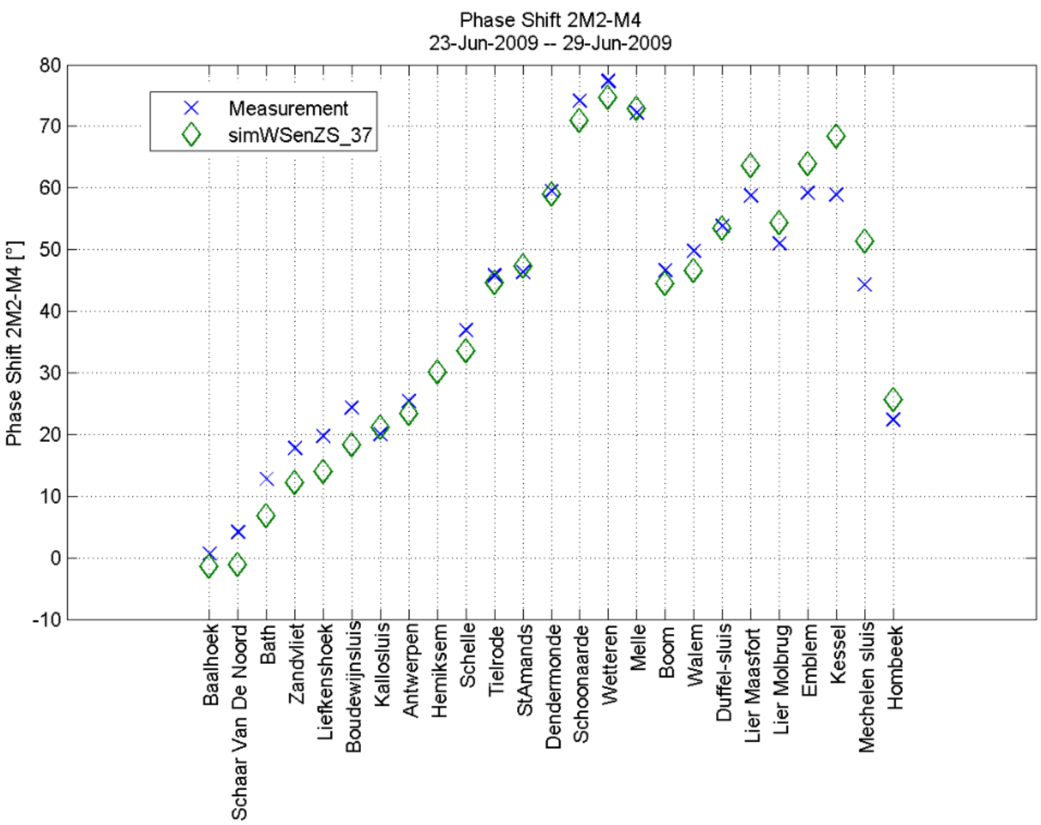


Figure 59 – Phase shift 2M2-M4

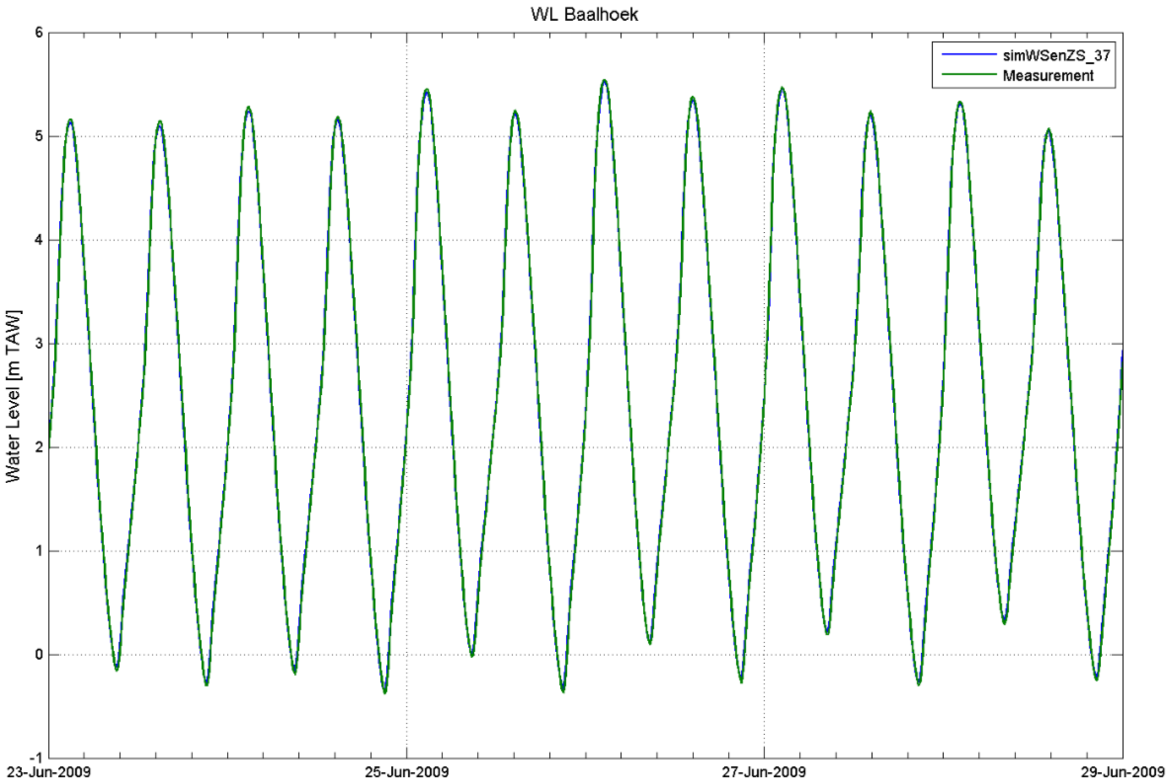


Figure 60 - Calculated and measured water levels at Baalhoek

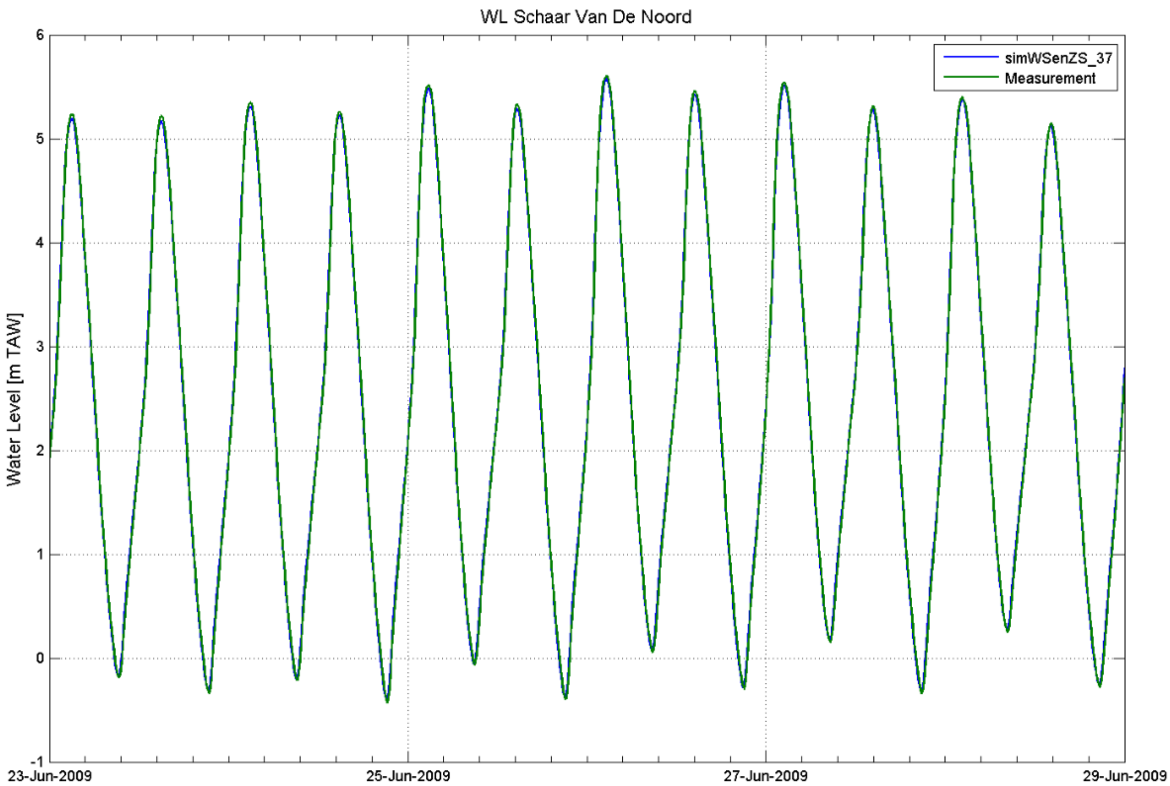


Figure 61 - Calculated and measured water levels at Schaar van de Noord

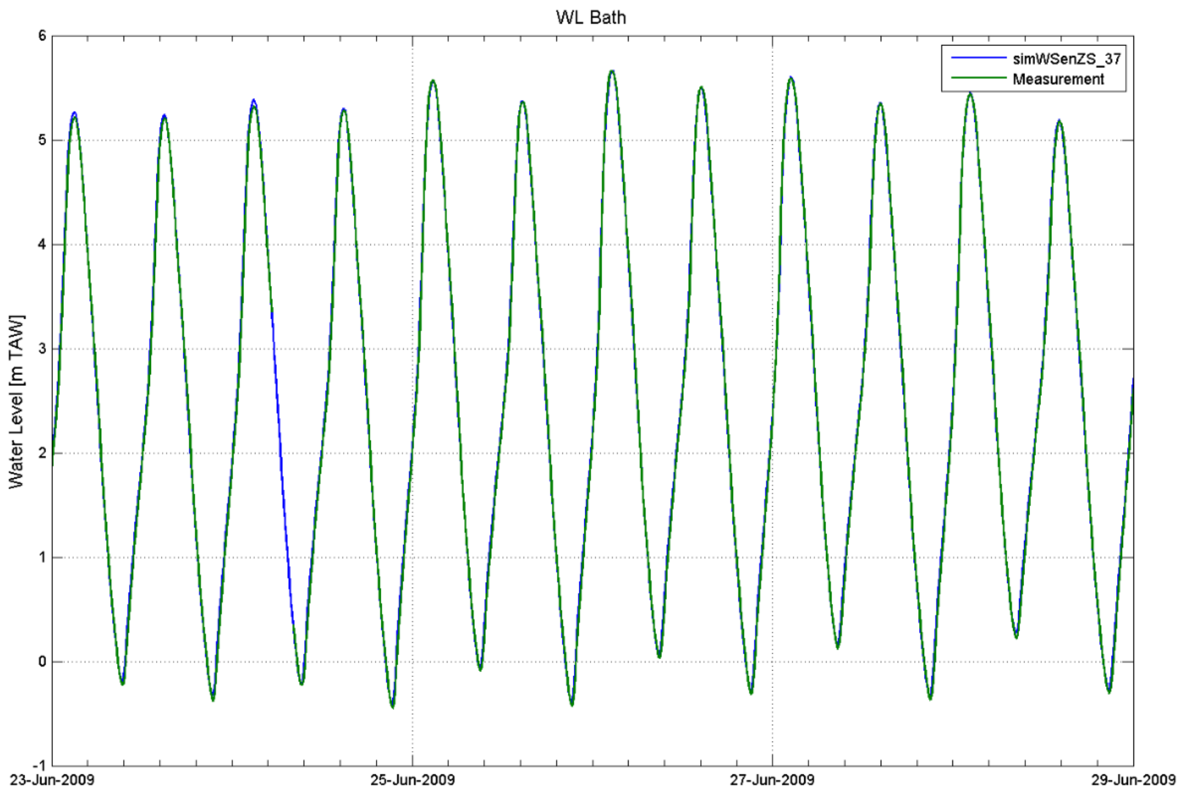


Figure 62 - Calculated and measured water levels at Bath

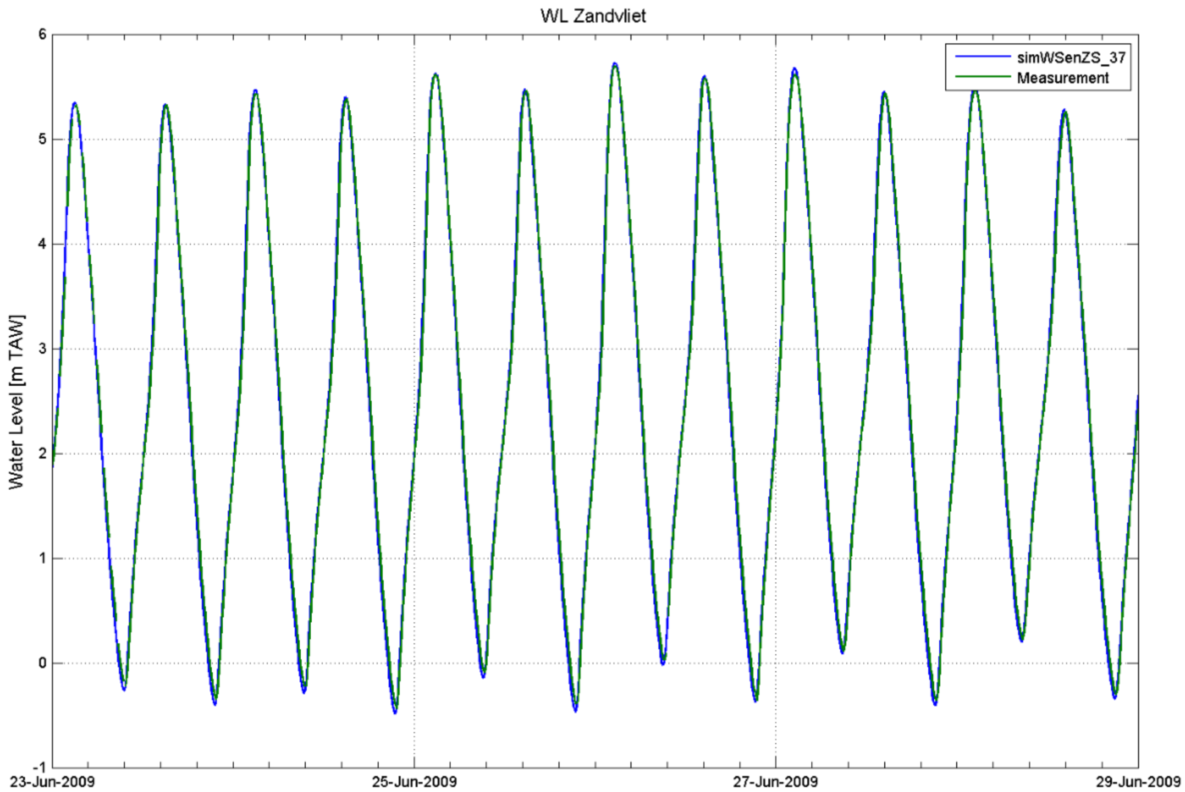


Figure 63 - Calculated and measured water levels at Zandvliet

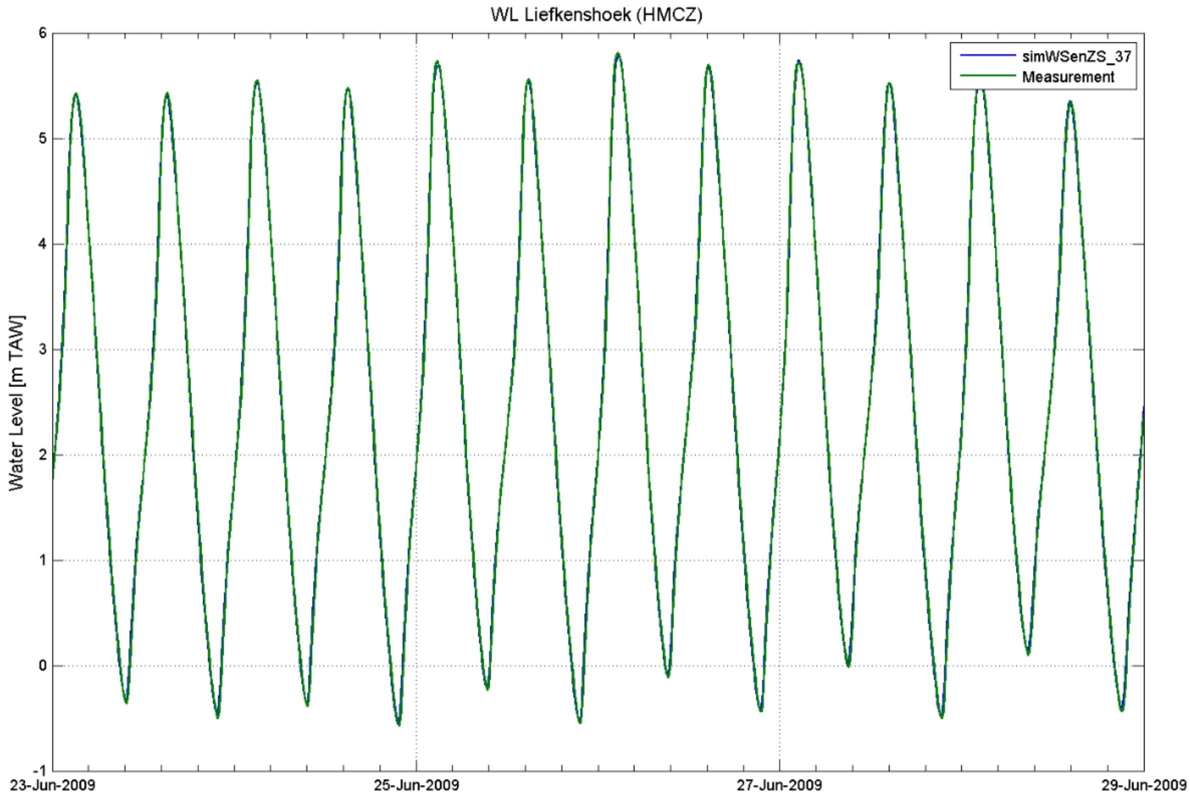


Figure 64 - Calculated and measured water levels at Liefkenshoek

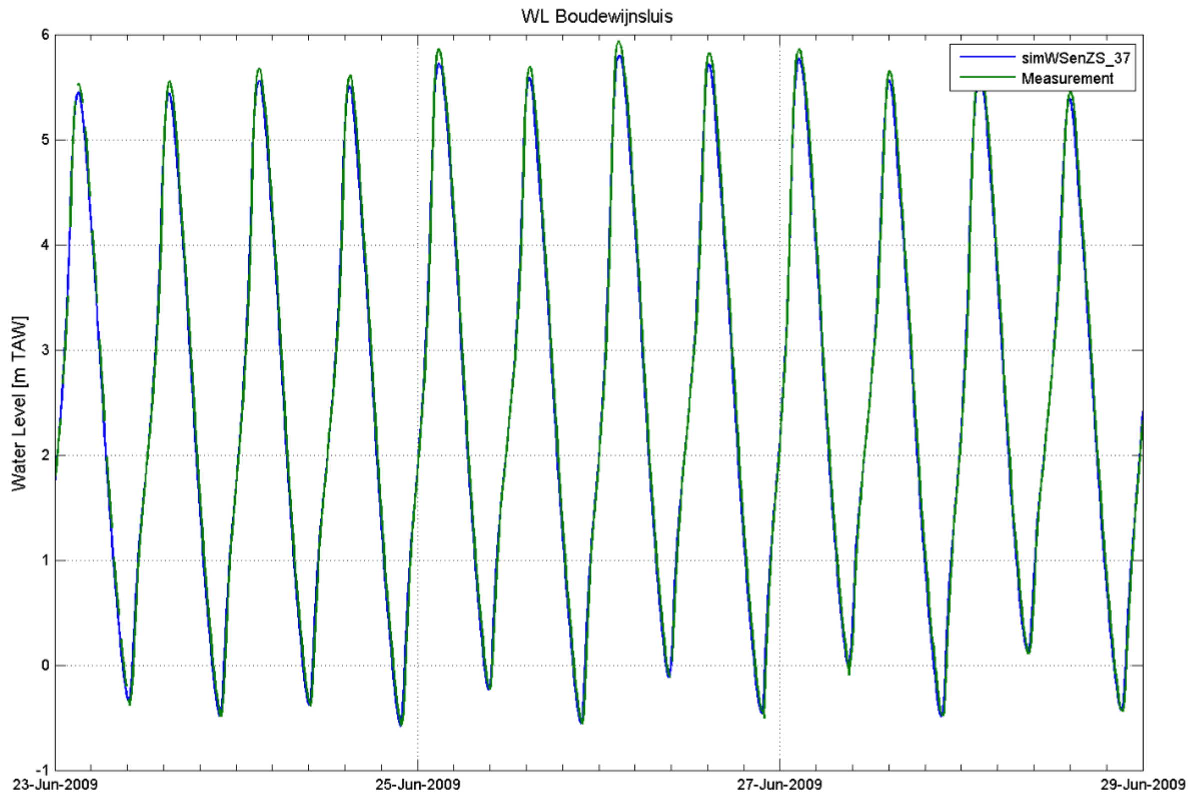


Figure 65 - Calculated and measured water levels at Boudewijn lock

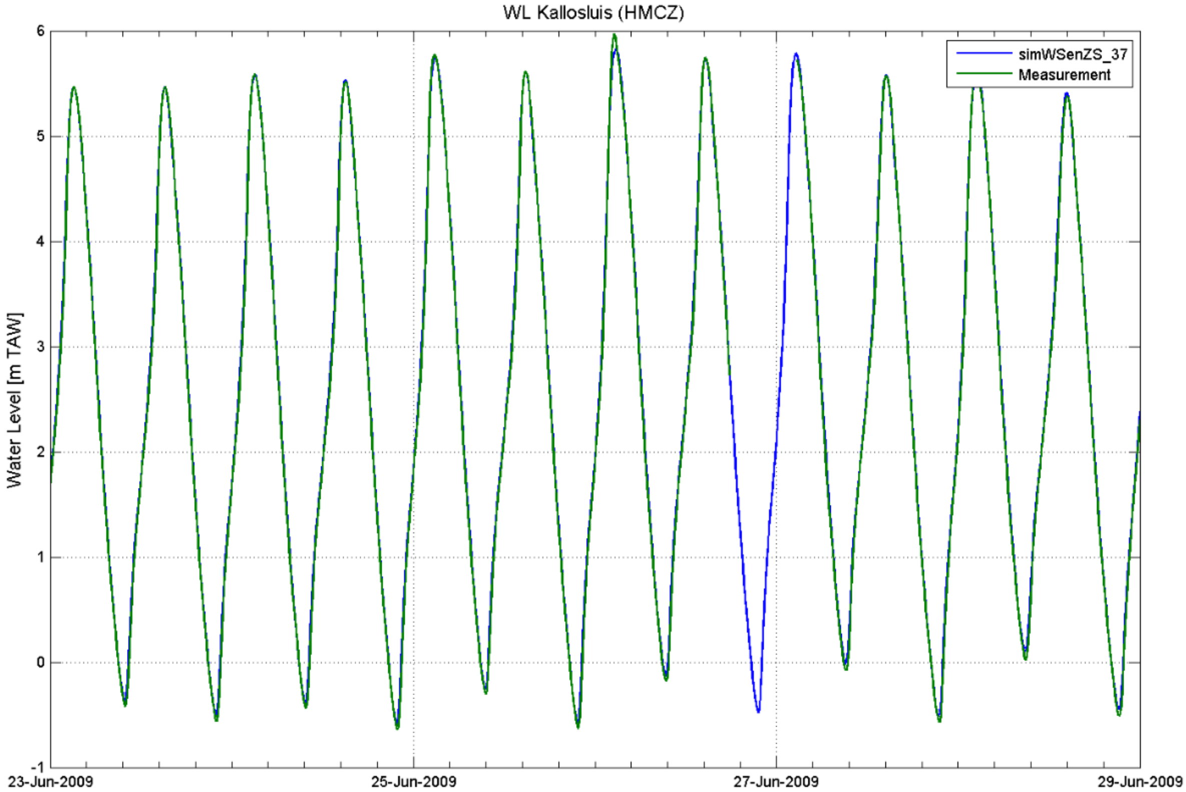


Figure 66 - Calculated and measured water levels at Kallo lock

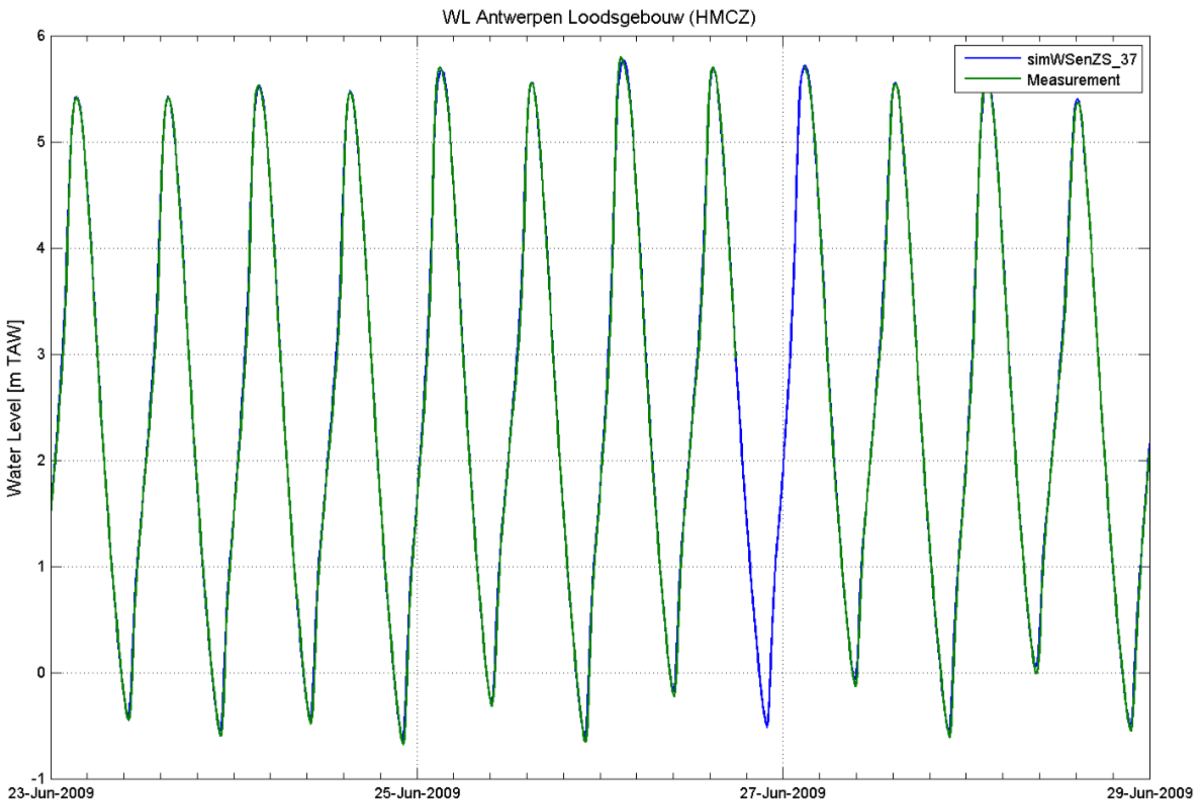


Figure 67 - Calculated and measured water levels at Antwerp

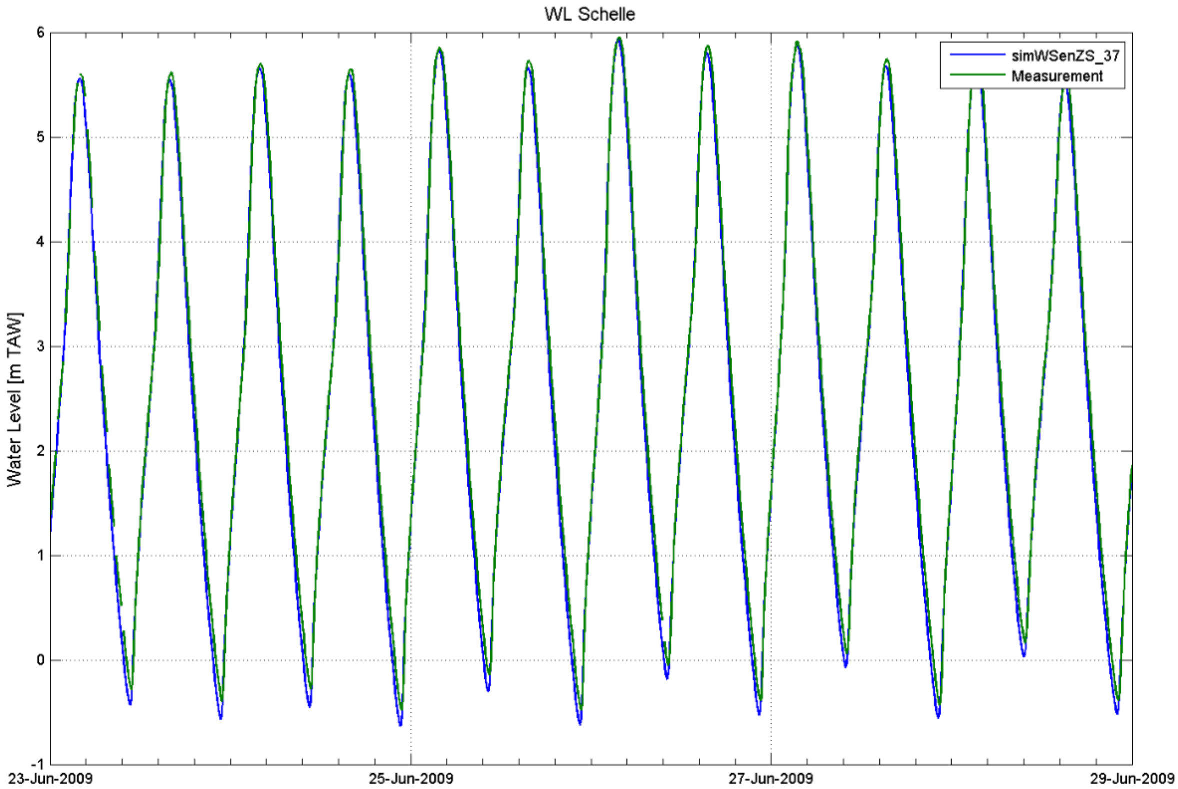


Figure 68 - Calculated and measured water levels at Schelle

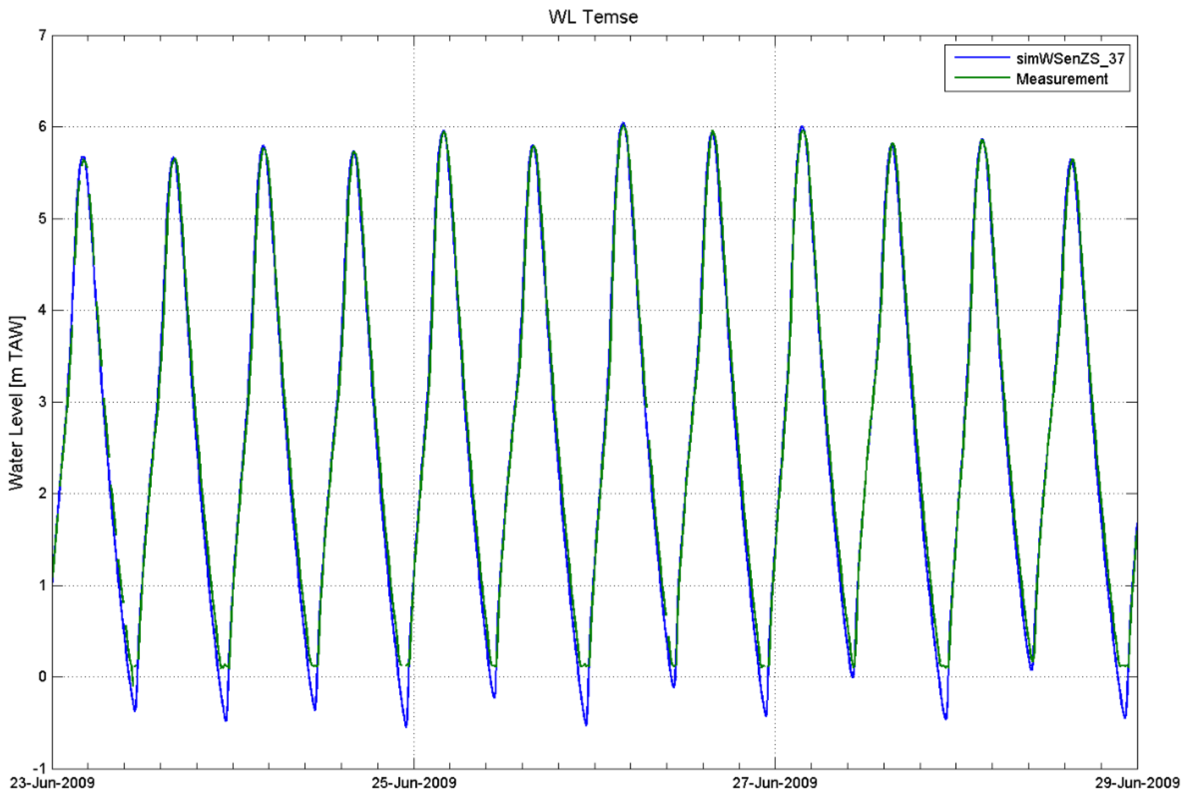


Figure 69 - Calculated and measured water levels at Temse

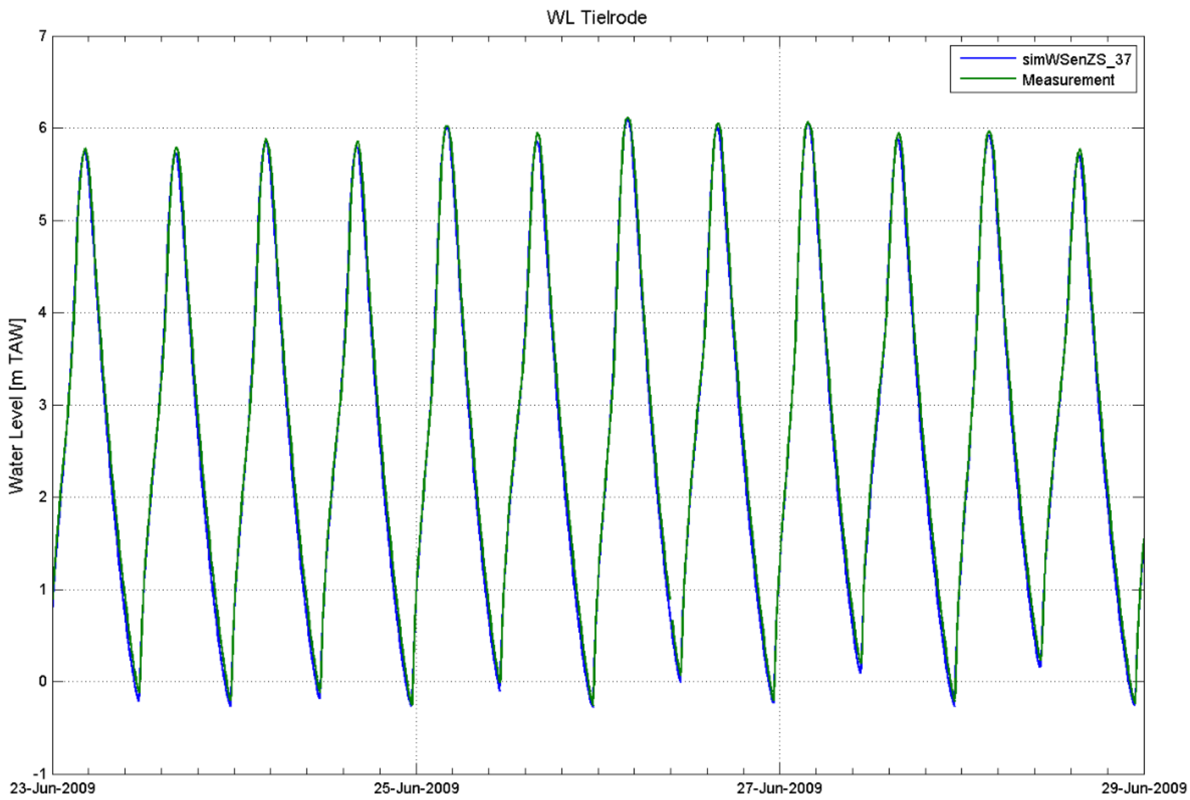


Figure 70 - Calculated and measured water levels at Tielrode

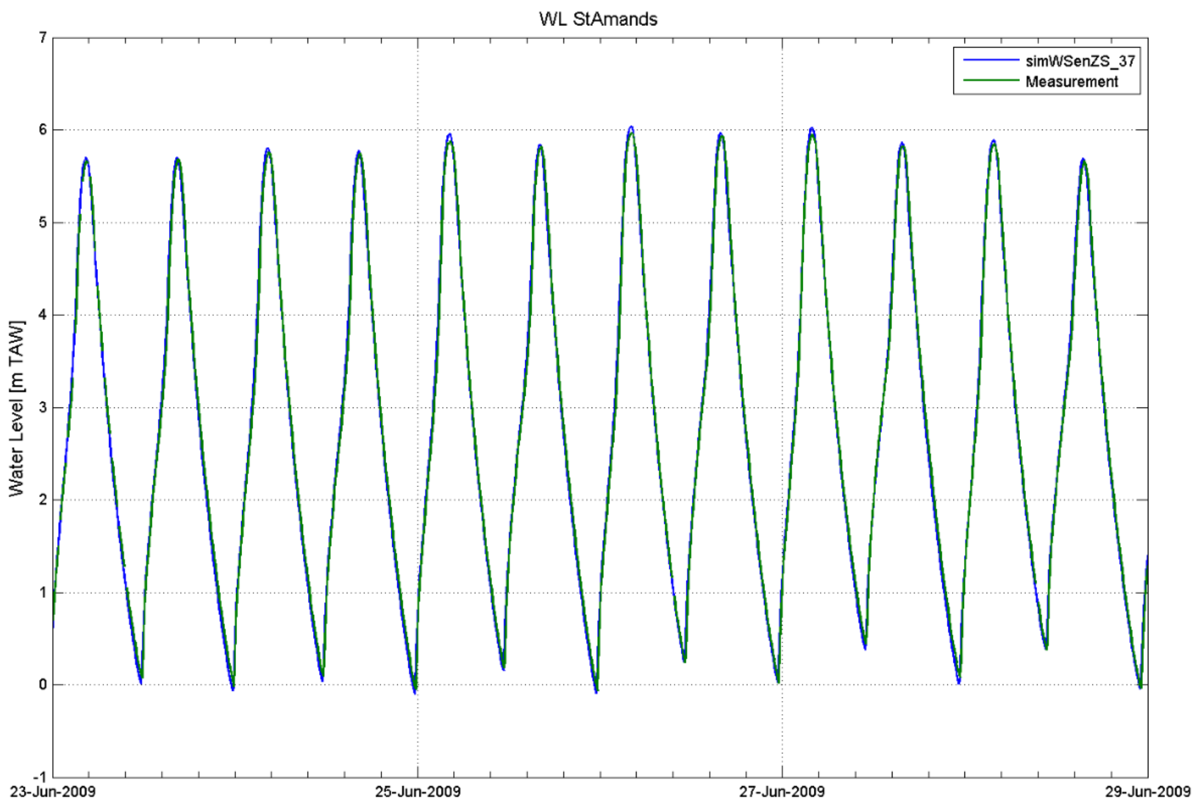


Figure 71 - Calculated and measured water levels at Sint Amands

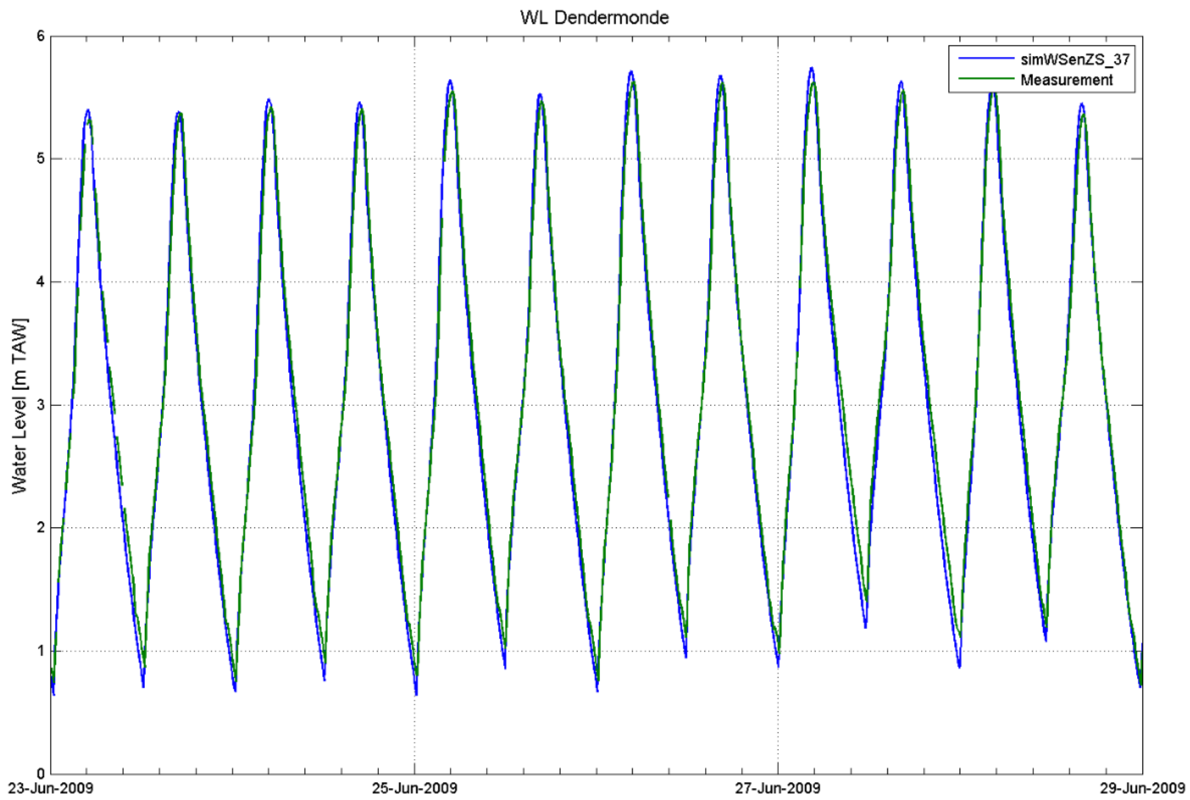


Figure 72 - Calculated and measured water levels at Dendermonde

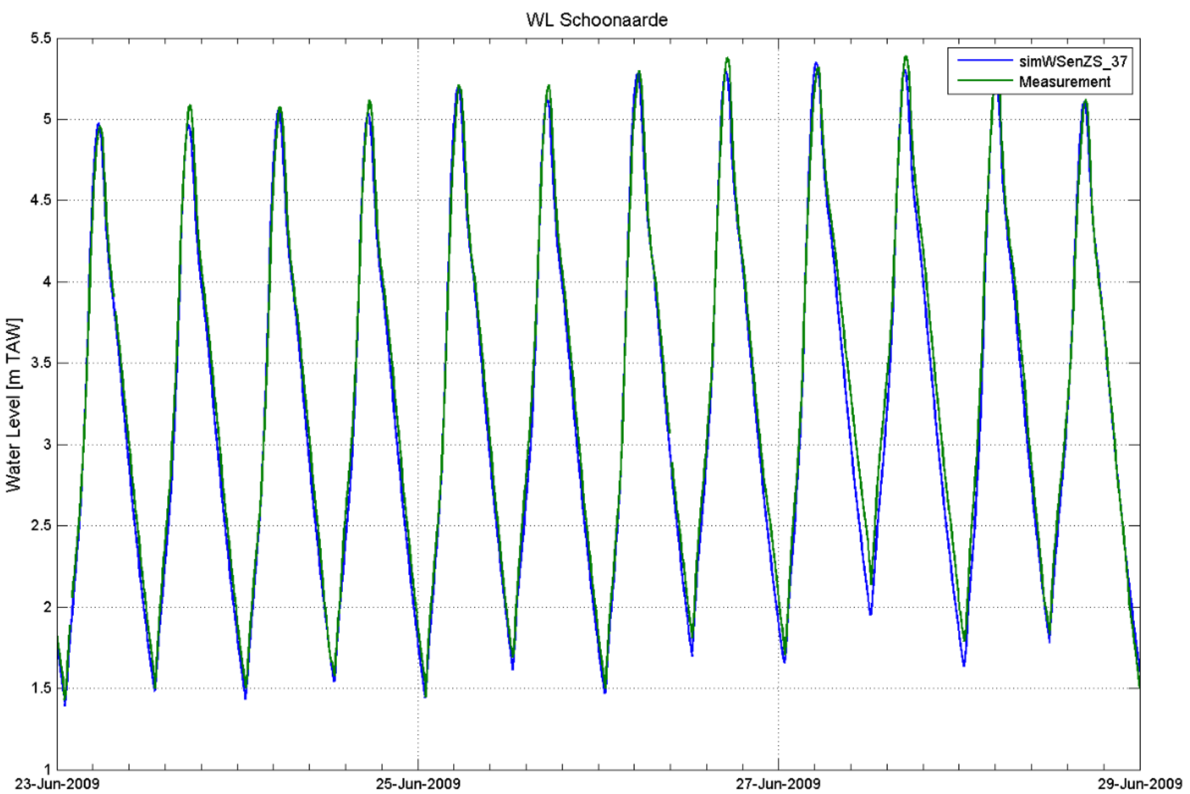


Figure 73 - Calculated and measured water levels at Schoonaarde

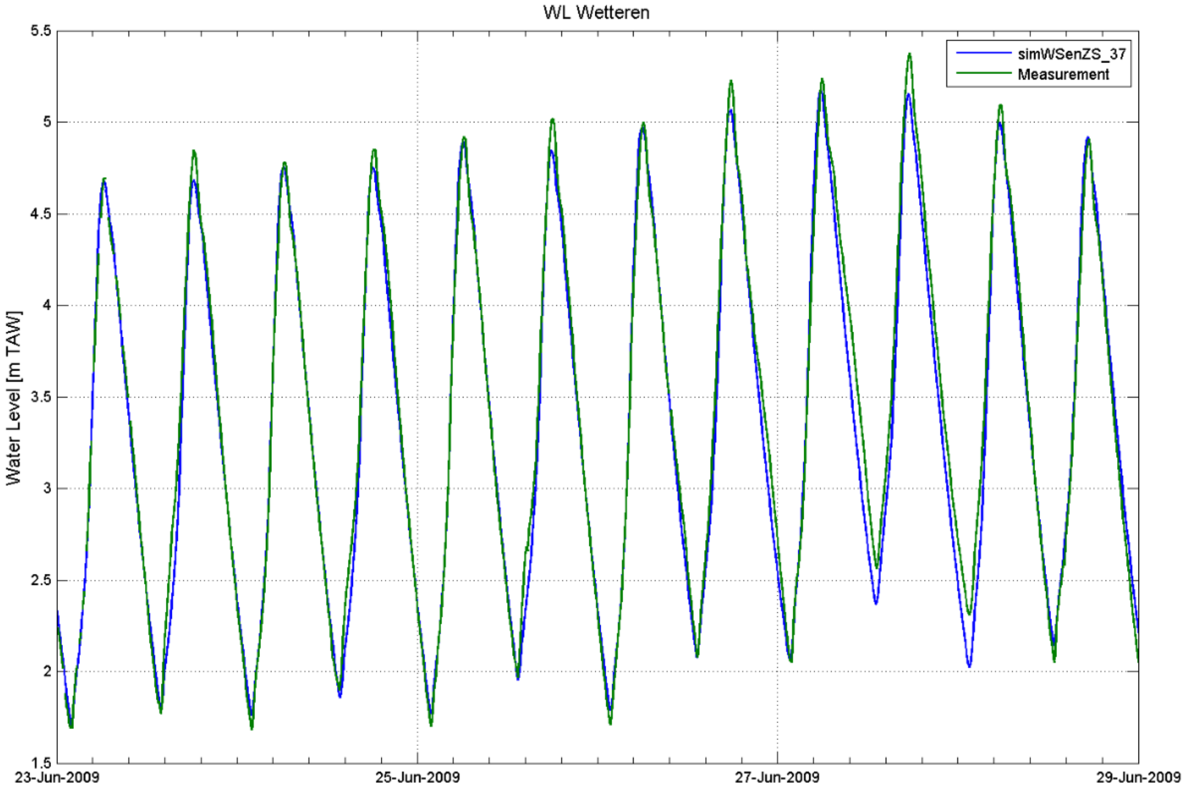


Figure 74 - Calculated and measured water levels at Wetteren

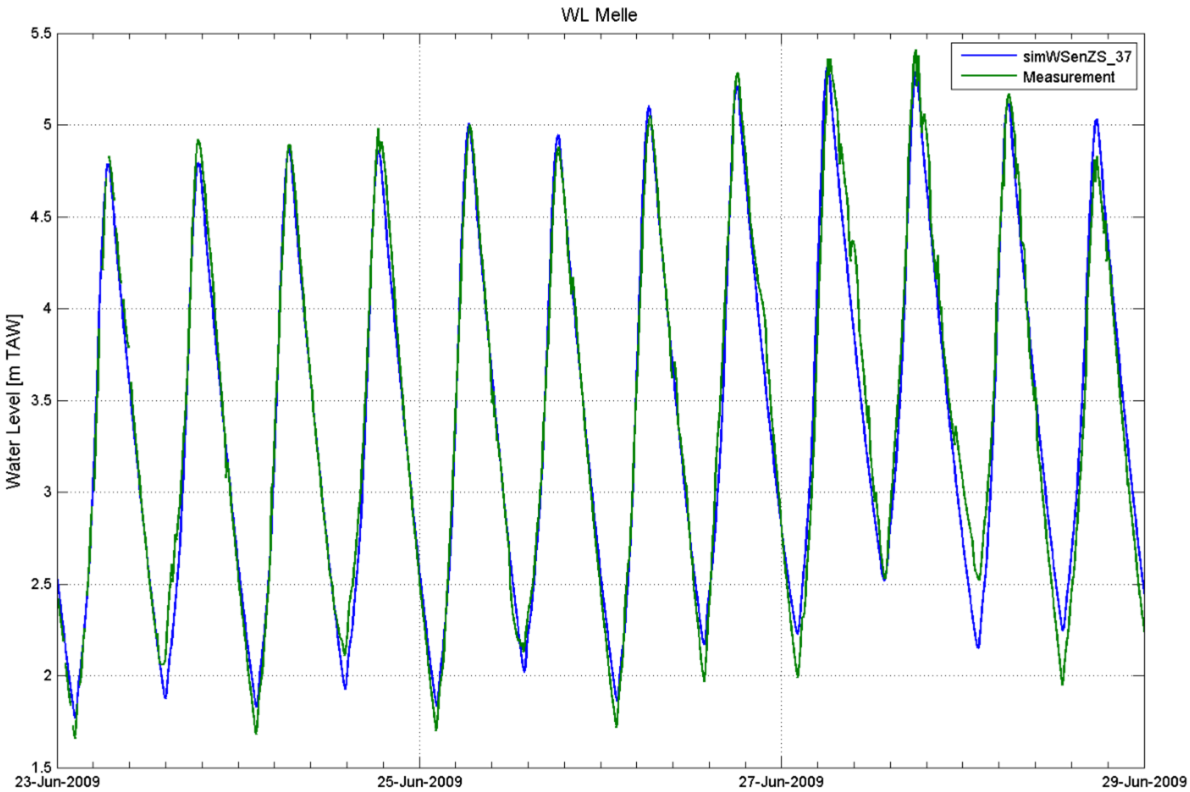


Figure 75 - Calculated and measured water levels at Melle

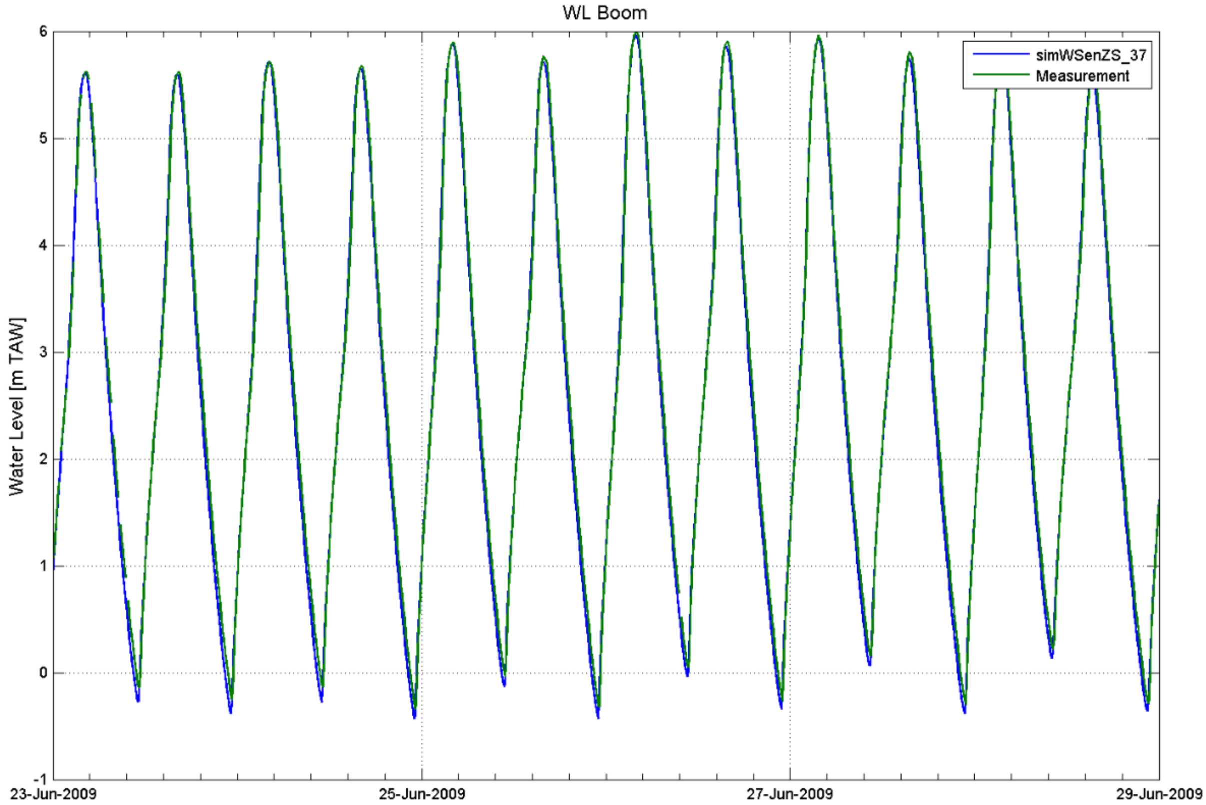


Figure 76 - Calculated and measured water levels at Boom

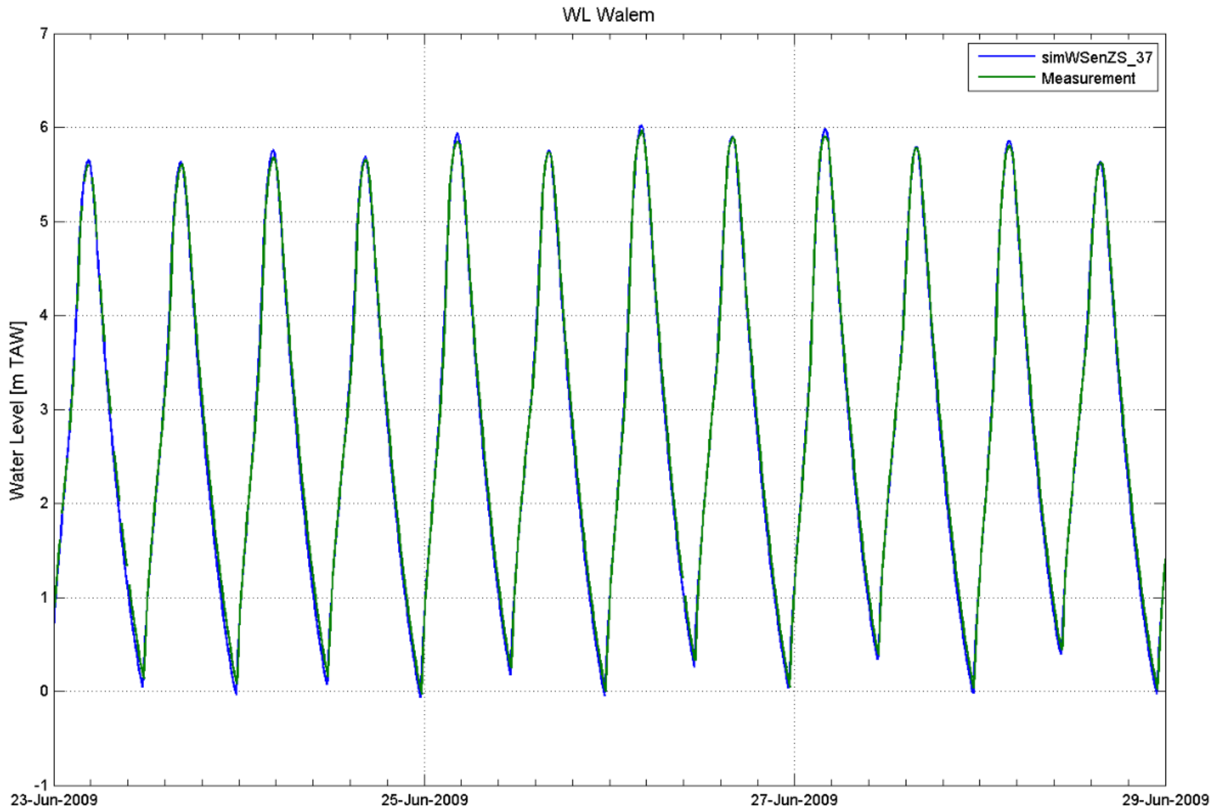


Figure 77 - Calculated and measured water levels at Walem

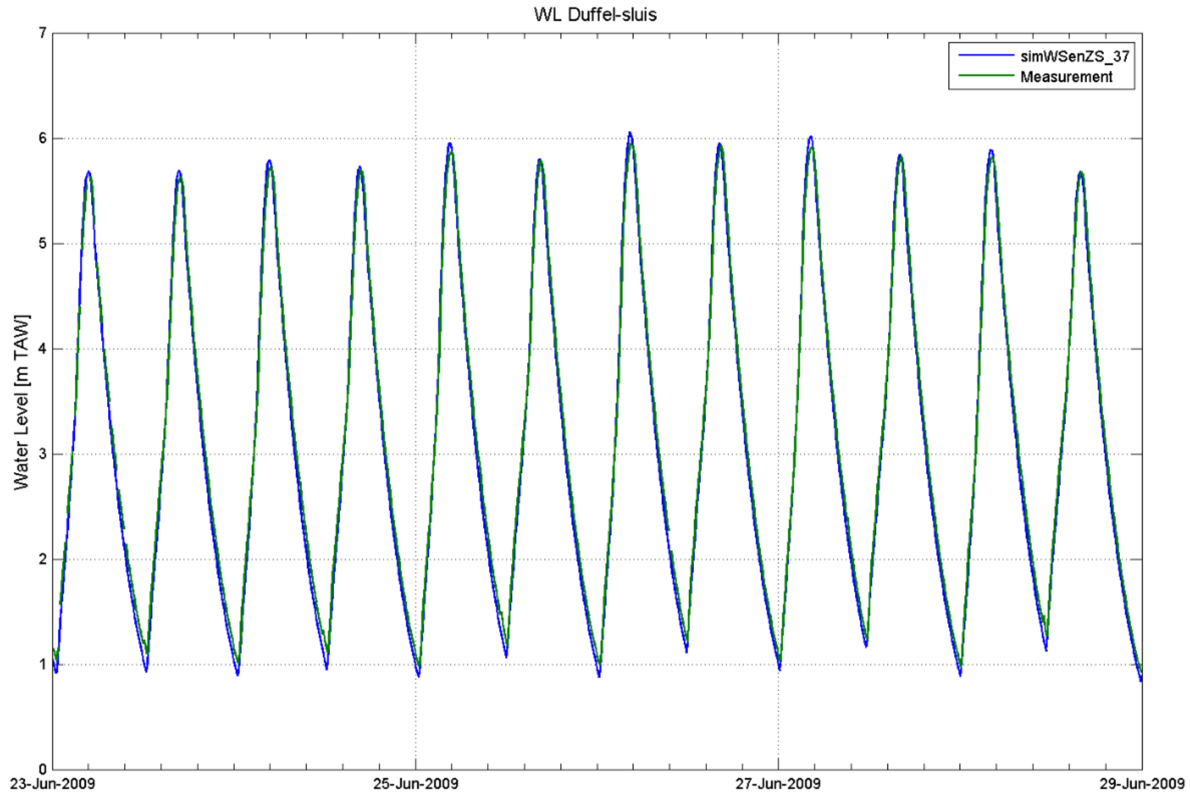


Figure 78 - Calculated and measured water levels at Duffel

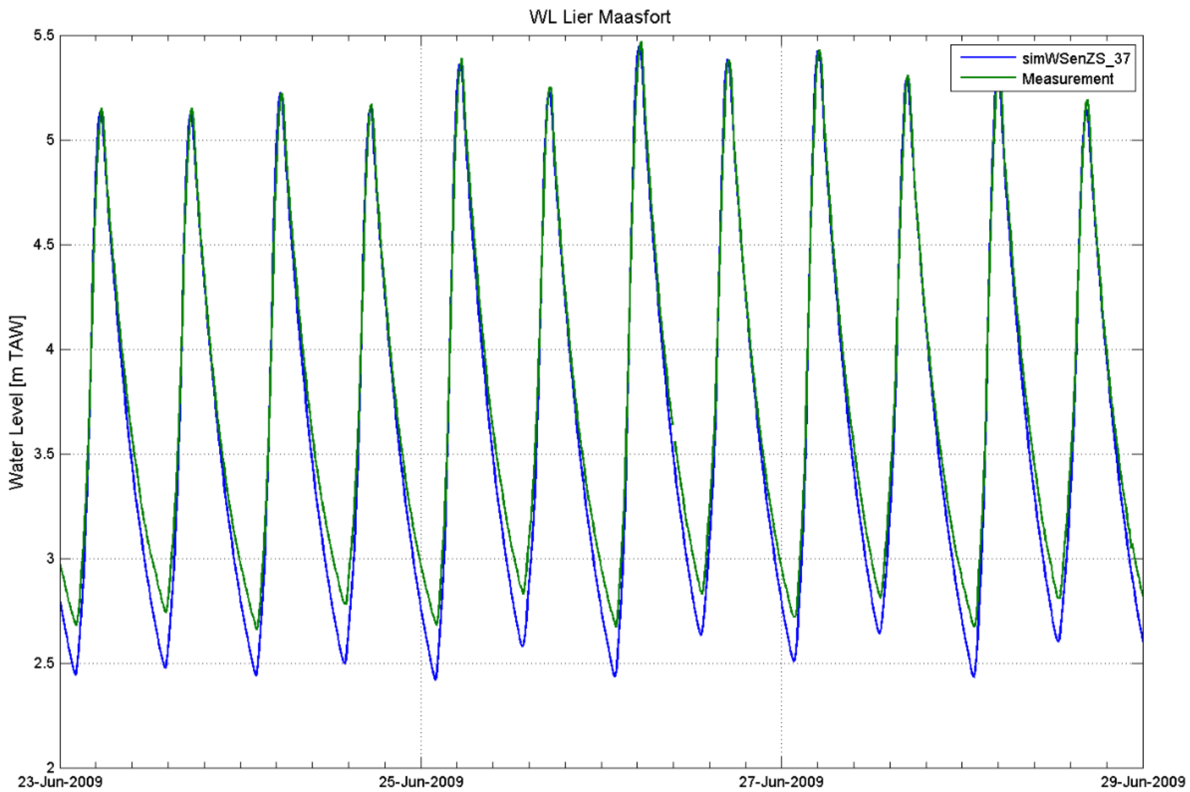


Figure 79 - Calculated and measured water levels at Lier Maasfort

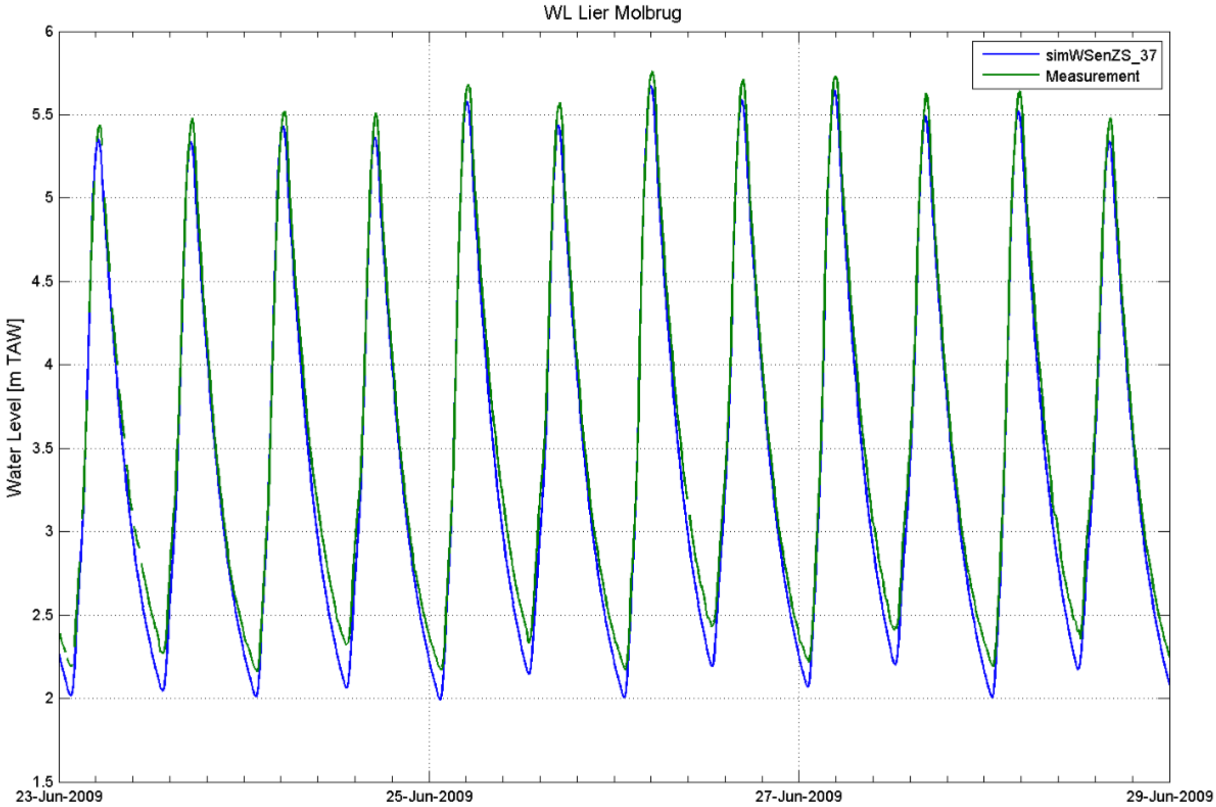


Figure 80 - Calculated and measured water levels at Lier Molbrug

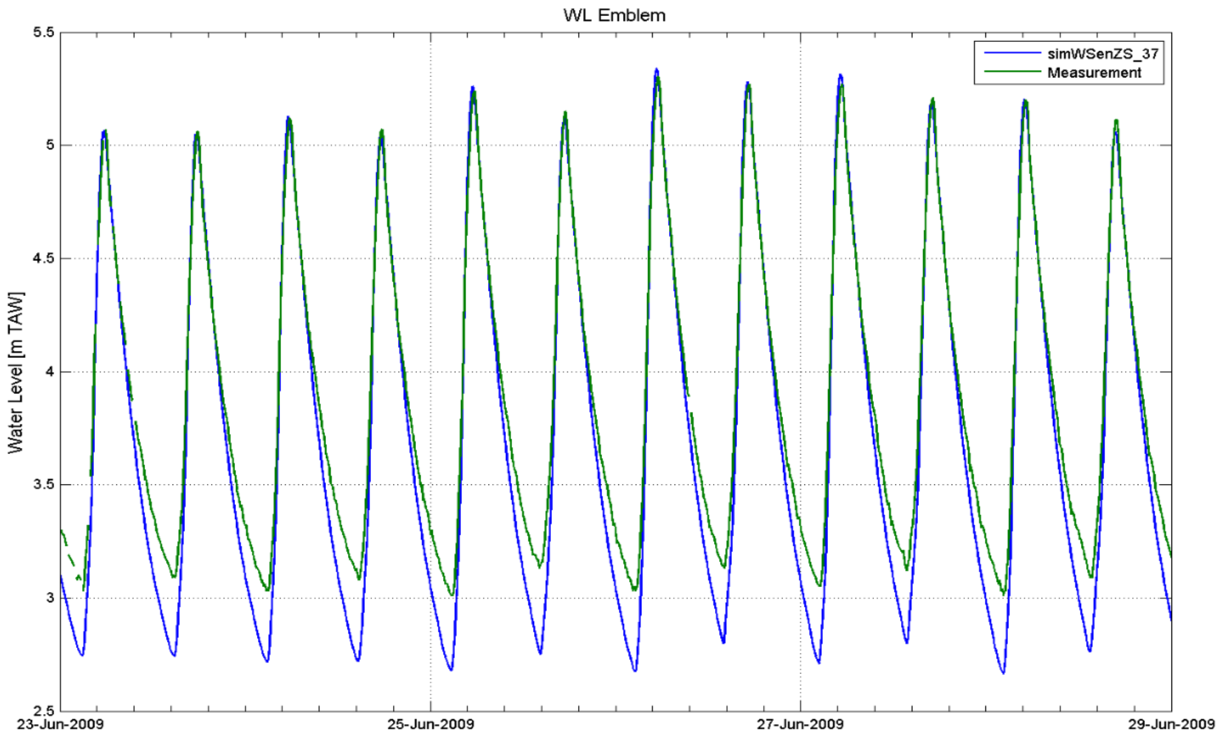


Figure 81 - Calculated and measured water levels at Emblem

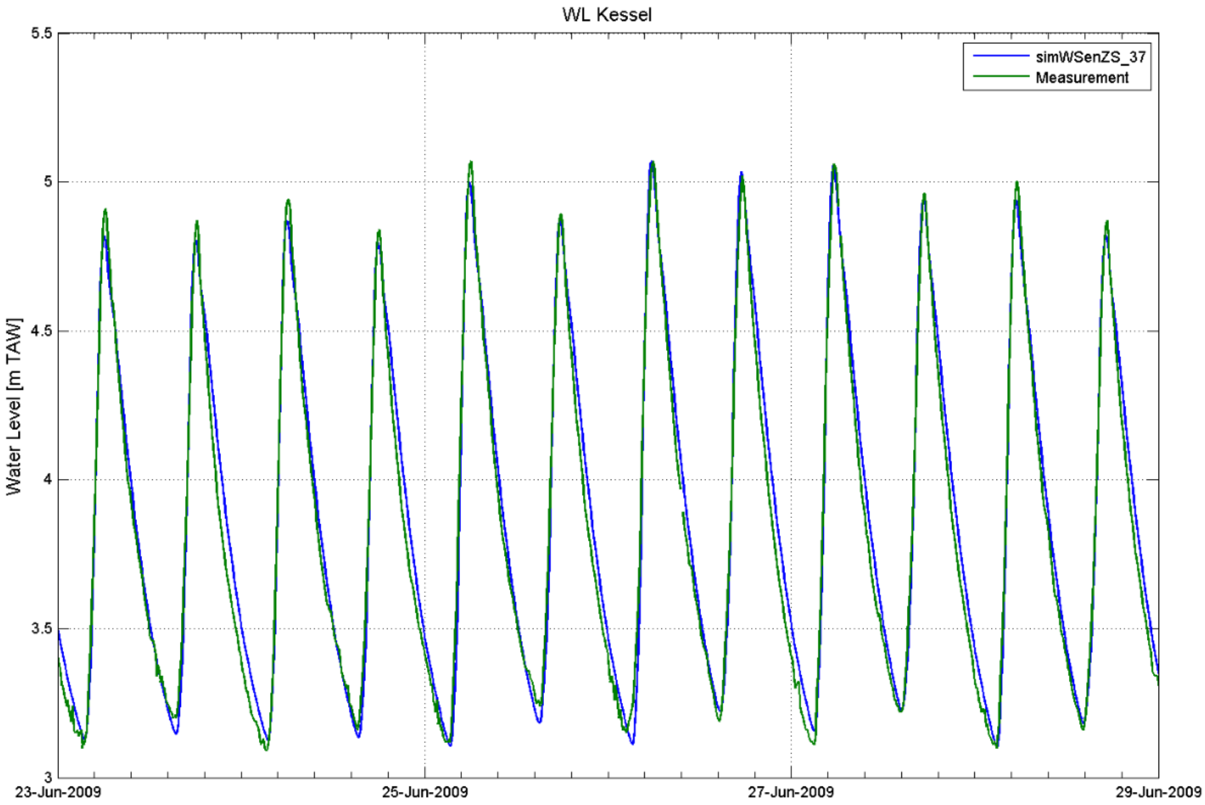


Figure 82 - Calculated and measured water levels at Kessel

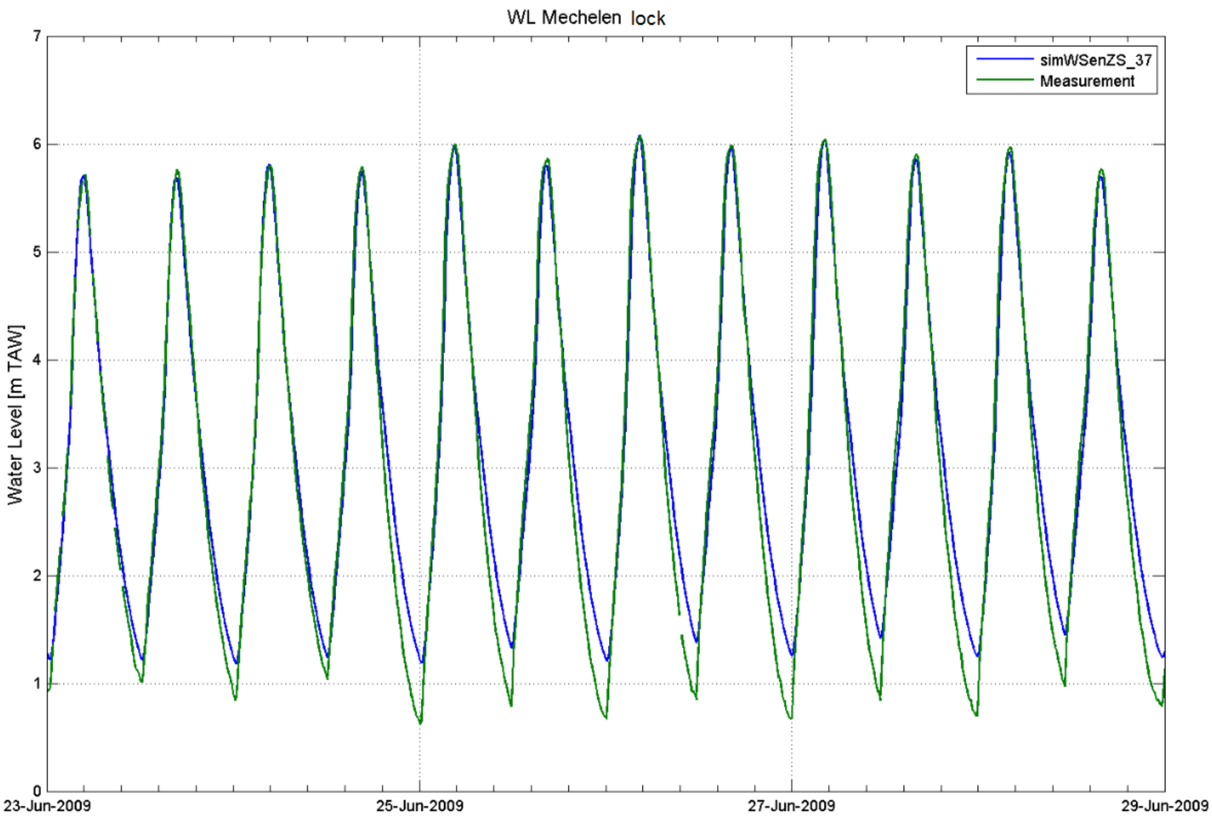


Figure 83 - Calculated and measured water levels at Mechelen lock

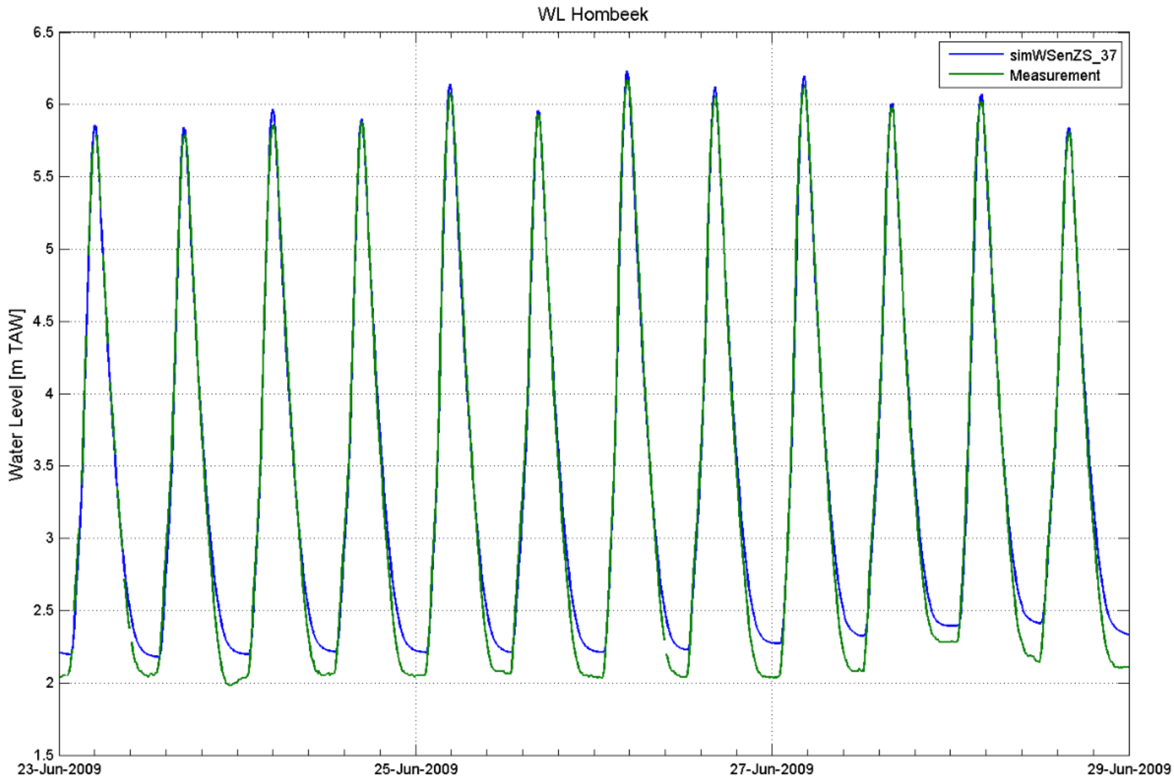


Figure 84 - Calculated and measured water levels at Hombeek

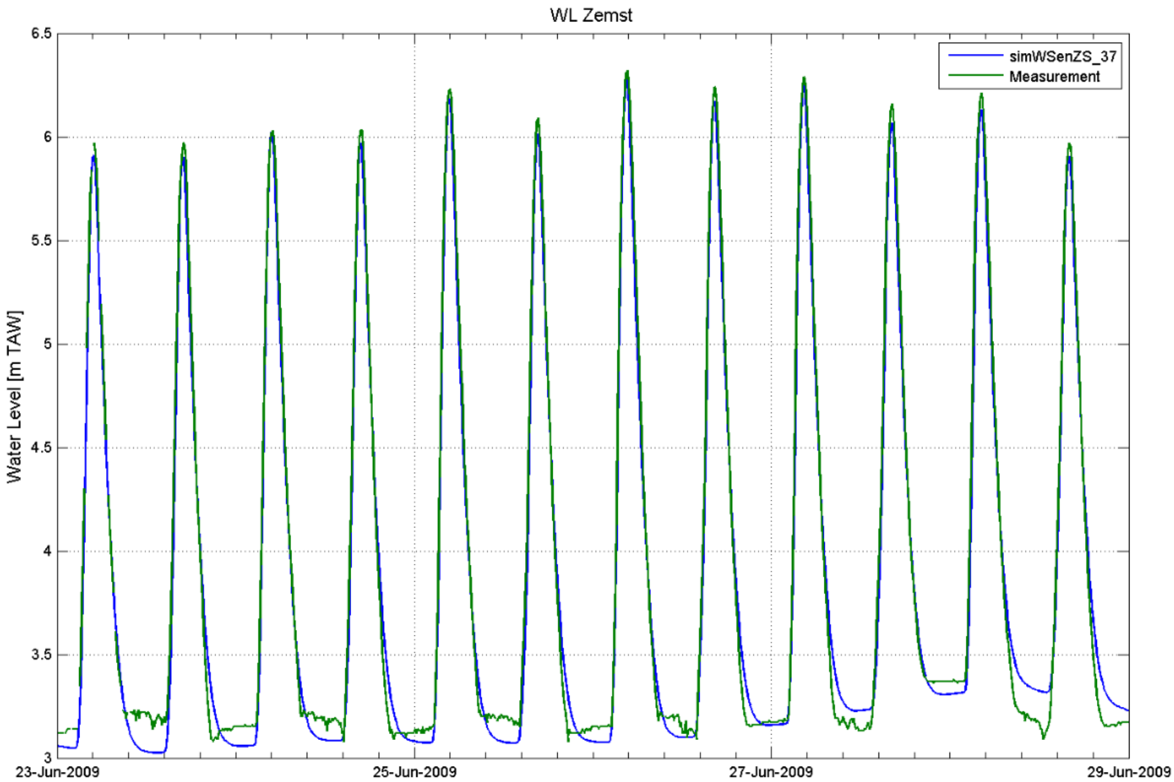


Figure 85 - Calculated and measured water levels at Zemst

Stationary velocities

Table 34. Statistical parameters for the components, magnitude and direction of stationary velocity

Location	Vector analysis		Magnitude			Direction		
	MAE TS	RMAE TS	BIAS TS	MAE TS	RMSE TS	BIAS TS	MAE TS	RMSE TS
	[m/s]	[-]	[m/s]	[m/s]	[m/s]	[°]	[°]	[°]
Buoy 84 bottom	0.22	0.45	0.15	0.17	0.19	3.53	19.24	39.36
Buoy 84 top	0.19	0.35	0.10	0.11	0.13	-2.37	20.18	40.50
Oosterweel bottom	0.16	0.27	0.07	0.14	0.16	-5.40	9.87	25.00
Oosterweel top	0.19	0.26	-0.05	0.17	0.20	-1.45	8.23	27.40
Total	0.19		0.07	0.15	0.17	-1.42	14.38	33.78

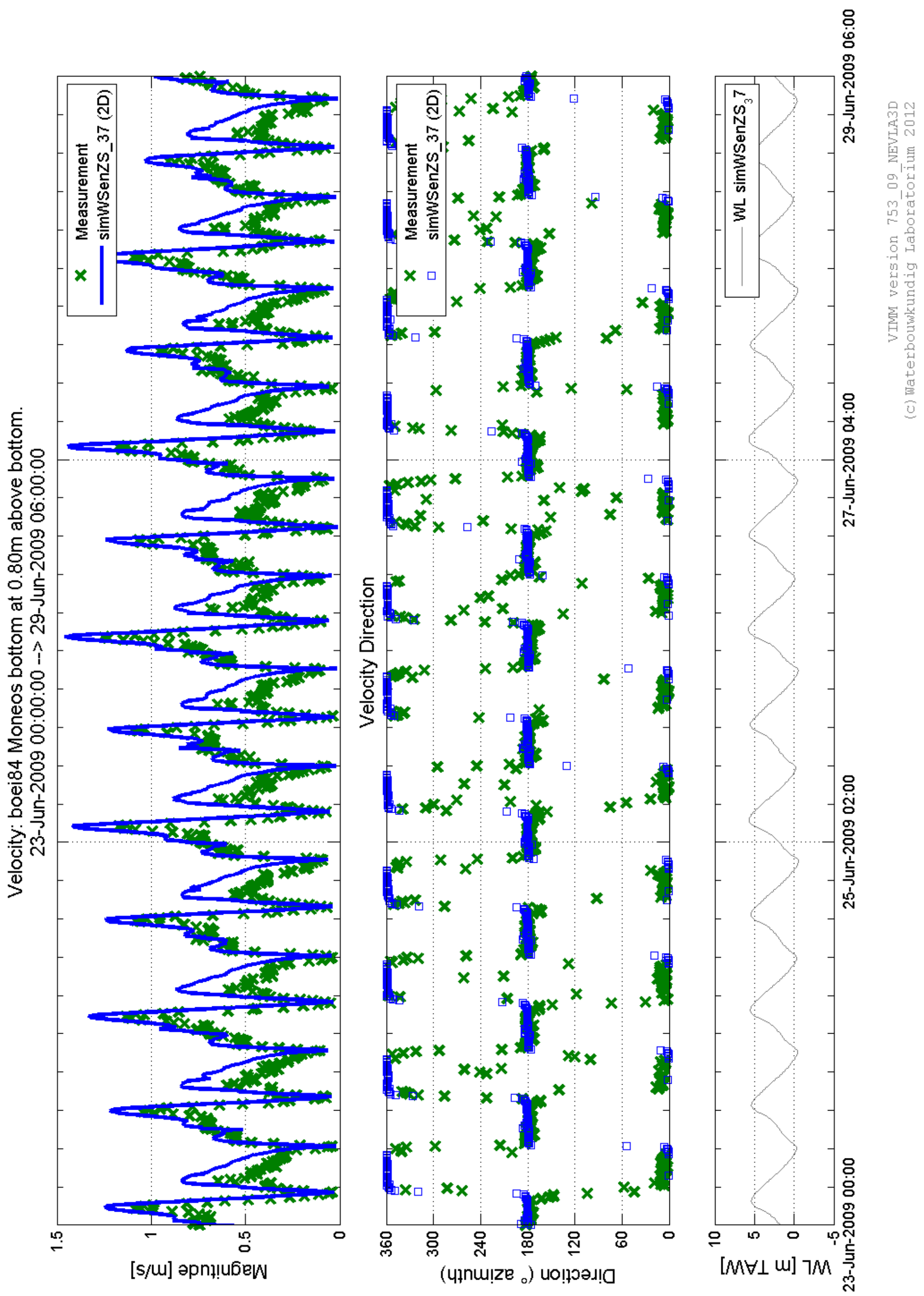


Figure 86 - Calculated (depth average) and measured (bottom) velocities at Buoy 84

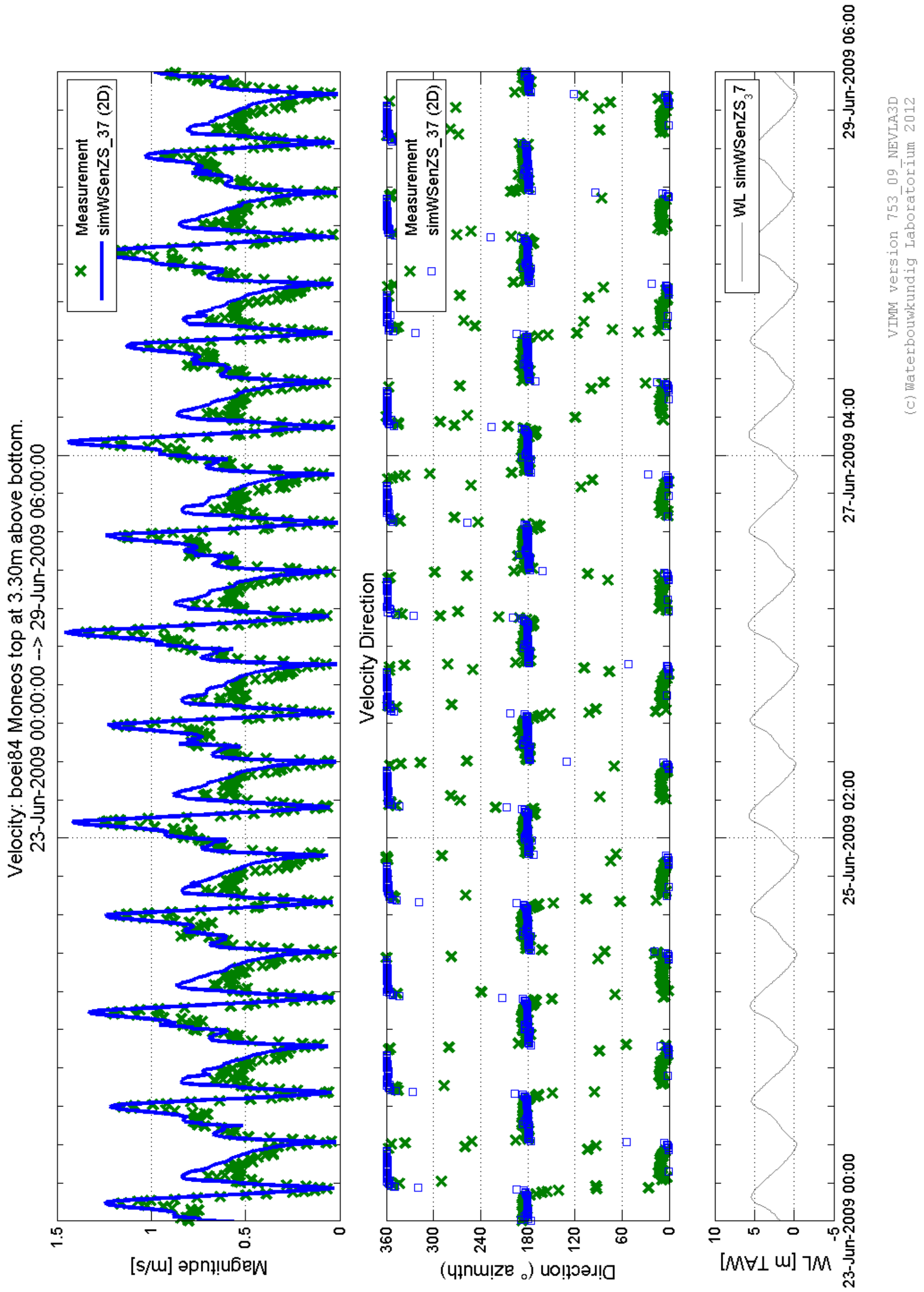


Figure 87 - Calculated (depth average) and measured (top) velocities at Buoy 84

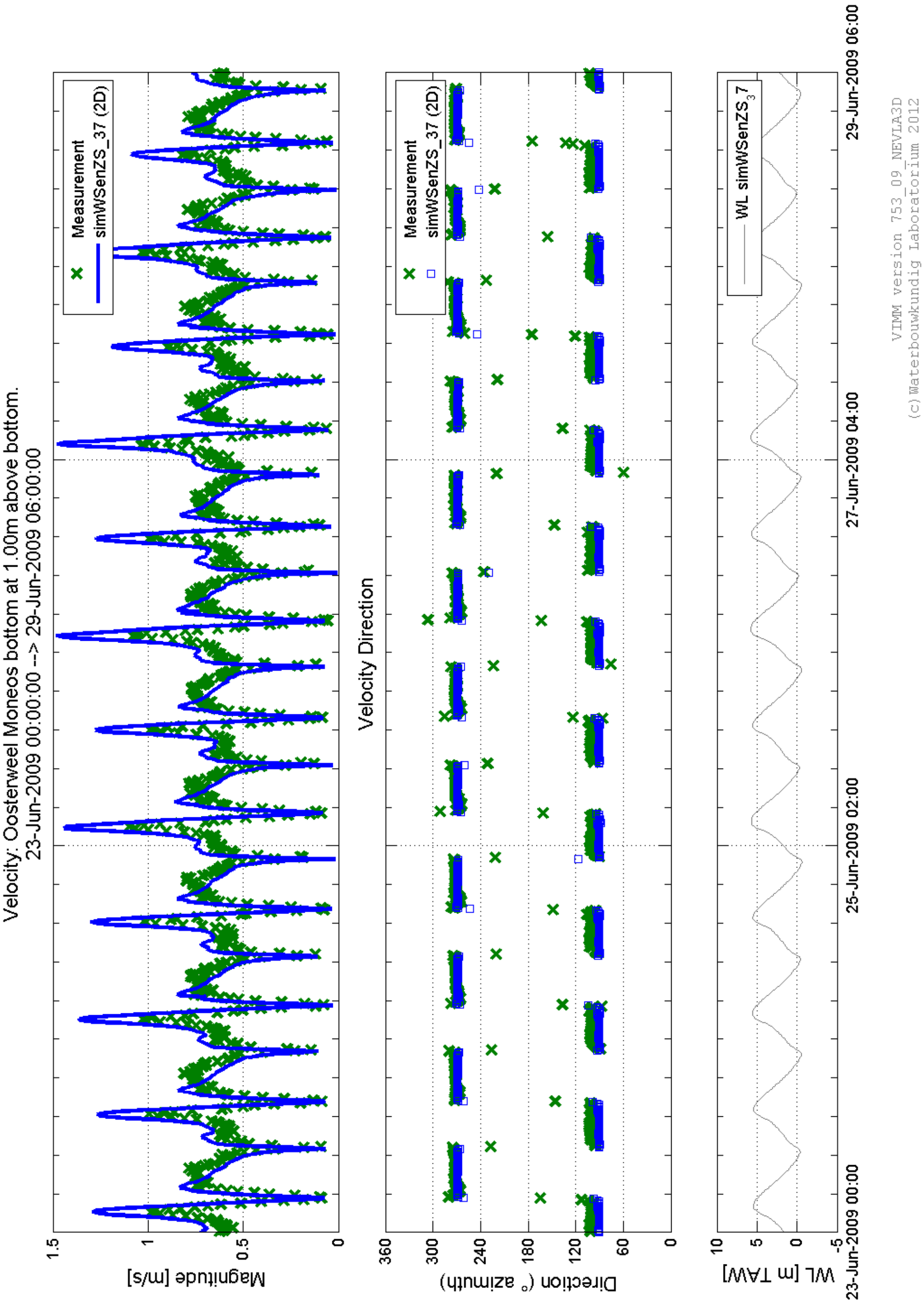


Figure 88 - Calculated (depth average) and measured (bottom) velocities at Oosterweel

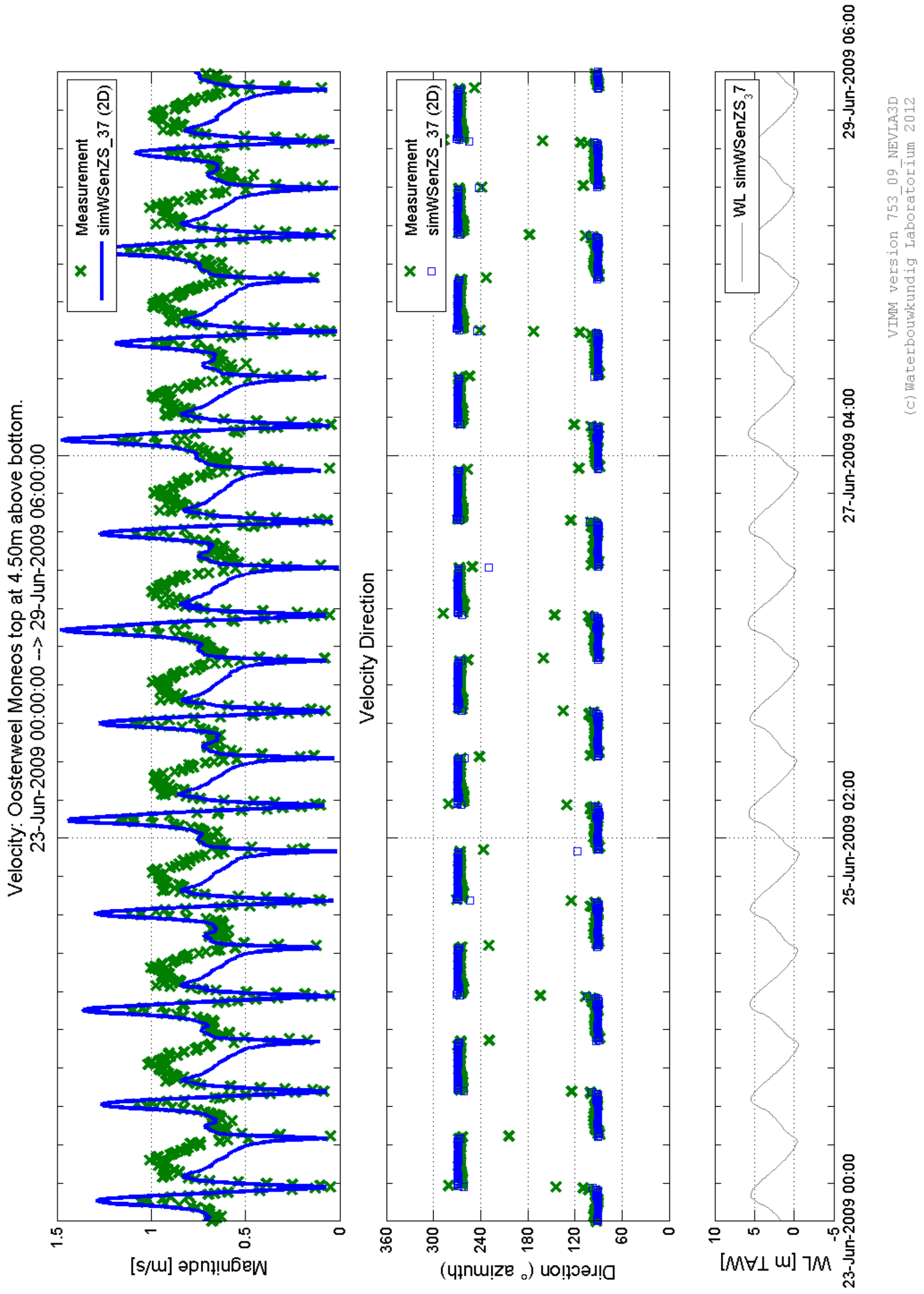


Figure 89 - Calculated (depth average) and measured (top) velocities at Oosterweel

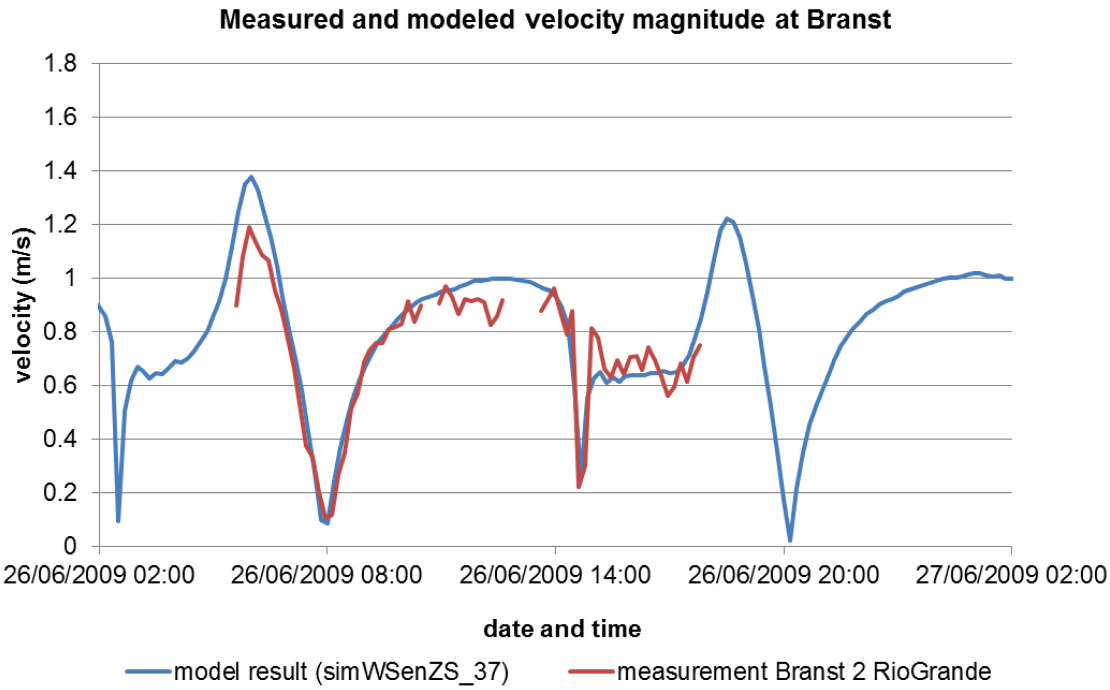


Figure 90 - Calculated (depth average) and measured (depth average) velocities at Branst

Discharges

Table 35. Statistical parameters for discharges (model vs. measurement)

Station	BIAS TS	RMSE TS		Order of magnitude of max discharge
	[m³/s]	[m³/s]	% of Qmax	[m³/s]
Liefkenshoek 2009	142.5	687.2	5	13000
Liefkenshoek 2010	115.9	490.3	4	
Oosterweel 2009	365.1	649.7	7	10000
Oosterweel 2010	97.1	476	5	
Kruibeke 2009	236.5	536	8	7000
Kruibeke 2010	416.3	495.3	7	
Driegoten 2009	33.5	93.2	4	2300
Driegoten 2010	31.6	132.7	6	
Boom 2009	10.5	71.3	5	1300
Boom 2010	10.6	63.6	5	
Schoonaarde 2010	17	43.3	9	500
Schoonaarde 2009	16.9	34.1	7	
Total	124.5	406.5		

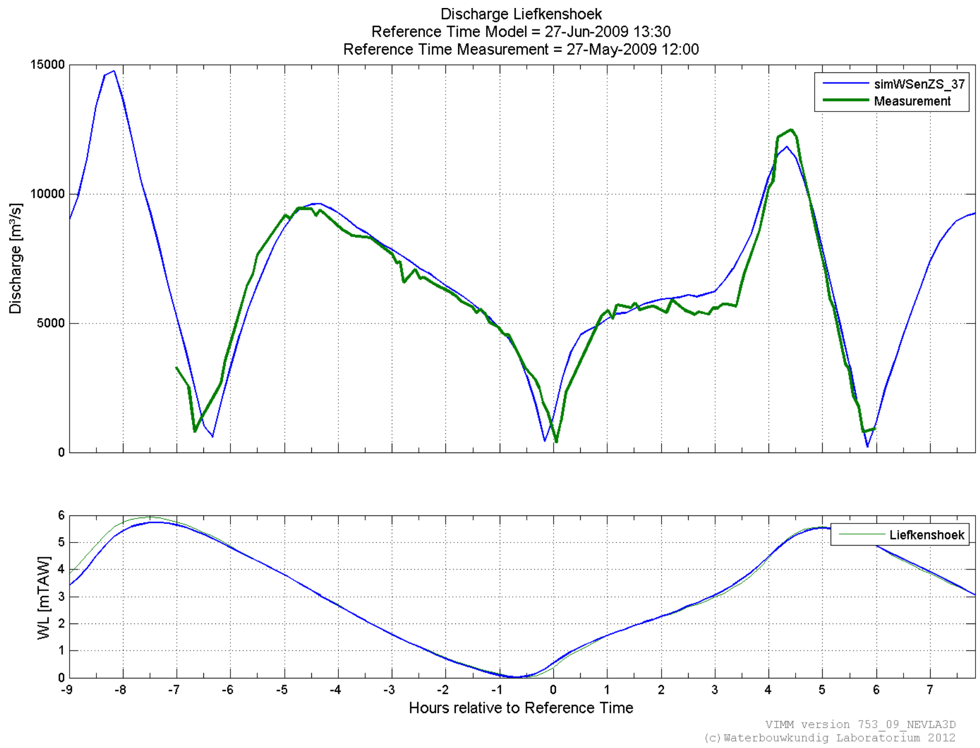


Figure 91 - Calculated and measured (2009) discharges at Liefkenshoek

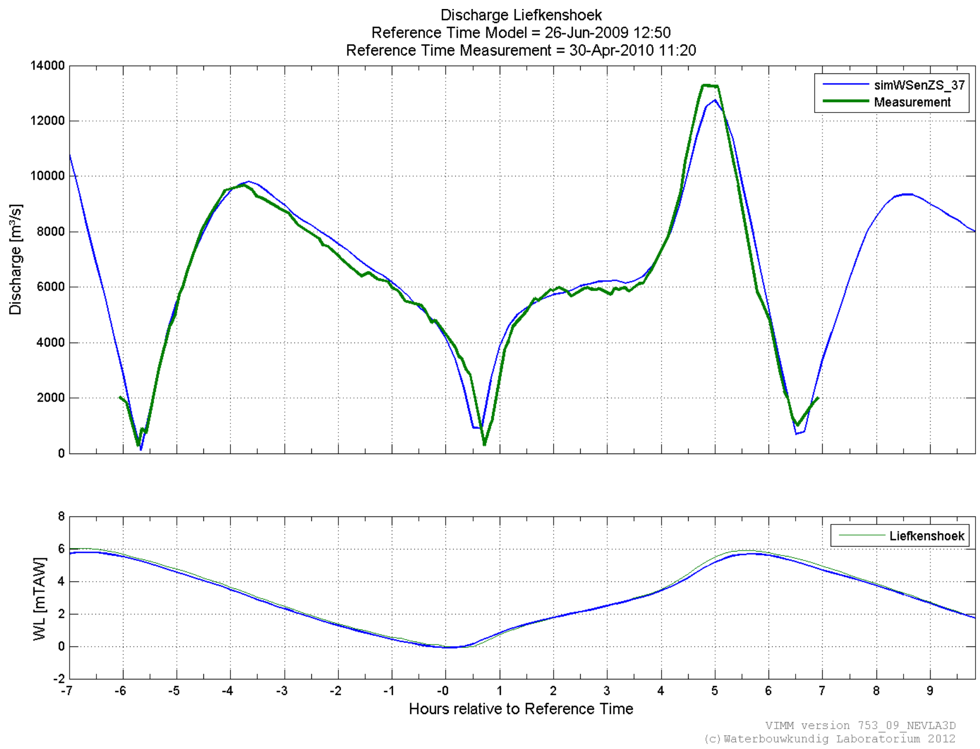


Figure 92 - Calculated and measured (2010) discharges at Liefkenshoek

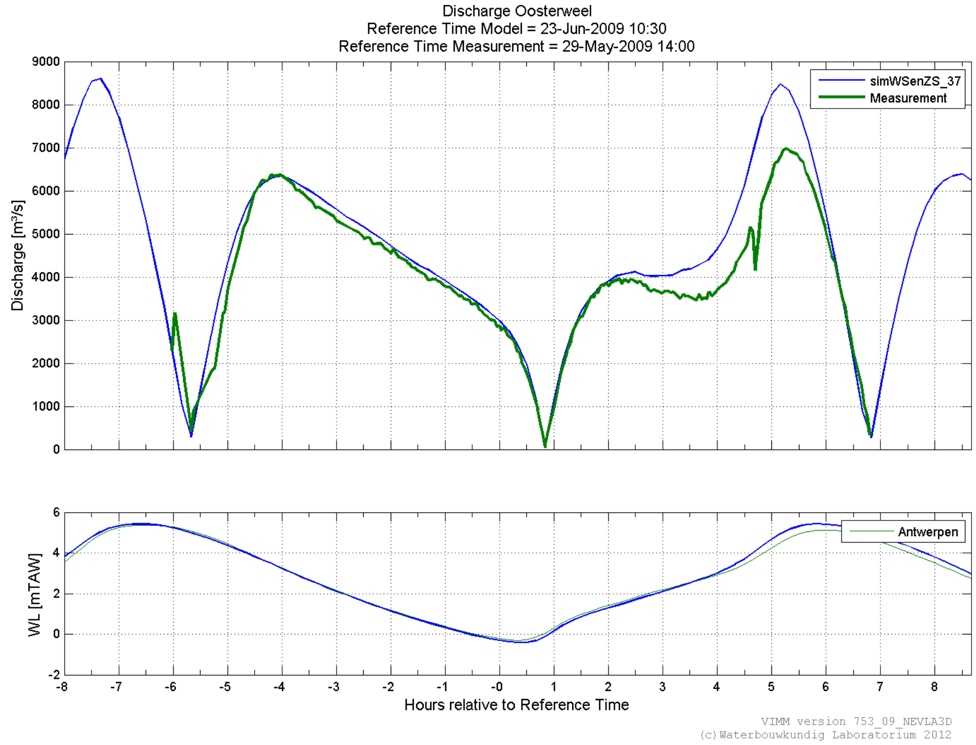


Figure 93 - Calculated and measured (2009) discharges at Oosterweel

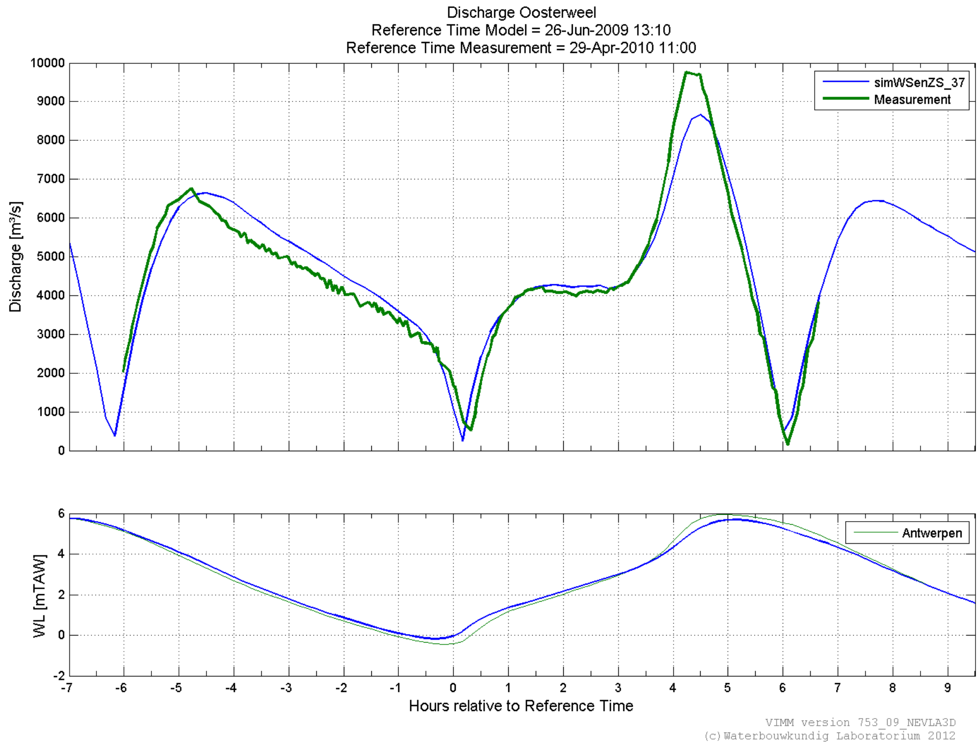


Figure 94 - Calculated and measured (2010) discharges at Oosterweel

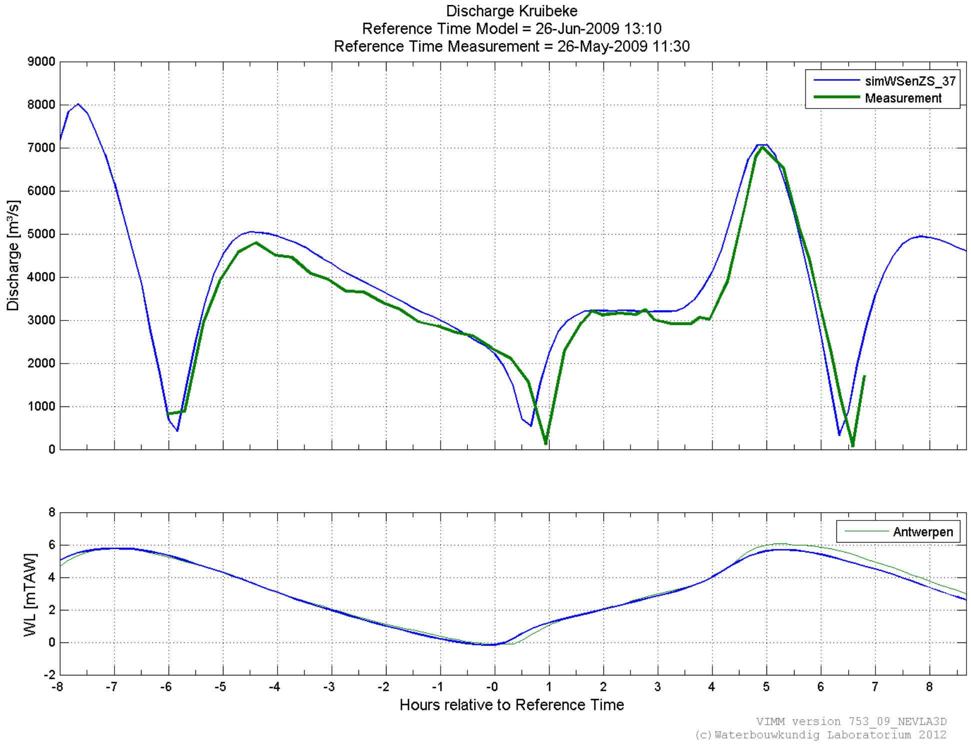


Figure 95 - Calculated and measured (2009) discharges at Kruibeke

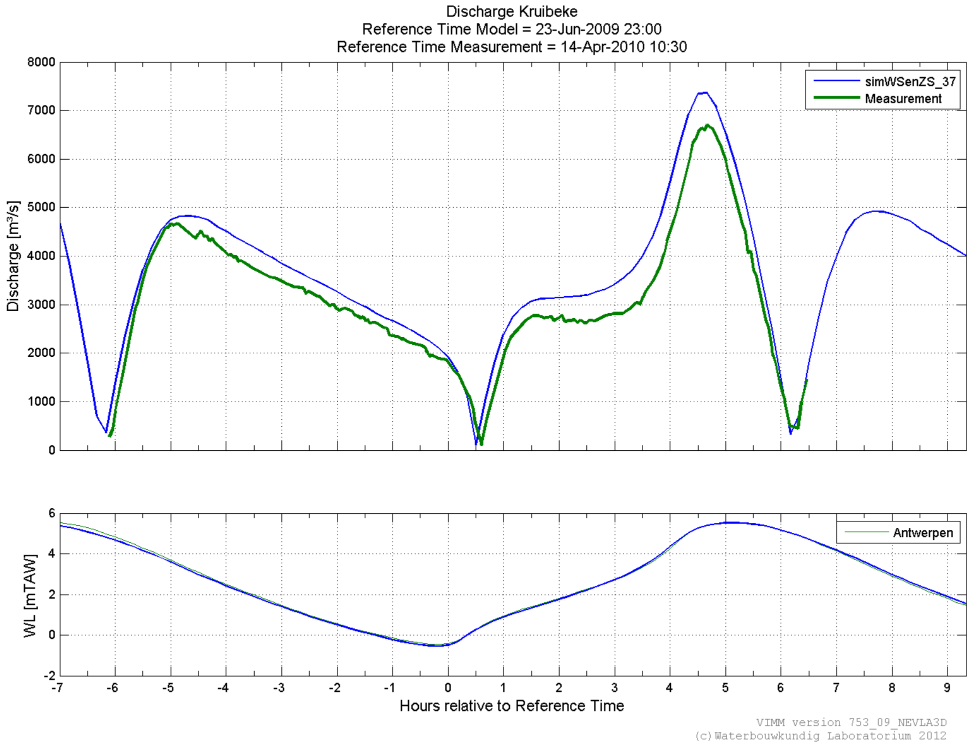


Figure 96 - Calculated and measured (2010) discharges at Kruibeke

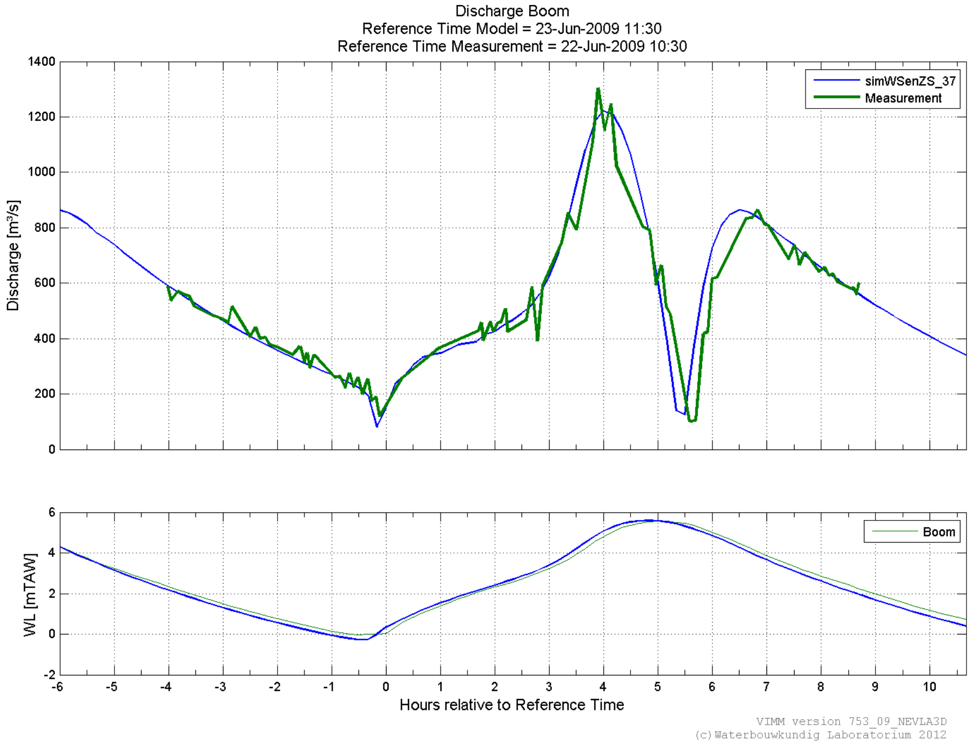


Figure 97 - Calculated and measured (2009) discharges at Boom

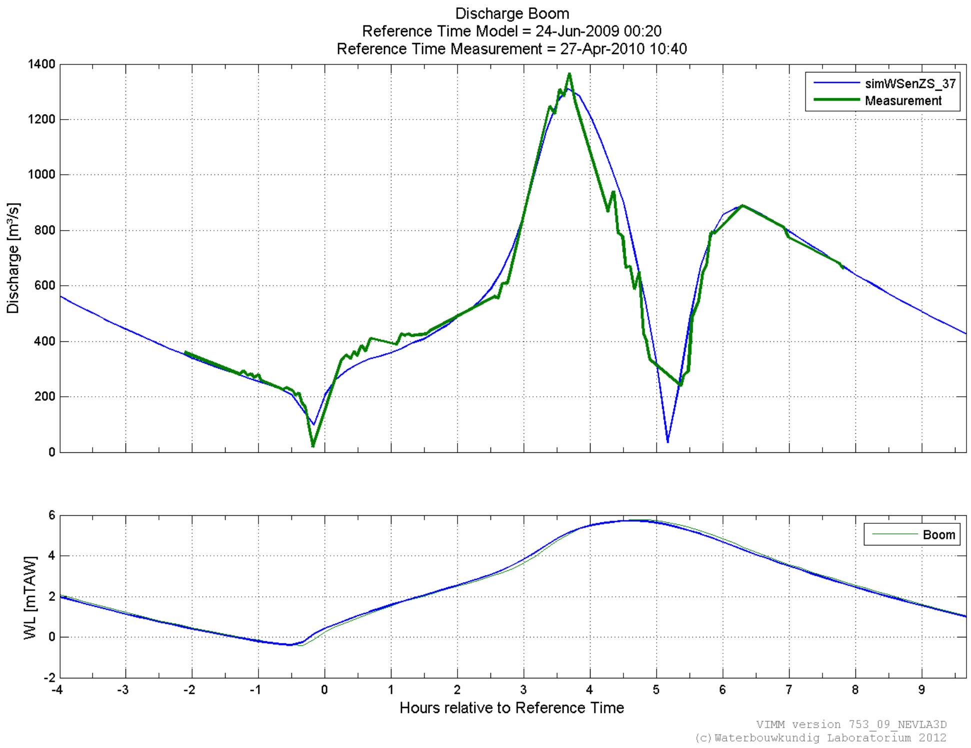


Figure 98 - Calculated and measured (2010) discharges at Boom

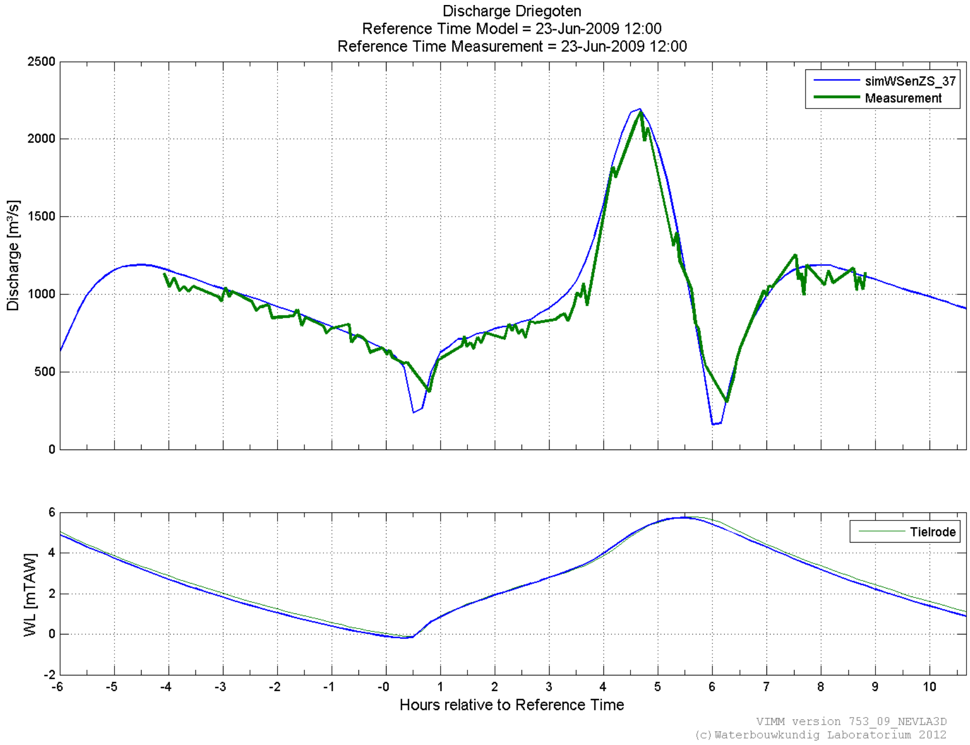


Figure 99 - Calculated and measured (2009) discharges at Driegoten

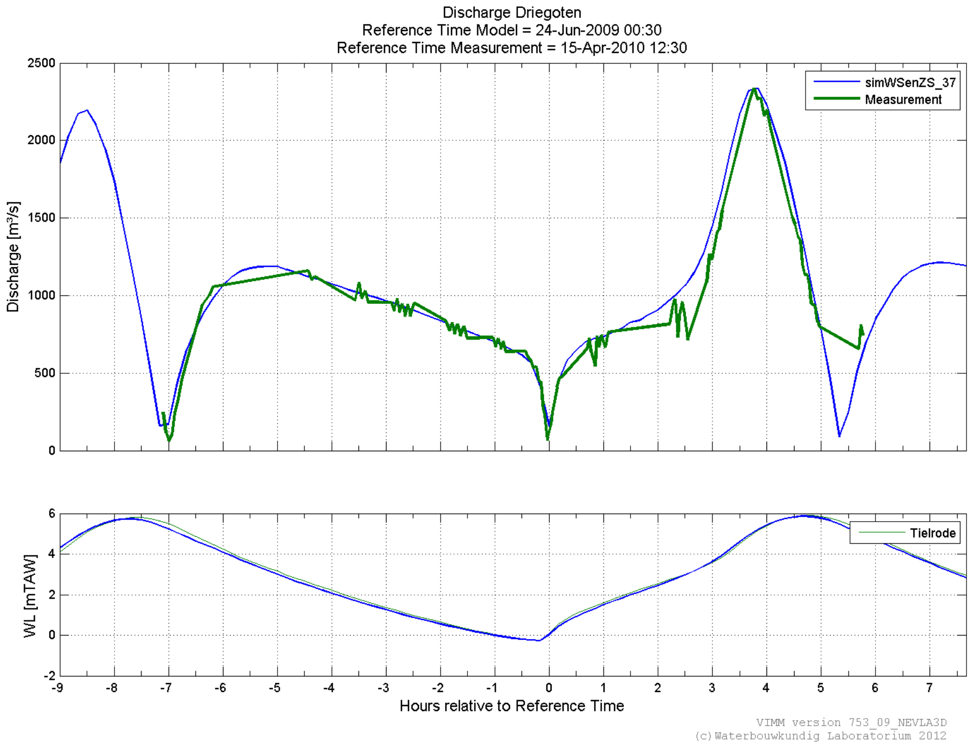


Figure 100 - Calculated and measured (2010) discharges at Driegoten

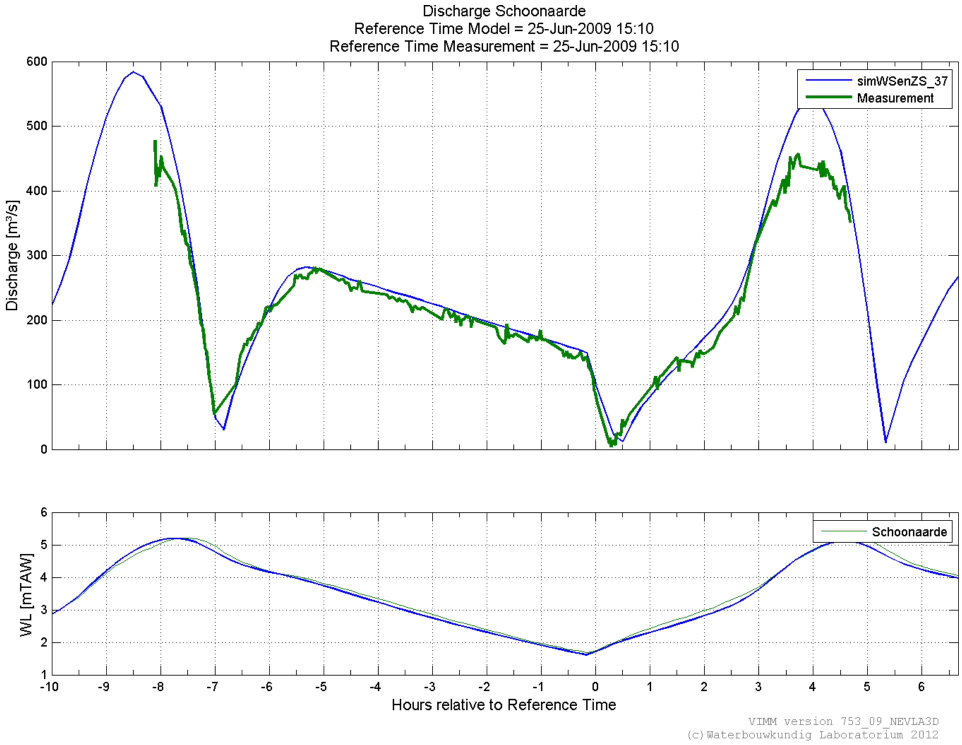


Figure 101 - Calculated and measured (2009) discharges at Schoonaarde

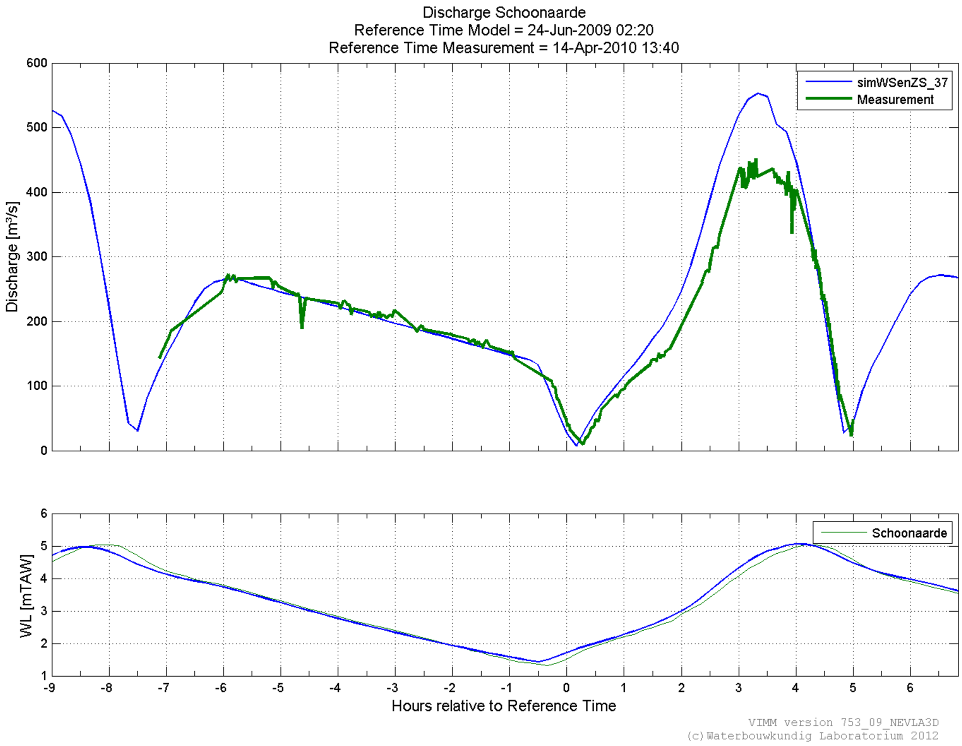


Figure 102 - Calculated and measured (2010) discharges at Schoonaarde

ADCP velocities

Table 36. Statistical parameters of velocities (calibrated model vs. ADCP measurements)

Transect number	Campaign	Time model	Time of measurement	Statistics for transects				Weight	Statistics for campaigns (weight of each transect is taken into account)	
				Bias mag (m)	Bias dir (degrees)	RMSE mag (m)	RMSE dir (degrees)		RMSE mag (m)	RMSE dir (degrees)
1	20110902_Galgenschoor_RioGrande	26/06/2009 07:00	02/09/2011 07:12	-0.02	8	0.05	10	20	0.15	53
2		26/06/2009 07:30	02/09/2011 07:33	-0.25	-1	0.26	4	285		
3		26/06/2009 08:00	02/09/2011 07:56	-0.29	14	0.32	36	223		
4		26/06/2009 08:30	02/09/2011 08:28	-0.11	2	0.13	5	238		
5		26/06/2009 09:00	02/09/2011 08:44	-0.29	1	0.30	4	206		
6		26/06/2009 09:30	02/09/2011 09:29	-0.12	-10	0.16	73	235		
7		26/06/2009 10:00	02/09/2011 10:01	-0.06	11	0.08	38	155		
8		26/06/2009 10:30	02/09/2011 10:29	-0.08	6	0.10	9	233		
9		26/06/2009 11:00	02/09/2011 11:01	-0.06	0	0.09	10	158		
10		26/06/2009 11:30	02/09/2011 11:33	-0.08	5	0.10	79	230		
11		26/06/2009 12:00	02/09/2011 11:49	-0.07	17	0.09	40	326		
12		26/06/2009 12:30	02/09/2011 12:28	-0.02	8	0.05	152	253		
13		26/06/2009 13:00	02/09/2011 13:01	0.22	-4	0.23	120	224		
14		26/06/2009 13:30	02/09/2011 13:37	-0.15	-11	0.19	28	236		
15		26/06/2009 14:00	02/09/2011 14:09	0.00	-6	0.10	30	210		
16		26/06/2009 14:30	02/09/2011 14:25	-0.03	-3	0.11	22	238		
17		26/06/2009 15:00	02/09/2011 14:58	0.13	5	0.14	31	235		
18		26/06/2009 15:30	02/09/2011 15:32	-0.03	-1	0.09	15	226		
19		26/06/2009 16:00	02/09/2011 15:48	0.07	-2	0.09	15	338		
20		26/06/2009 16:30	02/09/2011 16:43	-0.09	0	0.10	4	269		
21		26/06/2009 17:00	02/09/2011 17:01	-0.05	1	0.07	4	345		
22		26/06/2009 17:30	02/09/2011 17:26	-0.04	4	0.12	7	232		
23		26/06/2009 18:00	02/09/2011 18:02	-0.11	0	0.14	30	224		
24		26/06/2009 18:30	02/09/2011 18:34	0.02	-1	0.05	67	238		
25		26/06/2009 19:00	02/09/2011 18:50	0.07	43	0.09	69	255		

Transect number	Campaign	Time model	Time of measurement	Statistics for transects				Weight	Statistics for campaigns (weight of each transect is taken into account)	
				Bias mag (m)	Bias dir (degrees)	RMSE mag (m)	RMSE dir (degrees)		RMSE mag (m)	RMSE dir (degrees)
26	20090527_Liefkenshoek	27/06/2009 06:30	27/05/2009 05:27	0.40	-3	0.44	67	141	0.17	31
27		27/06/2009 07:00	27/05/2009 05:27	0.10	-11	0.14	43	141		
28		27/06/2009 07:30	27/05/2009 05:53	-0.03	12	0.09	44	125		
29		27/06/2009 08:00	27/05/2009 06:22	-0.04	11	0.07	17	108		
30		27/06/2009 08:30	27/05/2009 06:57	-0.12	3	0.13	6	127		
31		27/06/2009 09:00	27/05/2009 07:29	-0.09	1	0.12	5	136		
32		27/06/2009 09:30	27/05/2009 07:58	-0.05	2	0.15	5	131		
33		27/06/2009 10:00	27/05/2009 08:33	0.04	1	0.12	13	125		
34		27/06/2009 10:30	27/05/2009 09:04	-0.02	4	0.15	5	122		
35		27/06/2009 11:00	27/05/2009 09:28	-0.03	2	0.18	4	131		
36		27/06/2009 11:30	27/05/2009 09:59	0.03	6	0.14	24	106		
37		27/06/2009 12:00	27/05/2009 10:26	-0.04	2	0.20	6	131		
38		27/06/2009 12:30	27/05/2009 10:57	-0.03	3	0.16	5	126		
39		27/06/2009 13:00	27/05/2009 11:26	-0.03	4	0.18	18	108		
40		27/06/2009 13:30	27/05/2009 11:57	-0.13	2	0.20	55	107		
41		27/06/2009 14:00	27/05/2009 12:30	0.11	-1	0.19	57	166		
42		27/06/2009 14:30	27/05/2009 12:42	0.24	-1	0.27	17	119		
43		27/06/2009 15:00	27/05/2009 13:30	-0.05	3	0.13	13	98		
44		27/06/2009 15:30	27/05/2009 13:59	-0.02	1	0.15	7	118		
45		27/06/2009 16:00	27/05/2009 14:23	0.02	1	0.08	10	127		
46		27/06/2009 16:30	27/05/2009 14:59	0.04	1	0.10	11	158		
47		27/06/2009 17:00	27/05/2009 15:26	0.04	1	0.11	20	131		
48		27/06/2009 17:30	27/05/2009 15:57	0.09	-1	0.14	10	126		
49		27/06/2009 18:00	27/05/2009 16:28	-0.01	2	0.14	7	132		
50		27/06/2009 18:30	27/05/2009 16:58	-0.09	1	0.16	6	177		
51		27/06/2009 19:00	27/05/2009 17:25	0.00	5	0.13	24	159		
52		27/06/2009 19:30	27/05/2009 17:57	-0.07	2	0.15	49	125		
53		27/06/2009 20:00	27/05/2009 18:27	-0.08	33	0.14	81	116		

Transect number	Campaign	Time model	Time of measurement	Statistics for transects				Weight	Statistics for campaigns (weight of each transect is taken into account)	
				Bias mag (m)	Bias dir (degrees)	RMSE mag (m)	RMSE dir (degrees)		RMSE mag (m)	RMSE dir (degrees)
54	20090610_Ballooi_dwars	28/06/2009 09:30	10/06/2009 06:42	0.08	9	0.09	15	73	0.14	33
55		28/06/2009 10:00	10/06/2009 07:07	0.01	-4	0.10	7	59		
56		28/06/2009 10:30	10/06/2009 07:39	-0.03	-4	0.10	6	56		
57		28/06/2009 11:00	10/06/2009 08:08	0.02	-3	0.11	7	55		
58		28/06/2009 11:30	10/06/2009 08:39	0.03	-4	0.12	7	48		
59		28/06/2009 12:00	10/06/2009 09:11	0.03	4	0.11	7	44		
60		28/06/2009 12:30	10/06/2009 09:39	0.02	-5	0.10	6	41		
61		28/06/2009 13:00	10/06/2009 10:09	-0.05	5	0.12	7	50		
62		28/06/2009 13:30	10/06/2009 10:37	-0.05	-4	0.14	7	43		
63		28/06/2009 14:00	10/06/2009 11:10	-0.03	-4	0.11	6	42		
64		28/06/2009 14:30	10/06/2009 11:39	-0.05	4	0.13	6	42		
65		28/06/2009 15:00	10/06/2009 12:09	-0.09	5	0.12	6	35		
66		28/06/2009 15:30	10/06/2009 12:41	-0.27	-7	0.29	8	40		
67		28/06/2009 16:00	10/06/2009 13:08	0.48	49	0.48	99	53		
68		28/06/2009 16:30	10/06/2009 13:39	0.02	7	0.07	11	35		
69		28/06/2009 17:00	10/06/2009 14:09	-0.05	-4	0.11	6	40		
70		28/06/2009 17:30	10/06/2009 14:39	-0.01	-3	0.08	5	46		
71		28/06/2009 18:00	10/06/2009 15:08	-0.02	8	0.06	12	47		
72		28/06/2009 18:30	10/06/2009 15:39	0.01	6	0.08	12	43		
73		28/06/2009 19:00	10/06/2009 16:08	0.02	8	0.07	13	49		
74		28/06/2009 19:30	10/06/2009 16:39	0.05	-5	0.09	9	66		
75		28/06/2009 20:00	10/06/2009 17:08	0.00	-3	0.10	6	71		
76		28/06/2009 20:30	10/06/2009 17:39	-0.02	-4	0.09	7	76		
77		28/06/2009 21:00	10/06/2009 18:09	-0.07	-10	0.09	27	67		
78		28/06/2009 21:30	10/06/2009 18:39	0.05	-74	0.10	117	61		
79		28/06/2009 22:00	10/06/2009 19:08	0.04	-9	0.09	11	69		
80		28/06/2009 22:30	10/06/2009 19:20	0.06	11	0.11	15	59		

Transect number	Campaign	Time model	Time of measurement	Statistics for transects				Weight	Statistics for campaigns (weight of each transect is taken into account)	
				Bias mag (m)	Bias dir (degrees)	RMSE mag (m)	RMSE dir (degrees)		RMSE mag (m)	RMSE dir (degrees)
81	20090623_Driegoten	23/06/2009 07:00	23/06/2009 07:24	0.04	-3	0.12	6	318	0.16	22
82		23/06/2009 07:30	23/06/2009 07:29	0.08	-1	0.14	8	370		
83		23/06/2009 08:00	23/06/2009 07:56	0.07	-2	0.14	6	328		
84		23/06/2009 08:30	23/06/2009 08:28	0.06	-1	0.13	6	292		
85		23/06/2009 09:00	23/06/2009 09:00	0.06	-2	0.13	8	481		
86		23/06/2009 09:30	23/06/2009 09:23	0.09	-1	0.15	6	316		
87		23/06/2009 10:00	23/06/2009 10:00	0.07	-2	0.14	6	271		
88		23/06/2009 10:30	23/06/2009 10:27	0.08	-2	0.15	6	391		
89		23/06/2009 11:00	23/06/2009 10:57	0.08	-1	0.12	5	273		
90		23/06/2009 11:30	23/06/2009 11:30	0.06	-1	0.11	5	253		
91		23/06/2009 12:00	23/06/2009 11:51	-0.49	46	0.49	73	328		
92		23/06/2009 12:30	23/06/2009 12:27	0.01	2	0.11	5	270		
93		23/06/2009 13:00	23/06/2009 12:58	0.00	3	0.11	6	250		
94		23/06/2009 13:30	23/06/2009 13:18	-0.02	1	0.13	7	283		
95		23/06/2009 14:00	23/06/2009 13:59	0.02	2	0.10	5	289		
96		23/06/2009 14:30	23/06/2009 14:35	-0.02	2	0.10	6	481		
97		23/06/2009 15:00	23/06/2009 15:00	0.03	1	0.09	5	227		
98		23/06/2009 15:30	23/06/2009 15:39	0.00	1	0.17	4	234		
99		23/06/2009 16:00	23/06/2009 16:05	0.19	3	0.25	5	332		
100		23/06/2009 16:30	23/06/2009 16:18	-0.01	1	0.14	4	308		
101		23/06/2009 17:00	23/06/2009 16:53	-0.08	3	0.11	6	278		
102		23/06/2009 17:30	23/06/2009 17:21	-0.15	5	0.19	85	294		
103		23/06/2009 18:00	23/06/2009 17:59	-0.01	0	0.06	6	306		
104		23/06/2009 18:30	23/06/2009 18:29	0.01	-1	0.06	4	222		
105		23/06/2009 19:00	23/06/2009 19:01	0.02	-3	0.08	6	209		
106		23/06/2009 19:30	23/06/2009 19:33	0.05	-1	0.10	5	316		
107		23/06/2009 20:00	23/06/2009 20:05	0.04	-2	0.13	5	338		
108		23/06/2009 20:30	23/06/2009 20:11	0.07	-2	0.15	7	277		

Transect number	Campaign	Time model	Time of measurement	Statistics for transects				Weight	Statistics for campaigns (weight of each transect is taken into account)	
				Bias mag (m)	Bias dir (degrees)	RMSE mag (m)	RMSE dir (degrees)		RMSE mag (m)	RMSE dir (degrees)
109	20110805_Branst_Bijboot_Streampro	26/06/2009 06:30	05/08/2011 07:31	0.13	wrong measurement of direction	0.16	wrong measurement of direction	746	0.14	wrong measurement of direction
110		26/06/2009 07:00	05/08/2011 07:48	0.13		0.11		2544		
111		26/06/2009 08:00	05/08/2011 08:44	0.12		0.14		1570		
112		26/06/2009 11:30	05/08/2011 12:32	0.14		0.18		604		
113		26/06/2009 12:00	05/08/2011 13:04	0.10		0.16		2424		
114		26/06/2009 13:00	05/08/2011 13:47	0.11		0.14		1302		
115		26/06/2009 13:00	05/08/2011 14:10	0.09		0.17		1368		
116		26/06/2009 14:00	05/08/2011 14:53	0.11		0.18		890		
117		26/06/2009 14:00	05/08/2011 15:08	0.17		0.11		1269		
118		26/06/2009 14:30	05/08/2011 15:31	-0.01		0.16		1911		
119		26/06/2009 15:00	05/08/2011 16:03	-0.18		0.20		2078		
120		26/06/2009 16:00	05/08/2011 16:45	-0.02		0.10		1363		
121		26/06/2009 16:00	05/08/2011 17:08	-0.09		0.15		691		
122		26/06/2009 16:30	05/08/2011 17:26	-0.08		0.11		1428		
123		26/06/2009 17:00	05/08/2011 17:50	-0.06		0.14		1318		
124		26/06/2009 17:30	05/08/2011 18:13	-0.03		0.10		2787		
125		26/06/2009 18:00	05/08/2011 19:03	0.07		0.08		780		

Transect number	Campaign	Time model	Time of measurement	Statistics for transects: Bias mag (m)	Bias dir (degrees)	RMSE mag (m)	RMSE dir (degrees)	Weight	Statistics for campaigns (weight of each transect is taken into account): RMSE mag (m)	RMSE dir (degrees)
126	20090625_Schoonaarde	25/06/2009 07:00	25/06/2009 07:13	0.24	1	0.26	10	150	0.17	36
127		25/06/2009 07:30	25/06/2009 07:34	0.15	0	0.19	10	164		
128		25/06/2009 08:00	25/06/2009 07:57	-0.03	0	0.11	12	251		
129		25/06/2009 08:30	25/06/2009 08:19	-0.09	-32	0.13	144	171		
130		25/06/2009 09:00	25/06/2009 08:59	-0.04	-5	0.08	12	177		
131		25/06/2009 09:30	25/06/2009 09:27	0.07	-4	0.12	27	234		
132		25/06/2009 10:00	25/06/2009 09:58	0.00	2	0.13	10	228		
133		25/06/2009 10:30	25/06/2009 10:32	-0.04	2	0.11	8	298		
134		25/06/2009 11:00	25/06/2009 10:58	-0.02	1	0.16	14	292		
135		25/06/2009 11:30	25/06/2009 11:29	0.02	-1	0.14	12	206		
136		25/06/2009 12:00	25/06/2009 11:59	0.04	-1	0.14	8	189		
137		25/06/2009 12:30	25/06/2009 12:31	0.09	-2	0.18	17	122		
138		25/06/2009 13:00	25/06/2009 12:59	0.02	2	0.12	15	174		
139		25/06/2009 13:30	25/06/2009 13:29	0.04	6	0.12	20	164		
140		25/06/2009 14:00	25/06/2009 14:05	0.02	2	0.13	15	194		
141		25/06/2009 14:30	25/06/2009 14:24	0.01	2	0.11	12	176		
142		25/06/2009 15:00	25/06/2009 14:58	0.03	1	0.12	12	210		
143		25/06/2009 15:30	25/06/2009 15:34	0.08	-24	0.14	123	136		
144		25/06/2009 16:00	25/06/2009 15:56	-0.11	7	0.14	29	125		
145		25/06/2009 16:30	25/06/2009 16:29	0.05	6	0.11	35	123		
146		25/06/2009 17:00	25/06/2009 17:05	0.00	4	0.11	16	164		
147		25/06/2009 17:30	25/06/2009 17:29	0.06	0	0.11	9	155		
148		25/06/2009 18:00	25/06/2009 17:58	0.11	7	0.17	31	247		
149		25/06/2009 18:30	25/06/2009 18:36	0.01	0	0.12	7	185		
150		25/06/2009 19:00	25/06/2009 18:59	0.11	2	0.16	8	195		
151		25/06/2009 19:30	25/06/2009 19:28	0.16	-2	0.21	8	228		
152		25/06/2009 20:00	25/06/2009 19:58	0.02	1	0.11	11	223		
153		25/06/2009 20:30	25/06/2009 20:00	-0.51	2	0.53	10	211		
Total for all Campaigns (weighted average)				0.01	2	0.15	36			
Total for all Campaigns (not weighted average)									**0.16**	**35**

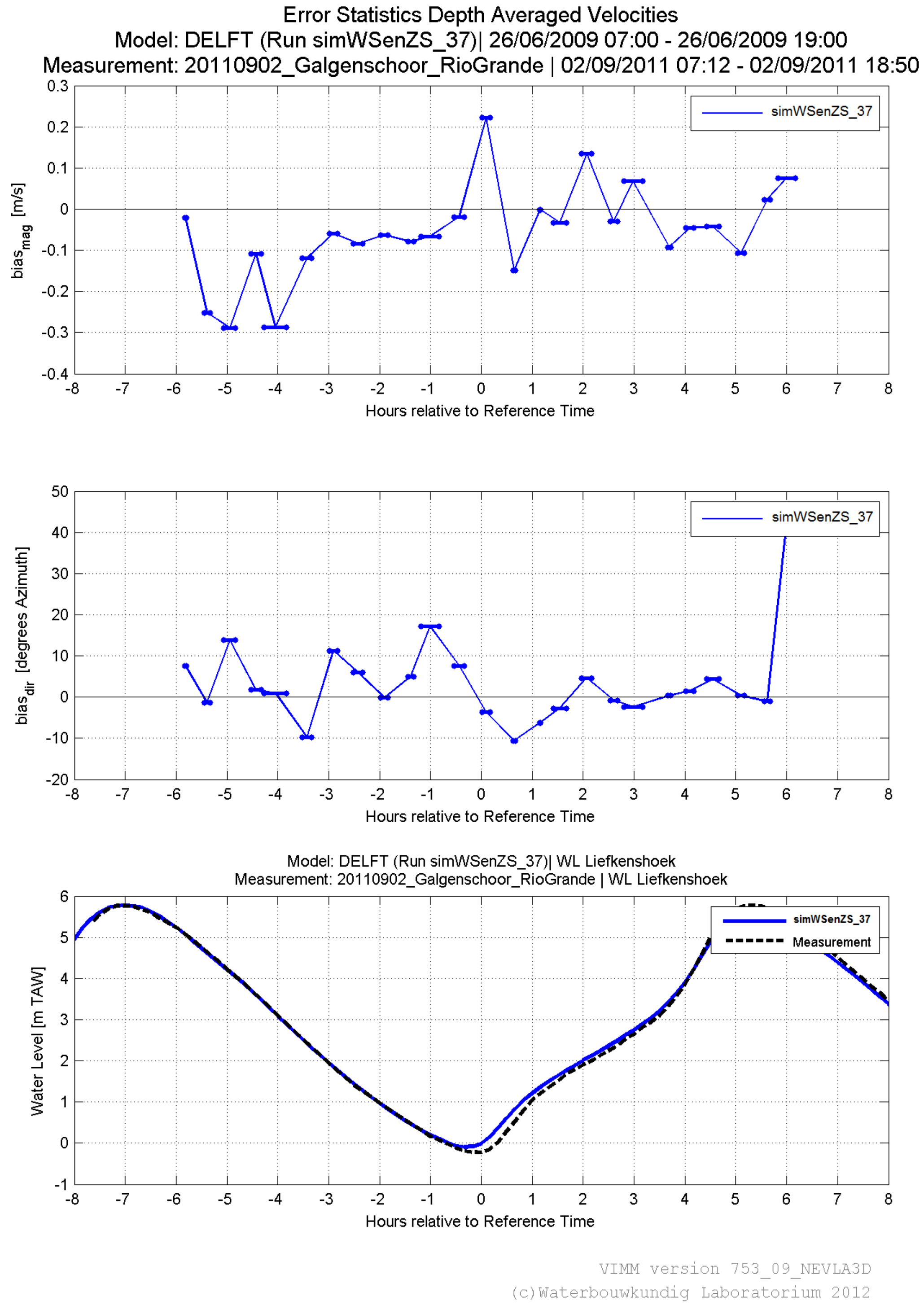


Figure 103 - Bias of velocity magnitude and direction at Galgenschoor (model vs. ADCP measurement)

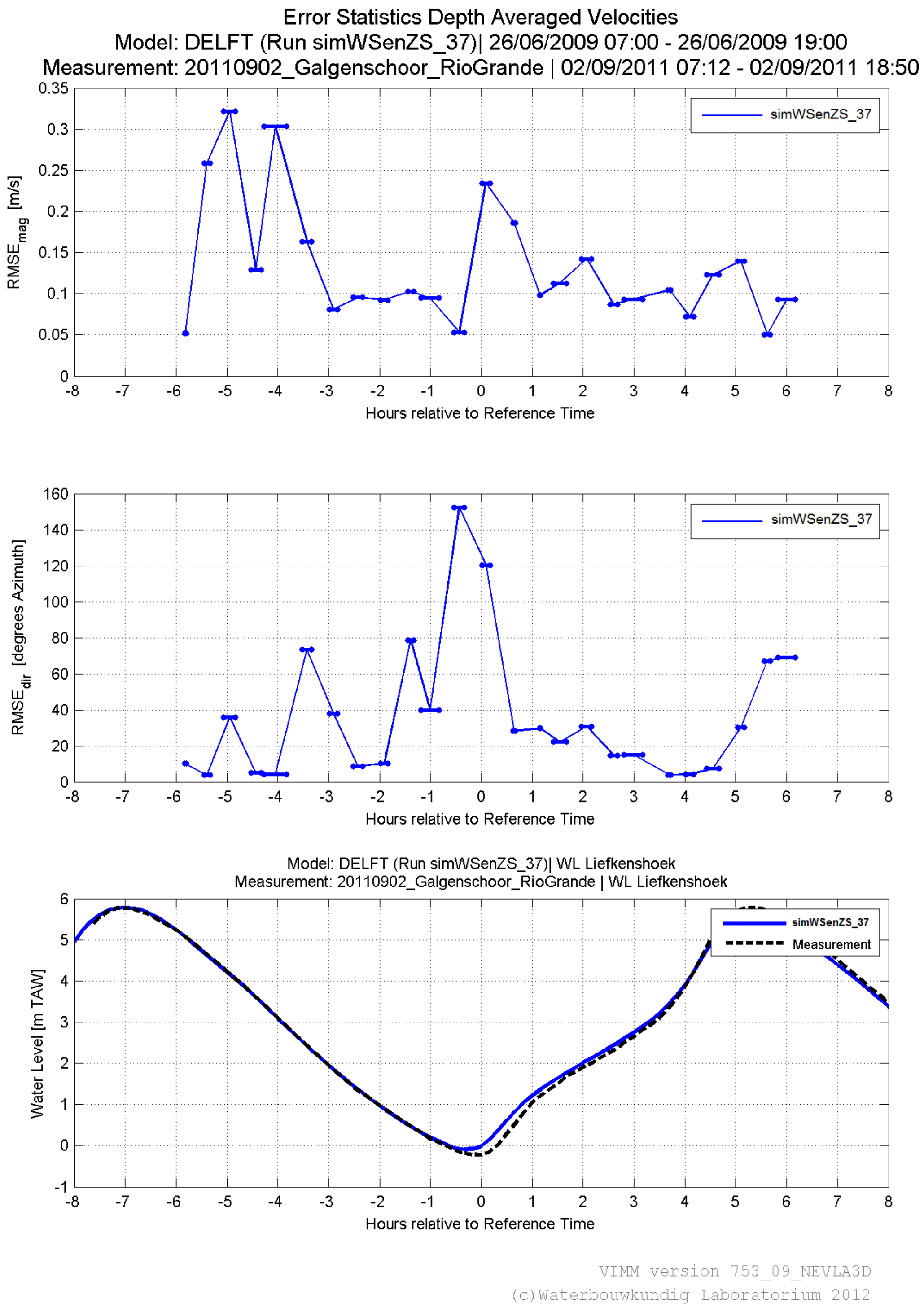


Figure 104 - RMSE of velocity magnitude and direction at Galgenschoor (model vs. ADCP measurement)

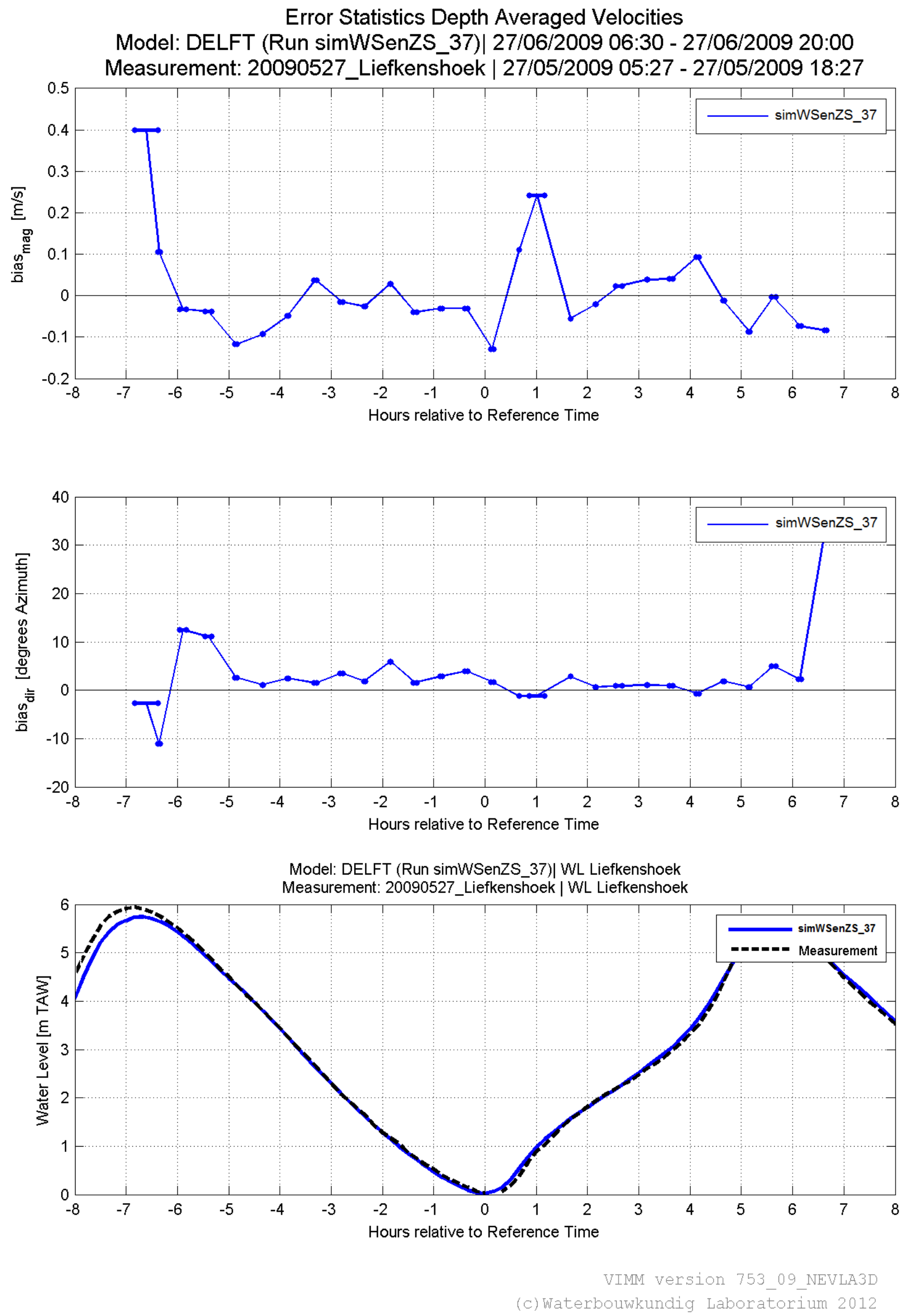


Figure 105 - Bias of velocity magnitude and direction at Liefkenshoek (model vs. ADCP measurement)

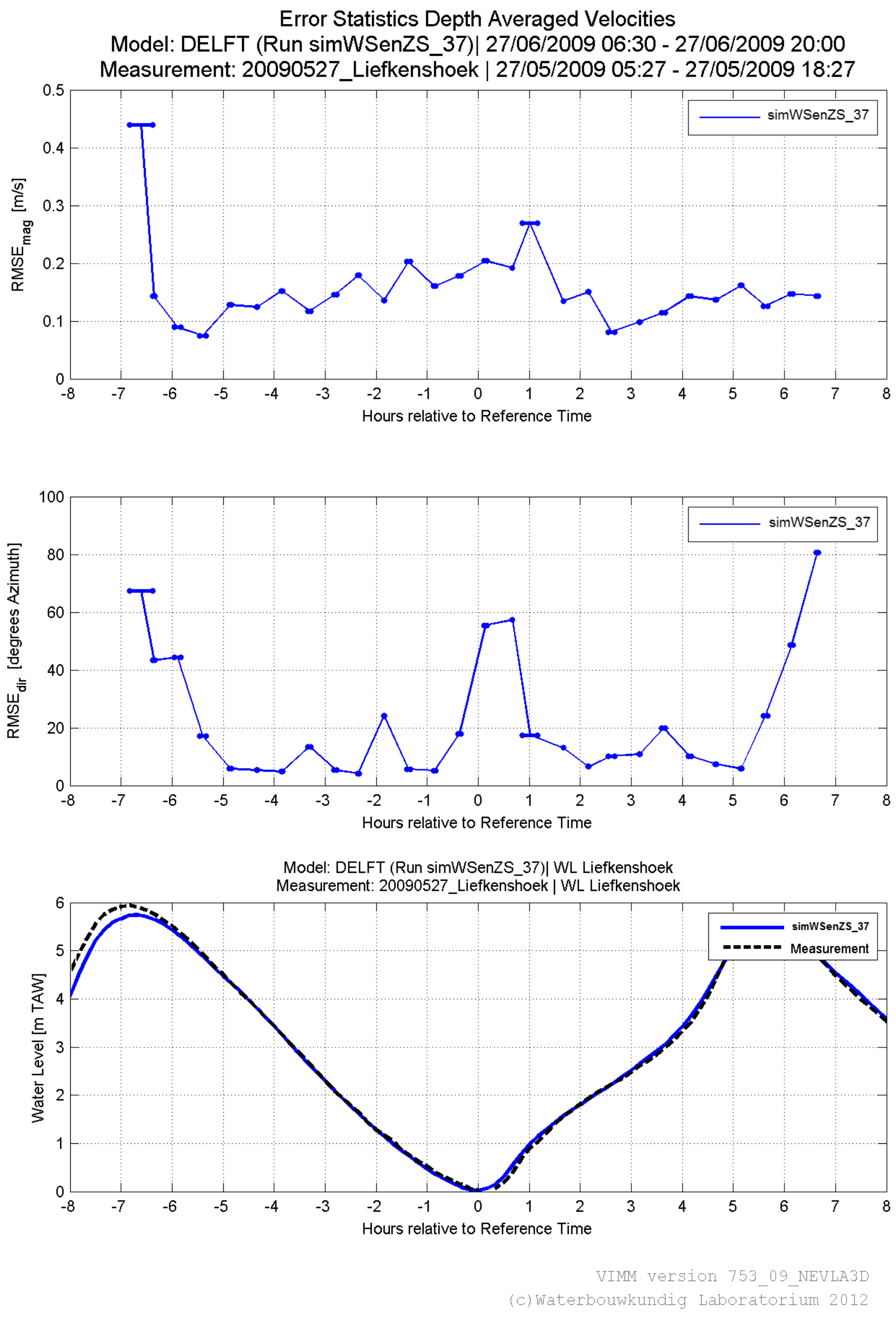


Figure 106 - RMSE of velocity magnitude and direction at Liefkenshoek (model vs. ADCP measurement)

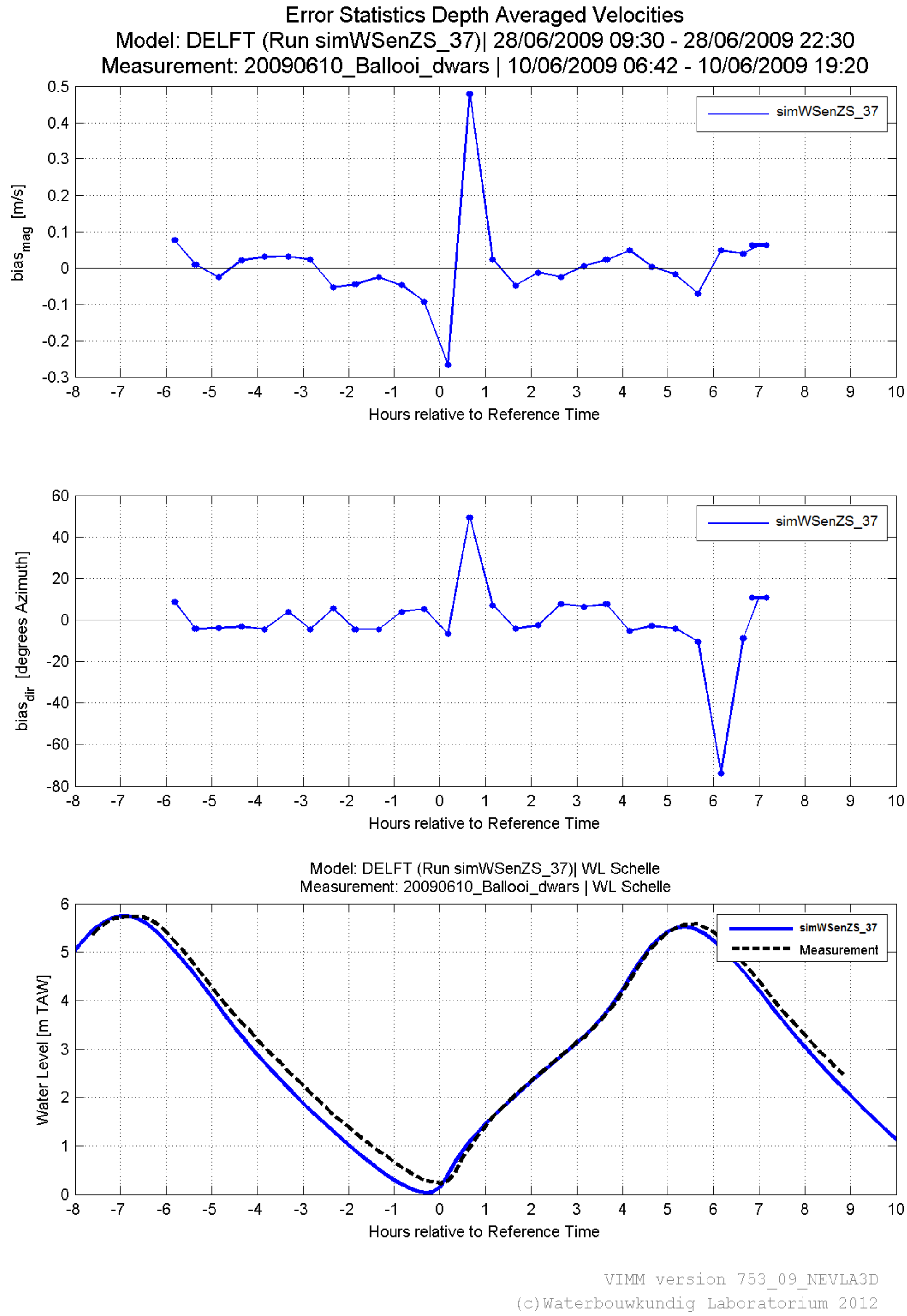


Figure 107 - Bias of velocity magnitude and direction at Ballooi (dwars) (model vs. ADCP measurement)

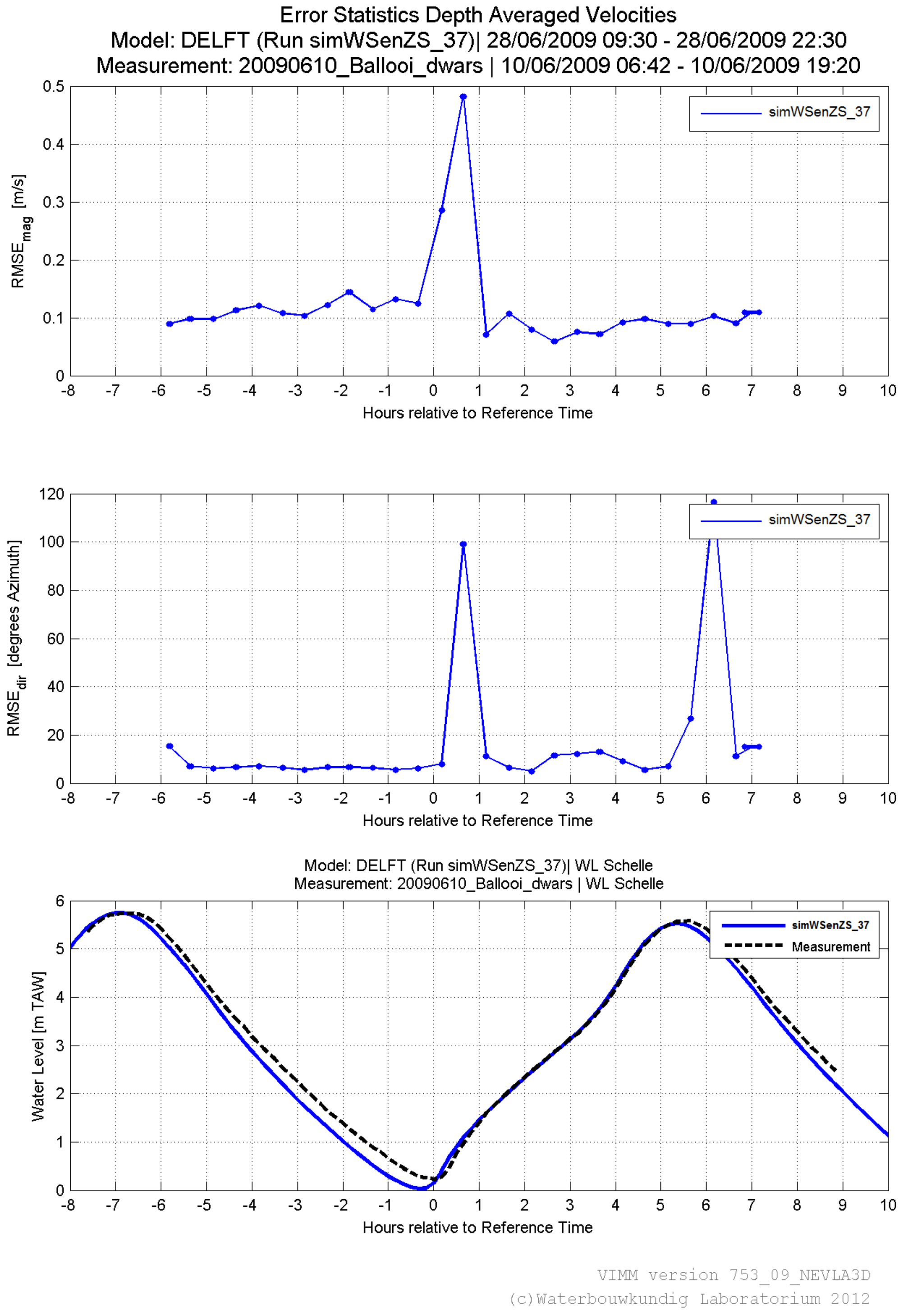


Figure 108 - RMSE of velocity magnitude and direction at Ballooi (dwars) (model vs. ADCP measurement)

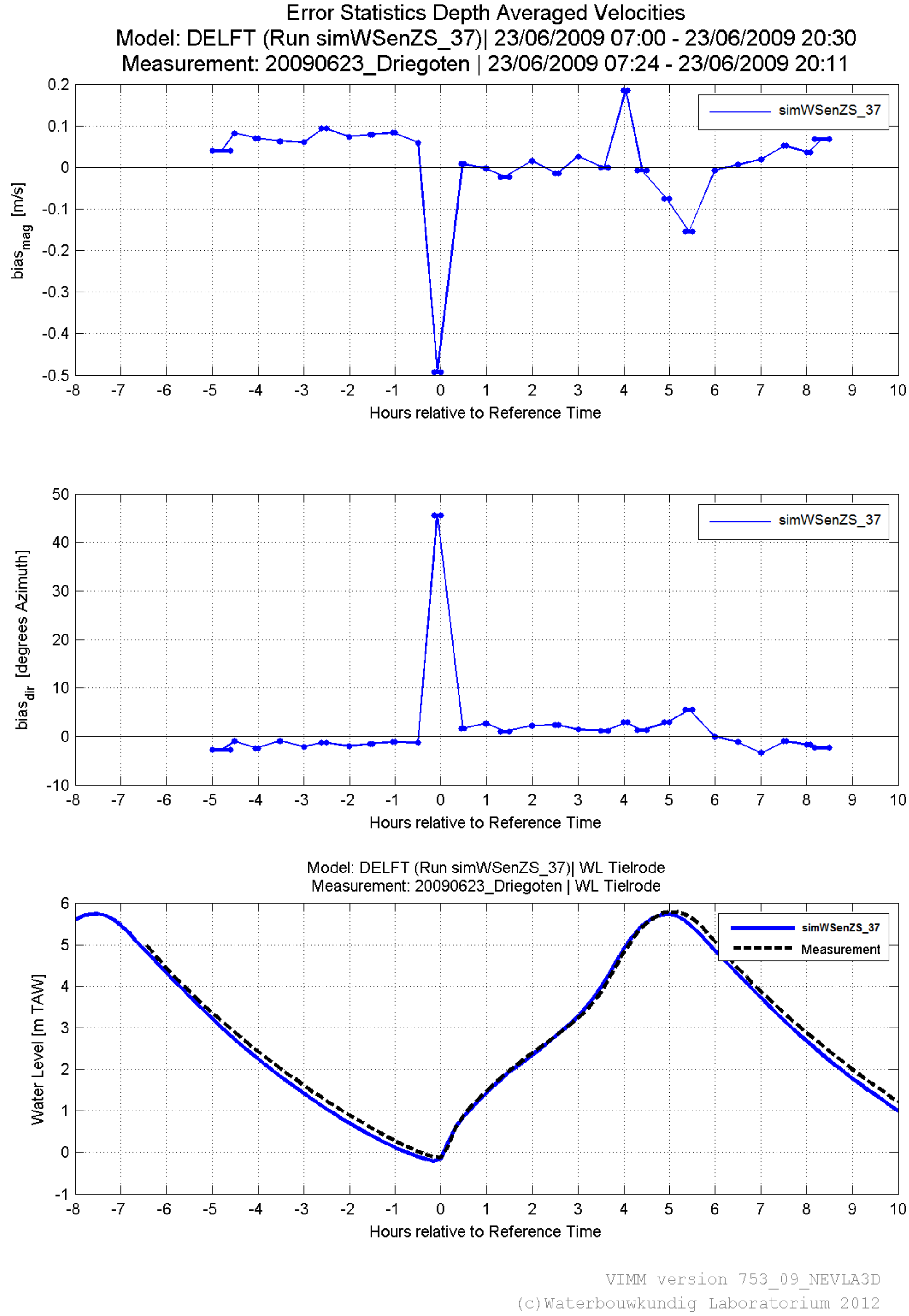


Figure 109 - Bias of velocity magnitude and direction at Driegoten (model vs. ADCP measurement)

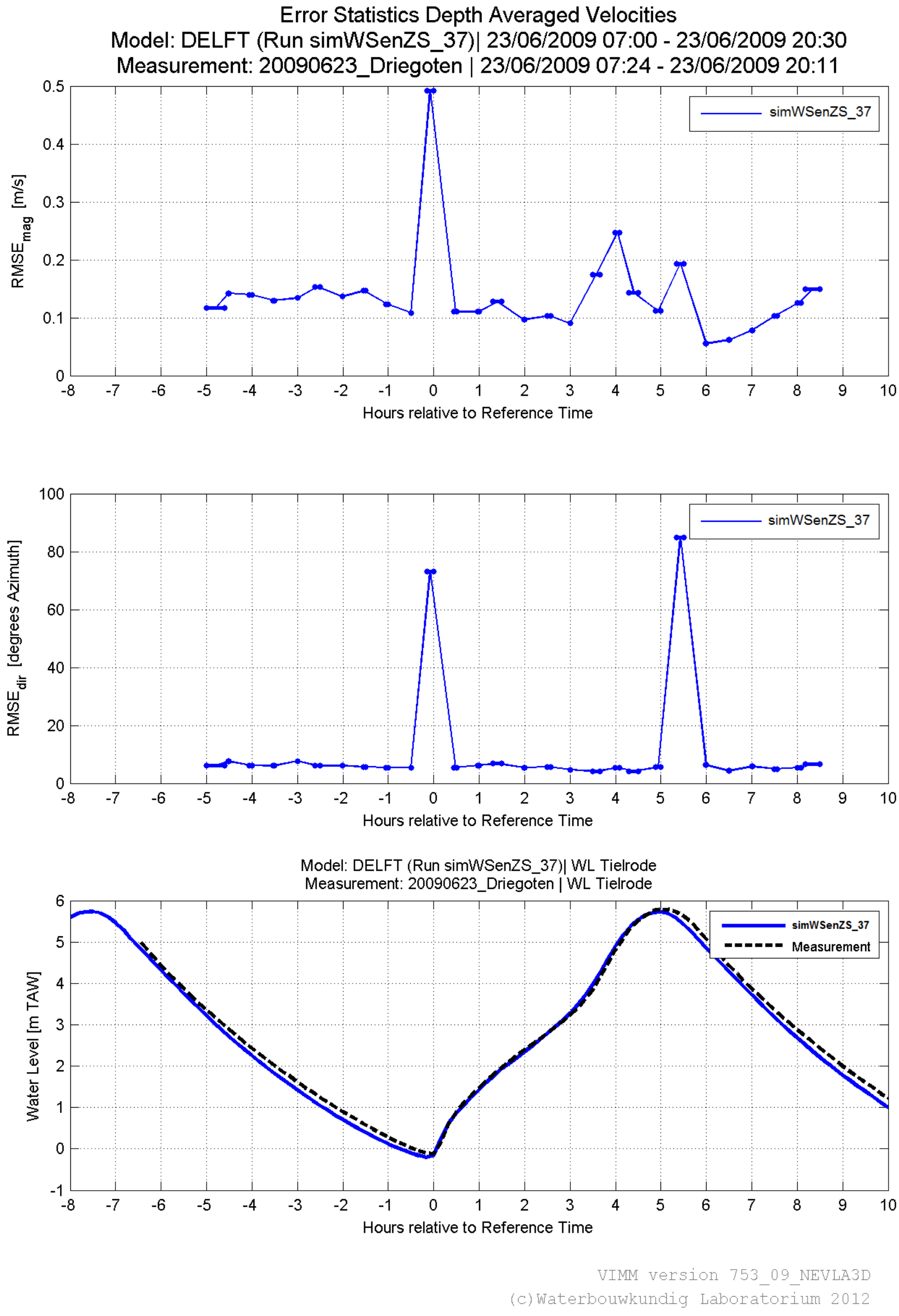


Figure 110 - RMSE of velocity magnitude and direction at Driegoten (model vs. ADCP measurement)

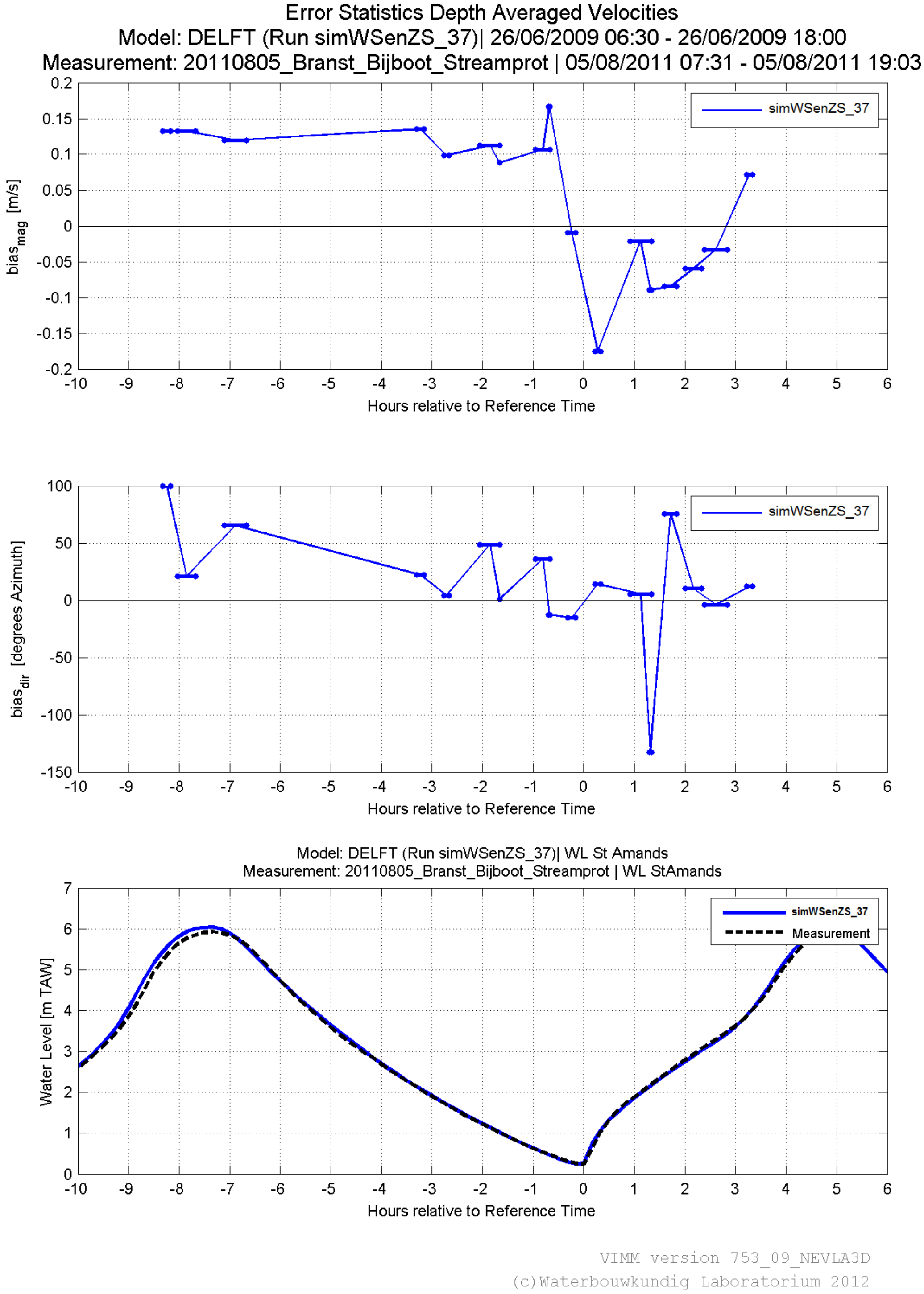


Figure 111 - Bias of velocity magnitude and direction at Branst (StreamPro) (measured direction is wrong) (model vs. ADCP measurement)

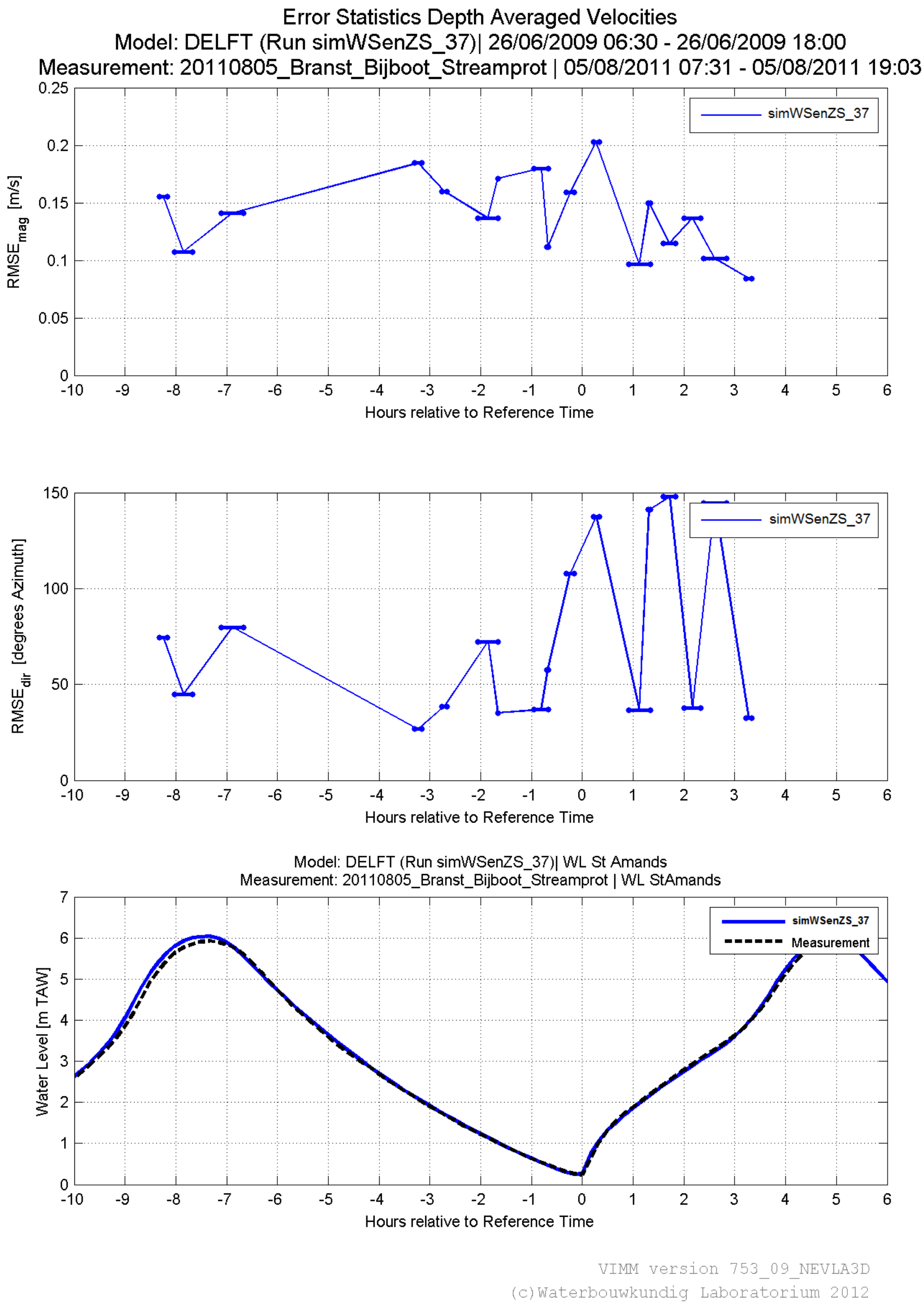


Figure 112 - RMSE of velocity magnitude and direction at Branst (StreamPro) (measured direction is wrong) (model vs. ADCP measurement)

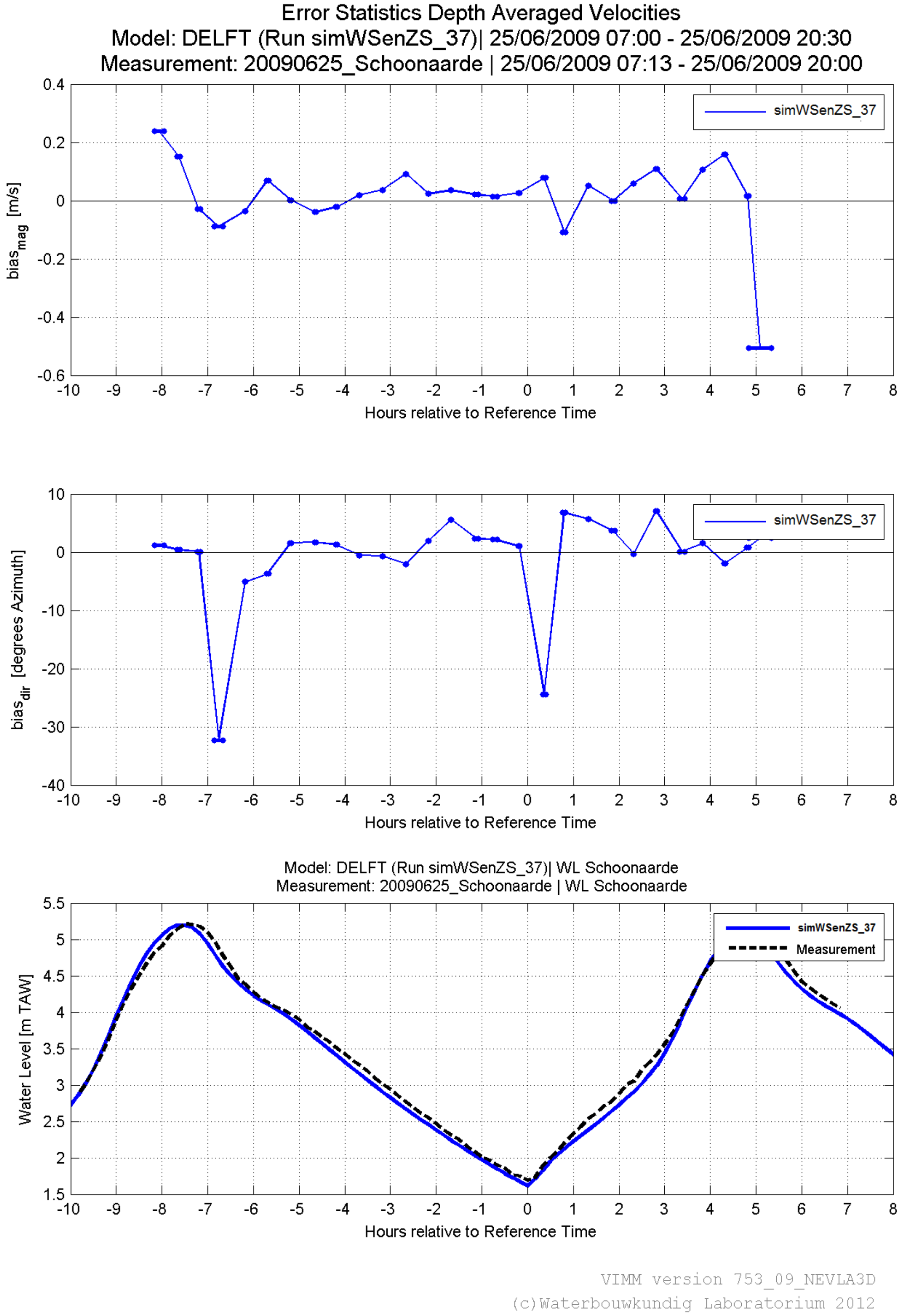


Figure 113 - Bias of velocity magnitude at Schoonaarde (model vs. ADCP measurement)

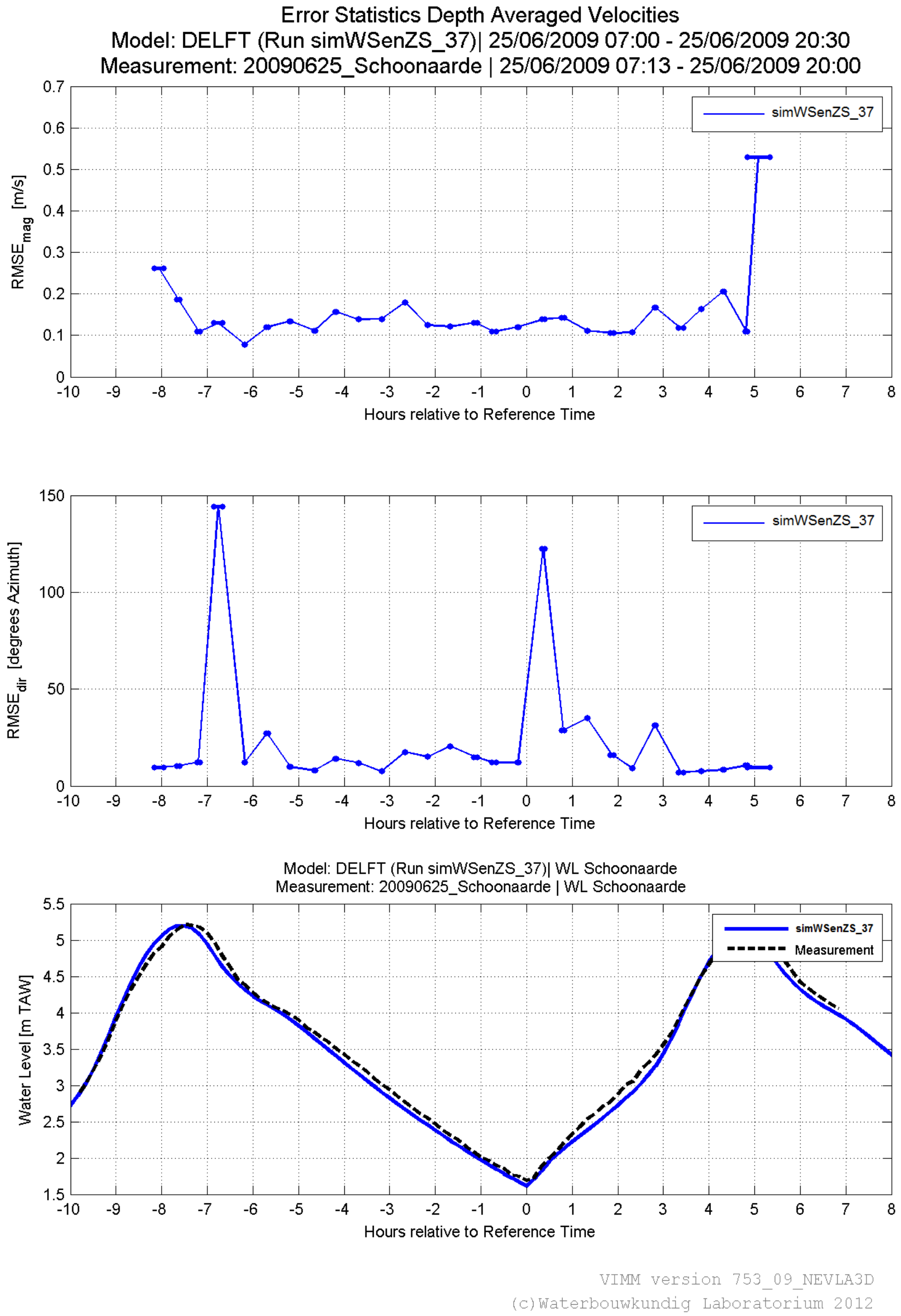


Figure 114 - RMSE of velocity magnitude at Schoonaarde (model vs. ADCP measurement)

Appendix 2. Results of the model validation

Discharges

Table 37. Statistical parameters of discharges used for the validation (model vs. measurement)

Station	BIAS TS	RMSE TS		Order of magnitude of max discharge
	[m³/s]	[m³/s]	% of Qmax	[m³/s]
R1 Vaarwater boven Bath	-41.8	1009.1	5.6	18000
R1 Ballastplaat 1*	35.4	599.5	15	4000
R1 Ballastplaat 2*	16.1	499.9	14	3500
R2 total	993.6	1662.2	6.6	25000

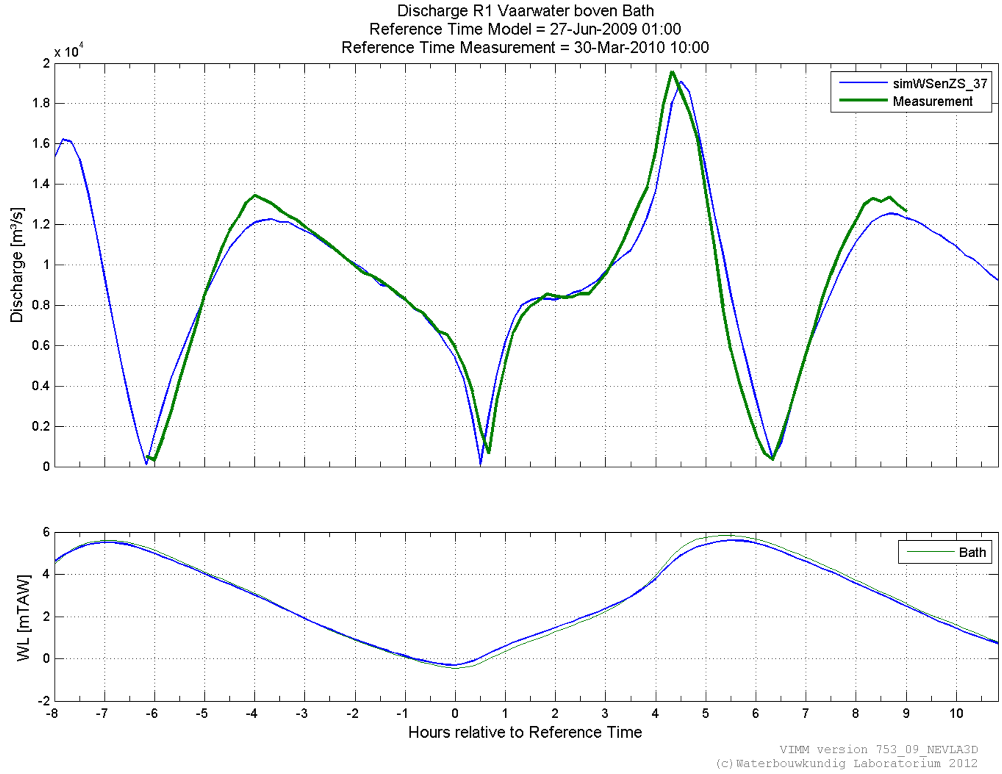


Figure 115 - Calculated and measured discharges R1 Vaarwater boven Bath

*The cross section R1 Ballastplaat 1 (from 0 to 800 m) is longer than R1 Ballastplaat 2 (from 0 to 700 m)

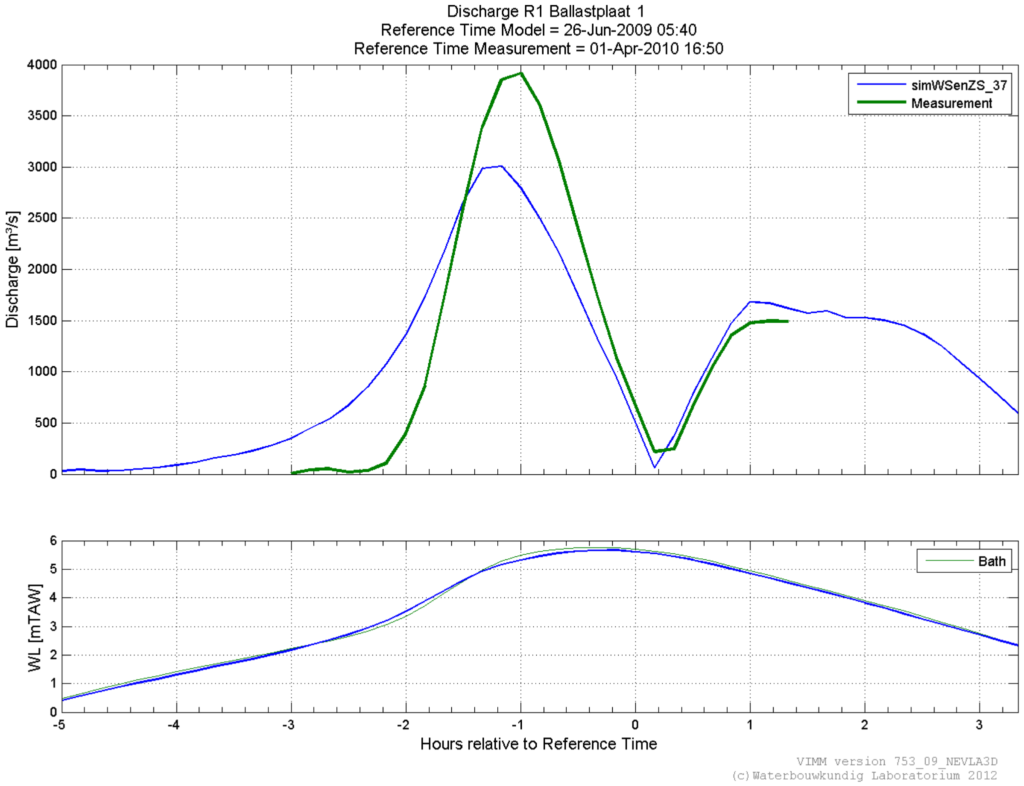


Figure 116 - Calculated and measured discharges R1 Ballastplaat 1

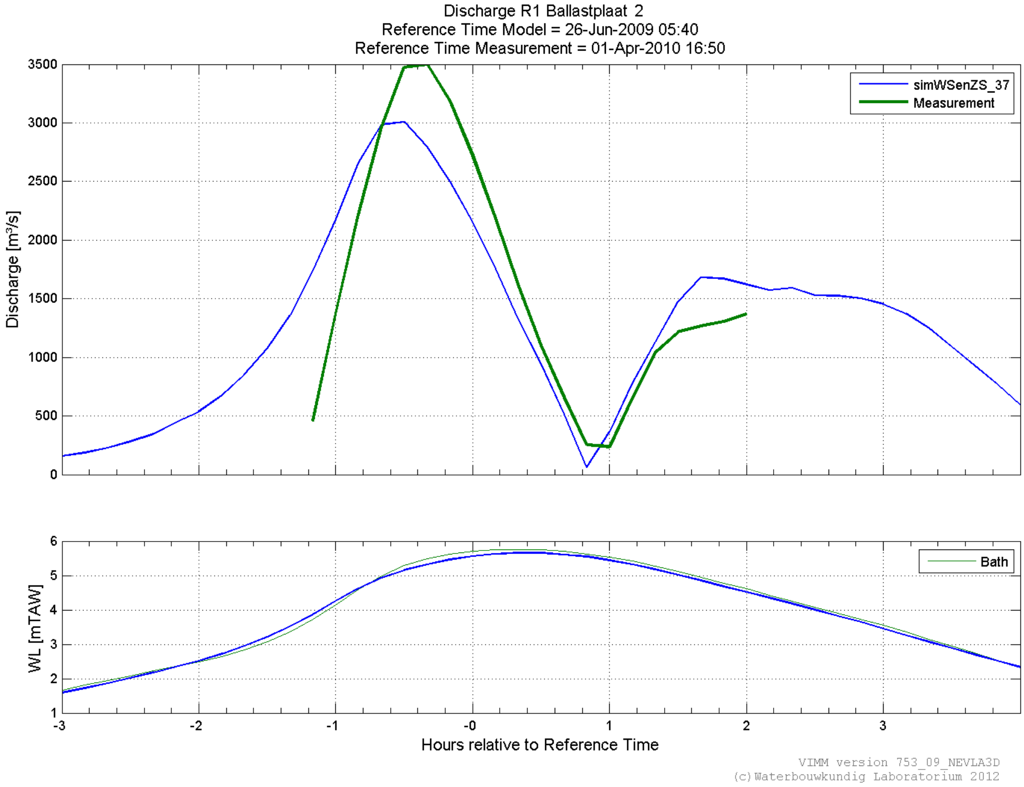


Figure 117 - Calculated and measured discharges R1 Ballastplaat 2

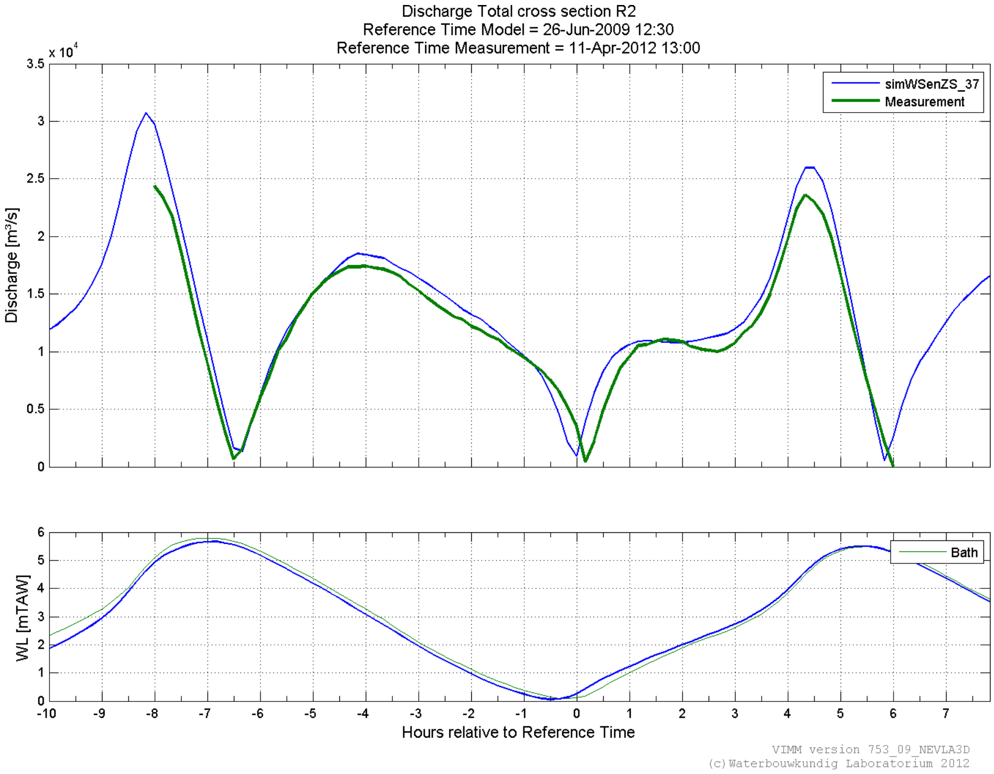


Figure 118 - Calculated and measured discharges R2 total cross section

ADCP velocities

Table 38. Statistical parameters of velocities (validated model vs. ADCP measurements)

Transect number	Campaign	Time model	Time of measurement	Statistics for transects				Weight	Statistics for campaigns (weight of each transect is taken into account)	
				Bias mag (m)	Bias dir (degrees)	RMSE mag (m)	RMSE dir (degrees)		RMSE mag (m)	RMSE dir (degrees)
1	20060912_Doelpolder	26/06/2009 06:30	12/09/2006 07:03	0.10	32	0.15	118	174	0.15	51
2		26/06/2009 07:00	12/09/2006 07:27	-0.12	63	0.13	65	29		
3		26/06/2009 07:30	12/09/2006 07:50	-0.10	13	0.11	14	30		
4		26/06/2009 08:00	12/09/2006 08:16	-0.08	-1	0.10	2	31		
5		26/06/2009 08:30	12/09/2006 08:52	-0.03	0	0.08	4	30		
6		26/06/2009 09:00	12/09/2006 09:20	-0.01	-3	0.11	4	32		
7		26/06/2009 09:30	12/09/2006 09:50	0.06	-2	0.10	6	33		
8		26/06/2009 10:00	12/09/2006 10:17	0.08	-7	0.11	8	30		
9		26/06/2009 10:30	12/09/2006 10:46	0.11	-13	0.13	18	48		
10		26/06/2009 11:00	12/09/2006 11:18	0.02	11	0.15	12	28		
11		26/06/2009 11:30	12/09/2006 11:47	0.26	10	0.27	11	56		
12		26/06/2009 12:00	12/09/2006 12:22	0.12	46	0.14	59	35		
13		26/06/2009 12:30	12/09/2006 12:45	0.02	-15	0.05	40	38		
14		26/06/2009 13:00	12/09/2006 13:17	0.18	0	0.22	5	52		
15		26/06/2009 13:30	12/09/2006 13:51	-0.17	-2	0.19	4	25		
16		26/06/2009 14:00	12/09/2006 14:16	0.01	2	0.08	6	50		
17		26/06/2009 14:30	12/09/2006 14:47	-0.16	-4	0.18	8	31		
18		26/06/2009 15:00	12/09/2006 15:17	-0.24	4	0.24	6	52		
19		26/06/2009 15:30	12/09/2006 15:45	-0.13	-7	0.14	7	40		
20		26/06/2009 16:00	12/09/2006 16:24	0.01	12	0.06	12	34		
21		26/06/2009 16:30	12/09/2006 16:45	0.13	-5	0.16	6	40		
22		26/06/2009 17:00	12/09/2006 17:15	0.00	0	0.14	4	199		
23		26/06/2009 17:30	12/09/2006 17:51	-0.08	3	0.10	4	36		
24		26/06/2009 18:00	12/09/2006 18:17	0.00	-1	0.09	3	54		
25		26/06/2009 18:30	12/09/2006 18:51	-0.01	-2	0.04	5	29		
26		26/06/2009 19:00	12/09/2006 18:54	-0.12	-2	0.13	103	54		

Transect number	Campaign	Time model	Time of measurement	Statistics for transects				Weight	Statistics for campaigns (weight of each transect is taken into account)	
				Bias mag (m)	Bias dir (degrees)	RMSE mag (m)	RMSE dir (degrees)		RMSE mag (m)	RMSE dir (degrees)
27	20100429_Oosterweel	26/06/2009 19:30	29/04/2010 05:07	-0.20	-33	0.20	69	137	0.19	24
28		26/06/2009 20:00	29/04/2010 05:07	0.30	0	0.31	5	137		
29		26/06/2009 20:30	29/04/2010 05:37	0.09	2	0.20	3	166		
30		26/06/2009 21:00	29/04/2010 06:08	-0.03	3	0.14	6	155		
31		26/06/2009 21:30	29/04/2010 06:42	-0.05	0	0.19	4	141		
32		26/06/2009 22:00	29/04/2010 07:13	0.02	1	0.19	5	164		
33		26/06/2009 22:30	29/04/2010 07:37	-0.03	0	0.19	5	145		
34		26/06/2009 23:00	29/04/2010 08:08	-0.04	2	0.21	7	163		
35		26/06/2009 23:30	29/04/2010 08:38	-0.05	-2	0.19	6	132		
36		27/06/2009 00:00	29/04/2010 09:09	-0.01	-3	0.16	7	144		
37		27/06/2009 00:30	29/04/2010 09:39	-0.02	-2	0.16	7	149		
38		27/06/2009 01:00	29/04/2010 10:07	-0.01	-2	0.15	7	121		
39		27/06/2009 01:30	29/04/2010 10:33	-0.05	-2	0.15	9	147		
40		27/06/2009 02:00	29/04/2010 11:08	-0.14	-3	0.19	9	122		
41		27/06/2009 02:30	29/04/2010 11:40	0.03	2	0.09	8	132		
42		27/06/2009 03:00	29/04/2010 12:13	-0.02	-1	0.10	9	129		
43		27/06/2009 03:30	29/04/2010 12:36	-0.01	-2	0.10	7	133		
44		27/06/2009 04:00	29/04/2010 13:12	-0.01	4	0.09	10	146		
45		27/06/2009 04:30	29/04/2010 13:41	0.04	4	0.10	9	180		
46		27/06/2009 05:00	29/04/2010 14:10	0.12	-1	0.15	9	139		
47		27/06/2009 05:30	29/04/2010 14:37	0.21	-1	0.23	8	145		
48		27/06/2009 06:00	29/04/2010 15:07	0.19	-1	0.21	7	151		
49		27/06/2009 06:30	29/04/2010 15:37	-0.19	-2	0.23	7	152		
50		27/06/2009 07:00	29/04/2010 16:08	-0.07	-4	0.14	10	151		
51		27/06/2009 07:30	29/04/2010 16:40	-0.08	1	0.10	10	169		
52		27/06/2009 08:00	29/04/2010 17:10	0.02	71	0.12	106	142		
53		27/06/2009 08:30	29/04/2010 17:36	0.20	5	0.22	9	312		
54		27/06/2009 09:00	29/04/2010 17:48	0.33	-1	0.39	7	132		

Transect number	Campaign	Time model	Time of measurement	Statistics for transects				Weight	Statistics for campaigns (weight of each transect is taken into account)	
				Bias mag (m)	Bias dir (degrees)	RMSE mag (m)	RMSE dir (degrees)		RMSE mag (m)	RMSE dir (degrees)
55	20090610_Notelaer_langs	28/06/2009 09:30	10/06/2009 07:00	-0.21	0	0.22	4	1179	0.14	26
56		28/06/2009 10:00	10/06/2009 07:00	-0.05	1	0.08	4	1179		
57		28/06/2009 10:30	10/06/2009 07:10	-0.15	2	0.19	19	6461		
58		28/06/2009 11:30	10/06/2009 08:35	-0.10	2	0.15	6	1987		
59		28/06/2009 12:00	10/06/2009 08:52	-0.12	2	0.18	12	2695		
60		28/06/2009 12:30	10/06/2009 09:26	-0.14	2	0.18	17	1859		
61		28/06/2009 13:00	10/06/2009 09:46	-0.11	2	0.19	13	4615		
62		28/06/2009 13:30	10/06/2009 10:46	-0.07	1	0.13	9	2868		
63		28/06/2009 14:00	10/06/2009 11:03	-0.03	2	0.15	19	4013		
64		28/06/2009 14:30	10/06/2009 11:42	-0.05	1	0.14	14	3921		
65		28/06/2009 15:00	10/06/2009 12:01	-0.08	2	0.14	11	5006		
66		28/06/2009 15:30	10/06/2009 12:45	-0.14	5	0.19	93	4635		
67		28/06/2009 16:00	10/06/2009 13:07	-0.01	2	0.11	11	3990		
68		28/06/2009 16:30	10/06/2009 13:26	-0.07	2	0.14	12	6002		
69		28/06/2009 17:00	10/06/2009 13:54	-0.08	2	0.13	16	4110		
70		28/06/2009 17:30	10/06/2009 14:27	0.00	3	0.10	14	3413		
71		28/06/2009 18:00	10/06/2009 15:02	0.00	3	0.08	16	3433		
72		28/06/2009 18:30	10/06/2009 15:39	-0.02	3	0.07	11	2689		
73		28/06/2009 19:00	10/06/2009 15:55	0.02	3	0.09	14	2295		
74		28/06/2009 19:30	10/06/2009 16:22	0.09	3	0.12	6	3623		
75		28/06/2009 20:00	10/06/2009 17:04	0.02	2	0.12	5	4116		
76		28/06/2009 20:30	10/06/2009 17:32	-0.03	2	0.08	10	2623		
77		28/06/2009 21:00	10/06/2009 18:10	-0.03	-4	0.07	84	935		
78		28/06/2009 21:30	10/06/2009 18:44	-0.04	1	0.08	11	2831		
79		28/06/2009 22:00	10/06/2009 19:01	-0.07	1	0.12	6	5055		
80		28/06/2009 22:30	10/06/2009 19:32	-0.17	2	0.19	6	1898		

Transect number	Campaign	Time model	Time of measurement	Statistics for transects				Weight	Statistics for campaigns (weight of each transect is taken into account)	
				Bias mag (m)	Bias dir (degrees)	RMSE mag (m)	RMSE dir (degrees)		RMSE mag (m)	RMSE dir (degrees)
81	20090611_Notelaer_dwars	28/06/2009 09:00	11/06/2009 07:15	-0.04	75	0.12	109	79	0.16	28
82		28/06/2009 09:30	11/06/2009 07:18	0.24	-10	0.25	23	60		
83		28/06/2009 10:00	11/06/2009 07:48	0.06	3	0.13	8	64		
84		28/06/2009 10:30	11/06/2009 08:19	0.01	8	0.15	9	61		
85		28/06/2009 11:00	11/06/2009 09:07	-0.04	-2	0.17	5	58		
86		28/06/2009 11:30	11/06/2009 09:19	0.00	7	0.12	10	65		
87		28/06/2009 12:00	11/06/2009 09:49	-0.03	8	0.16	11	58		
88		28/06/2009 12:30	11/06/2009 10:24	-0.04	-2	0.15	5	50		
89		28/06/2009 13:00	11/06/2009 10:48	-0.05	8	0.12	11	61		
90		28/06/2009 13:30	11/06/2009 11:18	-0.06	-3	0.18	6	49		
91		28/06/2009 14:00	11/06/2009 11:48	-0.07	9	0.17	11	53		
92		28/06/2009 14:30	11/06/2009 12:18	-0.07	9	0.16	10	54		
93		28/06/2009 15:00	11/06/2009 12:48	-0.14	11	0.19	14	56		
94		28/06/2009 15:30	11/06/2009 13:19	-0.33	2	0.35	8	57		
95		28/06/2009 16:00	11/06/2009 13:49	0.39	52	0.40	61	40		
96		28/06/2009 16:30	11/06/2009 14:19	-0.01	-4	0.10	7	48		
97		28/06/2009 17:00	11/06/2009 14:49	-0.09	9	0.13	11	52		
98		28/06/2009 17:30	11/06/2009 15:18	-0.06	-4	0.14	10	50		
99		28/06/2009 18:00	11/06/2009 15:48	-0.06	-2	0.12	10	60		
100		28/06/2009 18:30	11/06/2009 16:19	-0.03	11	0.09	16	66		
101		28/06/2009 19:00	11/06/2009 16:49	0.00	9	0.09	15	63		
102		28/06/2009 19:30	11/06/2009 17:19	0.02	-1	0.12	5	62		
103		28/06/2009 20:00	11/06/2009 17:48	0.05	-1	0.12	6	67		
104		28/06/2009 20:30	11/06/2009 18:19	0.04	6	0.10	8	69		
105		28/06/2009 21:00	11/06/2009 18:47	-0.06	-2	0.10	13	79		
106		28/06/2009 21:30	11/06/2009 19:18	0.06	-3	0.08	30	68		
107		28/06/2009 22:00	11/06/2009 19:49	-0.01	-2	0.06	6	62		
108		28/06/2009 22:30	11/06/2009 19:51	0.08	6	0.16	10	69		

Transect number	Campaign	Time model	Time of measurement	Statistics for transects				Weight	Statistics for campaigns (weight of each transect is taken into account)	
				Bias mag (m)	Bias dir (degrees)	RMSE mag (m)	RMSE dir (degrees)		RMSE mag (m)	RMSE dir (degrees)
109	20110804_Branst	26/06/2009 08:00	04/08/2011 08:44	-0.22	wrong measurement	0.05	wrong measurement	21	0.24	wrong measurement
110		26/06/2009 08:30	04/08/2011 08:51	0.02		0.12		32		
111		26/06/2009 09:00	04/08/2011 09:37	-0.48		0.23		9		
112		26/06/2009 09:30	04/08/2011 09:38	-0.15		0.16		594		
113		26/06/2009 10:00	04/08/2011 09:50	-0.23		0.29		2501		
114		26/06/2009 10:30	04/08/2011 10:35	-0.08		0.14		1216		
115		26/06/2009 11:00	04/08/2011 10:58	-0.23		0.30		1534		
116		26/06/2009 11:30	04/08/2011 11:36	-0.12		0.18		1524		
117		26/06/2009 12:00	04/08/2011 12:05	-0.24		0.26		1887		
118		26/06/2009 12:30	04/08/2011 12:46	-0.10		0.18		1021		
119		26/06/2009 13:00	04/08/2011 13:05	-0.19		0.27		1879		
120		26/06/2009 13:30	04/08/2011 13:45	-0.40		0.23		30		
121		26/06/2009 14:00	04/08/2011 14:10	-0.28		0.32		1423		
122		26/06/2009 14:30	04/08/2011 14:10	-0.62		0.59		1423		
123		26/06/2009 15:00	04/08/2011 15:03	-0.17		0.22		2181		
124		26/06/2009 15:30	04/08/2011 15:43	-0.06		0.12		2003		
125		26/06/2009 16:00	04/08/2011 16:22	-0.02		0.14		1827		
126		26/06/2009 16:30	04/08/2011 16:22	0.00		0.13		1827		
127		26/06/2009 17:00	04/08/2011 16:54	0.07		0.14		2035		
128		26/06/2009 17:30	04/08/2011 17:29	0.00		0.15		1732		
129		26/06/2009 18:00	04/08/2011 17:59	0.13		0.23		1433		
130		26/06/2009 18:30	04/08/2011 18:59	-0.08		0.04		19		
131		26/06/2009 19:00	04/08/2011 19:09	-0.03		0.18		2186		
132		26/06/2009 19:30	04/08/2011 19:09	-0.06		0.16		2186		

Transect number	Campaign	Time model	Time of measurement	Statistics for transects				Weight	Statistics for campaigns (weight of each transect is taken into account)	
				Bias mag (m)	Bias dir (degrees)	RMSE mag (m)	RMSE dir (degrees)		RMSE mag (m)	RMSE dir (degrees)
133	20110801_Appels	24/06/2009 07:00	01/08/2011 07:03	-0.13	wrong measurement	0.14	wrong measurement	259	0.23	wrong measurement
134		24/06/2009 07:30	01/08/2011 07:24	-0.01		0.07		787		
135		24/06/2009 08:00	01/08/2011 07:42	-0.09		0.19		828		
136		24/06/2009 08:30	01/08/2011 08:27	0.06		0.19		403		
137		24/06/2009 09:00	01/08/2011 08:50	-0.06		0.25		1084		
138		24/06/2009 09:30	01/08/2011 09:13	-0.12		0.26		1149		
139		24/06/2009 10:00	01/08/2011 10:03	-0.06		0.17		467		
140		24/06/2009 10:30	01/08/2011 10:26	-0.12		0.28		1098		
141		24/06/2009 11:00	01/08/2011 10:50	-0.12		0.30		1051		
142		24/06/2009 11:30	01/08/2011 11:14	-0.09		0.28		1169		
143		24/06/2009 12:00	01/08/2011 11:53	-0.30		0.37		512		
144		24/06/2009 12:30	01/08/2011 12:07	-0.16		0.33		1105		
145		24/06/2009 13:00	01/08/2011 12:33	-0.12		0.26		1152		
146		24/06/2009 14:00	01/08/2011 14:00	0.03		0.14		913		
147		24/06/2009 14:30	01/08/2011 14:26	-0.15		0.17		1011		
148		24/06/2009 15:00	01/08/2011 14:55	-0.12		0.14		966		
149		24/06/2009 15:30	01/08/2011 15:22	-0.09		0.10		466		
150		24/06/2009 16:00	01/08/2011 15:46	-0.07		0.16		897		
151		24/06/2009 16:30	01/08/2011 16:13	-0.06		0.14		1023		
152		24/06/2009 17:00	01/08/2011 16:38	-0.03		0.17		993		
153		24/06/2009 18:00	01/08/2011 17:58	0.01		0.25		738		
154		24/06/2009 18:30	01/08/2011 18:26	0.10		0.24		452		
155		24/06/2009 19:00	01/08/2011 19:02	0.01		0.14		849		
156		24/06/2009 19:30	01/08/2011 19:02	-0.15		0.22		849		
Total for all Campaigns (weighted)				-0.07	2	0.18	27			
Total for all Campaigns (average)									**0.18**	**32**

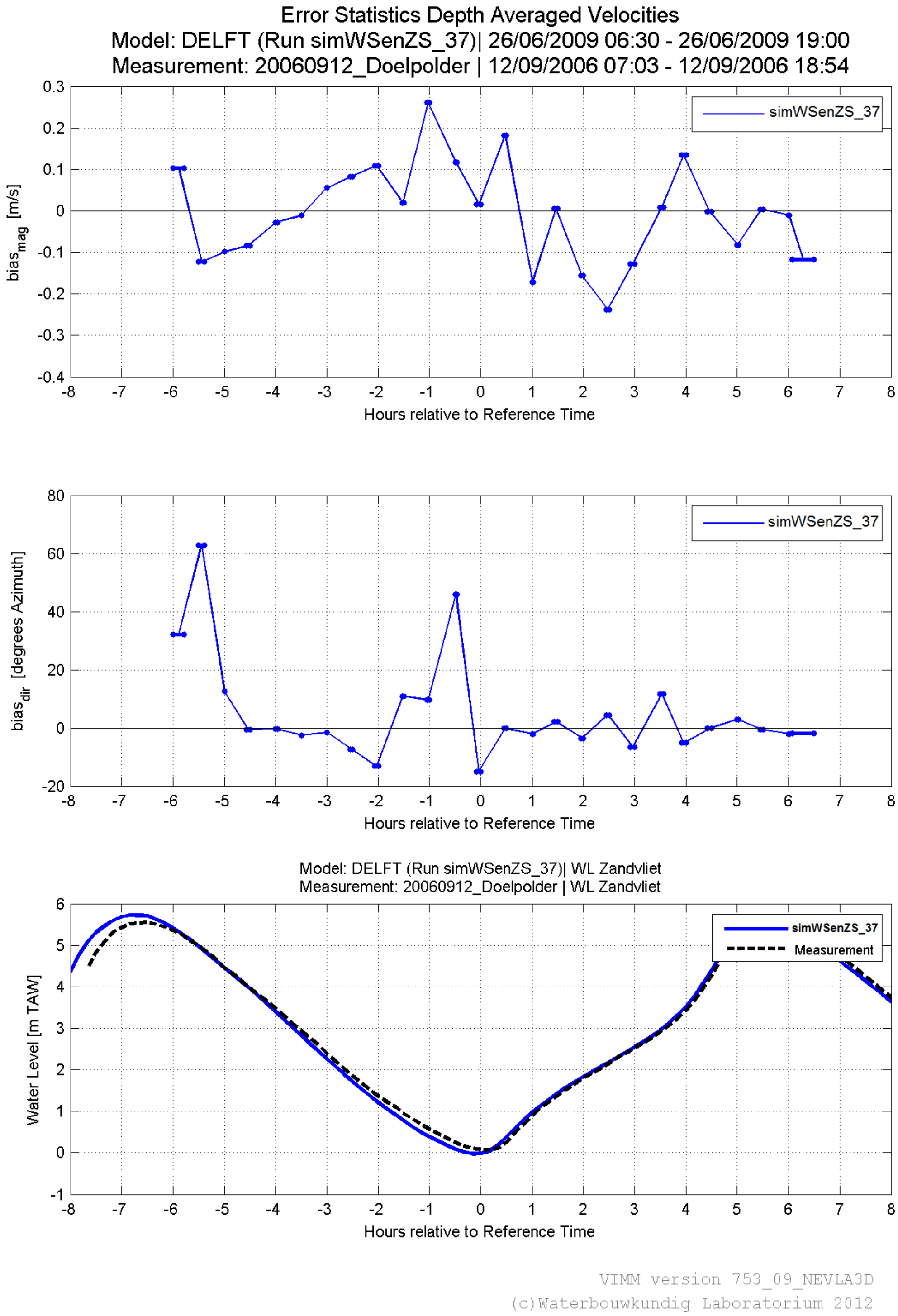


Figure 119 - Bias of velocity magnitude and direction at Doelpolder (model vs. ADCP measurement)

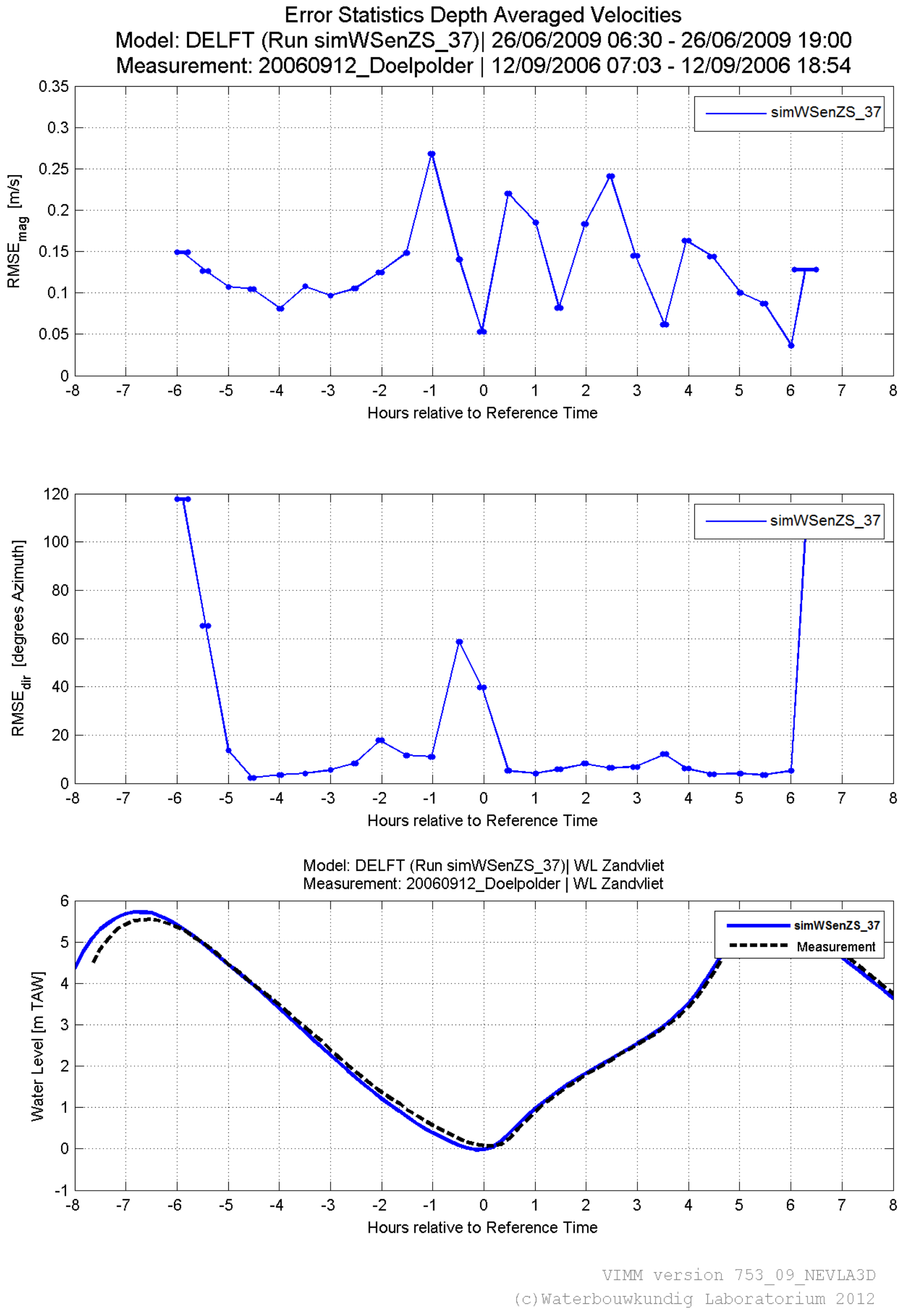


Figure 120 - RMSE of velocity magnitude and direction at Doelpolder (model vs. ADCP measurement)

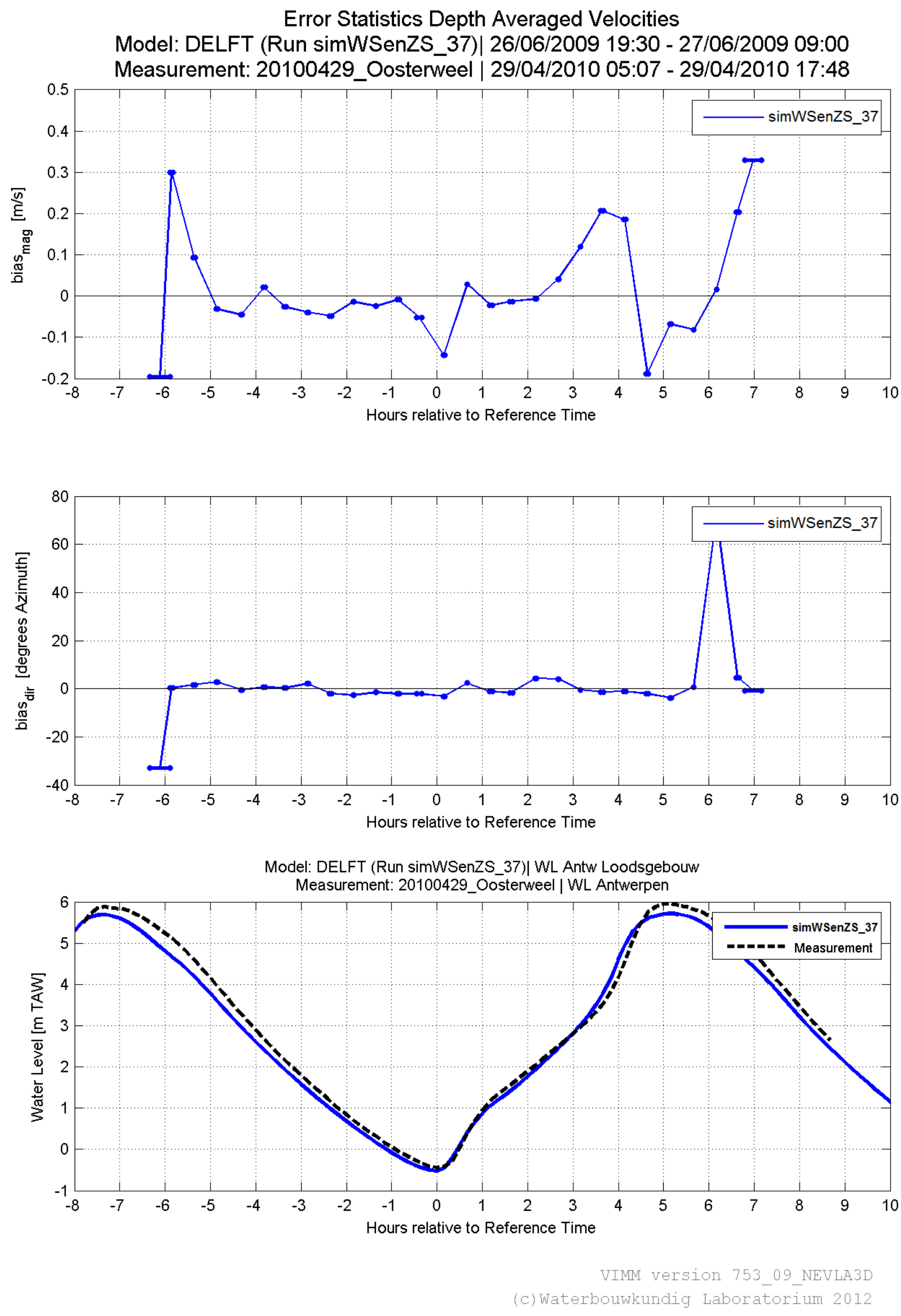


Figure 121 - Bias of velocity magnitude and direction at Oosterweel (model vs. ADCP measurement)

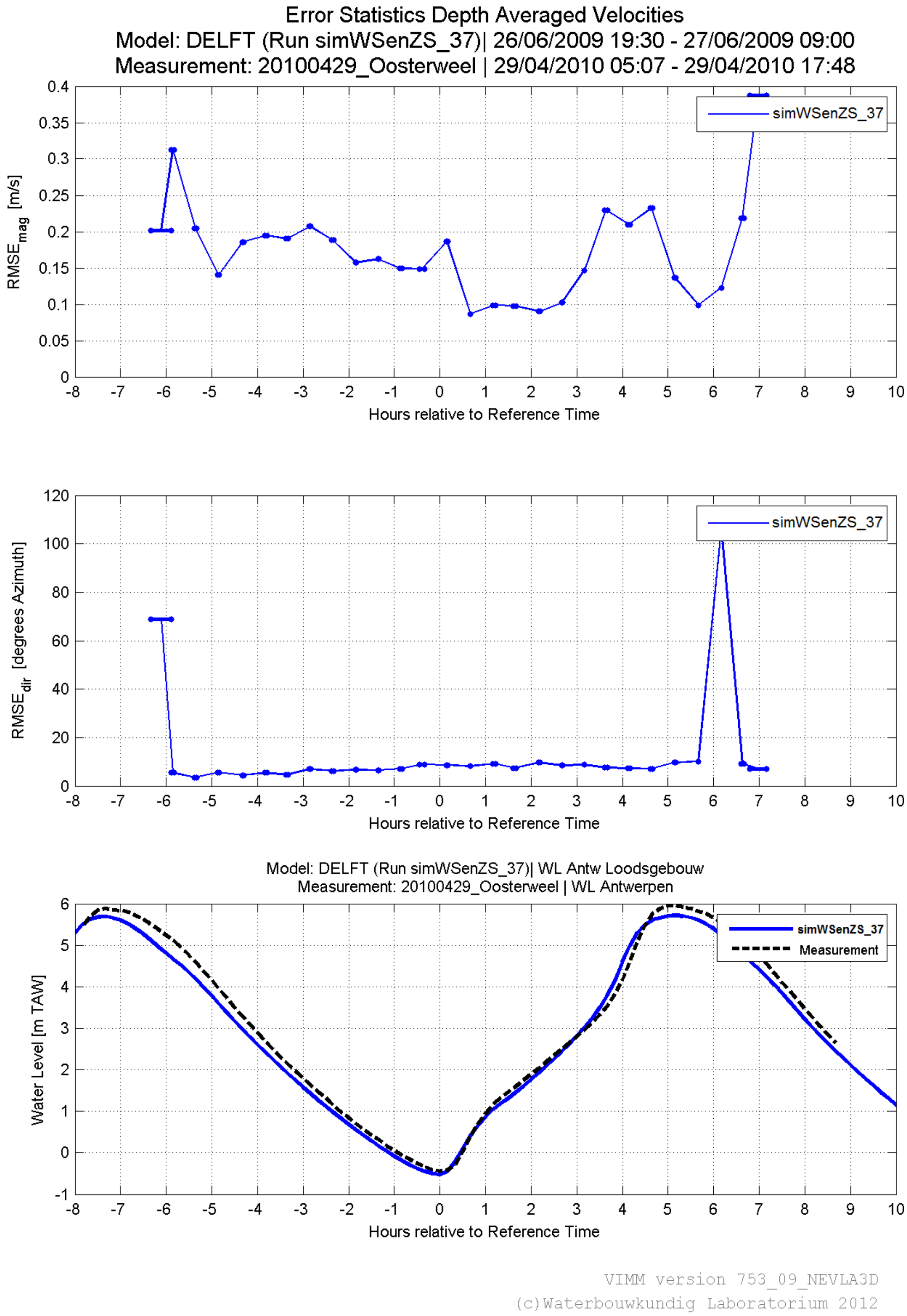


Figure 122 - RMSE of velocity magnitude and direction at Oosterweel (model vs. ADCP measurement)

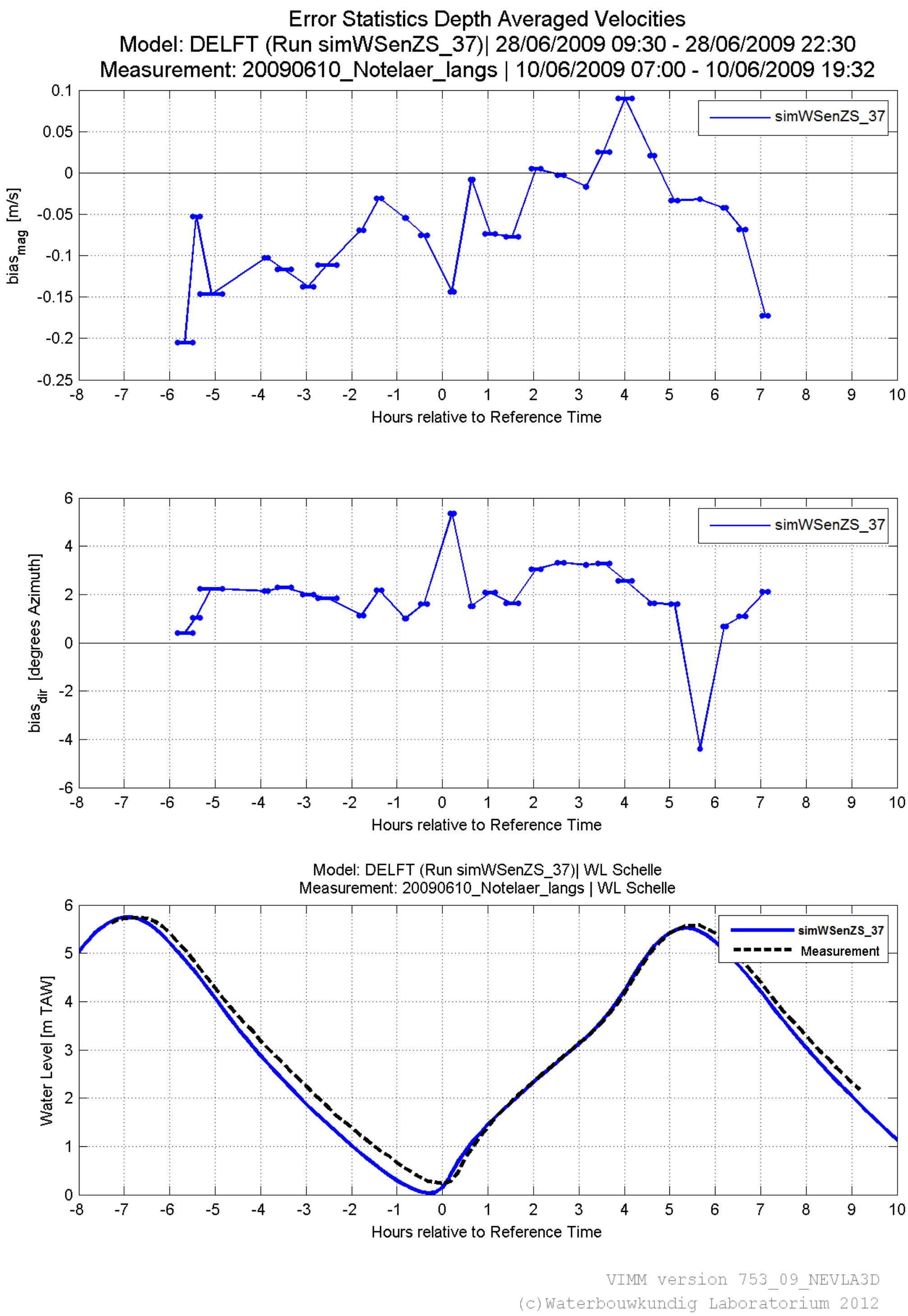


Figure 123 - Bias of velocity magnitude and direction at Notelaer (langs) (model vs. ADCP measurement)

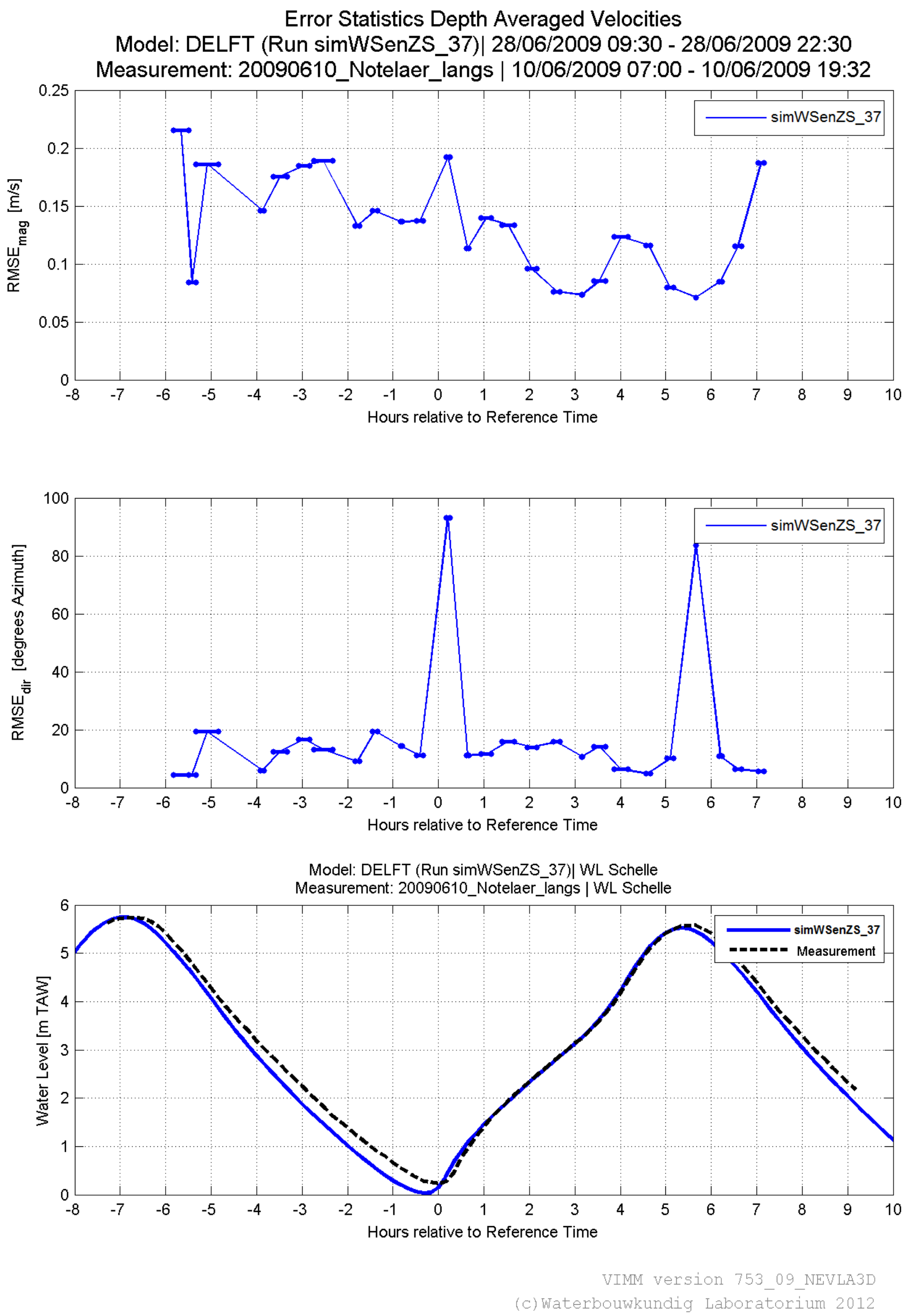


Figure 124 - RMSE of velocity magnitude and direction at Notelaer (langs) (model vs. ADCP measurement)

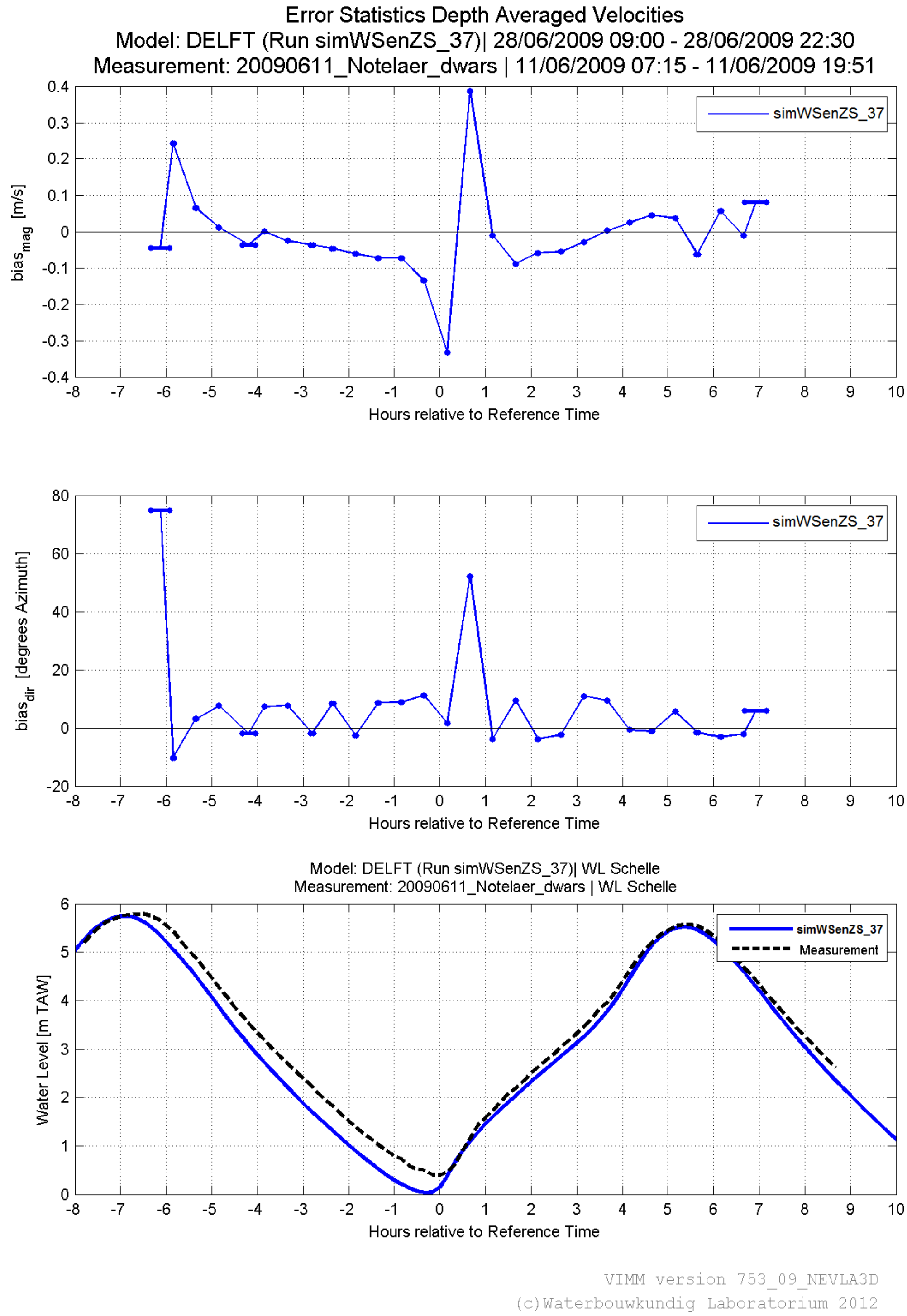


Figure 125 - Bias of velocity magnitude and direction at Notelaer (dwars) (model vs. ADCP measurement)

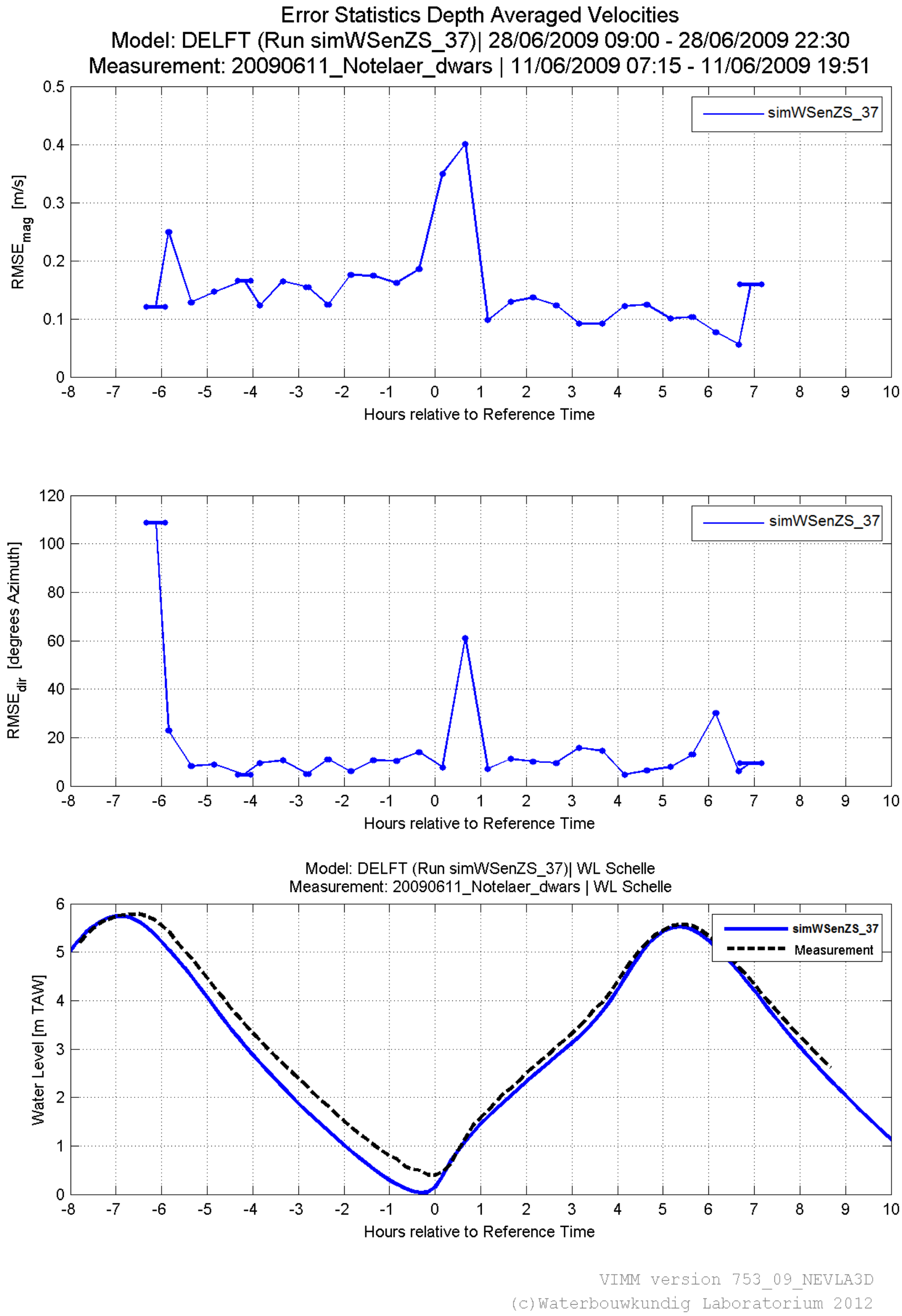


Figure 126 - RMSE of velocity magnitude and direction at Notelaer (dwars) (model vs. ADCP measurement)

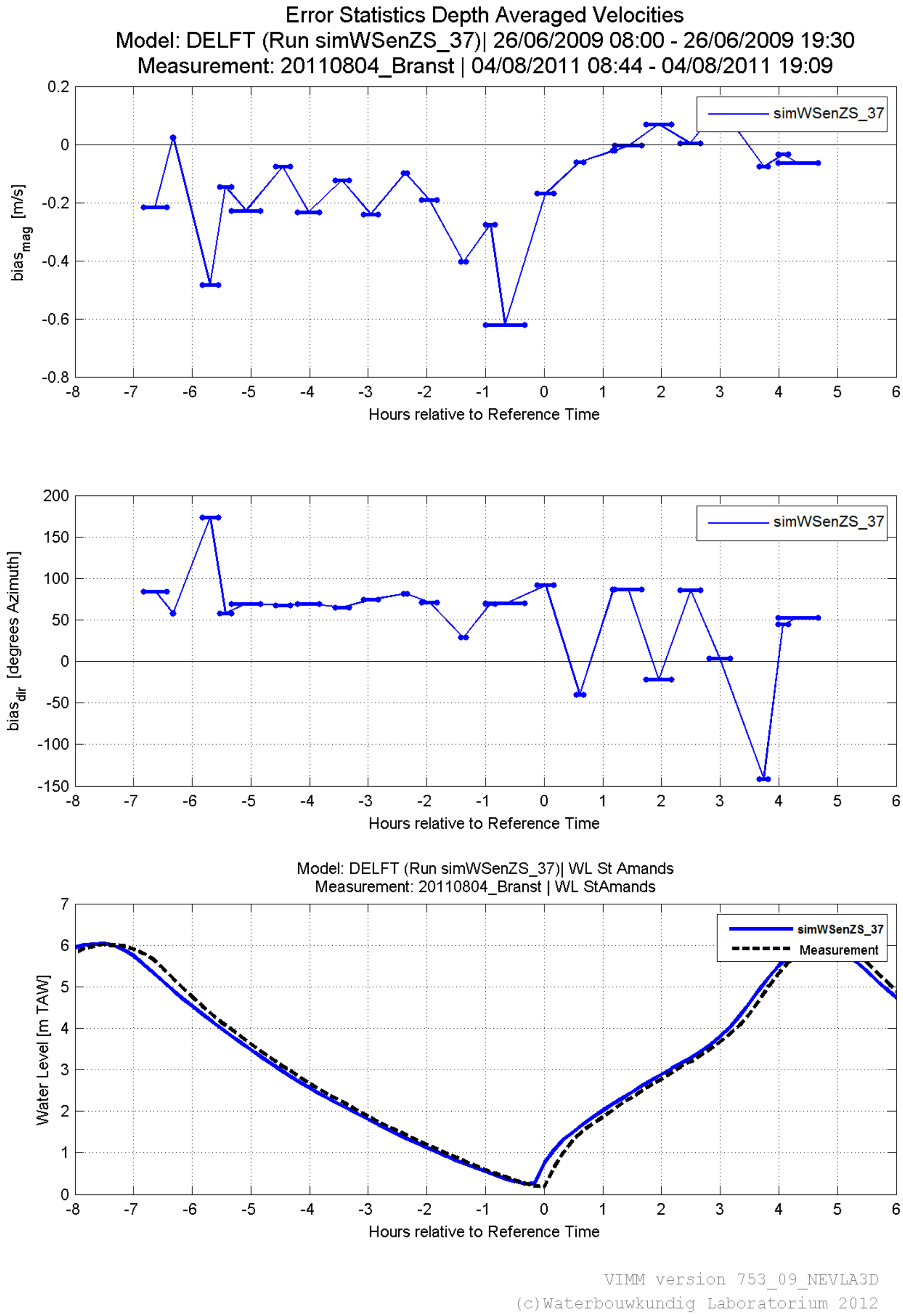


Figure 127 - Bias of velocity magnitude and direction at Branst (measured direction is wrong) (model vs. ADCP measurement)

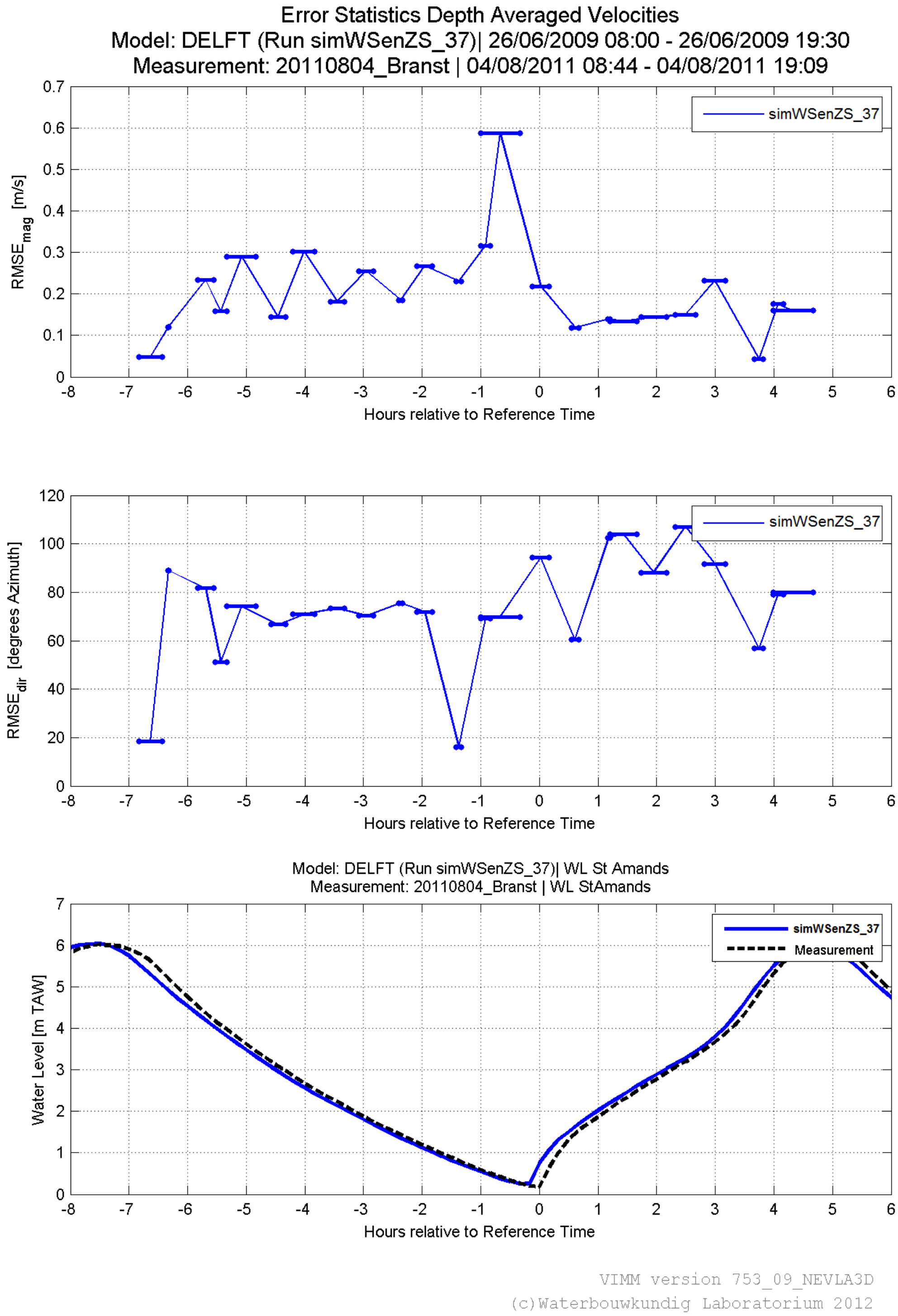


Figure 128 - RMSE of velocity magnitude and direction at Branst (measured direction is wrong) (model vs. ADCP measurement)

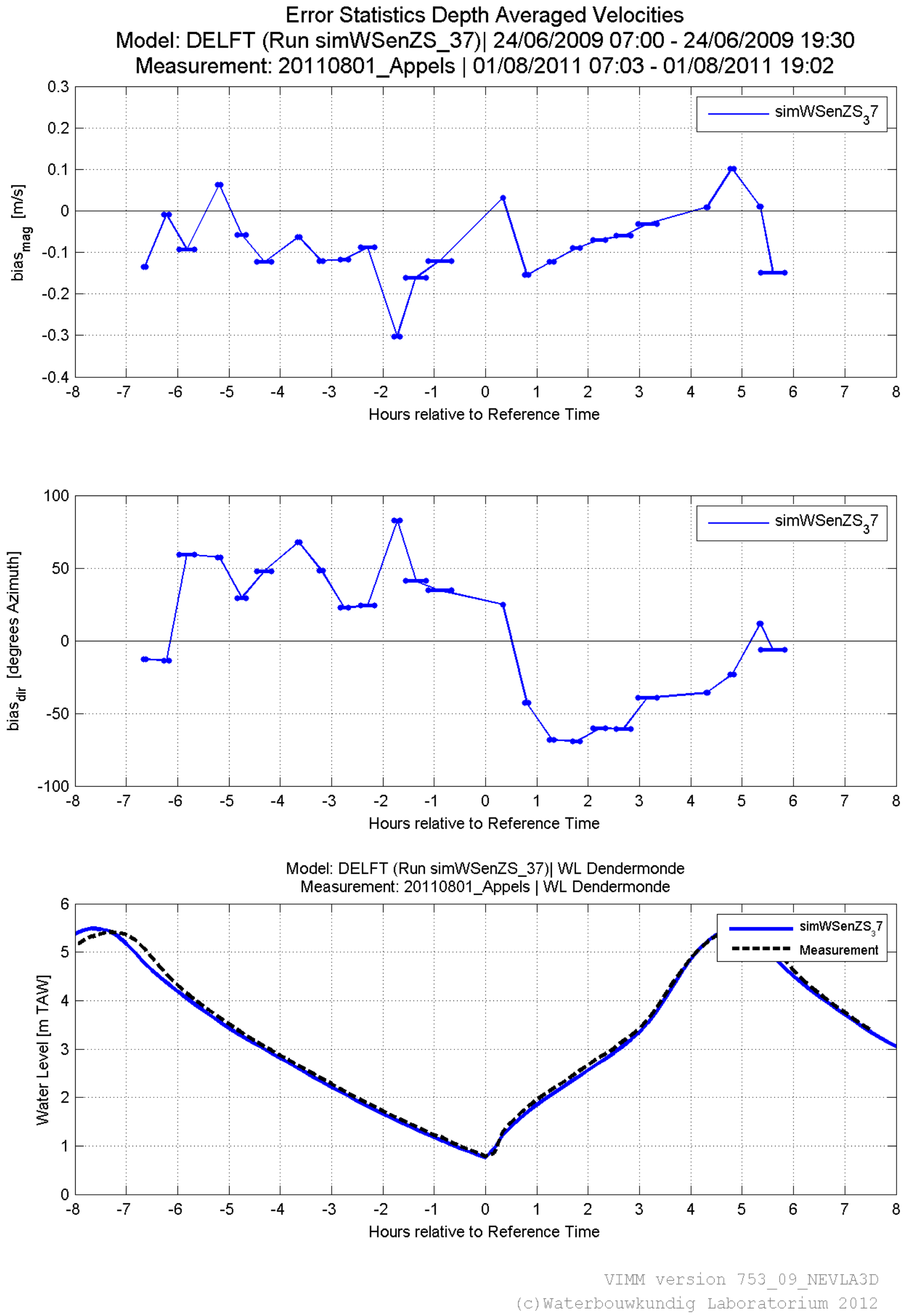


Figure 129 - Bias of velocity magnitude and direction at Appels (measured direction is wrong) (model vs. ADCP measurement)

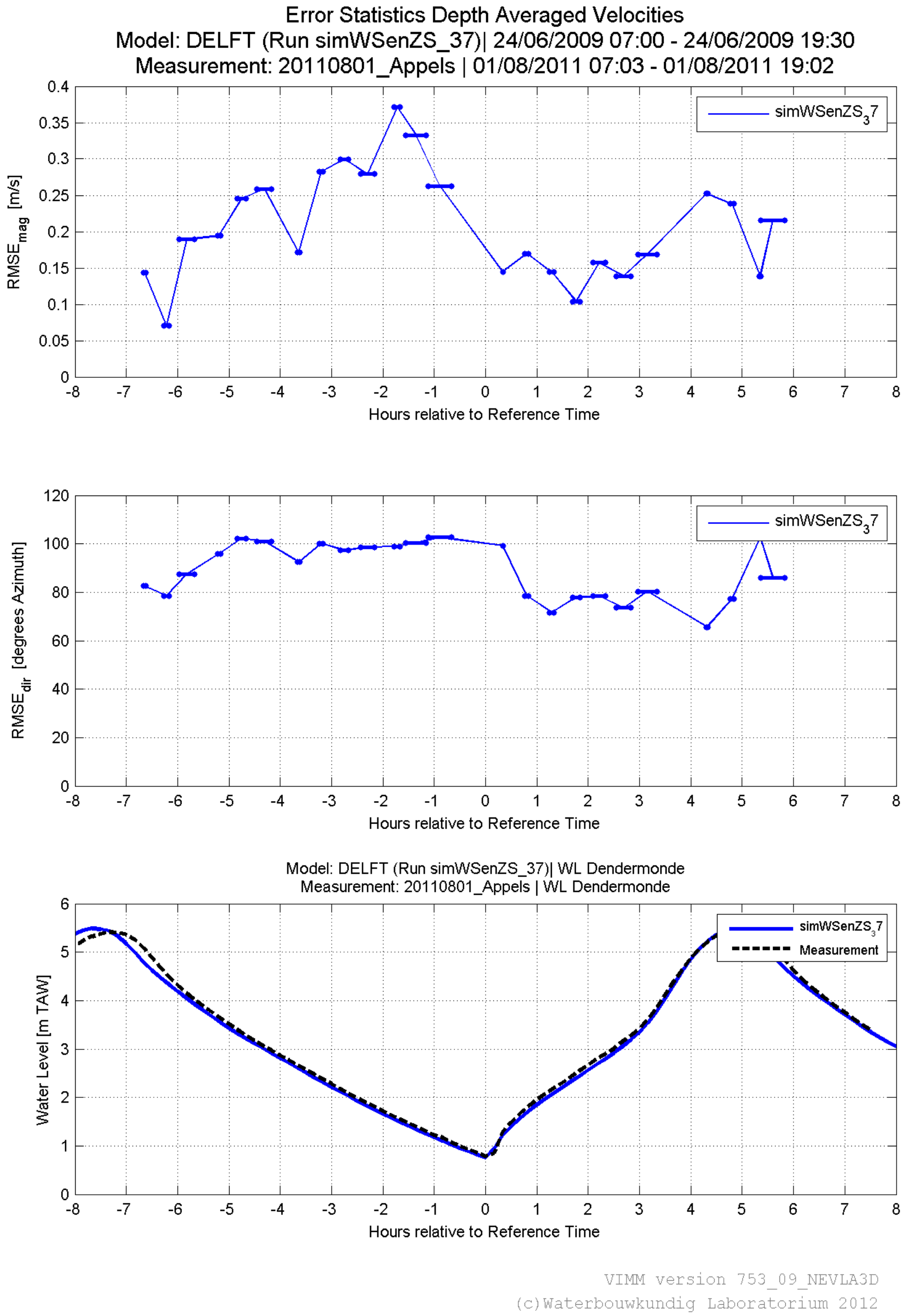


Figure 130 - RMSE of velocity magnitude and direction at Appels (measured direction is wrong) (model vs. ADCP measurement)

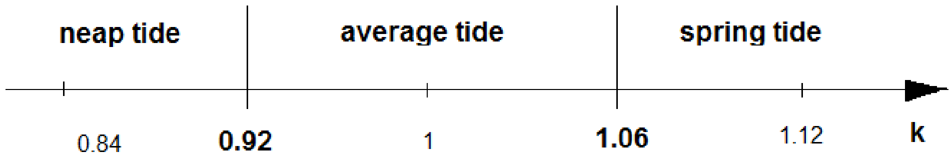
Appendix 3. Tidal coefficients

A tidal coefficient is calculated as a ratio of the tidal amplitude during the analyzed period to the amplitude of the average tide for the period from 1991 to 2000. Tidal coefficients are calculated for all analysed tides based on the measured water levels at Antwerp.

Table 39 shows the typical values of the tidal coefficients corresponding to the neap, average and spring tides. Tides with coefficients higher than 1.06 are considered to be spring tides; tides with coefficients lower than 0.92 are neap.

Table 39. Typical values of the tidal coefficients for neap, average and spring tides

Tide	Amplitude at Antwerp (m)	k
Neap	4.43	0.84
Average	5.29	1
Spring	5.95	1.12



Appendix 4. Statistical parameters

Time series of water levels, velocities and discharges

Straight setup (figure 131) is defined as the instantaneous difference between two time series. It gives an overall idea of the bias between the measured and modelled complete time series. The $RMSE_0$ (unbiased Root Mean Square Error) shows the variation of the error between modelled and measured data.

Oblique setup (figure 131) only takes into account the high and low waters. This way, the level and the timing of those events can be studied separately. Bias and $RMSE_0$ are calculated separately for level and timing of high and low waters.

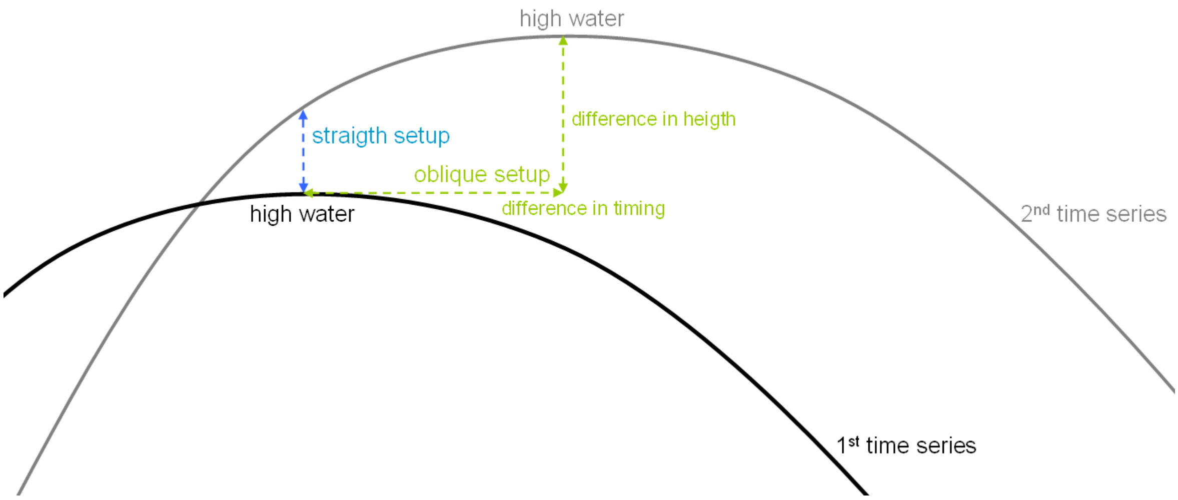


Figure 131 - Definition of straight and oblique setup (after *Adema*, 2006).

For both straight and oblique setup the statistical parameters bias, RMSE (root mean square error) and unbiased RMSE ($RMSE_0$) can be calculated. A positive bias value means that (in the case of water level or velocity magnitude) the modelled time series are an overestimation of the observed time series or (in the case of difference in timing) that the modelled time series lags behind the observed time series. A negative bias value means that (in the case of water level or velocity magnitude) the modelled time series are an underestimation of the observed time series or (in the case of difference in timing) that the modelled time series proceeds on the observed time series.

Hereafter, the reference time series will be presented as x and the time series that is subject to the test as y.

The **mean** values of the time series are represented by $\overline{x}$ (reference) and $\overline{y}$ (subject to test).

$$\overline{x} = \frac{1}{N}\sum_{i=1}^{N} x_i$$
$$\overline{y} = \frac{1}{N}\sum_{i=1}^{N} y_i$$

where N is the length of the time series.

The **bias** is the difference between the mean of the tested and the reference time series. The closer the bias is to zero, the better both time series correspond.

$$bias = \overline{y} - \overline{x}$$

The **root mean square error** (RMSE) is defined as:

$$RMSE = \sqrt{\frac{\sum_{i=1}^{N}(x_i - y_i)^2}{N}}$$

Corresponding time series will result in RMSE values close to zero. An important, extra source of information is the **unbiased root mean square error** or **RMSE$_0$.** If the tested time series shows apart from a constant offset (bias) to the reference time series no other differences in its signal, the RMSE$_0$ will be zero, while both bias and RMSE will be non zero. If x and y are time series of a tidal signal (water level, current), an RMSE$_0$ value of zero means that both signals are equal in phasing and amplitude. This does not imply there is no constant bias between both.

$$RMSE_0 = \sqrt{\frac{\sum_{i=1}^{N}\left[(x_i - y_i) - (\overline{x} - \overline{y})\right]^2}{N}}$$

The **relative error** or **Scatter Index** of the tested time series is given by the quotient of the RMSE and the mean value of the reference time series.

$$S.I. = \frac{RMSE}{\overline{x}}$$

The correlation between both signals is given by **Pearson's correlation coefficient**, defined as:

$$r = \frac{\sum_{i=1}^{N}(x_i - \overline{x})(y_i - \overline{y})}{\sqrt{\sum_{i=1}^{N}(x_i - \overline{x})^2}\sqrt{\sum_{i=1}^{N}(y_i - \overline{y})^2}}$$

Harmonic analysis

A parameter combining the evaluation of both the amplitude and the phase between the observed and modeled tidal components is the vector difference.

The vector difference can be calculated over one tidal station for the different considered tidal components or different tidal stations can be considered. The first summation takes all the errors of the different considered harmonic constituents in account in a certain station. Then the errors in all stations are summed and averaged (*de Brye et al.,* 2010).

$$e_s = \sum_{i=1}^{N_c}\sqrt{\left[A_{c,i}\cos(\varphi_{c,i}) - A_{m,i}\cos(\varphi_{o,i})\right]^2 + \left[A_{c,i}\sin(\varphi_{c,i}) - A_{m,i}\sin(\varphi_{o,i})\right]^2}$$

$$e = \frac{1}{N_s}\sum_{s=1}^{N_s} e_s$$

The error e_s is the vector difference for a specific station with $A_{c,i}$ and $\varphi_{c,i}$ (the calculated amplitude and phase of harmonic constituent i) and $A_{o,i}$ and $\varphi_{o,i}$ (the observed amplitude and phase of harmonic constituent i). The total error over all specified stations is e.

Velocities

(Sutherland et al., 2003) proposed a method to evaluate the combined effect of magnitude and direction of the current. The MAE (mean absolute error) is calculated based on the calculated (Y_1,Y_2) and observed (X_1,X_2) components of the current. A relative mean absolute error is derived (RMAE) to identify the order of magnitude of the error compared to the observed velocities. A table was proposed in which the RMAE was used to identify the model quality to represent the current.

$$MAE = \left\langle \left\| \vec{Y} - \vec{X} \right\| \right\rangle = \frac{1}{N} \sum_{n=1}^{N} \sqrt{\left(Y_{1,n} - X_{1,n}\right)^2 + \left(Y_{2,n} - X_{2,n}\right)^2}$$

$$RMAE = \frac{\left\langle \left\| \vec{Y} - \vec{X} \right\| \right\rangle}{\left\langle \left\| \vec{X} \right\| \right\rangle} = \frac{MAE}{\left\langle \left\| \vec{X} \right\| \right\rangle}$$

Table 40. Model qualification based on (*Sutherland et al.,* 2003)

Model qualification	RMAE
Excellent	<0.2
Good	0.2-0.4
Reasonable/fair	0.4-0.7
Poor	0.7-1.0
Bad	>1.0

Furthermore a statistical analysis can be performed on the magnitude and direction of currents as represented below.

$$BIAS_{mag} = \frac{1}{N} \sum_{n=1}^{N} \left(MAG_{Y,n} - MAG_{X,n}\right)$$

$$MAE_{mag} = \frac{1}{N} \sum_{n=1}^{N} \left\| MAG_{Y,n} - MAG_{X,n} \right\|$$

$$RMSE_{mag} = \sqrt{\frac{1}{N} \sum_{n=1}^{N} \left(MAG_{Y,n} - MAG_{X,n}\right)^2}$$

$$\Delta DIR_n = \begin{cases} DIR_{Y,n} - DIR_{X,n} & \ldots if\ -180 \leq DIR_{Y,n} - DIR_{X,n} \leq 180 \\ DIR_{Y,n} - DIR_{X,n} + 360 & \ldots if\ DIR_{Y,n} - DIR_{X,n} < -180 \\ DIR_{Y,n} - DIR_{X,n} - 360 & \ldots if\ DIR_{Y,n} - DIR_{X,n} > +180 \end{cases}$$

$$BIAS_{dir} = \frac{1}{N} \sum_{n=1}^{N} \Delta DIR_n$$

$$MAE_{dir} = \frac{1}{N} \sum_{n=1}^{N} \left\| \Delta DIR_n \right\|$$

$$RMSE_{dir} = \sqrt{\frac{1}{N} \sum_{n=1}^{N} \left(\Delta DIR_n\right)^2}$$

Appendix 5. The principle of the depth and velocity definition in the model

Delft3D-FLOW uses a staggered grid (figure 132). In the staggered grid not all quantities, such as the water level, the depth, the velocity components or concentration of substances, are defined at the same location in the numerical grid (and thus in the physical space) (*Deltares*, 2011).

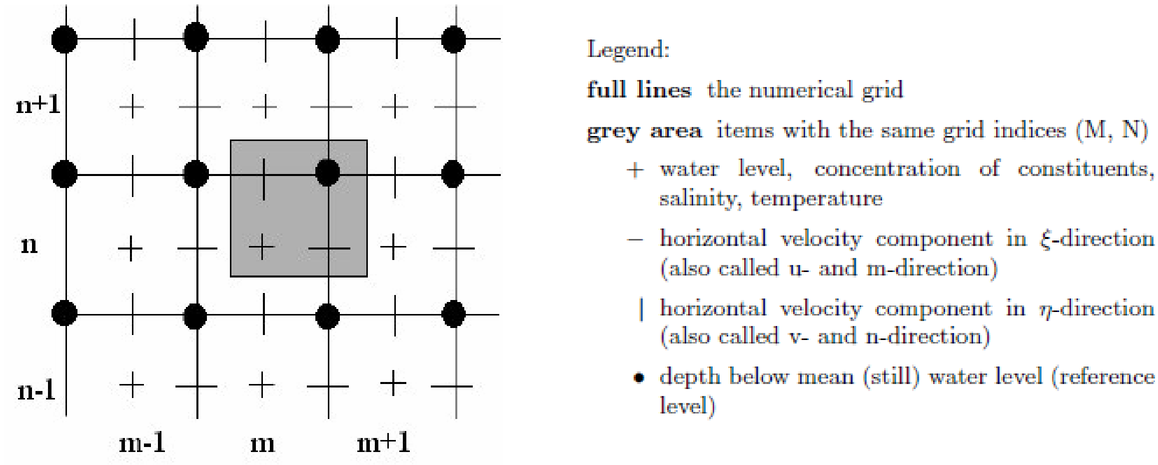


Figure 132 – Staggered grid of Delft3D (*Deltares*, 2011)

The depth values are defined in the grid cell corners, water levels are defined in the grid cell centers. The depth values in the cell centers (water level points) depend on the user choice. The use of maximal depth values is recommended. It has been found that the MAX procedure is more favourable and will produce a more smooth solution than other options (*Deltares*, 2011). Therefore, **the depth in the water level point is found as a maximum value of the four surrounding depth points. The depth in the water level points is used in the continuity equation.**

Velocity data are calculated in a staggered grid in different points. U-velocities are calculated on the U-grid; V-velocities are calculated on the V-grid. When velocities are found from maps or histories the U-data in the U-points and the V-data in the V-points are interpolated to the UV-data in the water level points. The velocity magnitude and direction are computed in the water level point using these UV-data.

However, the representative depth for these velocities is an average depth of the four surrounding depth points and not the depth calculated in the water level point. The reason for this is that the depth values in the U- and V-velocity points are used in the momentum equation and they are calculated by averaging the depths of the two adjacent depth points. The average of the depths of the surrounding velocity points corresponds with the average of the depths of the surrounding depth points.

Appendix 6. A short literature review on bed roughness

Spatial variation

A bed roughness was used in this study as a calibration parameter. The bed roughness coefficient expresses the resistance the flow experiences from the riverbed. Flow resistance is often attributed to, on one hand, the roughness of surface grains and, on the other hand, the form drag due to irregularities of the bed (bedforms) (*Spekkers et al.,* 2008). In this study no distinction was made between different geomorphological zones (bedforms) of the intertidal areas. In reality different bedforms result in different turbulence conditions. The model simulation with the bed roughness values related to the bedforms can be performed.

A spatially distributed approach to a hydraulic modelling scheme must be based on a map of the roughness elements over the floodplain at different scales (*Casas et al.,* 2010). Roughness parameterisation must account for energy losses due to geometric variability of the surface produced at scales finer than those represented in the mesh (discretisation scale) (*Lane*, 2005). A higher resolution model will explicitly encompass smaller topographic variations, provided the associated topographic data are at the same resolution. With a coarser model resolution, smaller topographic variations will need to be parameterized, either explicitly through a porosity type treatment (e.g. *Yu and Lane*, 2006) or upscaling of a roughness parameter.

The main problem of assessing spatial subscale effects upon flow is that, in practice, roughness parameterization must account not only for discrepancies between the intrinsic scale of the surface variability and the scale represented in a mesh, but also for the discrepancies between the intrinsic scale of the flow process and the processes explicitly represented in the numerical solution (i.e. the processes not explicitly represented because of the averaging of the flow equations in time or space, such as diffusive effects in the flow due to turbulence in a 2-D approach). Therefore, **the roughness parameter turns out to be an effective parameter commonly obtained through a calibration procedure** (e.g. *Lane and Ferguson*, 2005). This situation complicates the scale-dependent relationship between roughness and topography (*Casas et al*., 2010).

(*Van Prooijen en Dam,* 2005) tested the performance of the FINEL model with different bed roughness fields: the bed roughness obtained from the calibration of water levels and the bed roughness obtained based on the geomorphological map. The analysis showed that the morphology dependent roughness field is not necessarily better for a good representation of the flow velocities in the model. The differences in velocities calculated in the models with two different bed roughness fields were small. Therefore, it was concluded that it was not necessary to define the bed roughness based on the geomorphological data.

Time variation

Besides the variation of the bed roughness in space, it also varies in time. The direction of water movement and water levels change during the tidal cycle. Therefore, the bedforms interact with the flow differently during the flood and ebb periods and they have a different effect on the water movement. Since it is not possible to define a time varying bed roughness in the Delft3D model a constant in time bed roughness field was used in this study.

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