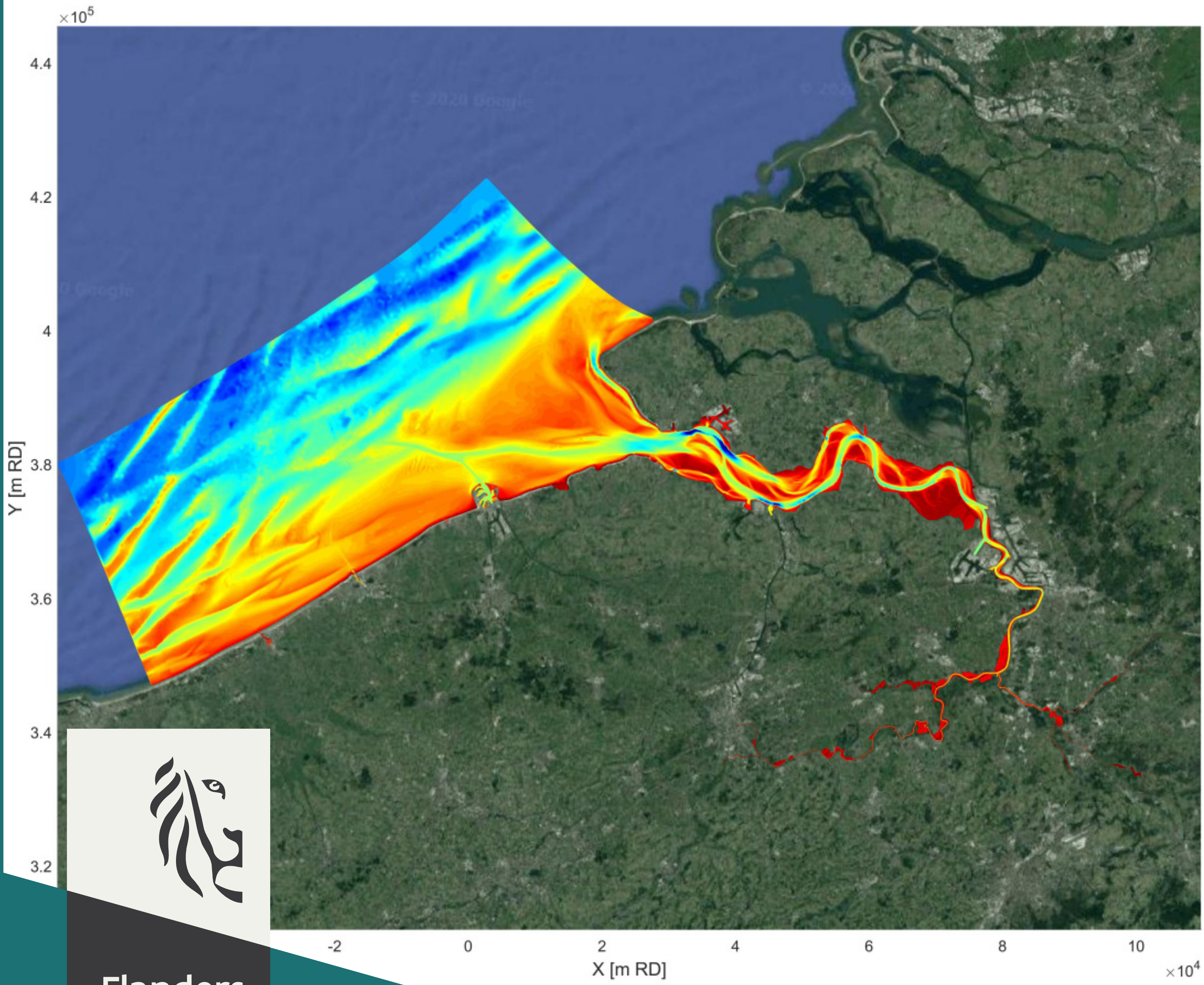

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Update SCALDIS 2019
a 3D hydrodynamic model of the Scheldt Estuary

Calibration report

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Update SCALDIS 2019:
a 3D hydrodynamic model of the Scheldt Estuary

Calibration report

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Abstract

The SCALDIS model is a reference model for the entire estuary of the Scheldt developed in TELEMAC 3D. The model was initially developed and calibrated for scenario analysis of measures in the Upper Sea Scheldt. Based on the hydrodynamic model, both a mud and a sand transport model were developed.

Vanlede et al. (2018) proposed an update cycle of 6 years for a re-calibration of the SCALDIS model. This is inspired by the availability of a new spatially covering bathymetry every 6 years. Since the original SCALDIS model was calibrated for 2013, the new calibration is carried out for 2019.

This report describes the model development, calibration and validation of the hydrodynamics for the year 2019. The model is calibrated for two spring-neap tidal cycles in 2019 against field data of water levels, velocities (ADCP sailed and stationary in deep and shallow zones) and salinity. Two more stormy periods are selected for calibration and validation respectively.

The re-calibrated SCALDIS 2019 model in general captures the hydrodynamics of the Scheldt estuary. The model is considered as a useful tool to analyze the effects of different scenarios of sediment transport and morphology for future studies.

Additional material to this report (full statistics for all measurements, over all subperiods) can be found on the project folder, in the following subdirectory:
p:\PA016-Ondrhd2D3Dmdl\3_Uitvoering\Scaldis_2019_addendum_to _report\

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1 Introduction

The SCALDIS model (Vanlede et al., 2015) is a reference model on which many different applications are based. It provides the hydrodynamic input for sediment transport calculations (sand and mud), and for the generation of ecotope maps. It is used to evaluate the effect of flood control areas on the hydrodynamics in the Scheldt estuary. Tracer dispersion experiments in the model are used to calibrate an ecosystem model at the University of Antwerp (UA). The flow fields it produces are also processed as a flow atlas, and are implemented in the shipping simulator of Flanders Hydraulics Research (FHR).

The SCALDIS model was initially developed and calibrated for an application in the Upper Sea Scheldt (Smolders et al., 2016). But even in this first iteration, the decision was made to develop a schematization of the entire Scheldt estuary and Belgian Coastal Zone. This first calibration was done against measurement data of 2013 (or earlier).

Vanlede et al. (2018) proposes an update cycle of 6 years for a re-calibration of the Scheldt model (in casu SCALDIS). This is inspired by the availability of a new spatially covering bathymetry every 6 years. Since the original SCALDIS model was calibrated for 2013, the new calibration is carried out for 2019.

1.1 Model aim

Since the SCALDIS model is meant to serve as a reference model with many different applications, the calibration shouldn’t focus solely on water levels (vertical tide). The horizontal tide (velocities) is equally important. Furthermore, since the model has potential applications over the entire estuary, the calibration should pay equal attention to good model skill over the entire estuary.

2 Abbreviations and Conventions

2.1 Abbreviations

Table 1 – Used abbreviations

Abbr.	Description
ADCP	Acoustic Doppler Current Profiler
BCZ	Belgian Coastal Zone
BeZS	Beneden-Zeeschelde (Lower Sea Scheldt)
BODC	British Oceanographic Data Centre
BoZS	Boven-Zeeschelde (Upper Sea Scheldt)
CSM	Continental shelf Model of the North Sea
GIS	Geographic Information System
HIC	Hydrological Information Centre
HMCZ	Hydro Meteo Centrum Zeeland
UTC	Universal Time Coordinate
MVB	Meetnet Vlaamse Banken
NAP	Normaal Amsterdams Peil (Dutch vertical reference level)
RD	Rijksdriehoekscoördinaten
RMAE	Relative Mean Absolute Error. See Annex 1 for mathematical description
RMSE	Root Mean Square Error. See Annex 1 for mathematical description
RWS	Rijkswaterstaat
SHOM	Service hydrografique et océanographique de la marine
SI	International System of Units
TAW	Tweede Algemene Waterpassing (Belgian vertical reference level)
WES	Westerschelde (Western Scheldt)
ZUNO	Zuidelijke Noordzee Model (Southern North Sea model)

2.2 Conventions

The following conventions are followed by this report:

- Times are represented in UTC.
- The coordinate reference system, used by the model and for presentation of the model output is RD Parijs, expressed in meters.
- The vertical reference level used in this project is NAP. NAP is 2.33 m above TAW level.
- Current directions refer to the direction in which the flow is flowing to: e.g. a current direction of 090°N means that the currents are flowing towards the east.
- Wind directions refer to the direction which it is coming from: e.g. a wind direction of 090°N means that the wind is coming from the East.
- SI units are used.

3 Available Data

3.1 Bathymetry

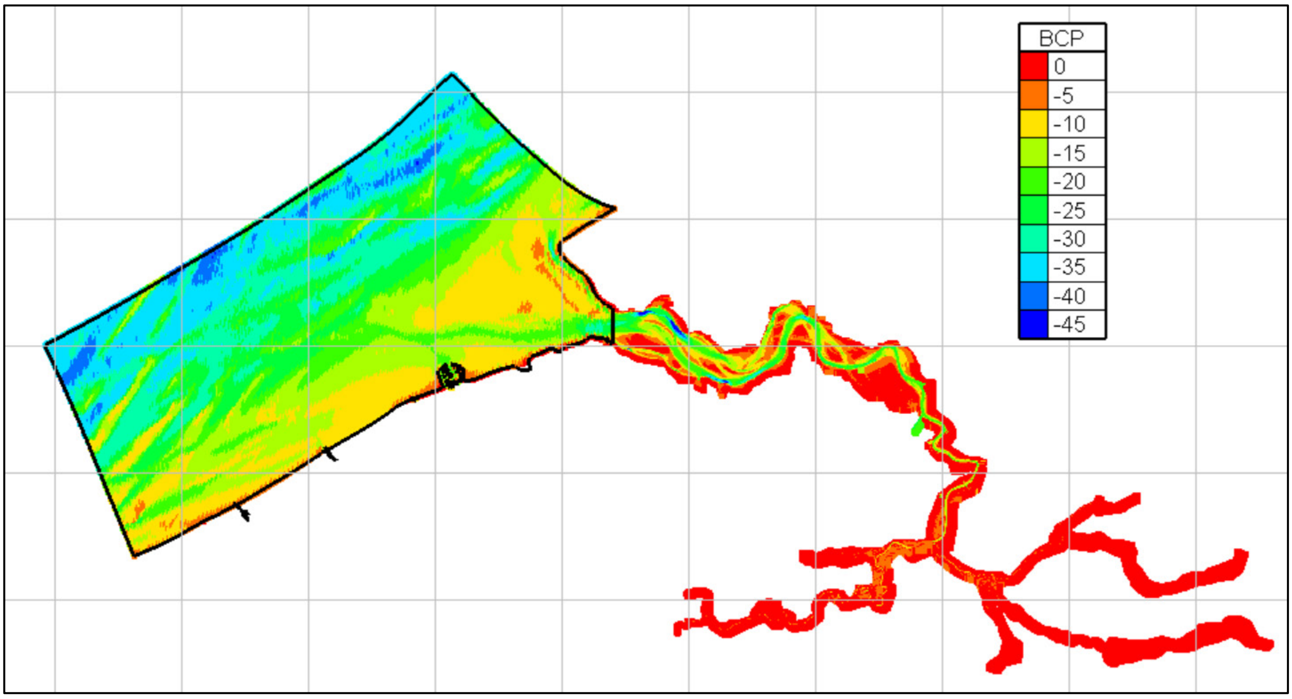
The files that were used to generate the model bathymetry are stored here:

P:\PA016-Ondrhd2D3Dmdl\2_Input_gegevens\Update Scaldis 2019\Bathy Combigrid

The bathymetric data of 2019 is provided as combigrids (combination between LIDAR and Bathy data into one consistent dataset) and pre-processed by the GIS group at aMT. The dataset has spatial resolution of 5 m in NAP and is projected in RD Parijs. A validation of the datasets against independent RTK data (Elsen et al., 2020) discerns between two types of combigrid. The classical combigrid prioritises bathymetric data over LIDAR data when there is overlap. The averaged combigrid uses the average value in case of overlap. The validation exercise showed that for the lower Sea Scheldt, the regular combigrid is used. For the upper Sea Scheldt and the tributaries, the average combigrid is better.

Because there are no bathymetry data in 2019 for the Belgian Coastal Zone (BCZ, shown by the black polygon in Figure 1), therefore the bathymetry for the BCZ is composed with data from year 2004 to 2016 (Chu et al., 2017) and the most recent Dutch vaklodingen bathymetric dataset for the coastal zone (Wang, 2018).

Figure 1 – Bathymetry data of 2019 in m NAP (positive up).



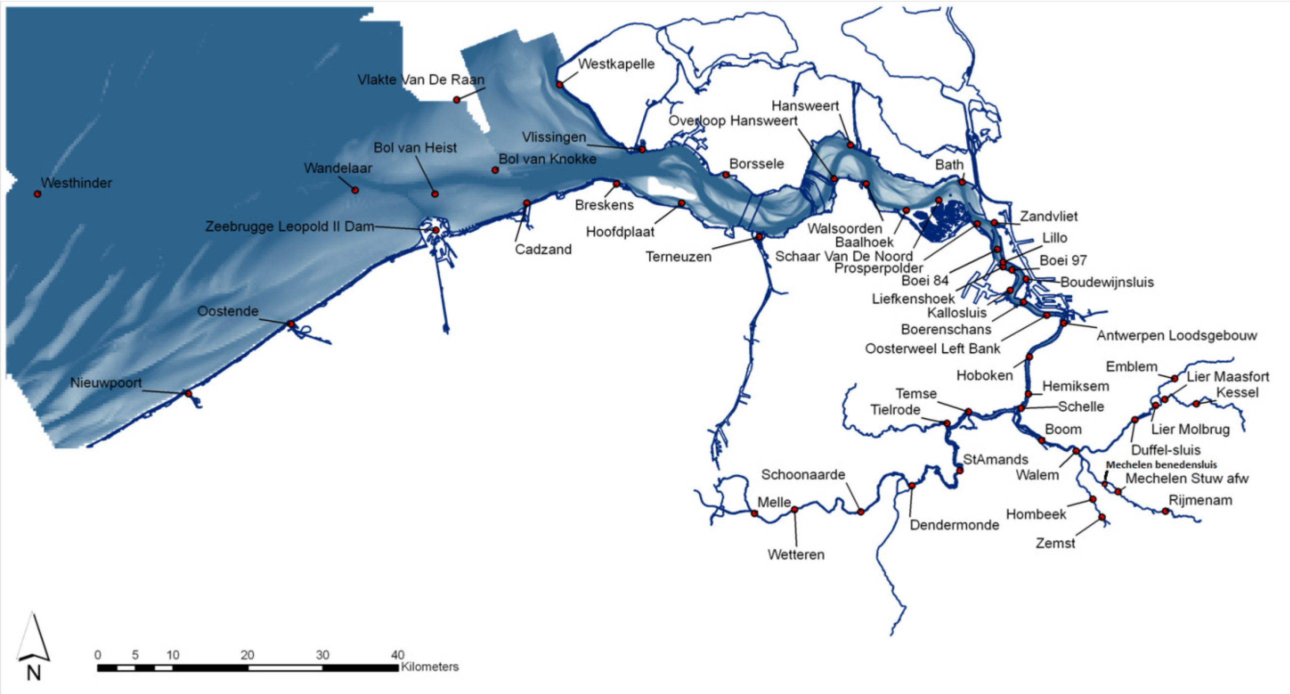
3.2 Water levels

For the year 2019, 53 stations are available with water level measurements every 10 minutes, see Table 2 and Figure 2. The British, French and Dutch stations (No. 1-21) are used to validate the DCSMV6-ZUNOv4 model.

Table 2 – Available water level measurements for the year 2019.

No.	Station Name	Source	No.	Station Name	Source
1	Leith	BODC	28	Cadzand	HMCZ
2	North Shields	BODC	29	Vlissingen	HMCZ
3	Whitby	BODC	30	Breskens	HMCZ
4	Immingham	BODC	31	Terneuzen	HMCZ
5	Cromer	BODC	32	Overloop Hansweert	HMCZ
6	Lowestoft	BODC	33	Hansweert	HMCZ
7	Harwich	BODC	34	Walsoorden	HMCZ
8	Sheerness	BODC	35	Baalhoek	HMCZ
9	Dover	BODC	36	Bath	HMCZ
10	Newhaven	BODC	37	Prosperpolder	HIC
11	Portsmouth	BODC	38	Liefkenshoek	HIC
12	Cherbourg	SHOM	39	Kallo	HIC
13	Le_havre	SHOM	40	Antwerpen	HIC
14	Boulogne-sur-mer	SHOM	41	Hemiksem	HIC
15	Calais	SHOM	42	Boom	HIC
16	Dunkerque	SHOM	43	Temse	HIC
17	Oosterschelde_11	HMCZ	44	Tielrode	HIC
18	Oosterschelde_4	HMCZ	45	Waasmunster	HIC
19	Oosterschelde_14	HMCZ	46	StAmands	HIC
20	Brouwhvsgt02	HMCZ	47	Dendermonde	HIC
21	Haringvliet_10	HMCZ	48	Schoonaarde	HIC
22	Westhinder	MVB	49	Wetteren	HIC
23	Nieuwpoort	MVB	50	Melle	HIC
24	Oostende	MVB	51	Mechelen_sluis	HIC
25	Zeebrugge	MVB	52	Rijmenam	HIC
26	Vvdr	HMCZ	53	Duffel	HIC
27	Westkapelle	HMCZ			

Figure 2 – Measurement locations of water level.



3.3 Velocities

3.3.1 Stationary velocities in deep areas

Timeseries of stationary velocity measurements from the year 2019 are available at 4 locations of Bol Van Heist, Scheur Wielingen, Lillo and Oosterweel (see locations in Figure 4 to Figure 6). Table 3 describes the data source and at which elevation the velocities are measured.

Table 3 – Description of stationary velocity measurements.

Location	Level	Time interval	Data Source
Bol Van Heist	Depth average	10 mins	MVB
Scheur Wielingen	Depth average	10 mins	MVB
Lillo Meetpaal top	Near surface	5 mins	HIC
Lillo Meetpaal bottom	Near bottom	5 mins	HIC
Oosterweel top	Near surface	5 mins	HIC

3.3.2 Stationary velocities in shallow areas

The first measurement campaign (shallow zones) in the Sea Scheldt on intertidal areas was carried out in 2014 and is described in Plancke et al. (2014). More recent measurements were carried out in 2015 and 2016 at various locations in de Zeeschelde, as is presented by Meire et al. (2017). These measurements range spatially from the east side of Saeftinghe (most downstream location) to Appels (most upstream location).

The new measurements on intertidal areas were conducted at 10 different locations in the Sea Scheldt. The overview of the data is shown in Figure 3 and Table 4. For the analysis of flow velocities in shallow zones it is very important that the measurement point and the analyzed point (node) in the model have similar depths. The differences in local depth may result in differences between the calculated and the measured velocities. Table 5 presents the information about the nearest node that have been used for comparison with the measurements. The table includes also the bottom levels as measured in the field and computed at each node.

Figure 3 – Overview of the measuring locations of stationary velocity at shallow zones along Scheldt estuary (adopted from Hassan et al., 2017).

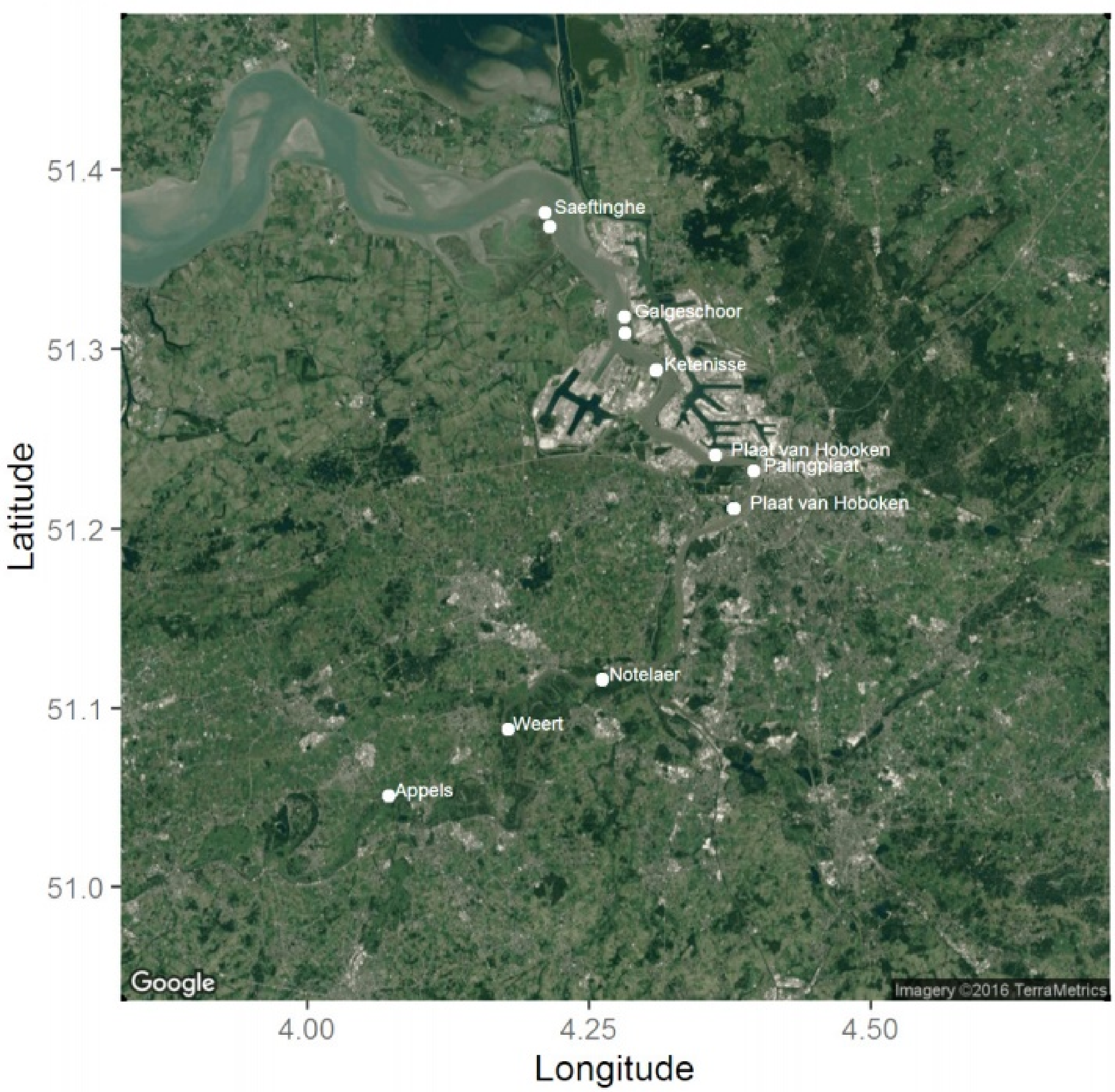


Table 4 – General overview of the measuring campaigns at each location.

Zone	Station	Year	Lon	Lat	Height Measured [m TAW]	Height Measured [m NAP]	Bottom level at nearest node in SCALDIS-model [m NAP]	Model - Measurement [m]	Node Nr.
BeZS	Saeftinghe_north	2016	4.21122	51.37614	0.09	-2.26	-2.06	-0.20	252235
	Saeftinghe_south	2016	4.21545	51.36805	0.54	-1.81	-1.93	0.12	252817
	Galgeschoor_north	2015	4.28102	51.31816	0.57	-1.78	-1.75	-0.03	261242
	Galgeschoor_south	2015	4.281759	51.30881	1.17	-1.18	-1.09	-0.09	261335
	Ketenisse_hoog	2015	4.30902	51.28806	3.34	0.99	1.87	-0.88	263977
	Ketenisse_laag	2015	4.30972	51.28843	0.18	-2.17	-2.12	-0.05	263867
	Plaat van Boomke_hoog	2015	4.362028	51.241111	2.41	0.06	-0.65	0.71	268100
	Plaat van Boomke_laag	2015	4.362028	51.241028	0.09	-2.26	-2.16	-0.10	268119
	Palingplaat_hoog	2016	4.39642	51.23223	1.76	-0.59	-0.37	-0.22	219348
	Palingplaat_laag	2016	4.39662	51.23228	0.85	-1.5	-2.04	0.54	219426
	Plaat van Hoboken_hoog	2015	4.37848	51.21147	2.1	-0.25	-0.29	0.04	217556
	Plaat van Hoboken_laag	2015	4.37887	51.21115	0.1	-2.25	-2.37	0.12	217617
BoZS	Notelaer_hoog	2016	4.26188	51.11575	1.34	-1.01	-1.09	0.08	322663
	Notelaer_laag	2016	4.2618	51.11579	1	-1.35	-1.37	0.02	322665
	Weert_hoog	2014	4.178186	51.08809	2.27	-0.08	-0.12	0.04	368057
	Weert_laag	2014	4.178083	51.08797	0.05	-2.3	-2.49	0.19	366629
	AppelsLO_hoog	2014	4.072383	51.05075			0.88		384661
	AppelsLO_laag	2014	4.072517	51.050583			-1.23		389783
	AppelsRO_hoog	2014	4.068041	51.04848			0.10		410417
	AppelsRO_laag	2014	4.068117	51.04866			-4.79		404806

3.3.3 ADCP sailed velocities

Currently there are in total **356** ADCP campaigns data available. In order to calibrate/validate the SCALDIS model sufficiently, we use the ADCP data to cover the entire Scheldt as much as possible. When there are multiple ADCP data available at one location, the most recent data are selected. **54** representative ADCP sailed dataset are selected as listed in Table 5 and Figure 4 to Figure 7. The measured tide during these 54 measurement campaigns is used to determine the modelling period from comparable tide analysis (§ 4.3).

Table 5 – Description of ADCP transects from downstream to upstream.
The campaign names contain the information of the date and location of the campaign.

Zone	No.	Campaign Names	Zone	No.	Campaign Names
BCZ	1	Zeebrugge_HCBS Scheur_20070802	WES	28	WES_Raai_2_20180529
	2	Zeebrugge_HCBS Wiel_20070803		29	WES_Raai_1A_20190319
	3	Zeebrugge_HCBS Zand_20070801		30	WES_Raai_1B_20190319
	4	WES_Wielingen_Zuid_20151002	BeZS	31	Zandvliet_20050217_Neap
	5	WES_Wielingen_Noord_20151003		32	Noordzeeterminal_20140715_Spring
WES	6	WES_Oostgat_West_20150928		33	Toegangsgeul_Zandvliet_Berendrecht_20181011
	7	WES_Oostgat_Oost_20150929		34	Doel_LangsraaiO_20100318_Spring
	8	WES_Raai_12_20170724		35	Doel_DwarsraaiD_20100319_Spring
	9	WES_Raai_12_20170725		36	Galgenschoor_20110902
	10	WES_Raai_12_20170726		37	DGD_20161018_Spring
	11	WES_Raai_11_20180712		38	DGD_Eddy Measurements_20120312_Spring_T2
	12	WES_Raai_11_20180713		39	DGD_Eddy Measurements_20120312_Spring_T3
	13	WES_Raai_10_20180912		40	Liefkenshoek_20170511
	14	WES_Raai_10_20180913		41	Kallo_20050218_Neap
	15	WES_Raai_9a_20190605		42	Oosterweel_20160511
	16	WES_Raai_9b_20190605		43	Galgenweel_20190520
	17	WES_Raai_9c_20190606		44	Palingplaat_20190521
	18	WES_Raai_7_20170822		45	Kruibeke_20170629
	19	WES_Raai_7_20170823		46	Schelle_20060928_Average
	20	Terneuzen_haven_20070321		47	Wintam_20130213
	21	WES_Raai_6_20180813	BoZS	48	Driegoten_20160622
	22	WES_Raai_6_20180814		49	Appels_Downstream_20110801
	23	Diepe_Put_Hansweert_20170720		50	Appels_Upstream_20110801
	24	Dwarsstroming_Ossenisse_20190323		51	Schoonaarde_20160606
	25	WES_Raai_5A_201900507		52	Schellebelle_20170626
	26	WES_Raai_5A_201900508		53	Boom_20100427
	27	WES_Raai_3_20170622		54	Terhagen_20170628

Figure 4 – Available ADCP measurements in the BCZ.
Green lines represent each transect. Red dot indicates the stationary velocity location.

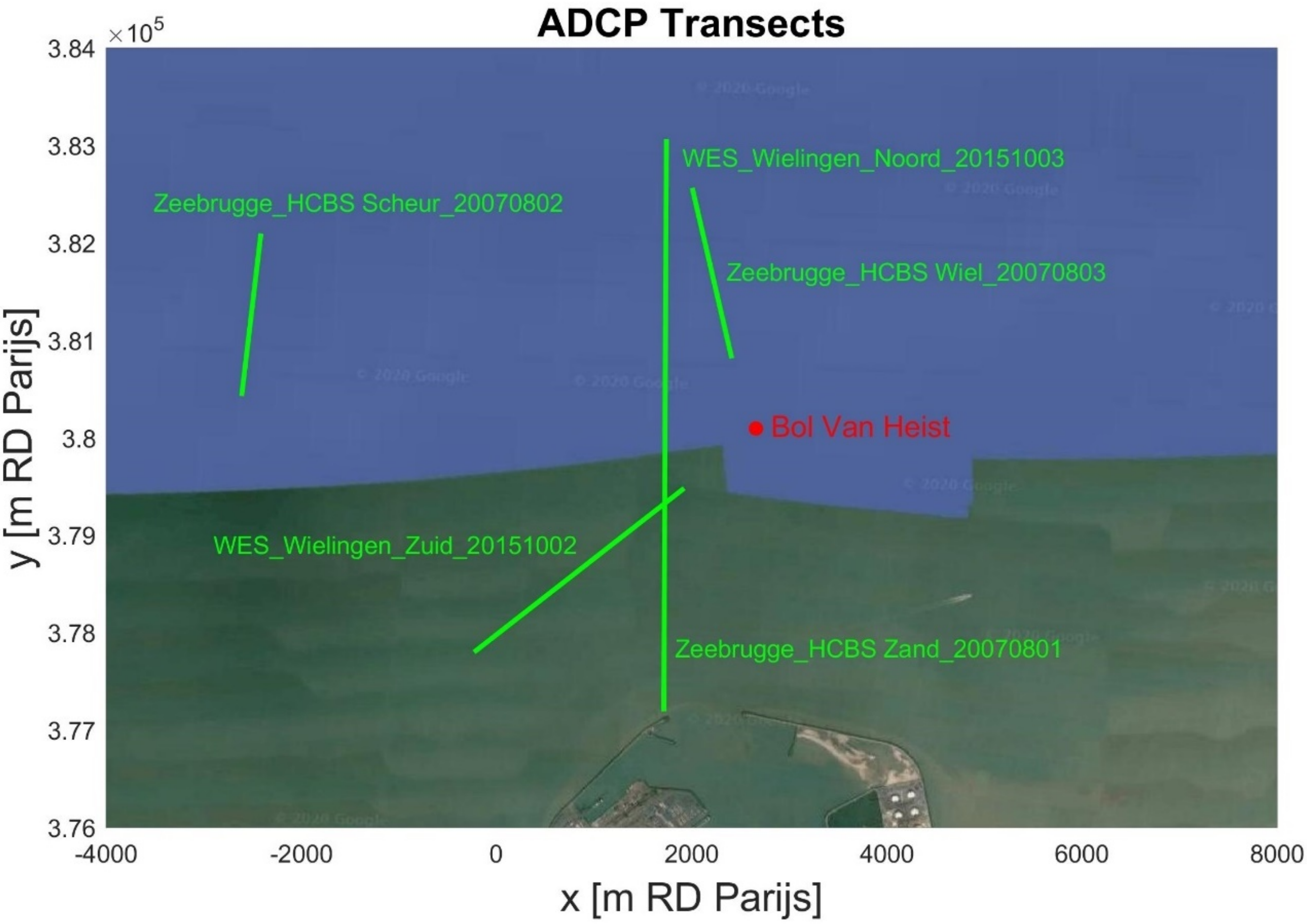


Figure 5 – Available ADCP measurements in the Western Scheldt.
Green lines represent each transect. Red dot indicates the stationary velocity location.

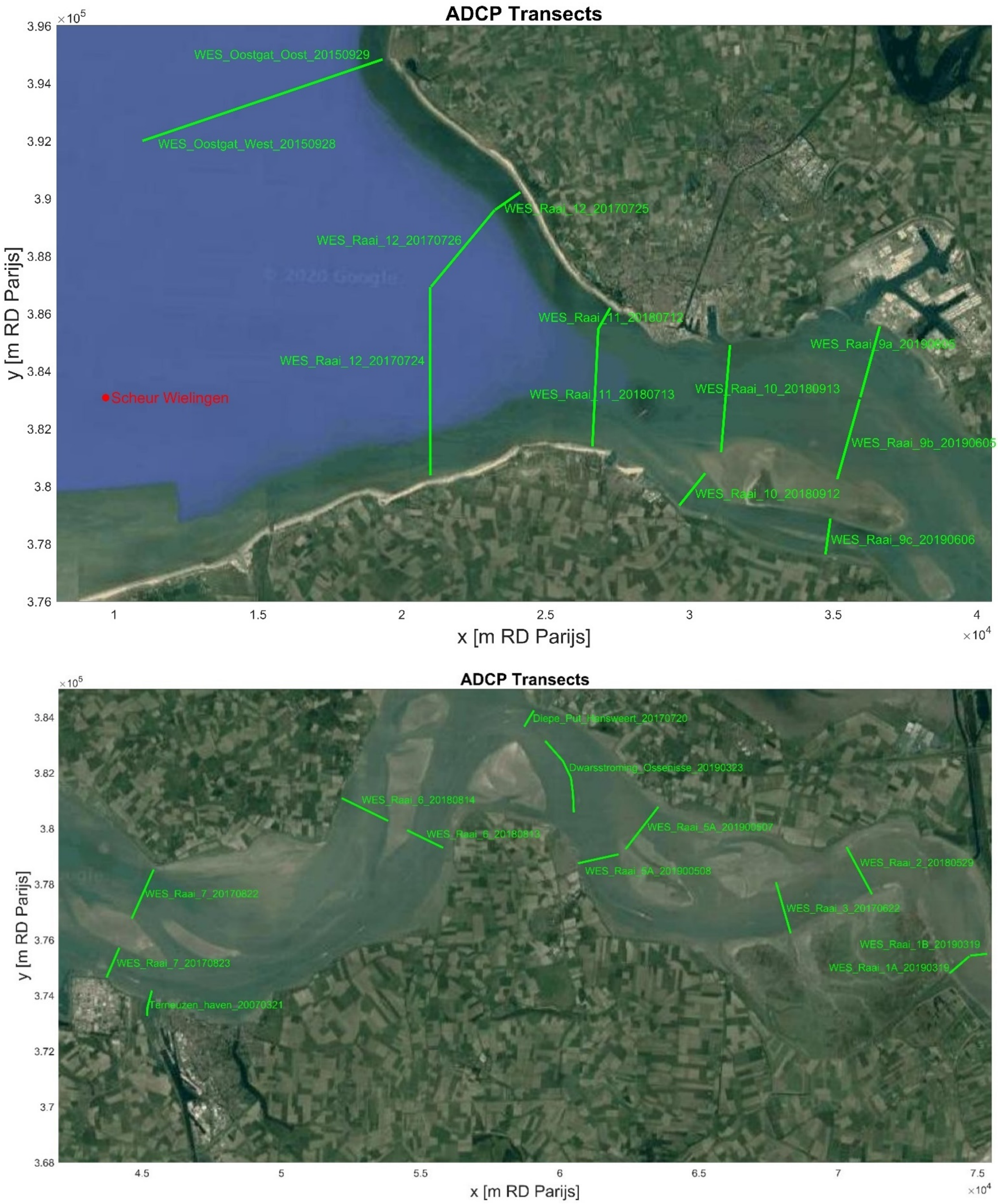


Figure 6 – Available ADCP measurements in the Lower Sea Scheldt.
Green lines represent each transect. Red dot indicates the stationary velocity location.

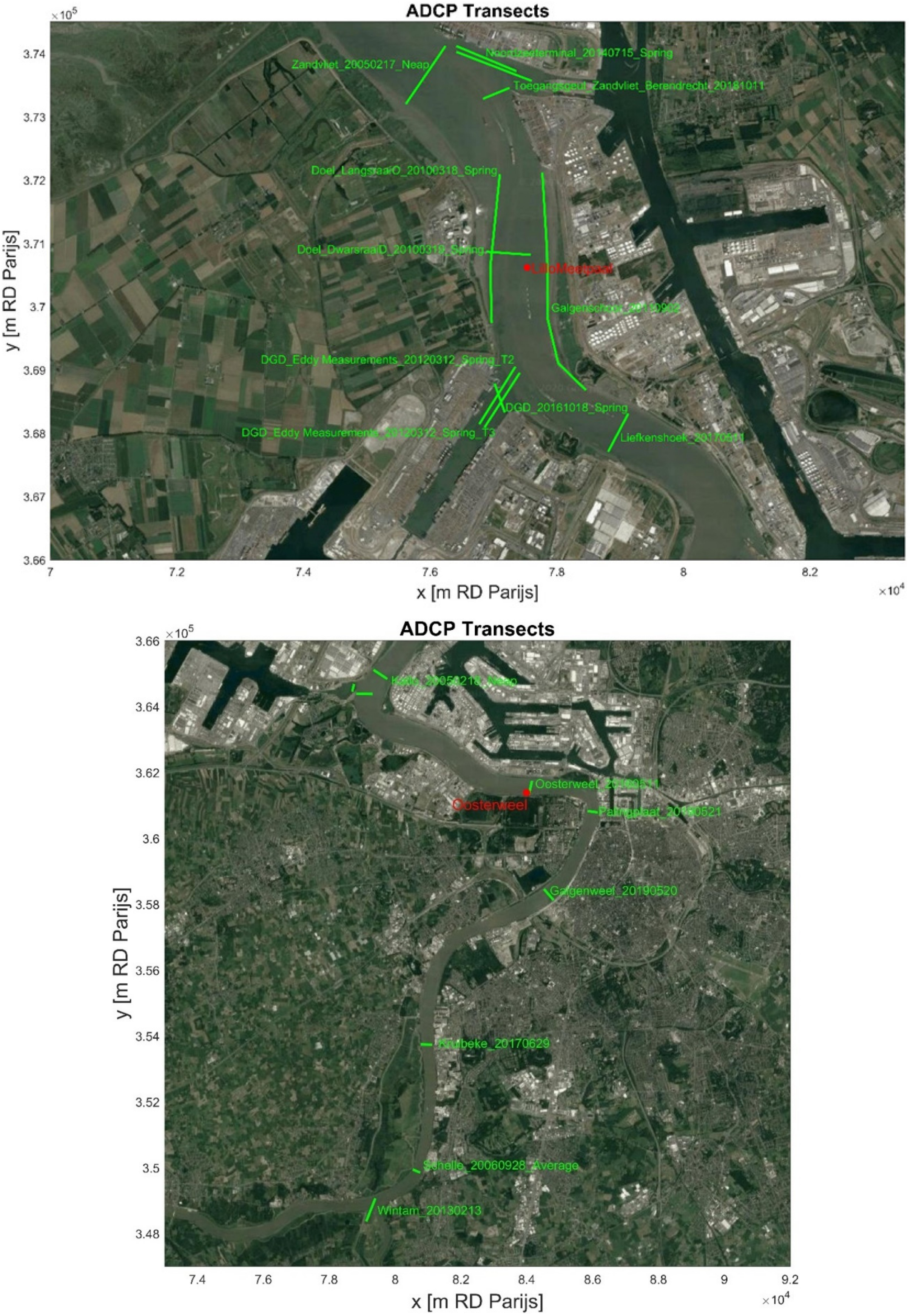


Figure 7 – Available ADCP and stationary measurements in the Upper Sea Scheldt and Rupel.
Green lines represent each transect.

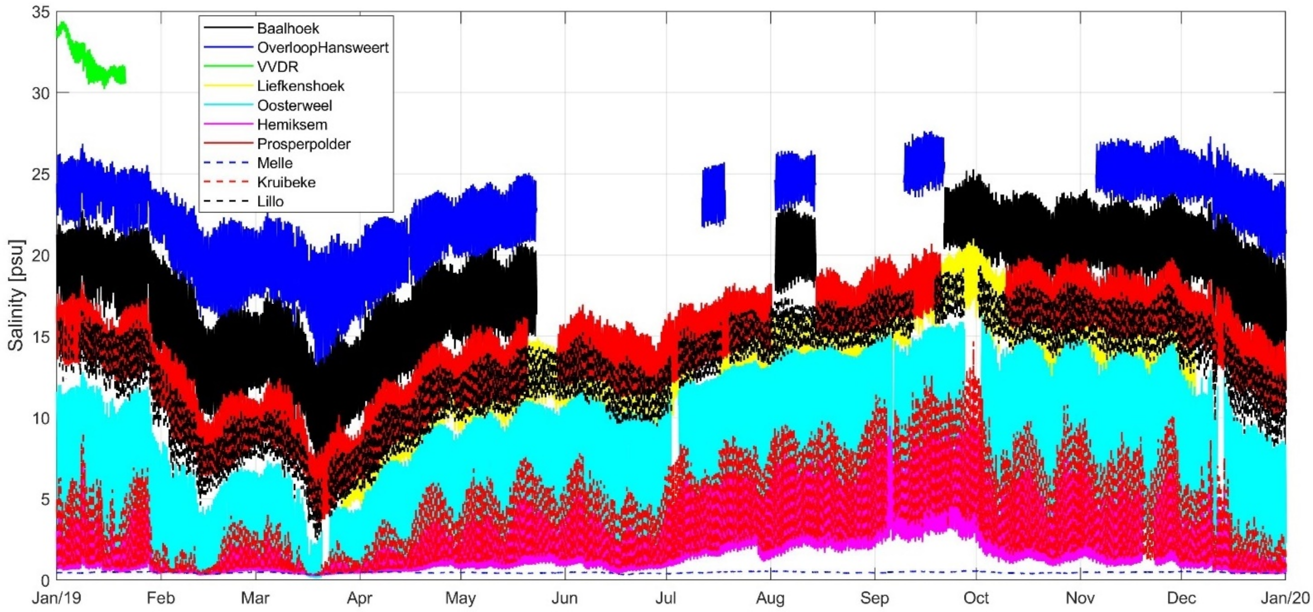
3.4 Salinity

Salinity measurements with 10-min time interval are available at 10 stations as listed in Table 6 and Figure 8. Salinity measurements are used to initialize the SCALDIS model and also for model validation. The initial salinity field is constructed by linear interpolation along the estuary with the salinity measurements at the start of the model simulation (after hydrodynamic spin-up). More details are given in § 4.8.

Table 6 – Overview of available stations with salinity measurements.

No.	Measuring station	Data source
1	Vlakte Van De Raan	HMCZ
2	Overloop Hansweert	HMCZ
3	Baalhoek	HMCZ
4	Prosperpolder	HIC
5	Lillo-Meetpaal	HIC
6	Liefkenshoek	HIC
7	Oosterweel	HIC
8	Kruibeke	HIC
9	Hemiksem	HIC
10	Melle	HIC

Figure 8 – Time series of salinity data of 2019.



3.5 Discharges

River discharges are imposed at 8 stations in the SCALDIS model (See details in Table 7). River discharge data at Terneuzen is not available for the year 2019. Alternatively an averaged value of discharge over the entire year of 2014 (37.78 m^3/s) is applied there. Note that the discharge at Terneuzen is less substantial, with limited impact on the model results.

The time series of discharge at the other stations for the year 2019 are presented in Figure 9 and Figure 10. Most of the fresh water is imported from Bath (where every 10 minutes data are available).

Table 7 – Description of river discharge data 2019.

Station Names	Source	Year	Data Type	Temporal Resolution
Kleine Nete	HIC	2019	Measurement	1 hour
Grote Nete	HIC	2019	Measurement	1 hour
Dijle	HIC	2019	Measurement	1 hour
Dender	HIC	2019	Measurement	1 hour
Melle	HIC	2019	Measurement	1 hour
Zenne	HIC	2019	Measurement	1 hour
Bath	RWS	2019	Measurement	10 minutes
Ternuezen	RWS	2014	Calculated	Constant at 37.78 m^3/s

Figure 9 – Time series of river discharge data of 2019.

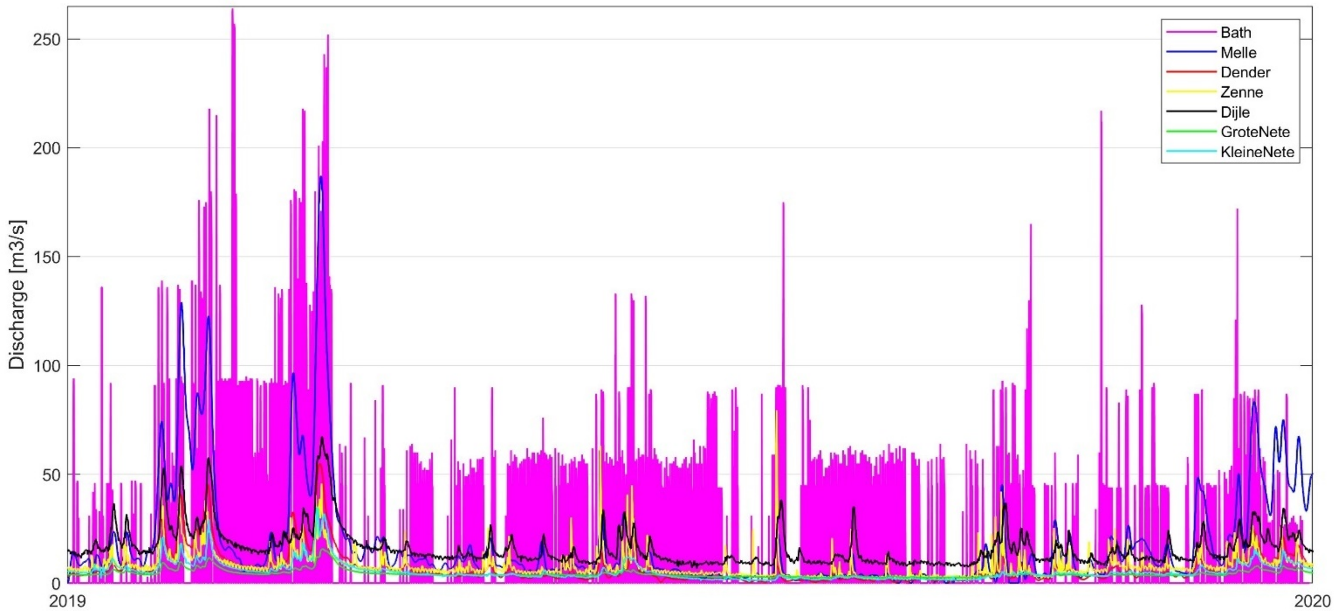
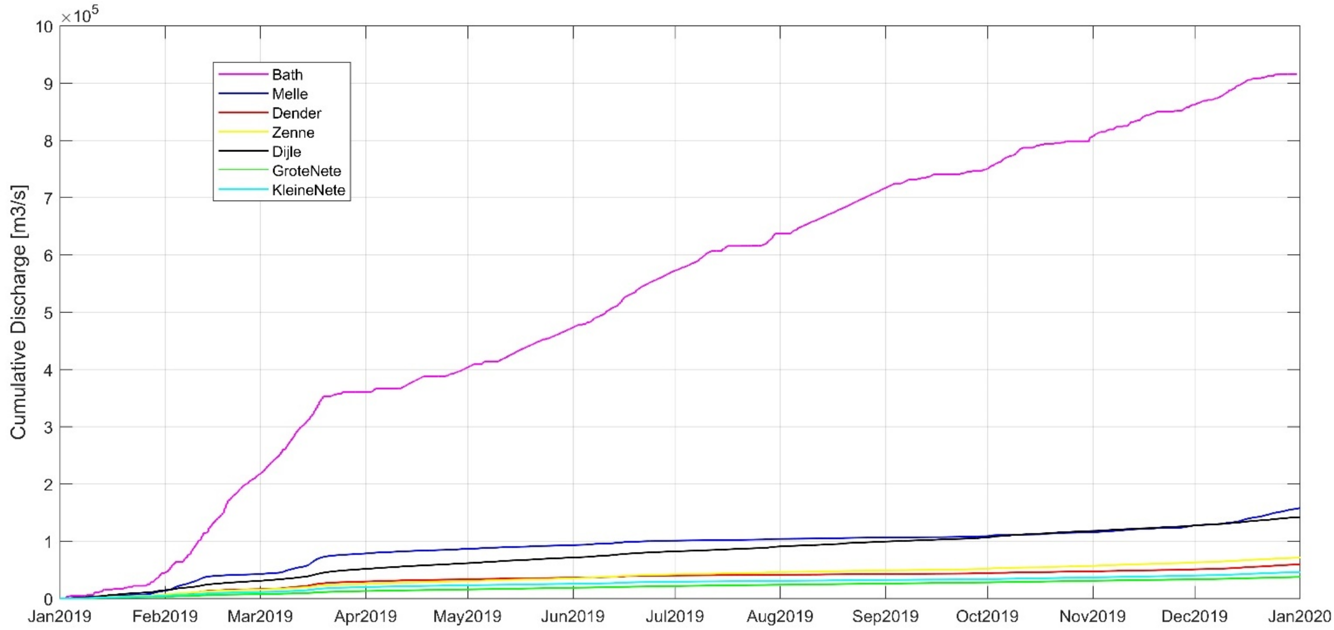


Figure 10 – Cumulative river discharge data of 2019.



3.6 Wind

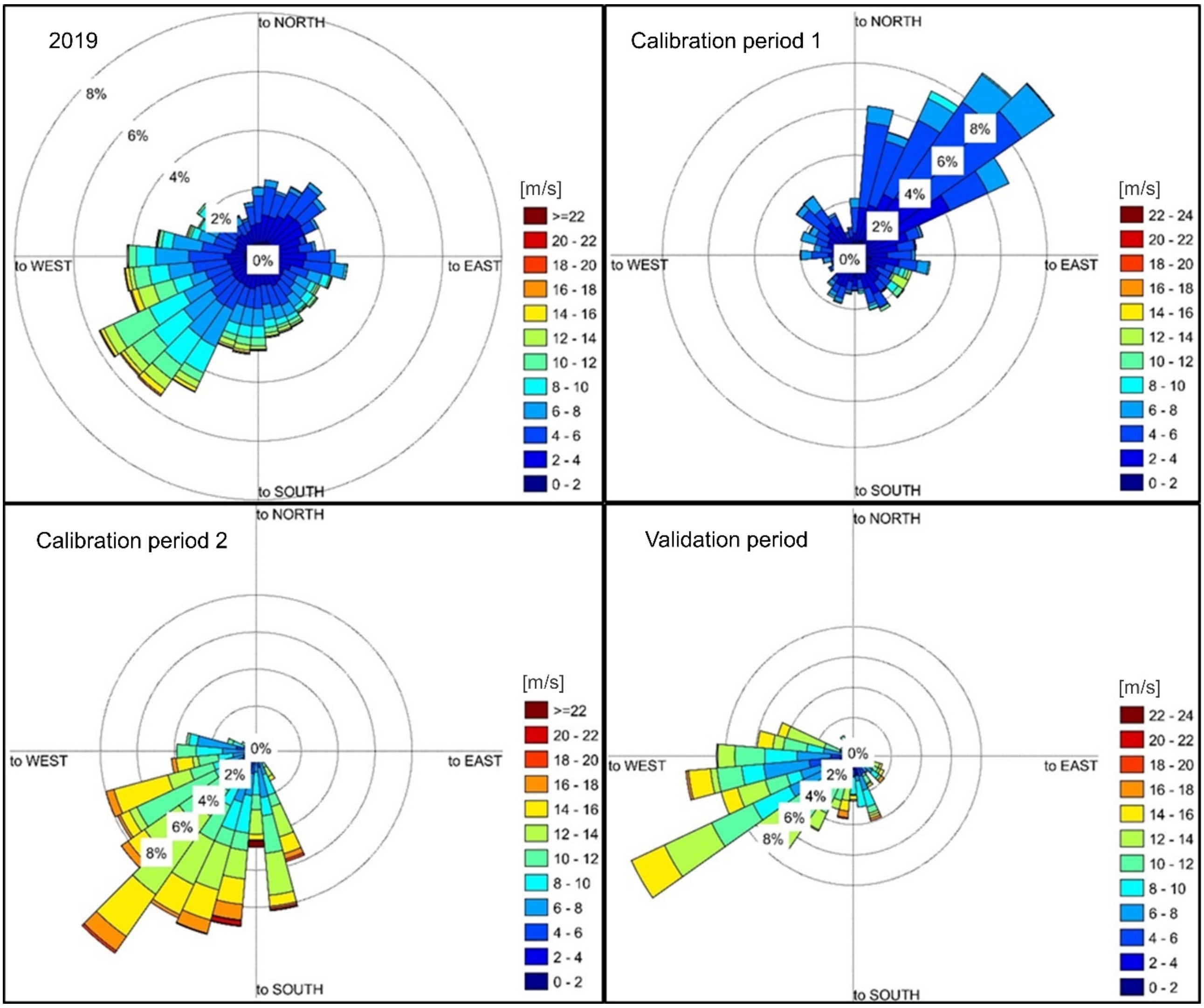
3.6.1 ERA5 wind for DCSMv6-ZUNOv4

The ERA5 wind field data (format: Grib) are received from ECMWF. The Grib data are converted into a SDS-file (binary format) by means of Simona script of waqwnd. The spatial resolution is 0.25 degree and the temporal resolution is 1 hour. The ERA5 wind field data are utilized to force the DCSMv6-ZUNOv4 model with spatial and temporal varying Charnock coefficient provided by ERA5.

3.6.2 Measured wind at Hansweert for SCALDIS

Wind measurements are available at Hansweert with time interval of 10 minutes (HMCZ). The time series of wind measurement at Hansweert of 2019 are utilized to force the SCALDIS model. Figure 11 shows the wind rose plot for the entire year 2019 and for the calibration/validation periods. For calibration period I (calm condition), wind mainly comes from northeast direction. During stormy period the wind is mainly coming from southwest direction.

Figure 11 – Wind rose plot with HMCZ wind data from Hansweert



4 Description of SCALDIS 2019

The calibrated models are stored in:

https://wl-subversion.vlaanderen.be/svn/repoSpNumMod/TELEMAC/Scaldis/PA016%20BenO/SCALDIS_2019

4.1 Software

This study is carried out using two different modelling suites: SIMONA (for the boundary conditions model, see §4.10) and TELEMAC. Table 8 specifies the modelling suites.

SIMONA (Simulatie Modellen Natte waterstaat) is a software suite developed by Rijkswaterstaat, for 2D (WAQUA module) and 3D (TRIWAQ module) modelling of water movement. It consists of a number of programs for pre-processing (preparation of simulations) and post processing (visualisation of the model results). The **2017 version** of SIMONA is used in this study.

The TELEMAC software is based on the finite element method. The model domain is discretized into an unstructured grid of triangular elements and can be locally refined in the study area. This way, the complex geometry of the study area can be taken into account. The Blue Kenue software is used for the grid and bathymetry generation. The **v7p2r1 version** of TELEMAC is used in this study.

Parallel computing is used for both models to decrease the computational time.

Table 8 – Overview of use of different modelling suites.

No.	Model	Modelling suite	Software version
1	CSMv6 – ZUNOv4	SIMONA	2017
2	SCALDIS2019	TELEMAC – 3D	V7p2r1

4.2 Mesh

The mesh of the SCALDIS 2019 model covers the Belgian Coastal Zone and the entire Scheldt river estuary. Figure 12 shows the model domain and bathymetry. The mesh resolution gradually decreased from more than 500 m near the offshore boundary to ~ 5m in the upper river tributaries (Figure 13 to Figure 16). To fulfil the requirement of nautical ship simulation, the mesh is locally refined in zones of interests as proposed in Table 9. The total number of computational nodes are 478,290, with 915,622 triangular elements. To better represent the flow patterns, the SCALDIS 2019 model runs in 3D mode with 5 vertical interfaces (4 layers) using sigma coordinates. The distribution of vertical interfaces from bottom to top are 0, 0.12, 0.3, 0.6 and 1.0.

The mesh was made in a way to be more aligned with the flow lines of the water movement inside the estuary, e.g. using soft-lines along the channel to guide the generation of the mesh. In the upper-stream, channel mesh is used to structure the triangles of the mesh in such a way that they follow better the channel geometry and the flow direction (Smolders et al., in preparation). Some examples are shown in Figure 17 to Figure 20. Figure 21 exemplifies the comparison of the mesh used in SCALDIS 2013 and SCALDIS 2019.

Figure 12 – Mesh and bathymetry (m NAP) of SCALDIS 2019 model.

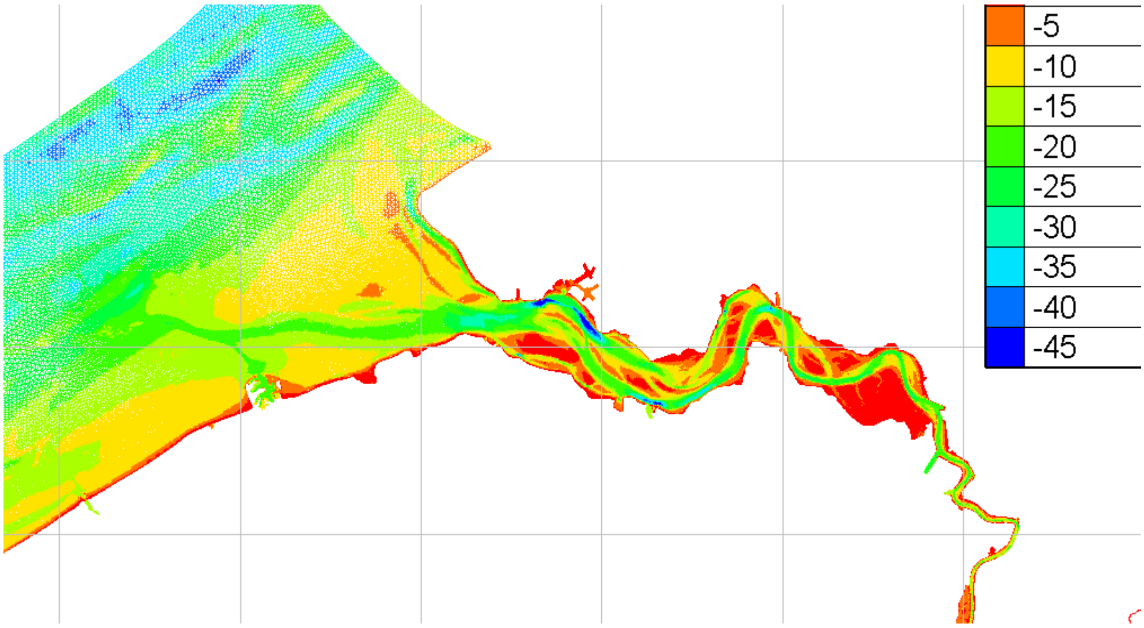


Figure 13 – Mesh resolution (edge length expressed in meters).

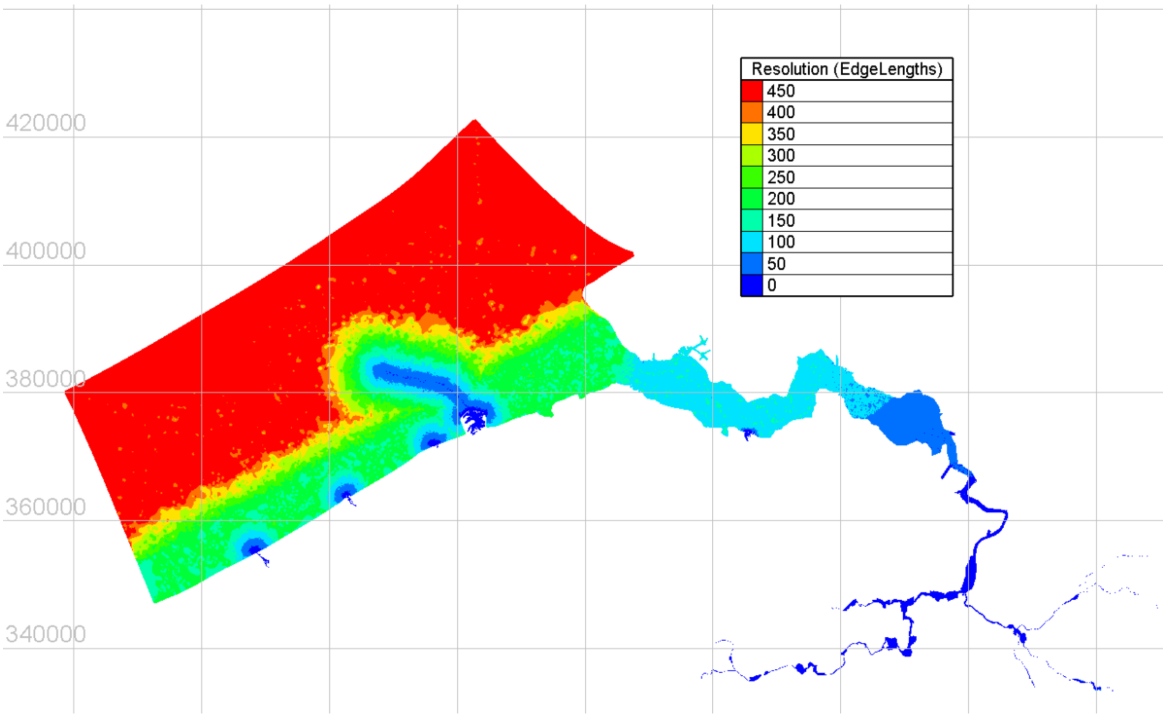


Figure 14 – Mesh resolution in the Western Scheldt (edge length expressed in meters).

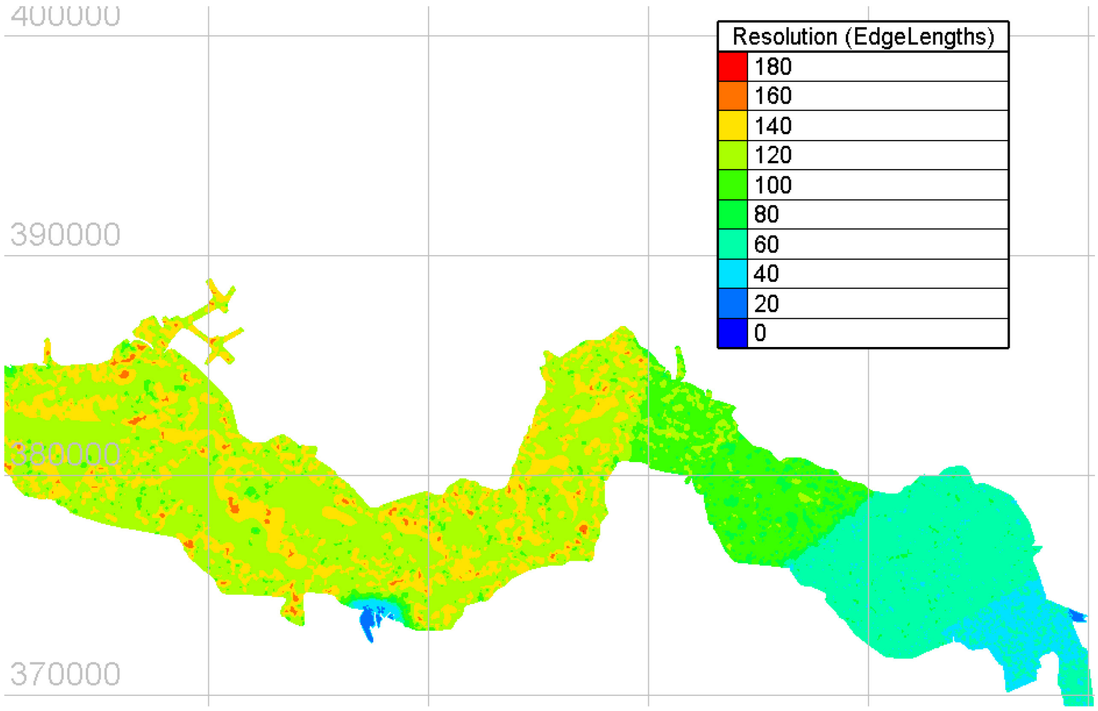


Figure 15 – Mesh resolution in the lower Sea Scheldt (edge length expressed in meters).

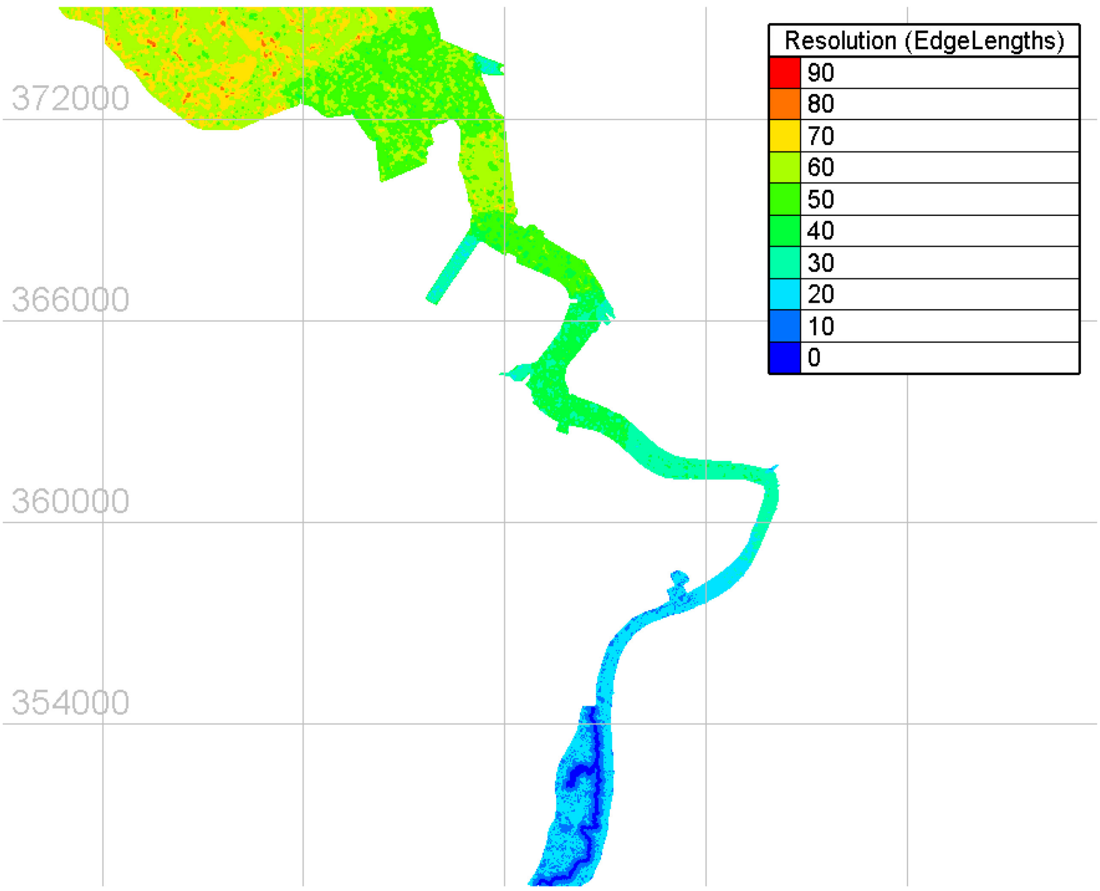


Figure 16 – Mesh resolution in the upper Sea Scheldt (edge length expressed in meters).

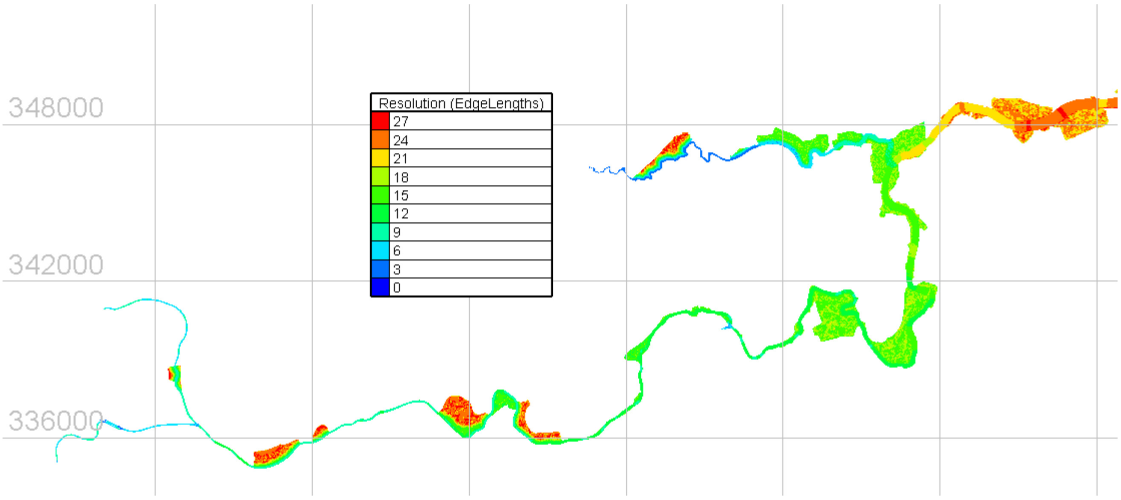


Table 9 – Mesh resolution required by nautical ship simulator and the mesh resolution in the model.

Zones	Requested for nautical applications	Model
Coastal Zone	200 x 200 m	200 m
Access channels (eg Pas van het Zand)	50 x 50 m	50 m
Zeebrugge	30 x 30 m	30 m
Oostende	30 x 30 m	30 m
Terneuzen	30 x 30 m	30 m
Western Scheldt	100 x 50 m	100 m
Berendrechtsluis	30 x 30 m	30 m
Deurganckdok	30 x 30 m	30 m
Boudewijnsluis	30 x 30 m	30 m
Kallosluis	30 x 30 m	30 m
Antwerp loodsgebouw	30 x 30 m	20 m
Wintamlock	30 x 30 m	20 m
Antwerp to Wintam	100 x 30 m	10 to 30 m

Figure 17 – Detailed presentation of mesh in a part of the Western Scheldt.

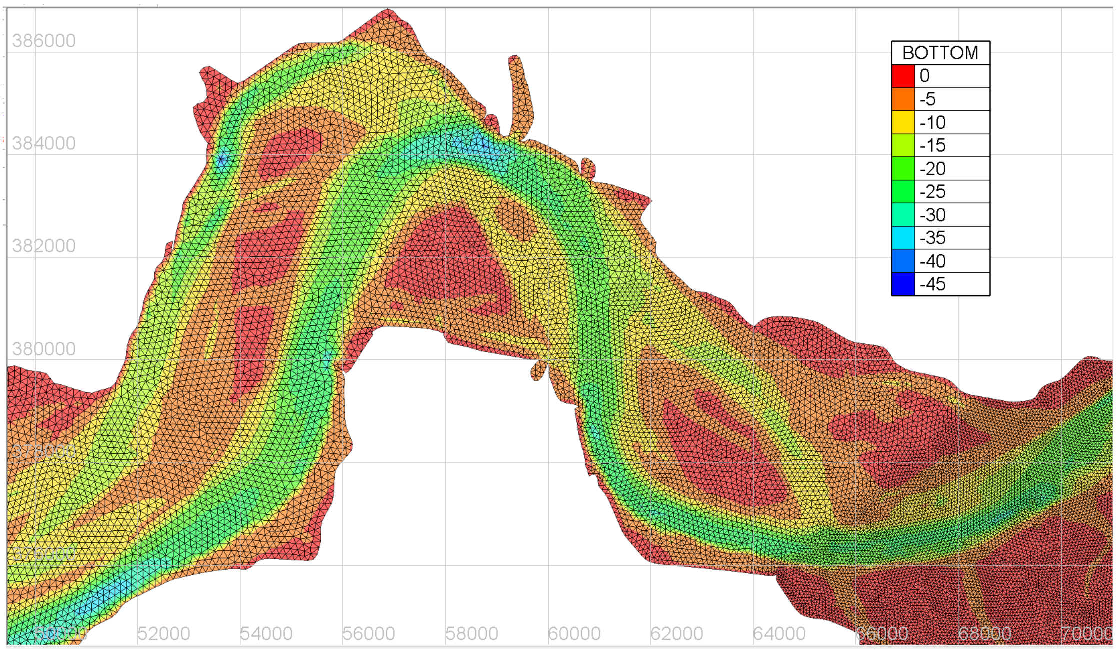


Figure 18 – Detailed presentation of mesh in a part of the Lower Sea Scheldt.

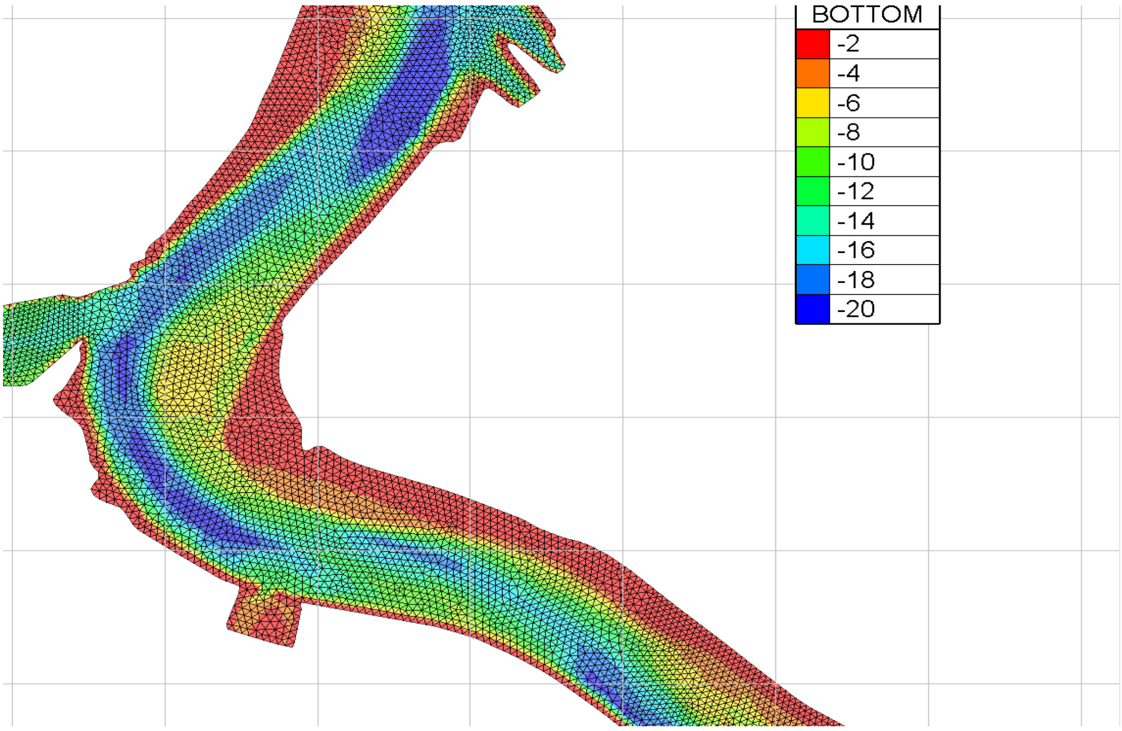


Figure 19 – Detailed presentation of mesh in a part of the Upper Sea Scheldt, channel mesh is used.

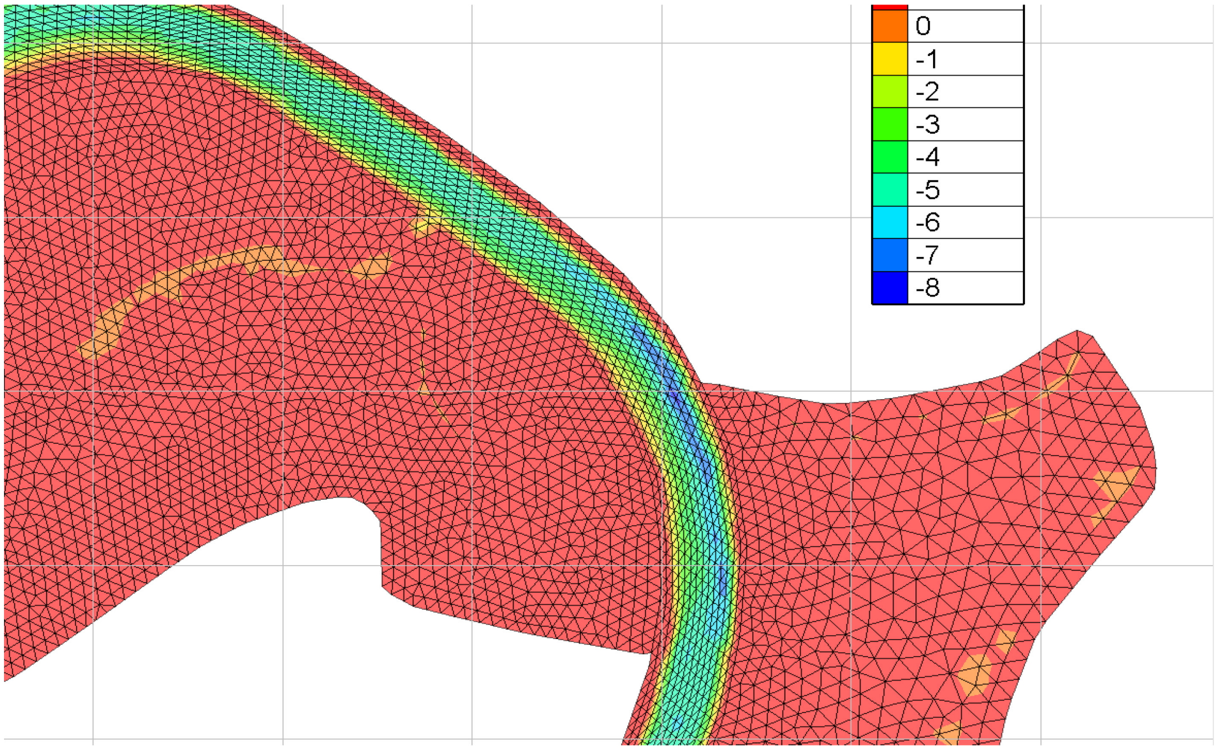


Figure 20 – Detailed presentation of mesh in a part of the Rupel, channel mesh is used.

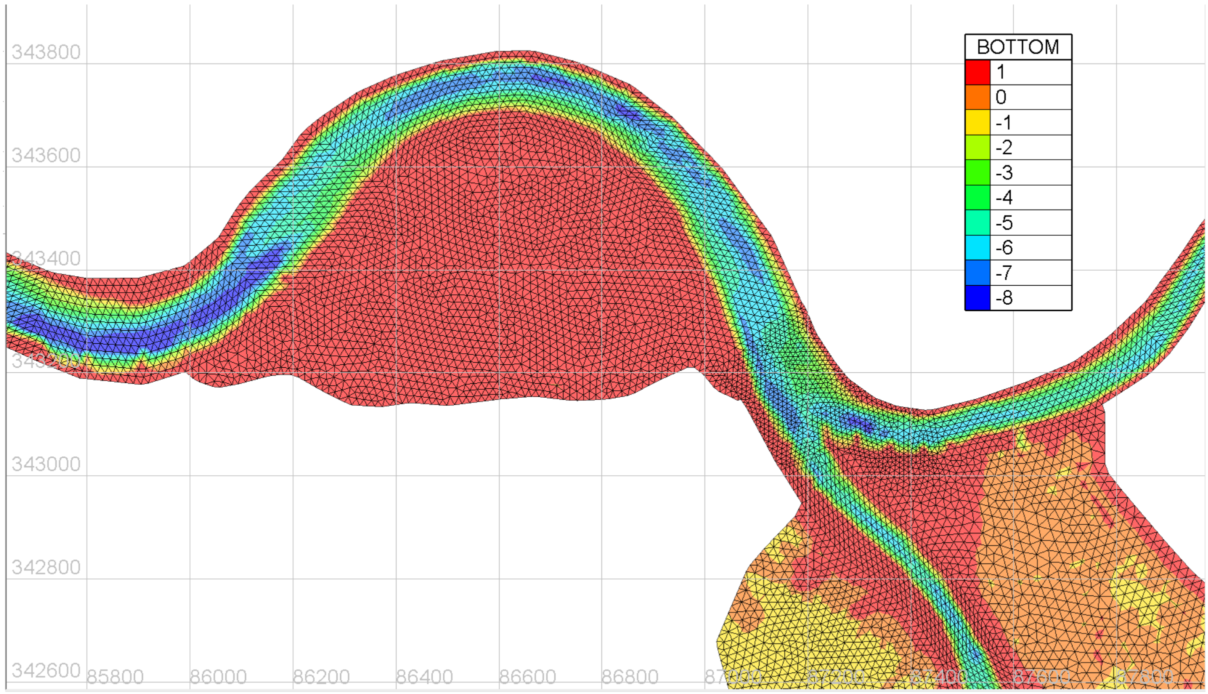
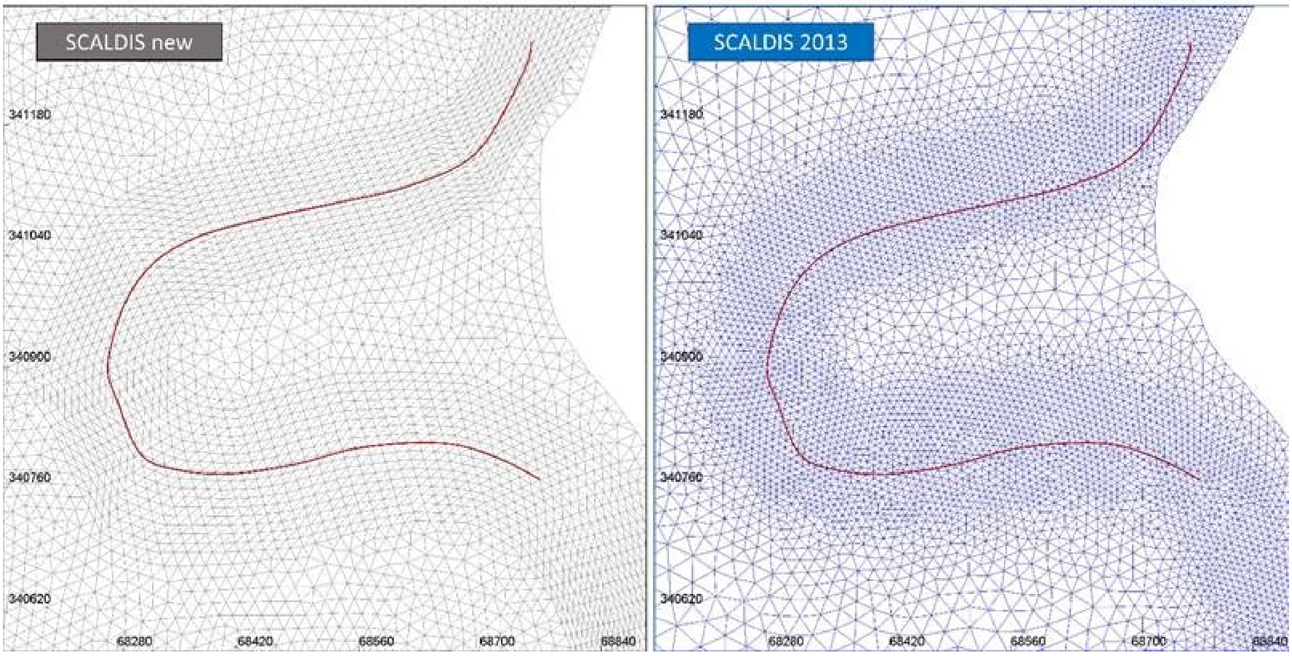


Figure 21 – Comparison of model mesh between SCALDIS 2013 (right) and SCALDIS 2019 (left).



4.3 Modelling Period

The modelling in this study involves 3 periods as shown in Table 10.

The modelling periods are chosen using a comparable tide analysis, based on the available data (see chapter 3). Comparable tide analysis is a method that allows comparison of model results to measurements which are outside of the simulation period. The short term water level that occurred during a 13h measurement campaign (ADCP) is compared with a long term water level measurements (measurements of the year 2019 in this case). Those tidal cycles within the long term water level that have the best match with the tidal cycles in the short term water level are found and ranked. For this project, the match is determined by minimising the bias-corrected RMSE (RMSE0, see definition in Annex 1). From this analysis, the period with a given length that contains the best similar tides to a set of 13h measurements (ADCP) is determined.

Table 10 – Summary of modelling periods

Name	Date	Number of days	Condition
Calibration Period I	22-Mar-2019 to 20-April-2019	29	Calm
Calibration Period II	03-Mar-2019 to 17-Mar-2019	14	Stormy
Validation Period	08-Dec-2019 to 16-Dec-2019	8	Stormy

4.3.1 Calibration periods

The modelling period for calibration is chosen to cover two spring-neap cycles (29 days)

For this study the comparable tide analysis searched the best representative period in the entire year 2019. Figure 22 shows the results of this analysis. The computed RMSE0 gently increases from **5.3 cm** (if an entire year would be modelled) to **7.2 cm** when the searching period is limited to 29 days. The selected representative period is found from **22-Mar-2019 to 20-April-2019.** The graph in Figure 22 basically allows the modeller to make the trade-off between the length of the simulation, and the average error that is made in selecting the comparable tide. For instance, searching period of 60 days gives lower RMSE0 of **6.1 cm**, which however will double the simulation period and thus increase the computational cost.

The actual modelling period for calibration is taken as **20-Mar-2019 00:00** to **20-April-2019 00:00**. The first two days are taken as hydrodynamic spin-up time and will be excluded from the analysis of the results.

The calibration period corresponds to a calm period as shown in green in Figure 23. The averaged surge at Vlissingen during the calibration period is **-0.1 m** while the averaged wind speed at Hansweert during the calibration period is **4.3 m/s**. The ADCP campaigns are often carried out during calm conditions. Therefore the best match of tidal cycles coming out of comparable tide analysis is naturally to be a calm period as well.

A second calibration period for stormy conditions is selected between **03-Mar-2019 00:00** to **17-Mar-2019 00:00** (one spring-neap cycle) as shown in Figure 23. The averaged surge at Vlissingen during this stormy period is **0.32 m** while the averaged wind speed at Hansweert is **11 m/s** (with a maximum wind speed of **25.3 m/s**). The actual modelling period is taken from **01-Mar-2019 00:00** to **17-Mar-2019 00:00**. The first two days are taken as hydrodynamic spin-up time and will be excluded from the analysis of the results.

4.3.2 Validation period

The validation period is selected between **08-Dec-2019 00:00** to **16-Dec-2019 00:00** (8 days). The averaged surge at Vlissingen during this stormy period is **0.28 m** while the averaged wind speed at Hansweert is **9.7 m/s** (with a maximum wind speed of **19.9 m/s**). The actual modelling period is taken from **06-Dec-2019 00:00** to **16-Dec-2019 00:00**. The first two days are taken as hydrodynamic spin-up time and will be excluded from the analysis of the results.

Figure 23 shows the meteo conditions of 2019, with an indication of the selected modelling periods.

Figure 22 – Comparable tide analysis results based on RMSE0 calculation for the entire year of 2019.

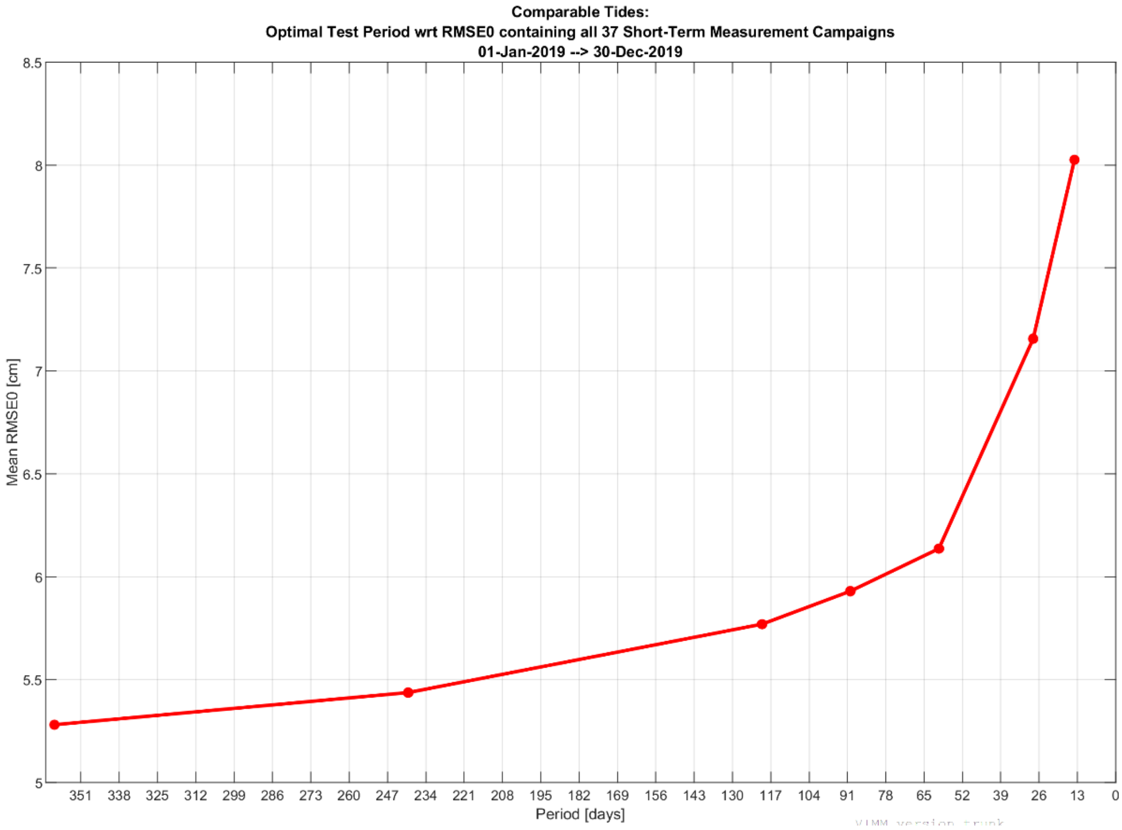
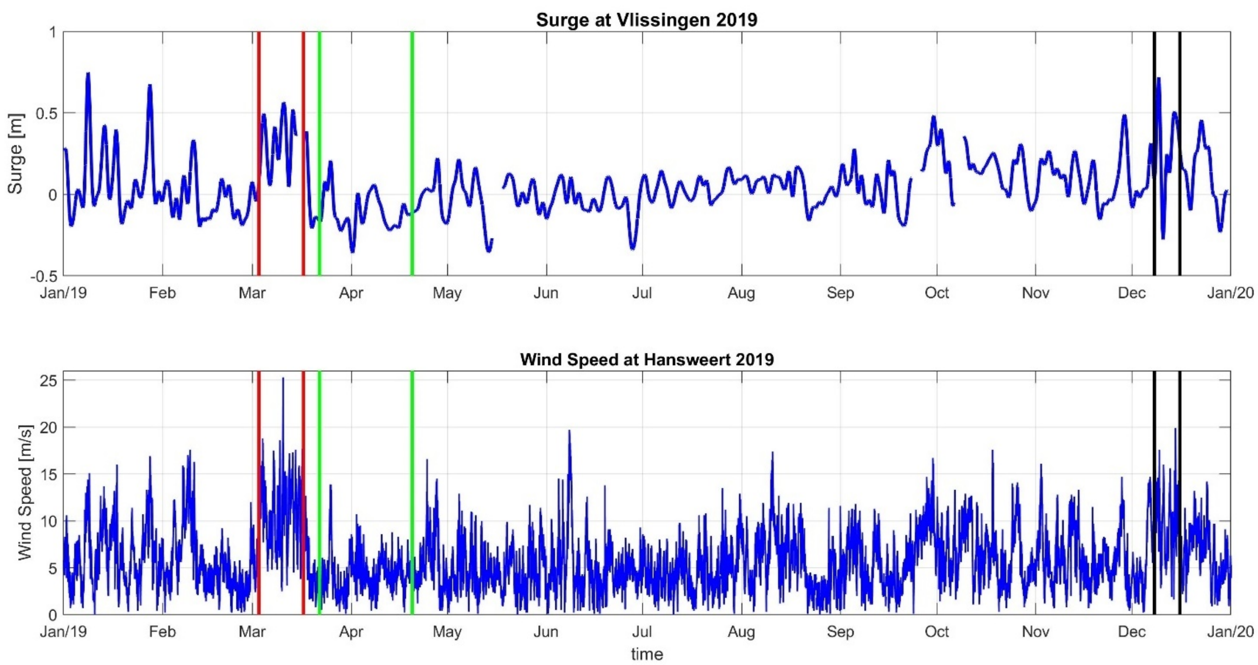


Figure 23 – Meteo conditions of 2019: surge at Vlissingen (top) and wind speed at Hansweert (bottom).
The block between green lines indicates the calibration period I for calm conditions between 22/03 – 20/04/2019.
The block between red lines indicates the calibration period II for stormy conditions between 03/03 – 17/03/2019.
The block between black lines indicates the validation period between 08/12 – 16/12/2019.



4.4 Parameter settings

The parameter settings of the SCALDIS 2019 model are taken from the SCALDIS 2013 model (Smolders et al., 2016) as summarized in Table 11.

An important exception is that the roughness formula is changed from Manning to Nikuradse law, which is closely related to the logarithmic profile of velocity. In this way, changes in the water depth are better taken into account when computing the bed shear stress and it therefore represents the physics in a better way.

In case the bed roughness is expressed with Manning's formula, the bed shear stress is calculated based on depth-averaged velocity $\overline{U}$ and the Manning coefficient n:

$$\tau = \rho C_d \overline{U}^2$$

$$C_d = gn^2/h^{\frac{1}{3}}$$

In the case we use Nikuradse's formulation, the bed shear stress is calculated (for hydraulically rough flow) as:

$$\begin{cases} \tau = \rho u*^2 \\ U(z) = \frac{u*}{\kappa} ln(\frac{z}{z_0}) \\ z_0 = \frac{k_s}{30} \end{cases}$$

Where u* is the friction velocity [m/s]; κ is Von Kaman's constant [-] of 0.4; z_0 is the bed roughness length [m]; k_s is the Nikuradse equivalent sand roughness [m].

Table 11 – Model parameters SCALDIS model

Parameter	Value
Time step	4 s
Initial condition	2 days spin-up from constant water level
Number of vertical levels	5
Version TELEMAC	v7p2r1
Salt transport	On
Roughness formula	Nikuradse law
Bed roughness value	varying roughness field
Option for the treatment of tidal flats	1: equations solved everywhere with correction on tidal flats
Treatment of negative depths	2: flux control
Free surface gradient compatibility	0.9
Vertical turbulence model	2: mixing length
Mixing length model	3: Nezu and Nakagawa
Horizontal turbulence model	4: Smagorinski
Scheme for advection of velocities	1: characteristics
Scheme for advection of depth	5: conservative scheme
Scheme for advection of tracers	13: Leo Postma for tidal flats
Scheme for diffusion of velocities	1: implicit (1 is default; 0 cancels the diffusion)
Scheme for diffusion of tracers	1: implicit
Solver	7: GMRES

The impact on the model of the change in roughness formulation is discussed in section 5.1.

4.5 Bottom friction

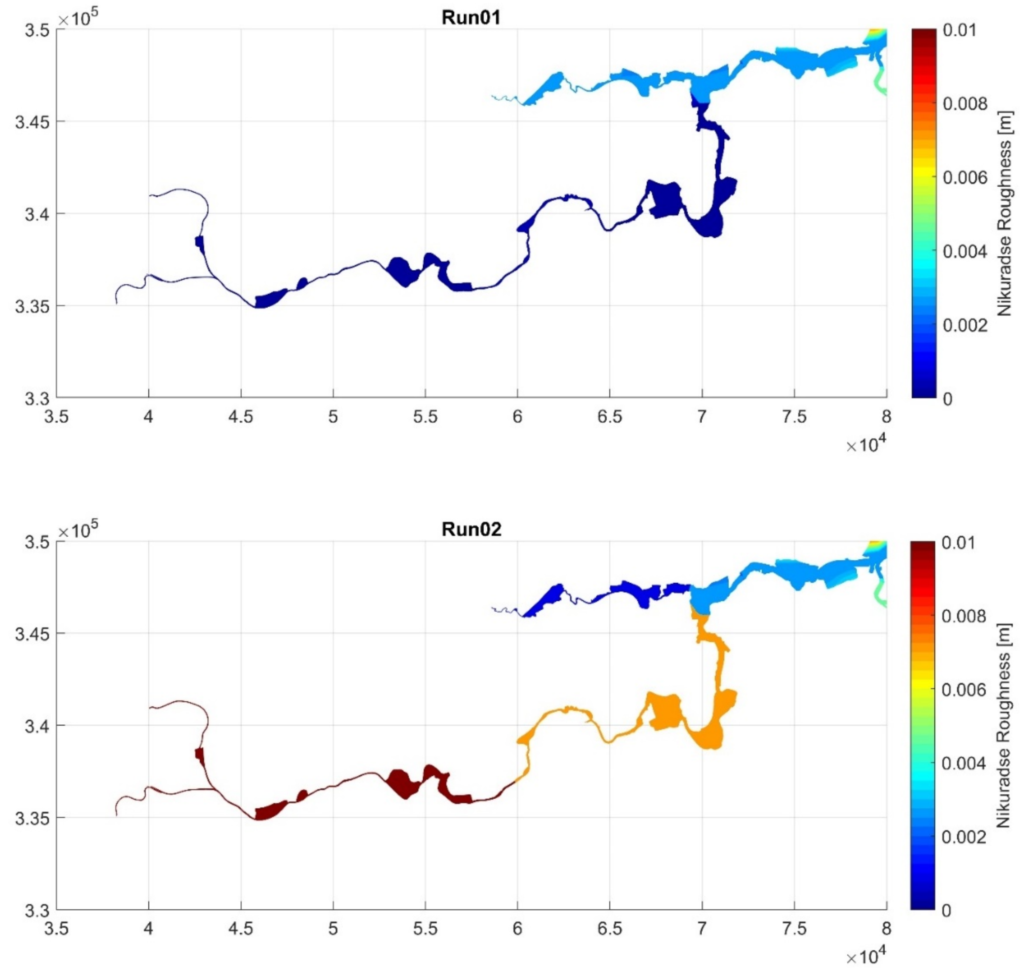
Table 12 lists the comparison of Nikuradse values between Run01 (see Table 14) and Run02 (after calibration). The roughness fields are shown in Figure 24.

The Nikuradse value used in the zone from Schoonaarde to upper stream is 0.1 m which is several orders larger than that used in the Durme tributary and in the section from Tielrode to Schoondaarde. However, the relation between bed shear stress and Nikuradse values are logarithmic. For instance, given water depth of 5 m, Nikuradse value of 0.1 m leads to Manning coefficient of 0.0264 which is still normal roughness values.

Table 12 – Summary of calibration runs on bottom roughness

	Zones	Run01	Run02
Nikuradse roughness value [m]	Durme	0.003	0.001
	Tielrode to Schoonaarde	0.0002	0.007
	Schoonaarde to Upper tidal limit	0.0002	0.1
	Rest of the domain	roughness SCALDIS 2013 converted to Nikuradse values	

Figure 24 – Comparison of roughness used in the calibration between Run01 and Run02.



4.6 Culverts

Flood Control Areas (FCA) together with a Controlled Reduced Tide (CRT) system are implemented in the Scheldt estuary to reduce the risk of flooding. The former is defined by an area specifically located in the regions where the bottom elevation is lower than the mean tide elevation. This area is surrounded by an outer higher dyke (ring dyke) and in the interface with the river, it has a lower dyke (overflow dyke) that allows the flow to overtop the structure during storm surges. The CRT is based on the construction of inlet and outlet sluices that control the flow between the river and the polder depending on the water levels on both sides. FCAs play important roles under stormy conditions, therefore in Run06 the FCAs are included in the model with functionality of culvert (see details in Smolders et al., 2016). The culverts are added into the model based on input data of SCALDIS 2013 (Smolders et al., 2016) in which 35 culverts are implemented (Figure 25).

From 2013 to 2019, additional 75 culverts at KBR and Zennegat are activated and therefore are added to the SCALIDS 2019 model (Figure 26) in this study. The parameter settings of all culverts can be found in Annex 7.

Even though CRT's are also active during calm conditions, they were disabled during simulations of calm conditions, for reasons of computational efficiency. This omission is believed to only have a small effect on the hydrodynamics in the estuary.

It is known that the FCA's only play roles during stormy period, therefore the functionality of culvert are only switched on for Calibration period II (storm conditions) and not used for Calibration period I (calm conditions).

Figure 25 – Culvert implemented in SCALDIS 2019.
Red and black dots indicate the inlet and outlet of the culvert.

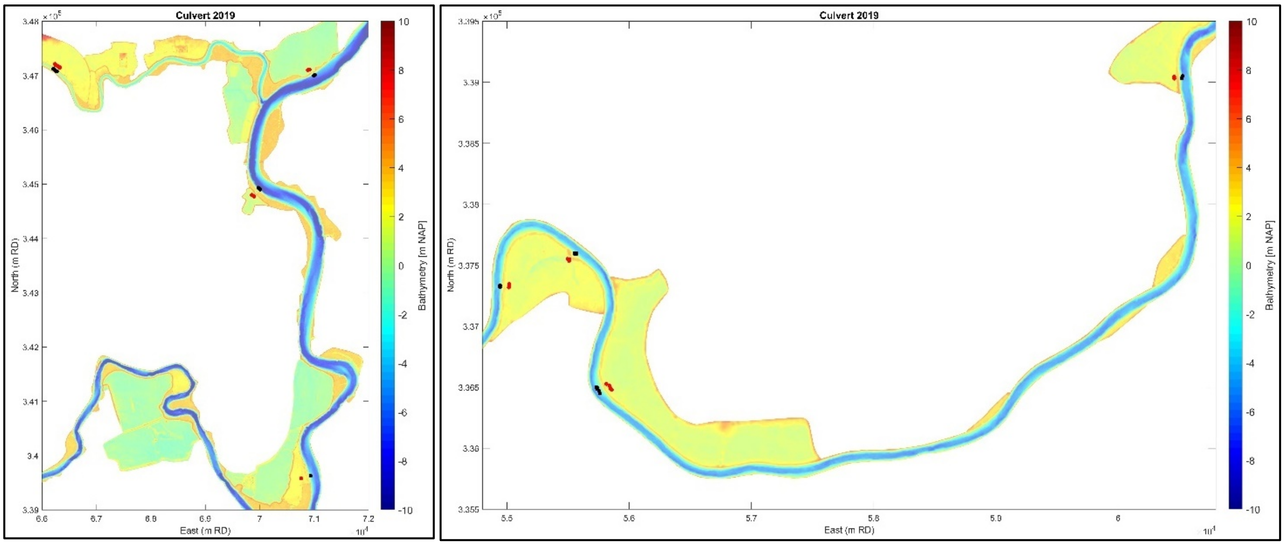
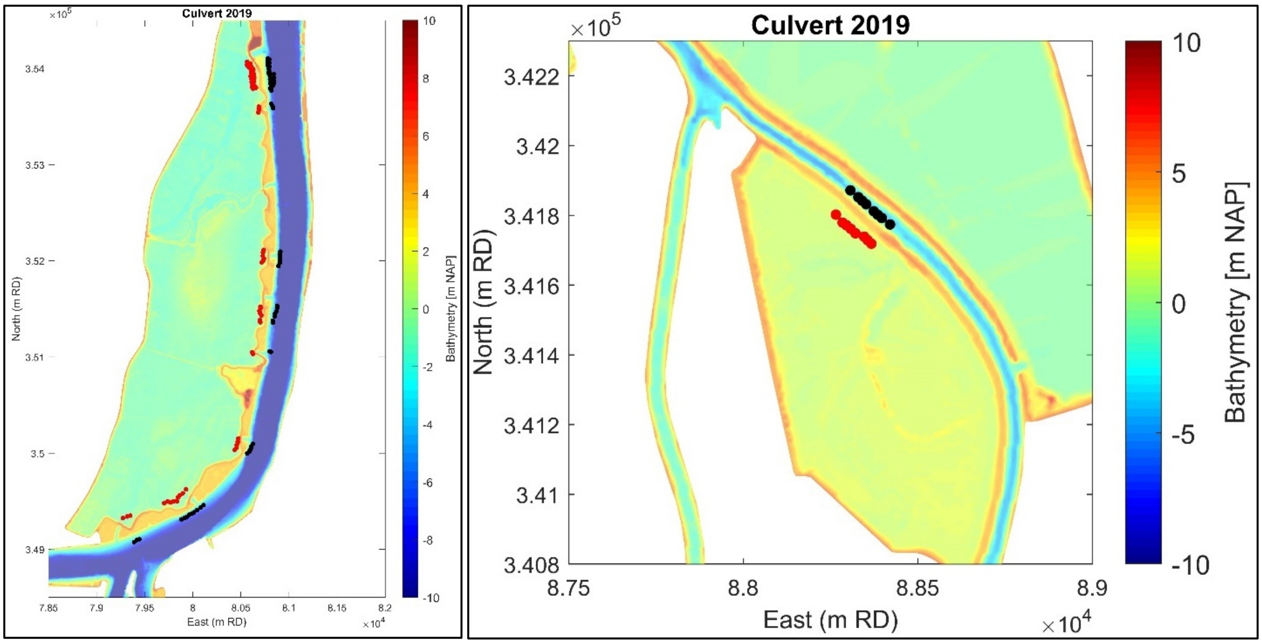


Figure 26 – vCulvert implemented in SCALDIS2019 at KBR (left) and Zennegat (right).
Red and black dots indicate the inlet and outlet of the culvert.



4.7 Initial condition of water level and velocity

As described in § 4.3, the first two days of the simulation period are taken as hydrodynamic spin-up time. The 3D output of water level and velocity over the entire domain at the end of the spin-up are stored, and provided as a hot-start file to the actual calibration/validation run.

4.8 Initial condition of salinity

The initial condition of salinity is constructed based on spatial interpolation of point measurements along the Scheldt (see §3.4). Figure 27, Figure 28 and Figure 29 present the initial salinity field applied on the SCALDIS 2019 model for calibration period I, calibration period II and validation period respectively.

Figure 27 – Initial condition of salinity for Calibration period I.

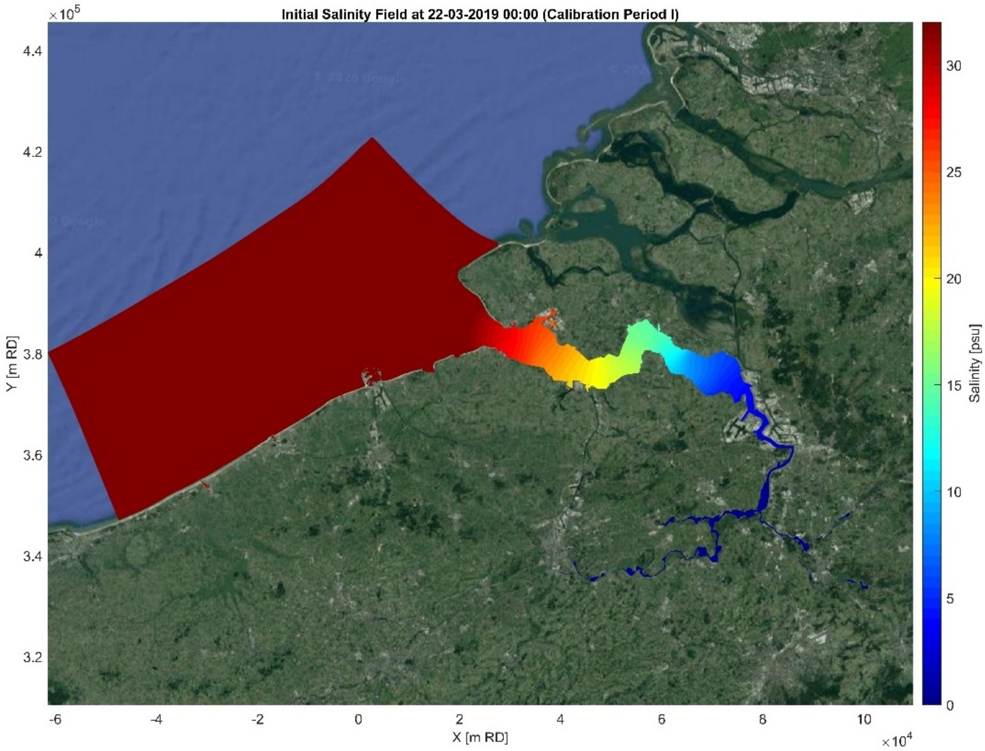


Figure 28 – Initial condition of salinity for Calibration period II.

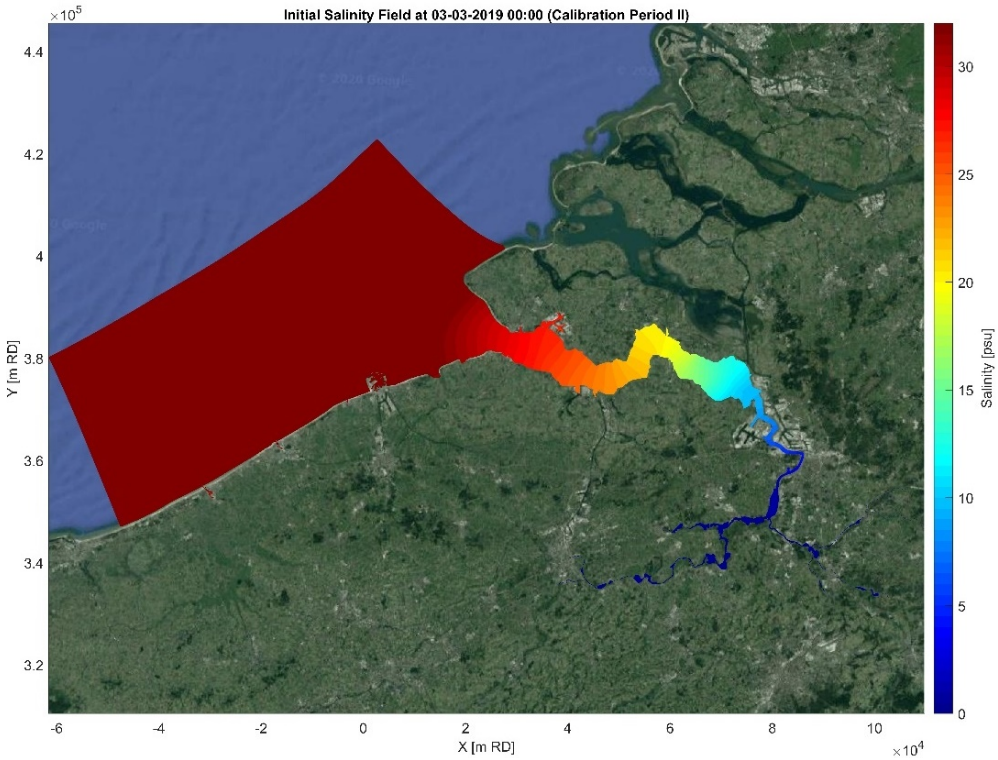
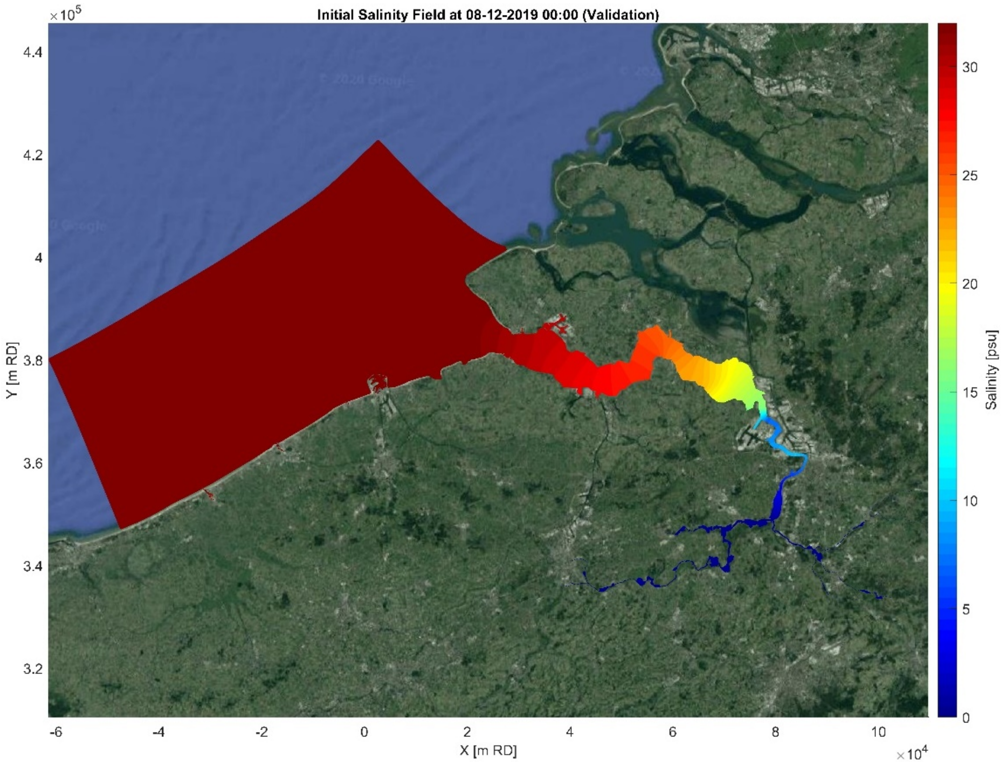


Figure 29 – Initial condition of salinity for the validation period.



4.9 Boundary conditions of salinity

Figure 8 suggests that there are no salinity data at Vlakte van de Raan (VvdR) during the calibration and validation period in 2019. There are no alternative measurement stations near the modelled area, therefore we use constant salinity of 32 psu to force the model at open boundaries.

This schematization is still valid in a sense because the dispersion of salinity at the time scale of one to two spring-neap cycles is more driven by the initial condition of salinity instead of its boundary conditions. Besides, the purpose of including salinity in the simulation is due to its impact on the hydrodynamics, e.g. changes on water level can go up to ~10 cm as demonstrated in Smolders et al. (2016). The boundary condition of salinity only becomes important when studying the dynamics of salinity at a much longer time scale (months to years), which is however not the primary purpose of this study.

4.10 Boundary conditions offshore

4.10.1 DCSMv6 – ZUNOv4

The comparison of different DCSM-ZUNO models (Chu et al., 2020) reveals that the DCSMv6-ZUNOv4 holds the highest accuracy in simulating hydrodynamics along the Belgian coast. Therefore this model is used in this study to generate the boundary conditions for SCALDIS 2019.

DCSMv6 – ZUNOv4 has been developed at Deltares as an application of WAQUA in SIMONA, a framework for hydrodynamic modelling of free-surface water systems (Zijl, 2013). The DCSMv6-ZUNOv4 model consists of two separate domains coupled together by means of horizontal domain decomposition. Figure 30 demonstrates the computational model grid. Table 13 listed the general settings of the DCSMv6 and ZUNOv4.

Figure 31 shows the RMSE of water level computed by the DCSMv6-ZUNOv4 2019 run which yields an averaged RMSE of 7.4 cm along the Belgian coast. The model is quite accurate to provide boundary conditions for the SCALDIS 2019 model.

Figure 30 – Overview of the DCSMv6-ZUNOv4 hydrodynamic model grids, with the DCSMv6 domain in green and the ZUNOv4 domain in blue.

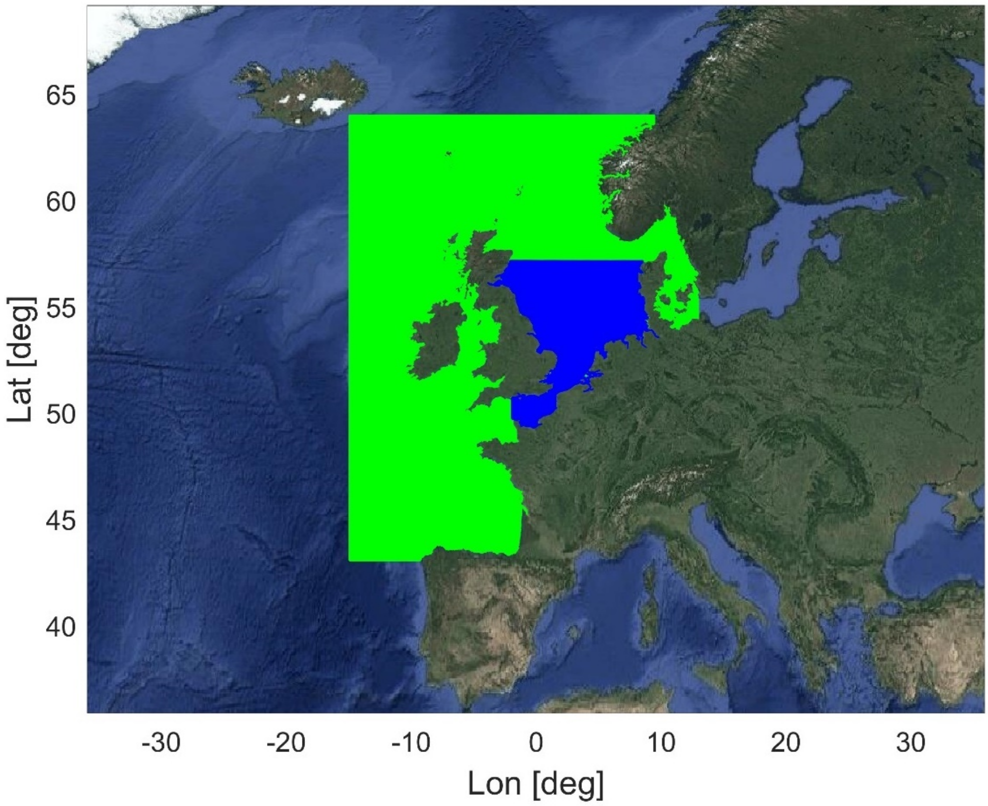
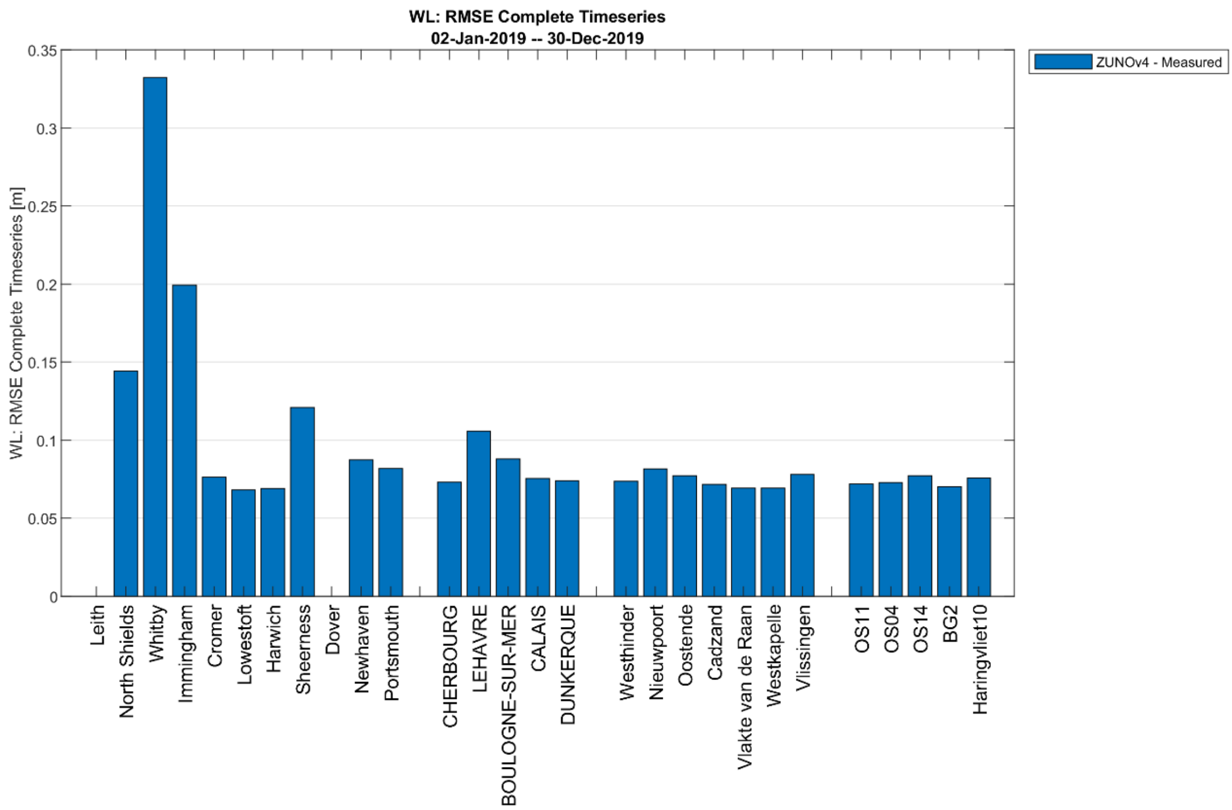


Table 13 – Parameter settings of the DCSM-v6-ZUNOv4.

Settings	DCSM-v6	ZUNO-v4
Grid resolution	1.5’ in east-west direction and 1.0’ in north-south direction (2×2 km), with a refinement in the southern North Sea and Dutch coastal waters.	25-500 m nearshore and 2-3 km offshore.
Number of grids	1120 in east-west direction and 1260 in north-south direction.	1448 in east-west direction and 637 in north-south direction.
Open boundary condition	Water level defined by 38 tidal constituents. The non-tidal effect of local pressure is considered with inversed barometer correction	Calculated by DCSM-v6 via domain decomposition.
Coordinate system	WGS84 geographical	
Time Zone	GMT	
Roughness	Spatially varying Manning values determined by automatic calibration with OpenDA	

Tide generating force	Components of the tide with a Doodson number from 55.565 to 375.575 are included.
Wind	ECMWF – ERA5 dataset
Drying and flooding	Threshold value of 0.1 m.
Vertical reference	MSL
Time step	1 mins

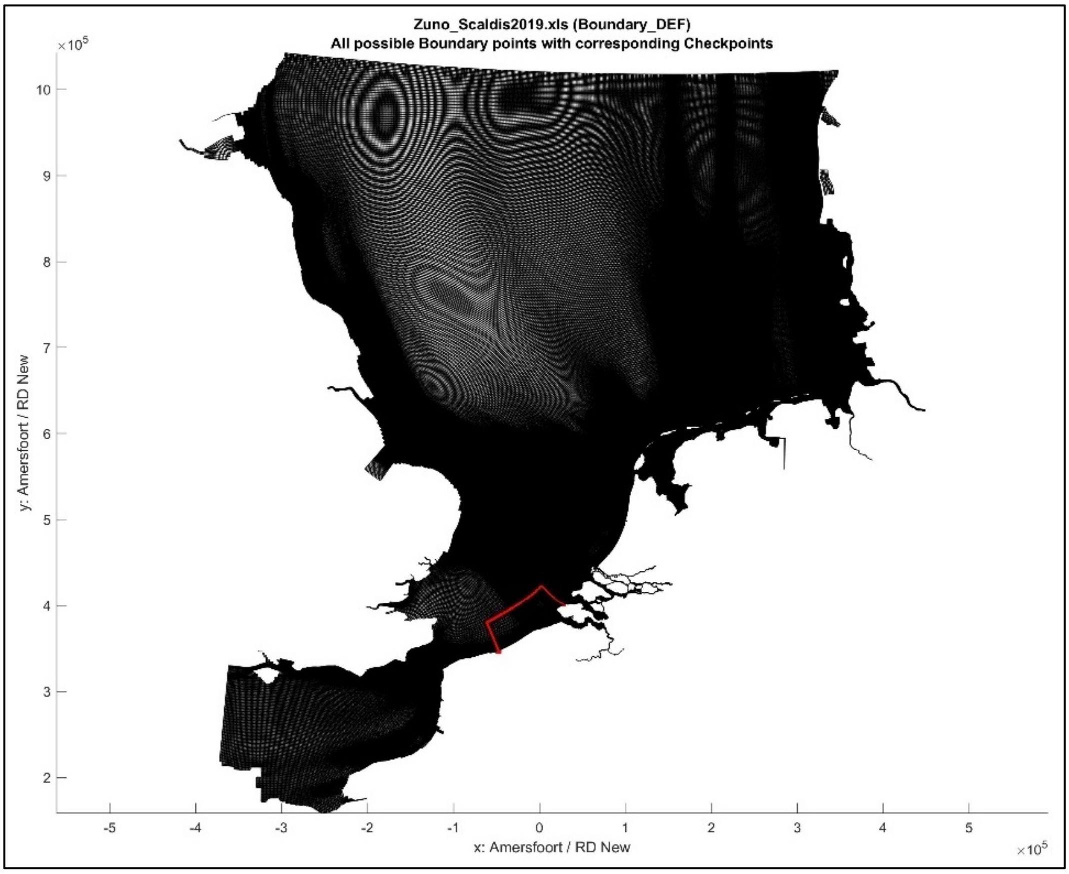
Figure 31 – RMSE of water level from DCSMv6-ZUNOv4 2019.

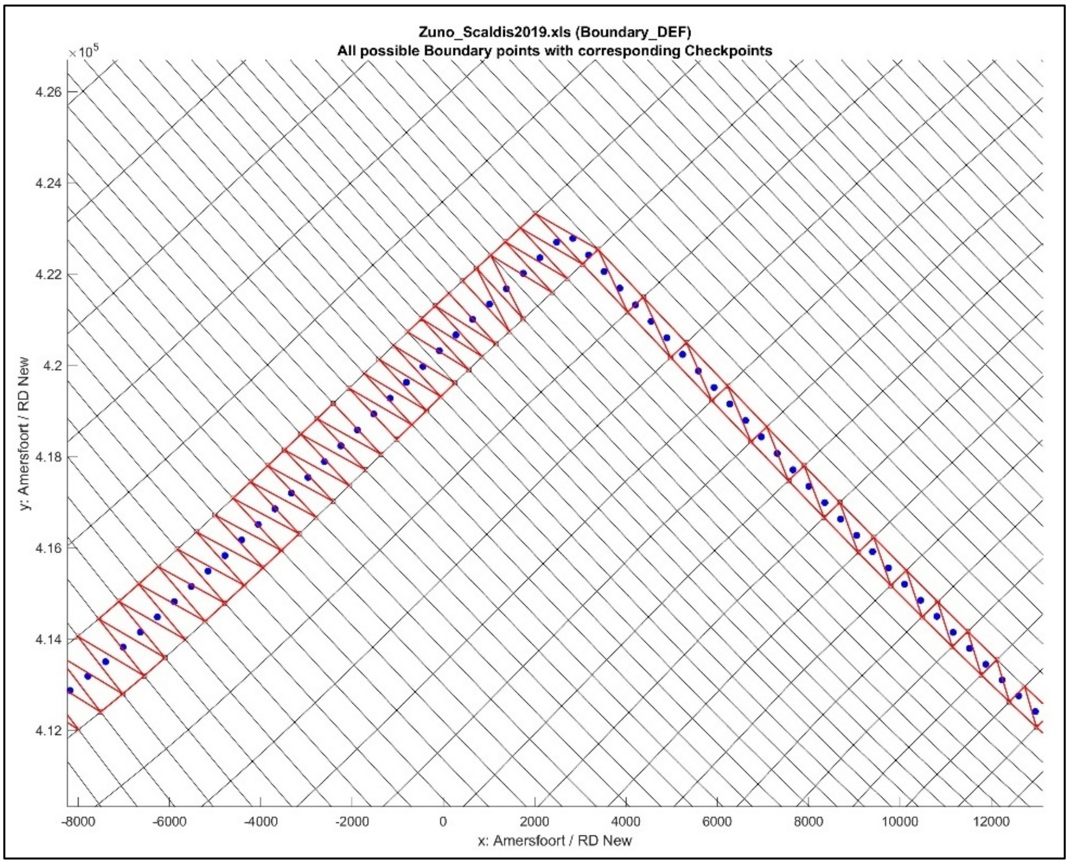


4.10.2 Nesting

The in-house Matlab nesting toolbox was used for flow boundary nesting (Figure 32). The offshore boundary points of the SCALDIS model were added to DCSMv6-ZUNOv4 model (Nesting 1) as history point to record output of water level and velocity. When the DCSMv6-ZUNOv4 model is finished, Nesting2 was launched to interpolate the results from DCSMv6-ZUNOv4 to the offshore boundary points of the SCALDIS model. The black lines represent the mesh of ZUNOv4. The blue dots indicate the open boundary points of the SCALDIS 2019 model. The red dots are determined by Nesting 1 and are added to ZUNOv4 as output points for recording water level and velocity data. The red triangles represent the interpolation network.

Figure 32 – Upper panel: overview of the boundary nesting between ZUNOv4 and SCALDIS2019. Lower panel: detailed view.





5 Sensitivity Analysis

5.1 Impact of roughness formulation and mesh

SCALDIS 2019 is inter-compared with the original SCALDIS 2013 model as reported by Smolders et al. (2016). To ensure a fair comparison, both models are run for the same period in 2019, with the same forcing of bathymetry of 2019 interpolated on the two different meshes (see **Fout! Verwijzingsbron niet gevonden.**), wind, discharge and boundary conditions (nested from ZUNOv4). The only differences are the mesh and roughness as listed in Table 14 and Figure 33.

The roughness formula is changed from Manning to Nikuradse law, which is based on the logarithmic profile of velocity. In this way, changes in the water depth are better taken into account when computing the bed shear stress and it therefore represents the physics in a better way.

See also section 4.4 for a discussion on the switch of the roughness formulation, and section 4.2 on the model mesh.

Table 14 – Description of model runs of SCALDIS comparison.

Run ID	Mesh	Roughness
Run00a	Original SCALDIS (Smolders et al.,2016)	Original roughness of Manning coefficients
Run00b	Original SCALDIS (Smolders et al.,2016)	Original roughness but converted to Nikuradse values
Run01	SCALDIS2019 (§4.2)	Original roughness but converted to Nikuradse values

The conversion between Manning coefficient *n* and Nikuradse roughness *ks* length (TELEMAC-3D – User Manual) are done via the drag coefficient C_d:

$$Cd = \frac{g \times n^2}{h^{\frac{1}{3}}} (Manning\ formula) = \left(\frac{\kappa}{ln\left(\frac{30h}{e \times ks}\right)}\right)^2 (Nikuradse\ formula)$$

Where *n* is Manning coefficient [$m^{-1/3}s$]; *h* is water depth (averaged value over one spring-neap cycle extracted from Run00a); κ is Von Kaman's constant of 0.4; *e* is Euler's constant of 2.71828; *ks* is the Nikuradse roughness length [m].

For instance, assuming h = 5 m and n = 0.017 $m^{-1/3}s$, we get ks = 0.003 m.

Figure 34 and Figure 35 present the comparison of RMSE and M2 amplitude between the 3 different runs.

Figure 33 – Comparison of roughness between Run00a, Run00b and Run01.
top: overall; bottom: zoom in to the Scheldt River.

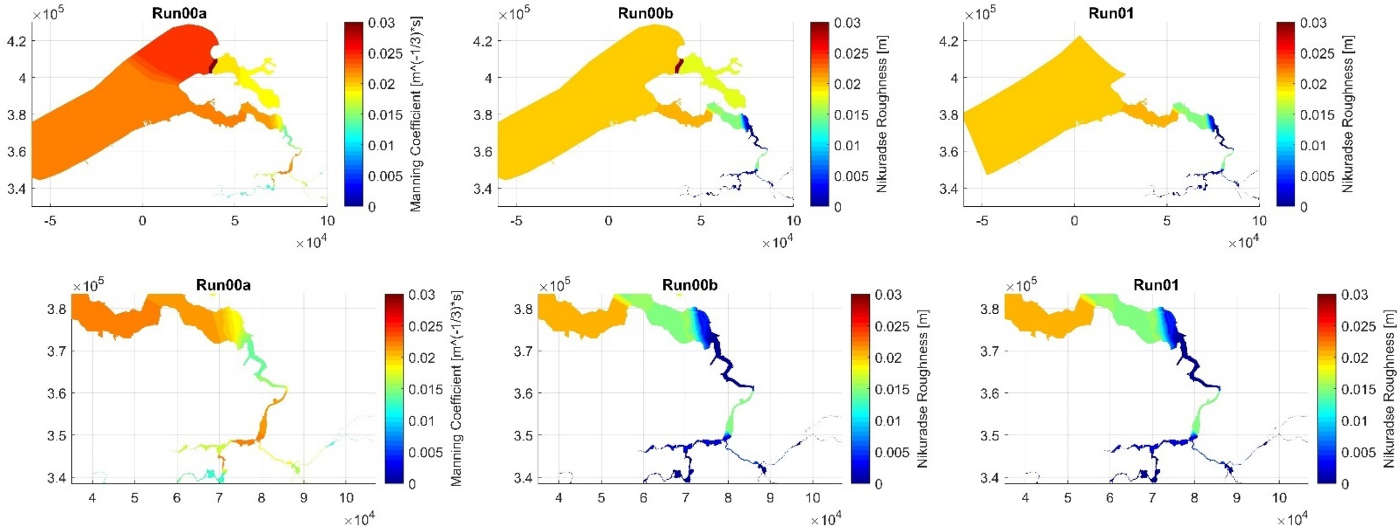


Figure 34 – RMSE of water level between original SCALDIS and SCALDIS2019.

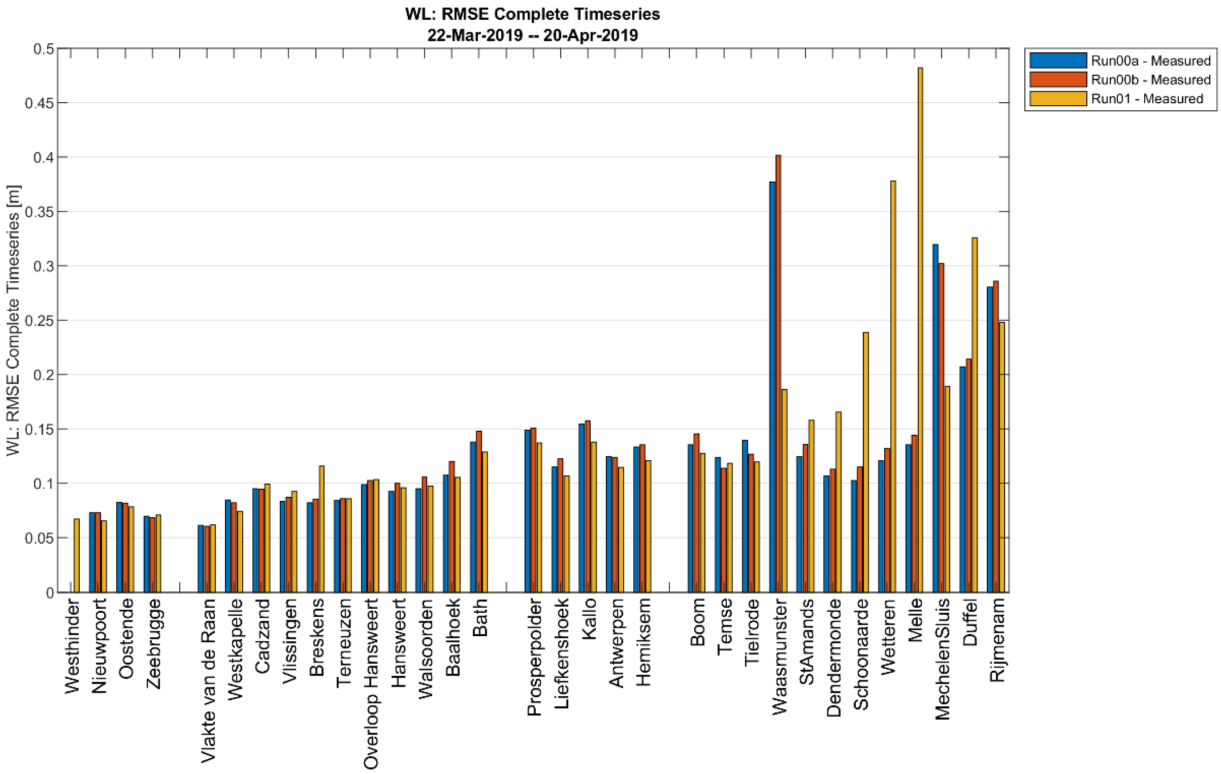
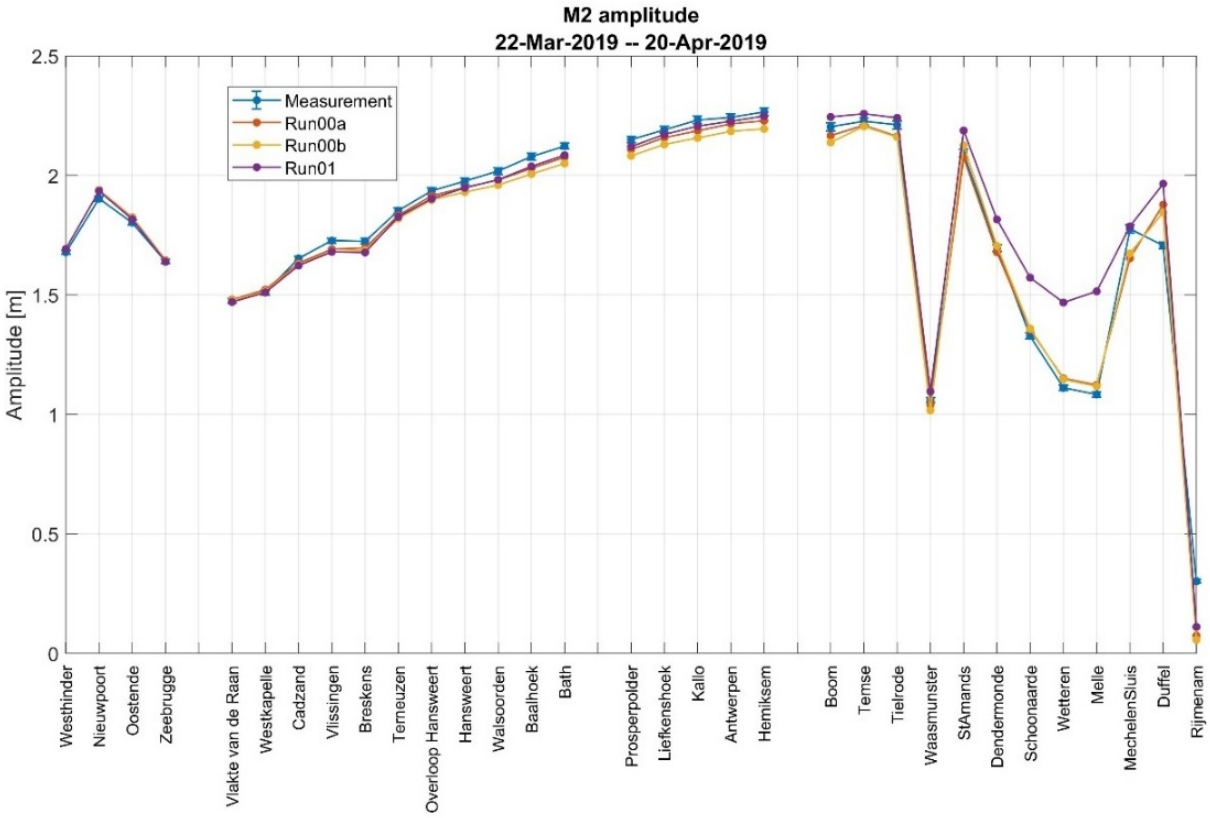


Figure 35 – M2 tidal amplitude between original SCALDIS and SCALDIS2019.



In general, using Manning coefficients or Nikuradse roughness length lead to similar results. Run00a (Manning coefficients) gives slightly better results compared with Run00b (Nikuradse roughness length) since the original SCALDIS model was calibrated on Manning coefficients instead of Nikuradse value.

Run01 gives much better results at Waasmunster compared with Run00a and Run00b. Figure 36 shows that the tidal range at Waasmunster is under-predicted by Run00a and Run00b which suggests that the roughness used in the original SCALDIS model is way too high (Manning coefficient of 0.017 $m^{-1/3}s$ in Run00a; Nikuradse value of 0.003 m in Run00b). Figure 37 shows that the mesh used in SCALDIS2019 is more aligned with the tidal channel compared with the mesh used in the original SCALDIS model. Thus, the additional energy loss is less in Run01. Therefore using the same Nikuradse value of 0.003 m in Run01 could lead to better prediction of water level at Waasmunster. Further improvement is foreseen by further decreasing the Nikuradse value in Durme which is considered in the model calibration of SCALDIS2019 (§5).

Figure 36 – Comparison of water level at Waasmunster.

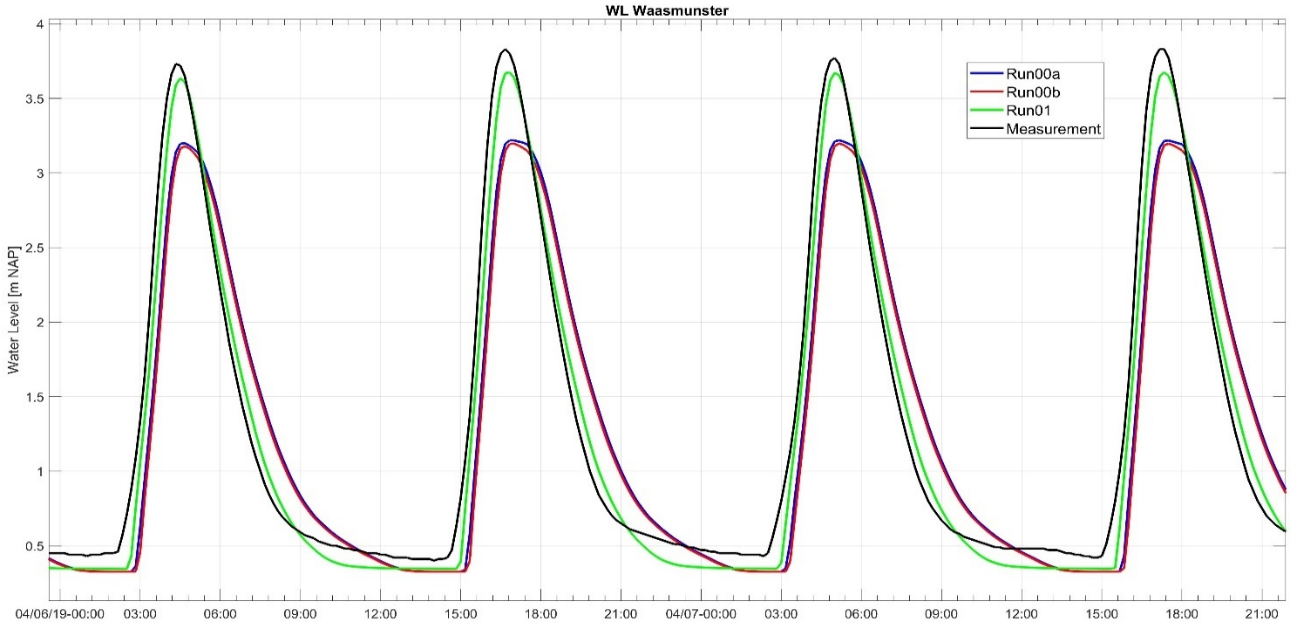
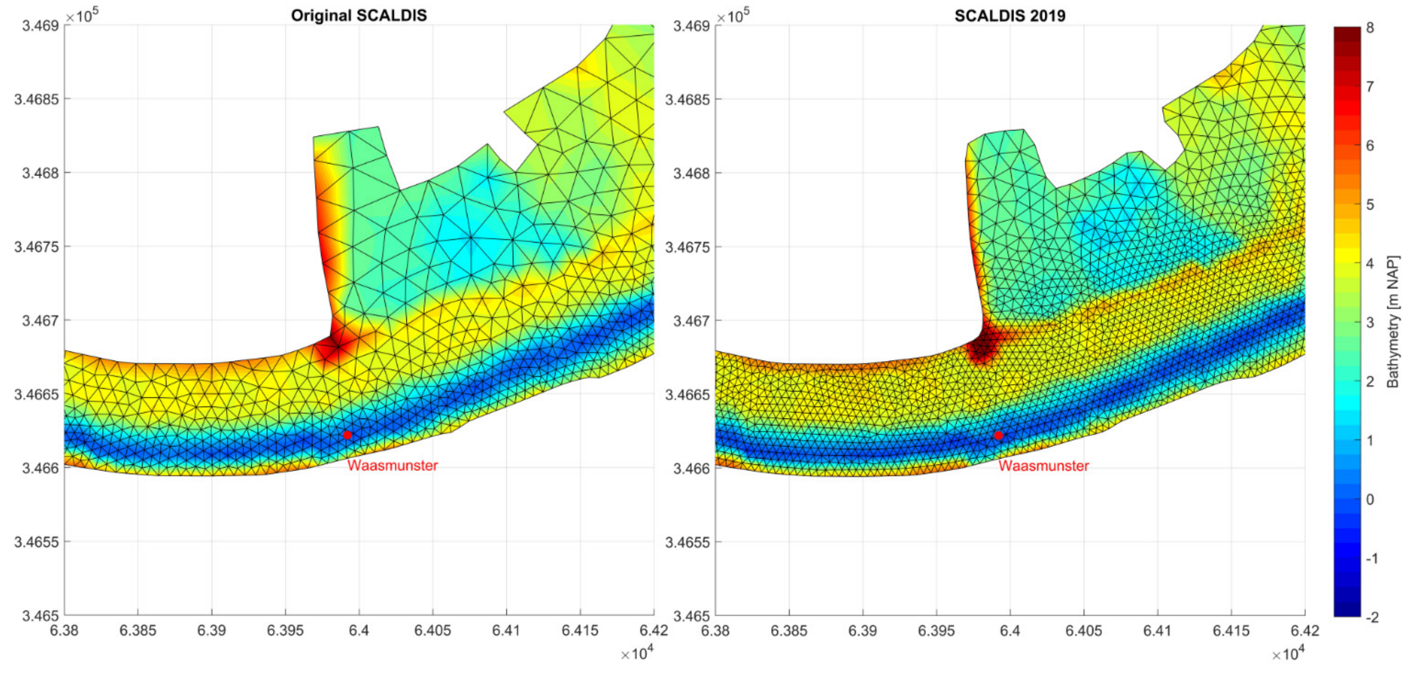


Figure 37 – Comparison of mesh near Waasmunster between Original SCALDIS and SCALDIS2019.



Run01 leads to much higher RMSE of water level at BoZS (from StAmands to Melle) compared with Run00a and Run00b. Figure 38 exemplifies that the tidal range at Melle is over-predicted by about 1 m from Run001 which suggests that roughness at BoZS in Run001 is way too low (Nikuradse value of 0.0002 m). However such low roughness leads to reasonable good results for Run00a (Manning coefficient of 0.013 $m^{-1/3}s$) and Run00b (Nikuradse value of 0.0002 m). The reason is that the mesh in the SCALDIS 2013 model has triangles with a random orientation which causes more numerical diffusion and loss of tidal energy. Lower bottom roughness coefficient values were used to compensate for the loss of tidal energy. SCALDIS 2019 (Run001) uses a mesh where the triangles are structured so that they follow better the flow lines in the model. This exercise proves that it significantly reduces the energy dissipation. Combined with using the low bottom roughness coefficient value on the updated grid leads to an overestimation of the tidal range.

Figure 38 – Comparison of water level at Melle.

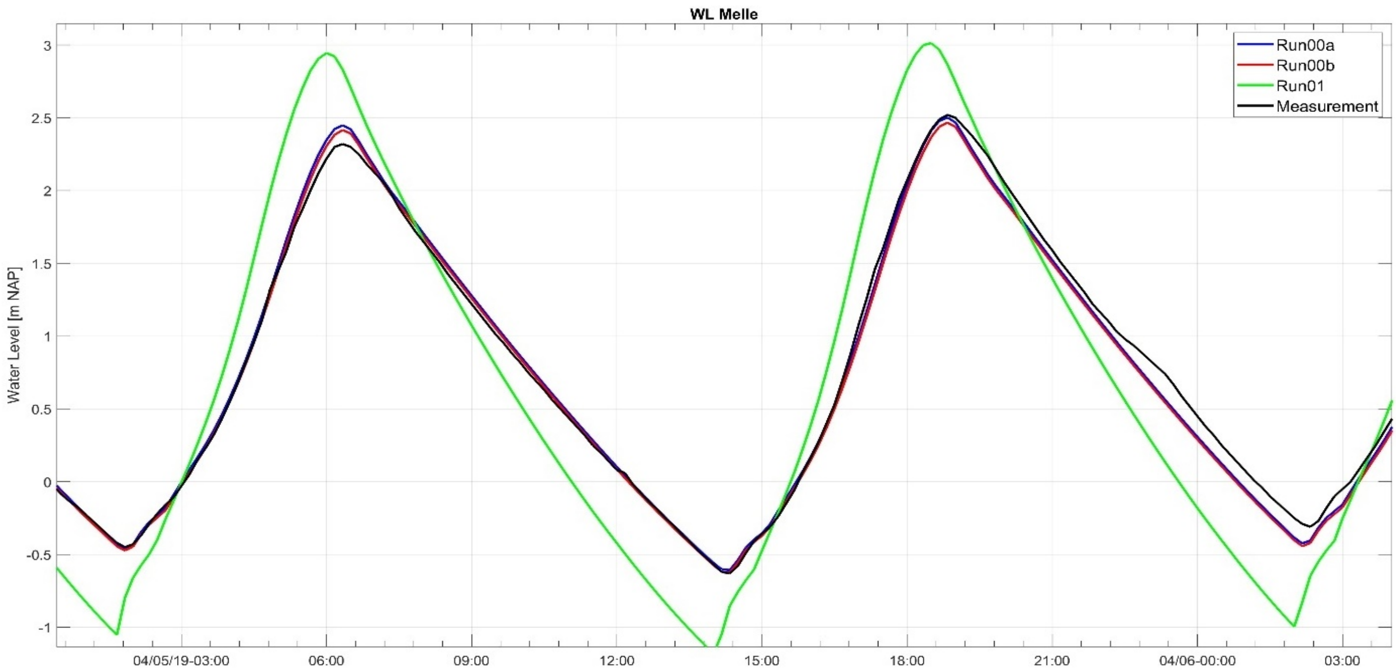
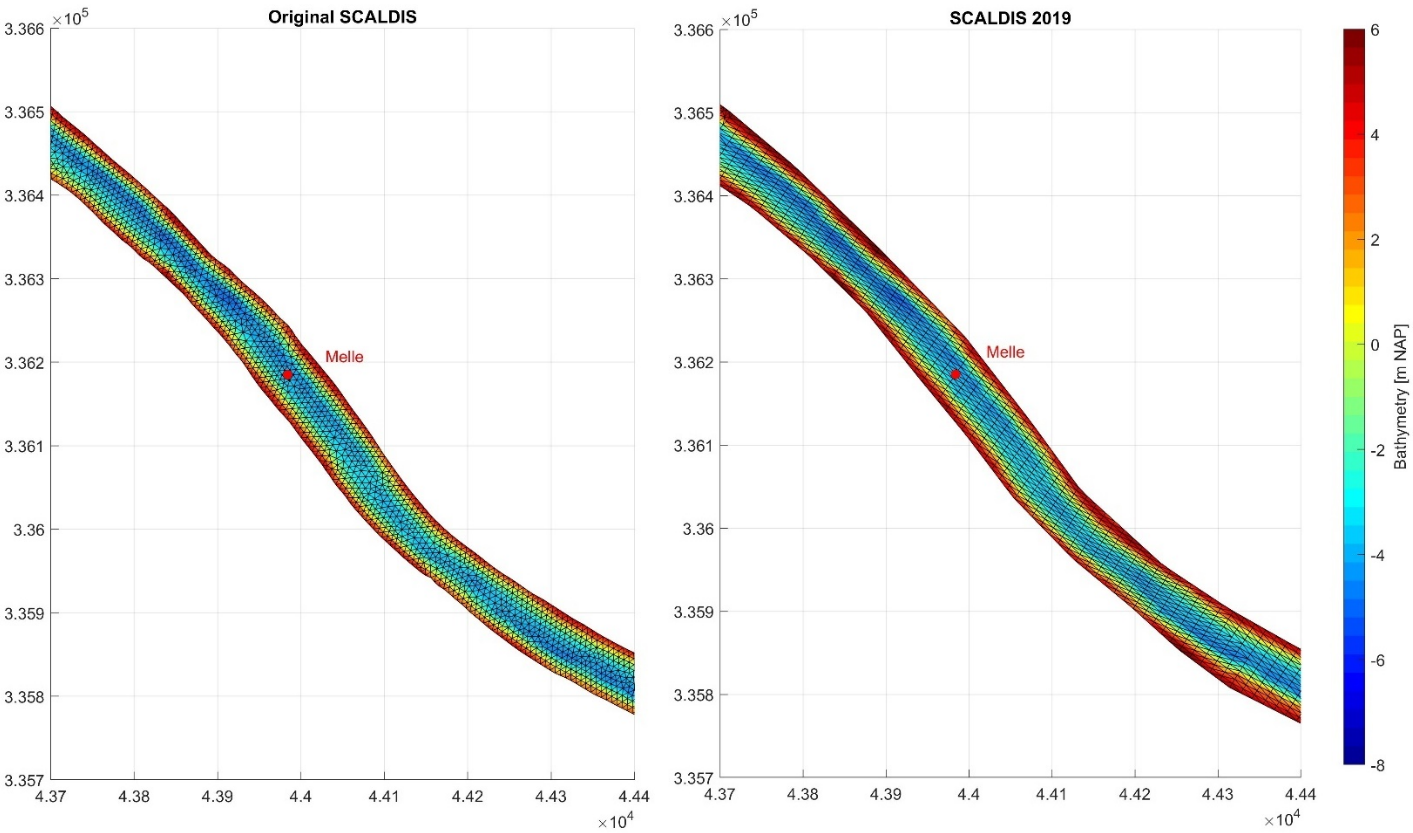


Figure 39 – Comparison of mesh near Melle between Original SCALDIS (2013) and SCALDIS 2019.



5.2 Impact of wind drag formulation

As described in § 3.6.2, the time series of wind measurement at Hansweert of 2019 are utilized to force the SCALDIS model (space-constant, time-varying). In order to verify the importance of wind, Table 15 presents 3 scenario runs with different settings of wind forcing. These 3 scenarios run for both Calibration period I and II.

Table 15 – Summary of simulations for checking the impact of wind .

RunID	Wind
A	Off
B	space/time constant wind drag (default setting in v7p2), user-defined coefficient of 0.565E-3.
C	Charnock formula (1955), user-defined coefficient of 0.04.

Run A is identical to Run02 as presented in Table 12.

Run B includes wind and uses space- and time constant wind drag coefficient of 0.565 E-3 which is the default setting in TELEMAC v7p2.

Run C uses Charnock formula (1995) with Charnock coefficient β of 0.04 which is a common value found for the Belgian coast and estuary (Chu et al., 2020). The mathematical equation of Charnock wind drag formula is expressed as below, where ***W*** represents wind speed; ***u**** is the wind friction velocity; ***z*** represents 10 meter height; ***z₀*** is roughness height; ***κ*** is the Von Karman constant of 0.4; **β** is Charnock coefficient of 0.04 used in this study.

$$\left.\begin{aligned} W(z) &= \frac{u_*}{\kappa}\ln\left(\frac{z}{z_0}\right) \\ C_d &= \frac{u_*^2}{W_{10}^2} \\ z_0 &= \frac{\beta u_*^2}{g} \end{aligned}\right\} \quad \frac{1}{\sqrt{C_d}} = \frac{1}{\kappa}\ln\left(\frac{10g}{\beta W_{10}^2 C_d}\right)$$

Equation (1)

Figure 40 illustrates the relation between wind speed at 10 m W_{10} and the wind drag coefficient C_d.

Figure 40 – Relation between wind speed at 10 m height and different wind drag coefficients used in calibration.

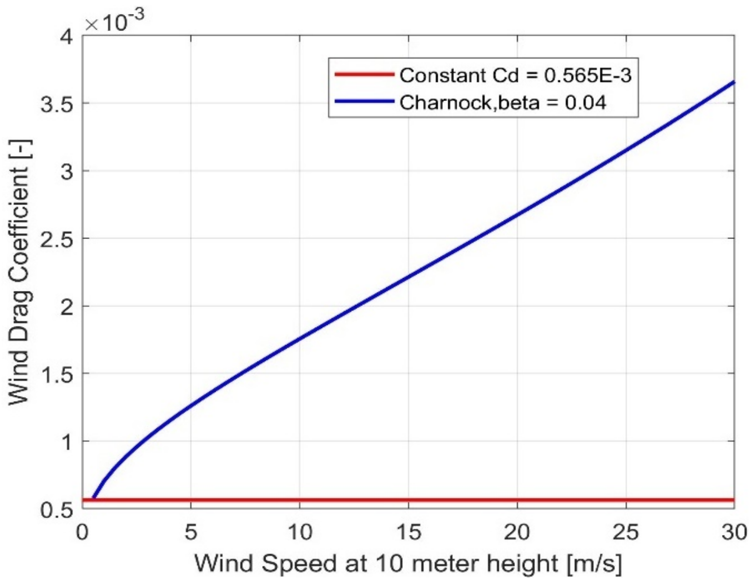


Figure 41 presents the influence of wind on RMSE of water level for calibration period I. Wind forcing is not a dominant factor for calm conditions, the RMSE of water level along the Scheldt are slightly decreased by ~ 1 cm with Charnock coefficient of 0.04 (Run C).

Figure 42 presents the influence of wind on RMSE of water level for calibration period II. Wind forcing plays more important roles for stormy period. Run C significantly reduced the RMSE of water level in general.

Figure 45 shows the water level at Antwerp which is better predicted with Charnock coefficient of 0.04 (Run C).

Figure 43 and Figure 44 provide more details of the wind impact on high and low water levels respectively. It shows that the Run C improved the low water levels more than the high water levels. It is also noteworthy that the RMSE at Melle slightly increased by ~ 1 cm with Charnock coefficient of 0.04 (Run C).

Figure 46 shows the low water level at Melle is further overestimated in Run C.

Also note that wind plays a more important role in the Western Scheldt and the Lower Sea Scheldt then in the Upper Sea Scheldt.

Therefore, Charnock formula (Equation 1) with Charnock coefficient of 0.04 is adopted in this study. This is implemented in SUBROUTINE BORD3D and solved implicitly with NEWTON-RAPHSON iterator (see example in https://wl-subversion.vlaanderen.be/svn/repoSpNumMod/TELEMAC/Scaldis/PA016%20BenO/SCALDIS_2019).

Figure 41 – Influence of wind on RMSE of time series of water level for calibration period I (calm).

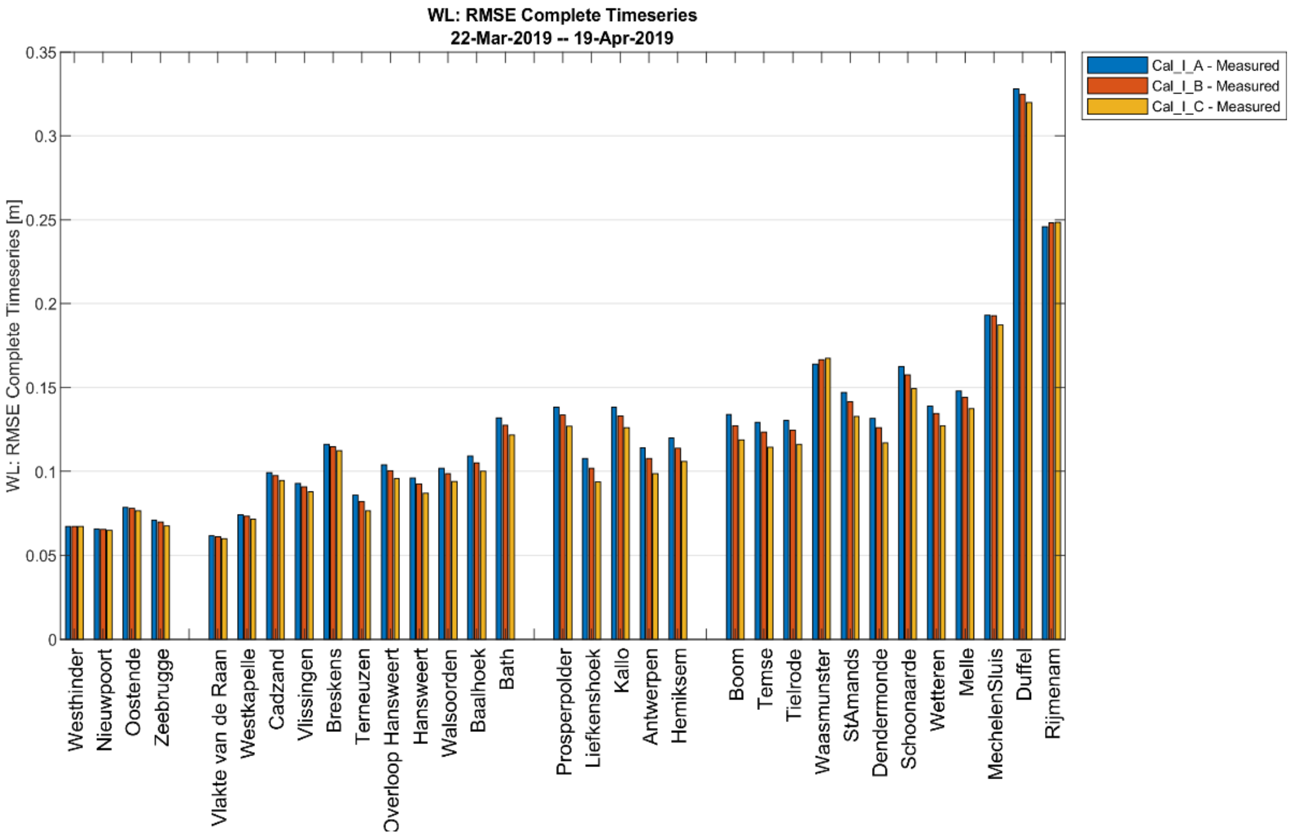


Figure 42 – Influence of wind on RMSE of time series of water level for calibration period II (stormy).

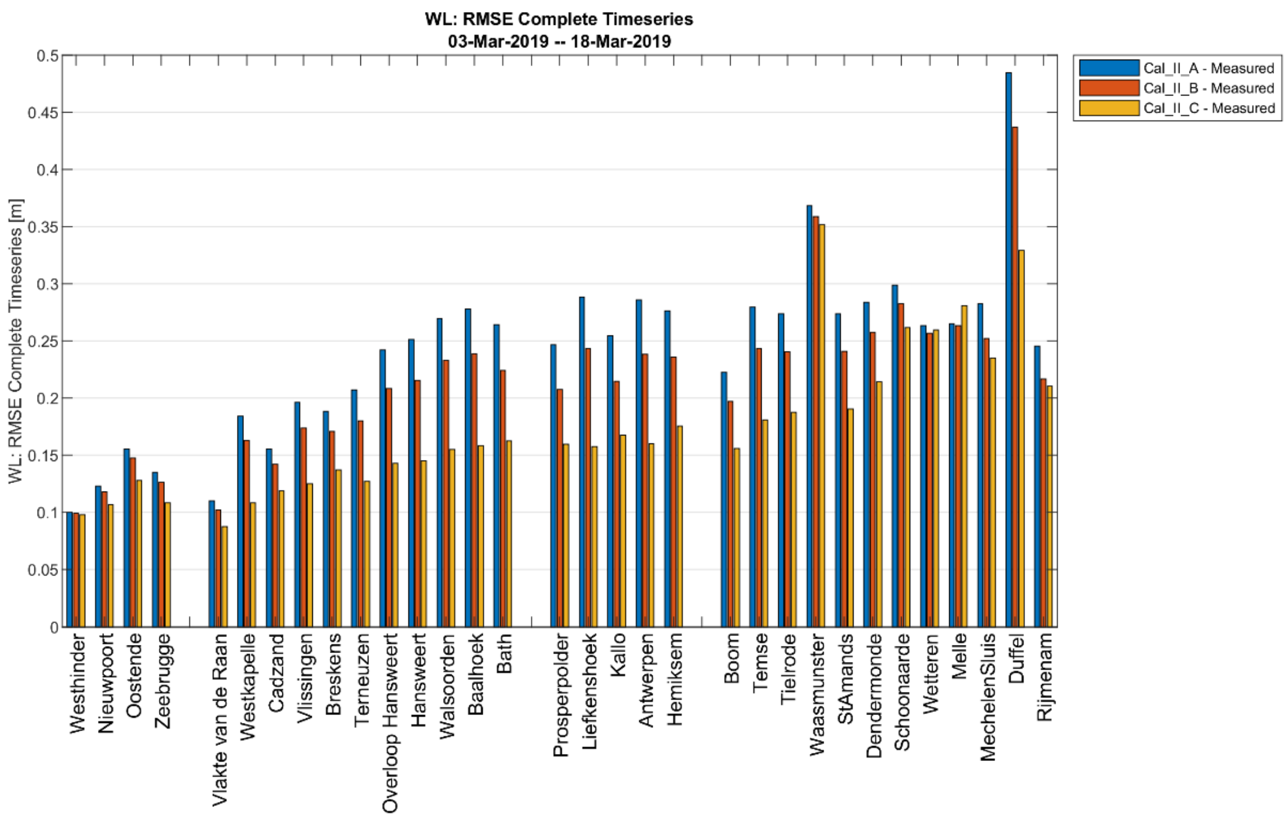


Figure 43 – Influence of wind on RMSE of high water level for calibration period II (stormy).

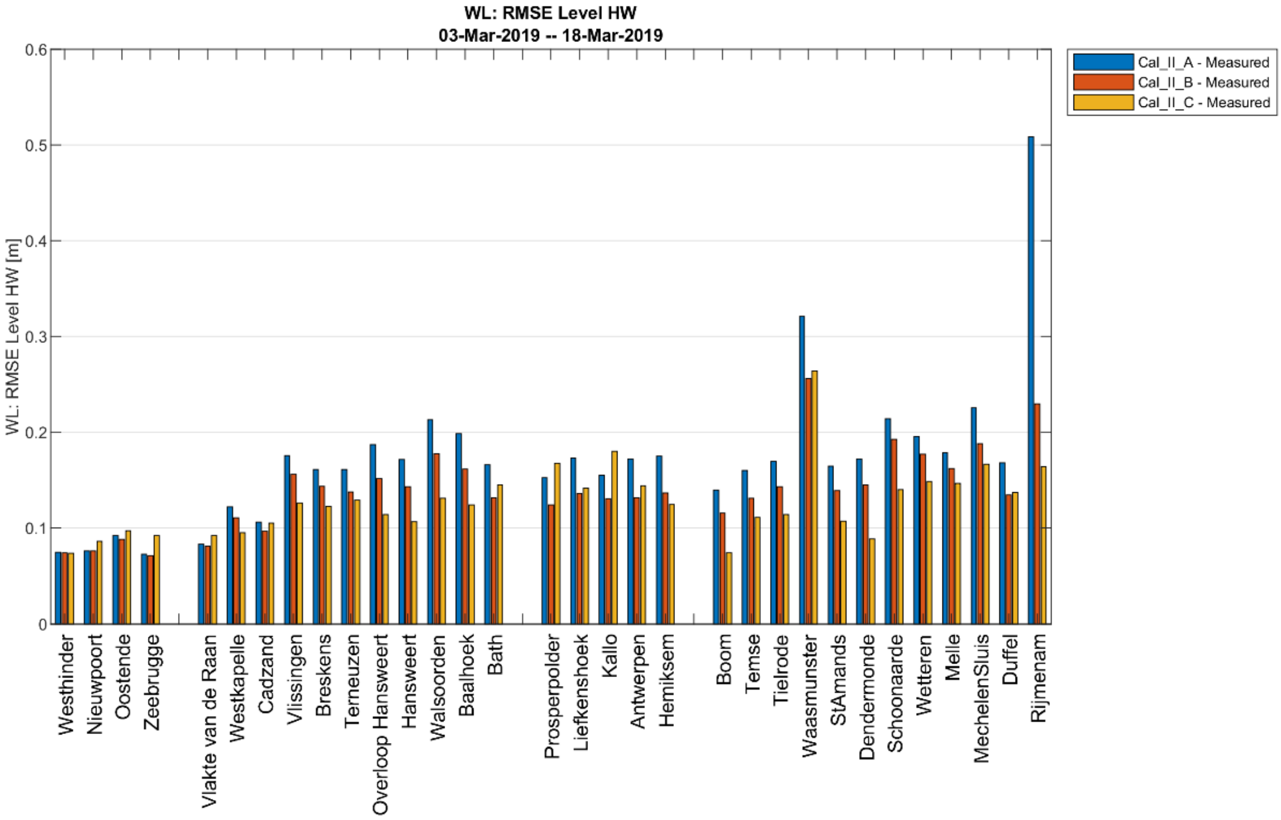


Figure 44 – Influence of wind on RMSE of low water level for calibration period II (stormy).

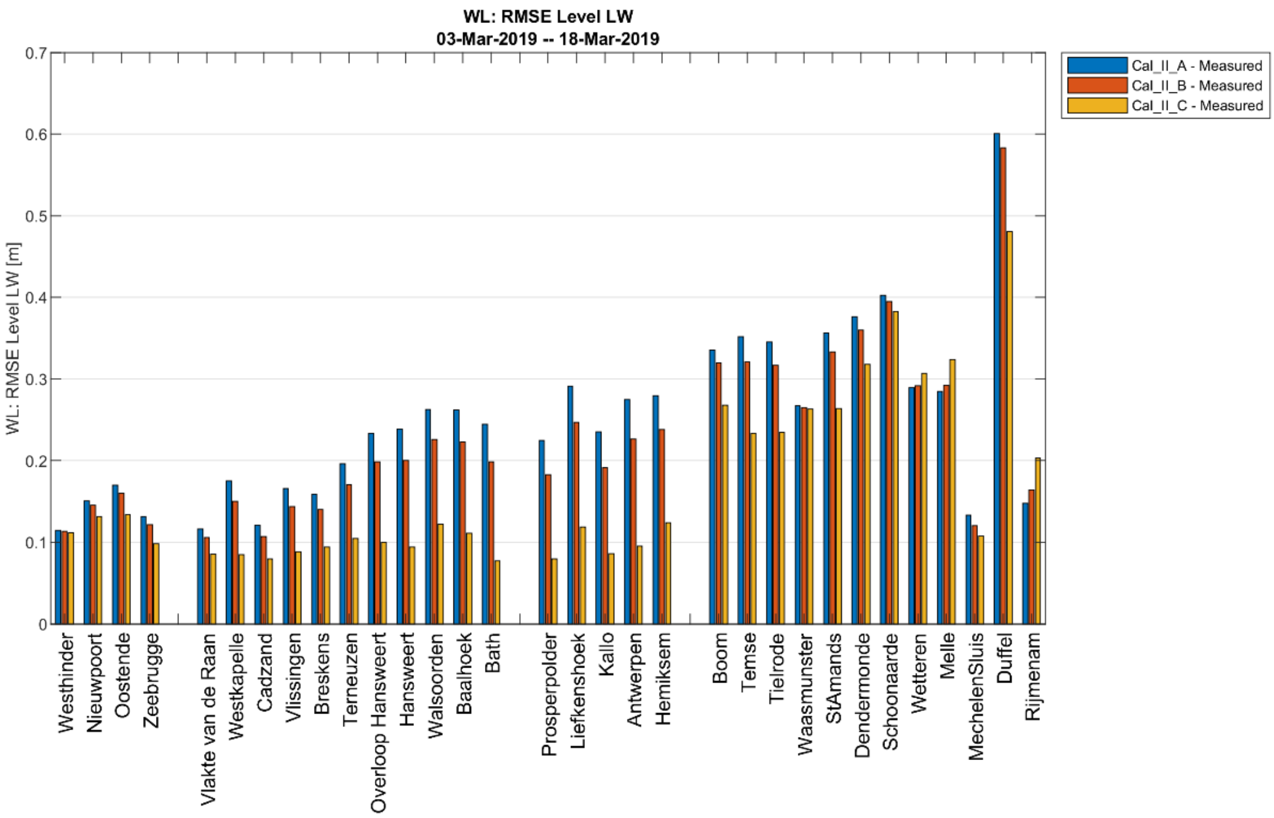


Figure 45 – Influence of wind on water level at Antwerp for calibration period II (stormy).

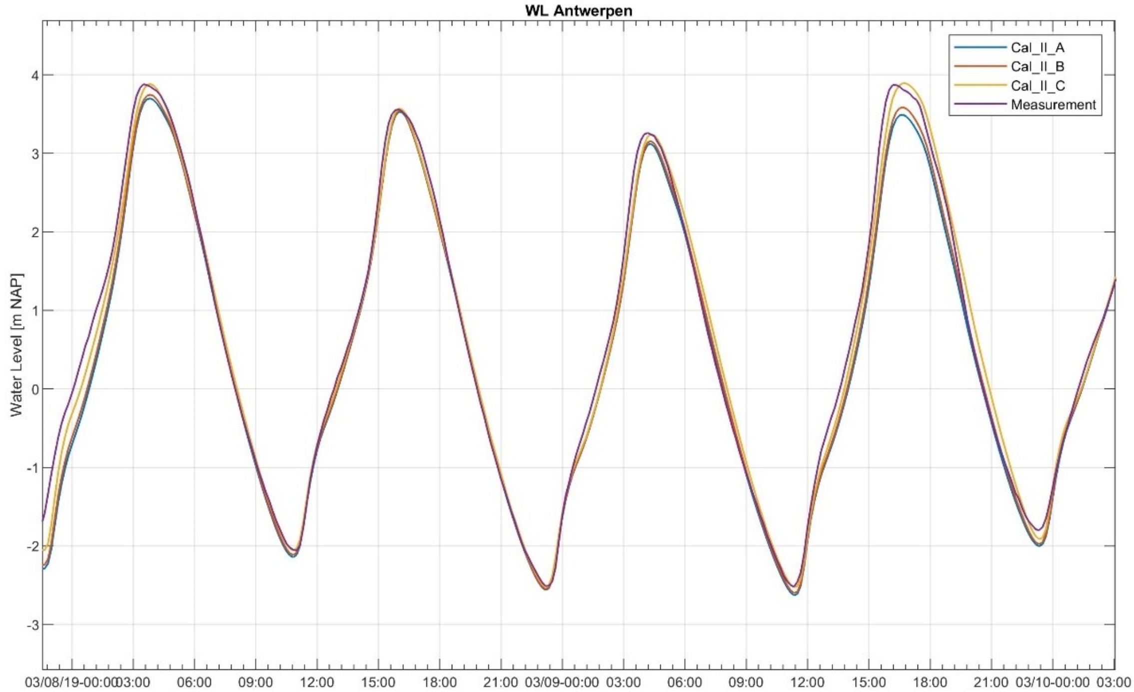
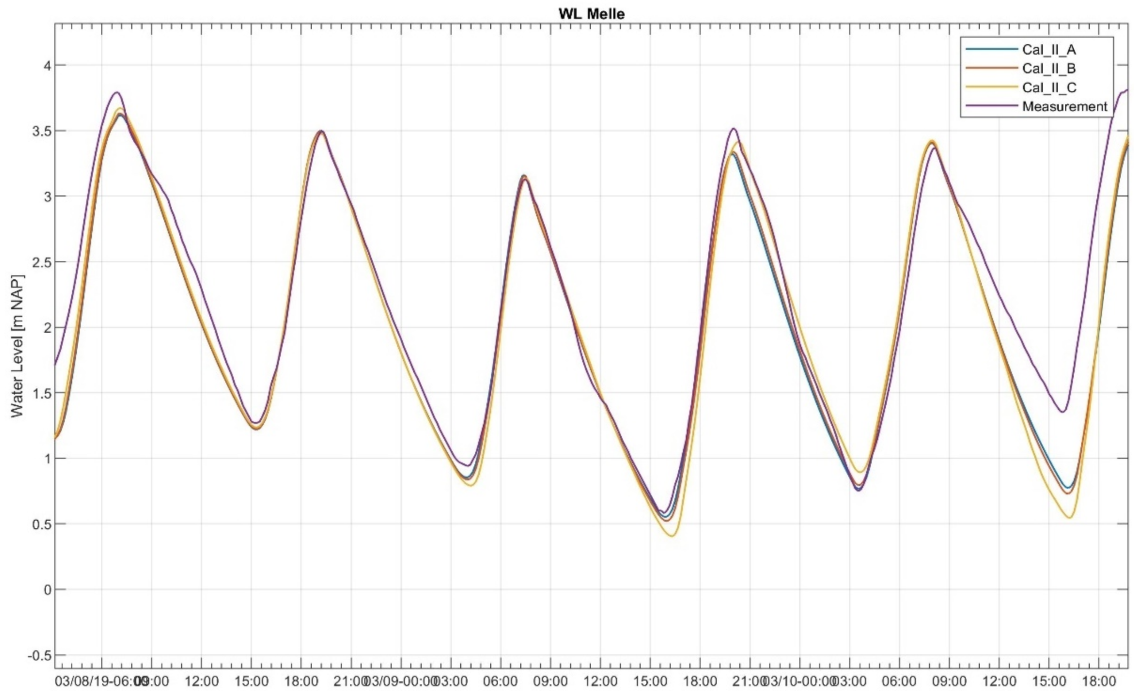


Figure 46 – Influence of wind on water level at Melle for calibration period II (stormy).



6 Calibration method – Cost function

The main objective of the model calibration is to improve the model performance on hydrodynamics in the Scheldt estuary. Bed roughness is used as a calibration parameter. A cost function is used to evaluate the calibration process.

6.1 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** (Run01 in Table 14), so a value lower than 100% indicates an improvement (Smolders et al., 2016). The use of the cost functions is illustrated for calibration period 1 in section 7.6.

$$Cost = \sum \frac{max(Factor_i, Threshold_i)}{max(Factor_{i,ref}, Threshold_i)} * Weight_i$$

Several parameters are selected as factors for the calculation of the cost function (Table 16):

- RMSE of the water level time series, RMSE of high waters, vector difference (that shows the accuracy of harmonic components in the model) and bias of M2 tidal amplitude.

- RMAE for each location with the available ADCP measurements. The RMAE gives information about the model accuracy for both velocity magnitude and direction;

- RMSE of stationary velocity magnitude.

Formulas and further explanation on RMSE and RMAE is given in ANNEX1.

An expected observation error (a threshold for different parameters) needs to be taken into account to assess the accuracy of the model reference in relation to the pre-defined modelling objective (Vos et al., 2000). For example, the threshold for the M2 amplitude is 2 cm. It means that if the error in M2 amplitude in both runs is smaller than 2 cm, the cost of this parameter will remain the same. This methodology helps to avoid giving too much weight to a very small improvement or deterioration of a parameter. The threshold for the M2 amplitude was obtained from the VIMM output for harmonic components. The threshold for the RMSE of water levels is 3 cm as suggested by Smolders et al. (2016). In the cost function the weights are more or less equally given to different regions of the entire estuary.

6.2 Selected weights and thresholds

The stated model aim (§1.1) is translated in the following weights.

Table 16 – Weights and thresholds used in the cost function.

	Zone	Factor	Weights [%]			Threshold
Vertical Tide (water levels)	BCZ	RMSE water level time series (cm)	3	12	48	3
		RMSE high water level (cm)	3			3
		Vector difference	3			0
		delta M2 amplitude (cm)	3			2
	Western Scheldt	RMSE water level time series (cm)	3	12		3
		RMSE high water level (cm)	3			3
		Vector difference	3			0
		delta M2 amplitude (cm)	3			2
	Lower Sea Scheldt	RMSE water level time series (cm)	3	12		3
		RMSE high water level (cm)	3			3
		Vector difference	3			0
		delta M2 amplitude (cm)	3			2
	Upper Sea Scheldt	RMSE water level time series (cm)	3	12		3
		RMSE high water level (cm)	3			3
		Vector difference	3			0
		delta M2 amplitude (cm)	3			2
Horizontal Tide (velocities)	BCZ	RMAE of sailed ADCP	6.5	13	52	0.05
		RMSE of stationary velocity deep (cm/s)	6.5			2
	Western Scheldt	RMAE of sailed ADCP	6.5	13		0.05
		RMSE of stationary velocity deep (cm/s)	6.5			2
	Lower Sea Scheldt	RMAE of sailed ADCP	4.5	13		0.05
		RMSE of stationary velocity deep (cm/s)	4.25			2
		RMSE of stationary velocity shallow (cm/s)	4.25			2
	Upper Sea Scheldt	RMAE of sailed ADCP	6.5	13		0.05
		RMSE of stationary velocity shallow (cm/s)	6.5			2
Sum					100	

7 Calibration results - period I

The model was calibrated on bottom friction after the update of the grid (see §4.2) and the boundary conditions (see §4.10).

The full set of output figures and statistic tables for Calibration period I can be found under: p:\PA016-Ondrhd2D3Dmdl\3_Uitvoering\Scaldis_2019_addendum_to _report\Calib1_03042019\

7.1 Water Level

7.1.1 Time series of water level

Table 18 presents the statistics of Bias, RMSE and RMSE0 (see definitions in ANNEX1) of the complete time series, high water levels and low water levels respectively. The statistical values are color-coded by the definition shown in Table 17. The statistical results are also illustrated in Figure 47 to Figure 55.

The calibrated model in general produces decent results for calibration period I. The average value of the absolute bias of water level is around 2 cm at BCP, WES and BoZS. It is relatively larger at BeZS (5 cm) and at Rupel basin and Durme (8 cm).

The RMSE of water level gradually increase from 7 cm near the offshore to 13 cm in BoZS. There is still room for further improvement at Rupel basin and Durme (RMSE of 20.4 cm) where the local roughness is not yet optimized during the calibration of SCALDIS 2019. This will be considered for future studies.

Note how the error (eg RMSE measures) is not zero at Vlissingen. This corresponds to the error that is “imported” from the mother model that generates the boundary conditions (see also section 7.1.2). This error is mainly due to errors in surge prediction, and stems partly from the fact that North sea models are forced with simulated wind fields (that also have an error to them). The quality of the model is really how this error increases further upstream the estuary.

Table 17 – Definition of colour code in terms of bias, RMSE and RMSE0.

Legend	|Bias| [cm]	RMSE [cm]	RMSE0 [cm]
(dark green)	0-5	0-5	0-5
(light green)	5-10	5-10	5-10
(yellow)	10-15	10-15	10-15
(orange)	15-20	15-20	15-20
(red)	>20	>20	>20

Table 18 – Bias, RMSE and RMSE0 of water level for Calibration period I.

Zones	Stations	Complete TimeSeries			High Water Level			Low Water Level		
		BIAS [cm]	RMSE [cm]	RMSE0 [cm]	BIAS [cm]	RMSE [cm]	RMSE0 [cm]	BIAS [cm]	RMSE [cm]	RMSE0 [cm]
BCZ	Westhinder	-4.3	6.7	5.2	-4.2	6.6	5.2	-4.6	7.3	5.7
	Nieuwpoort	-1.6	6.5	6.3	-1.6	5.2	4.9	-4.5	7.4	5.9
	Oostende	-3.8	7.6	6.6	-3.5	6.2	5.1	-4.5	7.0	5.3
	Zeebrugge	0.6	6.8	6.7	-1.2	6.7	6.6	1.1	5.7	5.6
	|Average|	**2.6**	**6.9**	**6.2**	**2.6**	**6.2**	**5.4**	**3.7**	**6.8**	**5.6**
WES	Vlakte van de Raan	0.5	6.0	6.0	-3.1	7.0	6.3	-0.1	5.6	5.6
	Westkapelle	-0.7	7.2	7.1	-2.0	6.8	6.5	2.6	6.1	5.5
	Cadzand	4.1	9.5	8.5	-0.1	7.3	7.3	6.5	9.0	6.2
	Vlissingen	1.5	8.8	8.7	-6.6	10.2	7.7	5.8	8.4	6.0
	Breskens	4.0	11.2	10.5	-5.8	9.4	7.4	5.8	8.4	6.1
	Terneuzen	2.3	7.7	7.3	-2.0	7.4	7.1	4.6	7.6	6.0
	Overloop Hansweert	2.9	9.6	9.1	-1.4	6.8	6.6	4.4	7.9	6.5
	Hansweert	1.4	8.7	8.6	-1.8	7.6	7.4	3.2	6.8	6.0
	Walsoorden	0.2	9.4	9.4	-6.4	11.9	10.0	3.0	9.7	9.3
	Baalhoek	1.2	10.0	9.9	-4.2	10.4	9.6	3.1	7.1	6.4
	Bath	5.8	12.2	10.7	3.1	10.4	9.9	5.6	8.4	6.3
	|Average|	**2.2**	**9.1**	**8.7**	**3.3**	**8.7**	**7.8**	**4.1**	**7.7**	**6.4**
BeZS	Prosperpolder	8.6	12.7	9.3	6.8	11.7	9.5	7.8	9.9	6.1
	Liefkenshoek	2.4	9.4	9.1	3.5	10.7	10.1	0.9	6.1	6.1
	Kallo	8.2	12.6	9.6	9.7	14.2	10.3	7.1	9.4	6.2
	Antwerpen	2.8	9.9	9.4	6.4	12.0	10.2	0.4	6.3	6.3
	Hemiksem	3.7	10.6	9.9	5.2	11.2	9.9	-1.4	6.2	6.1
	|Average|	**5.1**	**11.0**	**9.5**	**6.3**	**12.0**	**10.0**	**3.5**	**7.6**	**6.1**
BoZS	Temse	-0.1	11.9	11.9	0.3	10.6	10.5	-14.6	15.6	5.5
	Tielrode	1.2	11.4	11.4	7.4	12.9	10.5	-12.1	13.5	5.9
	StAmands	2.0	11.6	11.5	7.8	14.4	12.1	-10.2	12.0	6.3
	Dendermonde	-4.7	16.8	16.1	3.6	14.1	13.6	-6.0	8.1	5.4
	Schoonaarde	0.3	13.3	13.3	8.6	14.5	11.7	-16.3	17.0	5.1
	Wetteren	-2.0	11.7	11.6	6.4	12.4	10.6	-16.2	16.9	5.0
	Melle	-4.2	14.9	14.3	11.6	14.9	9.4	-21.0	22.1	6.8
	|Average|	2.1	13.1	12.9	6.5	13.4	11.2	13.8	15.0	5.7
Rupel basin and Durme	Boom	-4.3	12.7	12.0	10.1	14.6	10.6	-11.3	15.0	9.8
	Waasmunster	-4.4	13.8	13.1	10.1	14.7	10.7	-11.5	15.3	10.1
	MechelenSluis	7.8	18.7	17.0	-11.1	14.8	9.8	15.1	19.9	13.1
	Duffel	-16.1	32.0	27.6	14.3	16.9	8.9	-7.6	20.4	18.9
	Rijmenam	10.0	24.8	22.8	-16.1	18.7	9.6	19.7	26.3	17.4
	|Average|	**8.5**	**20.4**	**18.5**	**12.3**	**16.0**	**9.9**	**13.0**	**19.4**	**13.9**
Overall		**3.7**	**11.8**	**11.0**	**5.9**	**11.1**	**8.9**	**7.5**	**11.1**	**7.3**

Figure 47 – Bias of complete time series of water levels along the Scheldt.

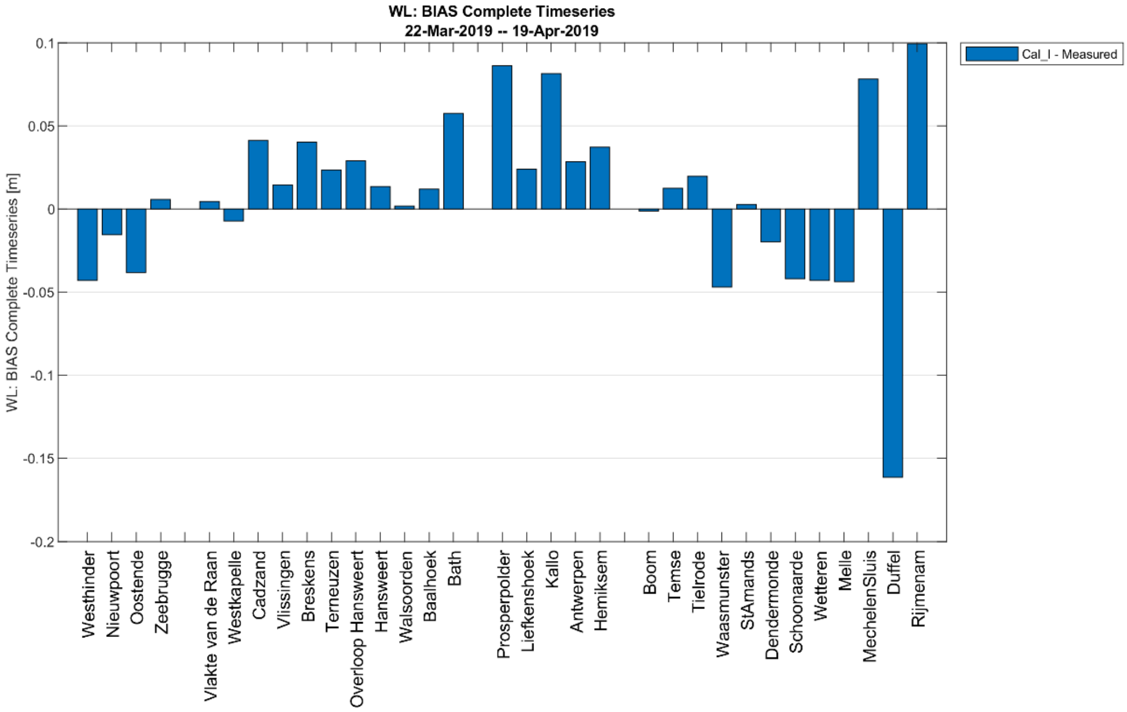


Figure 48 – RMSE of complete time series of water levels along the Scheldt.

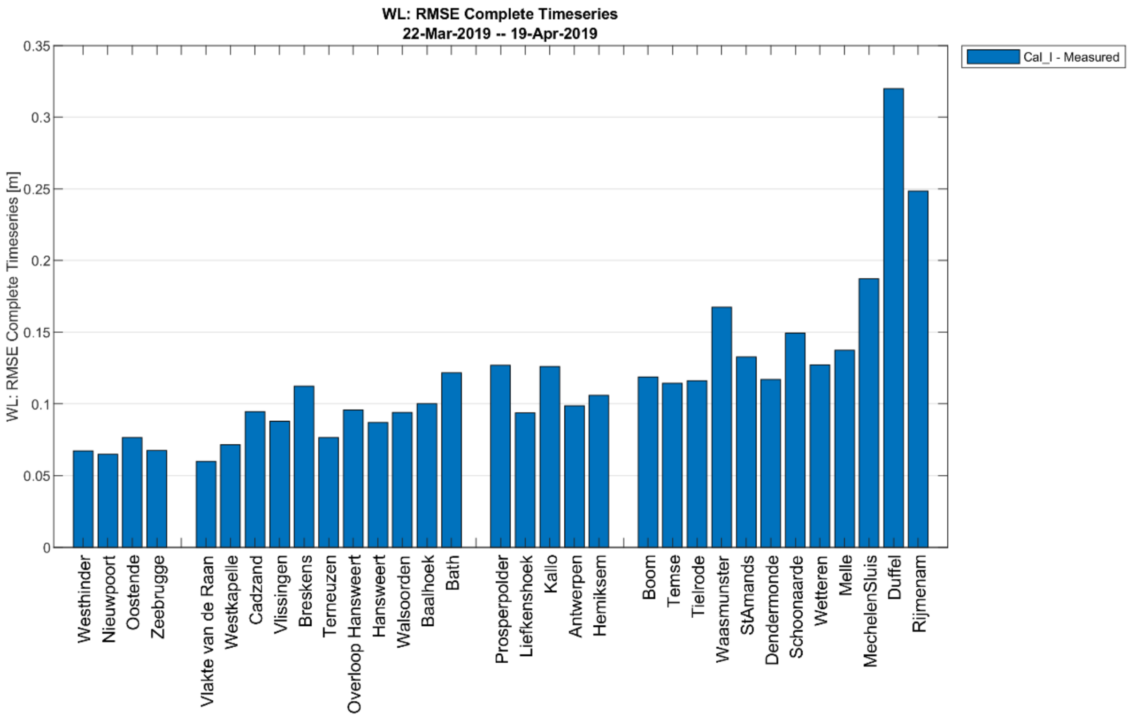


Figure 49 – RMSE0 of complete time series of water levels along the Scheldt.

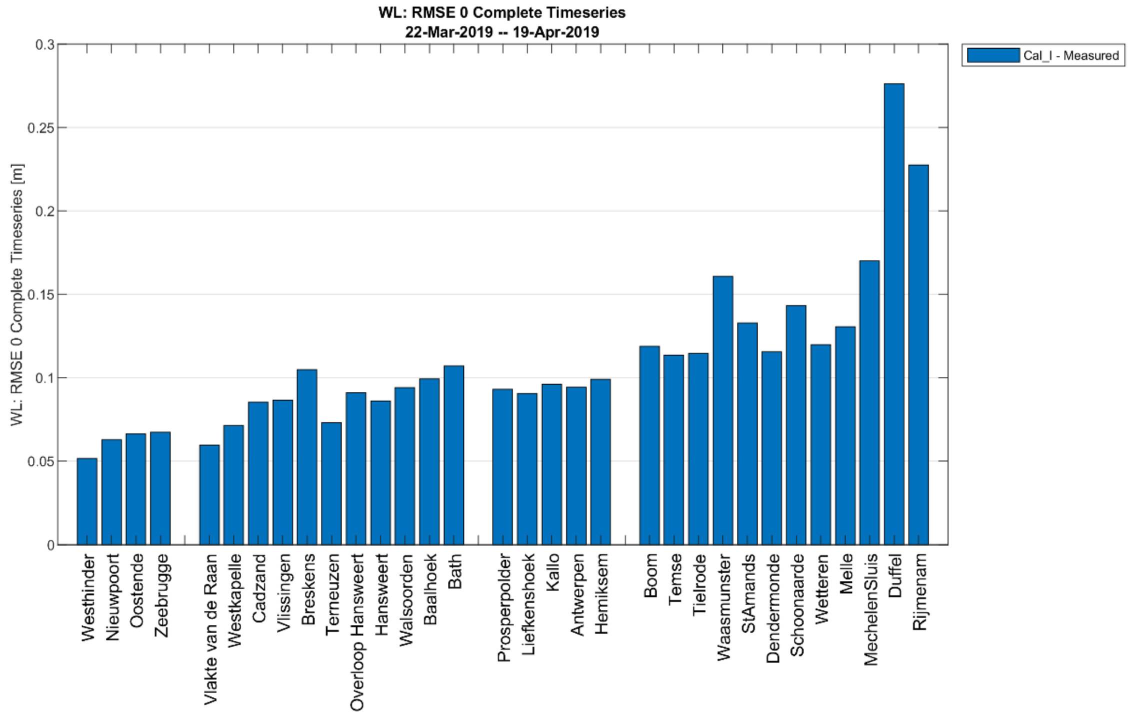


Figure 50 – Bias of high water levels along the Scheldt.

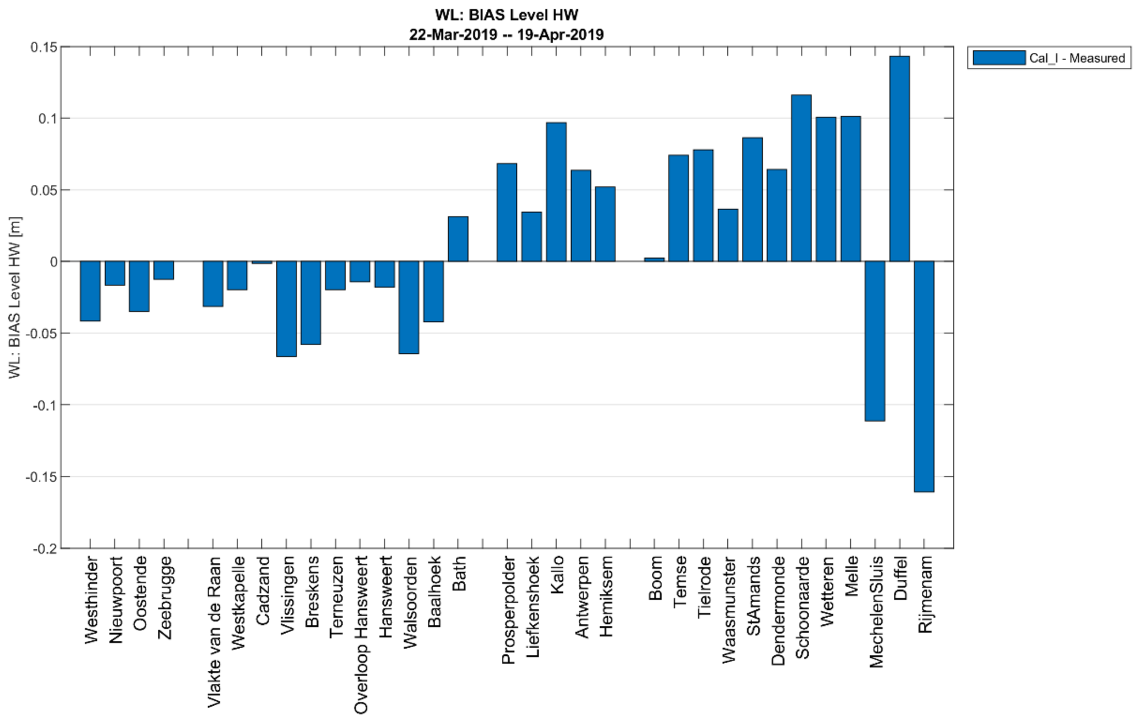


Figure 51 – RMSE of high water levels along the Scheldt.

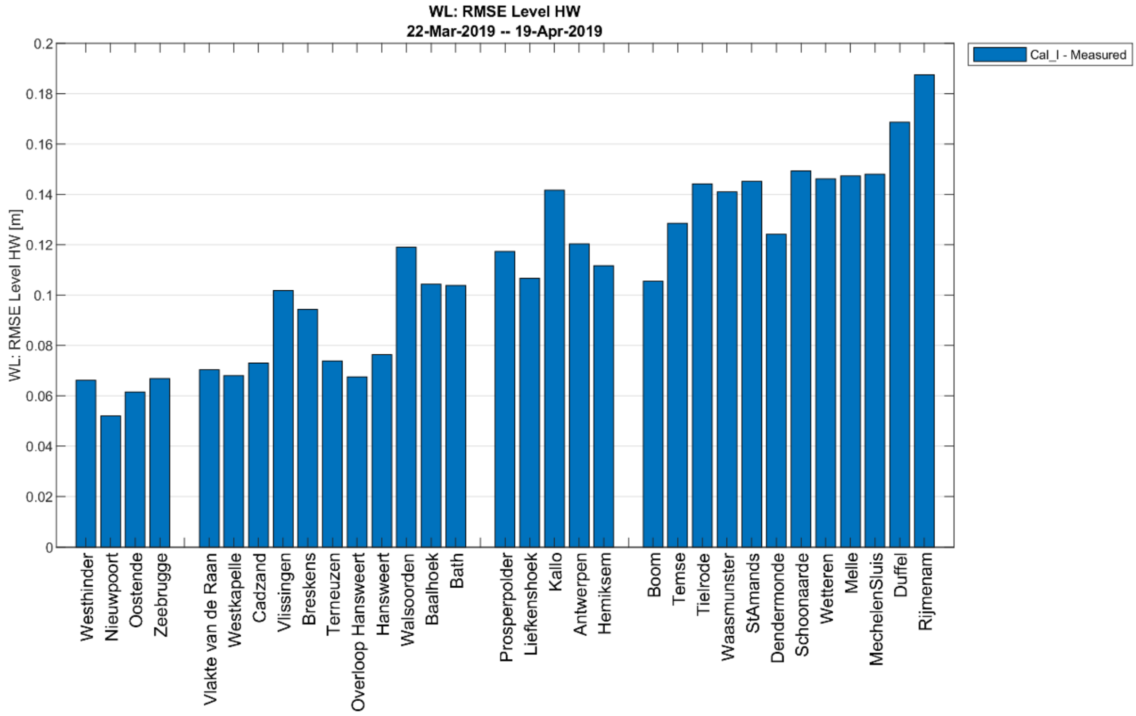


Figure 52 – RMSE0 of high water levels along the Scheldt.

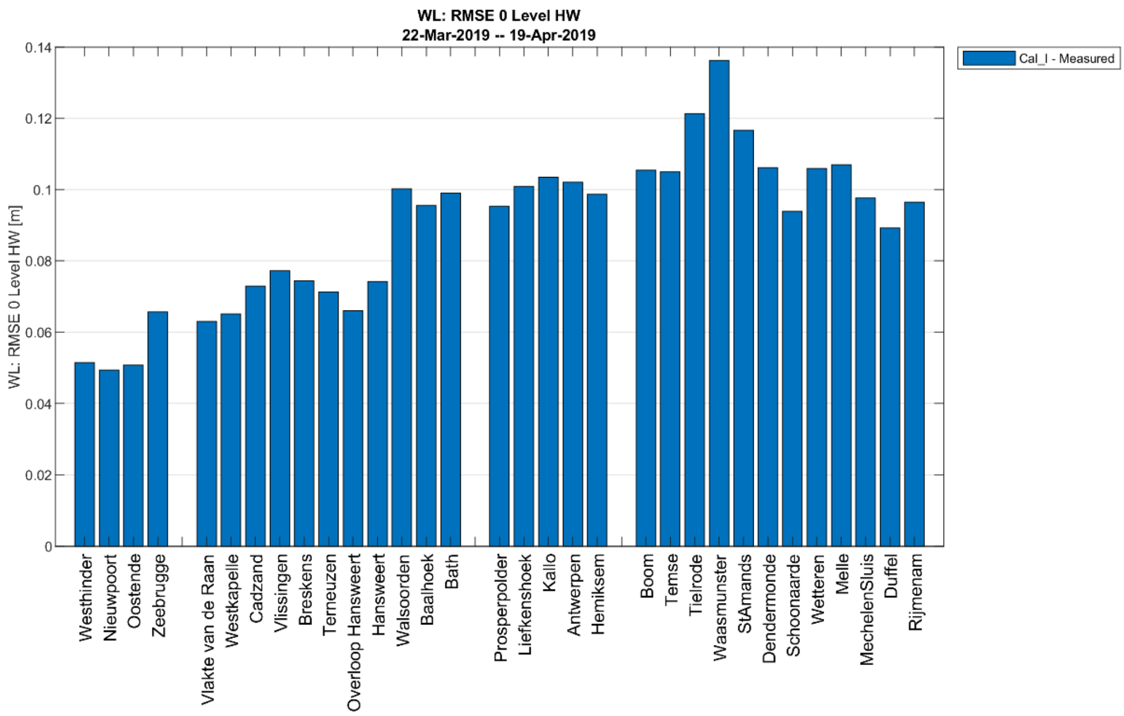


Figure 53 – Bias of low water levels along the Scheldt.

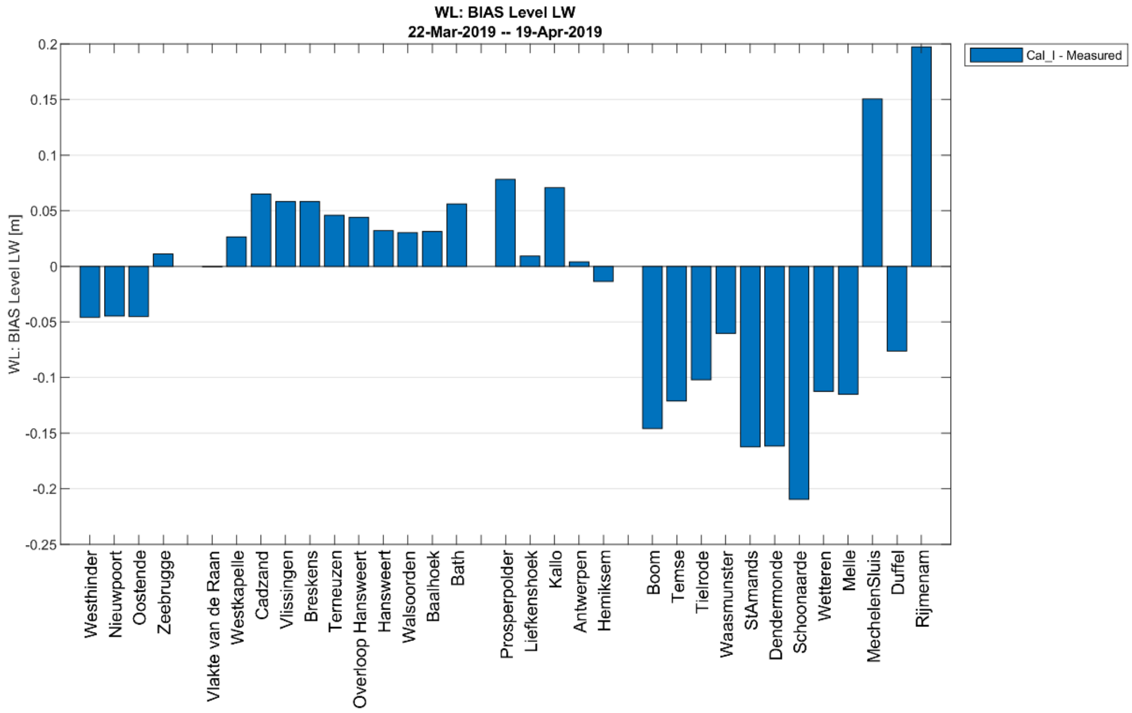


Figure 54 – RMSE of low water levels along the Scheldt.

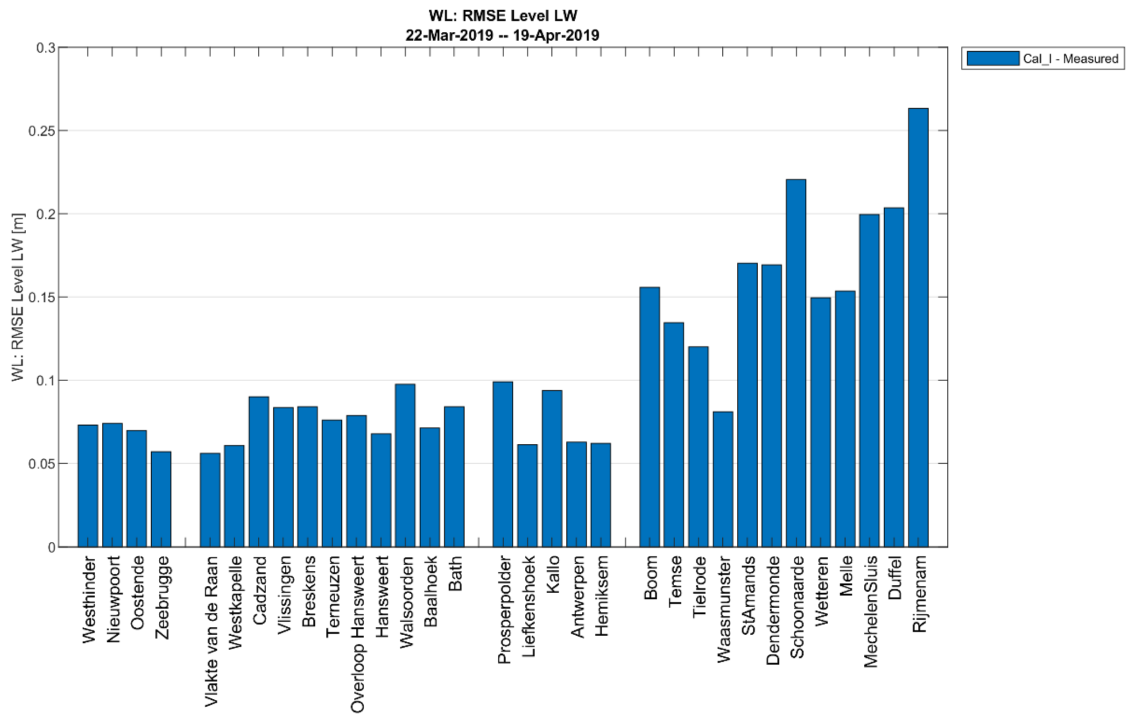
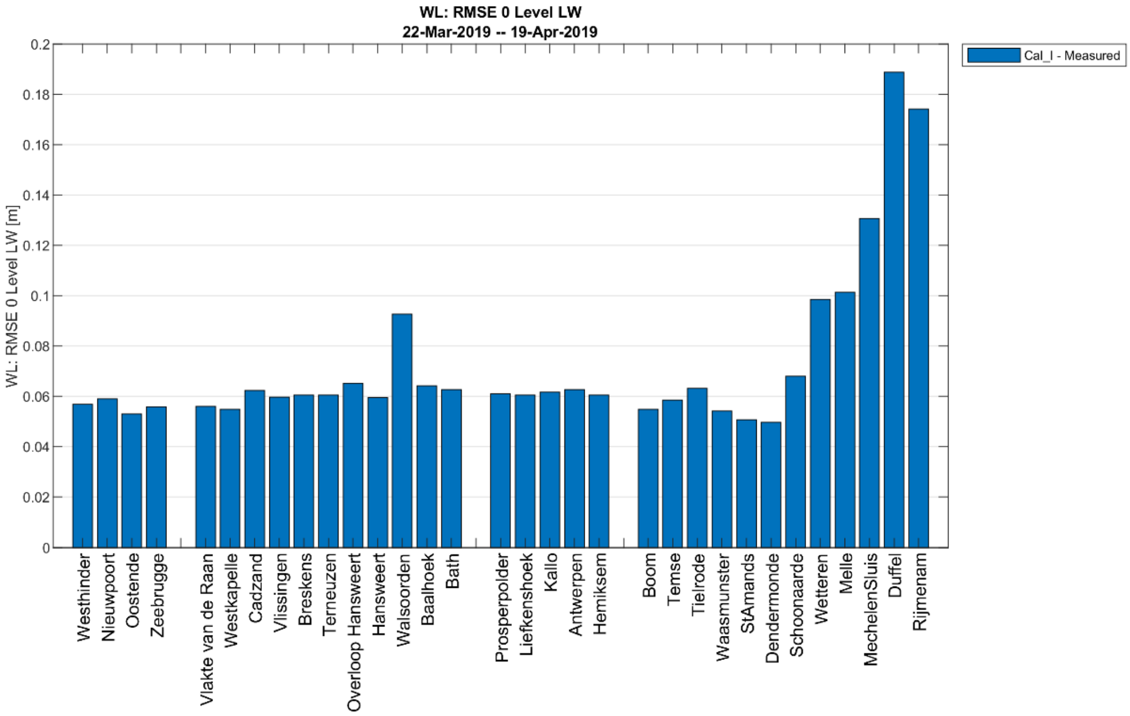


Figure 55 – RMSE0 of low water levels along the Scheldt.



7.1.2 Harmonic analysis

Table 20 presents the comparison of M2, S2, M4 tidal amplitude and phase and total vector difference (see definition in Annex 2) during calibration I. The statistical values are color-coded by the definition shown in Table 19. The corresponding plots are shown in Figure 56 to Figure 62.

The calibrated model in general produces decent results on harmonics for calibration period I. The average value of the absolute bias of M2 amplitude are 1.5, 3.1 and 1.8 cm at BCZ, WES and BeZS respectively. It is relatively larger at BoZS (7.2 cm) and Rupel basin and Durme (11.9 cm). The bias of M2 phase is insignificant except at Rupel basin and Durme (5.2 deg). Similar patterns are found for the S2 tidal component. The bias of M4 tidal phase is considerable from 3.7 deg at BCZ to 11.8 deg at BoZS. Probably this is the main reason that water level is not decently predicted at BoZS. The total vector difference gently increase from 12.4 cm at BCZ to 24.6 cm at BoZS and 38.3 cm at Rupel basin and Durme. There is still room for further improvement at BoZS, Rupel basin and Durme.

Table 19 – Definition of colour code for bias of tidal amplitude, phase and vector difference.

Legend	|Bias| Amplitude [cm]	|Bias| Phase [deg]	Vector Difference [cm]
	0-2.5	0-1.5	0-10
	2.5-5	1.5-3	10-20
	5-7.5	3-4.5	20-30
	7.5-10	4.5-6	30-40
	>10	>6	>40

Table 20 – M2, S2, M4 tidal component and vector difference for Calibration period I.

Zones	Stations	Bias: Model - Measurement						
		M2	M2	S2	S2	M4	M4	Vector
BCZ	Westhinder	1.4	0.4	-2.1	0.3	0.0	-1.8	10.9
	Nieuwpoort	3.2	-0.4	-1.8	-0.6	-0.8	-7.2	12.1
	Oostende	1.5	1.2	-2.3	1.8	-0.3	-2.7	14.7
	Zeebrugge	-0.2	1.3	-2.8	2.1	-0.4	-2.9	11.9
	|Average|	**1.5**	**0.9**	**2.2**	**1.2**	**0.4**	**3.7**	**12.4**
WES	Vlakte van de Raan	-0.4	0.9	-2.6	1.7	-1.4	1.3	10.7
	Westkapelle	0.1	1.7	-2.7	2.4	-0.2	-7.0	14.0
	Cadzand	-3.0	2.0	-4.3	3.0	-1.0	-1.1	20.6
	Vlissingen	-4.7	1.6	-4.3	2.5	-1.0	4.0	18.5
	Breskens	-4.8	2.8	-4.5	3.9	-2.5	-2.6	26.3
	Terneuzen	-2.7	0.1	-3.5	1.0	-0.7	4.4	14.6
	Overloop Hansweert	-3.4	1.7	-3.3	3.0	-1.0	1.2	19.9
	Hansweert	-2.8	1.2	-3.4	2.7	-0.6	3.6	16.0
	Walsoorden	-3.8	1.3	-3.7	2.8	-1.7	0.8	17.6
	Baalhoek	-4.3	1.4	-4.1	3.2	-1.7	-3.1	20.0
	Bath	-3.9	1.6	-4.0	3.7	-1.5	-4.5	25.8
	|Average|	**3.1**	**1.5**	**3.7**	**2.7**	**1.2**	**3.1**	**18.5**
BeZS	Prosperpolder	-3.1	0.8	-3.7	2.6	-1.8	-7.2	24.8
	Liefkenshoek	-2.0	0.4	-3.4	2.2	-1.3	-7.3	16.2
	Kallo	-2.5	0.4	-3.6	2.2	-1.3	-8.8	22.9
	Antwerpen	-1.1	-0.2	-3.4	1.8	-1.3	-8.2	15.9
	Hemiksem	-0.3	0.2	-3.5	2.8	-2.2	-11.3	18.1
	|Average|	**1.8**	**0.4**	**3.5**	**2.3**	**1.6**	**8.6**	**19.6**
BoZS	Temse	5.5	-0.5	-1.6	2.4	-4.6	-17.5	21.6
	Tielrode	5.6	-1.4	-1.9	1.2	-2.3	-15.1	21.5
	StAmands	5.6	-1.3	-2.4	1.4	-2.0	-13.7	22.4
	Dendermonde	4.9	4.9	-1.1	10.3	-1.8	8.2	33.3
	Schoonaarde	8.1	-2.0	-1.6	0.8	-2.0	-13.2	23.6
	Wetteren	8.2	-1.4	-0.8	1.6	-1.4	-8.5	21.4
	Melle	12.6	-3.5	1.5	-0.8	0.4	-6.4	28.6
	|Average|	**7.2**	**2.1**	**1.6**	**2.6**	**2.1**	**11.8**	**24.6**
Rupel basin and Durme	Boom	7.9	-2.5	0.8	0.6	2.8	-1.7	22.0
	Waasmunster	6.5	-2.6	0.7	-0.6	3.3	-6.8	23.0
	MechelenSluis	-0.1	1.4	-0.2	6.9	-7.5	7.3	36.6
	Duffel	26.0	-5.5	7.5	-0.9	0.5	-2.1	66.0
	Rijmenam	-18.8	-13.9	-4.0	-15.4	-3.9	9.8	43.5
	|Average|	**11.9**	**5.2**	**2.6**	**4.9**	**3.6**	**5.5**	**38.2**
Overall		**5.0**	**2.0**	**2.8**	**2.8**	**1.7**	**6.3**	**22.4**

Figure 56 – M2 amplitude along the River Scheldt for Calibration period I.

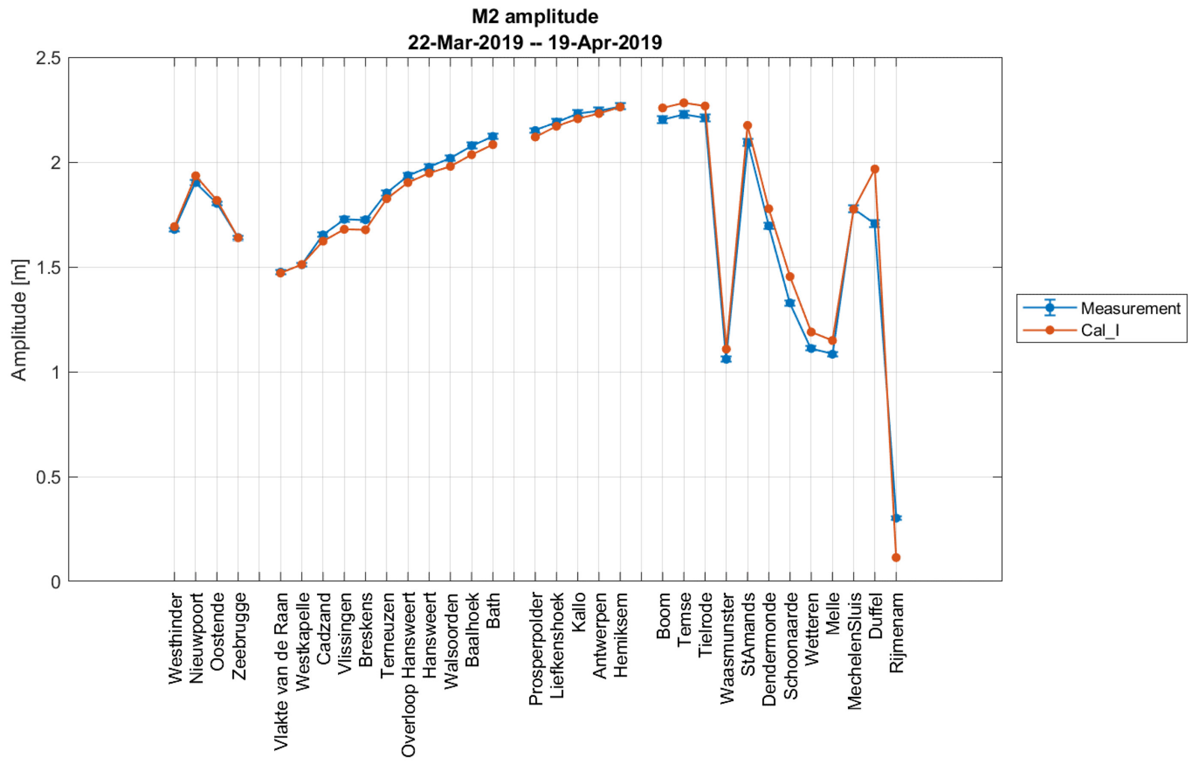


Figure 57 – M2 phase along the River Scheldt for Calibration period I.

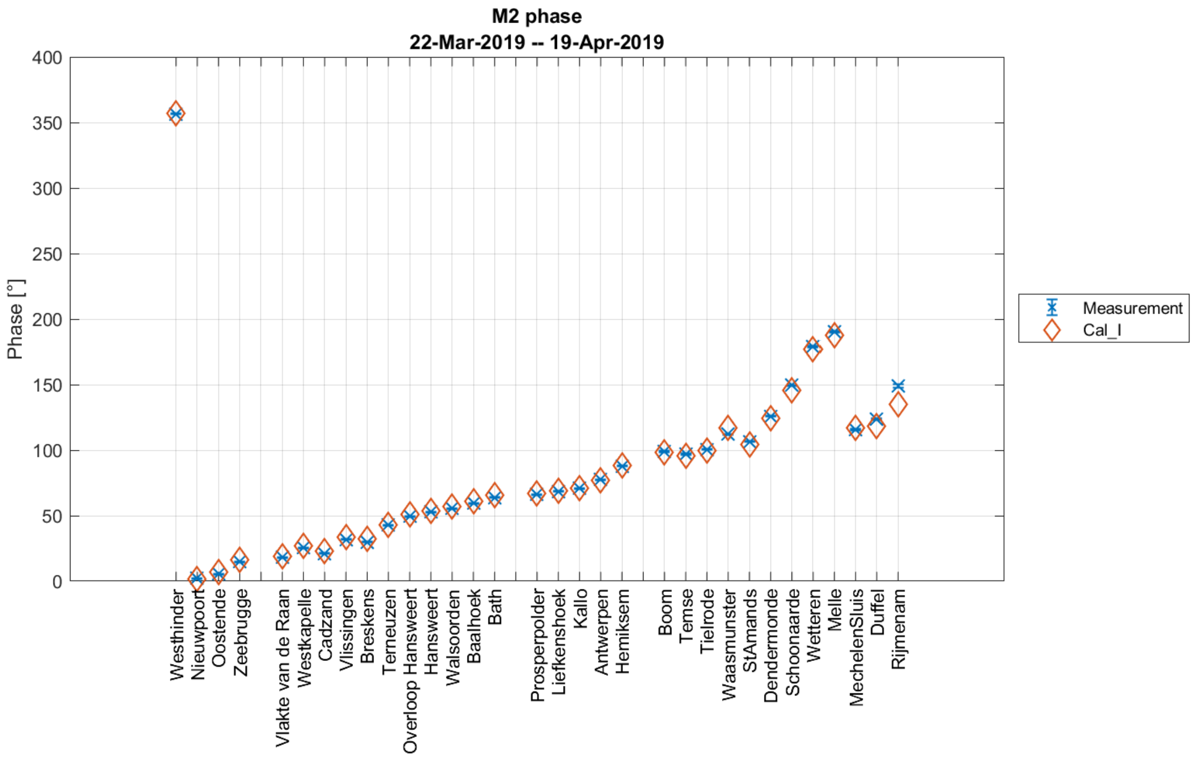


Figure 58 – S2 amplitude along the River Scheldt for Calibration period I.

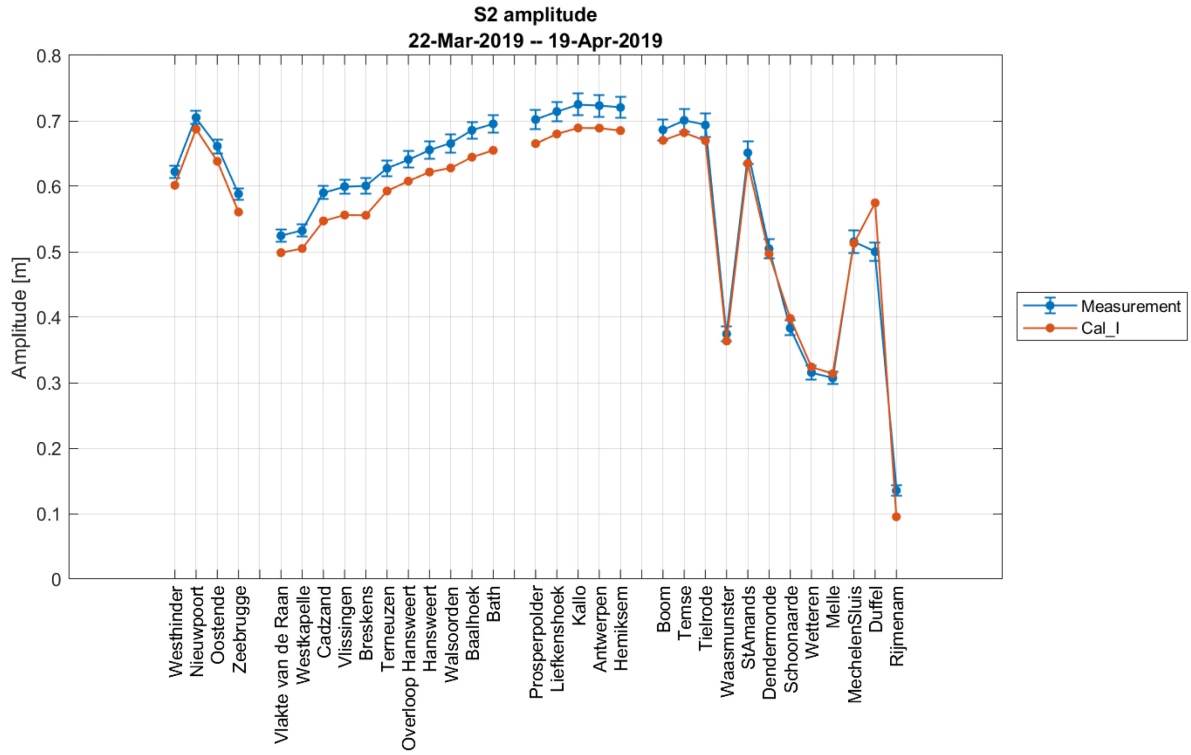


Figure 59 – S2 phase along the River Scheldt for Calibration period I.

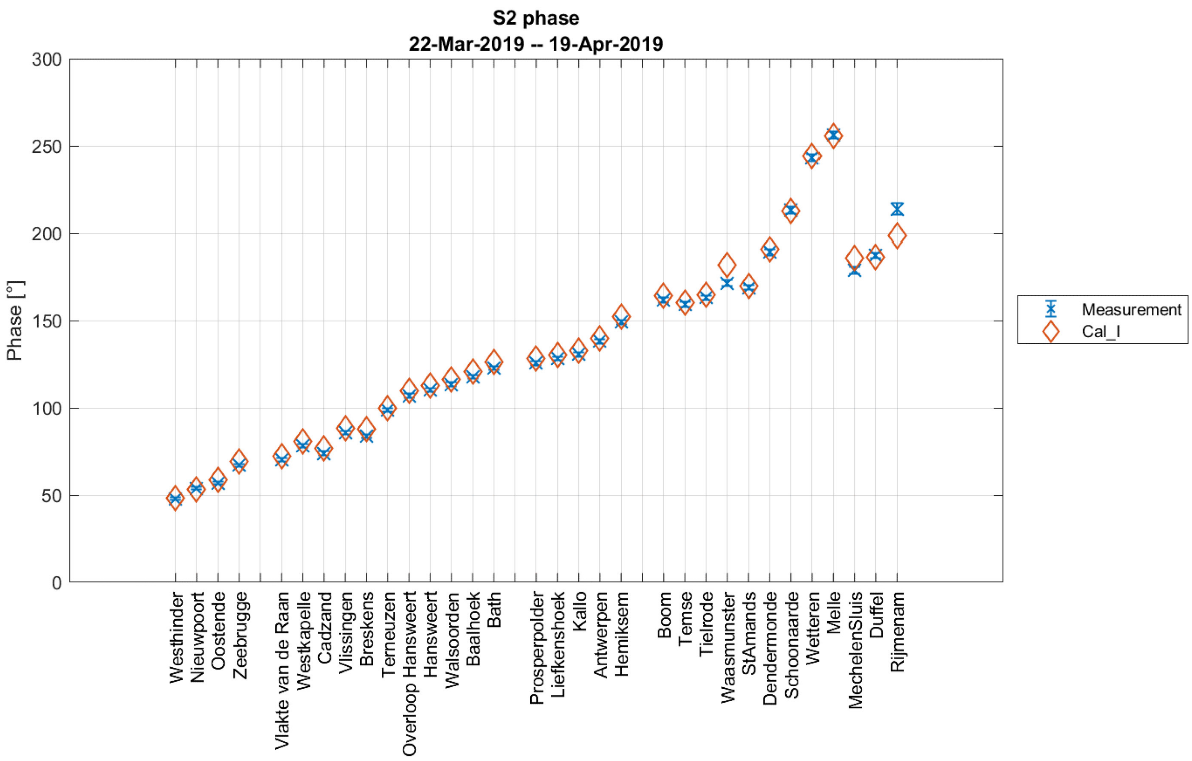


Figure 60 – M4 amplitude along the River Scheldt for Calibration period I.

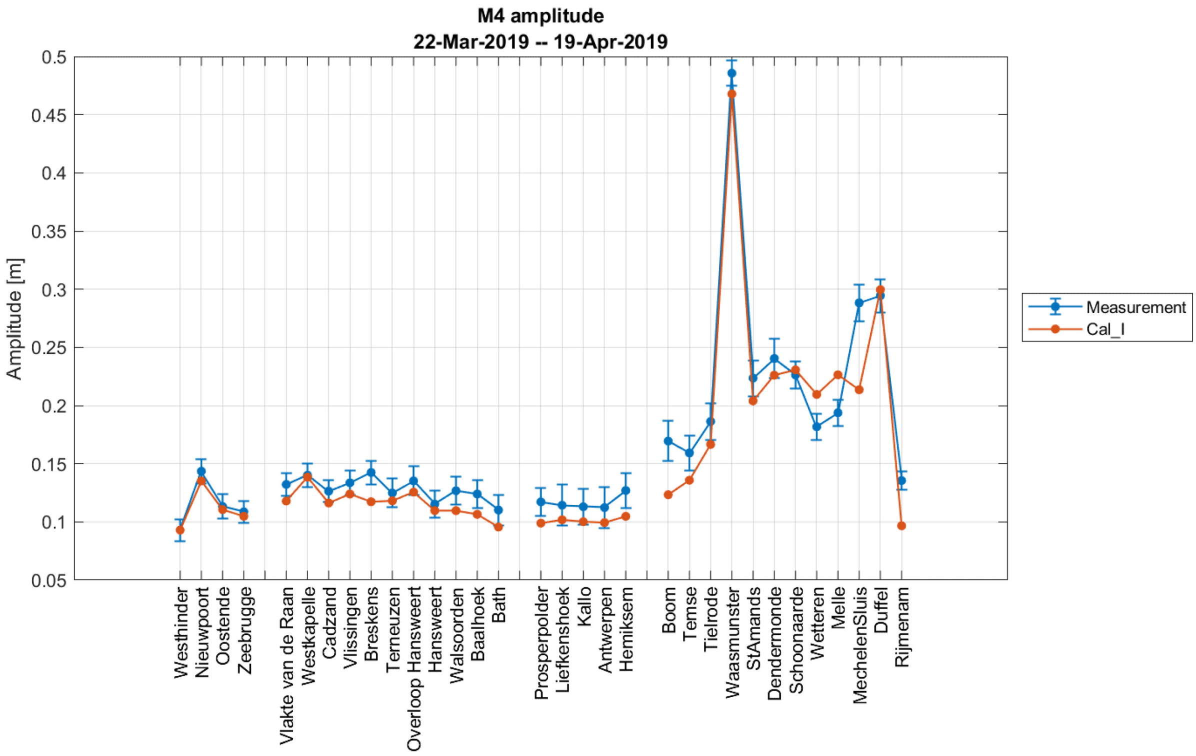


Figure 61 – M4 phase along the River Scheldt for Calibration period I.

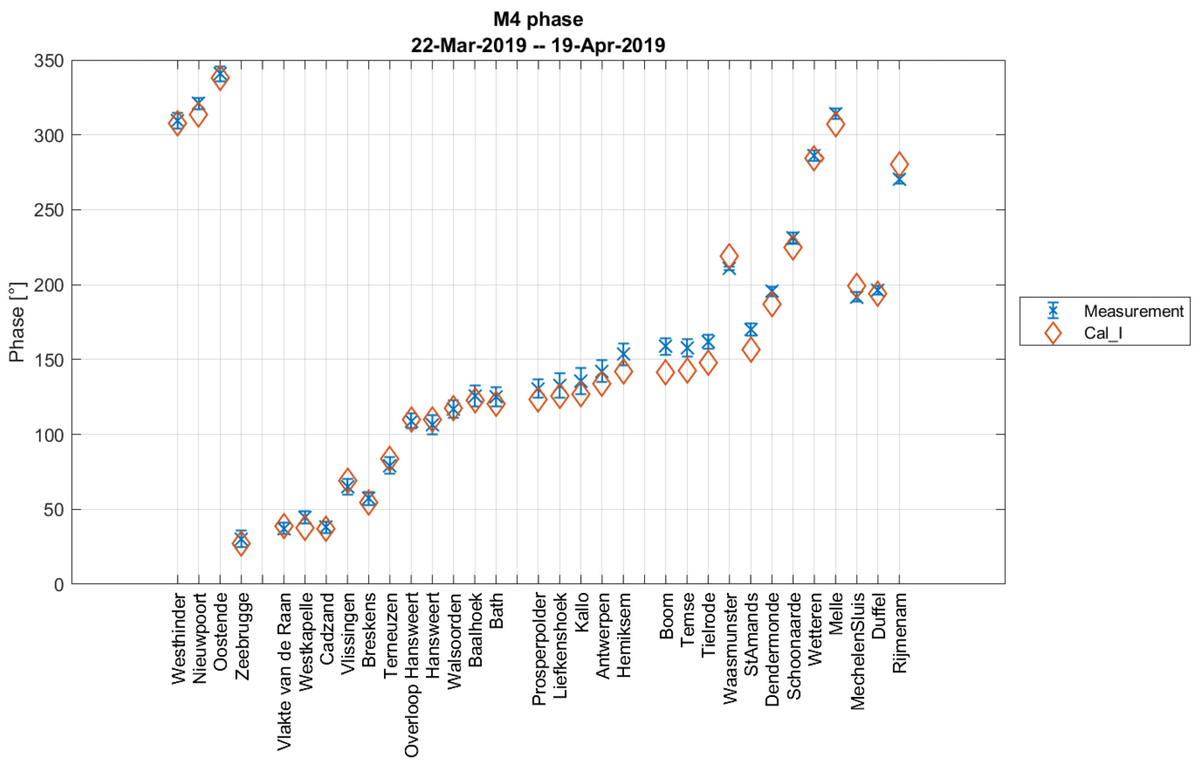
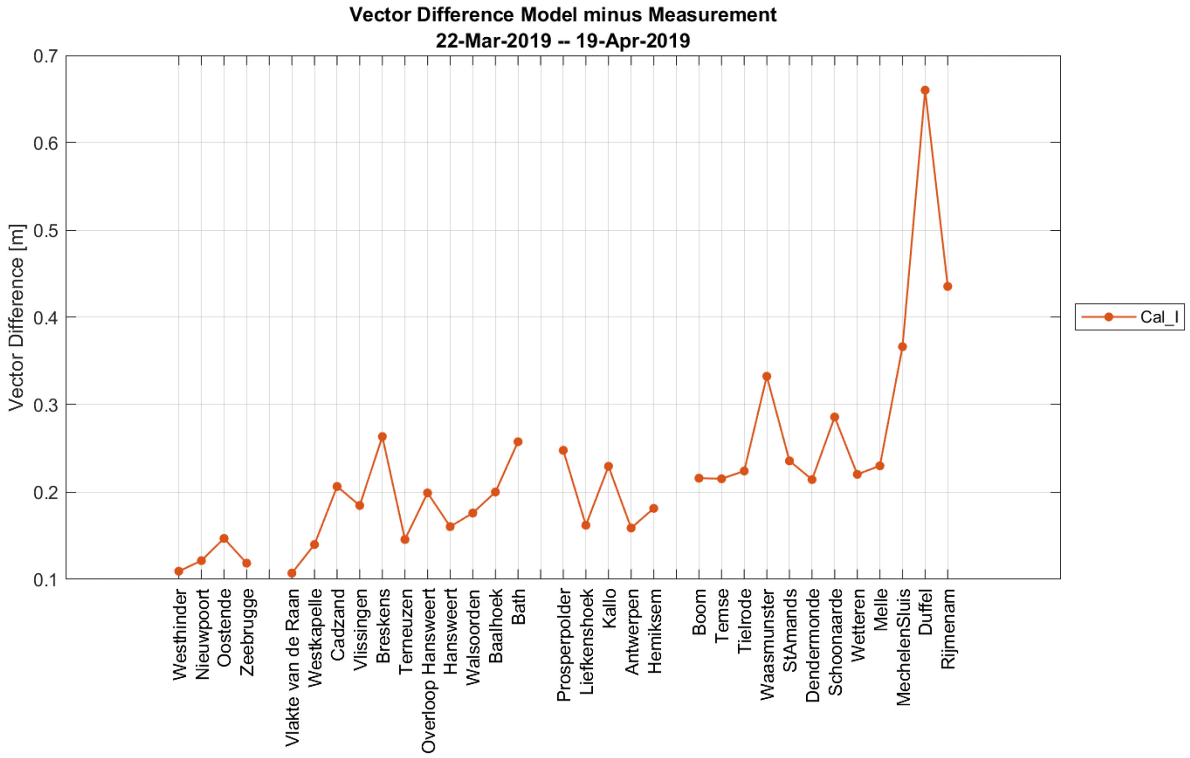


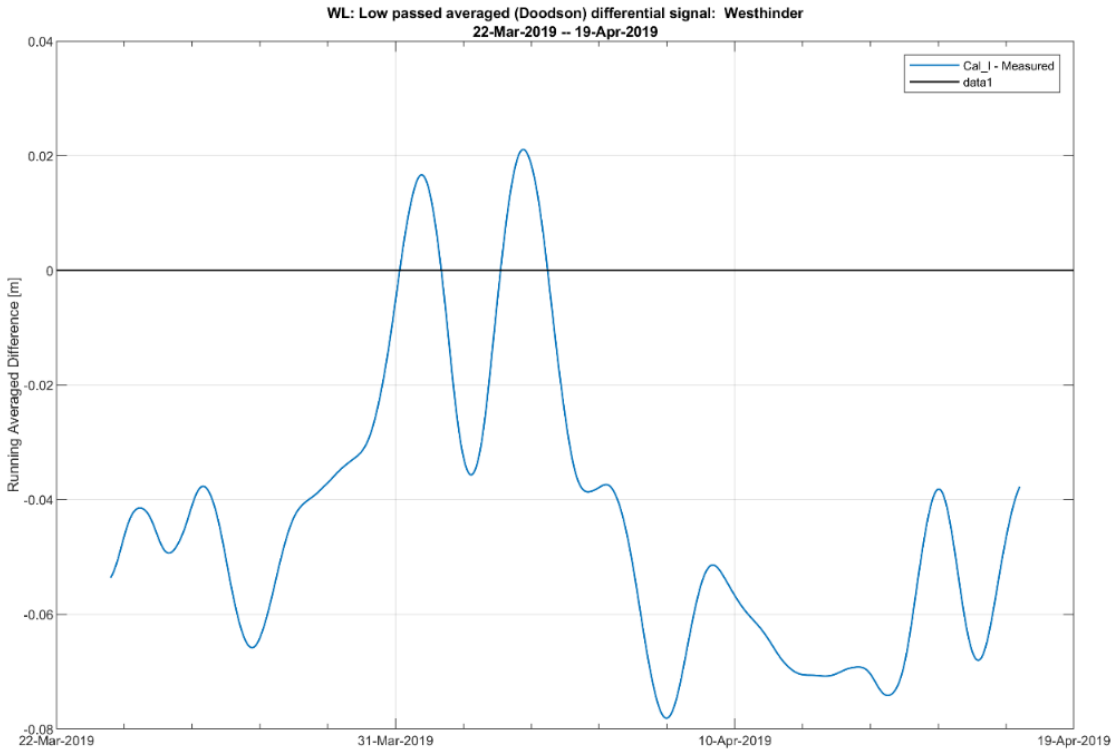
Figure 62 – Vector differences along the River Scheldt for Calibration period I.



7.1.3 Surge error from the open boundary

The low-passed averaged error signal is also evaluated in this study. We apply a three step low-pass filter according to Godin (1972) to a timeseries to remove tidal and higher frequency signals to obtain the residual signal. The filter applies a moving average over periods of 25, 24 and 25 hours respectively. By removing the tidal signal out of the error signal, you get a measure of the non-tidally varying part of the error. Surge is an important component of this error which is often used to evaluate the errors imported from the offshore boundaries. Figure 63 presents the errors of surge signals (model minus measurement) at Westhinder. The errors of surge signals is around -5 cm, which is rather low.

Figure 63 – Low-passed averaged differential signals at Westhinder for calibration period I.



7.1.4 Benchmark against SCALDIS 2013

The calibrated SCALDIS 2019 model is compared with the original calibrated SCALDIS 2013. Table 21 presents the RMSE, bias of M2 amplitude and total vector differences of the complete time series of water levels along the Scheldt.

The SCALDIS 2019 model gives better performance at BCZ (e.g. RMSE of 7.0 cm vs 10.0 cm), mainly because SCALDIS 2019 is nested to ZUNOv4 which is more accurate than ZUNOv3 that was used for boundary nesting to SCALIDS 2013 model. SCALDIS 2019 leads to similar or slightly lower RMSE at WES, BeZS and BoZS. The SCALDIS 2013 performs better in Rupel basin and Durme, where the local roughness is not modified during the calibration of SCALDIS 2019. This could be considered for future studies.

The SCALDIS 2013 model produces noticeable lower bias of M2 amplitude (overall average of 1.9 cm) compared with SCALDIS 2019 (overall average of 5 cm). In terms of total vector difference, SCALDIS 2019 leads to lower values at BCZ and BeZS and larger values at BoZS and Rupel basin and Durme. The overall averaged value of vector difference are similar between SCALDIS 2013 (21.5 cm) and SCALDIS2019 (22.1 cm).

The results analysis on water levels suggest that the model could be further improved at BoZS, Rupel basin and Durme, e.g. by further increasing the bottom friction.

Table 21 – Comparison between SCALDIS 2013 and SCALDIS 2019.

Zones		RMSE [cm]		Bias M2 [cm]		Vector Difference [cm]	
		SCALDIS2013	SCALDIS2019	SCALDIS2013	SCALDIS2019	SCALDIS2013	SCALDIS2019
BCZ	Nieuwpoort	9.0	6.5	0.0	3.2	15.0	12.1
	Oostende	10.0	7.6	4.0	1.5	21.0	14.7
	Zeebrugge	11.0	6.8	1.0	-0.2	22.0	11.9
	|Average|	**10.0**	**7.0**	**1.7**	**1.5**	**19.3**	**12.9**
WES	Vlakte van de Raan	8.0	6.0	2.0	-0.4	15.0	10.7
	Westkapelle	9.0	7.2	5.0	0.1	18.0	14.0
	Cadzand	10.0	9.5	-1.0	-3.0	20.0	20.6
	Vlissingen	9.0	8.8	1.0	-4.7	17.0	18.5
	Breskens	10.0	11.2	0.0	-4.8	18.0	26.3
	Terneuzen	11.0	7.7	1.0	-2.7	21.0	14.6
	Overloop Hansweert	10.0	9.6	1.0	-3.4	17.0	19.9
	Hansweert	10.0	8.7	0.0	-2.8	15.0	16.0
	Walsoorden	11.0	9.4	-1.0	-3.8	16.0	17.6
	Baalhoek	12.0	10.0	0.0	-4.3	19.0	20.0
	Bath	12.0	12.2	-2.0	-3.9	21.0	25.8
	|Average|	**10.2**	**9.1**	**1.3**	**3.1**	**17.9**	**18.5**
BeZS	Prosperpolder	12.0	12.7	0.0	-3.1	23.0	24.8
	Liefkenshoek	13.0	9.4	-1.0	-2.0	25.0	16.2
	Kallo	13.0	12.6	-2.0	-2.5	25.0	22.9
	Antwerpen	15.0	9.9	-2.0	-1.1	28.0	15.9
	Hemiksem	15.0	10.6	-2.0	-0.3	29.0	18.1
	|Average|	**13.6**	**11.0**	**1.4**	**1.8**	**26.0**	**19.6**
BoZS	Temse	13.0	11.9	-1.0	5.5	21.0	21.6
	Tielrode	14.0	11.4	-3.0	5.6	25.0	21.5
	StAmands	14.0	11.6	-2.0	5.6	23.0	22.4
	Dendermonde	13.0	16.8	-3.0	4.9	19.0	33.3
	Schoonaarde	12.0	13.3	1.0	8.1	16.0	23.6
	Wetteren	13.0	11.7	0.0	8.2	12.0	21.4
	Melle	18.0	14.9	1.0	12.6	21.0	28.6
	|Average|	**13.9**	**13.1**	**1.3**	**7.2**	**19.6**	**24.6**
	Boom	14.0	12.7	-2.0	7.9	23.0	22.0
	MechelenSluis	21.0	18.7	-13.0	-0.1	48.0	36.6
	Duffel	14.0	32.0	-1.0	26.0	24.0	66.0
	|Average|	16.3	21.1	5.3	11.9	**31.7**	**38.2**
Overall		**12.4**	**11.5**	**1.9**	**5.0**	**21.5**	**22.1**

7.2 Stationary Velocity in deep areas

The stationary velocities predicted by SCALDIS 2019 are compared with the measurements at Bol van Heist, Scheur Wielingen, Lillo and Oosterweel. Table 22 presents the statistical parameters which are used to to evaluate the model accuracy. Figure 64 to Figure 68 exemplify the time series plot of velocity magnitude and direction at each station respectively.

The model is capable of capturing periodic variation of tidal currents. The SCALDIS model reproduced the stationary velocity very well at Scheur Wielingenn (bias = -1.0 cm/s and RMSE = 8.9 cm/s). However the velocity magnitude at Bol Van Heist is visibly underestimated by the model. The underestimation has been reported by many previous studies and is considered to be associated with the installing location of the measurement station, where local bathymetric effects may play a significant role in the local flow (Kolokythas et al., 2020).

SCALDIS model leads to larger error statistics at Lillo and Oosterweel. This has been reported by Smolders et al., 2016. The discrepancy can be originated from the inaccuracies in the bathymetry implemented in the model or to the location of the point (in the river bend).

Comparing modelled velocity with stationary velocity measurements is often challenging because the point velocity is very sensitive to the local bathymetry, which therefore requires finer mesh, good quality of bathymetry and accurate representation of the location in the model. Besides, the stationary velocities are usually measured on the side slope which introduce difficulties for the representation in the model.

Table 22 – Statistics of stationary velocity in deep area for Calibration I.

Location	Magnitude		Direction
	BIAS TS [cm/s]	RMSE TS [cm/s]	RMSE TS [°]
Bol van Hesit	-3.5	10.0	17
Scheur Wielingen	-1.0	8.9	13
Lillo top	-5.3	22.1	32
Lillo bottom	-6.7	16.9	22
Oosterweel top	-5.6	16.1	24

Figure 64 – Comparison of velocity magnitude and direction at Bol van Heist for Calibration I.

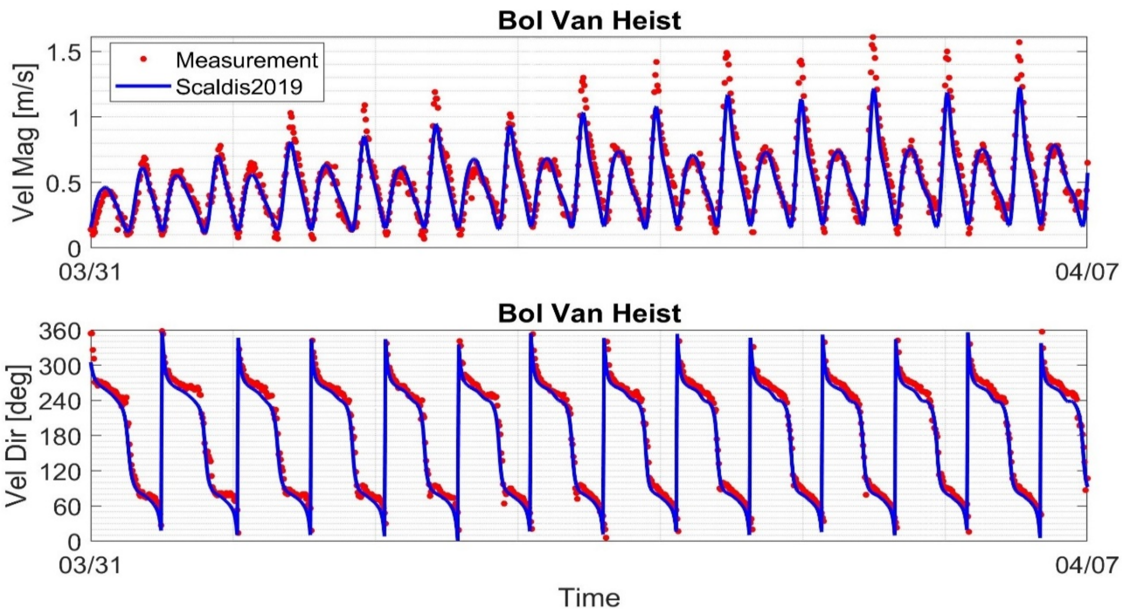


Figure 65 – Comparison of velocity magnitude and direction at Scheur Wielingen for Calibration I.

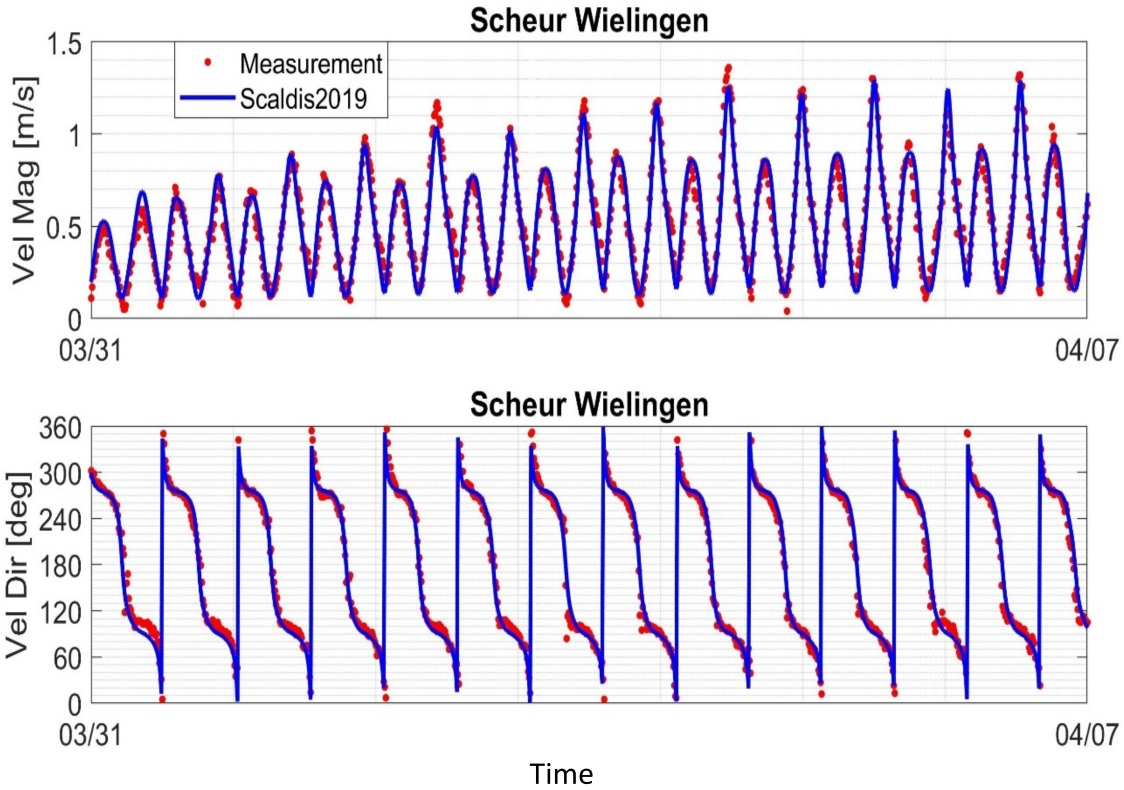


Figure 66 – Comparison of velocity magnitude and direction at Lillo top for Calibration I.

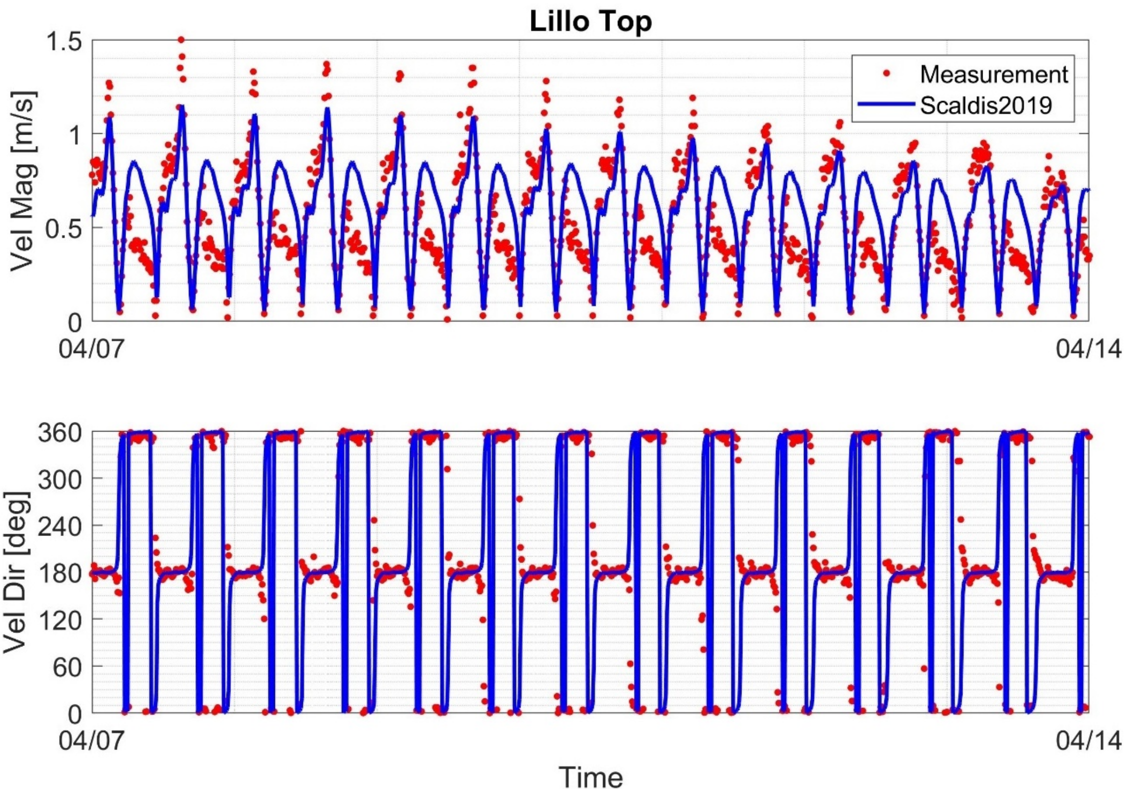


Figure 67 – Comparison of velocity magnitude and direction at Lillo bottom for Calibration I.

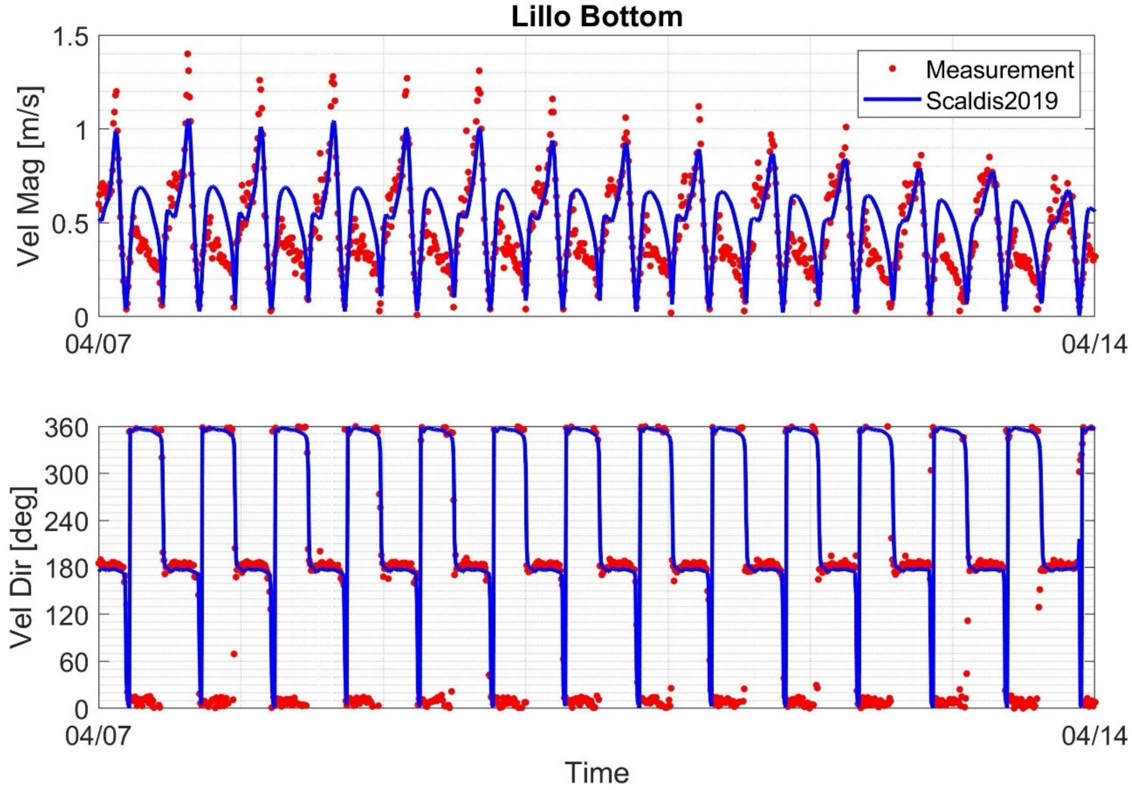
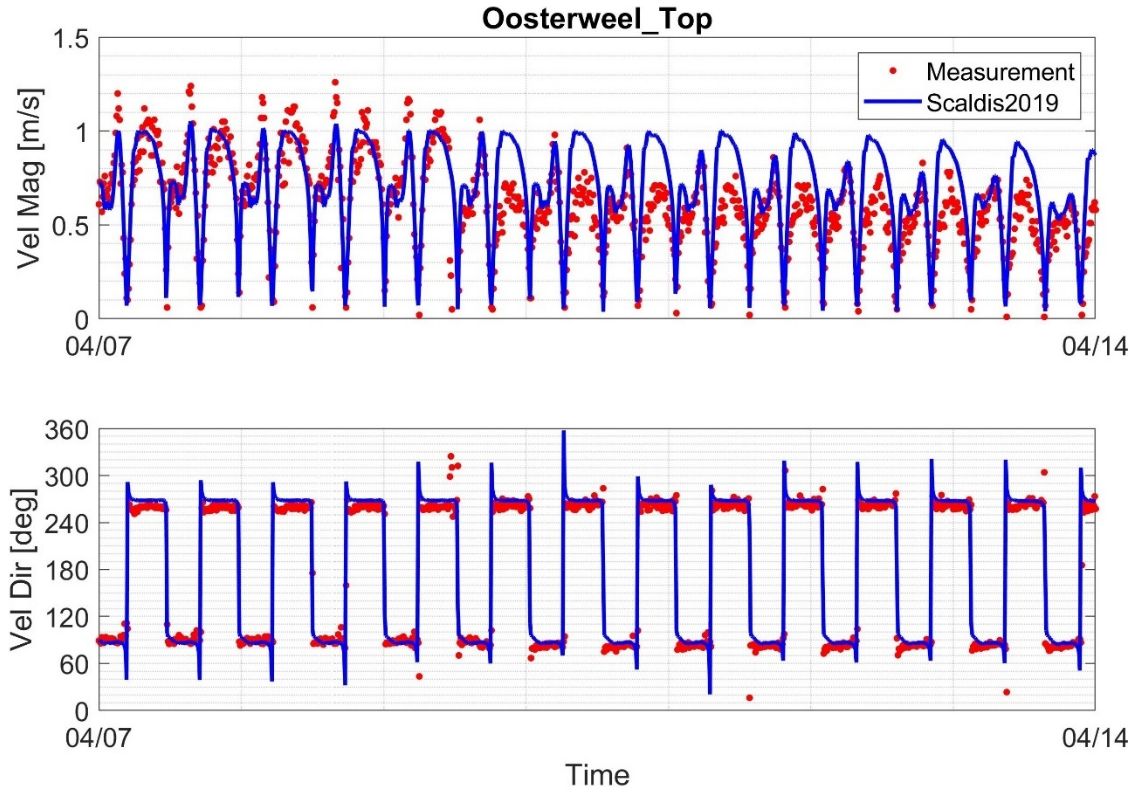


Figure 68 – Comparison of velocity magnitude and direction at Oosterweel top for Calibration I.



7.3 Stationary Velocity in shallow areas

The ensemble-averaged analysis of model results is compared with the ensemble-averaged velocity measurements for neap, average and spring tide at different locations as described in § 3.3.2. The ensemble analysis is carried out using an in-house MATLAB ensemble toolbox. In this analysis the measured and modeled depth-averaged velocities are split into individual tidal-cycles and averaged out over neap-, normal- and spring-tide.

The neap, average and spring-tide are defined by cumulative frequency of the tidal range at a location. Figure 69 exemplifies the cumulative frequency of tidal range at Liefkenshoek predicted by the SCALDIS model. Following Hassan et al. (2017), the neap tide is selected with cumulative frequency less than 25%, the average tide is selected with cumulative frequency between 25-75% while the spring tide is selected with cumulative frequency larger than 75%.

Figure 70 exemplifies the mean values of the ensemble-averaged velocities of the neap-tides as measured and computed at Galgeschoor_south. Each mean value (solid-line) is surrounded by the STD (standard deviation) of the ensemble-averaged velocities. In general the model shows a good performance during both flood and ebb phase. Phase-averaging provides useful information on intertidal dynamics, and focuses the attention on flow system behavior by averaging out events that are more episodic. The full sets of comparison at all the locations for neap, average and spring tides can be found in Annex 4.

Table 23 summarizes the RMSE calculated at each location. It is not possible to intercompare with the effort that Hassan et al. (2017) did in validating Scaldis 2013, as they did not quantify the model quality. In general the model reproduced reasonably well velocities in shallow areas with slight underestimation of the velocity magnitude. The averaged RMSE is 9.2 cm/s BeZS and 10.7 cm/s at BoZS. The discrepancies can be partly attributed to the differences in the bathymetry between model and measurement. For the analysis of flow velocities in shallow zones it is very important that the measurement point and the analyzed point in the model have similar depths. It was not always possible to find a model node with a similar depth close to the measurement location.

Figure 69 – Cumulative frequency of tidal range at Liefkenshoek predicted by SCALDIS model.

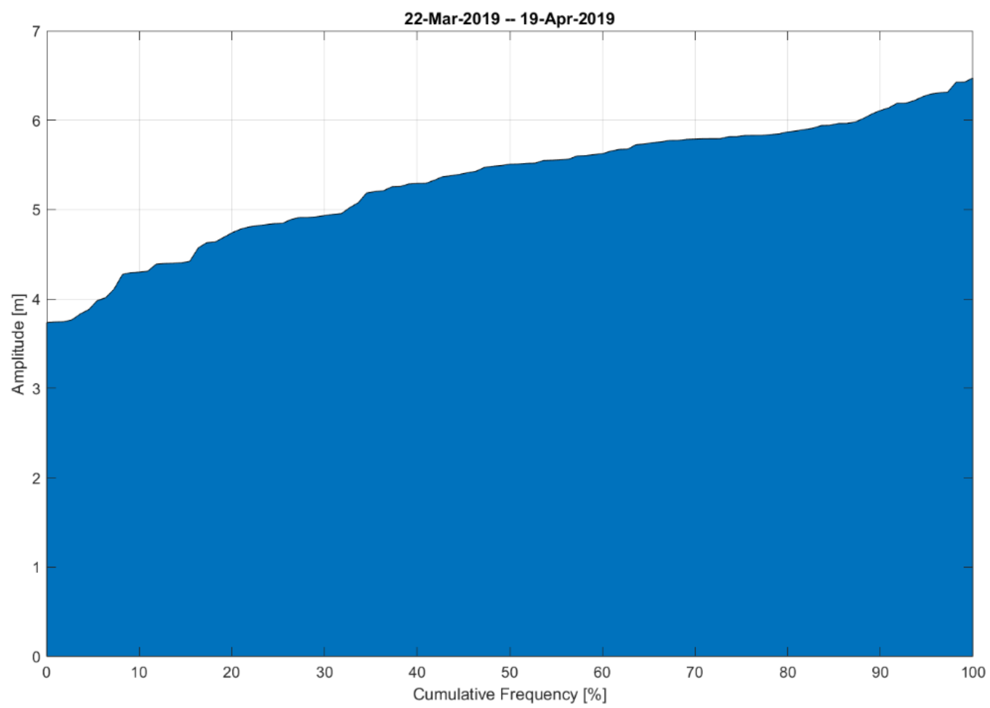


Figure 70 – Ensemble analysis of stationary velocity for neap tide at Galgeschoor_south.

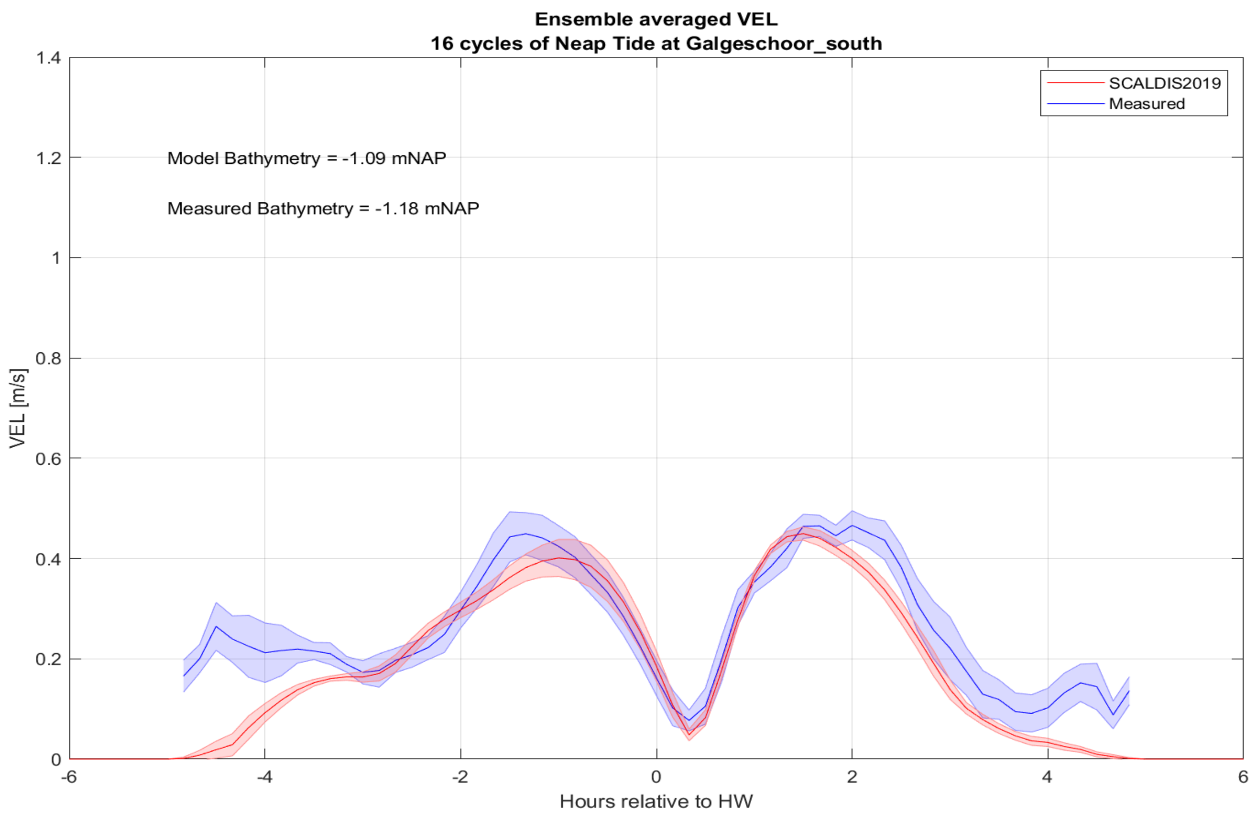


Table 23 – Comparison of RMSE of velocities in shallow areas. The water level stations are used to perform the ensemble analysis.

Zone	Station	Water Level Station	RMSE [cm/s]			
			Neap	Average	Spring	Total
BeZS	Saeftinghe_north	Bath	5.8	6.7	6.8	6.4
	Saeftinghe_south	Bath	7.7	7.0	6.3	7.0
	Galgeschoor_north	Liefkenshoek	8.9	11.0	9.3	9.7
	Galgeschoor_south	Liefkenshoek	6.4	10.5	7.0	8.0
	Ketenisse_hoog	Liefkenshoek	3.6	5.7	3.9	4.4
	Ketenisse_laag	Liefkenshoek	6.4	9.7	12.8	9.6
	Plaat van Boomke_hoog	Antwerp	5.2	8.4	8.0	7.2
	Plaat van Boomke_laag	Antwerp	14.2	13.1	14.1	13.8
	Palingplaat_hoog	Antwerp	11.3	12.5	11.4	11.7
	Palingplaat_laag	Antwerp	15.2	17.3	16.9	16.5
	Plaat van Hoboken_hoog	Antwerp	7.9	8.7	9.0	8.5
	Plaat van Hoboken_laag	Antwerp	8.3	8.7	7.1	8.0
	Average		**8.4**	**9.9**	**9.4**	**9.2**
BoZS	Notelaer_hoog	Temse	6.5	5.8	6.6	6.3
	Notelaer_laag	Temse	21.5	21.6	22.0	21.7
	Weert_hoog	Temse	15.0	12.2	12.4	13.2
	Weert_laag	Temse	13.7	12.1	14.5	13.5
	AppelsLO_hoog	Dendermonde	3.9	3.3	3.7	3.6
	AppelsLO_laag	Dendermonde	8.2	8.9	8.8	8.6
	AppelsRO_hoog	Dendermonde	7.0	5.5	6.1	6.2
	AppelsRO_laag	Dendermonde	10.0	15.6	11.0	12.2
	Average		**10.7**	**10.6**	**10.6**	**10.7**
All			**9.4**	**10.2**	**9.9**	**9.8**

7.4 ADCP sailed velocity

The depth averaged velocities predicted by the model are compared with depth averaged velocity from ADCP measurements.

The full set of output can be found: p:\PA016-Ondrhd2D3Dmdl\3_Uitvoering\Scaldis_2019_addendum_to_report\Calib1_03042019\JOB_04_VEL_Maps\

Table 25 (see Annex 1 for the definition of these statistical parameters). Note that RMAE includes the accuracy of both magnitude and direction. For the purpose of visualization, the RMSE is sorted by different colours with interval of every 10 cm/s (Table 24). Model performance according to RMAE is qualified following Sutherland et al (2003).

In the BCZ, the SCALDIS 2019 model in general shows decent performance ('Good') on velocity predictions with average RMSE of **13.6 cm/s** and RMAE value of **0.24**.

In the WES, the model also leads to good results with averaged RMSE of **18.3 cm/s** and RMAE of **0.30**. It is noticeable that the model leads to poor predictions of velocity along ***Dwarsstroming_Ossenisse_20190323*** where the eddy formation is not well-captured by the model.

In the BeZS, the model shows 'Good' performance with average RMSE of **16.4 m/s** and RMAE value of **0.37**. Modelling velocities inside the Deurganckdok is challenging, and model performances are categorized as 'Poor' along ***DGD_20161018_Spring*** (average RMAE of 0.79). However this is not deemed problematic because the large values of RMAE is mainly due to the local low velocities inside the Deurganckdok where water depth is great (>20 m). The RMSE of velocities are relatively small (7 cm/s).

In the BoZS, the RMSE of velocity is slightly increased to **17.6 cm/s** with RMAE of **0.35** ('Good').

The model predictive ability on ADCP sailed velocities are inter-compared with the original SCALDIS model simulation for the year 2015 (Chu et al., 2017). The resulted RMAE and RMSE per zone is presented in Table 26. Be noted that the SCALDIS 2015 model includes many old ADCP sailed data which were not considered in this study. Therefore it is not an one-on-one comparison. The SCALDIS 2015 gives slightly lower RMSE compared with SCALDIS 2019 model, e.g. 15.0 cm/s versus 18.3 cm/s at WES. However SCALDIS 2019 leads to slightly better RMAE, e.g. 0.27 versus 0.38, but both models are categorized as 'Good'. As RMAE is a measure of both flow magnitude and direction, this result suggests that the SCALDIS 2019 leads to slightly better predictions on flow direction.

Table 24 – Model qualification based on RMAE (Sutherland et al., 2003) and RMSE of flow magnitude.

Model qualification		RMAE [-]	RMSE[cm/s]
Excellent		<0.2	-
Good		0.2-0.4	<10
Reasonable/fair		0.4-0.7	10-20
Poor		0.7-1.0	20-30
Bad		>1.0	>30

Table 25 – Comparison of RMSE and RMAE of velocities along the 54 ADCP transects.

Zone	Campaign	RMSE [cm/s]	RMAE[-]
BCZ	Zeebrugge_HCBS Scheur_20070802	10.9	0.23
	Zeebrugge_HCBS Wiel_20070803	11.1	0.17
	Zeebrugge_HCBS Zand_20070801	17.8	0.30
	WES_Wielingen_Zuid_20151002	14.8	0.23
	WES_Wielingen_Noord_20151003	9.5	0.17
	WES_Oostgat_West_20150928	12.0	0.26
	WES_Oostgat_Oost_20150929	18.9	0.35
	Average	**13.6**	**0.24**
WES	WES_Raai_12_20170724	16.4	0.24
	WES_Raai_12_20170725	15.3	0.23
	WES_Raai_12_20170726	10.1	0.26
	WES_Raai_11_20180712	15.6	0.31
	WES_Raai_11_20180713	19.7	0.28
	WES_Raai_10_20180912	19.1	0.28
	WES_Raai_10_20180913	16.4	0.21
	WES_Raai_9a_20190605	13.3	0.22
	WES_Raai_9b_20190605	19.9	0.26
	WES_Raai_9c_20190606	25.0	0.39
	WES_Raai_7_20170822	13.8	0.17
	WES_Raai_7_20170823	16.7	0.19
	Terneuzen_haven_20070321	11.1	0.32
	WES_Raai_6_20180813	16.7	0.19
	WES_Raai_6_20180814	21.9	0.27
	Diepe_Put_Hansweert_20170720	16.7	0.17
	Dwarsstroming_Ossenisse_20190323	55	0.74
	WES_Raai_5A_201900507	14.4	0.26
	WES_Raai_5A_201900508	16.3	0.25
	WES_Raai_3_20170622	19.7	0.29
	WES_Raai_2_20180529	13.1	0.25
	WES_Raai_1A_20190319	17.5	0.28
	WES_Raai_1B_20190319	17.5	0.26
	Average	**18.3**	**0.3**
BeZS	Zandvliet_20050217_Neap	10.5	0.27
	Noordzeeterminal_20140715_Spring	25.5	0.56
	Toegangsgeul_Zandvliet_Berendrecht_20181011	18.0	0.4
	Doel_LangsraaiO_20100318_Spring	22.1	0.37
	Doel_DwarsraaiD_20100319_Spring	24.2	0.32
	Galgenschoor_20110902	16.7	0.35
	DGD_20161018_Spring	6.9	0.79
	DGD_Eddy Measurements_20120312_Spring_T2	9.5	0.66
	DGD_Eddy Measurements_20120312_Spring_T3	11.8	0.51
	Liefkenshoek_20170511	13.3	0.24
	Kallo_20050218_Neap	13.6	0.25
	Oosterweel_20160511	19.7	0.27
	Galgenweel_20190520	16.4	0.21
	Palingplaat_20190521	17.1	0.33
	Kruibeke_20170629	19.3	0.25
	Schelle_20060928_Average	21.9	0.19
	Wintam_20130213	13.1	0.32
	Average	**16.4**	**0.37**
BoZS	Driegoten_20160622	19.2	0.28
	Appels_Downstream_20110801	17.0	0.66
	Appels_Upstream_20110801	17.1	0.49
	Schoonaarde_20160606	17.9	0.25
	Schellebelle_20170626	17.8	0.26
	Boom_20100427	11.9	0.20
	Terhagen_20170628	22.1	0.31
	Average	**17.6**	**0.35**
All		**17.0**	**0.31**

Table 26 – Comparison of statistics of ADCP sailed velocities between SCALDIS2015 and SCALDIS2019.

Zone	RMSE [cm/s]		RMAE[-]	
	SCALDIS2015	SCALDIS2019	SCALDIS2015	SCALDIS2019
BPZ	N.A.	13.6	N.A.	0.24
WES	15.0	18.3	0.38	0.27
BeZS	14.8	16.4	0.41	0.37
BoZS	16.0	17.6	0.37	0.35
All	15.3	16.5	0.39	0.31

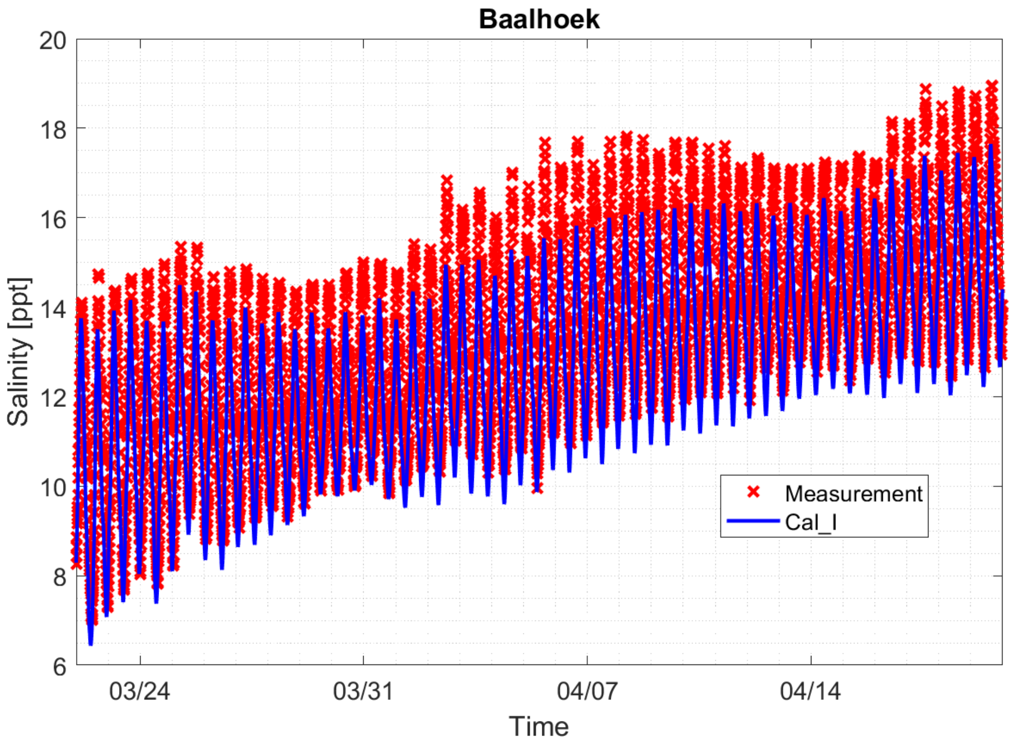
7.5 Salinity

Figure 71 exemplifies the comparison of the modelled and measured salinity time series at Baalhoek. The comparison at other station are presented in Annex 3. The statistical analysis results are presented in Table 27. Salinity is in general well reproduced by SCALDIS along the estuary. The RMSE are smaller than 2 psu for all stations. The discrepancies are mainly attribute to the less accurate initial salinity field applied into the model.

Table 27 – Statistical analysis of salinity for Calibration I.

Nr	Measuring station	Correlation Coefficient	RMSE	Model minus Measurement	
		R [-]	[psu]	Max [psu]	Min [psu]
1	Overloop Hansweert	0.86	1.6	0.8	-4.4
2	Baalhoek	0.95	1.0	1.1	-2.7
3	Prosperpolder	0.95	1.1	0.9	-2.5
4	LilloMeetpaal	0.91	1.5	0.2	-3.0
5	Liefkenshoek	0.91	1.7	0.2	-3.7
6	Oosterweel	0.89	1.0	2.1	-2.4
7	Kruibeke	0.78	0.5	2.0	-1.5
8	Hemiksem	0.78	0.4	1.7	-0.4

Figure 71 – Comparison of salinity between measurement and SCALDIS at Baalhoek for Calibration I.



7.6 Evaluation of the cost function

The model skill for the hydrodynamics can be summarised in the cost function. As described in § 5, the reference model is identical to Run01 in Table 14. The model is calibrated with updated roughness filed in the BoZS (§ 0) and wind forcing with Charnock coefficient of 0.04. The cost is reduced to **94.4 %** after calibration. The main improvement is found at the BoZS. The improvement is not that much because the reference model Run01 already performs decently from BCZ to BeZS.

8 Calibration results - period II

The calibrated model runs for a stormy period between **08/12 – 16/12/2019** (§4.3.1). As described in §4.6, the functionality of culvert is switched on for the stormy period. The full set of output figures and statistic tables for Calibration period II can be found under:

p:\PA016-Ondrhd2D3Dmdl\3_Uitvoering\Scaldis_2019_addendum_to _report\Calib2_032019\

8.1 Water Level

8.1.1 Time series of water level

Table 28 presents the statistics of Bias, RMSE and RMSE0 (dsee definitions in ANNEX1) of the complete time series, high water levels and low water levels respectively. The statistical values are color-coded by the definition shown in Table 17. The statistical results are also illustrated in Figure 72 to Figure 80.

The calibrated model in general produces decent results for calibration period II, but the model performance is slightly worse than calibration period I. The average value of the absolute bias of water level is around 6 cm at BCP, 3 cm at WES and 2.6 cm at BeZS. It is relatively larger at BoZS (9.7 cm) and at Rupel basin and Durme (8.4 cm).

The RMSE of water level at BCZ is 11 cm which is larger than that from the calibration period I (6.9 cm). The larger error is mainly coming from the ZUNOv4 model through boundary nesting (Figure 81). The RMSE of water level gradually increase to 21.5 cm in BoZS. There is still room for further improvement at Rupel basin and Durme (RMSE of 25.5 cm) where the local roughness is not yet optimized during the calibration of SCALDIS 2019 as discussed in the previous chapter.

Table 28 – Bias, RMSE and RMSE0 of water level for Calibration period II.

Zones	Stations	Complete TimeSeries			High Water Level			Low Water Level		
		BIAS [cm]	RMSE	RMSE0	BIAS [cm]	RMSE	RMSE0	BIAS [cm]	RMSE	RMSE0
BCZ	Westhinder	-6.9	9.8	7.0	-2.9	7.4	6.8	-9.9	11.2	5.2
	Nieuwpoort	-5.8	10.7	9.0	-1.6	8.6	8.5	-11.6	13.1	6.2
	Oostende	-7.7	12.8	10.2	-2.6	9.7	9.3	-11.8	13.4	6.2
	Zeebrugge	-3.8	10.9	10.2	0.9	9.2	9.2	-6.5	9.8	7.3
	|Average|	**6.0**	**11.0**	**9.1**	**2.0**	**8.7**	**8.4**	**10.0**	**11.9**	**6.2**
WES	Vlakte van de Raan	-2.3	8.7	8.4	-0.3	9.2	9.2	-6.3	8.5	5.7
	Westkapelle	-5.3	10.9	9.5	-2.9	9.5	9.0	-5.5	8.5	6.5
	Cadzand	-0.9	11.9	11.8	-1.5	10.5	10.4	-2.3	8.0	7.6
	Vlissingen	-3.5	12.5	12.0	-5.6	12.6	11.2	-4.0	8.8	7.8
	Breskens	-1.8	13.7	13.6	-5.3	12.2	11.0	-5.0	9.4	8.0
	Terneuzen	-3.1	12.7	12.3	-2.4	12.9	12.7	-6.2	10.4	8.4
	Overloop Hansweert	-2.4	14.2	14.0	-0.6	11.4	11.4	-5.8	10.0	8.1
	Hansweert	-2.8	14.4	14.1	-1.3	10.7	10.6	-5.4	9.3	7.6
	Walsoorden	-5.1	15.3	14.5	-3.5	13.1	12.6	-7.7	12.0	9.3
	Baalhoek	-4.2	15.7	15.1	-1.0	12.4	12.4	-7.3	10.9	8.0
	Bath	2.0	16.1	16.0	7.2	14.5	12.6	-1.4	7.6	7.4
	|Average|	**3.0**	**13.3**	**12.8**	**2.9**	**11.7**	**11.2**	**5.2**	**9.4**	**7.7**
BeZS	Prosperpolder	4.6	15.9	15.2	10.8	16.8	12.9	0.4	7.9	7.9
	Liefkenshoek	-2.0	15.5	15.4	6.2	14.2	12.7	-7.7	11.2	8.2
	Kallo	4.7	16.7	16.0	12.7	18.0	12.7	0.2	8.5	8.5
	Antwerpen	0.6	15.8	15.8	7.2	14.1	12.1	-3.5	8.8	8.1
	Hemiksem	1.1	17.2	17.2	3.9	12.1	11.5	-5.9	10.8	9.0
	|Average|	**2.6**	**16.2**	**15.9**	**8.2**	**15.0**	**12.4**	**3.5**	**9.4**	**8.3**
BoZS	Temse	-3.9	17.2	16.8	2.4	10.8	10.6	-18.2	20.8	10.2
	Tielrode	-3.2	18.0	17.7	1.6	11.2	11.1	-16.6	20.9	12.7
	StAmands	-5.5	17.9	17.1	1.0	10.6	10.6	-21.5	23.7	10.0
	Dendermonde	-10.9	20.0	16.7	-1.8	9.0	8.8	-25.3	28.6	13.4
	Schoonaarde	-15.8	24.2	18.3	-8.2	15.8	13.4	-29.9	34.3	16.8
	Wetteren	-14.2	25.1	20.7	-8.9	17.5	15.1	-18.1	29.4	23.2
	Melle	-14.6	27.8	23.6	-8.0	16.9	14.9	-14.7	31.8	28.2
	|Average|	9.7	21.5	18.7	4.6	13.1	12.1	20.6	27.1	16.4
Rupel basin and Durme	Boom	-3.2	14.7	14.4	-4.8	7.9	6.2	-23.3	24.1	6.3
	Waasmunster	-14.6	36.1	33.0	-14.3	25.5	21.1	-24.4	26.1	9.3
	MechelenSluis	3.5	23.4	23.2	-5.7	16.7	15.7	4.8	11.1	10.0
	Duffel	-17.1	32.3	27.4	8.3	13.0	10.0	-44.3	47.4	16.8
	Rijmenam	3.7	21.0	20.7	-7.6	16.7	14.8	12.9	20.3	15.6
	|Average|	**8.4**	**25.5**	**23.7**	**8.2**	**15.9**	**13.6**	**22.0**	**25.8**	**11.6**
Overall		**5.7**	**17.2**	**15.9**	**4.8**	**12.8**	**11.6**	**11.6**	**16.2**	**10.1**

Figure 72 – Bias of complete time series of water levels along the Scheldt for Calibration II.

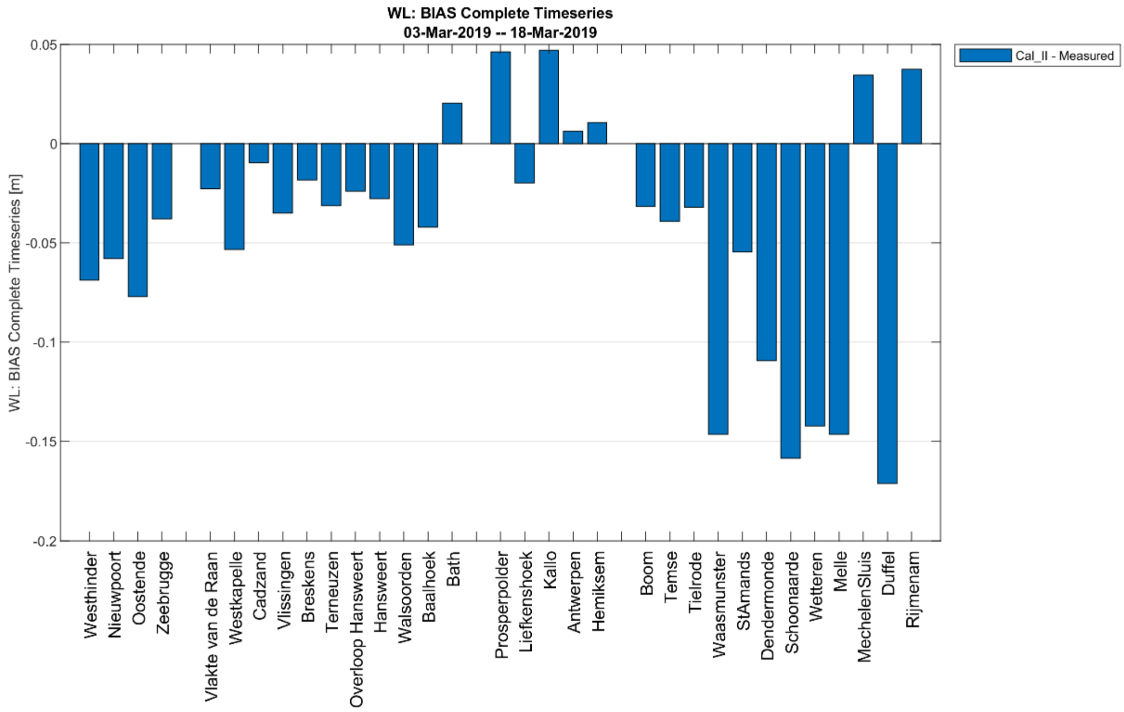


Figure 73 – RMSE of complete time series of water levels along the Scheldt for Calibration II.

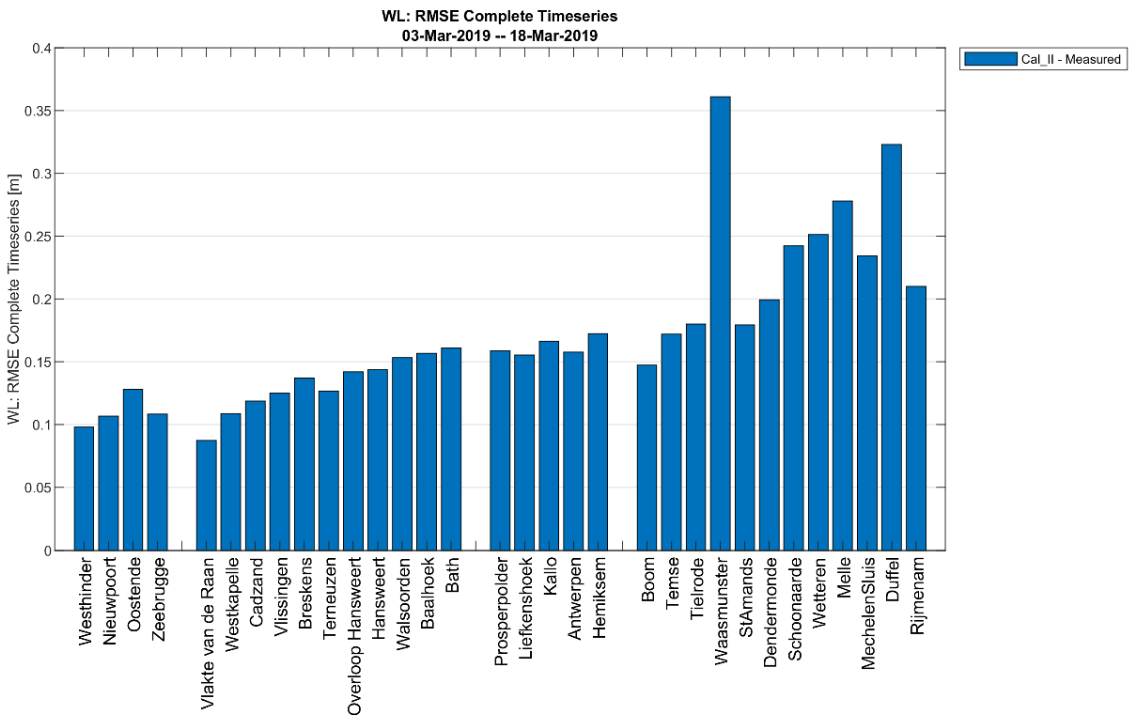


Figure 74 – RMSE0 of complete time series of water levels along the Scheldt for Calibration II.

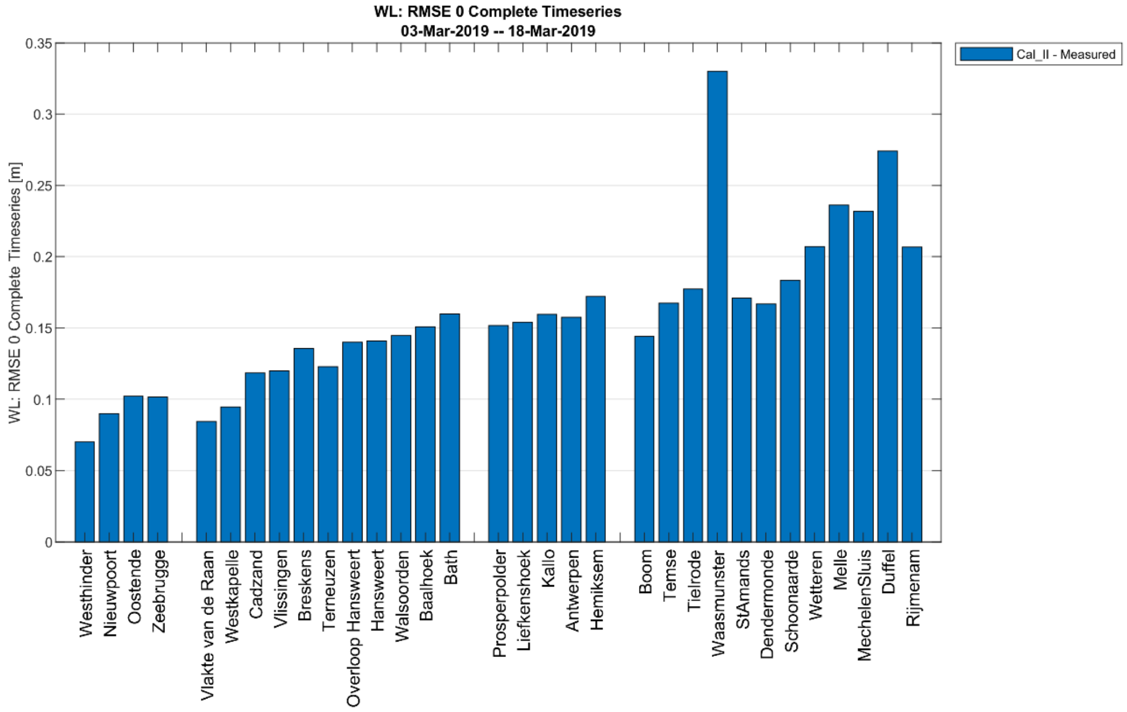


Figure 75 – Bias of high water levels along the Scheldt for Calibration II.

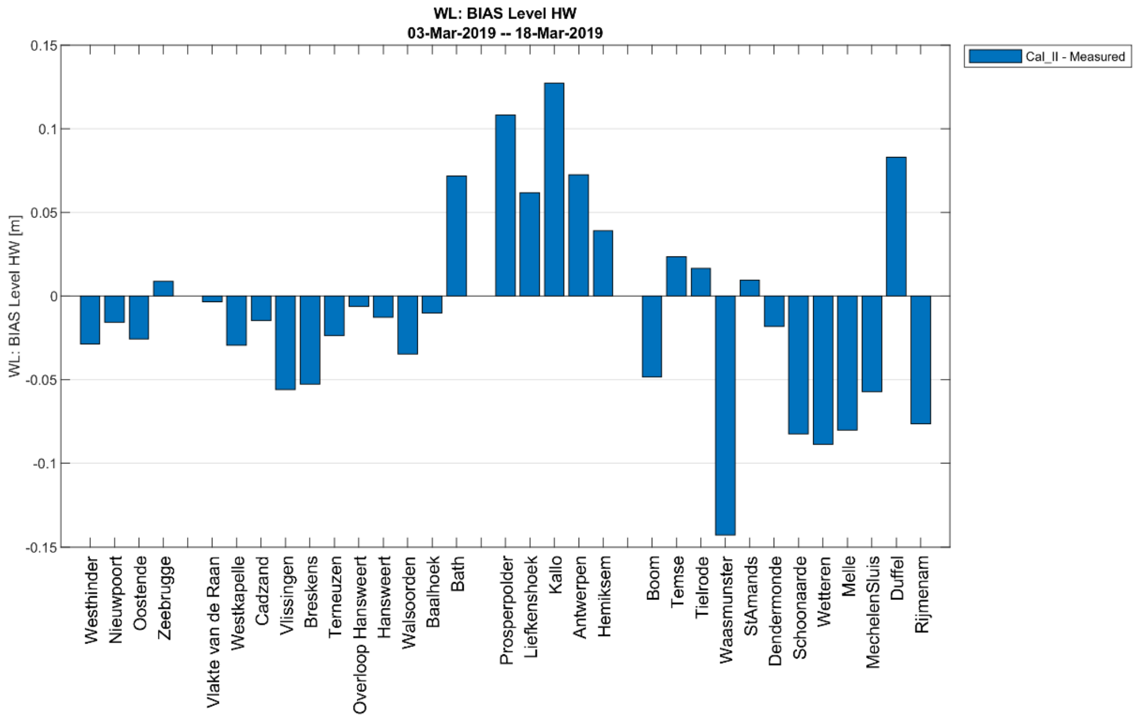


Figure 76 – RMSE of high water levels along the Scheldt for Calibration II.

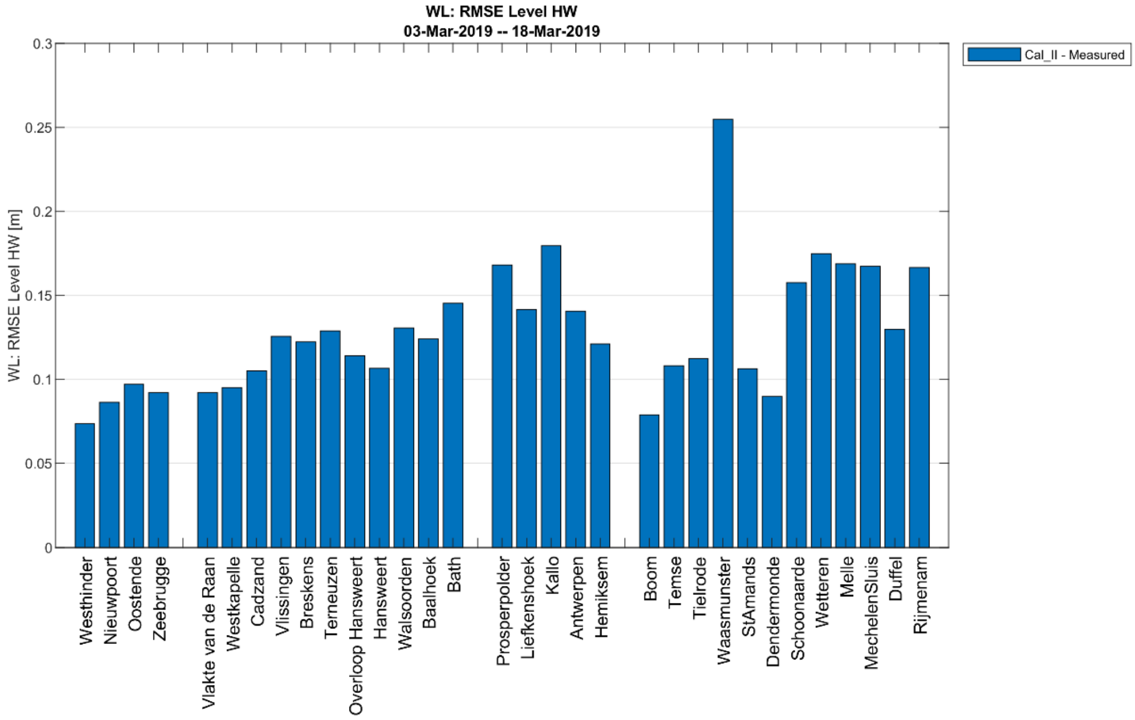


Figure 77 – RMSE0 of high water levels along the Scheldt for Calibration II.

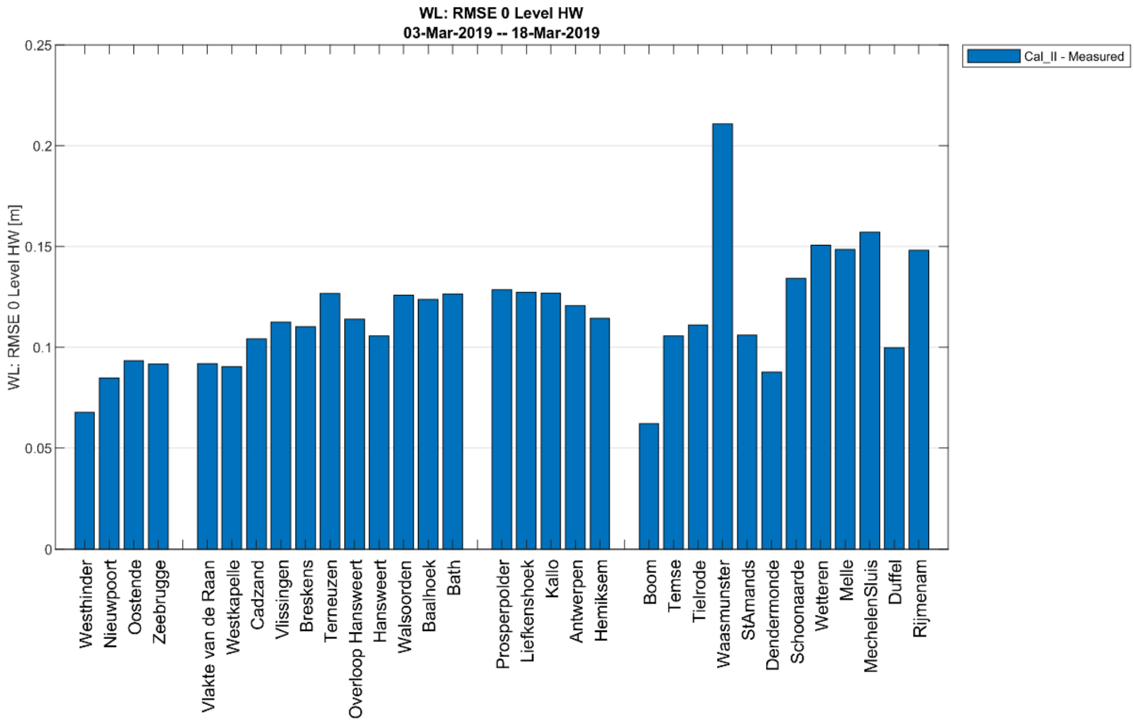


Figure 78 – Bias of low water levels along the Scheldt for Calibration II.

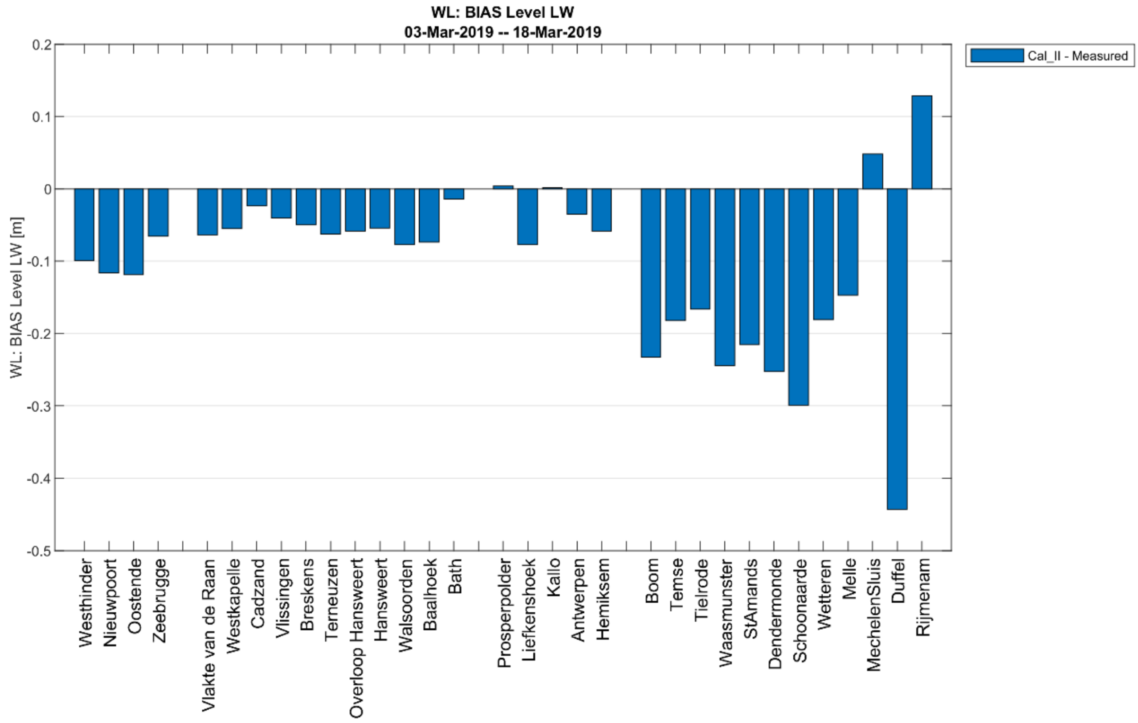


Figure 79 – RMSE of low water levels along the Scheldt for Calibration II.

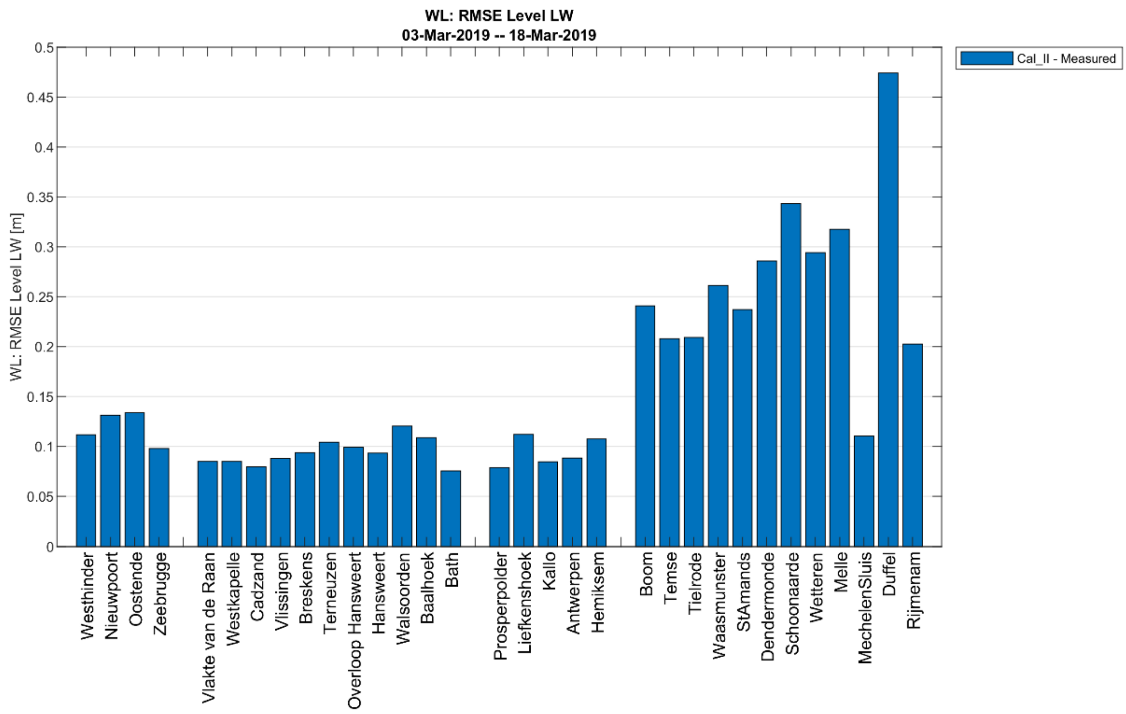


Figure 80 – RMSE0 of low water levels along the Scheldt for Calibration II.

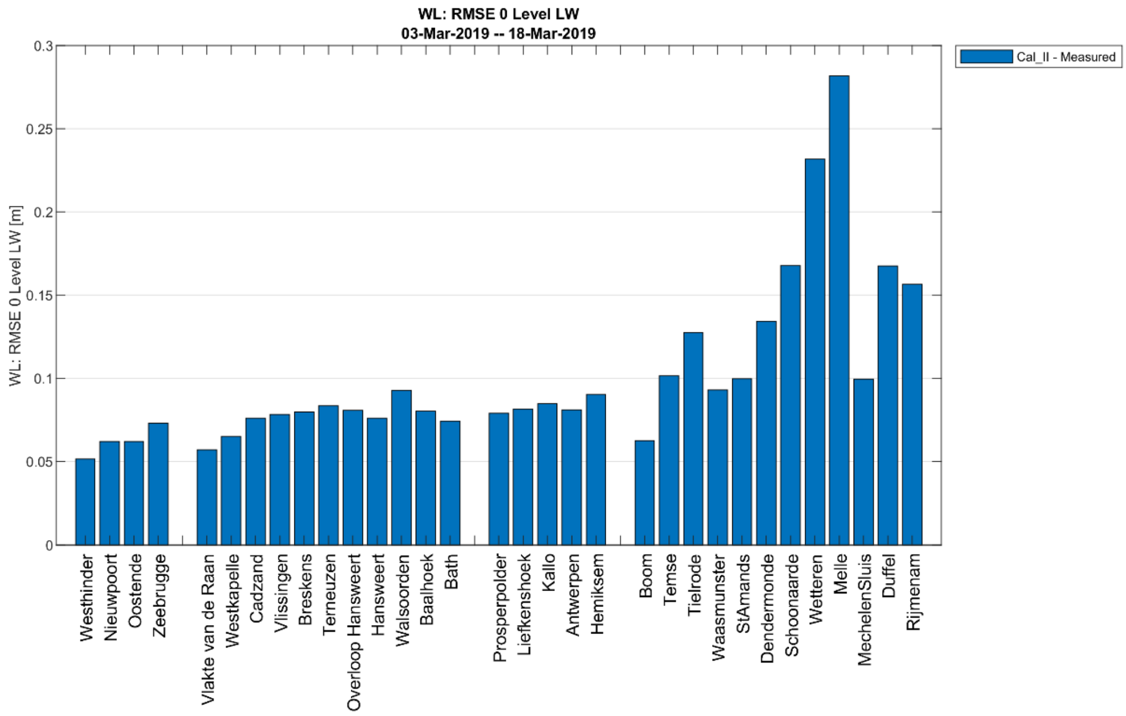
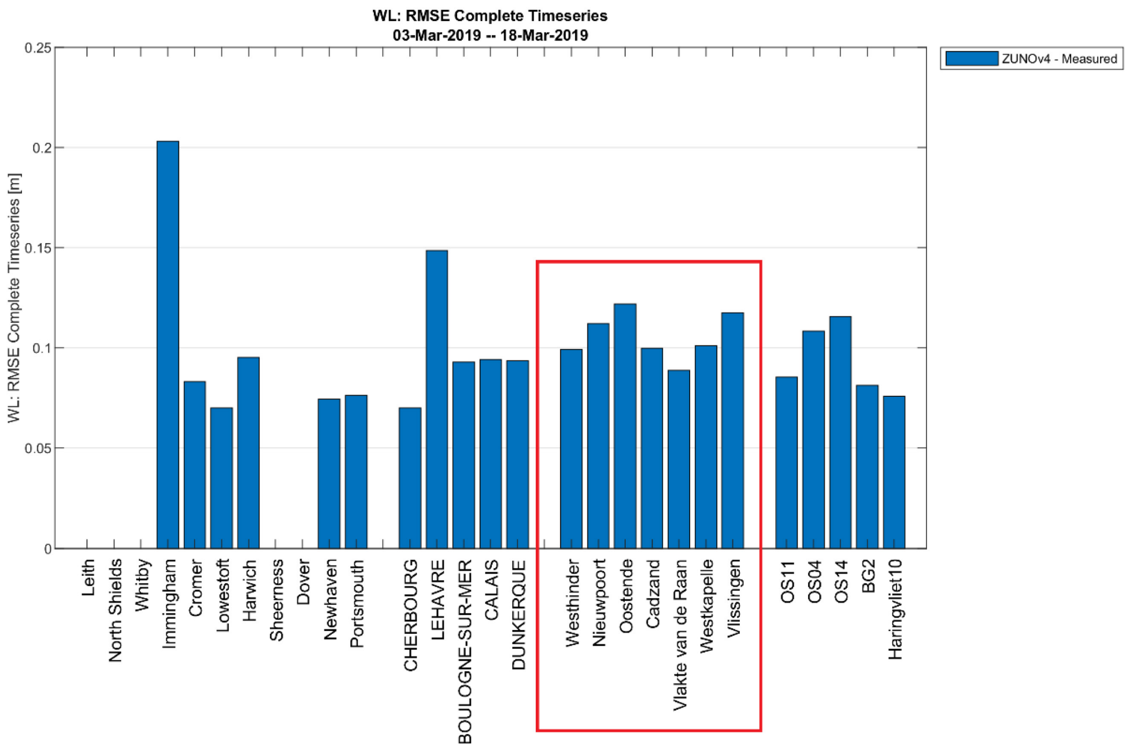


Figure 81 – RMSE of complete time series of water level from ZUNOv4 for Calibration II.



8.1.2 Harmonic analysis

Table 29 presents the comparison of M2, S2 tidal amplitude and phase and total vector difference (see definition in Annex 2) during calibration II. The statistical values are color-coded by the definition shown in Table 19. The corresponding plots are shown in Figure 82 to Figure 86.

The calibrated model in general produces decent results on harmonics for calibration period II. The average value of the absolute bias of M2 amplitude is relatively large of 5.4 cm in BCZ compared with calibration period I (1.5 cm). This error is mainly coming from the ZUNOv4 model via boundary nesting (see Figure 87). The average value of the absolute bias of M2 amplitude are 1.5 cm and 1.2 cm at WES and BeZS respectively. It is relatively larger at BoZS (6.3 cm) and Rupel basin and Durme (12.2 cm). The bias of M2 phase is insignificant except at Rupel basin and Durme (6.0 deg). Similar patterns are found for the S2 tidal component. The total vector difference gently increase from 21.0 cm at BCZ to 32.1 cm at BoZS and 57.9 cm at Rupel basin and Durme. There is still room for further improvement at BoZS, Rupel basin and Durme.

Table 29 – M2, S2 tidal component and vector difference for Calibration period II.

Zones	Stations	Bias: Model - Measurement				
		M2 Amplitude	**M2 Phase**	**S2 Amplitude**	**S2 Phase**	**Vector Difference**
BCZ	Westhinder	4.3	1.1	0.1	0.7	18.0
	Nieuwpoort	6.6	0.3	1.6	0.3	20.2
	Oostende	5.9	1.8	1.2	2.1	25.2
	Zeebrugge	4.6	2.0	0.3	2.9	20.7
	|Average|	**5.4**	**1.3**	**0.8**	**1.5**	**21.0**
WES	Vlakte van de Raan	4.2	1.9	-0.7	2.5	16.6
	Westkapelle	2.8	2.1	-0.9	3.1	21.2
	Cadzand	0.9	3.3	-1.9	4.3	20.9
	Vlissingen	0.4	3.0	-1.8	3.8	23.4
	Breskens	0.3	4.1	-1.7	5.0	26.6
	Terneuzen	2.0	2.0	-1.0	2.2	20.4
	Overloop Hansweert	1.7	3.1	-0.5	3.6	25.4
	Hansweert	1.8	3.0	-0.6	3.4	25.8
	Walsoorden	0.9	3.0	-0.8	3.4	28.7
	Baalhoek	0.7	3.0	-1.0	3.6	29.1
	Bath	0.6	3.2	-0.9	3.8	28.4
	|Average|	**1.5**	**2.9**	**1.1**	**3.5**	**24.2**
BeZS	Prosperpolder	1.3	2.5	-0.5	2.9	27.9
	Liefkenshoek	2.3	2.2	-0.2	2.7	25.2
	Kallo	1.4	2.4	-0.6	2.8	28.7
	Antwerpen	0.6	2.5	-0.6	2.7	24.5
	Hemiksem	0.4	3.3	-0.7	3.9	29.2
	|Average|	**1.2**	**2.6**	**0.5**	**3.0**	**27.1**
BoZS	Temse	5.4	2.1	0.9	2.9	28.4
	Tielrode	4.6	2.4	0.0	3.2	29.7
	StAmands	7.1	1.7	1.2	2.6	28.4
	Dendermonde	7.1	2.0	1.9	2.8	31.8
	Schoonaarde	10.3	0.8	3.2	1.0	37.0
	Wetteren	6.6	0.2	2.9	1.1	35.3
	Melle	3.0	-1.3	2.8	-0.2	34.3
	|Average|	**6.3**	**1.1**	**1.9**	**1.9**	**32.1**
Rupel basin and Durme	Boom	5.1	13.3	-2.9	17.5	77.2
	Waasmunster	1.6	5.2	2.5	7.3	46.0
	MechelenSluis	28.1	-0.5	12.1	-0.1	69.0
	Duffel	-14.0	-5.4	-9.9	-6.2	39.2
	Rijmenam	12.2	5.5	5.6	7.2	57.9
	|Average|	**12.2**	**6.0**	**6.6**	**7.7**	**57.9**
Overall		**4.7**	**2.8**	**2.0**	**3.5**	**31.4**

Figure 82 – M2 amplitude along the River Scheldt for Calibration period II.

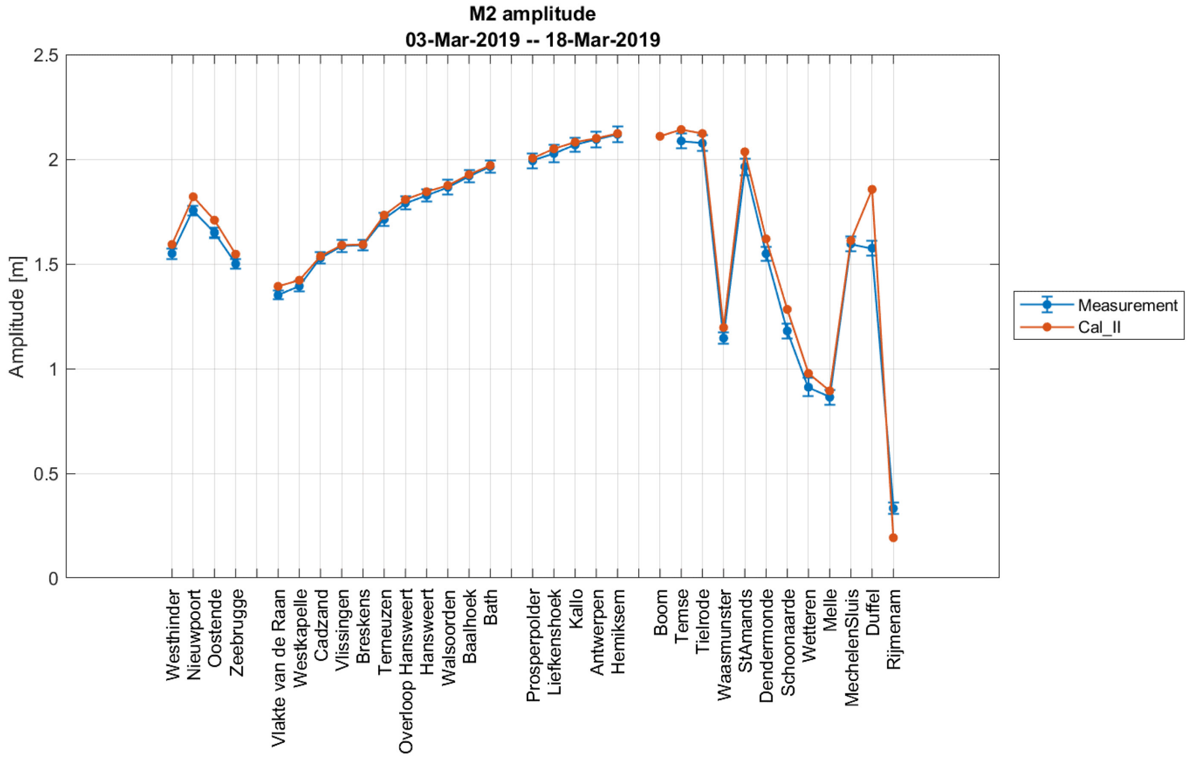


Figure 83 – M2 phase along the River Scheldt for Calibration period II.

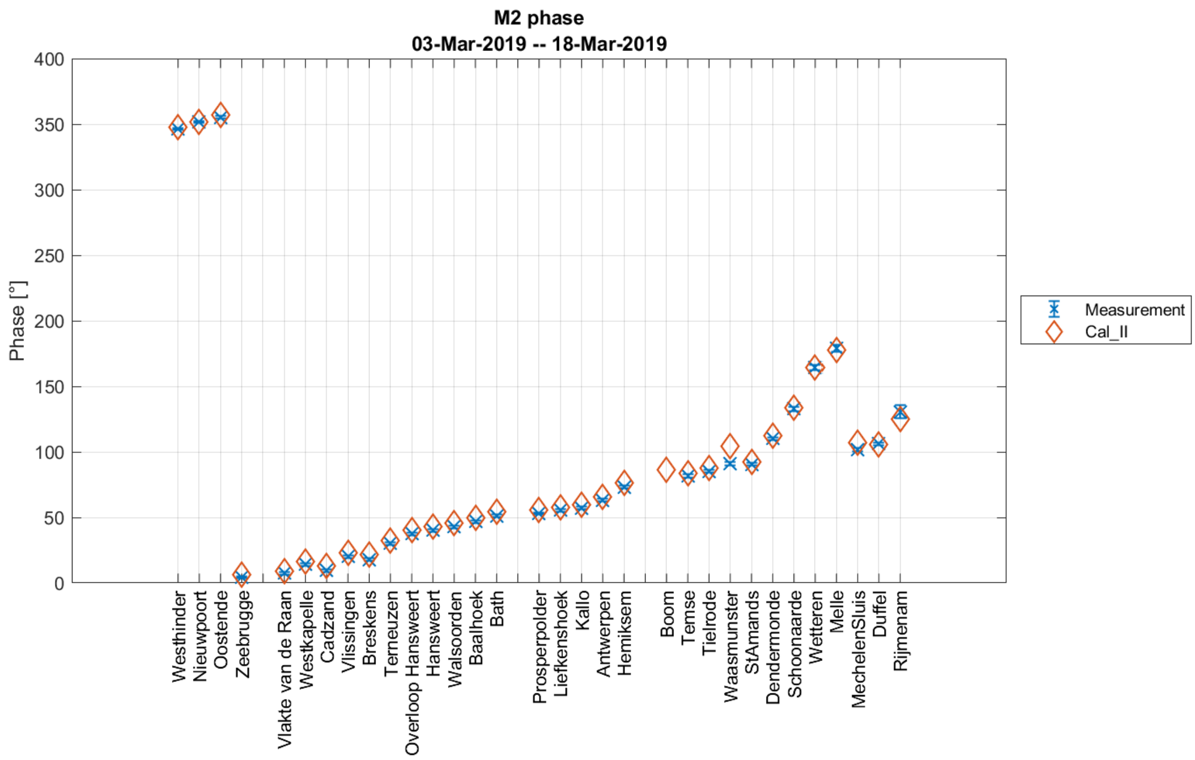


Figure 84 – S2 amplitude along the River Scheldt for Calibration period II.

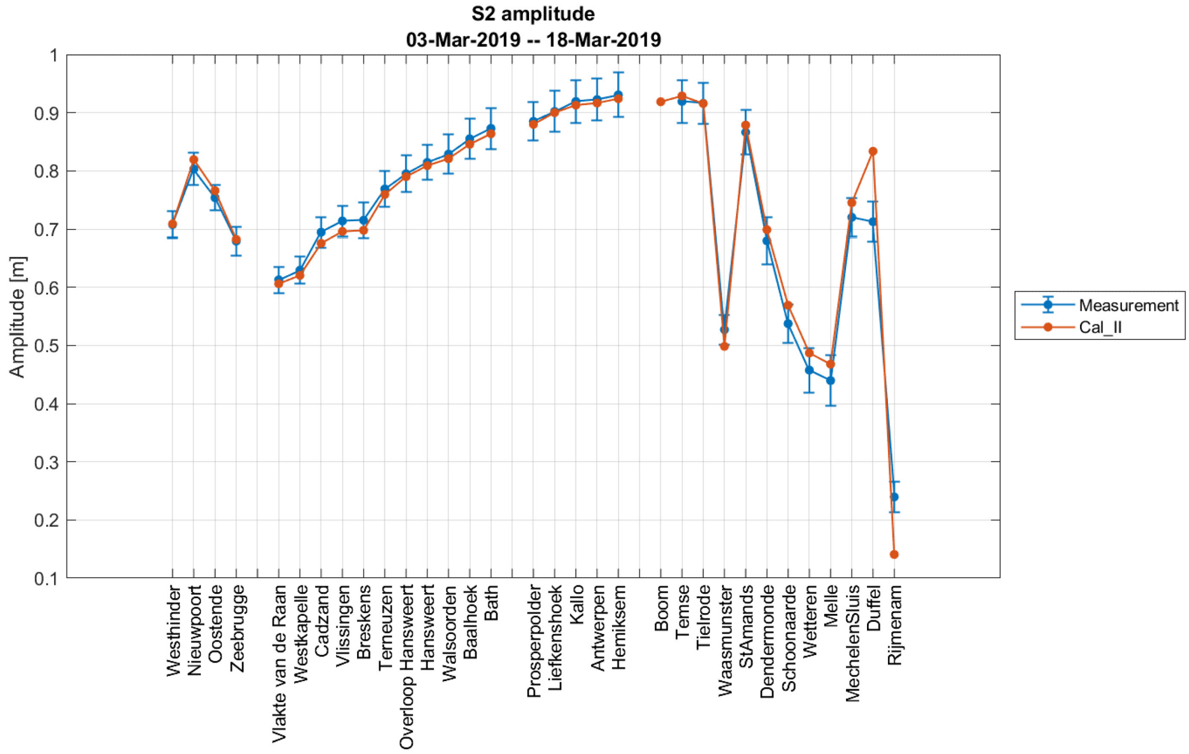


Figure 85 – S2 phase along the River Scheldt for Calibration period II.

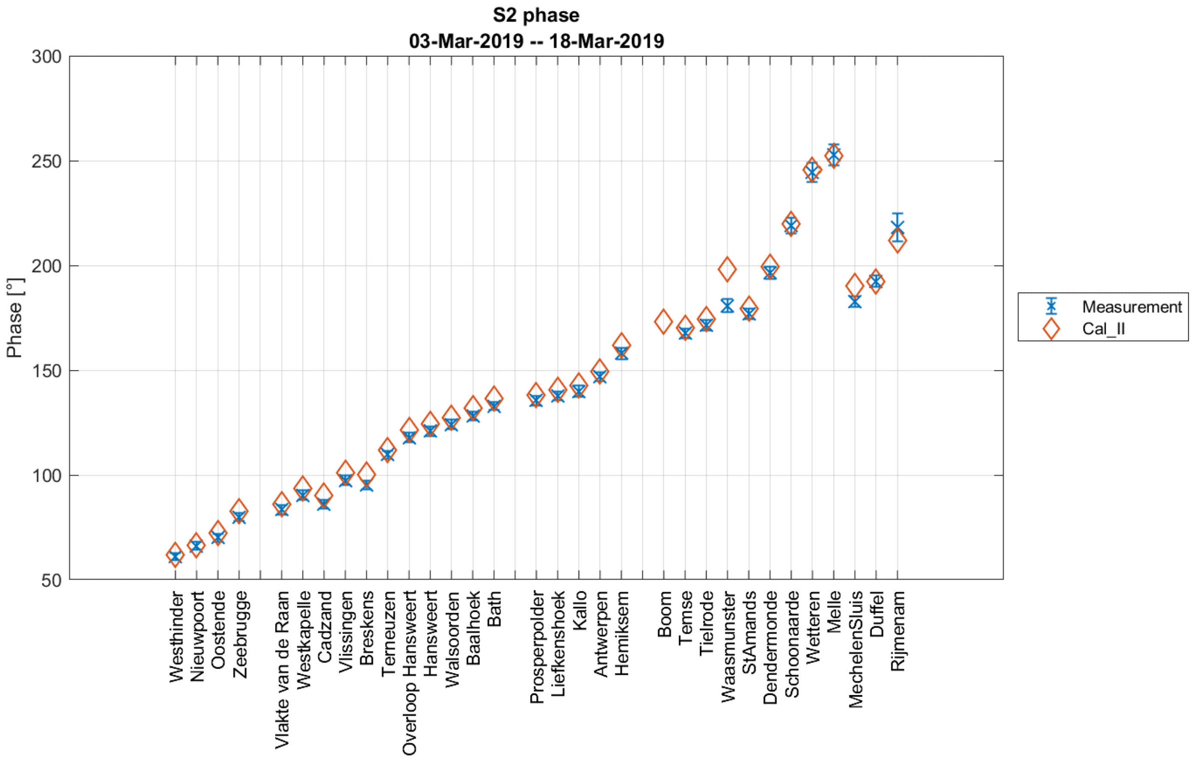


Figure 86 – Vector differences along the River Scheldt for Calibration period II.

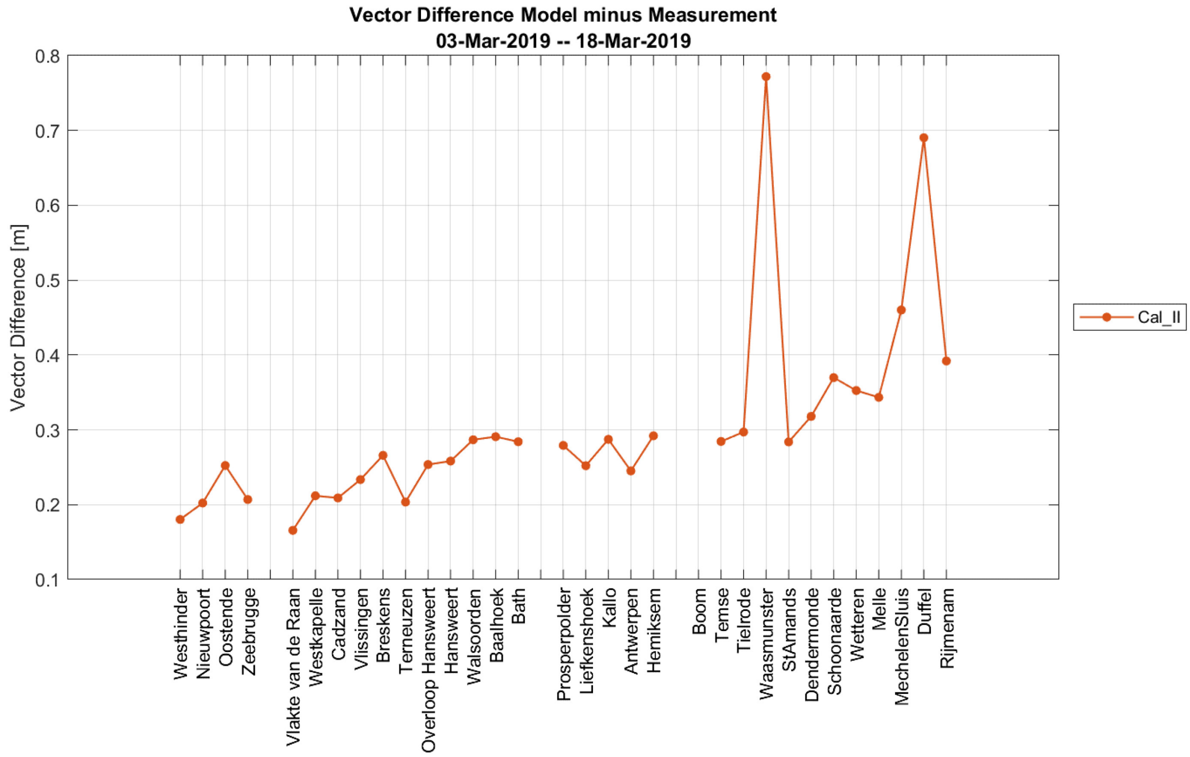
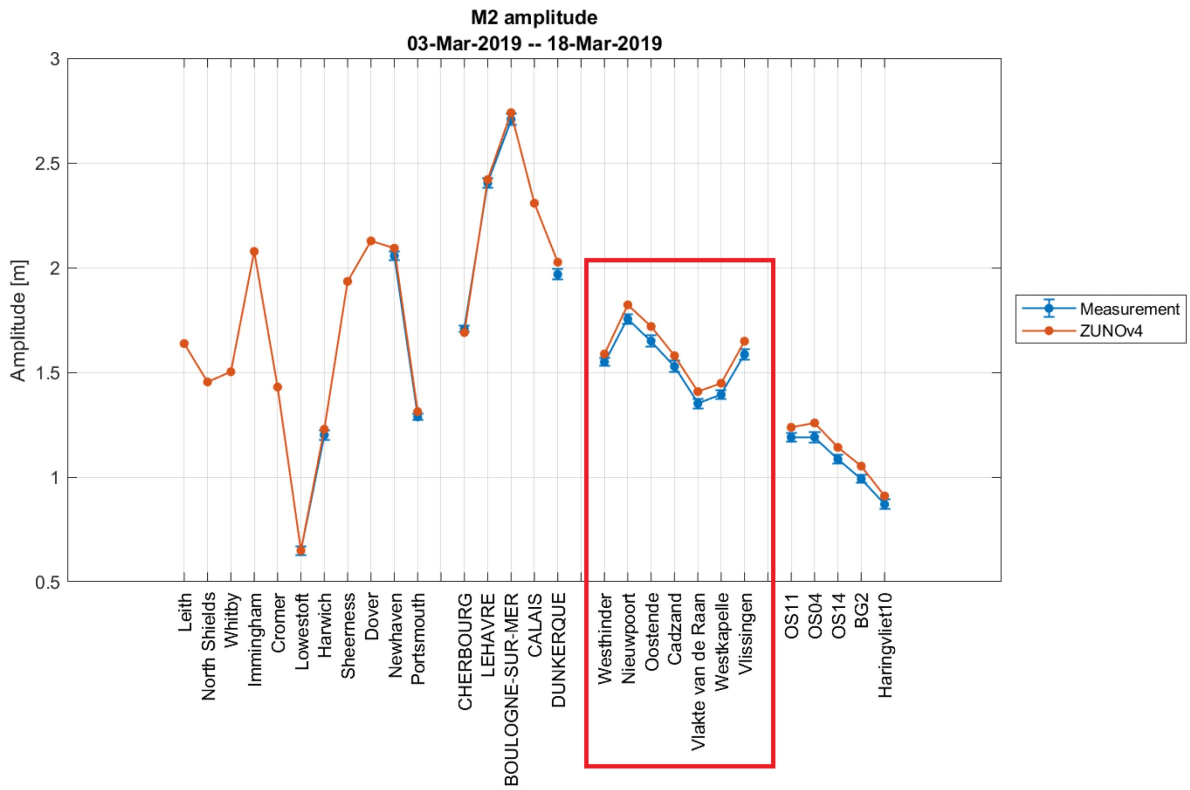


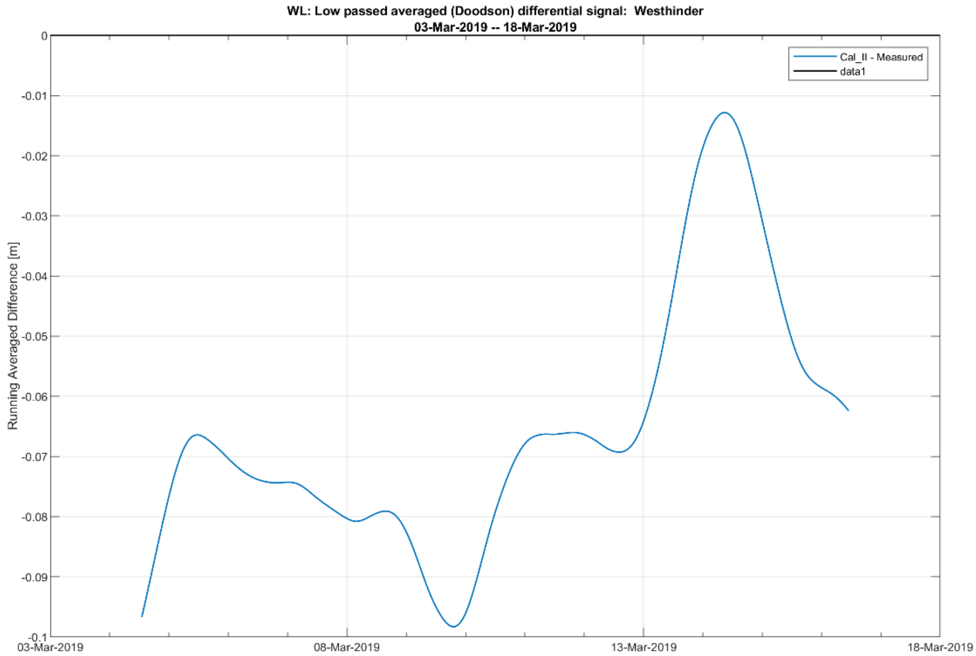
Figure 87 – M2 amplitude in the North Sea from ZUNOv4 for Calibration period II.



8.1.3 Surge error from the open boundary

The low-passed averaged; error signal is also evaluated for calibration period II (see context in § 7.1.2). Figure 88 presents the errors of surge signals (model minus measurement) at Westhinder. The errors of surge signals can go up to -10 cm. This could explain that the model performance in BCZ is slightly worse for calibration period II.

Figure 88 – Low-passed averaged differential signals at Westhinder for calibration period II.



8.2 Stationary Velocity in deep areas

Similar to calibration period I, the stationary velocities predicted by SCALDIS2019 are compared with the measurements at Bol van Hesit, Scheur Wielingen, Lillo and Oosterweel for calibration period II. Table 30 presents the statistical parameters which are used to to evaluate the model accuracy. Figure 89 to Figure 93 exemplify the time series plot of velocity magnitude and direction at each station respectively.

The model is capable of capturing periodic variation of tidal currents in general. However the model performance is slightly worse compared with calibration period I. For instance at Scheur Wielingenn the RMSE of velocity magnitude is 12.2 cm/s which is slightly higher than calibration period I (8.9 cm/s). Similar to calibration period I, the velocity magnitude at Bol Van Heist is visibly underestimated by the model and SCALDIS model leads to larger error statistics at Lillo and Oosterweel.

Table 30 – Statistics of stationary velocity in deep area for Calibration II.

Location	Magnitude		Direction
	BIAS TS [cm/s]	RMSE TS [cm/s]	RMSE TS [°]
Bol van Hesit	- 0.8	12.4	32
Scheur Wielingen	- 0.8	12.2	20
Lillo top	10.8	25.4	37
Lillo bottom	6.8	16.8	26
Oosterweel top	0.2	12.2	26

Figure 89 – Comparison of velocity magnitude and direction at Bol van Heist for Calibration II.

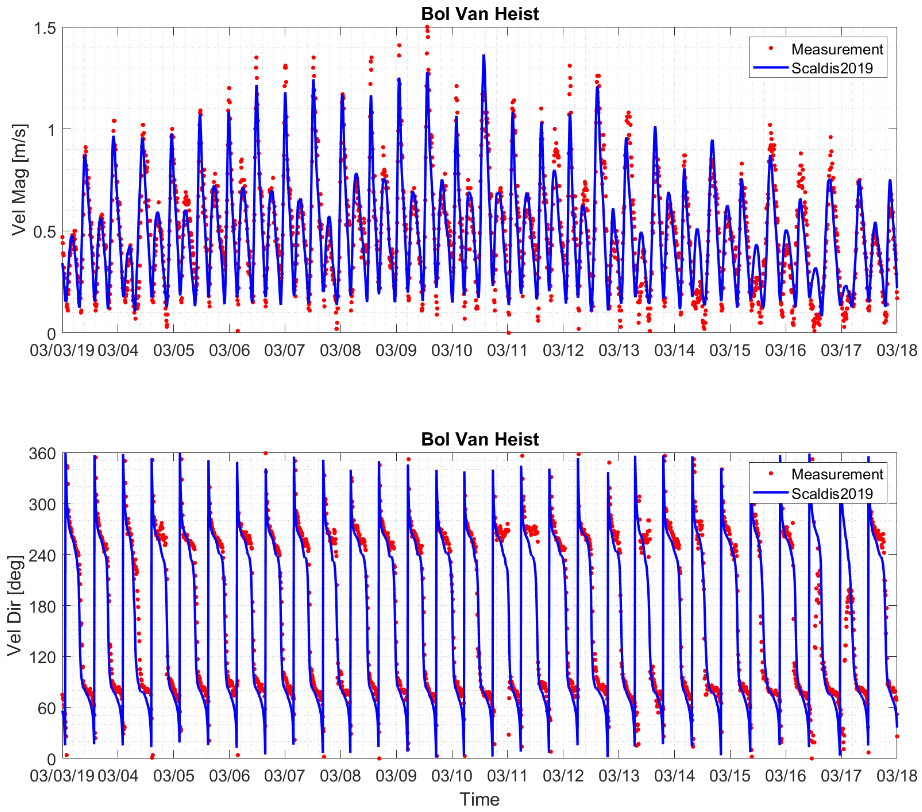


Figure 90 – Comparison of velocity magnitude and direction at Scheur Wielingen for Calibration II.

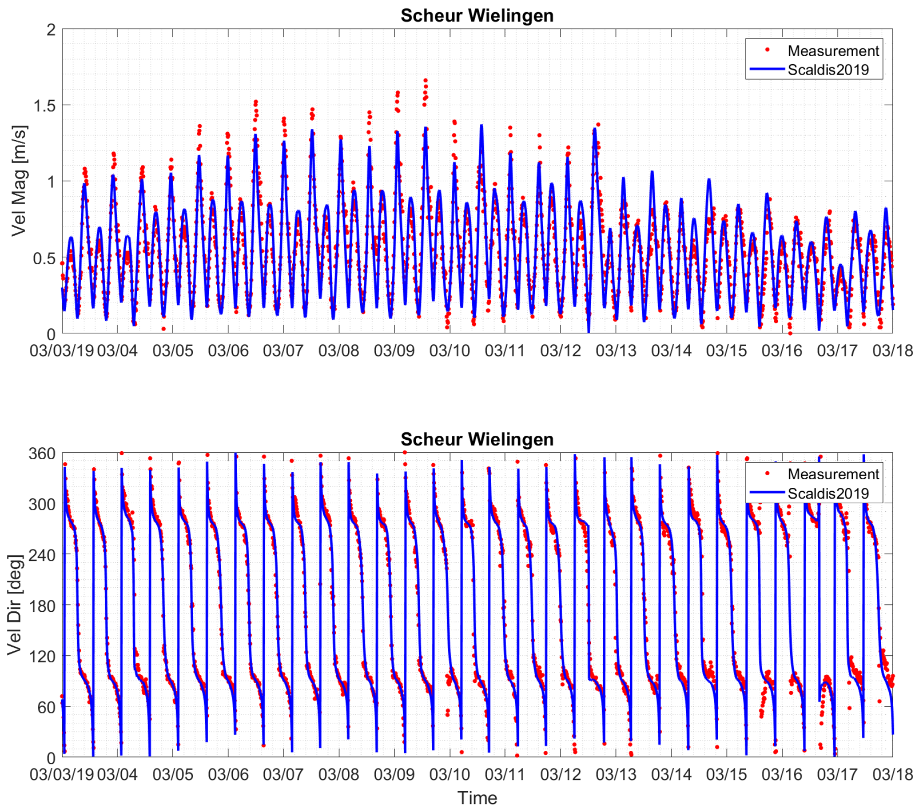


Figure 91 – Comparison of velocity magnitude and direction at Lillo top for Calibration II.

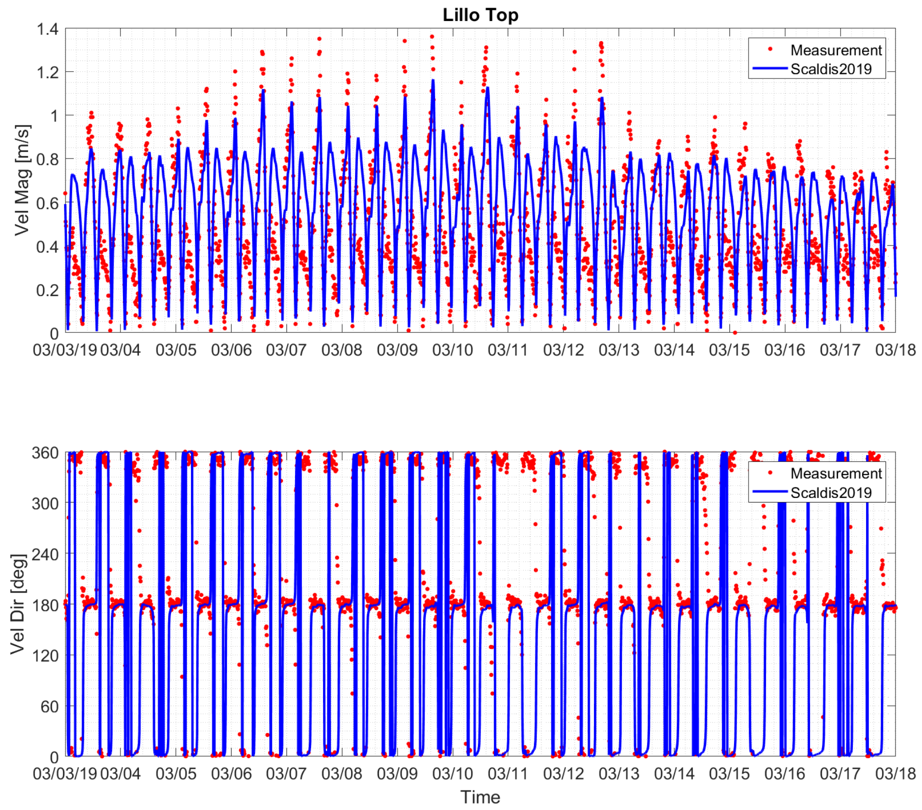


Figure 92 – Comparison of velocity magnitude and direction at Lillo bottom for Calibration II.

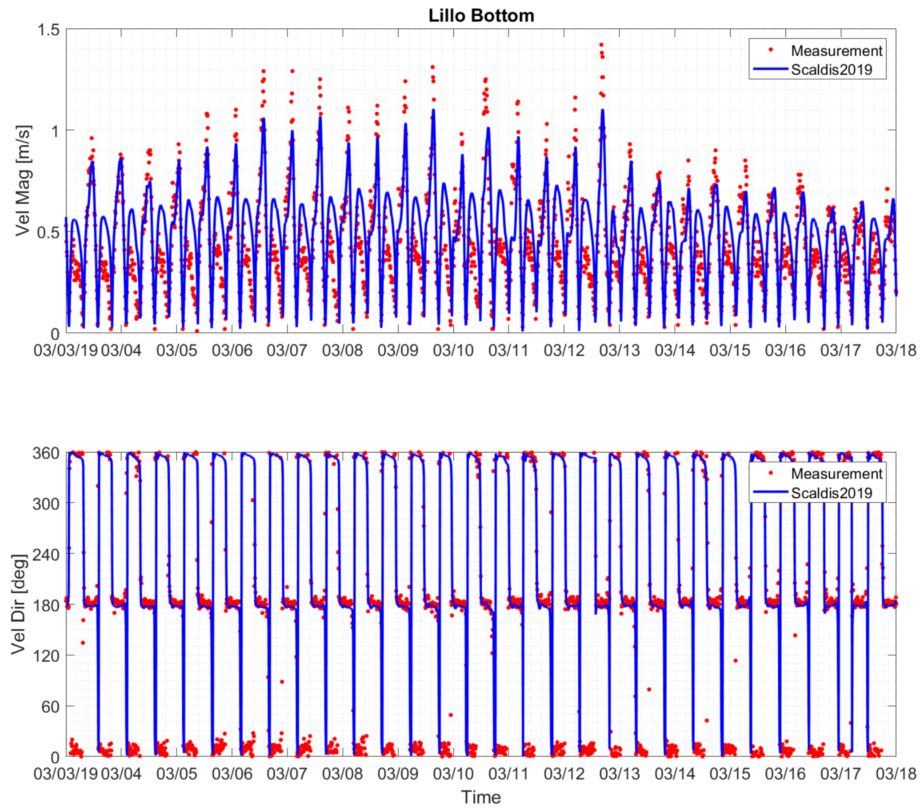
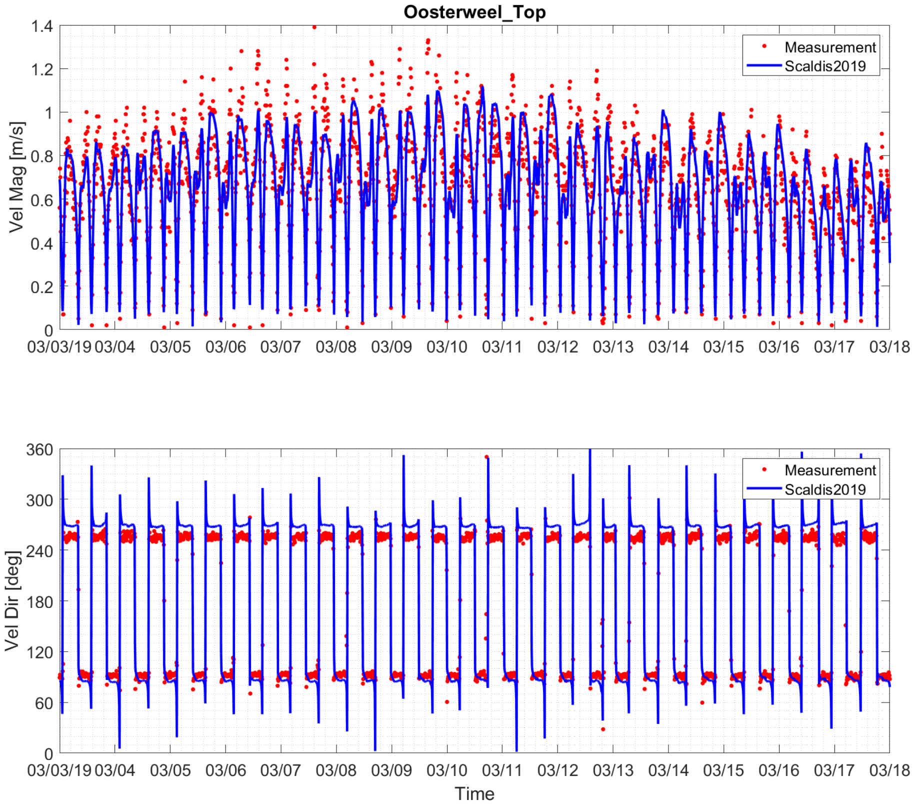


Figure 93 – Comparison of velocity magnitude and direction at Oosterweel top for Calibration II.



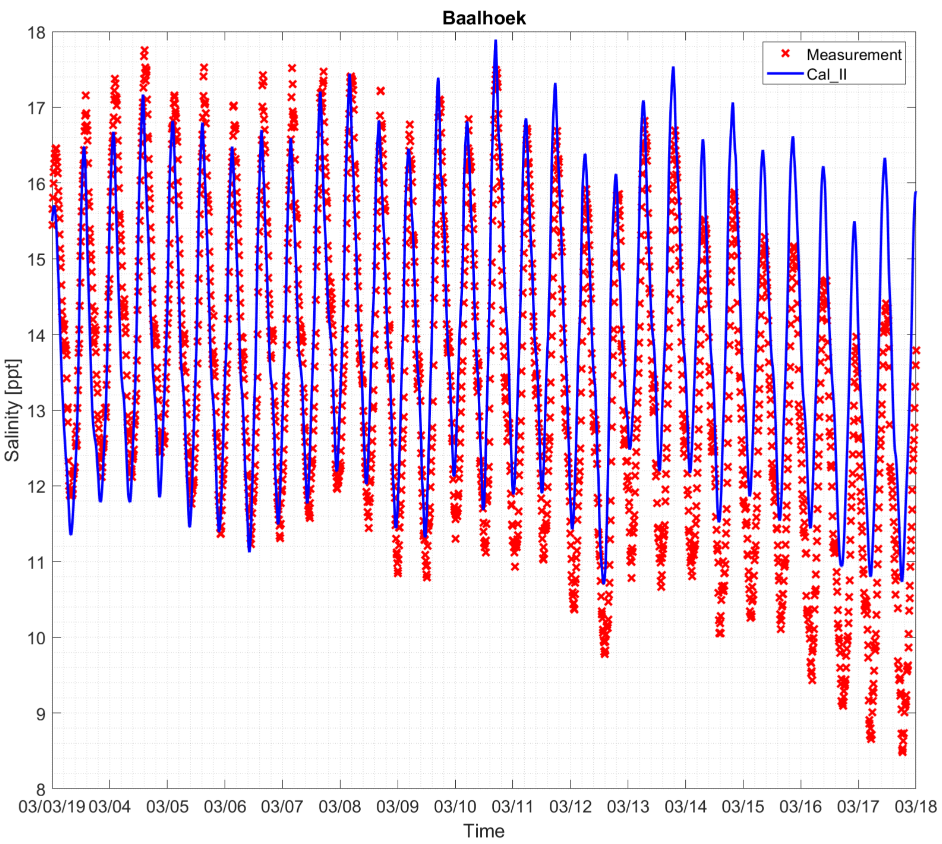
8.3 Salinity

Figure 94 exemplifies the comparison of the modelled and measured salinity time series at Baalhoek. The comparison at other station are presented in Annex 5. The statistical analysis results are presented in Table 31. Salinity is in general well reproduced by SCALDIS along the estuary. But the maximum difference between model and measurement are slightly larger (e.g. 3.2 psu at Overloop Hansweert) compared with calibration period I (0.8 psu). This could be resulted from the slightly worse predictions on hydrodynamics for calibration period II.

Table 31 – Statistical analysis of salinity for Calibration II.

Nr	Measuring station	Correlation Coefficient	RMSE	Model minus Measurement	
		R [-]	[psu]	Max [psu]	Min [psu]
1	Overloop Hansweert	0.7	1.0	3.2	-3.5
2	Baalhoek	0.9	1.2	3.0	-1.7
3	Prosperpolder	0.8	1.0	3.1	-1.5
4	LilloMeetpaal	0.8	1.0	2.3	-2.1
5	Oosterweel	0.9	1.0	2.1	-2.3
6	Kruibeke	0.8	0.5	1.5	-1.8
7	Hemiksem	0.7	0.3	1.0	-1.2

Figure 94 – Comparison of salinity between measurement and SCALDIS at Baalhoek for Calibration II.



9 Validation results

The calibrated model also runs for a stormy period between **03/03 – 17/03/2019** (§4.3.1) as validation. As described in §4.6, the functionality of culvert is switched on for this period as well. The full set of output figures and statistic tables for validation can be found under:

p:\PA016-Ondrhd2D3Dmdl\3_Uitvoering\Scaldis_2019_addendum_to _report\Validation_122019\

9.1 Water Level

9.1.1 Time series of water level

Table 32 presents the statistics of Bias, RMSE and RMSE0 (see definitions in ANNEX1) of the complete time series, high water levels and low water levels respectively. The statistical values are color-coded by the definition shown in Table 17. The statistical results are also illustrated in Figure 95 to Figure 103.

The model in general produces decent results for the validation period. The model performance is similar to that from the calibration period II and it is slightly worse than calibration period I. The average value of the absolute bias of water level is around 4.7 cm at BCP, 2.4 cm at WES and 2.9 cm at BeZS. It is relatively larger at BoZS (8.5 cm) and at Rupel basin and Durme (11.2 cm).

The RMSE of water level at BCZ is 11.8 cm which is larger than that from the calibration period I (6.9 cm). The larger error is mainly coming from the ZUNOv4 model through boundary nesting (Figure 104). The RMSE of water level gradually increase to 19.9 cm in BoZS. This is similar to the calibration period II. There is still room for further improvement at Rupel basin and Durme (RMSE of 26.7 cm) where the local roughness is not yet optimized during the calibration of SCALDIS2019 as discussed in the previous chapter.

Table 32 – Bias, RMSE and RMSE0 of water level for Validation.

Zones	Stations	Complete TimeSeries			High Water Level			Low Water Level		
		BIAS [cm]	RMSE	RMSE0	BIAS [cm]	RMSE	RMSE0	BIAS [cm]	RMSE	RMSE0
BCP	Westhinder	-5.7	10.2	8.5	0.2	7.4	7.4	-9.0	11.9	7.8
	Nieuwpoort	-4.6	12.3	11.4	0.9	7.6	7.6	-12.5	17.0	11.4
	Oostende	-6.1	13.1	11.6	-1.7	7.9	7.7	-12.5	17.2	11.8
	Zeebrugge	-2.5	11.4	11.2	1.2	4.8	4.7	-6.0	13.9	12.6
	|Average|	**4.7**	**11.8**	**10.7**	**1.0**	**6.9**	**6.8**	**10.0**	**15.0**	**10.9**
WES	Vlakte van de Raan	0.7	10.5	10.5	0.5	6.8	6.8	-3.9	10.6	9.8
	Westkapelle	-3.6	10.7	10.1	-3.1	8.2	7.6	-3.8	10.6	9.9
	Cadzand	0.4	12.8	12.8	-0.5	6.4	6.3	-1.2	12.5	12.4
	Vlissingen	-1.6	11.9	11.7	-3.9	9.3	8.5	-3.8	12.9	12.3
	Breskens	-0.8	14.1	14.1	-3.0	12.0	11.6	-5.8	14.7	13.6
	Terneuzen	-4.5	12.6	11.8	-4.2	10.4	9.5	-9.2	16.3	13.5
	Overloop Hansweert	-2.0	13.3	13.2	-1.1	9.4	9.4	-7.0	14.3	12.5
	Hansweert	-2.3	13.1	12.9	-0.4	9.4	9.3	-6.0	13.4	12.0
	Walsoorden	-4.0	14.3	13.7	-3.7	9.9	9.2	-4.1	20.1	19.7
	Baalhoek	-4.3	14.0	13.3	-1.7	8.4	8.3	-8.4	14.9	12.3
	Bath	2.7	14.3	14.1	9.5	13.2	9.2	-3.0	12.2	11.8
	|Average|	**2.4**	**12.9**	**12.6**	**2.9**	**9.4**	**8.7**	**5.1**	**13.9**	**12.7**
ZES	Prosperpolder	4.3	14.1	13.4	10.4	13.7	9.0	-2.6	12.2	11.9
	Liefkenshoek	2.7	14.2	14.0	12.9	15.5	8.6	-6.0	12.7	11.2
	Kallo	5.6	15.5	14.4	15.9	17.8	7.9	-2.4	11.3	11.0
	Antwerpen	0.5	14.8	14.8	8.9	11.7	7.5	-6.5	12.1	10.3
	Hemiksem	1.7	17.2	17.1	5.4	12.1	10.8	-7.6	12.8	10.3
	|Average|	**2.9**	**15.2**	**14.7**	**10.7**	**14.2**	**8.8**	**5.0**	**12.2**	**10.9**
BOZ	Temse	-2.9	16.7	16.4	4.4	13.4	12.6	-19.2	21.8	10.3
	Tielrode	-1.8	17.1	17.0	4.2	14.3	13.7	-16.8	19.9	10.7
	StAmands	-9.2	19.0	16.6	-0.9	13.8	13.7	-27.8	29.1	8.5
	Dendermonde	-8.8	18.1	15.8	-0.6	14.9	14.9	-24.5	26.2	9.1
	Schoonaarde	-12.6	20.6	16.4	-4.4	21.2	20.7	-27.9	29.8	10.5
	Wetteren	-12.1	22.5	19.0	-5.5	22.2	21.5	-17.9	25.7	18.4
	Melle	-12.1	25.0	21.9	-4.5	21.0	20.5	-15.8	28.0	23.2
	|Average|	**8.5**	**19.9**	**17.6**	**3.5**	**17.3**	**16.8**	**21.4**	**25.8**	**13.0**
Rupel basin and Durme	Boom	-4.7	18.2	17.6	-1.9	12.5	12.4	-24.9	27.1	10.6
	Waasmunster	-18.2	34.2	28.9	-7.2	22.3	21.1	-35.1	36.3	9.3
	MechelenSluis	-0.8	19.3	19.3	-6.3	11.7	9.8	-3.6	10.7	10.1
	Duffel	-18.5	34.1	28.7	10.9	18.0	14.4	-47.6	53.5	24.5
	Rijmenam	13.5	27.7	24.2	-2.1	11.5	11.3	27.2	29.6	11.7
	|Average|	**11.2**	**26.7**	**23.7**	**5.7**	**15.2**	**13.8**	**27.7**	**31.4**	**13.2**
Overall		**5.6**	**16.9**	**15.6**	**4.5**	**12.5**	**11.0**	**12.9**	**19.2**	**12.3**

Figure 95 – Bias of complete time series of water levels along the Scheldt for Validation.

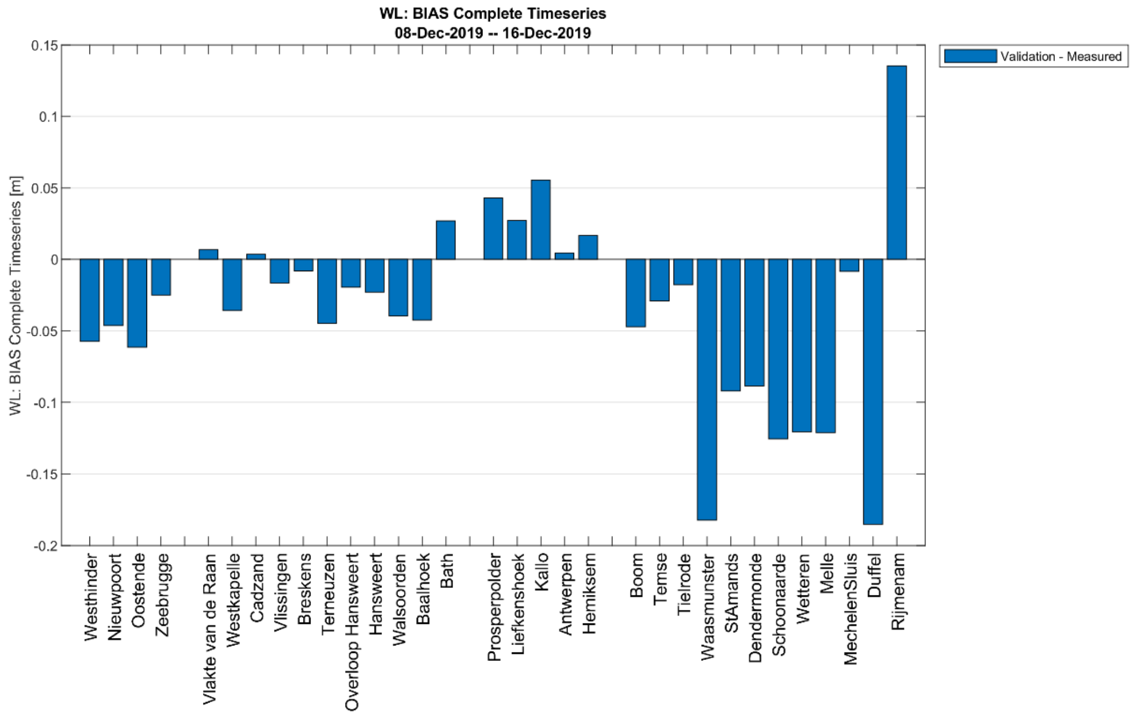


Figure 96 – RMSE of complete time series of water levels along the Scheldt for Validation.

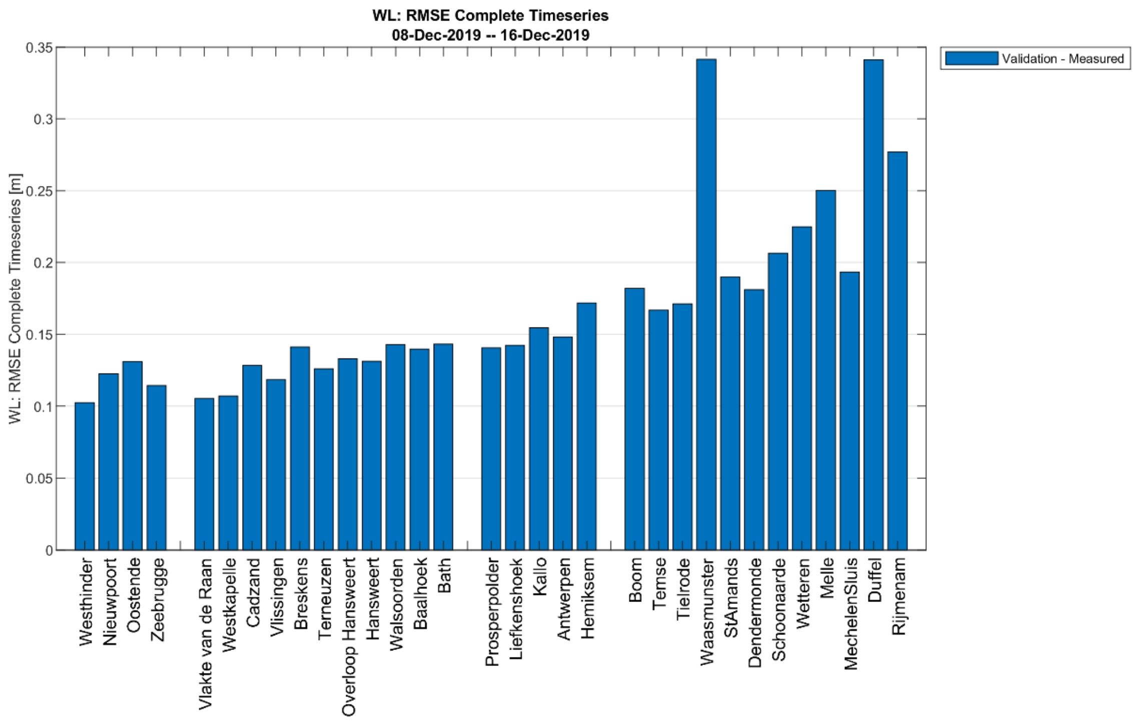


Figure 97 – RMSE0 of complete time series of water levels along the Scheldt for Validation.

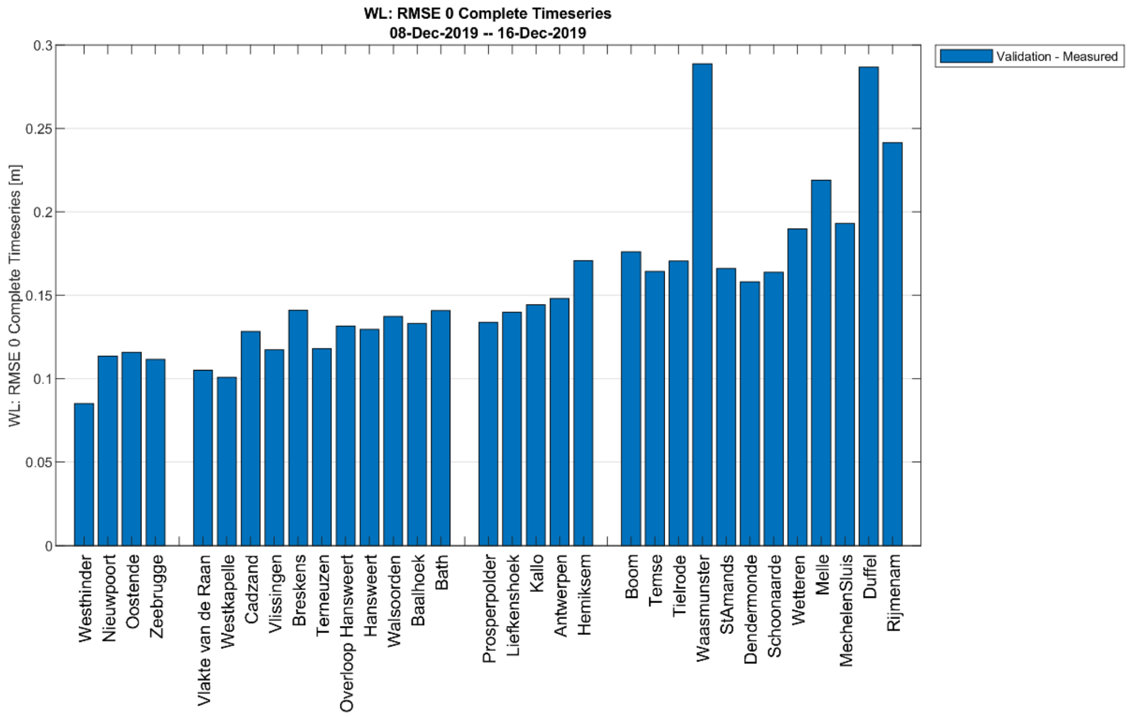


Figure 98 – Bias of high water levels along the Scheldt for Validation.

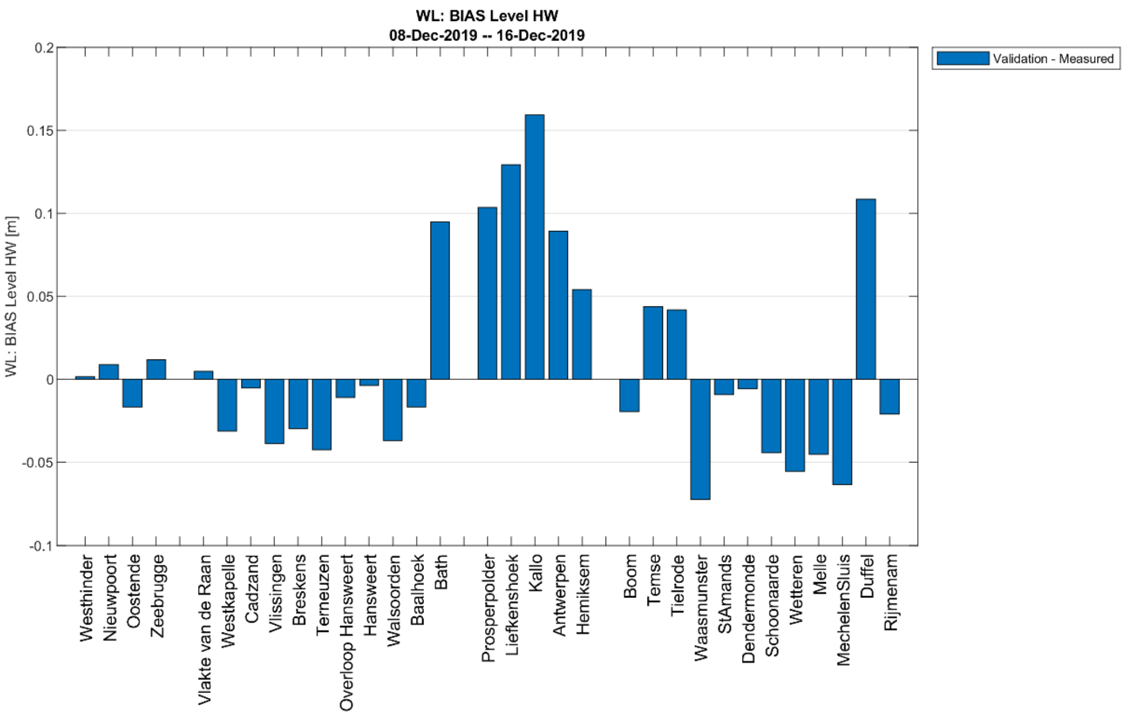


Figure 99 – RMSE of high water levels along the Scheldt for Validation.

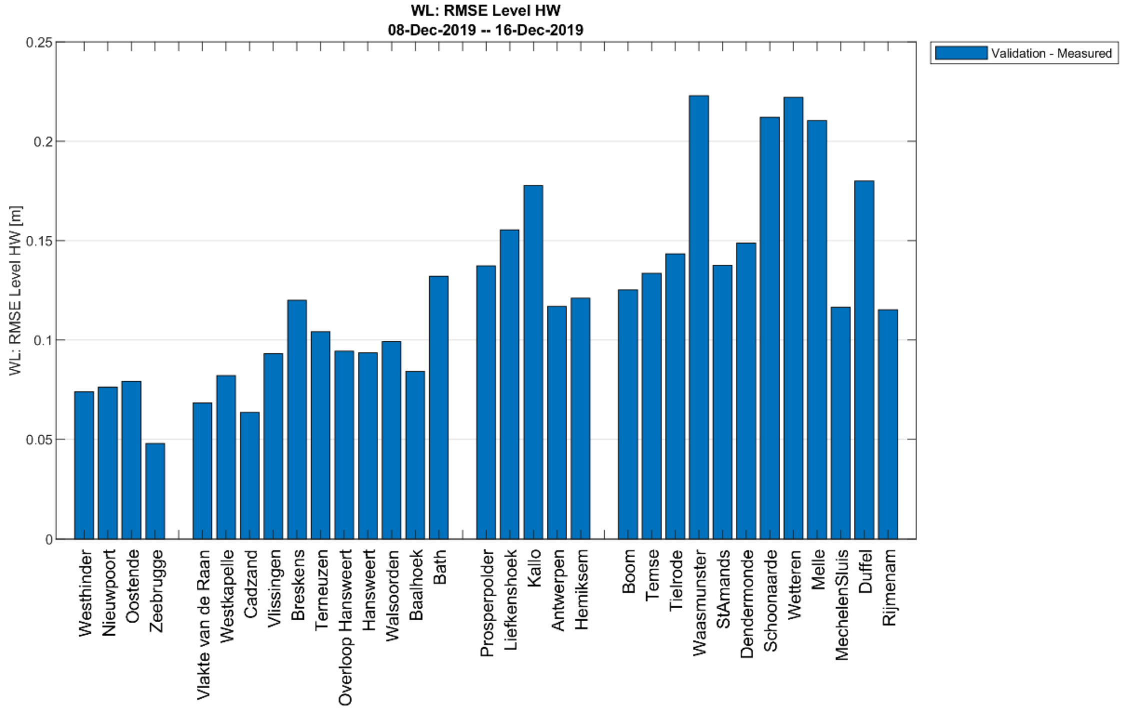


Figure 100 – RMSE0 of high water levels along the Scheldt for Validation.

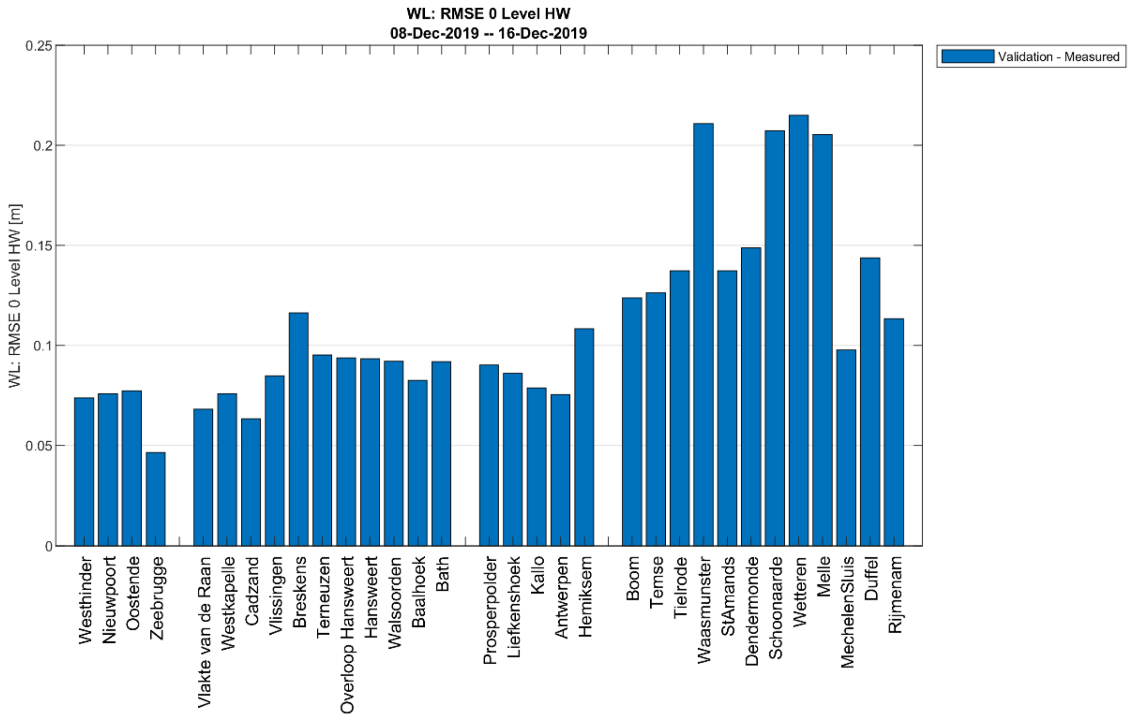


Figure 101 – Bias of low water levels along the Scheldt for Validation.

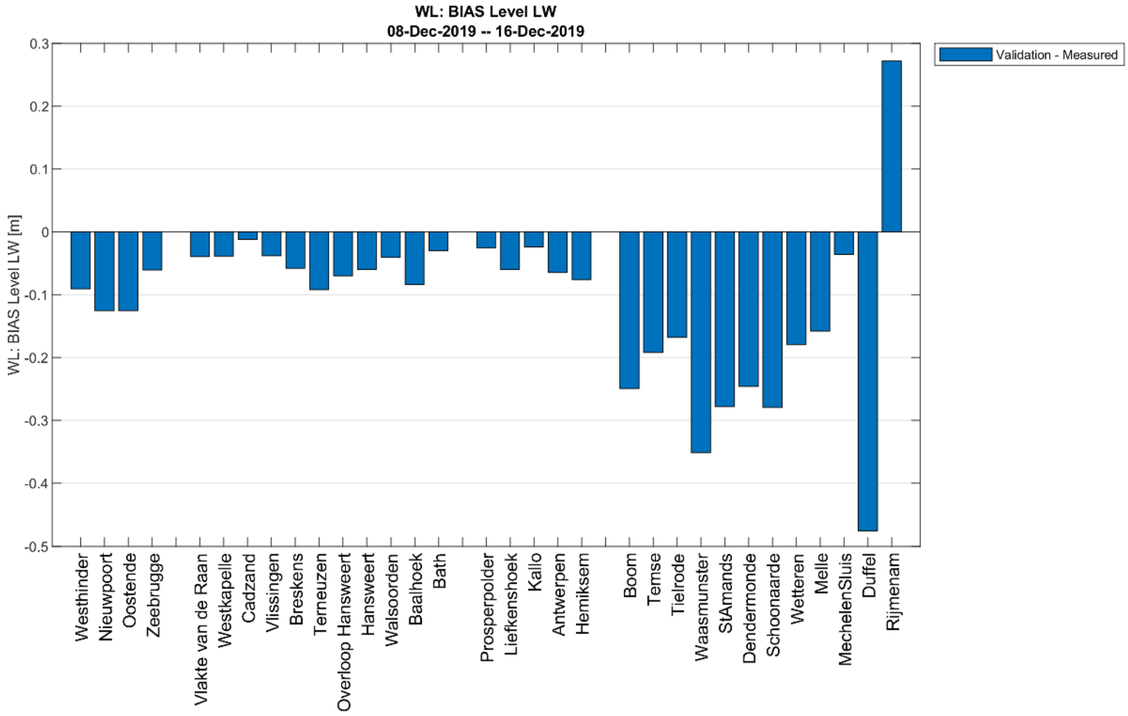


Figure 102 – RMSE of low water levels along the Scheldt for Validation.

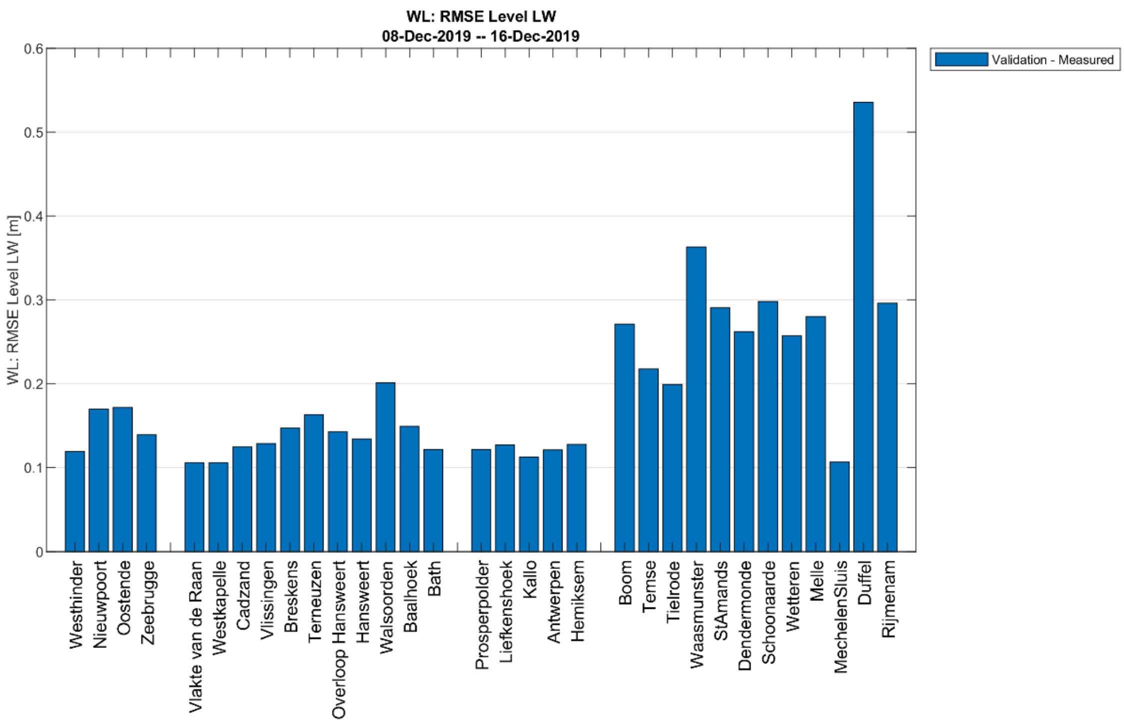


Figure 103 – RMSE0 of low water levels along the Scheldt for Validation.

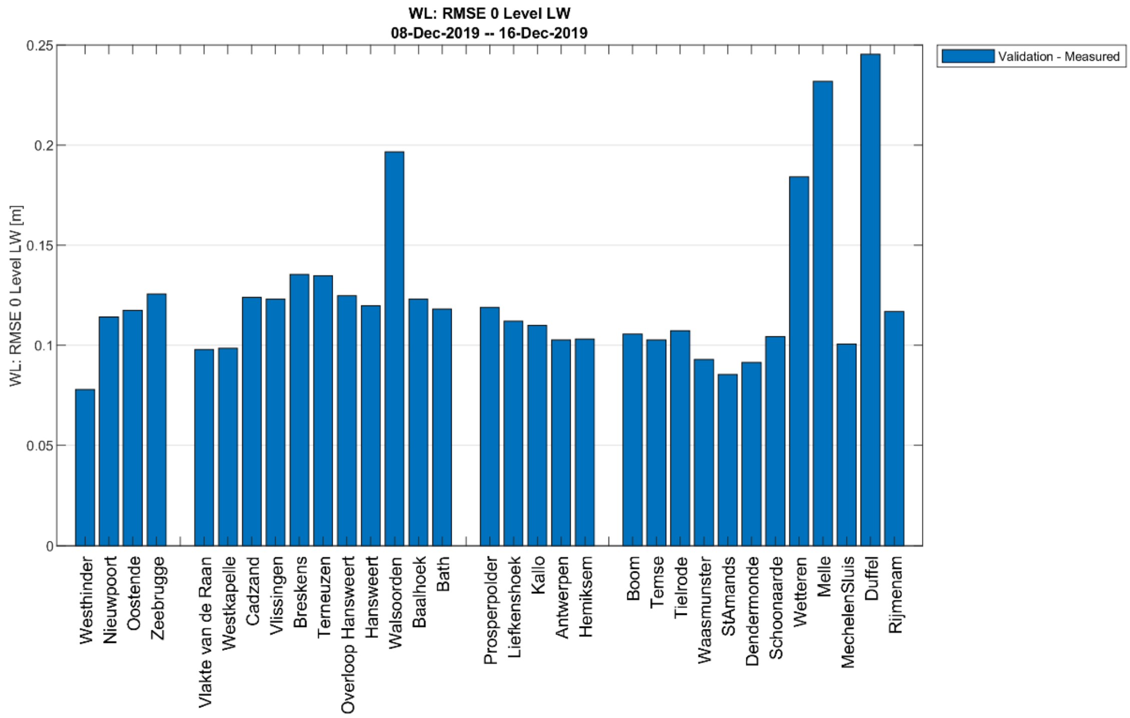
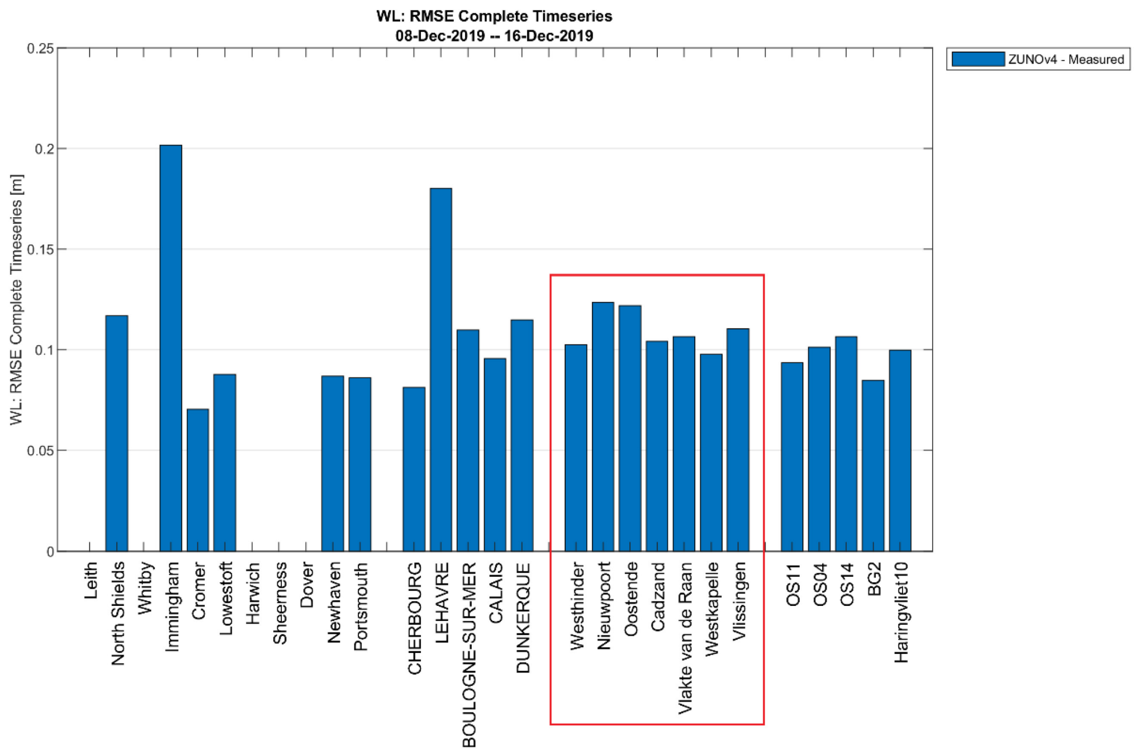


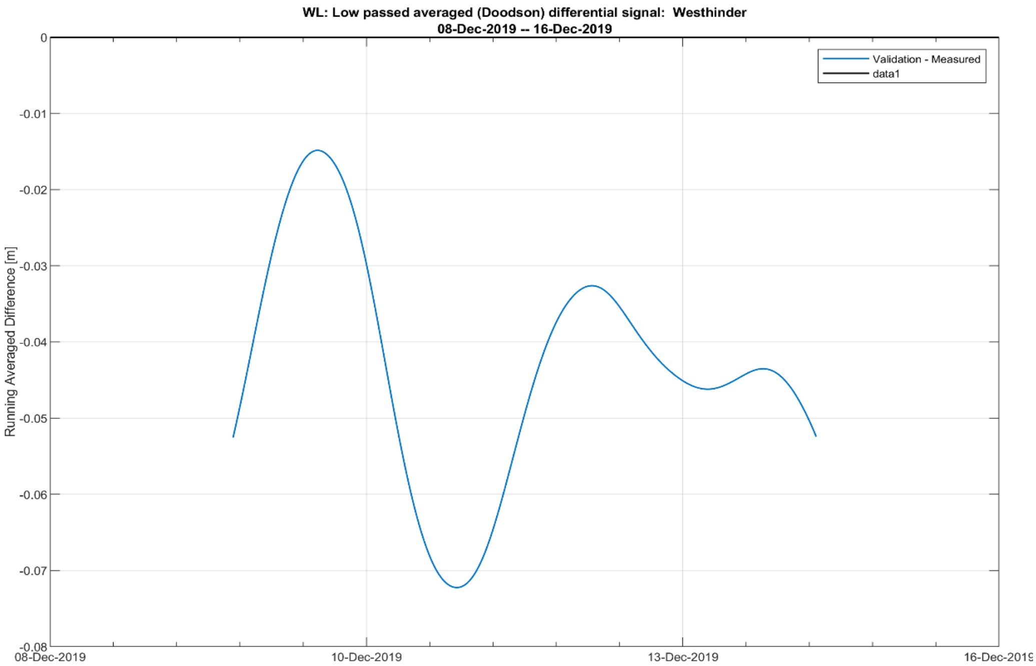
Figure 104 – RMSE of complete time series of water level from ZUNOv4 for Validation.



9.1.2 Surge error from the open boundary

The low-passed averaged error signal is also evaluated for validation (see context in § 7.1.2). Figure 105 presents the errors of surge signals (model minus measurement) at Westhinder. The errors of surge signals go up to -7 cm. This could explain the model performance in BCZ is slightly worse for the validation period.

Figure 105 – Low-passed averaged differential signals at Westhinder for validation.



9.2 Stationary Velocity in deep areas

The stationary velocities predicted by SCALDIS2019 are compared with the measurements at Bol van Heist, Scheur Wielingen, Lillo and Oosterweel for validation. Table 33 presents the statistical parameters which are used to to evaluate the model accuracy. Figure 106 to Figure 110 exemplify the time series plot of velocity magnitude and direction at each station respectively.

The model performance is similar to calibration period II, but slightly worse compared with calibration period I. For instance at Scheur Wielingenn the RMSE of velocity magnitude is 11.9 cm/s (similar to calibration period II of 12.2 cm/s) which is slightly higher than calibration period I (8.9 cm/s). Similar to calibration period I, the velocity magnitude at Bol Van Heist is visibly underestimated by the model and SCALDIS model leads to larger error statistics at Lillo and Oosterweel.

Table 33 – Statistics of stationary velocity in deep area for Validation.

Location	Magnitude		Direction
	BIAS TS [cm/s]	RMSE TS [cm/s]	RMSE TS [°]
Bol van Heist	-2.3	11.7	27
Scheur Wielingen	-1.4	11.9	13
Lillo top	12.3	23.8	38
Lillo bottom	7.5	15.8	25
Oosterweel top	-1	12.5	25

Figure 106 – Comparison of velocity magnitude and direction at Bol van Heist for Validation.

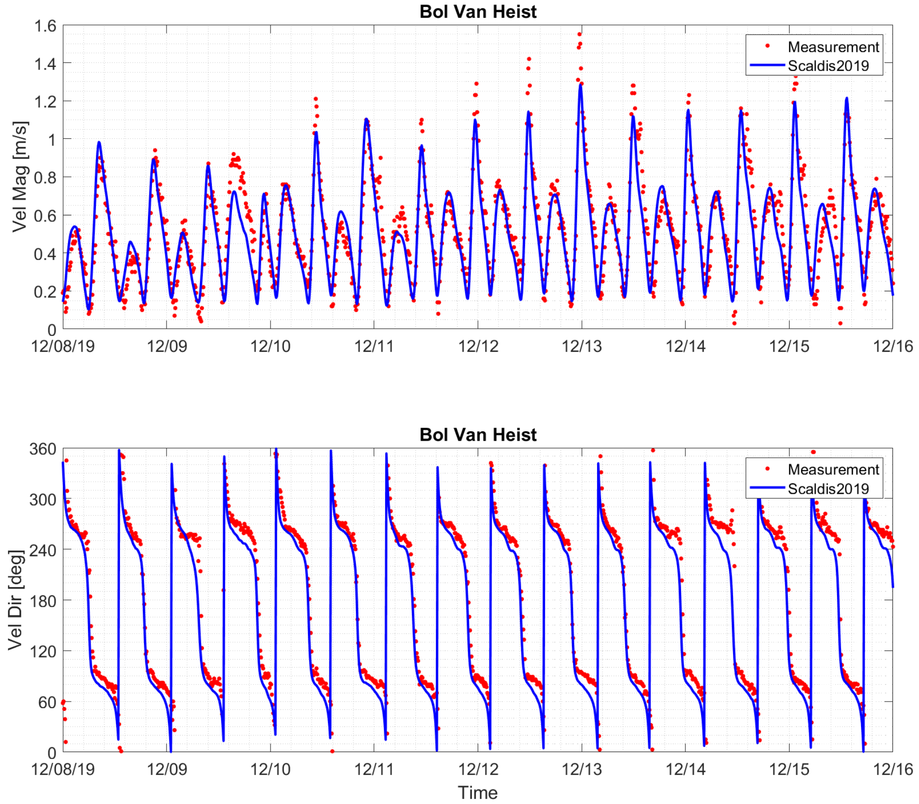


Figure 107 – Comparison of velocity magnitude and direction at Scheur Wielingen for Validation.

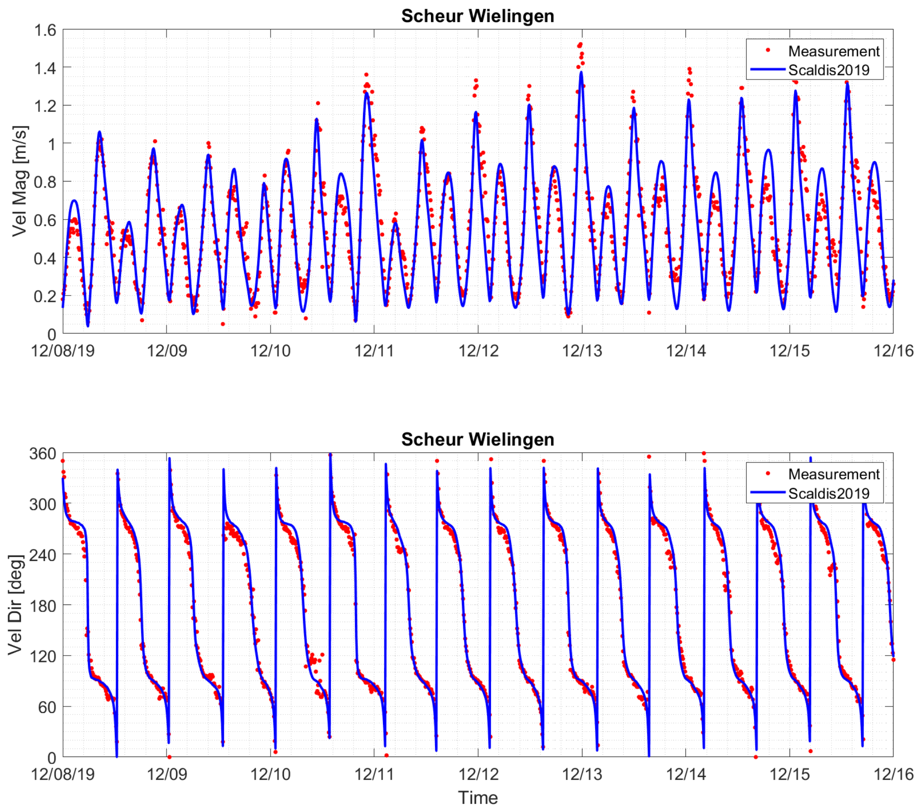


Figure 108 – Comparison of velocity magnitude and direction at Lillo top for Validation.

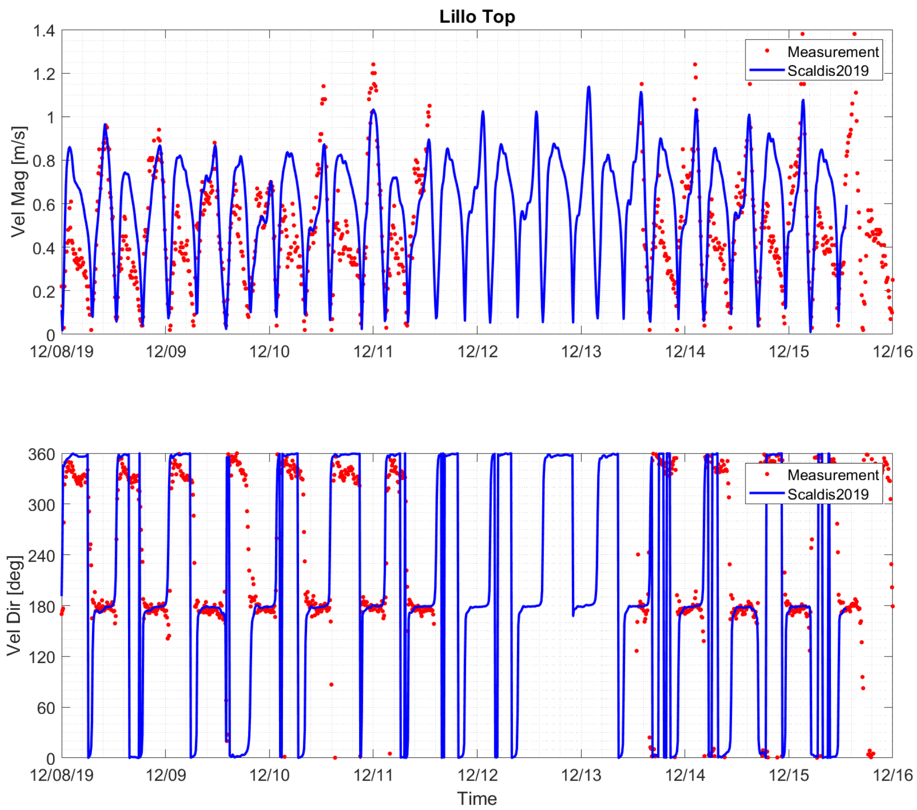


Figure 109 – Comparison of velocity magnitude and direction at Lillo bottom for Validation.

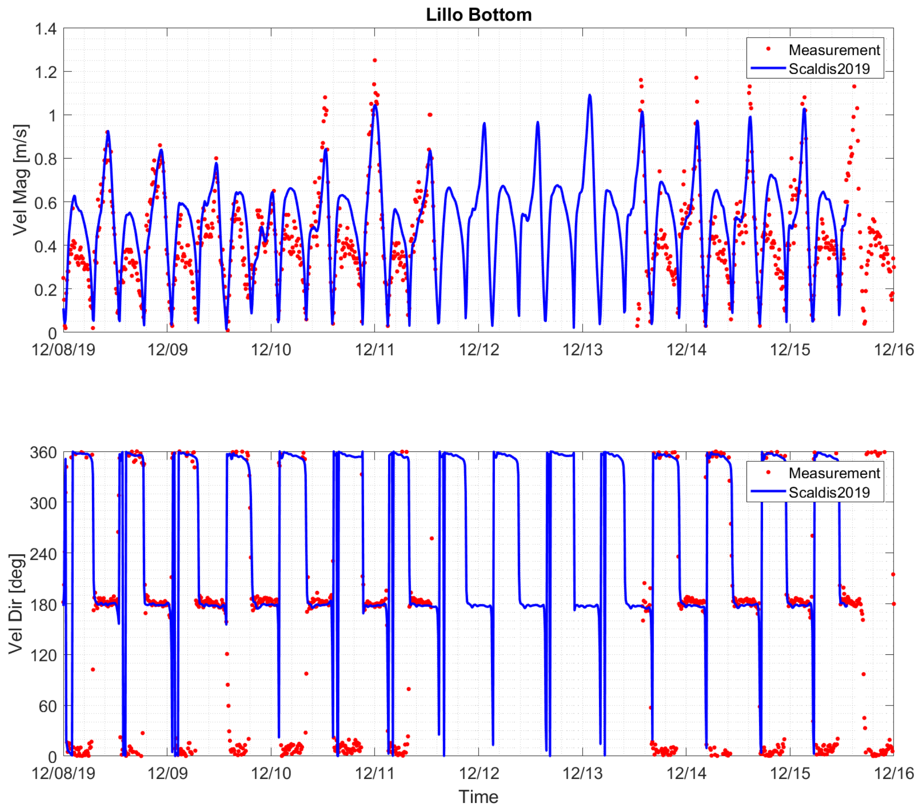
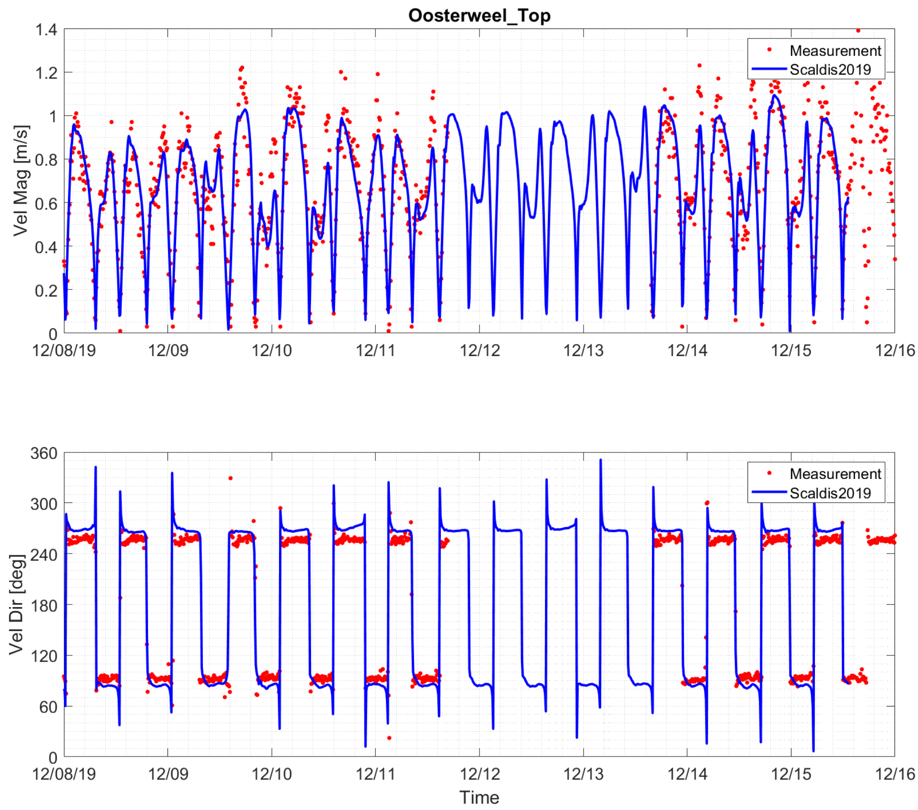


Figure 110 – Comparison of velocity magnitude and direction at Oosterweel top for Validation.



9.3 Salinity

Figure 111 exemplifies the comparison of the modelled and measured salinity time series at Baalhoek. The salinity is generally well captured by the model at Baalboek. The comparison at other station are presented in Annex 5. The statistical analysis results are presented in Table 34. The model predicted salinity is slightly worse at BeZS compared with calibration period I and II. For instance, the maximum discrepancy between model and measurement at LilloMeetpaal is more than 8 psu. There is no clear explanation at the moment. This requires detailed evaluation for future studies.

Figure 111 – Comparison of salinity between measurement and SCALDIS at Baalhoek for Validation.

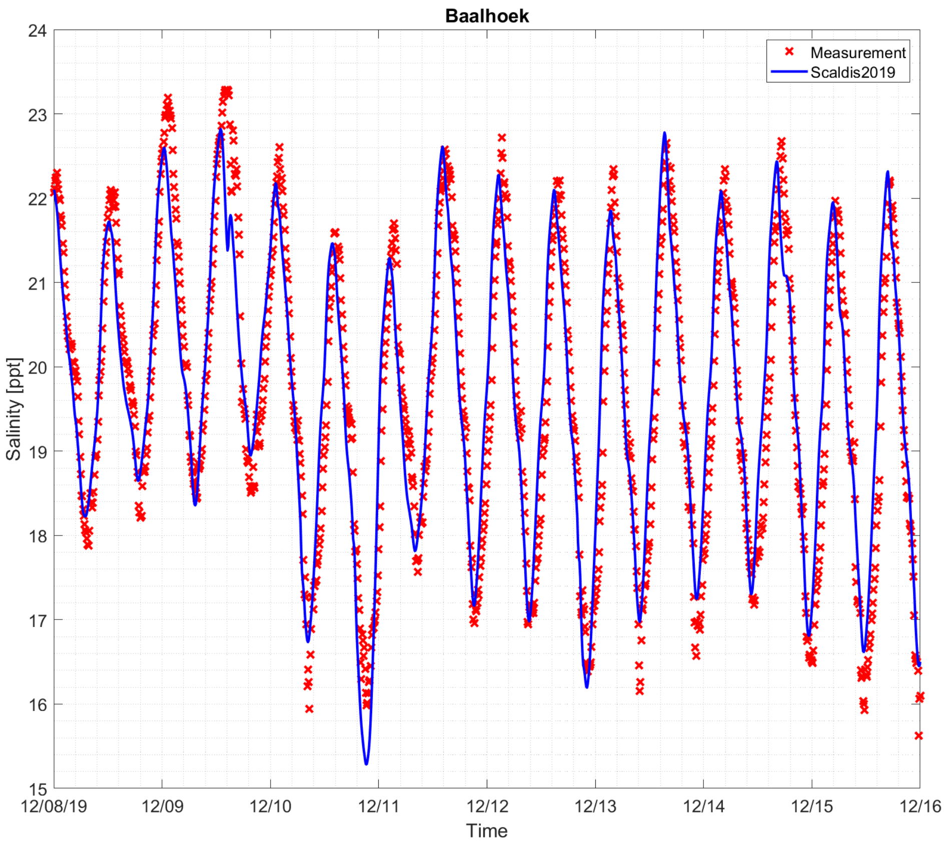


Table 34 – Statistical analysis of salinity for Validation.

Nr	Measuring station	Correlation	RMSE	Model minus Measurement	
		R [-]	[psu]	Max [psu]	Min [psu]
1	Overloop Hansweert	0.7	0.8	1.3	-2.8
2	Baalhoek	0.9	0.7	2.1	-1.9
3	Prosperpolder	0.7	2.2	0.9	-7.7
4	LilloMeetpaal	0.6	2.9	0.2	-8.2
5	Oosterweel	0.9	2.3	1.3	-5.1
6	Kruibeke	0.8	1.5	1.2	-5.5
7	Hemiksem	0.8	0.9	0.8	-4.4

10 Conclusion and recommendations

This report describes the re-calibration and validation of the 3D SCALDIS model for the year 2019. The model update consisted of the following main elements:

- The bathymetric data was updated to 2019.
- The offshore boundary conditions are updated to the latest DCSMv6-ZUNOv4 model.
- The mesh is adjusted in a way that it follows the navigation channel as much as possible. In the upstream branches, channel mesh is adopted. It is found that the updated mesh reduces the energy loss in the upstream reaches.
- The Charnock wind formula is used with Charnock coefficient of 0.04.
- The bottom friction law is changed from Manning to Nikuradse.

The model is calibrated with the Nikuradse roughness for two spring-neap cycles for a calm period and one spring-neap cycle for a stormy period (maximum wind speed up to 25 m/s). The model is calibrated against field data of water levels, velocities (ADCP sailed and stationary in deep and shallow zones) and salinity. A weighted dimensionless cost function is used to analyze the model results. The cost function attributes more or less equal weight to the horizontal and vertical tide. The weights are given to different parameters based on the importance of these parameters for the model calibration. Afterwards, the model is validated for a 8-day period of stormy condition.

The RMSE of water level gradually increase from 7 cm near the offshore to 13 cm in BoZS. There is still room for further improvement at Rupel basin and Durme (RMSE of 20.4 cm) where the local roughness is not yet optimized during the calibration of SCALDIS 2019.

The average bias of M2 amplitude is 1.5, 3.1 and 1.8 cm at BCZ, WES and BeZS respectively. It is relatively larger at BoZS (7.2 cm) and Rupel basin and Durme (11.9 cm). The bias of M2 phase is insignificant except at Rupel basin and Durme (5.2 deg). Similar patterns are found for the S2 tidal component. The total vector difference gently increases from 12.4 cm at BCZ to 24.6 cm at BoZS and 38.3 cm at Rupel basin and Durme. There is still room for further improvement at BoZS, Rupel basin and Durme. This should be considered for future studies.

The RMSE of stationary velocity magnitude in the deep areas is around 10 cm/s in BCZ and between 16-22 cm/s in BeZS. The RMSE of stationary velocity magnitude in the shallow areas is 9.2 cm/s in BeZS and 10.7 cm/s in BoZS.

The model is calibrated against 54 ADCP sailed velocities though out the estuary. The overall RMSE of velocity magnitude is 17 cm/s. The overall RMAE is 0.31, with which the model is categorized as ‘Good’. The model predictive ability on ADCP sailed velocities is in a line with the original SCALDIS model of 2015 run (Chu et al., 2017).

Salinity is well-reproduced, with the initial salinity field constructed by linear interpolation of measurements.

The model performance drops slightly for a stormy period (calibration II and validation). For instance, the RMSE of water level at BCZ is 11 cm (for calibration period II) which is larger than that from the calibration period I (6.9 cm). The larger error is mainly imported from the (nested) boundary conditions from the ZUNOv4 model.

In future model developments of Scaldis, it is recommended that the culvert formulation would be active in all runs, not just during the calm periods. It is believed that there is still some room for improvement in the tributaries. It would be interesting for example, to include the lessons learnt from the detailed model for the Durme (project 19_016) into future versions of Scaldis. Furthermore, it would also be interesting to quantify the model quality specifically during some specific individual storm events.

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Annex 1: Definition of Statistics

Water levels

The **Bias** of water level represents the average deviation of the differences between model predicted water level and measurement.

The **RMSE** of water level is a measure of the spread of the predicted values level around the measurement. It corresponds to a sample standard deviation.

The **RMSE0** is the bias corrected root mean square error which describes the forecast errors not associated with the bias.

The mathematical expressions are listed below. *y* and *x* represent modeled and measured values respectively and *n* is the number of samples.

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

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

$$RMSE0 = \sqrt{\frac{\sum_{1}^{n} ((y_i - x_i) - (\overline{y} - \overline{x}))^2}{n}}$$

ADCP velocities

Average velocity magnitude and direction for each transect are calculated as the magnitude and direction of the average vector (based on the average U and V components), (average means the combination of the depth average and average over the transect). This means that both magnitude and direction of velocities are taken into account. For example, a direction of the velocity with a higher magnitude has more weight in the calculation of an average direction than a direction of the velocity with a smaller magnitude.

$$\overrightarrow{V_{met}}(x,z,t) = \overrightarrow{e_x} U_{met}(x,z,t) + \overrightarrow{e_y} V_{met}(x,z,t)$$

$$\overrightarrow{V_{\mathrm{mod}}}(x,z,t) = \overrightarrow{e_x} U_{\mathrm{mod}}(x,z,t) + \overrightarrow{e_y} V_{\mathrm{mod}}(x,z,t)$$

where $\overrightarrow{V_{met}}(x,z,t)$ is the vector of the measured velocity;

$\overrightarrow{V_{\mathrm{mod}}}(x,z,t)$ is the vector of the modeled velocity.

Average velocity magnitude and direction:

$$MAG_{met}(t) = \left\| \frac{\sum_{x} \left\langle \overrightarrow{V_{met}} \right\rangle}{n} \right\| \qquad DIR_{met}(t) = dir\left(\frac{\sum_{x} \left\langle \overrightarrow{V_{met}} \right\rangle}{n} \right)$$

$$MAG_{\mathrm{mod}}(t) = \left\| \frac{\sum_x \left\langle \overrightarrow{V_{\mathrm{mod}}} \right\rangle}{n} \right\| \qquad DIR_{\mathrm{mod}}(t) = dir\left(\frac{\sum_x \left\langle \overrightarrow{V_{\mathrm{mod}}} \right\rangle}{n} \right)$$

where $\left\langle \overrightarrow{V_{\mathrm{mod}}} \right\rangle (x,t)$ and $\left\langle \overrightarrow{V_{met}} \right\rangle (x,t)$ are depth average modeled and measured velocities.

The **bias of magnitude and direction** is calculated as the difference between the calculated and measured average velocity magnitude and direction.

$$BIAS_{mag}(t) = MAG_{\mathrm{mod}} - MAG_{met}$$

$$BIAS_{dir}(t) = DIR_{\mathrm{mod}} - DIR_{met}$$

The **RMSE of velocity magnitude and direction** is calculated based on the depth average velocity magnitude and direction for each point along the transect. Magnitude is not taken into account for the calculation of the RMSE of velocity direction and vice-versa. Therefore, the RMSE plots show more variation between the model and measurements than the plots of average velocity magnitude and direction for all transects.

$$RMSE_{mag}(t) = \sqrt{\frac{\sum_x \left(\left\| \left\langle \overrightarrow{V_{\mathrm{mod}}} \right\rangle \right\| - \left\| \left\langle \overrightarrow{V_{met}} \right\rangle \right\| \right)^2}{n}}$$

$$RMSE_{dir}(t) = \sqrt{\frac{\sum_x \left(dir\left(\left\langle \overrightarrow{V_{\mathrm{mod}}} \right\rangle \right) - dir\left(\left\langle \overrightarrow{V_{met}} \right\rangle \right) \right)^2}{n}}$$

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. The **RMAE** (relative mean absolute error) is derived 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.

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

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

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

Annex 2: Definition of Vector Difference

The vector difference analysis combines the results from different tidal components regarding both amplitude and phase. In short vector difference is a unified variable with one value describing the model accuracy from harmonic point of view. The mathematical expression of vector difference is shown as below.

$$e_s = \sum_{i=1}^{N} \sqrt{[A_{c,i} cos(\phi_{c,i}) - A_{m,i} cos(\phi_{m,i})]^2 + [A_{c,i} sin(\phi_{c,i}) - A_{m,i} sin(\phi_{m,i})]^2}$$

where e_s is the vector difference calculated at a certain station. c and m represent the model computed and measured value. A and φ represent the tidal amplitude and phase. i represents the number of tidal components.

Annex 3: Salinity – Calibration period I

Figure 112 – Comparison of salinity at Overloop Hansweert.

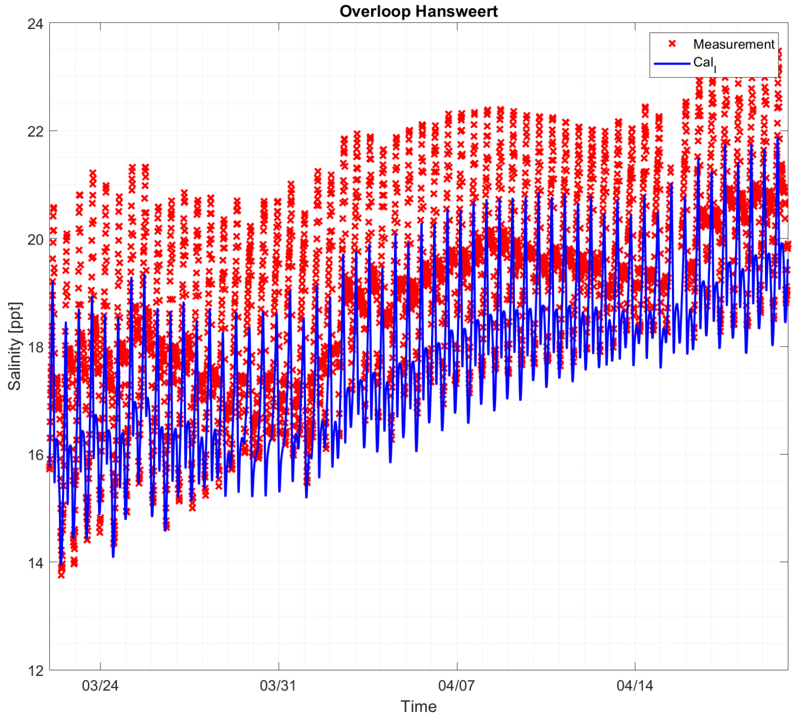


Figure 113 – Comparison of salinity at Prosperpolder.

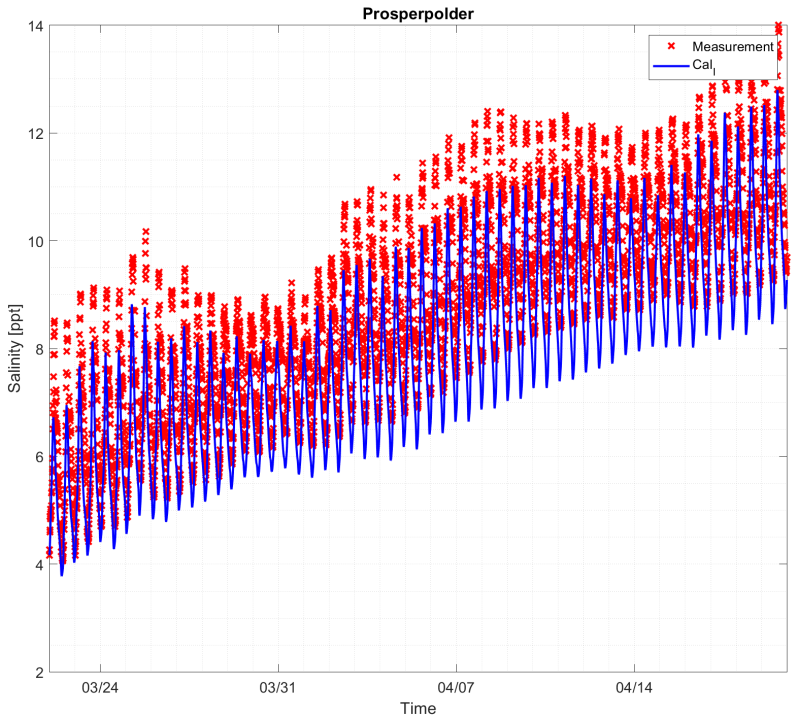


Figure 114 – Comparison of salinity at Lillo.

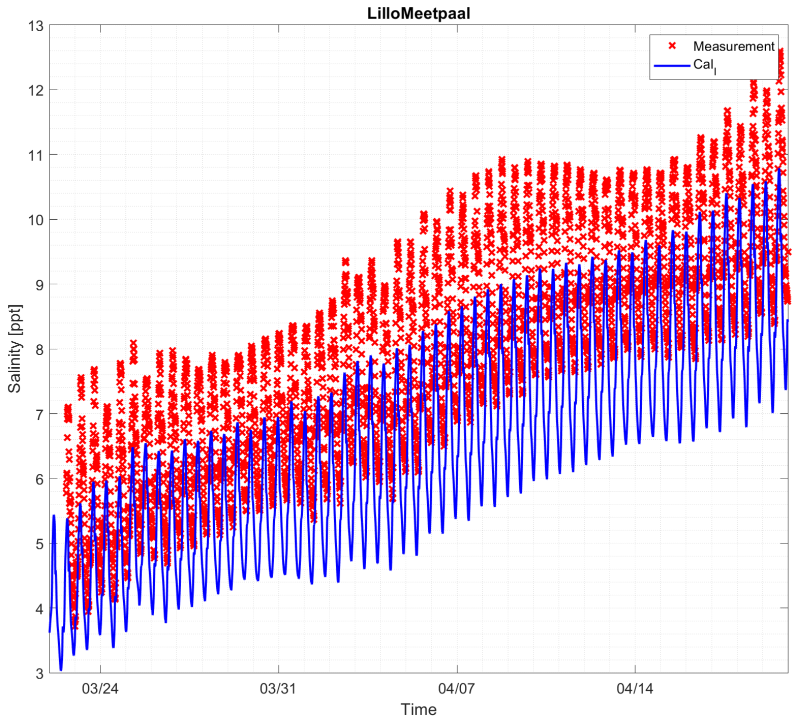


Figure 115 – Comparison of salinity at Liefkenshoek.

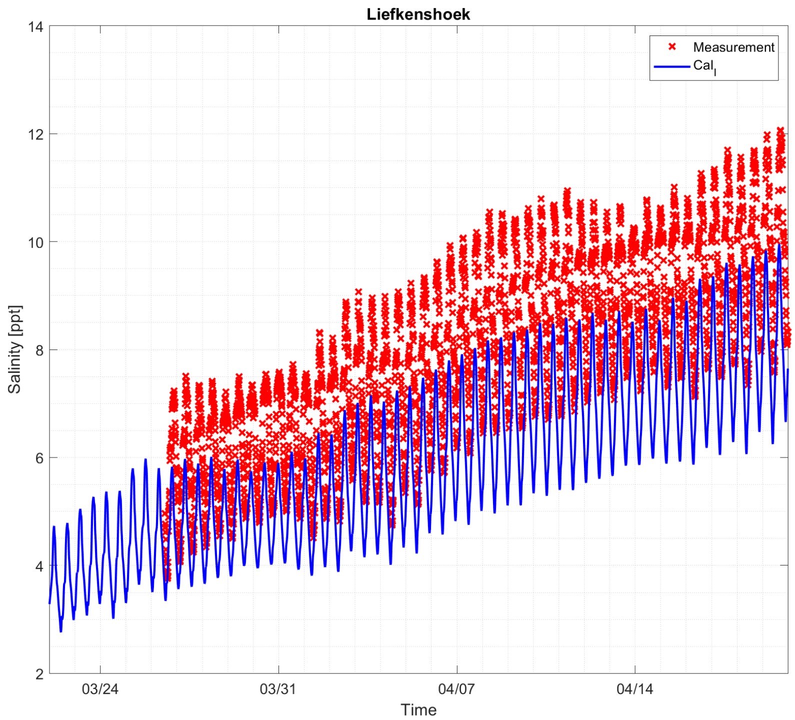


Figure 116 – Comparison of salinity at Oosterweel.

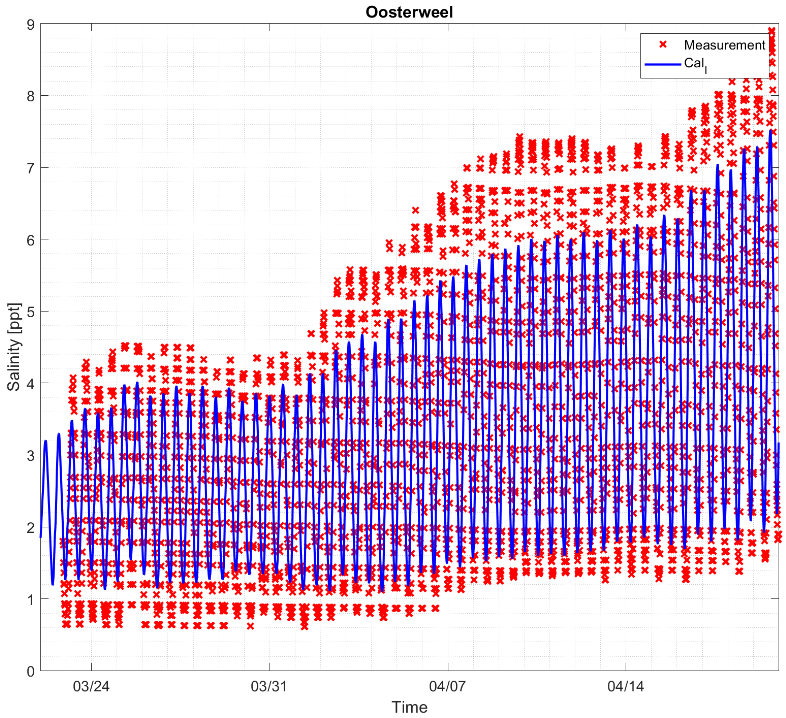


Figure 117 – Comparison of salinity at Kruibeke.

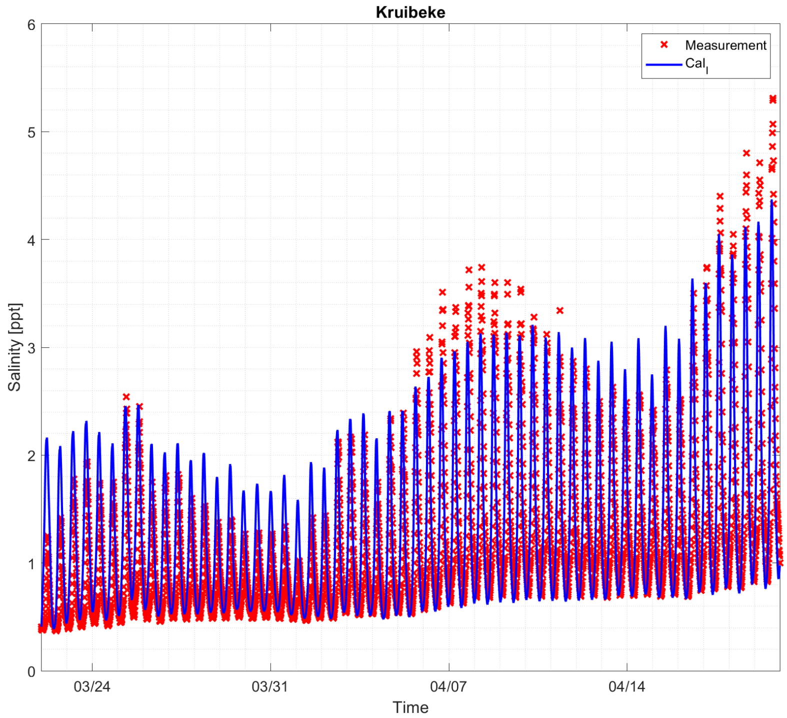
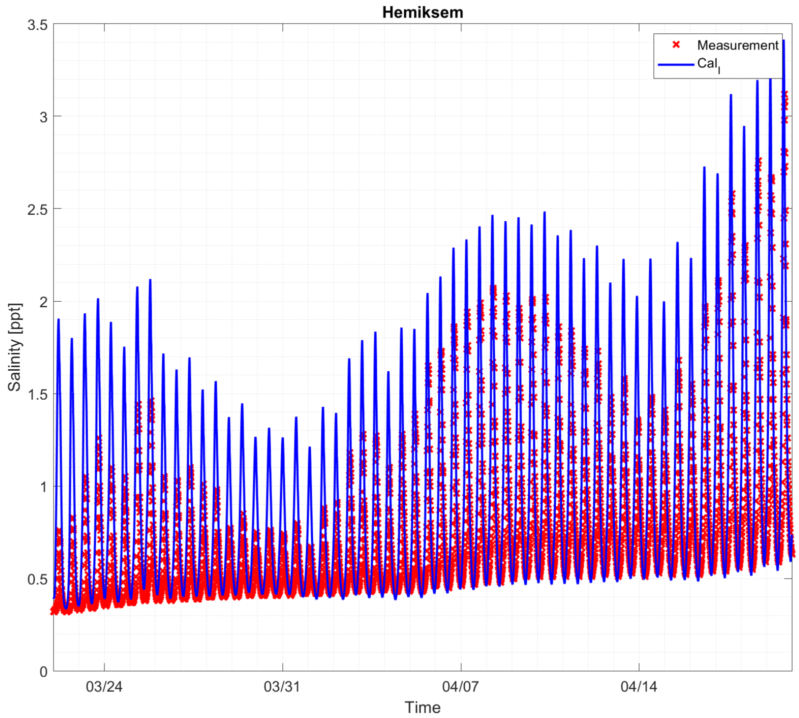


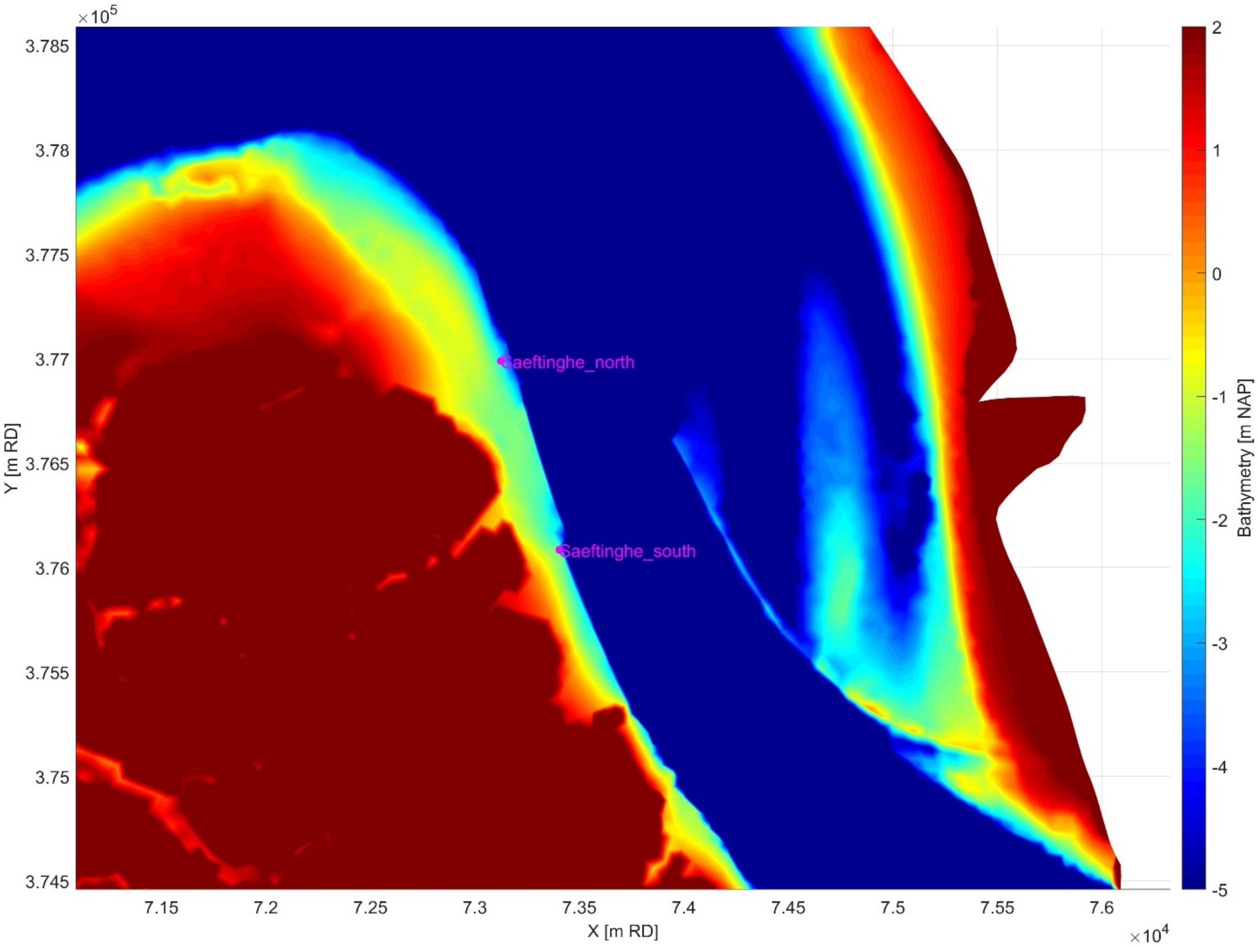
Figure 118 – Comparison of salinity at Hemiksem.

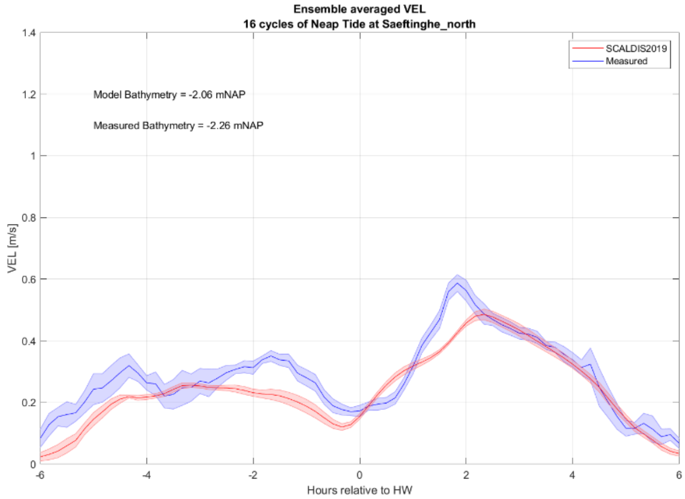


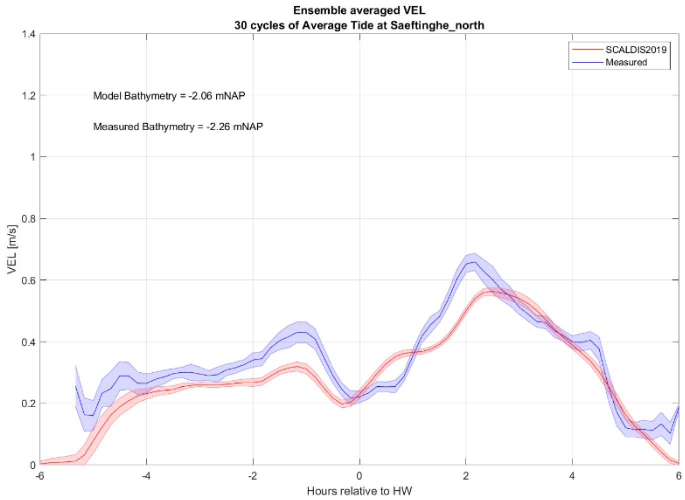
Annex 4: Stationary velocity in shallow areas

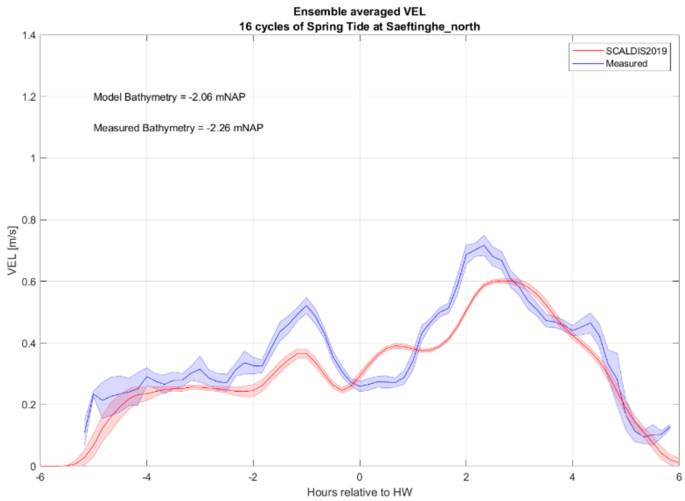
The calibration results of stationary velocity in shallow areas are shown per location for **Neap, Average and Spring** tide respectively. The exact locations of the measurement are demonstrated on top of the local bathymetry.

Saeftinghe_north

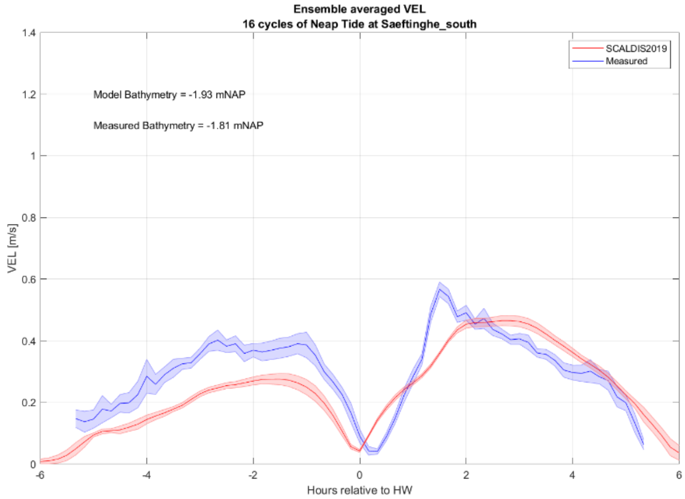


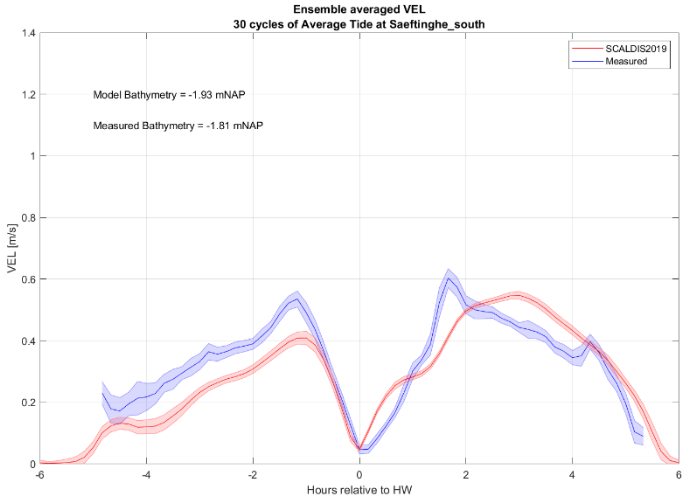

Ensemble averaged VEL
16 cycles of Neap Tide at Saeftinghe_north
SCALDIS2019
Measured
Model Bathymetry = -2.06 mNAP
Measured Bathymetry = -2.26 mNAP
VEL [m/s]
Hours relative to HW

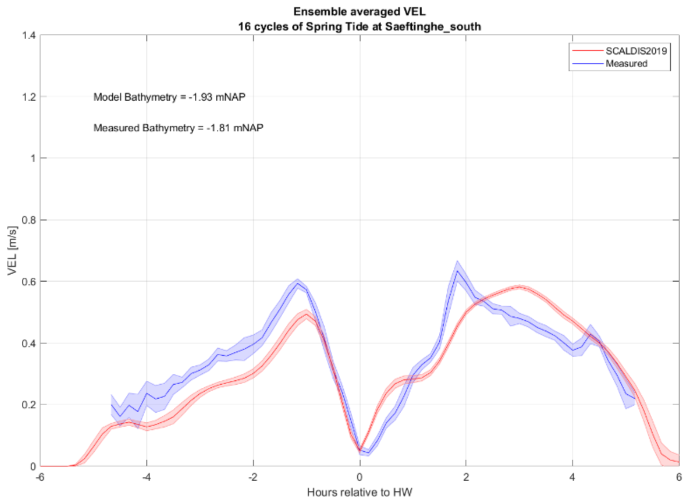

Ensemble averaged VEL
30 cycles of Average Tide at Saeftinghe_north
SCALDIS2019
Measured
Model Bathymetry = -2.06 mNAP
Measured Bathymetry = -2.26 mNAP
VEL [m/s]
Hours relative to HW


Ensemble averaged VEL
16 cycles of Spring Tide at Saeftinghe_north
SCALDIS2019
Measured
Model Bathymetry = -2.06 mNAP
Measured Bathymetry = -2.26 mNAP
VEL [m/s]
Hours relative to HW

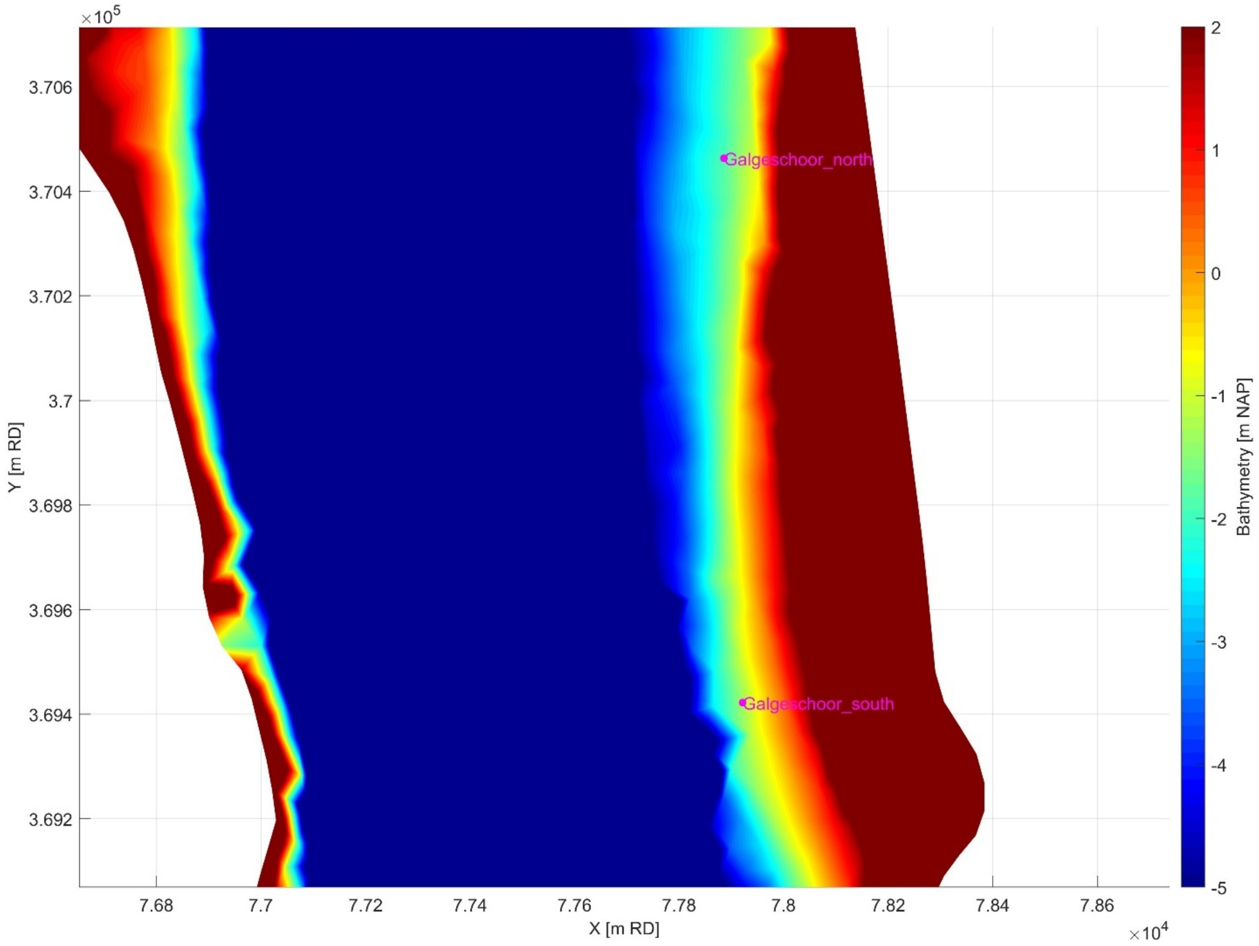
Saeftinghe_south

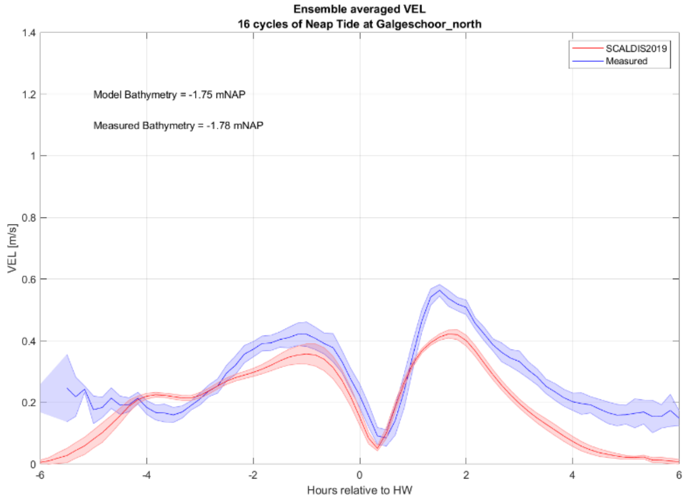


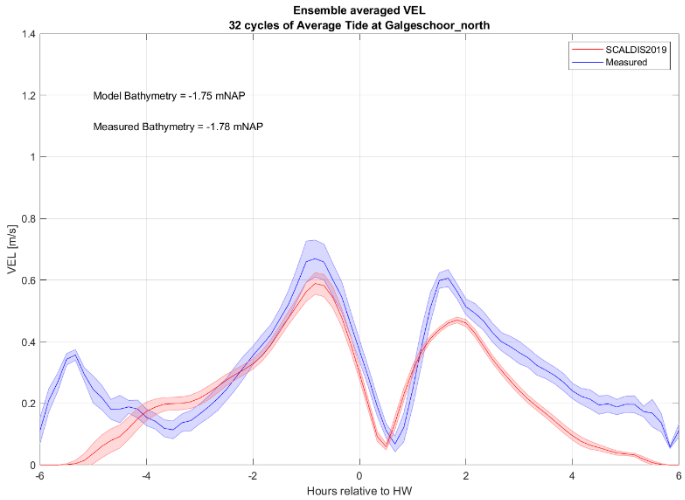


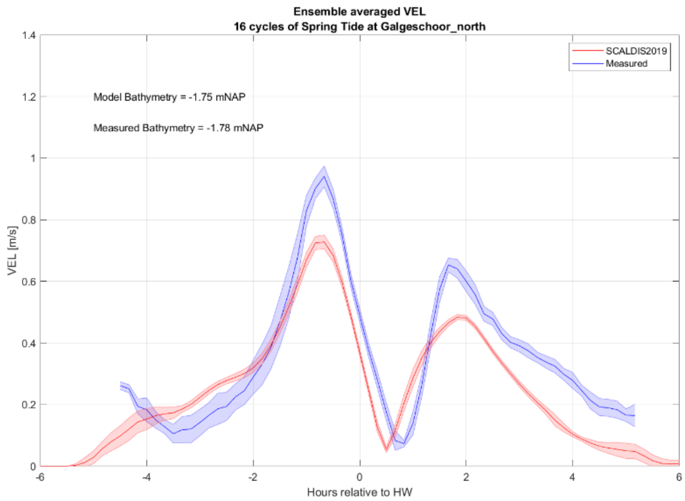


Galgeschoor_north

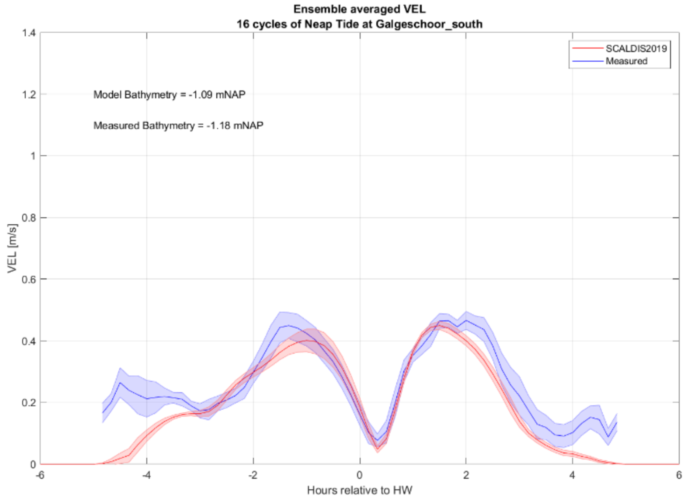


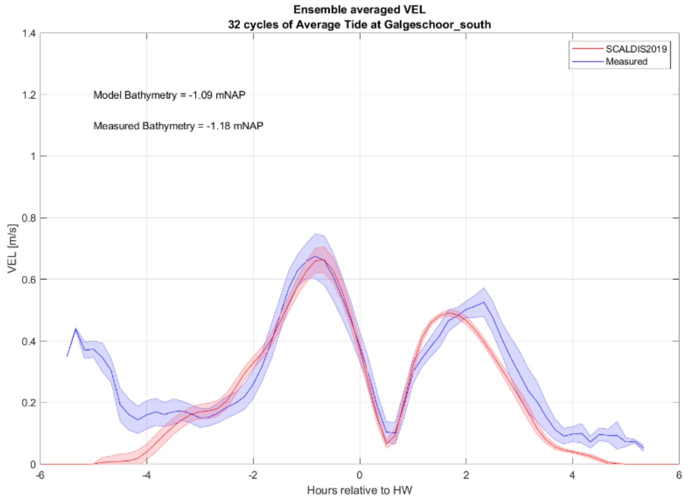

Ensemble averaged VEL
16 cycles of Neap Tide at Galgeschoor_north
SCALDIS2019
Measured
Model Bathymetry = -1.75 mNAP
Measured Bathymetry = -1.78 mNAP
VEL [m/s]
Hours relative to HW

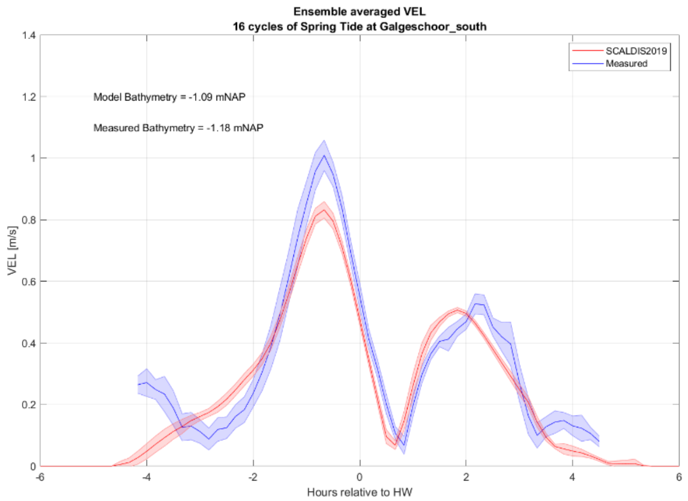

Ensemble averaged VEL
32 cycles of Average Tide at Galgeschoor_north
SCALDIS2019
Measured
Model Bathymetry = -1.75 mNAP
Measured Bathymetry = -1.78 mNAP
VEL [m/s]
Hours relative to HW


Ensemble averaged VEL
16 cycles of Spring Tide at Galgeschoor_north
SCALDIS2019
Measured
Model Bathymetry = -1.75 mNAP
Measured Bathymetry = -1.78 mNAP
VEL [m/s]
Hours relative to HW

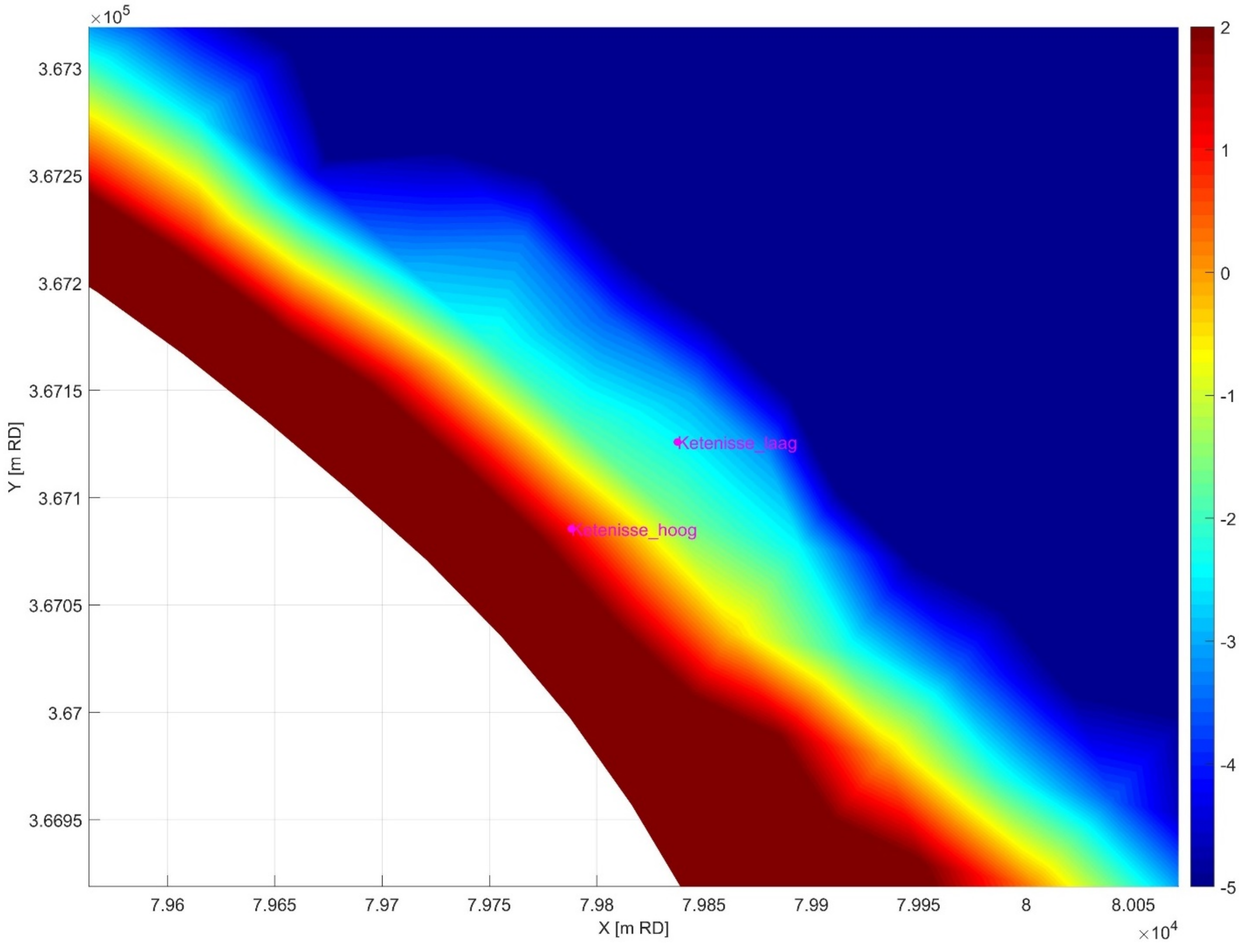
Galgeschoor_south

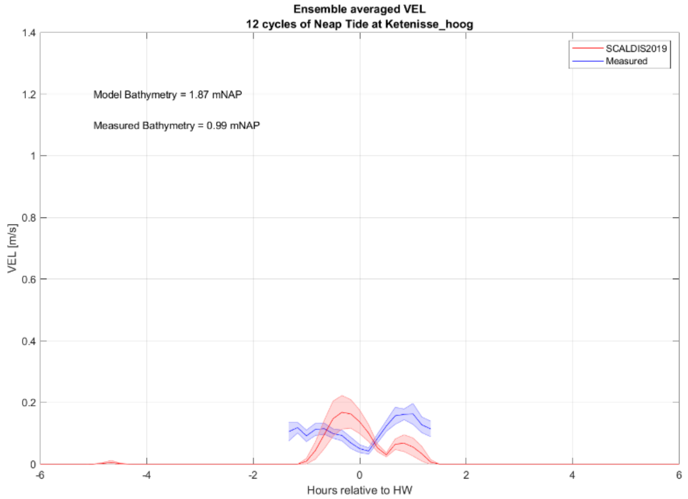


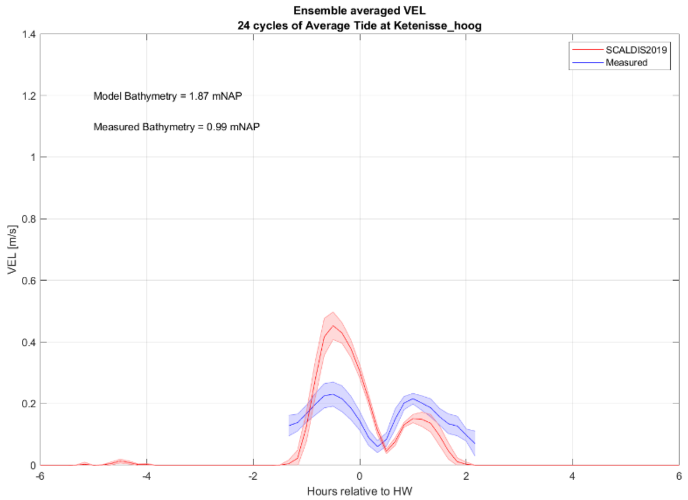


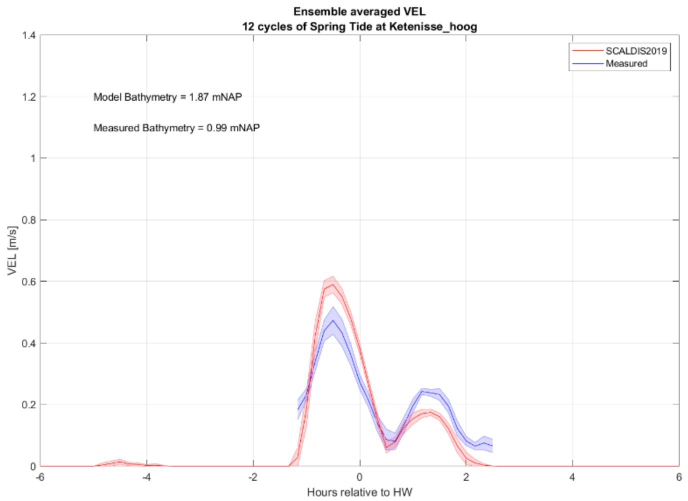


Ketenisse_hoog

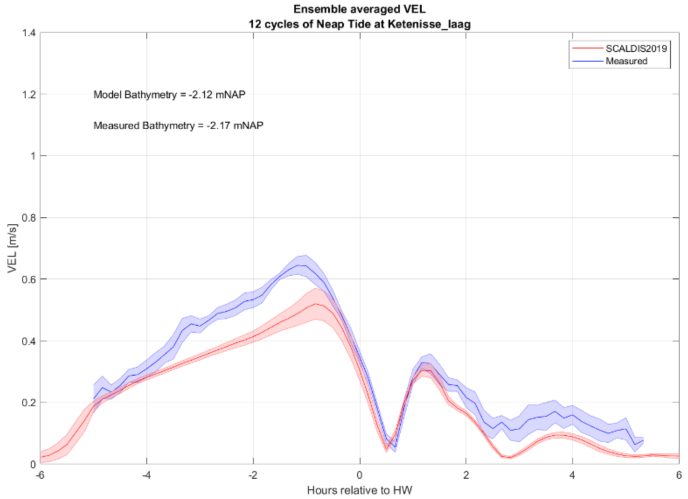


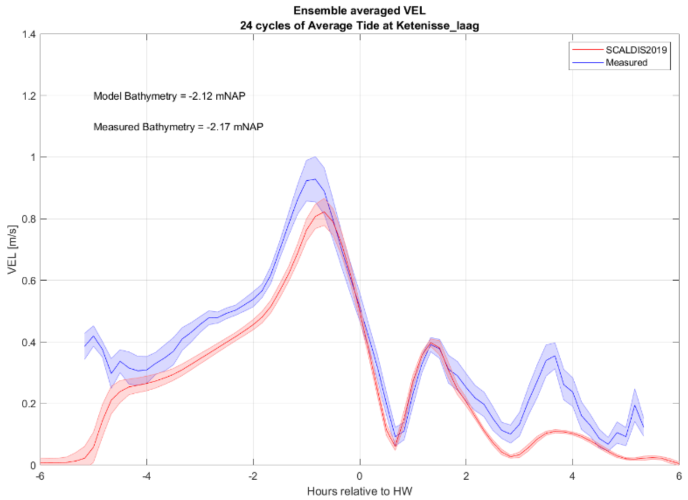

Ensemble averaged VEL
12 cycles of Neap Tide at Ketenisse_hoog
SCALDIS2019
Measured
Model Bathymetry = 1.87 mNAP
Measured Bathymetry = 0.99 mNAP
VEL [m/s]
Hours relative to HW

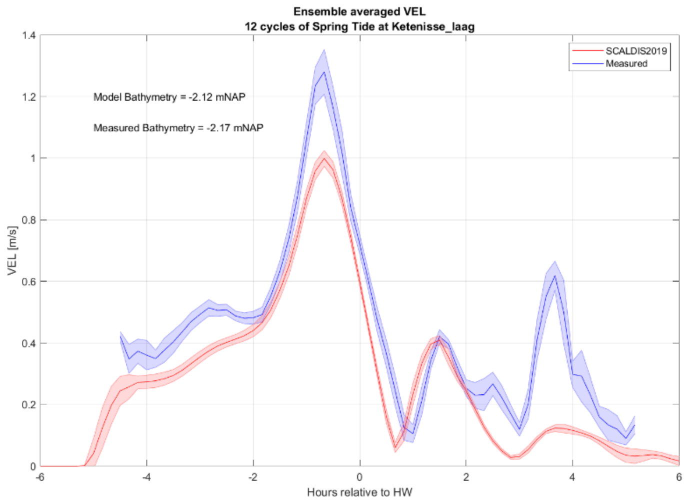

Ensemble averaged VEL
24 cycles of Average Tide at Ketenisse_hoog
SCALDIS2019
Measured
Model Bathymetry = 1.87 mNAP
Measured Bathymetry = 0.99 mNAP
VEL [m/s]
Hours relative to HW


Ensemble averaged VEL
12 cycles of Spring Tide at Ketenisse_hoog
SCALDIS2019
Measured
Model Bathymetry = 1.87 mNAP
Measured Bathymetry = 0.99 mNAP
VEL [m/s]
Hours relative to HW

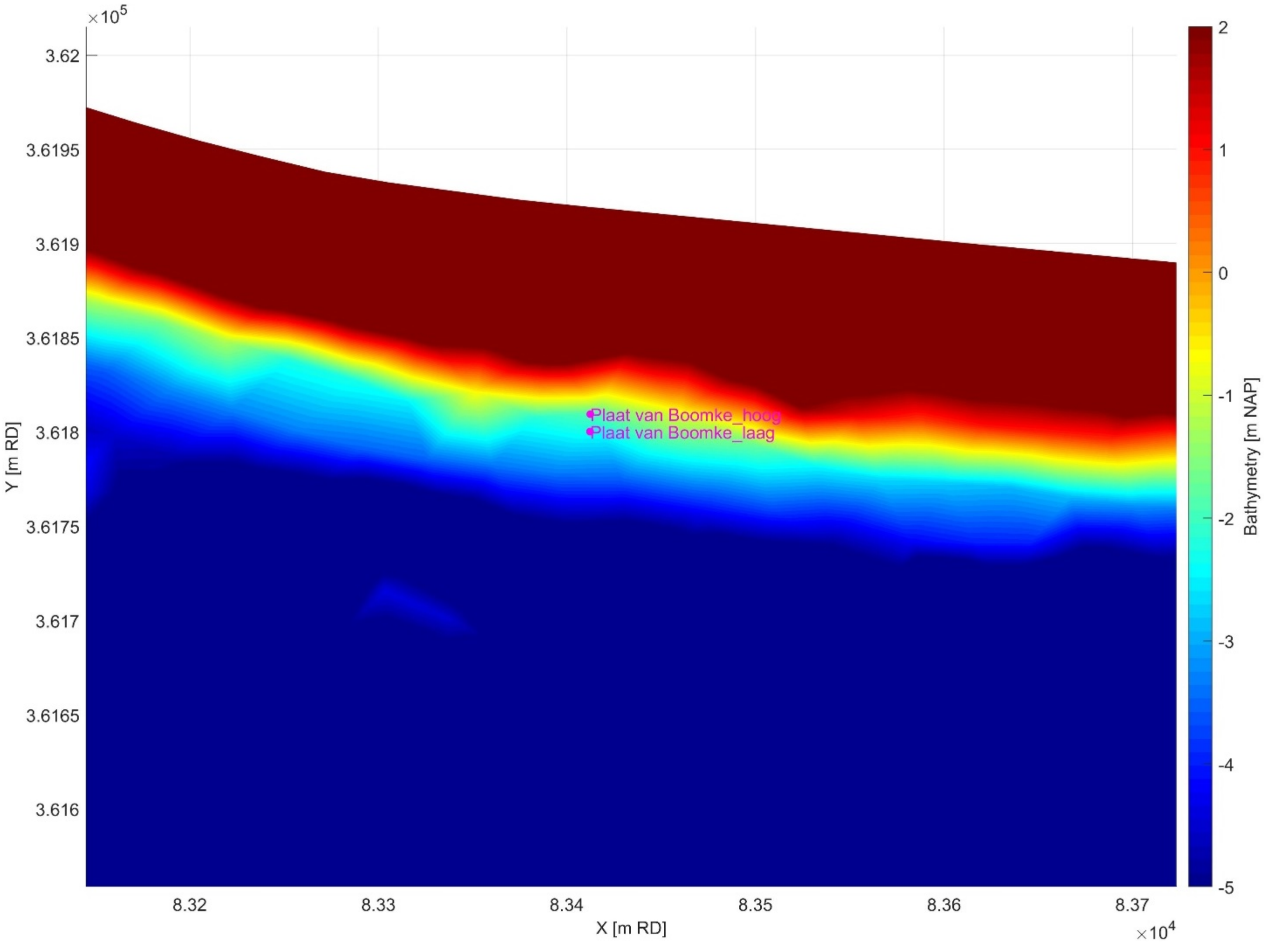
Ketenisse_laag

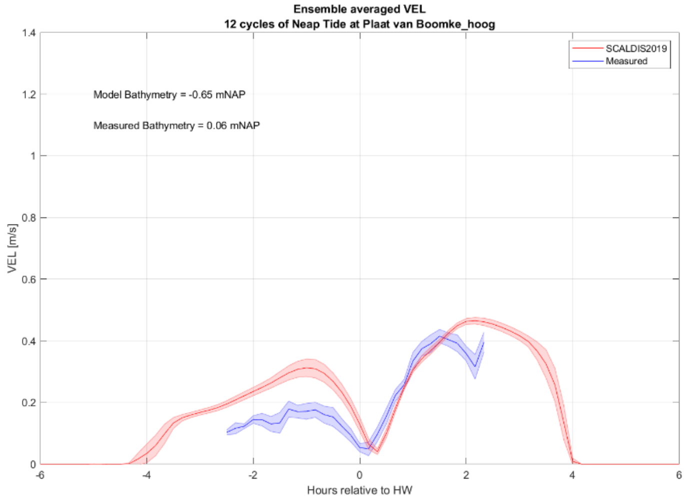


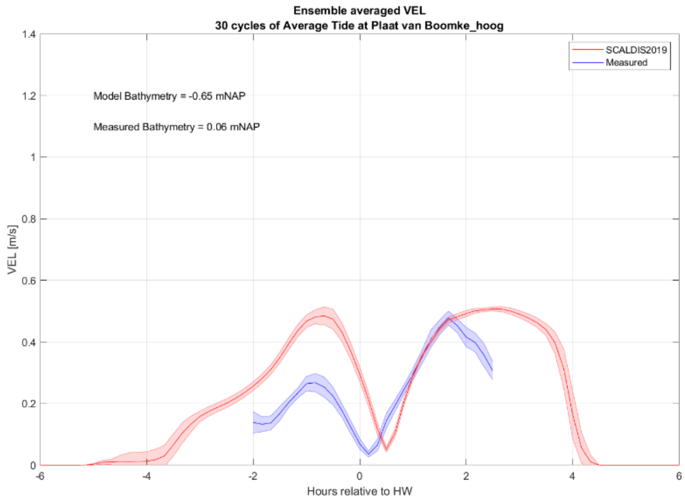


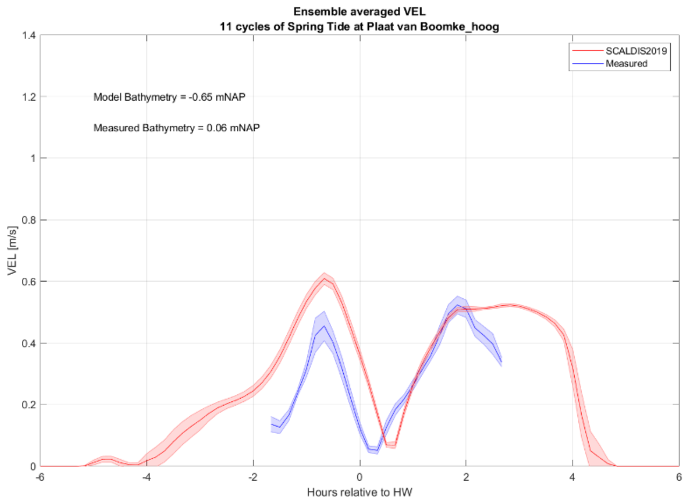


Plaat van Boomke_hoog

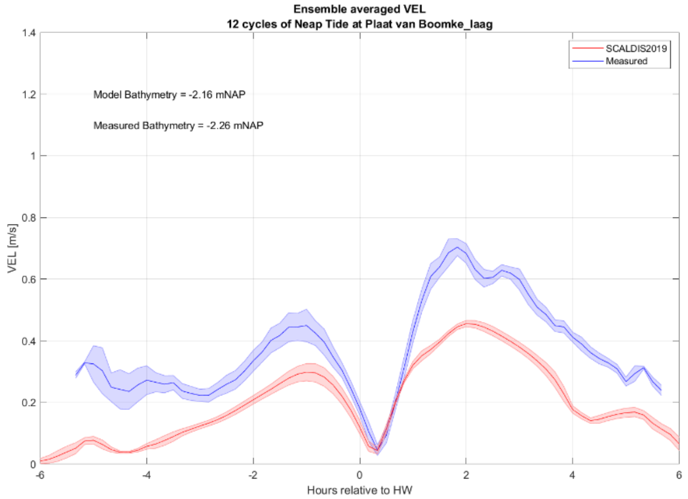


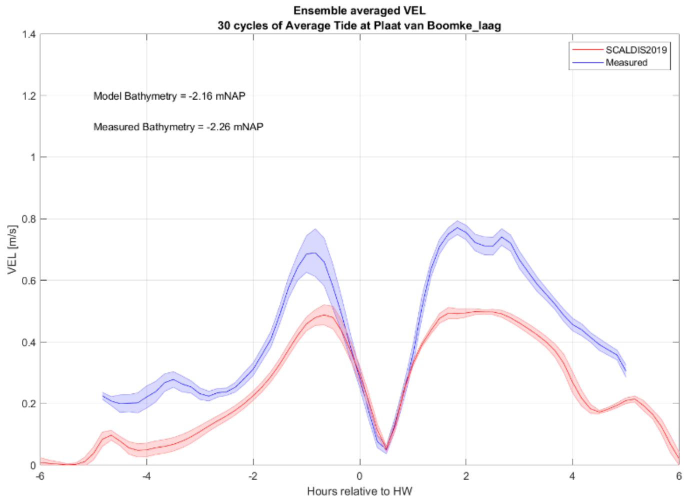

Ensemble averaged VEL
12 cycles of Neap Tide at Plaat van Boomke_hoog
SCALDIS2019
Measured
Model Bathymetry = -0.65 mNAP
Measured Bathymetry = 0.06 mNAP
VEL [m/s]
Hours relative to HW

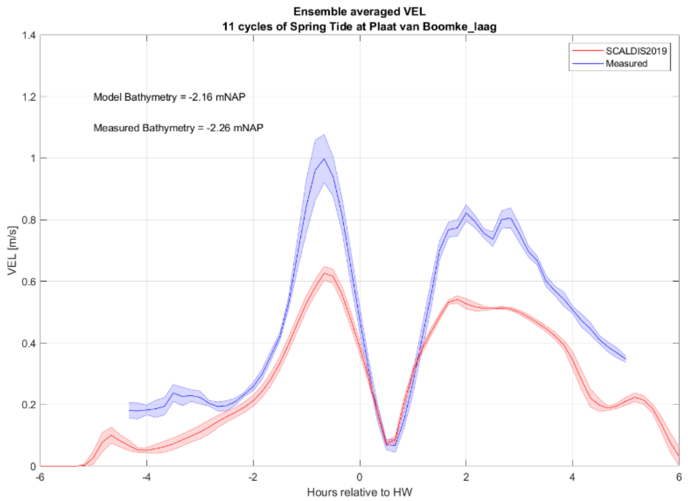

Ensemble averaged VEL
30 cycles of Average Tide at Plaat van Boomke_hoog
SCALDIS2019
Measured
Model Bathymetry = -0.65 mNAP
Measured Bathymetry = 0.06 mNAP
VEL [m/s]
Hours relative to HW


Ensemble averaged VEL
11 cycles of Spring Tide at Plaat van Boomke_hoog
SCALDIS2019
Measured
Model Bathymetry = -0.65 mNAP
Measured Bathymetry = 0.06 mNAP
VEL [m/s]
Hours relative to HW

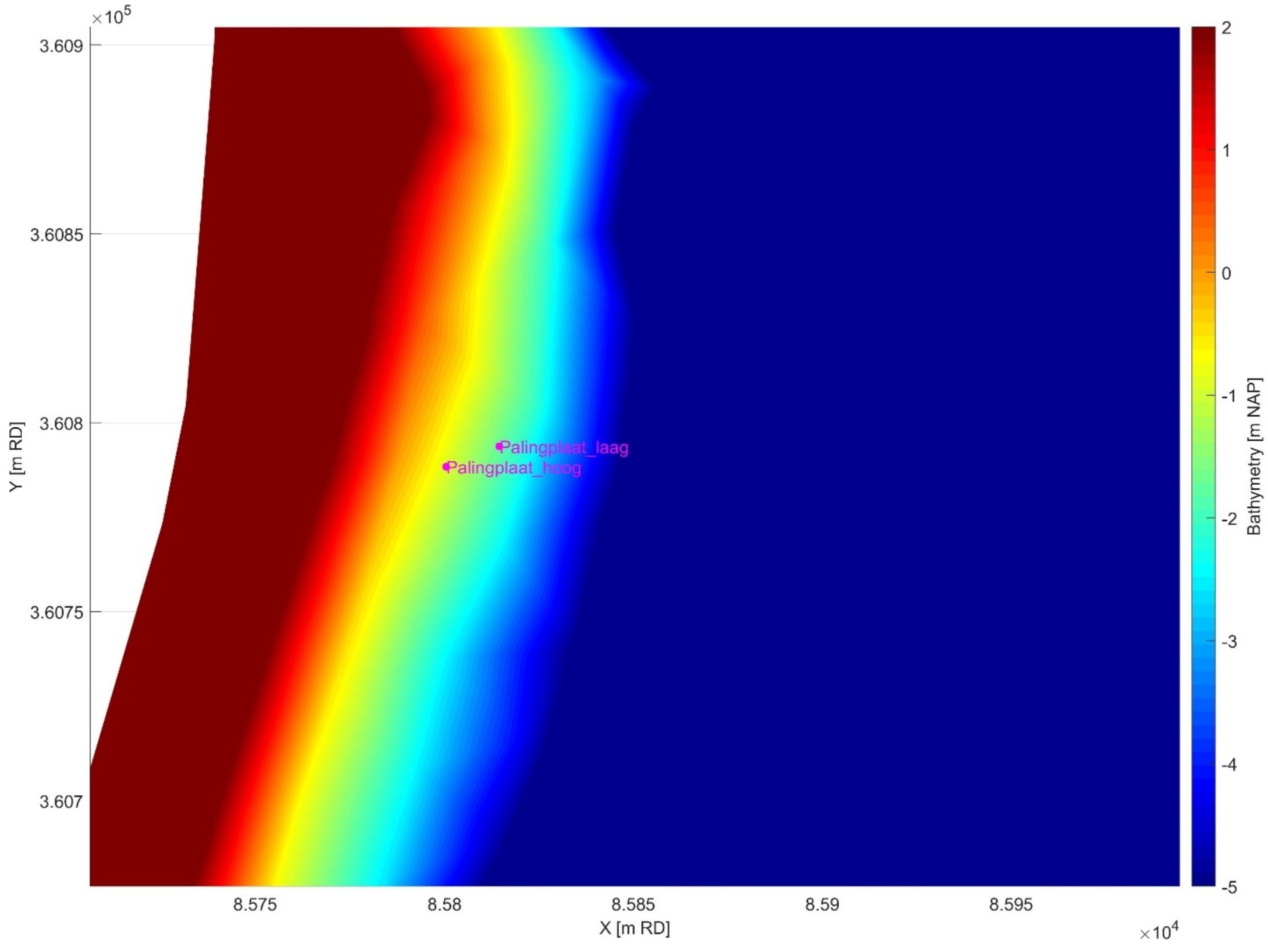
Plaat van Boomke_laag

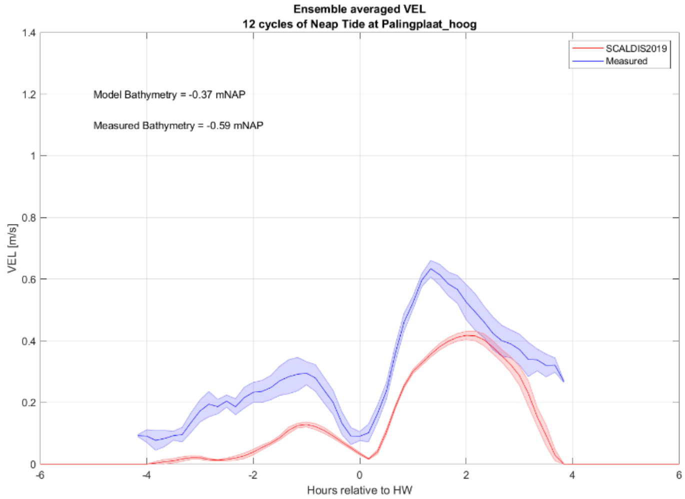


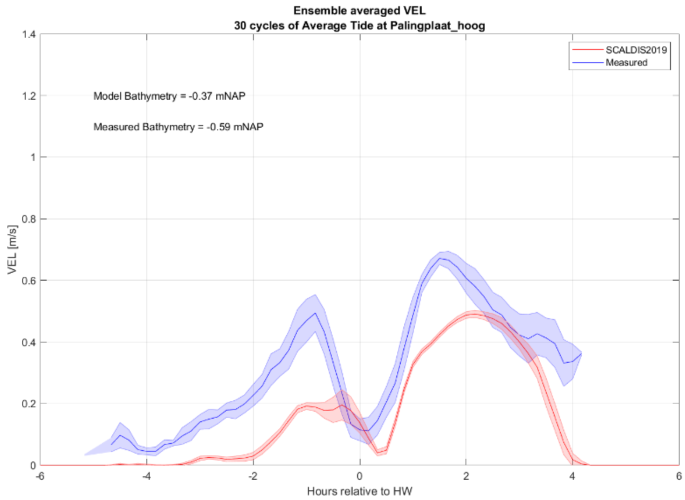


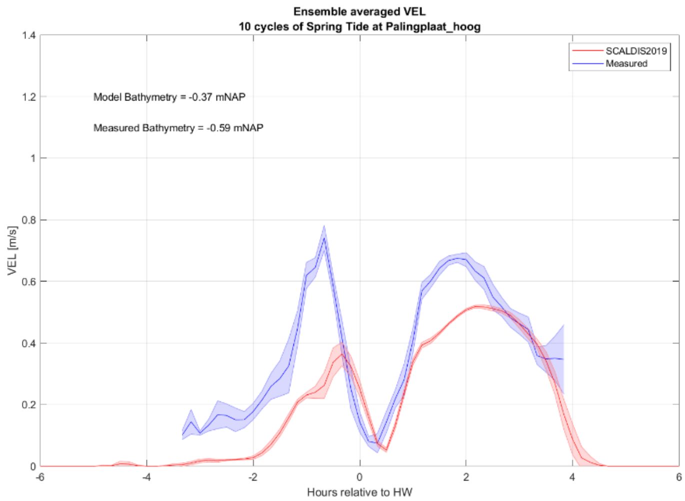


Palingplaat_hoog

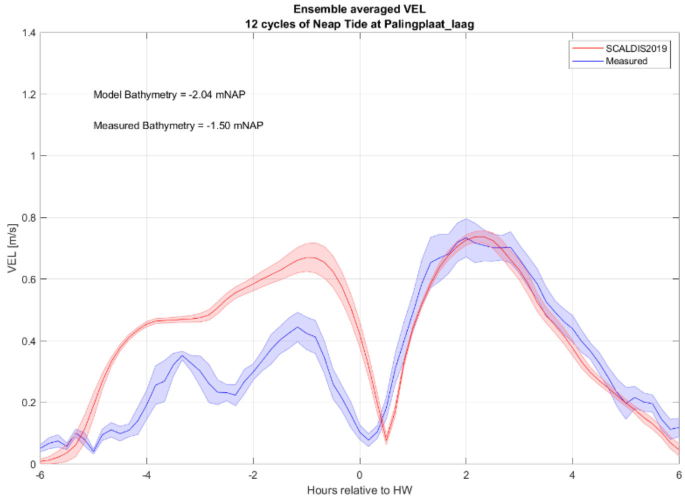


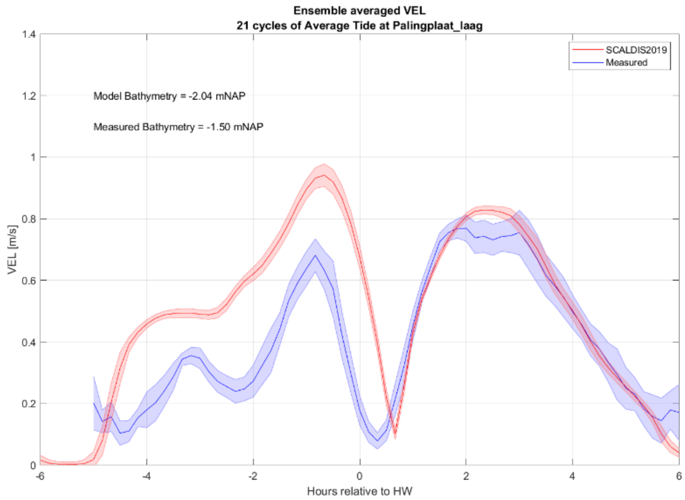

Ensemble averaged VEL
12 cycles of Neap Tide at Palingplaat_hoog
SCALDIS2019
Measured
Model Bathymetry = -0.37 mNAP
Measured Bathymetry = -0.59 mNAP
VEL [m/s]
Hours relative to HW

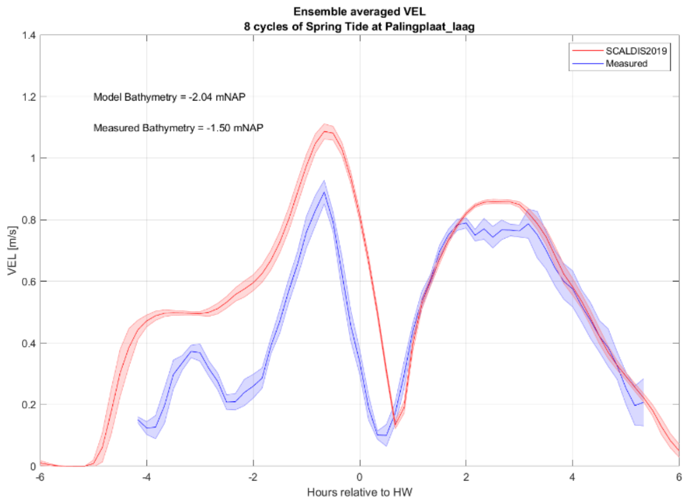

Ensemble averaged VEL
30 cycles of Average Tide at Palingplaat_hoog
SCALDIS2019
Measured
Model Bathymetry = -0.37 mNAP
Measured Bathymetry = -0.59 mNAP
VEL [m/s]
Hours relative to HW


Ensemble averaged VEL
10 cycles of Spring Tide at Palingplaat_hoog
SCALDIS2019
Measured
Model Bathymetry = -0.37 mNAP
Measured Bathymetry = -0.59 mNAP
VEL [m/s]
Hours relative to HW

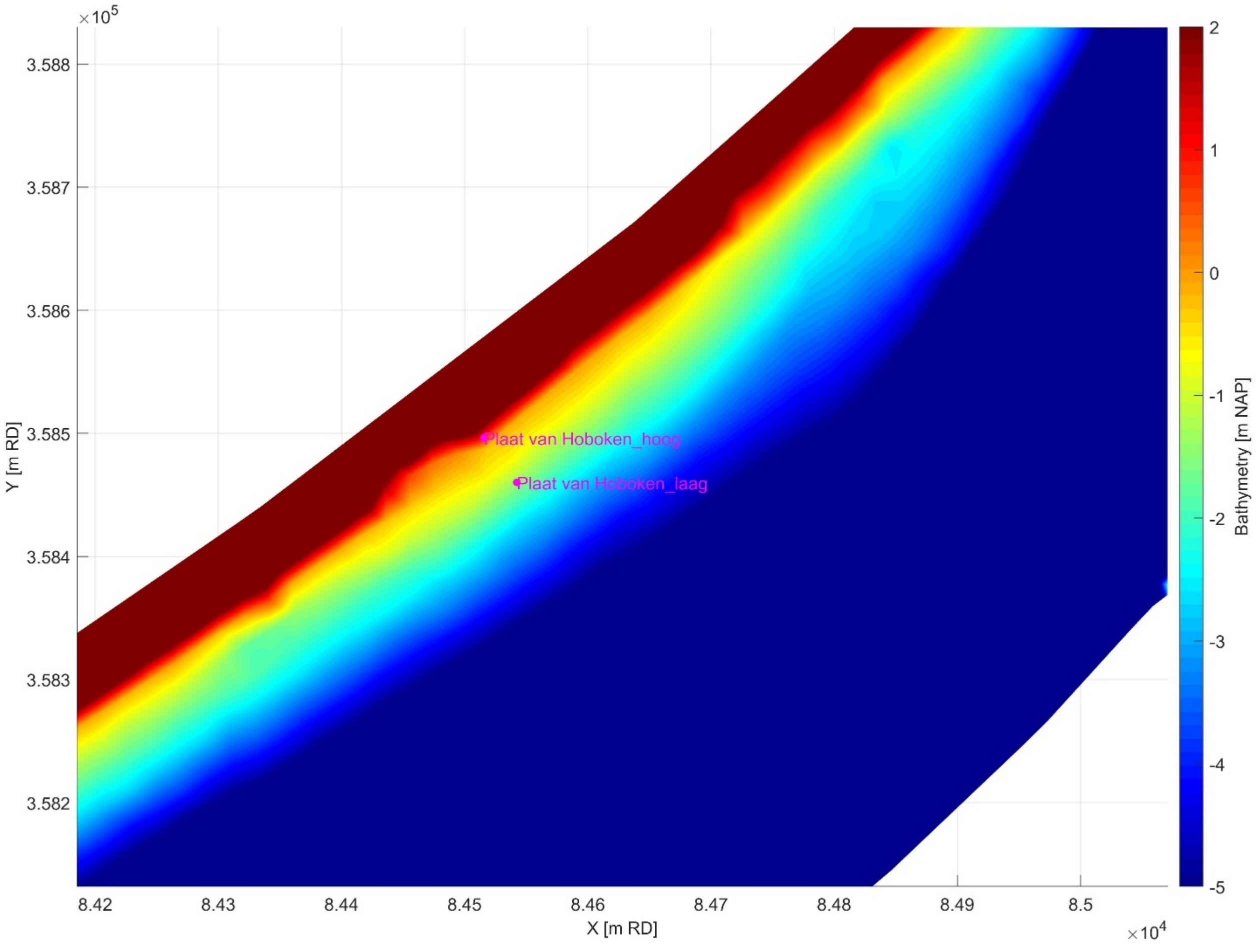
Palingplaat_laag

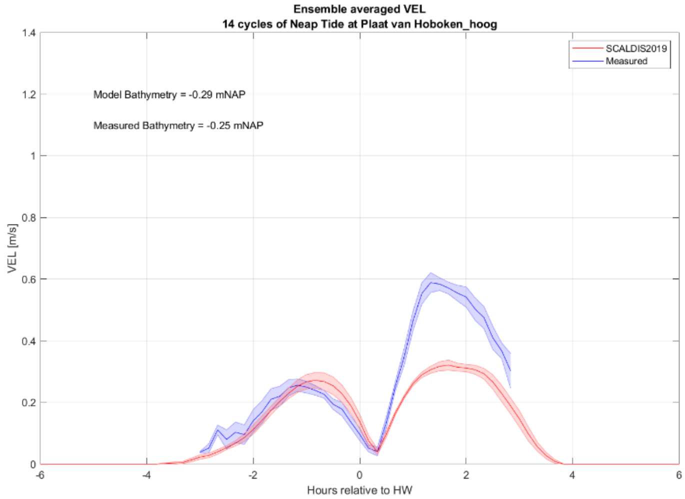


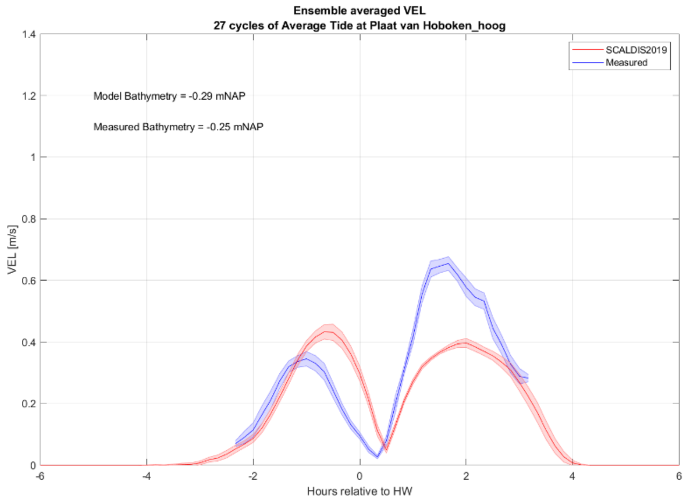


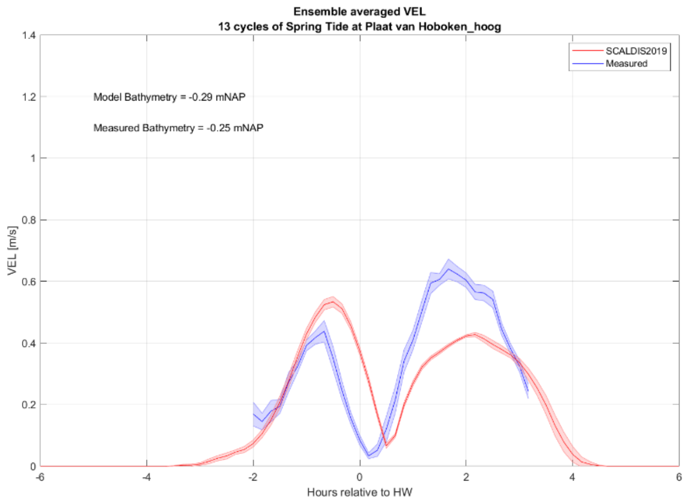


Plaat van Hoboken_hoog

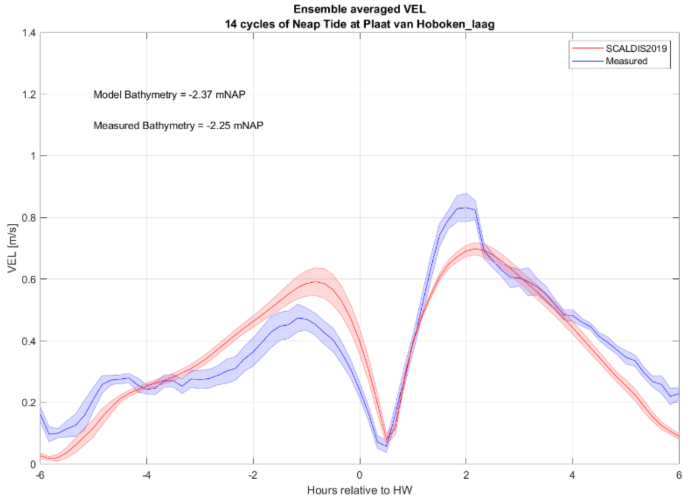


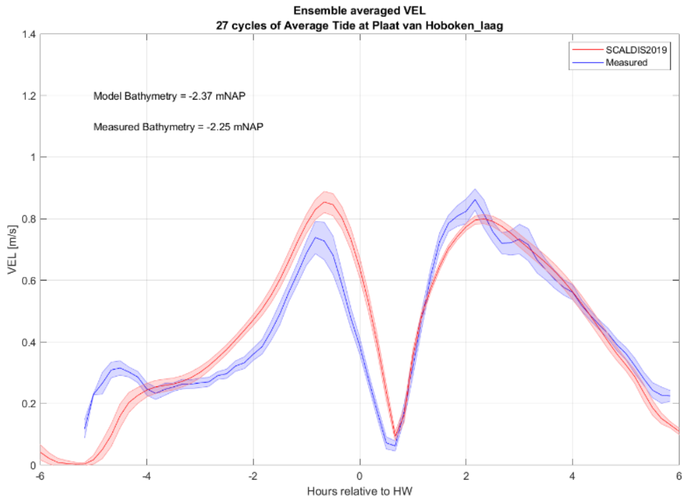

Ensemble averaged VEL
14 cycles of Neap Tide at Plaat van Hoboken_hoog
SCALDIS2019
Measured
Model Bathymetry = -0.29 mNAP
Measured Bathymetry = -0.25 mNAP
VEL [m/s]
Hours relative to HW

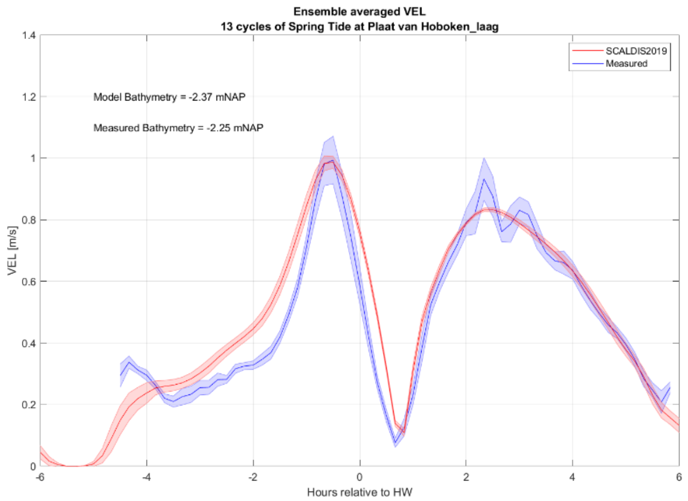

Ensemble averaged VEL
27 cycles of Average Tide at Plaat van Hoboken_hoog
SCALDIS2019
Measured
Model Bathymetry = -0.29 mNAP
Measured Bathymetry = -0.25 mNAP
VEL [m/s]
Hours relative to HW


Ensemble averaged VEL
13 cycles of Spring Tide at Plaat van Hoboken_hoog
SCALDIS2019
Measured
Model Bathymetry = -0.29 mNAP
Measured Bathymetry = -0.25 mNAP
VEL [m/s]
Hours relative to HW

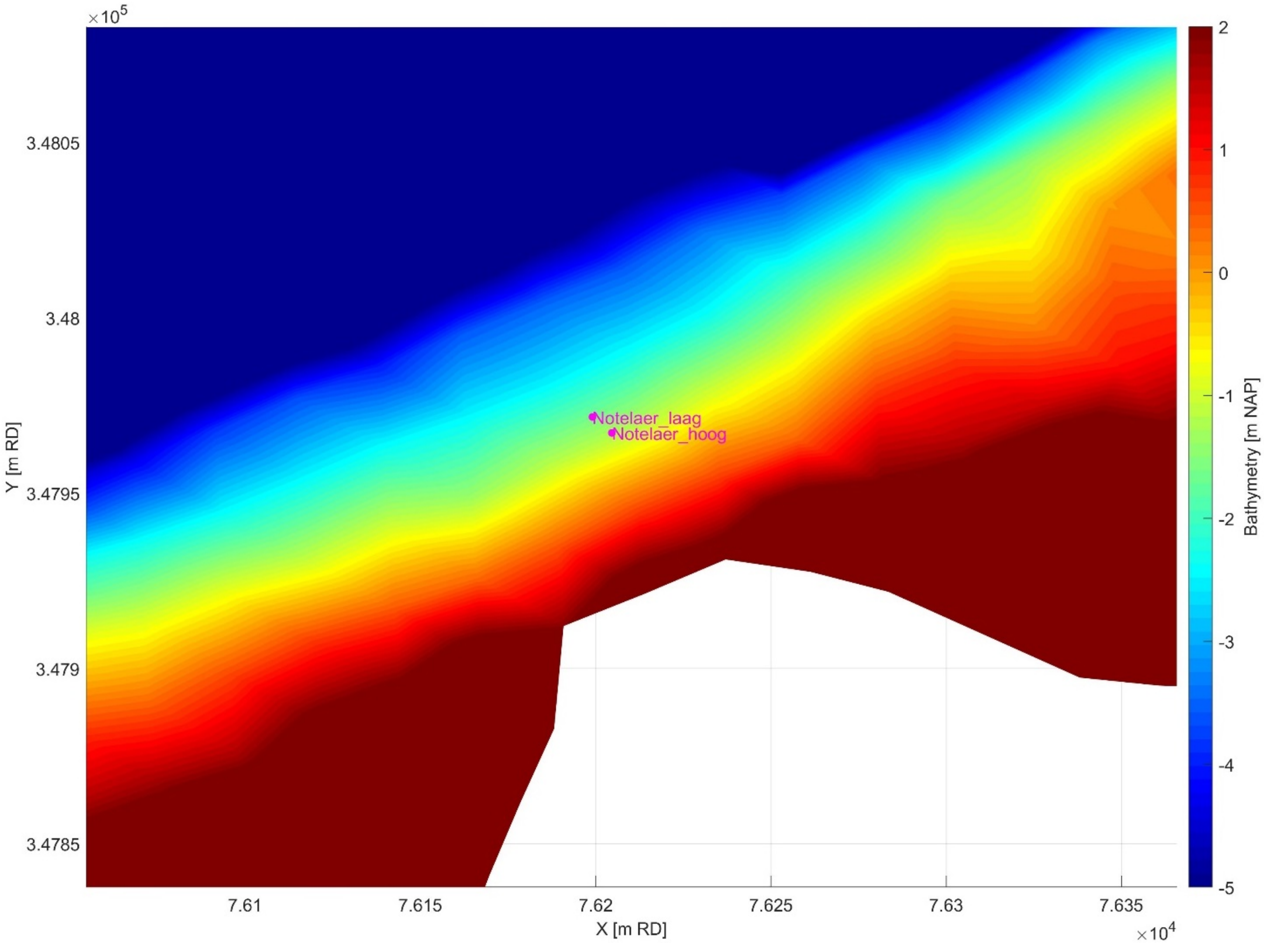
Plaat van Hoboken_laag

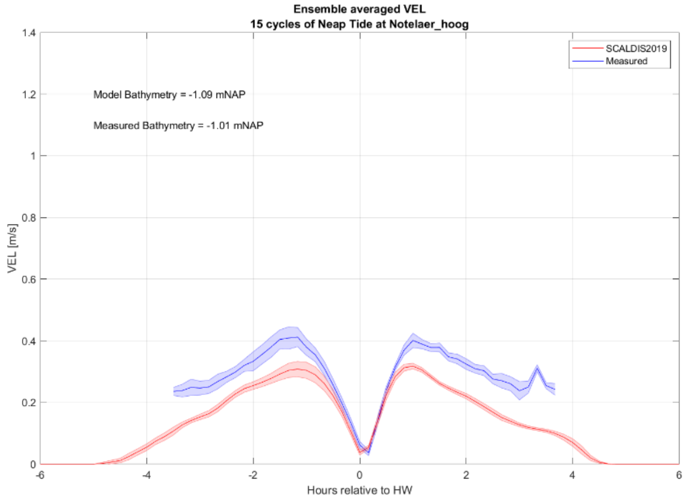


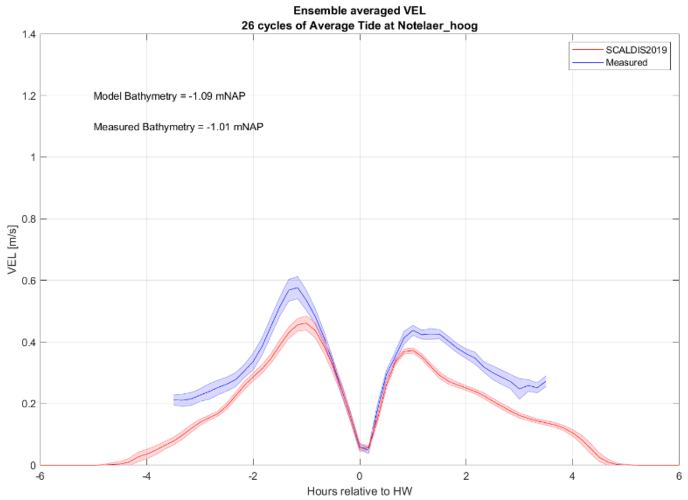


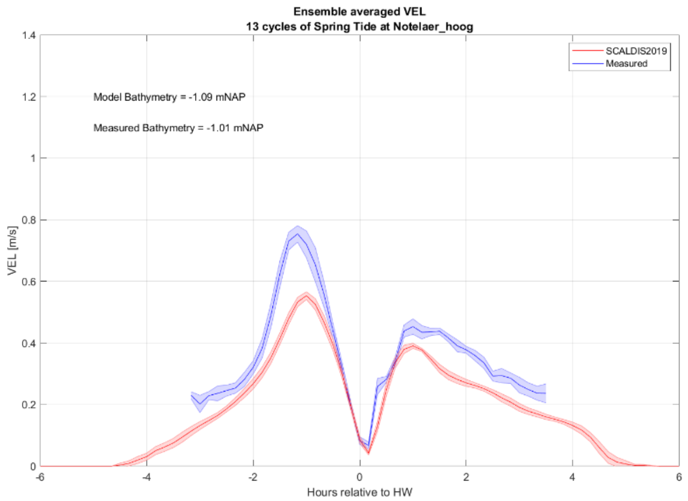


Notelaer_hoog

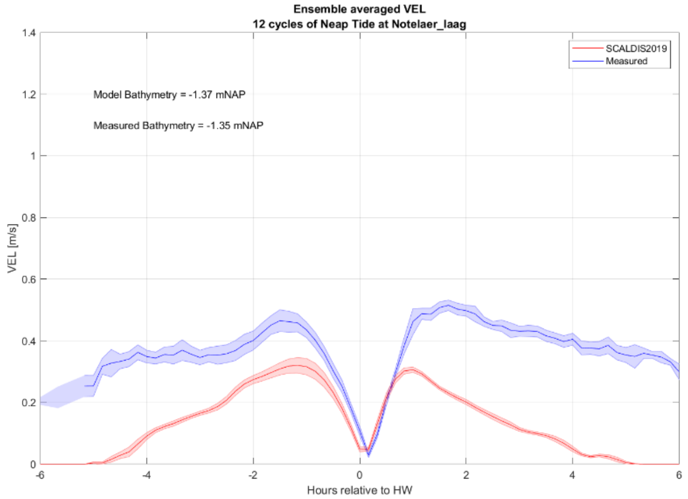


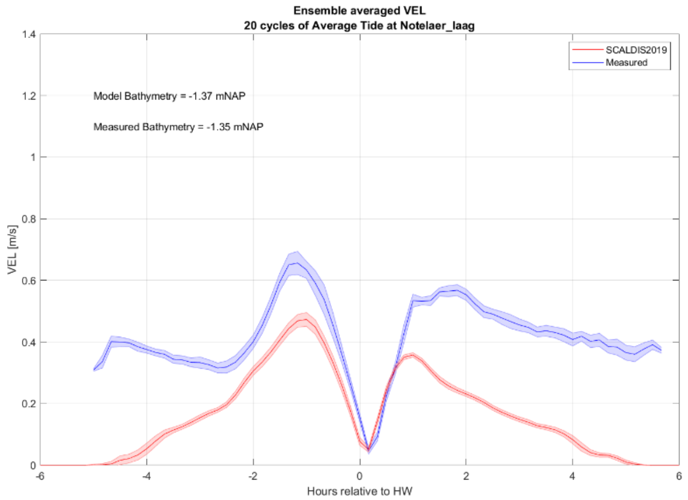

Ensemble averaged VEL
15 cycles of Neap Tide at Notelaer_hoog
SCALDIS2019
Measured
Model Bathymetry = -1.09 mNAP
Measured Bathymetry = -1.01 mNAP
VEL [m/s]
Hours relative to HW

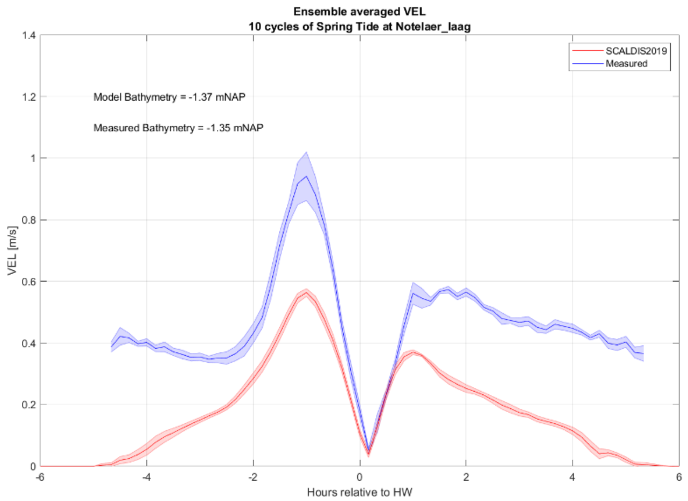

Ensemble averaged VEL
26 cycles of Average Tide at Notelaer_hoog
SCALDIS2019
Measured
Model Bathymetry = -1.09 mNAP
Measured Bathymetry = -1.01 mNAP
VEL [m/s]
Hours relative to HW


Ensemble averaged VEL
13 cycles of Spring Tide at Notelaer_hoog
SCALDIS2019
Measured
Model Bathymetry = -1.09 mNAP
Measured Bathymetry = -1.01 mNAP
VEL [m/s]
Hours relative to HW

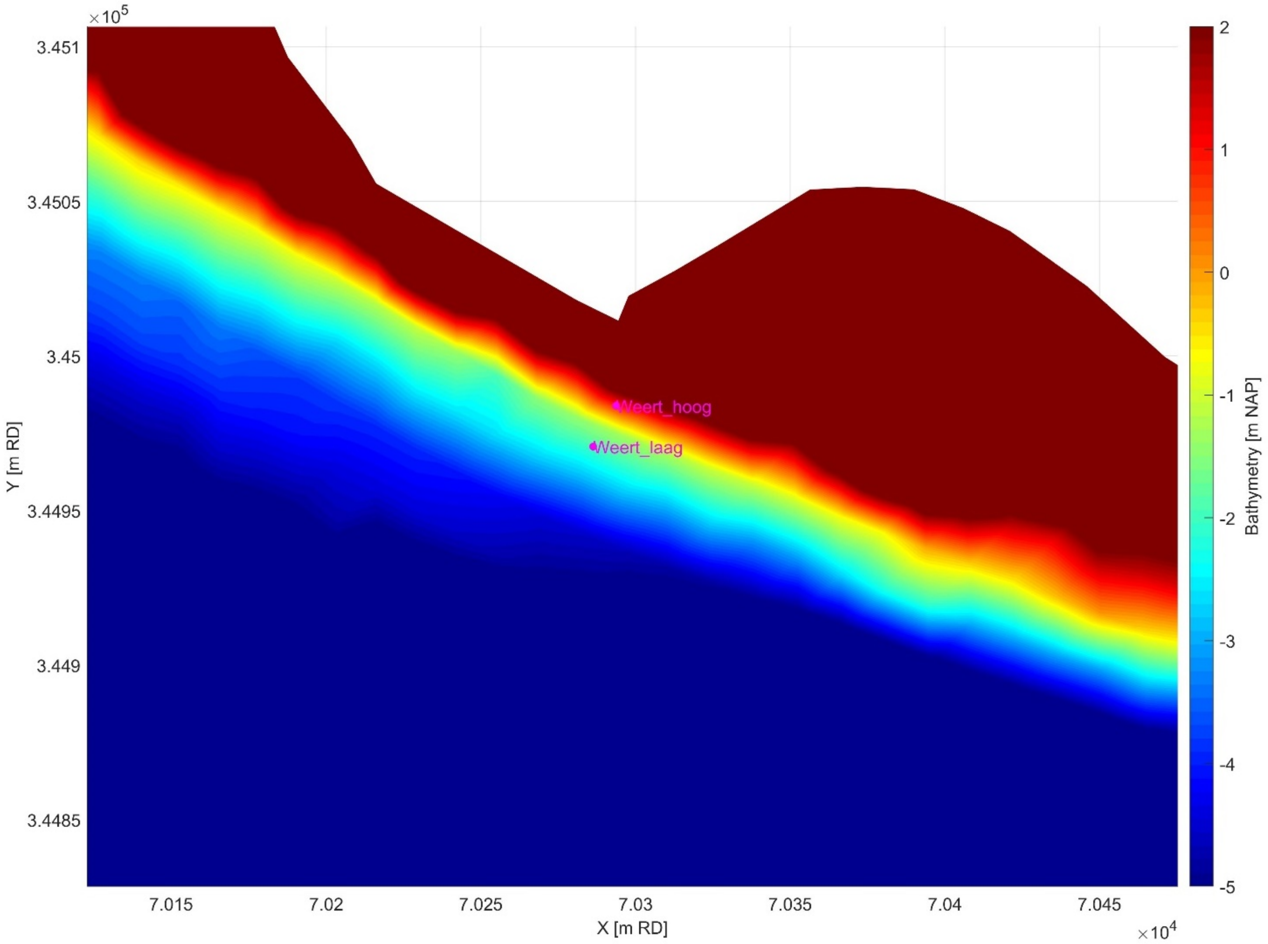
Notelaer_laag

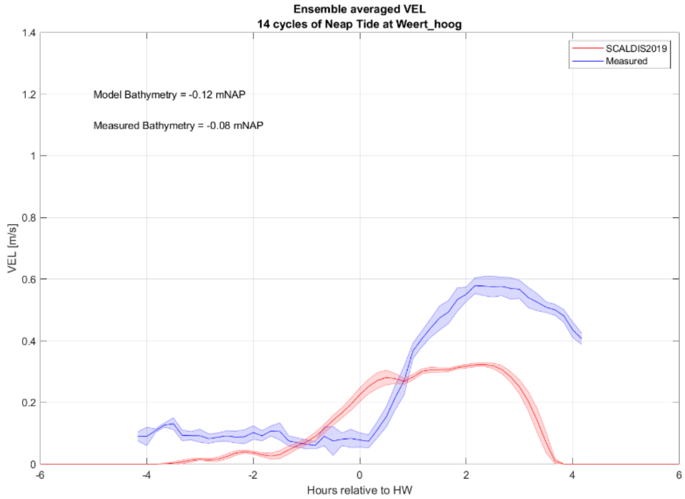


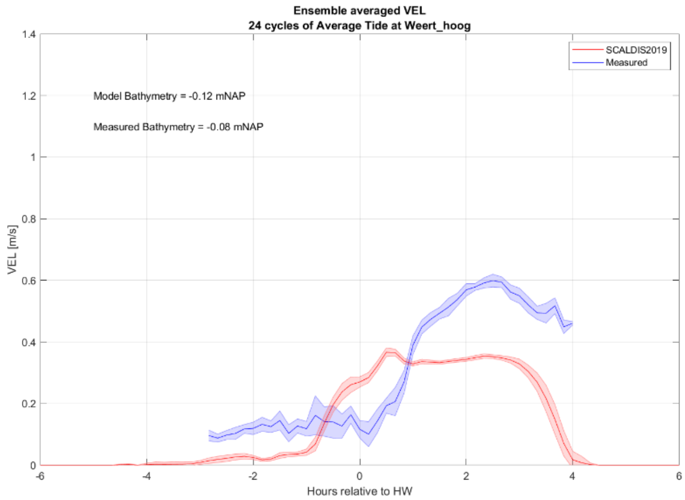


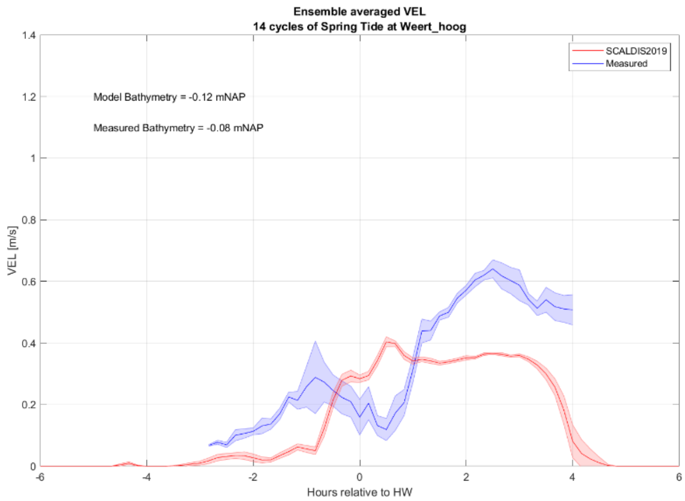


Weert_hoog

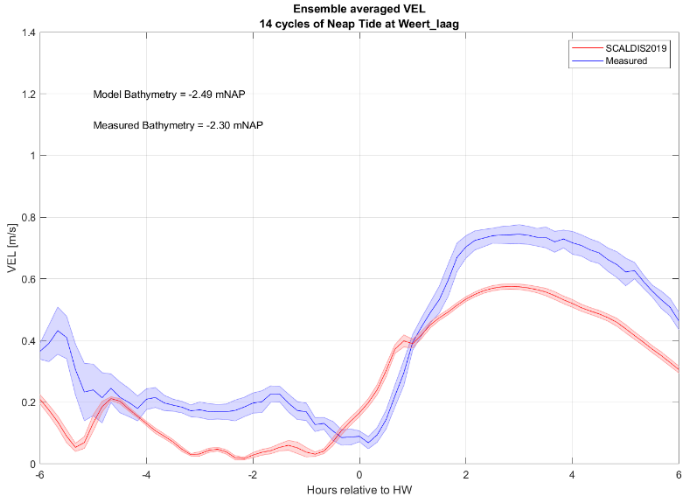

×10^5
3.451
3.4505
3.45
3.4495
3.449
3.4485
Y [m RD]
7.015
7.02
7.025
7.03
7.035
7.04
7.045
×10^4
X [m RD]
Weert_hoog
Weert_laag
2
1
0
-1
-2
-3
-4
-5
Bathymetry [m NAP]

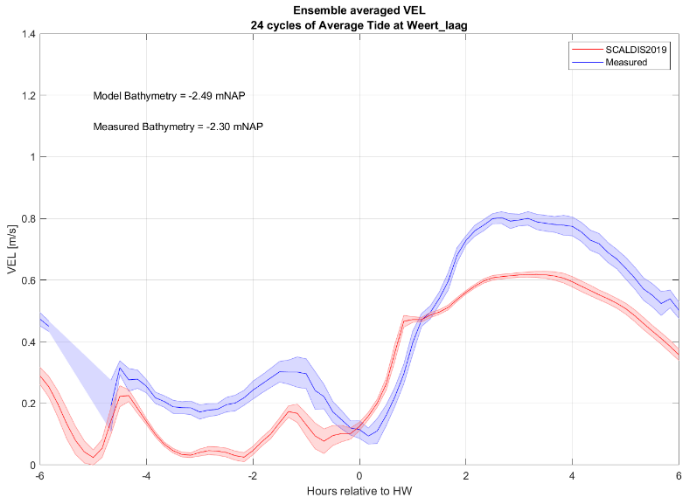

Ensemble averaged VEL
14 cycles of Neap Tide at Weert_hoog
SCALDIS2019
Measured
Model Bathymetry = -0.12 mNAP
Measured Bathymetry = -0.08 mNAP
VEL [m/s]
Hours relative to HW

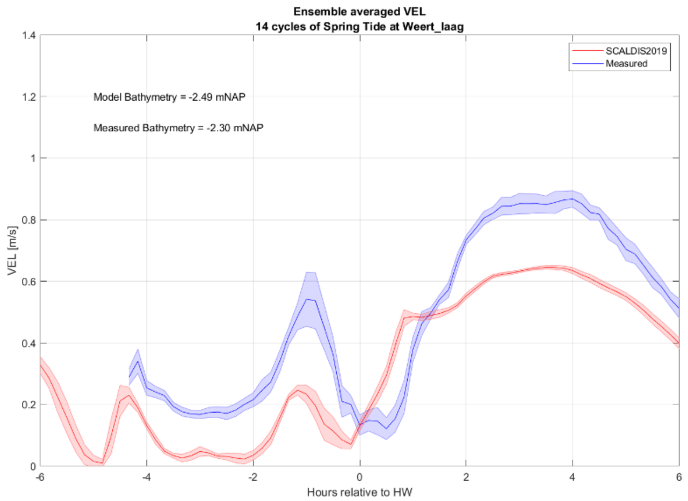

Ensemble averaged VEL
24 cycles of Average Tide at Weert_hoog
SCALDIS2019
Measured
Model Bathymetry = -0.12 mNAP
Measured Bathymetry = -0.08 mNAP
VEL [m/s]
Hours relative to HW


Ensemble averaged VEL
14 cycles of Spring Tide at Weert_hoog
SCALDIS2019
Measured
Model Bathymetry = -0.12 mNAP
Measured Bathymetry = -0.08 mNAP
VEL [m/s]
Hours relative to HW

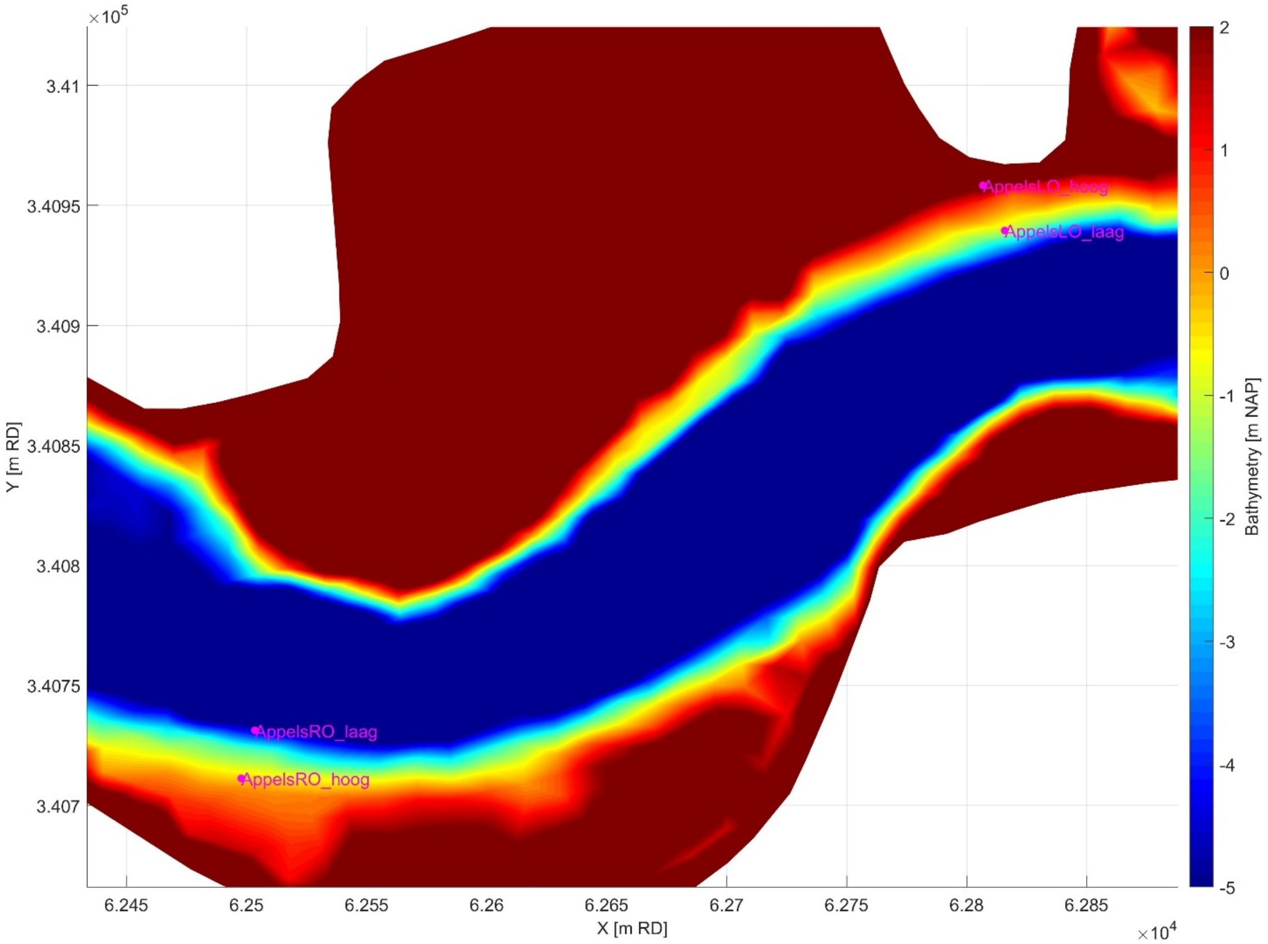
Weert_laag

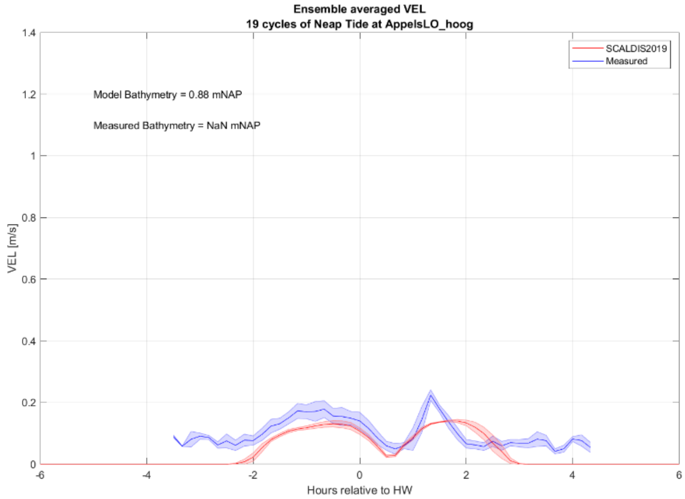

Ensemble averaged VEL
14 cycles of Neap Tide at Weert_laag
SCALDIS2019
Measured
Model Bathymetry = -2.49 mNAP
Measured Bathymetry = -2.30 mNAP
VEL [m/s]
Hours relative to HW

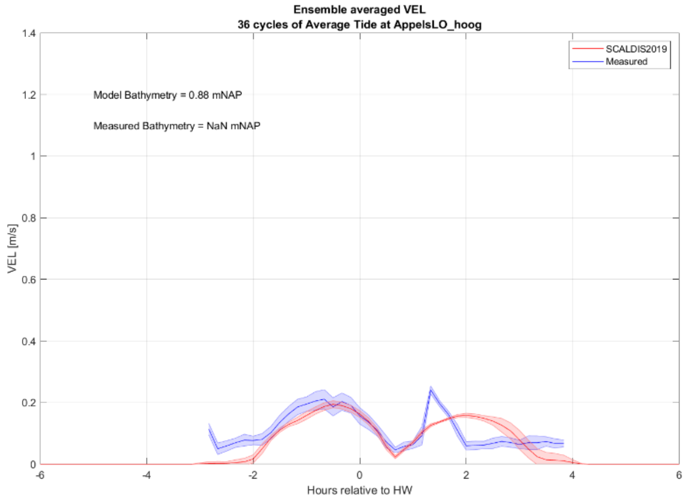

Ensemble averaged VEL
24 cycles of Average Tide at Weert_laag
SCALDIS2019
Measured
Model Bathymetry = -2.49 mNAP
Measured Bathymetry = -2.30 mNAP
VEL [m/s]
Hours relative to HW

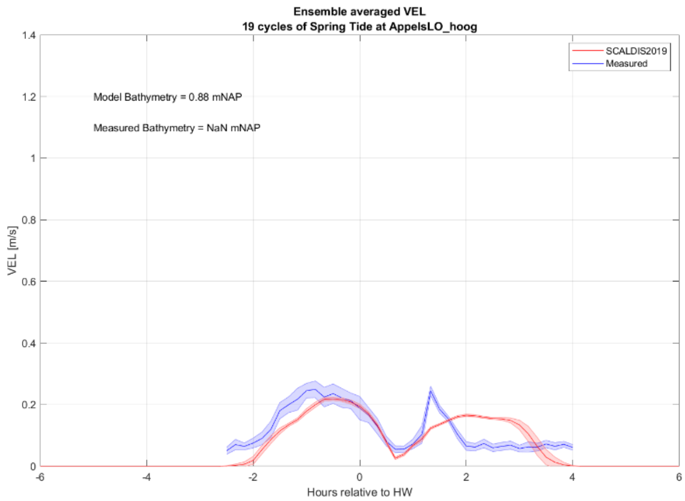

Ensemble averaged VEL
14 cycles of Spring Tide at Weert_laag
SCALDIS2019
Measured
Model Bathymetry = -2.49 mNAP
Measured Bathymetry = -2.30 mNAP
VEL [m/s]
Hours relative to HW

AppelsLO_hoog

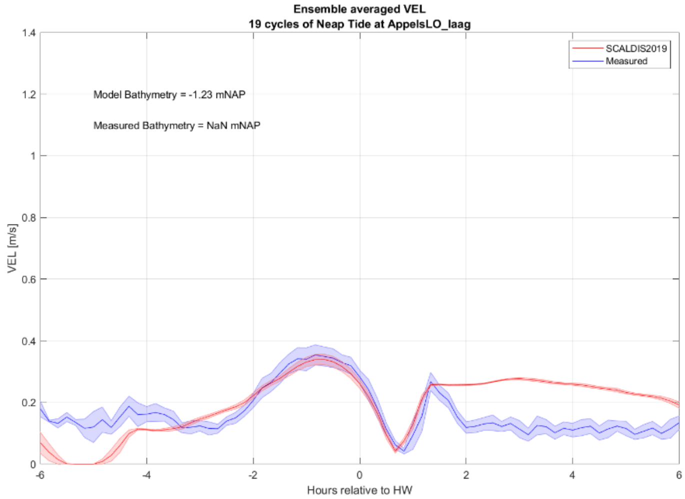


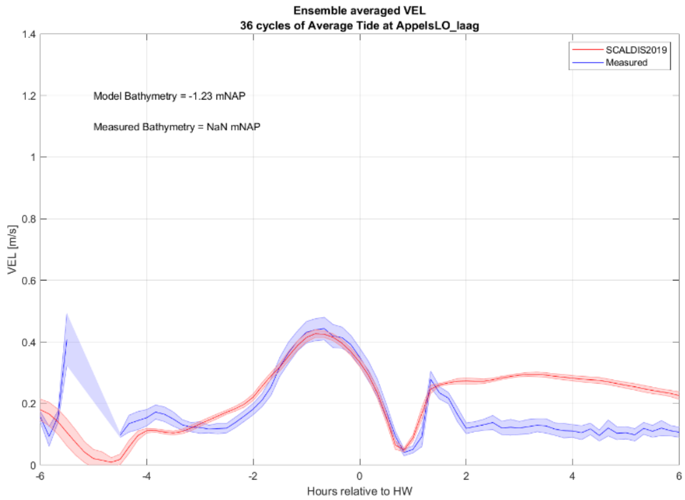

Ensemble averaged VEL
19 cycles of Neap Tide at AppelsLO_hoog
SCALDIS2019
Measured
Model Bathymetry = 0.88 mNAP
Measured Bathymetry = NaN mNAP
VEL [m/s]
Hours relative to HW

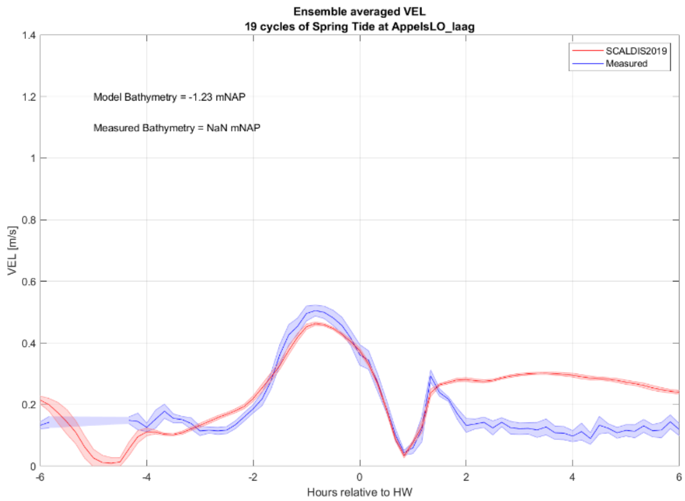

Ensemble averaged VEL
36 cycles of Average Tide at AppelsLO_hoog
SCALDIS2019
Measured
Model Bathymetry = 0.88 mNAP
Measured Bathymetry = NaN mNAP
VEL [m/s]
Hours relative to HW


Ensemble averaged VEL
19 cycles of Spring Tide at AppelsLO_hoog
SCALDIS2019
Measured
Model Bathymetry = 0.88 mNAP
Measured Bathymetry = NaN mNAP
VEL [m/s]
Hours relative to HW

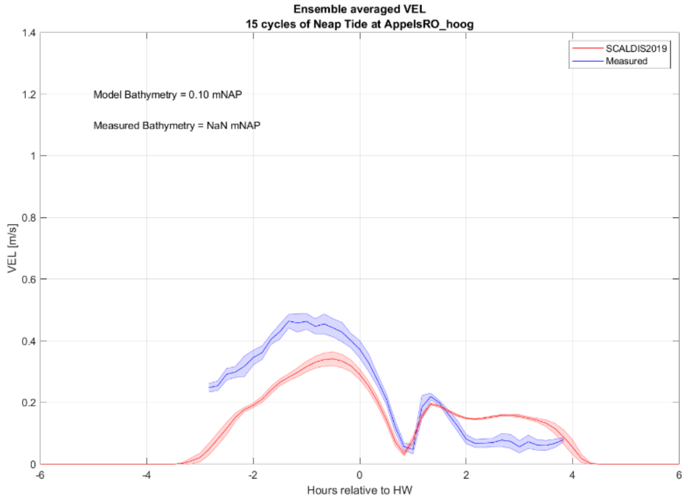
AppelsLO_laag

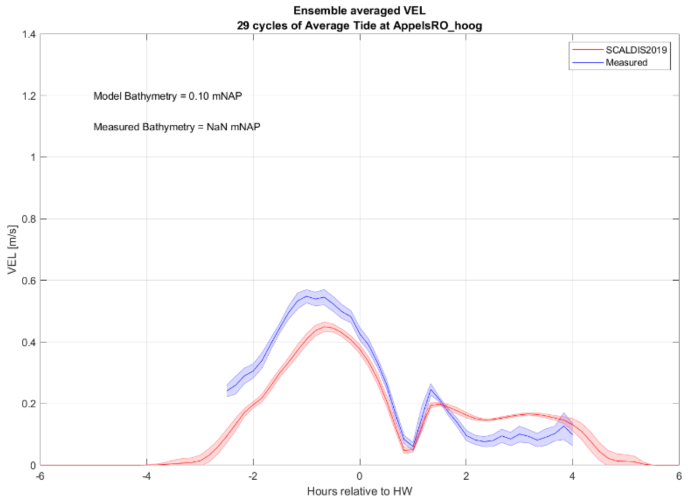


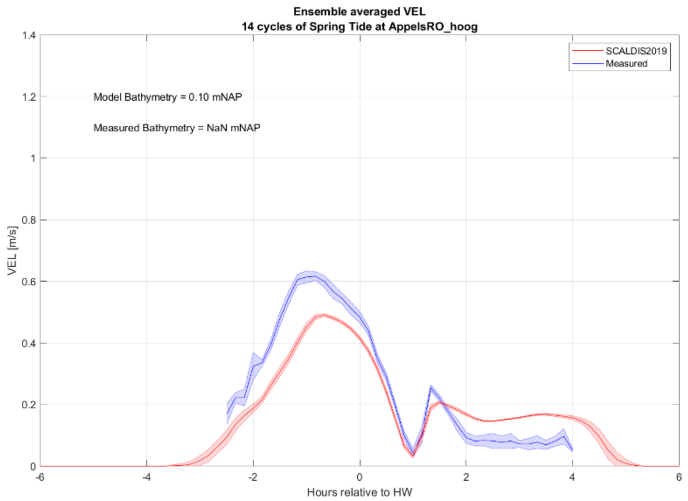




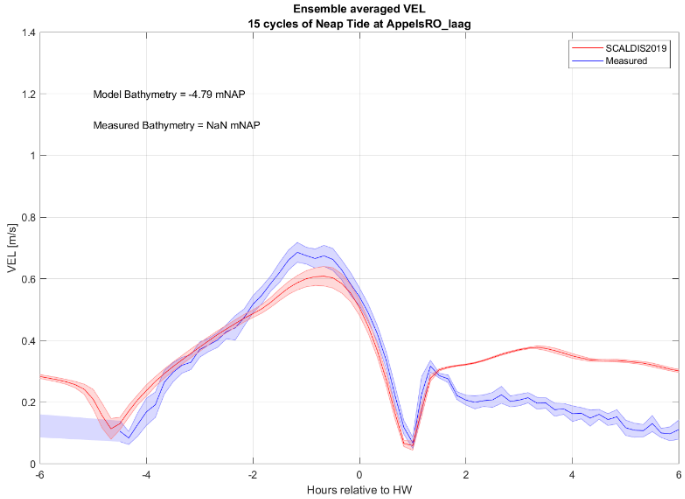
AppelsRO_hoog

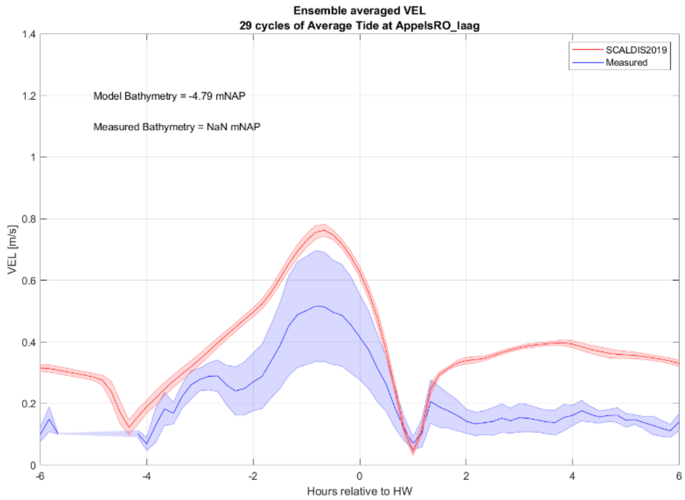


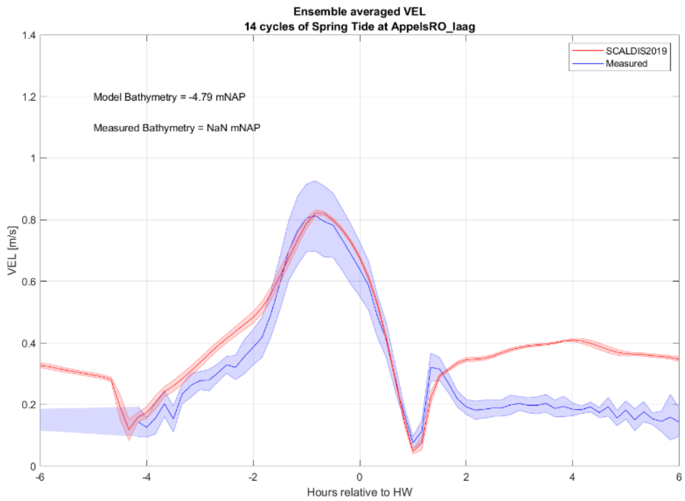




AppelsRO_laag







Annex 5: Salinity – Calibration period II

Figure 119 – Comparison of salinity at Overloop Hansweert.

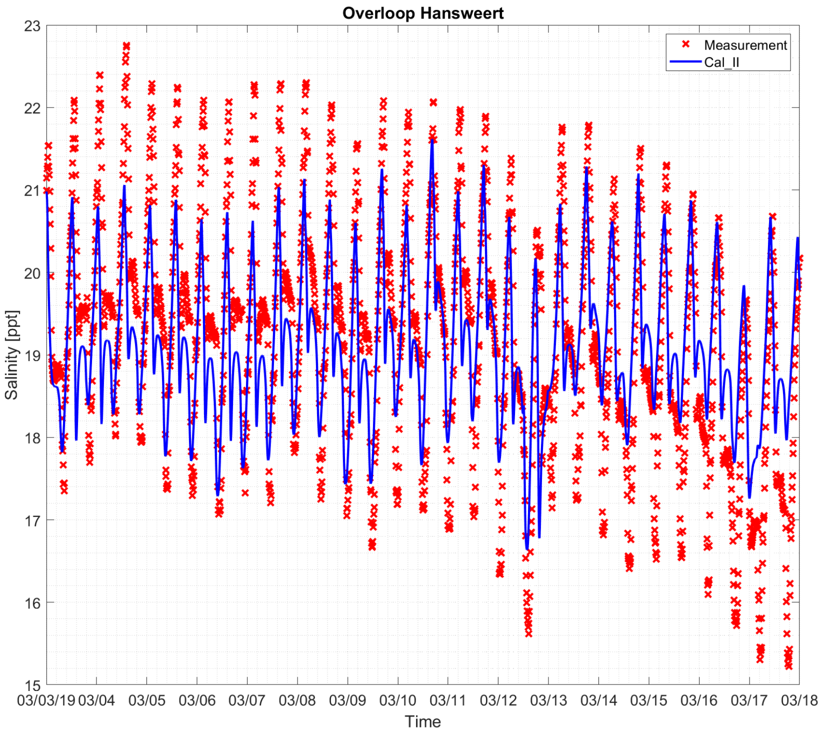


Figure 120 – Comparison of salinity at Prosperpolder.

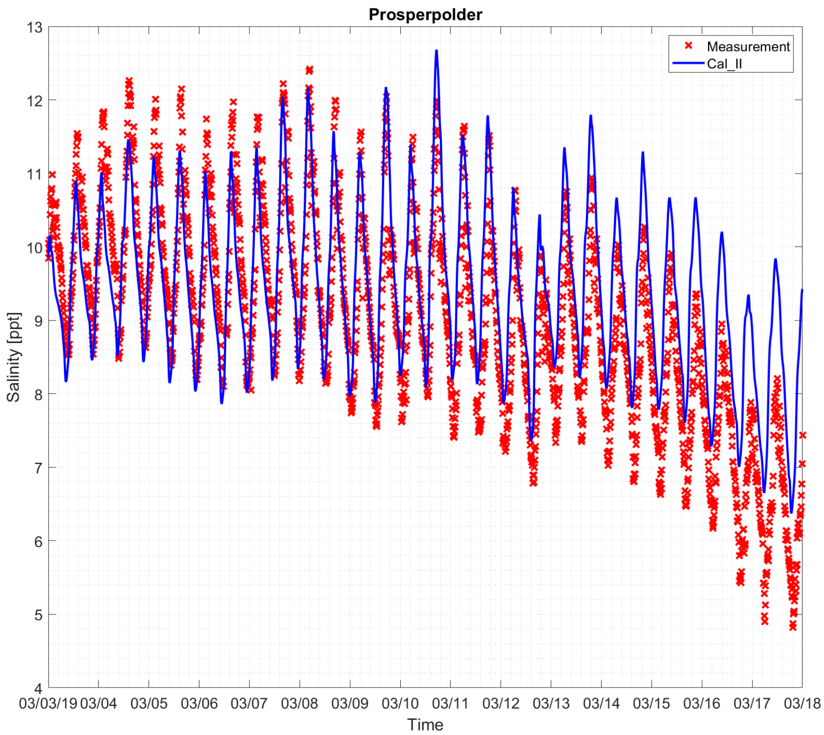


Figure 121 – Comparison of salinity at Lillo.

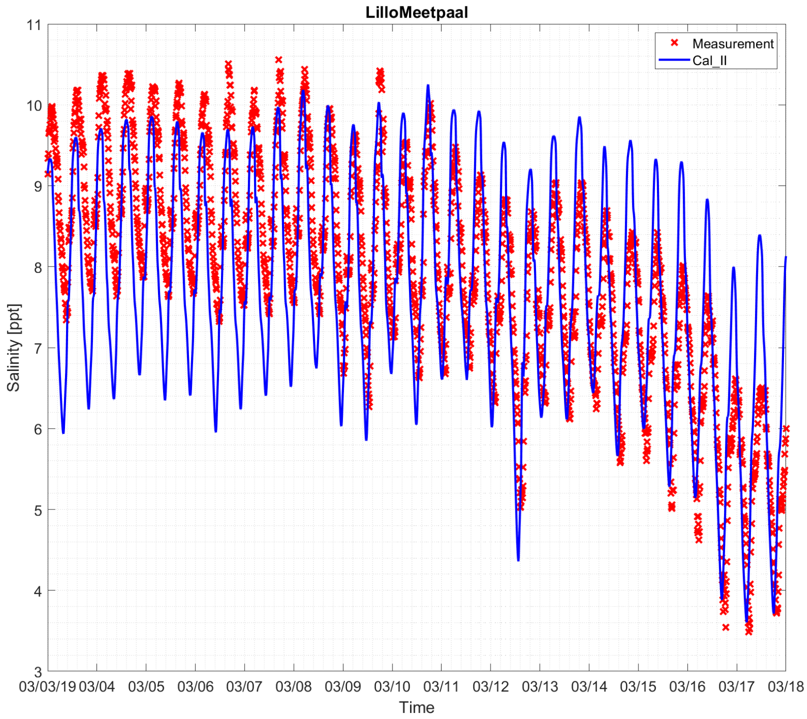


Figure 122 – Comparison of salinity at Oosterweel.

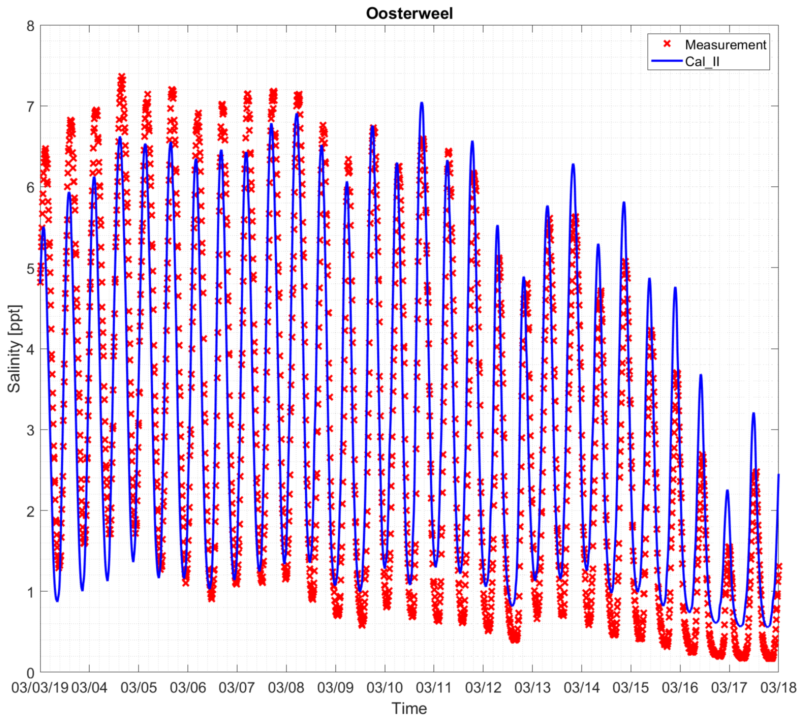


Figure 123 – Comparison of salinity at Kruibeke.

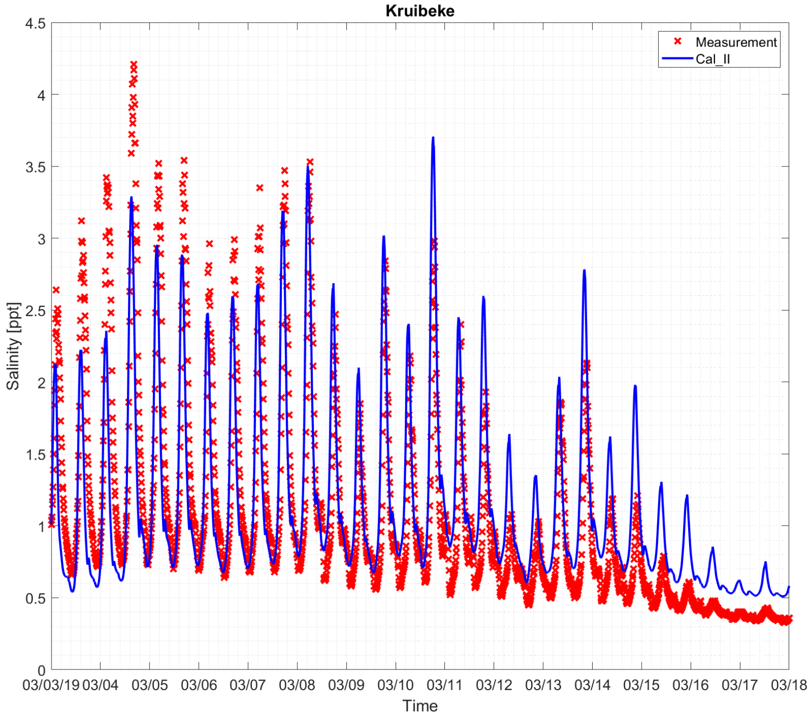
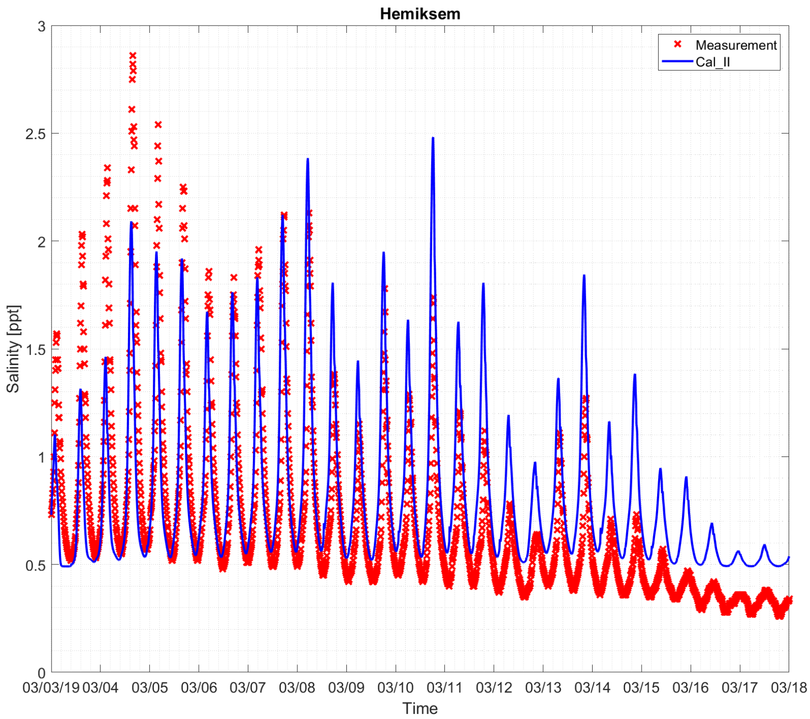


Figure 124 – Comparison of salinity at Hemiksem.



Annex 6: Salinity – Validation

Figure 125 – Comparison of salinity at Overloop Hansweert.

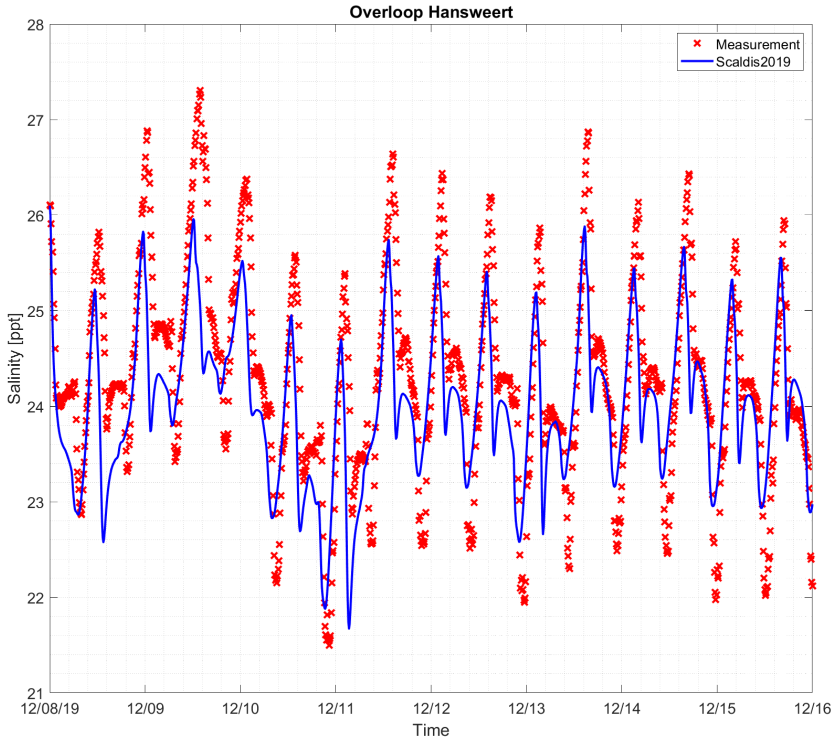


Figure 126 – Comparison of salinity at Prosperpolder.

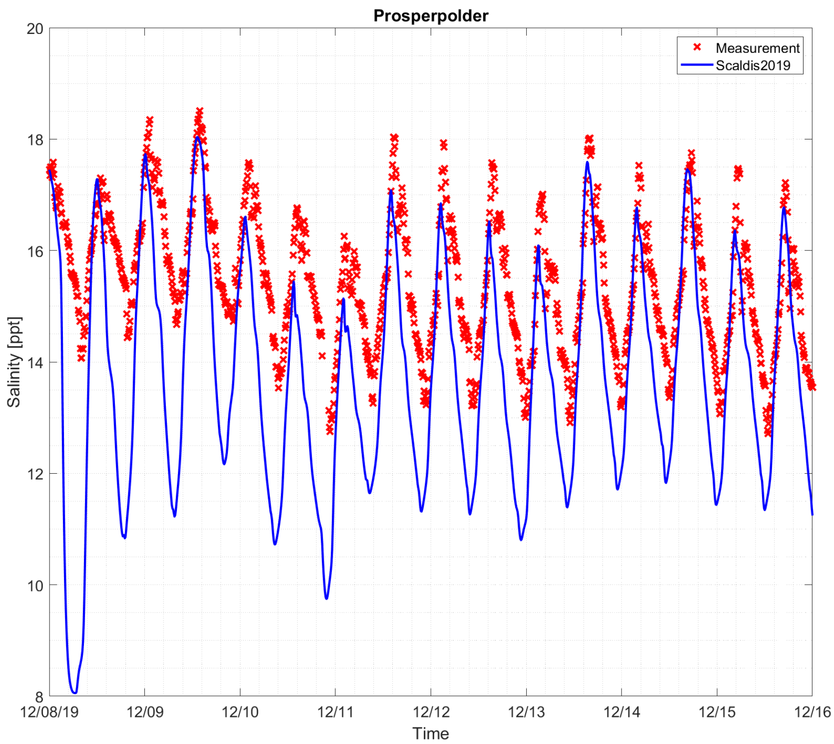


Figure 127 – Comparison of salinity at Lillo.

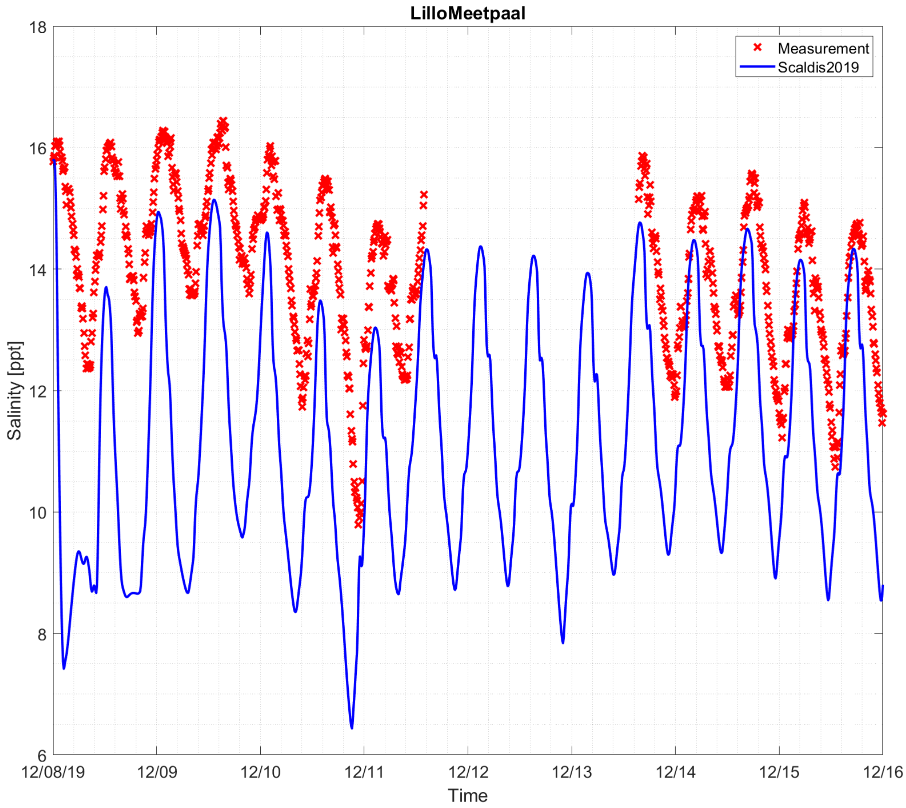


Figure 128 – Comparison of salinity at Oosterweel.

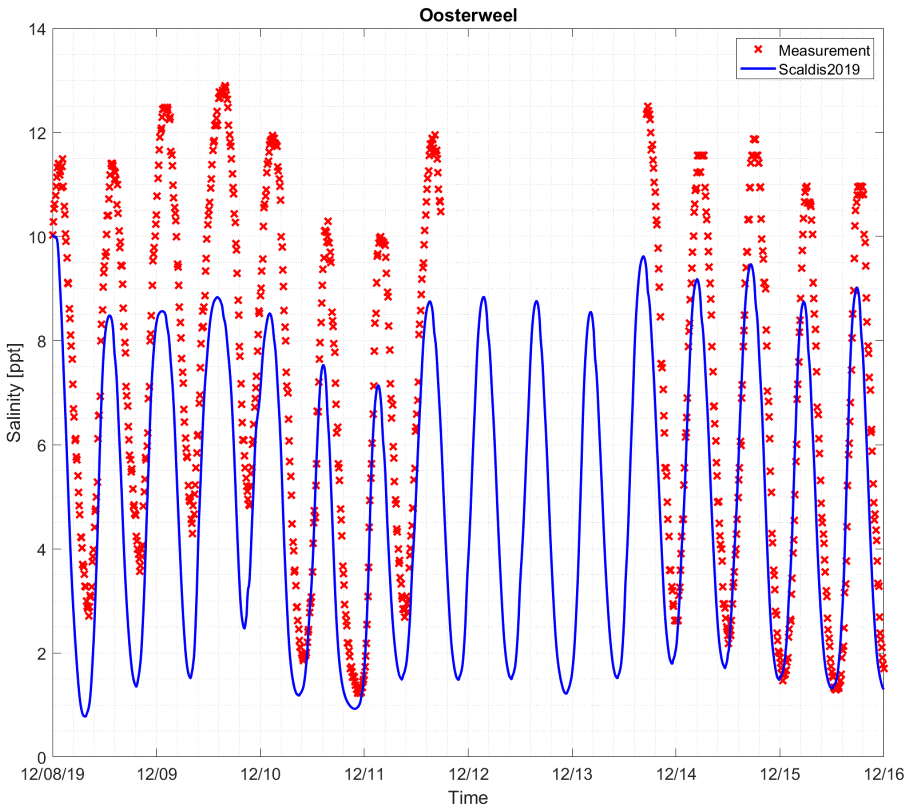


Figure 129 – Comparison of salinity at Kruibeke.

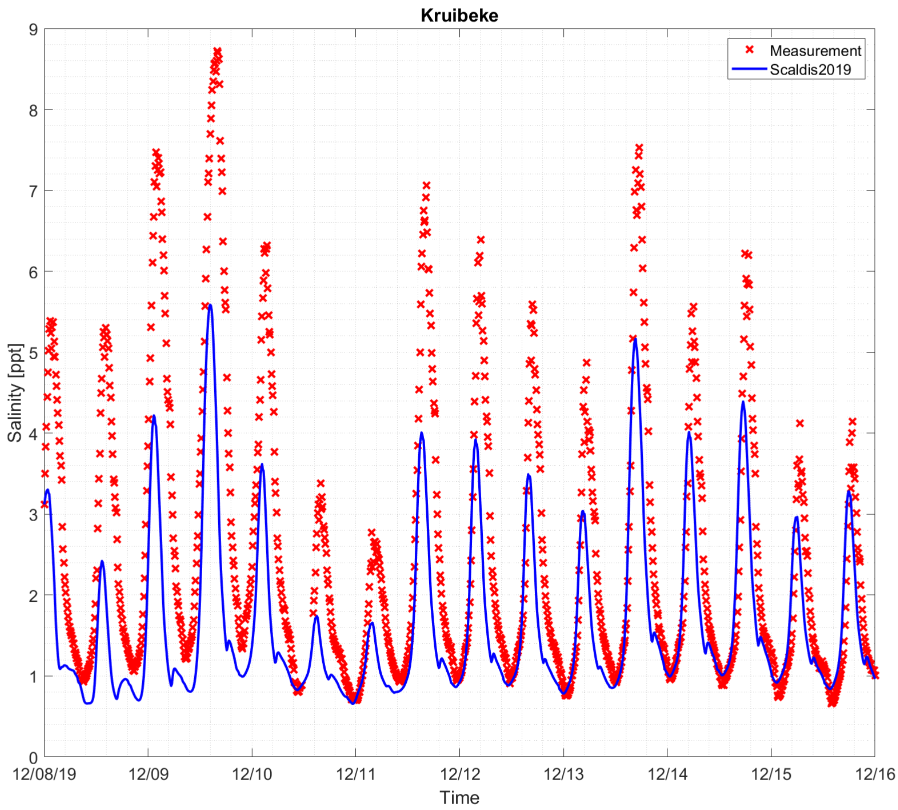
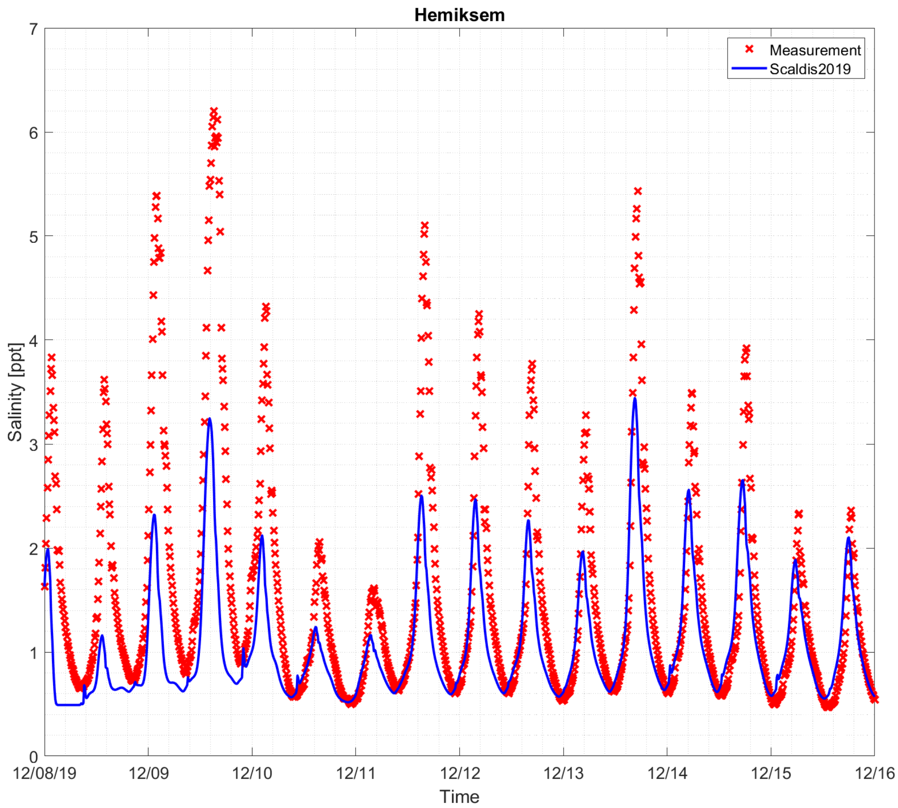


Figure 130 – Comparison of salinity at Hemiksem.



Annex 7: Parameters for culverts

Relaxation Number of culverts

0.8 110

I1 I2 CE1 CE2 CS1 CS2 LRGbus Haut1 CLP LBUS z1 z2 CV C56 CV5 C5 Ctrash Haut2 Fric length circ

397991 381707 0.5 0.5 1 1 1.5 1.5 2 0.2 0.15 0.15 1 10 1.5 6 0.1 1.5 0.015 30 0

399866 381686 0.5 0.5 1 1 1.5 1.5 2 0.2 0.15 0.15 1 10 1.5 6 0.1 1.5 0.015 30 0

399865 381686 0.5 0.5 1 1 1.5 1.5 2 0.2 0.15 0.15 1 10 1.5 6 0.1 1.5 0.015 30 0

397989 381675 0.5 0.5 1 1 1.5 1.5 2 0.2 0.65 0.65 1 10 1.5 6 0.1 1.5 0.015 30 0

399862 381611 0.5 0.5 1 1 1.5 1.5 2 0.2 0.65 0.65 1 10 1.5 6 0.1 1.5 0.015 30 0

381067 380939 0.9 0.5 1 1 2.7 1.45 0 0.2 2.05 1.85 0 10 1.5 6 1 2.25 0.015 9.5 0

381067 380969 0.9 0.5 1 1 2.7 1.3 0 0.2 2.15 1.85 0 10 1.5 6 1 2.25 0.015 9.5 0

381067 380969 0.9 0.5 1 1 2.7 1.3 0 0.2 2.15 1.85 0 10 1.5 6 1 2.25 0.015 9.5 0

411179 380939 0.9 0.5 1 1 2.7 1.6 0 0.2 1.85 1.85 0 10 1.5 6 1 2.25 0.015 9.5 0

411180 380939 0.9 0.5 1 1 2.7 1.6 0 0.2 1.85 1.85 0 10 1.5 6 1 2.25 0.015 9.5 0

409310 380971 0.9 0.5 1 1 2.7 1.6 0 0.2 1.85 1.85 0 10 1.5 6 1 2.25 0.015 9.5 0

381067 380939 0.5 0.5 1 1 3 1.1 2 0.2 0.35 -0.15 1 10 1.5 6 1 2.25 0.015 18.5 0

381067 380969 0.5 0.5 1 1 3 1.1 2 0.2 0.35 -0.15 1 10 1.5 6 1 2.25 0.015 18.5 0

381067 380969 0.5 0.5 1 1 3 1.1 2 0.2 0.35 -0.15 1 10 1.5 6 1 2.25 0.015 18.5 0

411179 380939 0.5 0.5 1 1 1.5 1.8 2 0.2 0.75 0.71 1 10 1.5 6 1 2.6 0.015 20 0

411180 380939 0.5 0.5 1 1 1.5 1.8 2 0.2 0.65 0.64 1 10 1.5 6 1 2.6 0.015 20 0

409310 380971 0.5 0.5 1 1 1.5 1.8 2 0.2 0.55 0.57 1 10 1.5 6 1 2.6 0.015 20 0

407507 379623 0.5 0.5 1 1 1.5 1.5 2 0.2 0.15 0.15 1 10 1.5 6 1 1.5 0.015 30 0

407507 379607 0.5 0.5 1 1 1.5 1.5 2 0.2 0.15 0.15 1 10 1.5 6 1 1.5 0.015 30 0

407508 379601 0.5 0.5 1 1 1.5 1.5 2 0.2 0.65 0.15 1 10 1.5 6 1 1.5 0.015 30 0

318109 154035 0.5 0.5 1 1 3 2.2 2 0.2 -1.85 -1.85 1 10 1.5 6 3 2.2 0.015 30 0

318110 153928 0.5 0.5 1 1 3 2.2 2 0.2 0.43 0.43 1 10 1.5 6 3 2.2 0.015 30 0

126167 126538 0.5 0.5 1 1 2 1 2 0.2 -0.47 -0.47 1 10 1.5 6 1 1 0.015 30 0

126028 126442 0.5 0.5 1 1 2 2.3 2 0.2 -0.39 -0.39 1 10 1.5 6 1 2.3 0.015 30 0

125956 126150 0.5 0.5 1 1 2 1.95 2 0.2 -0.36 -0.36 1 10 1.5 6 1 1.95 0.015 30 0

125898 126274 0.5 0.5 1 1 2 1.5 2 0.2 -0.74 -0.74 1 10 1.5 6 1 1.5 0.015 30 0

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125719 125918 0.5 0.5 1 1 2 0.86 2 0.2 0.16 0.16 1 10 1.5 6 1 0.86 0.015 30 0

349774 346087 0.5 0.5 1 1 1 1.9 0 0.2 1.65 2.95 0 10 1.5 6 0.8 0.6 0.015 13 0

349773 346068 0.5 0.5 1 1 1 1.9 0 0.2 1.65 2.65 0 10 1.5 6 0.8 0.9 0.015 13 0

349772 346010 0.5 0.5 1 1 1 1.9 0 0.2 1.65 2.35 0 10 1.5 6 0.8 1.2 0.015 13 0

349775 345984 0.5 0.5 1 1 2 1.5 2 0.2 -0.85 -0.85 1 10 1.5 6 0.1 1.5 0.015 40 0

351620 341738 0.5 0.5 1 1 2 1.5 2 0.2 -1.05 -1.05 1 10 1.5 6 0.1 1.5 0.015 30 0

391887 385972 0.5 0.5 1 1 3 2.2 2 0.2 1.15 1.15 1 10 1.5 6 0.1 2.2 0.015 30 0
393762 385969 0.5 0.5 1 1 2 1.5 2 0.2 0.1 0.1 1 10 1.5 6 0.1 1.5 0.015 30 0
202836 189700 0.9 0.5 1 1 2.6 1.8 0 0.2 1.85 1.85 0 10 0 6 1 1.8 0.015 18 0
203651 191061 0.9 0.5 1 1 2.6 1.8 0 0.2 1.85 1.85 0 10 0 6 1 1.8 0.015 18 0
202716 189469 0.9 0.5 1 1 2.6 1.8 0 0.2 1.85 1.85 0 10 0 6 1 1.8 0.015 18 0
202623 191360 0.9 0.5 1 1 2.6 1.8 0 0.2 1.85 1.85 0 10 0 6 1 1.8 0.015 18 0
203581 189930 0.9 0.5 1 1 2.6 1.8 0 0.2 1.85 1.85 0 10 0 6 1 1.8 0.015 18 0
202935 192005 0.9 0.5 1 1 2.6 1.8 0 0.2 1.85 1.85 0 10 0 6 1 1.8 0.015 18 0
204052 190854 0.9 0.5 1 1 2.6 1.8 0 0.2 1.85 1.85 0 10 0 6 1 1.8 0.015 18 0
203855 192597 0.9 0.5 1 1 2.6 1.8 0 0.2 1.85 1.85 0 10 0 6 1 1.8 0.015 18 0
203569 191599 0.9 0.5 1 1 2.6 1.8 0 0.2 1.85 1.85 0 10 0 6 1 1.8 0.015 18 0
203583 192592 0.9 0.5 1 1 2.6 1.8 0 0.2 1.85 1.85 0 10 0 6 1 1.8 0.015 18 0
203806 191476 0.9 0.5 1 1 2.6 1.8 0 0.2 1.85 1.85 0 10 0 6 1 1.8 0.015 18 0
203095 193003 0.9 0.5 1 1 2.6 1.8 0 0.2 1.85 1.85 0 10 0 6 1 1.8 0.015 18 0
203742 191208 0.9 0.5 1 1 2.6 1.8 0 0.2 1.85 1.85 0 10 0 6 1 1.8 0.015 18 0
204190 193220 0.9 0.5 1 1 2.6 1.8 0 0.2 1.85 1.85 0 10 0 6 1 1.8 0.015 18 0
203950 191593 0.9 0.5 1 1 2.6 1.8 0 0.2 1.85 1.85 0 10 0 6 1 1.8 0.015 18 0
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