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Een geïntegreerde aanpak voor de Durme

Sub report 3 – Set-up and calibration of a detailed Durme model

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Set-up and calibration of a detailed Durme model

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Abstract

De Vlaamse Waterweg (DVW) wants to evolve from the current management of the Durme to a more sustainable management. Two problems are identified. First of all the tidal channel is characterized by a continuous sedimentation. Secondly, a combination of spring or storm tide with intense rainfall leads to too high water levels (with increased inundation risks), both in the tidal and non-tidal part of the Durme.

Within the framework of the actualised Sigmaplan, important management works in the Durme valley are foreseen. In the near future, several areas will be depoldered (Groot Broek and Klein Broek) and a controlled reduced tide area is built (De Bunt). Next to the extent of the river valley the problems in the river channel itself are also tackled, by carrying out important dredging work, to counteract the sedimentation.

To assess the impact of the different measures within the Sigmaplan on the hydrodynamics and sediment dynamics of the Durme area, it is necessary to construct a numerical model that has a high resolution to capture well the area dynamics. In this project, a new and detailed hydrodynamic model was set up for the Durme area in the Telemac software. This model covers the whole tidal Durme valley and extents in the Zeeschelde from Sint-Amands till Temse. The model has been calibrated with the available water levels in the Durme and Schelde, and also a few available measurements of velocity. Both situations before and after the dredging works were considered in the calibration setup. The calibrated model will be used to assess the impact of (potential) management works on the system behaviour.

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1 Introduction

1.1 The project

De Vlaamse Waterweg (DVW) wants to evolve to a more sustainable management of the Durme tributary. The Durme is subject to high sedimentation rate, which leads to high maintenance costs for regular dredging works. Within the project 19_016: “An integrated approach for the Durme”, these evolutions are analysed and quantified, by bathymetric and tidal analysis. To assess the impact of the different (possible) measures within the Sigmaplan, the construction of a new and detailed numerical model is appropriate.

1.2 Model goals

This report discusses the set-up and calibration of a new hydrodynamic model for the Durme, more precisely the part of the Durme subject to tides, ranging from Tielrode to Lokeren.

In order to set-up a new model, it is important to state clearly what the intended uses for the model will be. These criteria will support design decisions in the model setup, and set the targets for the model calibration.

The detailed model of the Durme should be able to address the following research questions:

1. Better understanding of hydrodynamics and sediment dynamics of the Durme tributary, both in terms of historical silting up and the reaction of the system to recent dredging works
2. Assess the possible mitigation measures to reduce siltation:
    a. Steering of the upstream discharge: optimal pumping regime
    b. Effects of/on the design of the surrounding Sigma areas
3. Assess the effect of channel geometry on hydrodynamics: re-connection of the old Durme tributary

Research questions 2b and 3 determine the extent of the model grid (discussed in §5.1)

Research question 1 requires that the model gives an accurate description of the hydrodynamics, both in a historical situation and in the current situation. The calibration strategy employed in this report (see §7.1) aims to find a model parameterization that gives reliable results under different bathymetries (one representing the situation in 2010 and one in 2019).

2 Units and reference plane

The horizontal coordinate reference used in the model is RD Parijs (EPGS code 28992). The vertical coordinate system (e.g. depths, heights and water levels) is expressed in m TAW (“Tweede Algemene Waterpassing”). The time zone used in the model is MET or winter time (UTC + 1).

3 System description

3.1 The Durme catchment

The Durme river is a tributary of the Scheldt river with a length of approximately 18 km. At the upstream end at Lokeren, a dam was built. The current location of the dam was fixed in 1973, more recent (in 2015) a new pumping station was constructed. This dam stops the tidal influence in the river. At the downstream end, the Durme joins the Scheldt at Tielrode/Driegoten. At this location, the tidal amplitude in the Scheldt estuary reaches its maximal value.

At Lokeren the Durme is around 10 to 20 m wide, whereas at Tielrode the channel is approximately 100 m wide during high waters. Due to the high sedimentation, the Durme is becoming very shallow going upstream. This has serious implications on the tidal penetration in the Durme and the characteristics of the tidal curve. At Tielrode the tidal curve is still sinusoidal, more upstream there is a very short flood phase, and therefore a very long ebb phase. The ebb phase consists of a sharp decrease of the water level in the beginning of the ebb phase, followed by a period where the water levels remain almost stable (see e.g. Meire et al., (2024a).

Due to the high sedimentation rates in the Durme, several dredging campaigns have been conducted in the Durme. The last campaign has been performed in the period 2012 to 2014, where dredging has been done from Tielrode up to Waasmunster Brug (see e.g. Meire et al., 2024b).

3.2 Sigma areas

in Figure 1 an overview of the location of different (present and intended) Sigma areas, which are connected to the Durme river itself, is given. In Table 1 an overview of the characteristics of these areas is given.

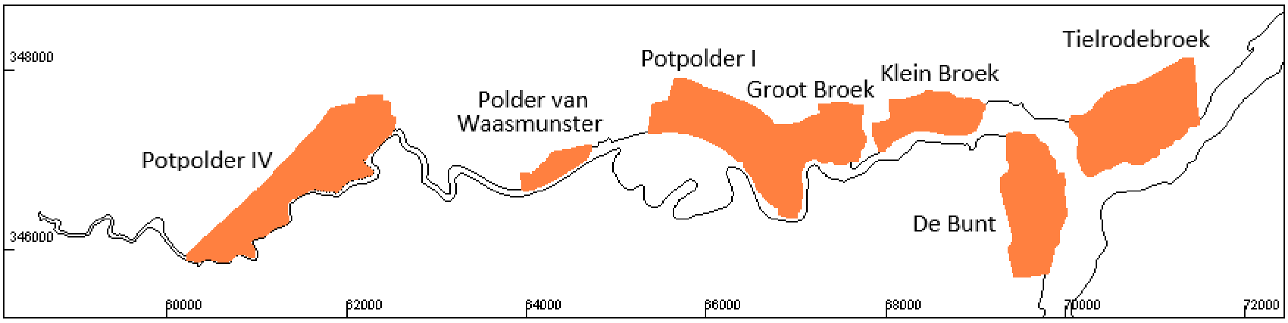


Figure 1 – Sigma areas (in orange) in the Durme valley, connected to the river

Table 1 – Overview of the Sigma areas within the Durme valley
(FCA = Flood Control Area, CRT = Controlled Reduced Tide, TBD = To be Decided)

Area	Type	Area (ha)	In use since/from
Tielrodebroek	FCA	96 ha	1992
De Bunt	FCA / CRT	84.5	
Klein Broek	depoldering	32.8 ha	2023
Groot Broek	depoldering	64.2 ha	
Potpolder I	FCA => depoldering		
Polder van Waasmunster	depoldering		
Potpolder IV	FCA	48,5 ha	

3.2.1 Tielrodebroek

Tielrodebroek is a flood control area since 1992 with a surface area of 96 ha (Van Ryckegem et al., 2006). It is situated on the left bank at the mouth of the Durme (Figure 1). The dike at the Scheldt river side was lowered with the crest level varying between 6.75 and 6.95 mTAW (Smolders et al., 2017). There are four culverts implemented (for details: Smolders et al., 2017). A transition of the FCA Tielrode to a FCA with CRT is foreseen within the Sigma plan, however this is a 2025 project.

3.2.2 De Bunt

De Bunt is a flood control area with controlled reduced tide (CRT), currently under construction, with a surface area of 84.5 ha. It is situated on the right bank at the mouth of the Durme (Figure 1, Figure 2). There is one inlet-outlet construction on the right bank of the Durme, close to the mouth. A second outlet construction is planned in the south of the area, connecting de Bunt directly to the Scheldt (IMDC, 2019a).

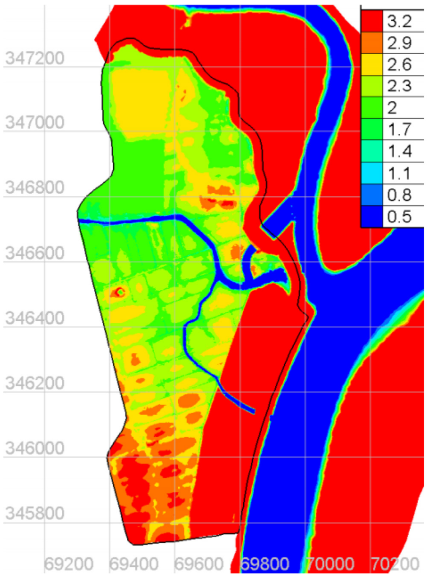


Figure 2 – Planview of de Bunt area (IMDC, 2019a)

3.2.3 Klein Broek

Klein Broek (Figure 1, Figure 3) is an area which is recently depoldered (2023). Two connections with the Durme are foreseen, where the original dikes are breached. The total area is approximately 33 ha. In 2023 the dike between Klein Broek and the Durme was breached.

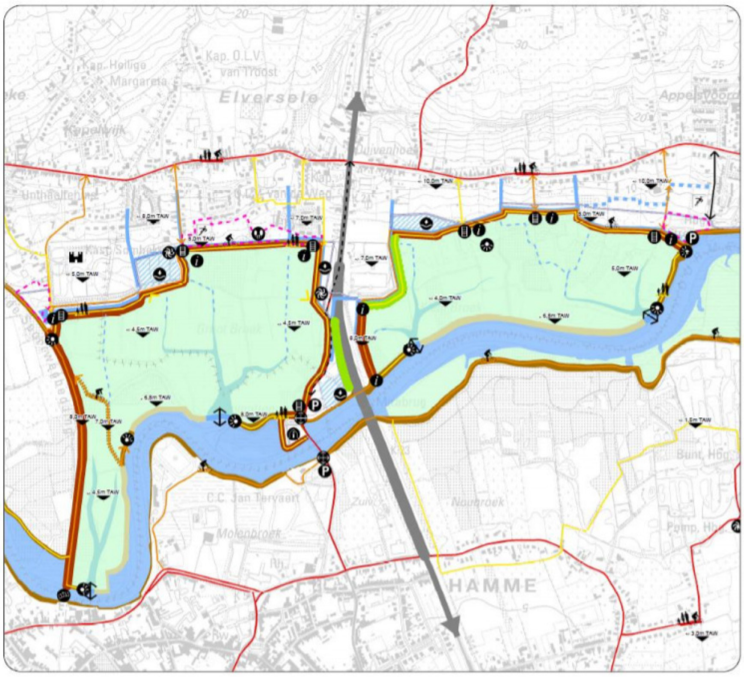


Figure 3 – Implementation of the Klein Broek (east) and Groot Broek (west)

3.2.4 Groot Broek

Groot Broek (Figure 1, Figure 3) is an area which will be depoldered in the near future. In fact, it consists of two areas, which are not connected. Each area will be connected to the Durme through one breach.

3.2.5 Potpolder I & Polder van Waasmunster

Potpolder I (or the Sombeekse Meersen) and Polder van Waasmunster (Figure 1) have been originally designed as depoldered areas. Nowadays Potpolder I is functioning as a flood control area, but a depoldering is foreseen within the actualized Sigmaplan.

3.2.6 Potpolder IV

Potpolder IV will be further implemented as a flood control area, as this is also today the function of this area. The total area of the region which is covered in the model is approximately 115 ha. The total area of the currently designed flood control area is 48,5 ha (IMDC, 2019c).

4 Available measurements

This chapter summarizes the relevant data available for the set-up and calibration of the hydrodynamic model of the Durme.

4.1 Bathymetric data

In Meire et al. (2024, b) four different topo-bathymetric data sets were composed, based on the available lidar and bathymetric data. The details of these topo-bathymetric data are summarized in Table 2. One of the topo-bathymetric coverings (2010) dates from before the capital dredging, one dates from the period of these capital dredging works (2013), and two measurements (2018 and 2020) are available from after these measures.

The construction of the model bathymetries and data sets used are presented in detail in §5.2

Table 2 – Overview of composed topo-bathymetric data for the Durme

Topo – bathy	**Bathy**	**Lidar**	**Comment**
2010	2010	2011	Before dredging works
2013	2013	2013	During/after dredging works
2018	2017	2019	After dredging works (5 y)
2020	2020	2019	After dredging works (7y)

4.2 Water levels

There are several tidal gauges located within the model domain (see Figure 4). The measured water levels at these locations were used both as the boundary condition and for thecalibration of the model (see §5.3, §7)

In the Sea Scheldt, three tidal gauges are available within the model domain Sint-Amands, Driegoten, Temse (Figure 4). The water levels at Sint-Amands and Temse were used as boundary condition of the hydrodynamic model.

In the Durme tributary, there are five water level stations: Tielrode, Waasmunster-Brug, Waasmunster-Manta, Zele and Dam Lokeren (Figure 4). These water level stations, together with their distance from the mouth of the Durme are summarized in Table 3. However, some changes have occurred over time. Additionally to the previously mentioned locations, also measurements at Hamme are available, but only from 2020 onwards. At the upstream locations, no determination of the HW and LW is foreseen. As such, the continuous time series are used.

In summary, water levels at five tidal gauges in the Durme and one tidal gauge in the Scheldt can be used for the calibration of the model.

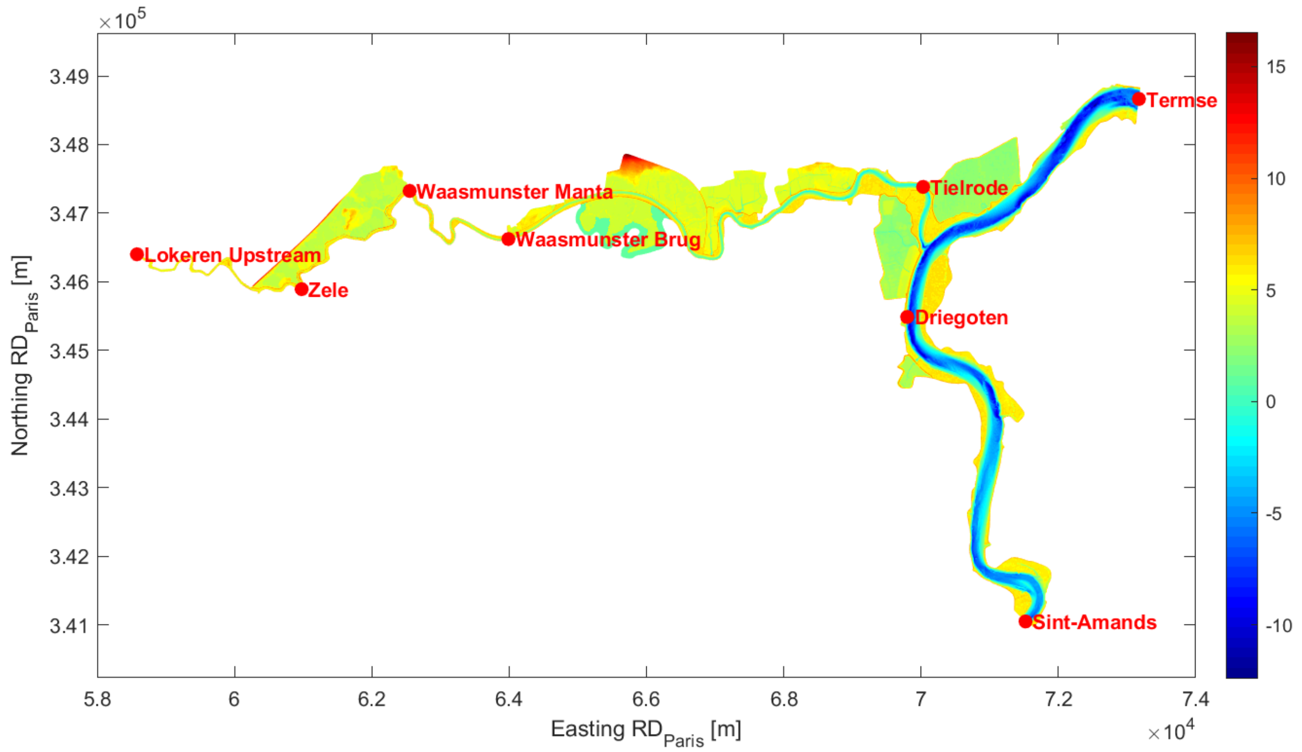


Figure 4 – Gauging stations along the Durme and in the Scheldt, used in the study

Table 3 – Overview of tidal gauges along the Durme
(WL = Waterbouwkundig Labo, EMT = Elektromechanica en Telematica, VMM = Vlaamse Milieu Maatschappij)

Stadftion	Km (from mouth)	Data supplier	2019	2010	Remarks
Tielrode	1.0	WL	10 min	HWLW	
Hamme	3.5	WL	x	x	
Waasmunster - Brug	8.9	WL	10 min	HWLW	
Waasmunster - Manta	11.4	WL	10 min	10 min	
Zele	14.5	WL	5 min	HWLW	
Dam Lokeren (upstream)	17.9	EMT	5 min	x	Pumping station built in 2015
		VMM	15 min	15 min	

Table 4 gives an overview of the main tidal characteristics of the average tides: high water (HW), low water (LW) and tidal range (TR) for the period 2011-2015 for the locations within the considered domain measured by HIC, Flanders Hydraulics.

Table 4 – Overview of tidal data (High Water (HW), Low Water (LW) and Tidal Range (TR)) of the average tides during the period 2011-2015 for locations within the considered domain (from Hertoghs et al., 2018)

Location	***HW [mTAW]***	***LW [mTAW]***	***TR [m]***
Boven - Zeeschelde			
Temse	*5.59*	*0.07*	*5.51*
Driegoten	*5.69*	*0.19*	*5.50*
Sint-Amands	*5.59*	*0.34*	*5.25*
Durme			
Tielrode	*5.61*	*0.09*	*5.52*
Waasmunster - Brug	*5.82*	*3.23*	*2.60*
Waasmunster - Manta	*NA*	*NA*	*NA*
Zele	*5.29*	*4.80*	*0.49*
Dam Lokeren	*NA*	*NA*	*NA*

4.3 Discharge

An overview of the different sources of discharge into the Durme is given in Figure 5. At the upstream end, the discharges of the Bovendurme, the Ledebeek and the wastewater treatment plant enter the Durme. The dam between the Bovendurme and Durme has 2 jacks, with a respective capacity of 5 and 2.5 m^3/s. The pumping station of the Ledebeek has 5 jacks, with a total capacity of 7 m^3/s (2 jacks with a capacity of 0.5 m^3/s and 3 jacks with a capacity of 2.0 m^3/s). Apart from the theoretical pumping capacity, no information is available on the effective pumped discharges. For the wastewater treatment plant at Lokeren, daily discharges are available, delivered by Aquafin.

Further downstream, some extra discharge point sources are present. At Zele, there is a pumping station on the Zelebeek with a theoretical pumping capacity of 3.5 m^3/s, consisting of 3 jacks with equal capacity. The Lokerenbeek has a pumping station with a capacity of 1.6 m^3/s.

The theoretical maximal discharge in the Durme, upstream Waasmunster Brug, is 20.3 m^3/s.

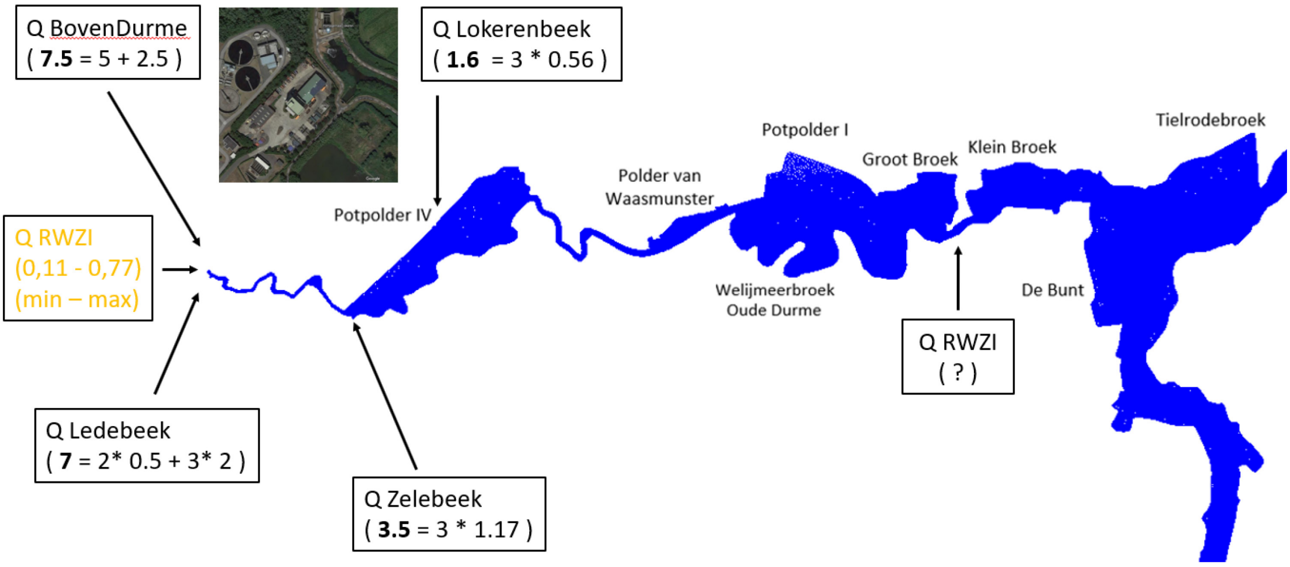


Figure 5 – Overview of the discharge sources, with their theoretical pump capacities in m³/s

4.4 ADCP sailed velocity measurements

In the model domain, some ADCP velocity measurements are available along several cross-sections, which were used for the calibration of the model (see Figure 6 for the location). In the framework of the MONEOS monitoring, several 13h measurements were performed at Driegoten/Weert. One measurement was performed during the calibration period for 2010, which was used for the calibration.

On the Durme itself one 13h campaign was performed at Tielrode on 16-09-2019 (Figure 6). On the same day, a measurement at Waasmunster Brug was also conducted. A detailed description of these measurements can be found in Aquavision (2019) and IMDC (2019b), respectively. An overview of the ADCP sailed data used in this study are presented in Table 5.

Available campaigns are stored in W:\SPNumMod\VIMM Datablokken\VIMM datablok ADCP sailed

Table 5 – ADCP sailed measurements used in the study

Cross-section	Measurement date	Remark
Driegoten	15-04-2010	
Weert	02-09-2019	
Waasmunster Brug	16-09-2019	
Tielrode	16-09-2019	Problem with recording of the coordinates, only discharge used

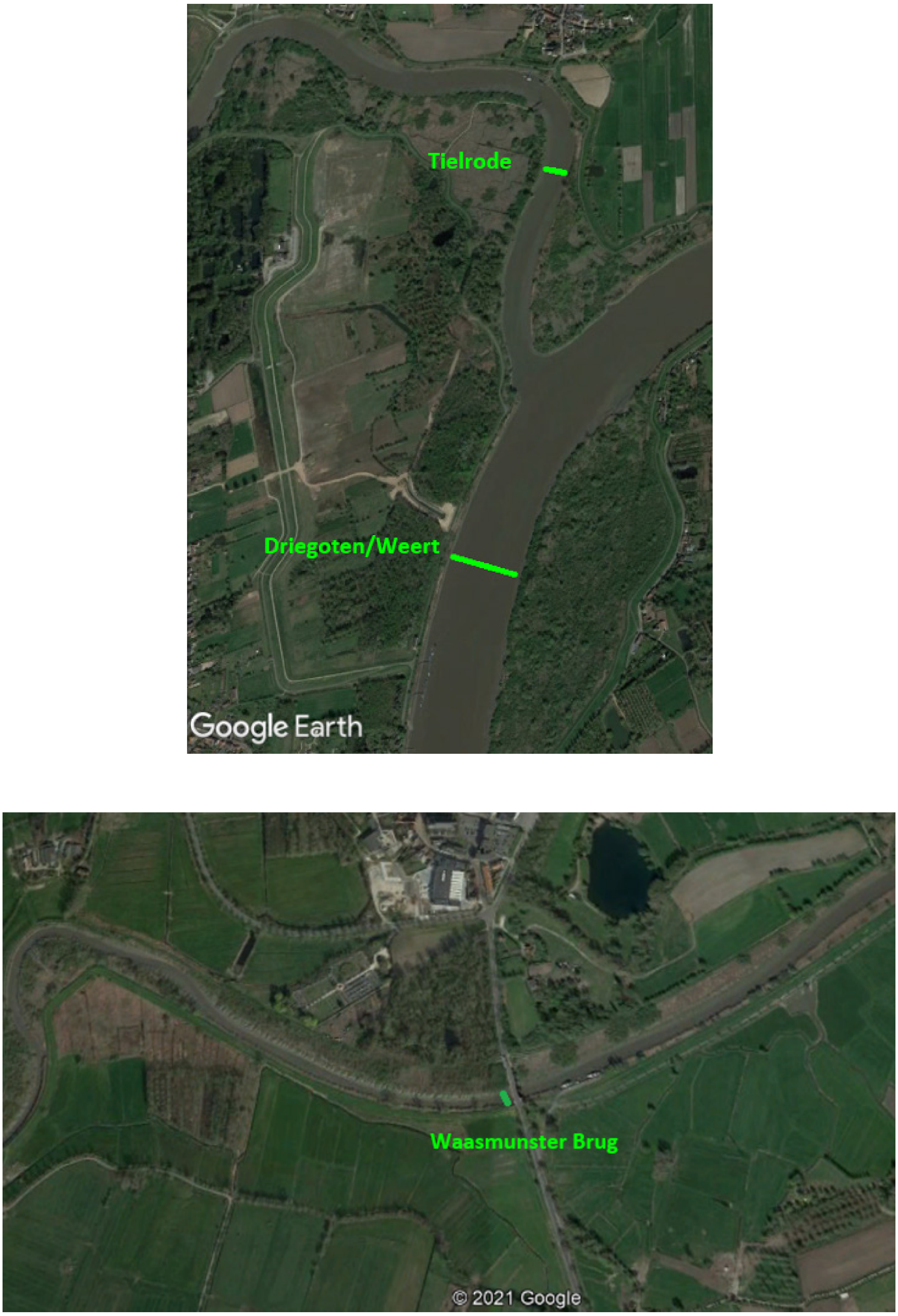


Figure 6 – ADCP transects at Driegoten/Weert and Tielrode (upper) and Waasmunster Brug (lower)

5 Model set-up

The Telemac software, version v7p2r2 (EDF-R&D, 2014), has been used to conduct the hydrodynamic numerical simulations. This software is based on the finite element method. The model grid is unstructured and includes triangular elements, which can be varied in size.

5.1 The Durme model grid

The detailed Durme model covers the complete tidal Durme river, up until the dam at Lokeren at the upstream end. At the downstream end, the Durme joins the Upper Sea Scheldt. The Upper Sea Scheldt is included in the model domain from Temse (in the north) to Sint-Amands (in the south). In total, the model covers approximately 10.5 km along the Upper Sea Scheldt and 18 km along the Durme. The whole model domain is shown in Figure 7.

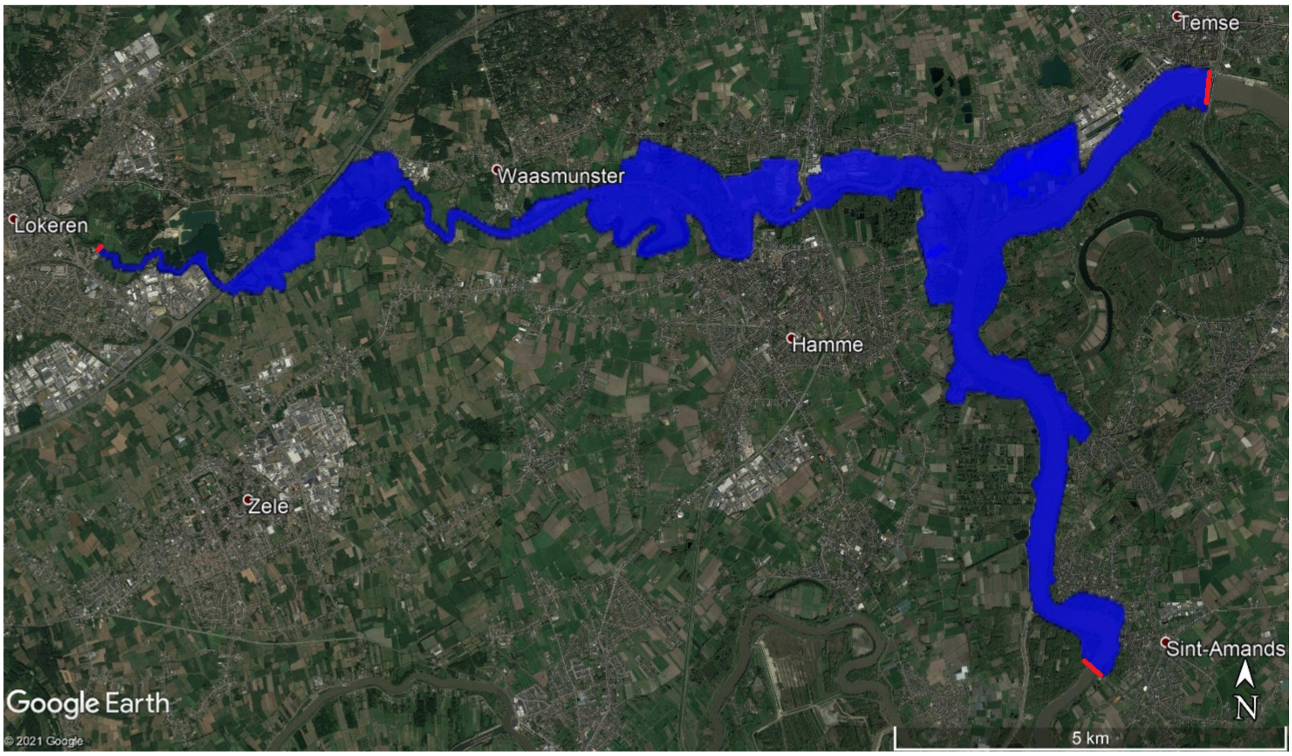


Figure 7 – The Durme model grid (model boundaries in red)

The grid for the Durme area was constructed using Blue Kenue, version 3.3.4 (Canadian Hydraulics Centre, 2011). The T3 Channel Mesher within Blue Kenue was used to construct regular channel meshes and the T3 Mesh Generator was employed to generate a fully unstructured mesh, incorporating the channel meshes as submeshes. The grid along the dikes was refined or/and represented with hard lines using the Mesh Generator. Hard lines were also used to represent narrow creeks, borders, etc. The position of nodes for the channel meshes and hard lines are fixed. The edge growth ratio (defined as the ratio of the edge length of the two adjacent elements) was set at 1.1.

The Durme model grid contains in total 175385 nodes and 343377 elements. The grid resolution varies from 1.5 m at the upstream end of the Durme river to about 20 m at the Sigma areas and the floodplain along the Scheldt river (Figure 8). In the high-elevated area at the upper part of Potpolder I, the resolution increases up to 30 m, which is the coarsest resolution within the model area. This coarser grid here is chosen because no important water flows are expected due to its elevation, and as such the area is only important to store water.

The following sections present the model grid implementation in more detail.

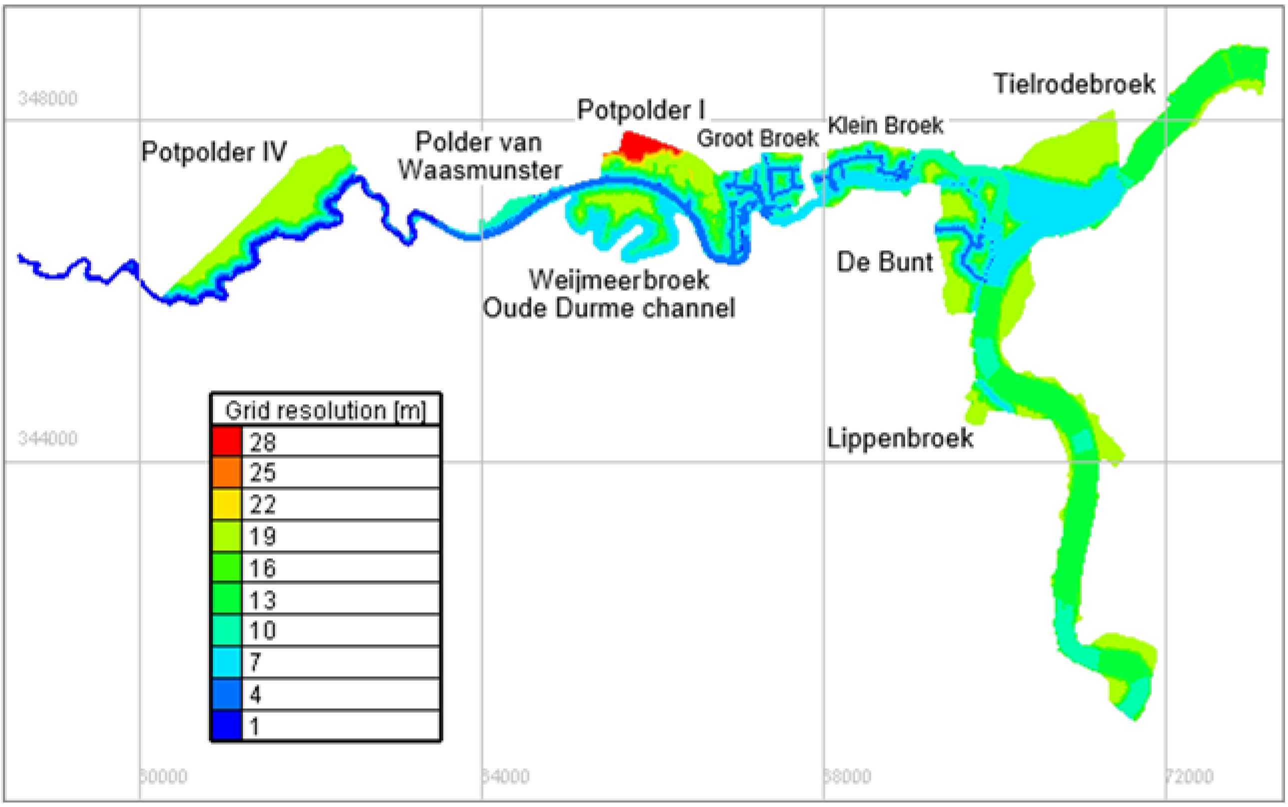


Figure 8 – The grid resolution of the Durme model

5.1.1 Channel meshes with T3 Channel Mesher

The T3 Channel Mesher can be used to generate regular channel meshes for channels, levees,... The triangles can be stretched in the direction of the flow and thus the number of nodes can be reduced. This technique was used to construct triangular meshes for the Scheldt river, Durme river and ditches within the flood control areas (FCA) and polders.

The average river width of the northern and southern part of the Upper Sea Scheldt within the domain is respectively about 300 m and 250 m. The grid of these two sections was constructed with the T3 Channel Mesher (24 points cross-shore, 14 m apart). An example of the grid for the Upper Sea Scheldt is presented in Figure 9.

The channel width of the Durme varies from about 10 m upstream to about 100 m near the mouth, considering the level +6 mTAW. The T3 Channel Mesher was applied to construct triangular meshes of the deeper part (up to the level of about +6 mTAW) of the Durme river (see an example in Figure 10). The channel was represented by 12 points cross-shore. Along the river, it was split into 10 sections and 10 corresponding channel meshes were generated. The grid interval varies from 2 m at the river upstream section to 12 m near the Durme river mouth.

The T3 Channel Mesher was also used to generate the ditches within the FCA De Bunt and the polders Klein Broek, Groot Broek (see Figure 12, Figure 13 and Figure 14).

For the convenience to refine the mesh or to connect different channel meshes, some channel sections were not constructed as channel mesh with T3 Channel Mesher, but as normal mesh using the T3 Mesh Generator, e.g. the area at the mouth of the Durme river, the areas in front of the dike sections where the dike breaching has been planned for the formation of the polders Groot Broek and Klein Broek.

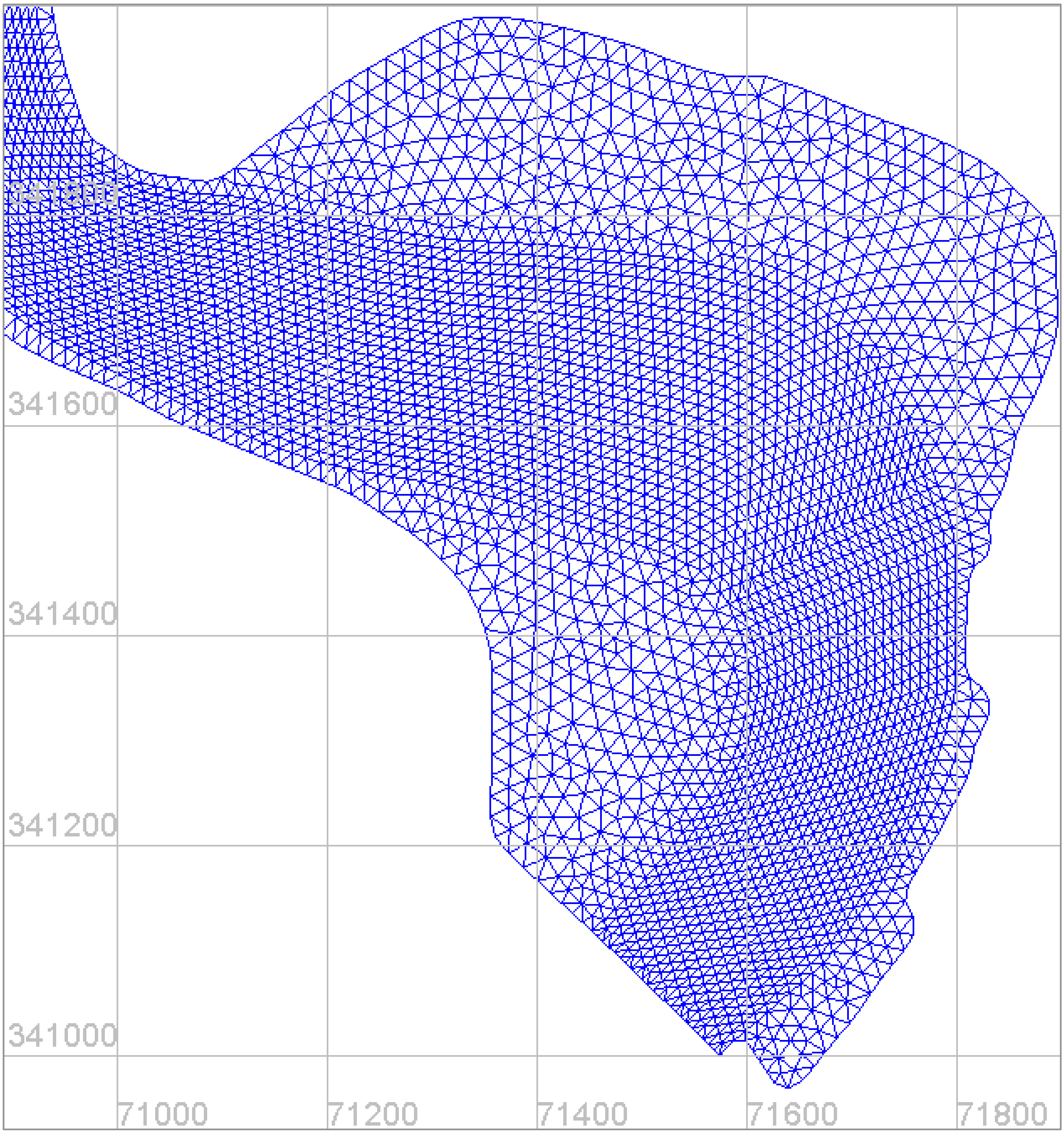


Figure 9 – Grid details for the Upper Sea Scheldt section, near the southern boundary: channel mesh incorporated in full mesh

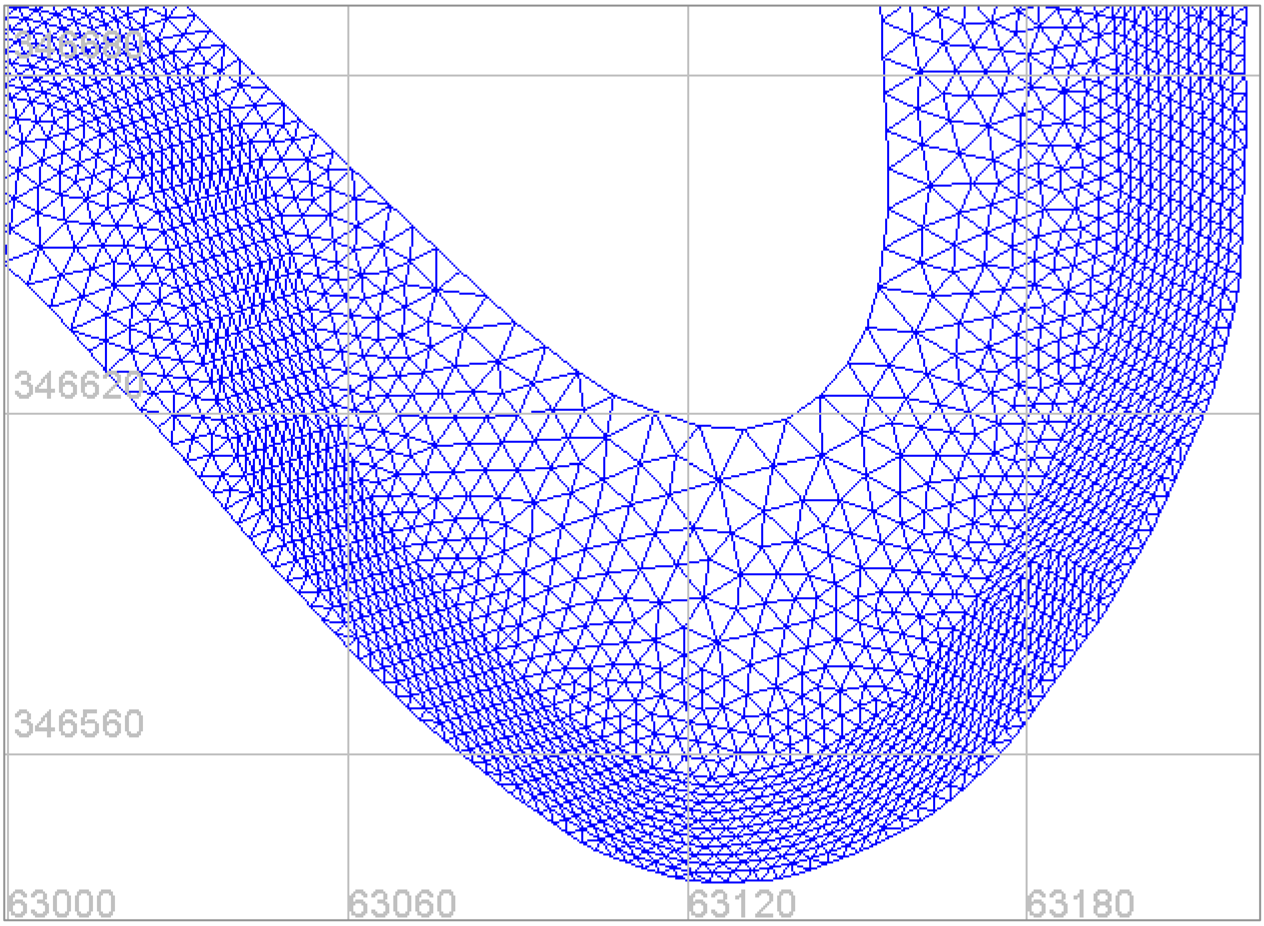


Figure 10 – Grid details for a section of the Durme: channel mesh incorporated in full mesh

5.1.2 The grid at the Sigma areas

The existing and planned Sigma areas (Tielrodebroek, De Bunt, Klein Broek, Groot Broek, Potpolder I, Polder van Waasmunster, Potpolder IV) presented in §3.2 were included in the model grid (Figure 7, Figure 8).

For the FCA-CRT Tielrodebroek, the grid was set at 20 m at the northern area (Figure 11). Its southern part near the Scheldt and Durme river was refined to 9 m for future scenarios to construct a CRT, to construct a side channel connecting the Durme river to the Scheldt river or to include variations in the orientation of the Durme mouth.

The grid for the FCA De Bunt and the polders Klein Broek and Groot Broek was constructed following the design of IMDC (IMDC, 2019a, 2020) (Figure 12, Figure 13, Figure 14). The ditches, creeks within these areas were implemented with Channel Mesher or hard lines with high resolution (see also Figure 8).

For the Potpolder I, the grid resolution was limited to 20 m, except for its upper area with the resolution being up to 30 m (Figure 15). The bottom level of this part is currently high, which does not play any role in water storage or exchange.

The Weijmeerbroek - Oude Durme channel are currently wetland areas. They were included in the model to assess the impact of a meandering river on the tidal characteristics. The grid resolution of the Oude Durme channel is 9.5 m and varies between 10 m and 20 m at Weijmeerbroek (Figure 15).

The grid resolution at Polder van Waasmunster was limited to 11 m (Figure 16). For Potpolder IV, the resolution was set up to 20 m (Figure 17).

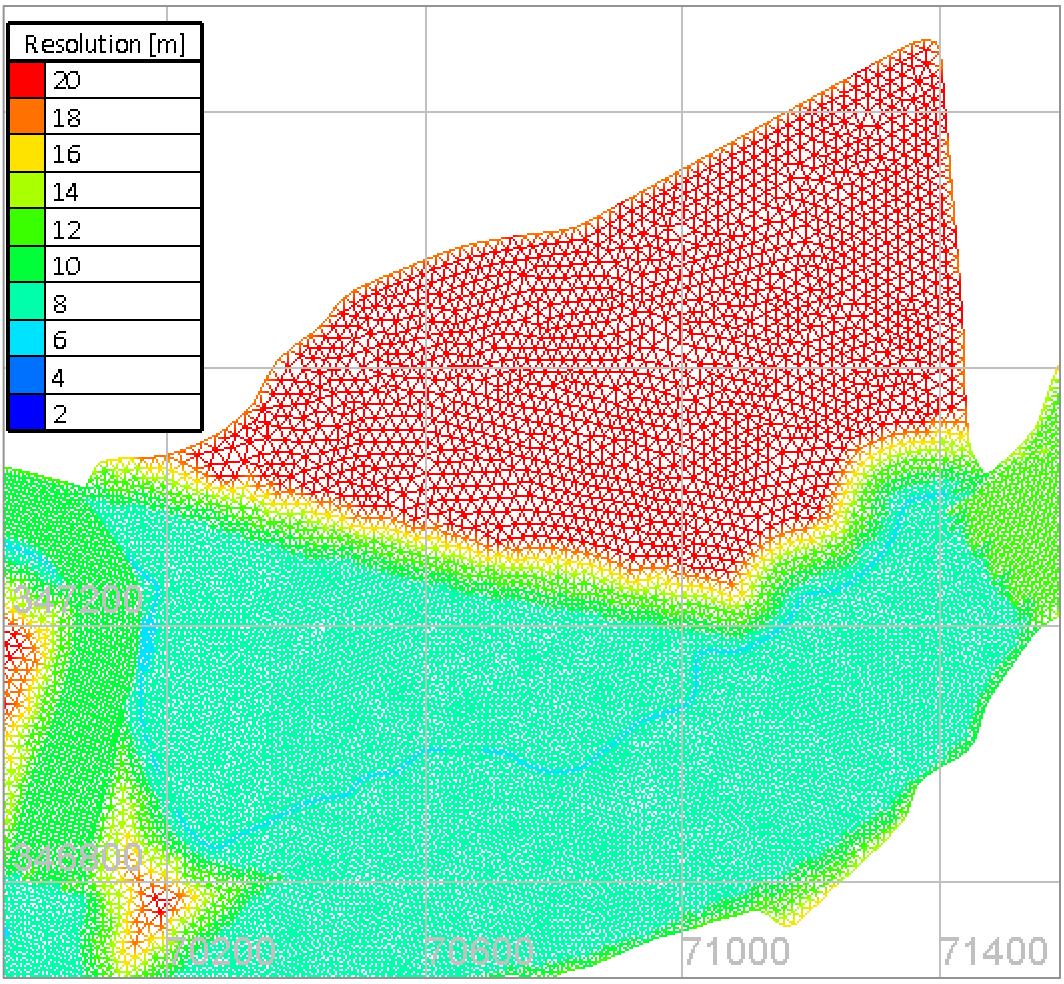


Figure 11 – Refinement at the southern area of Tielrodebroek

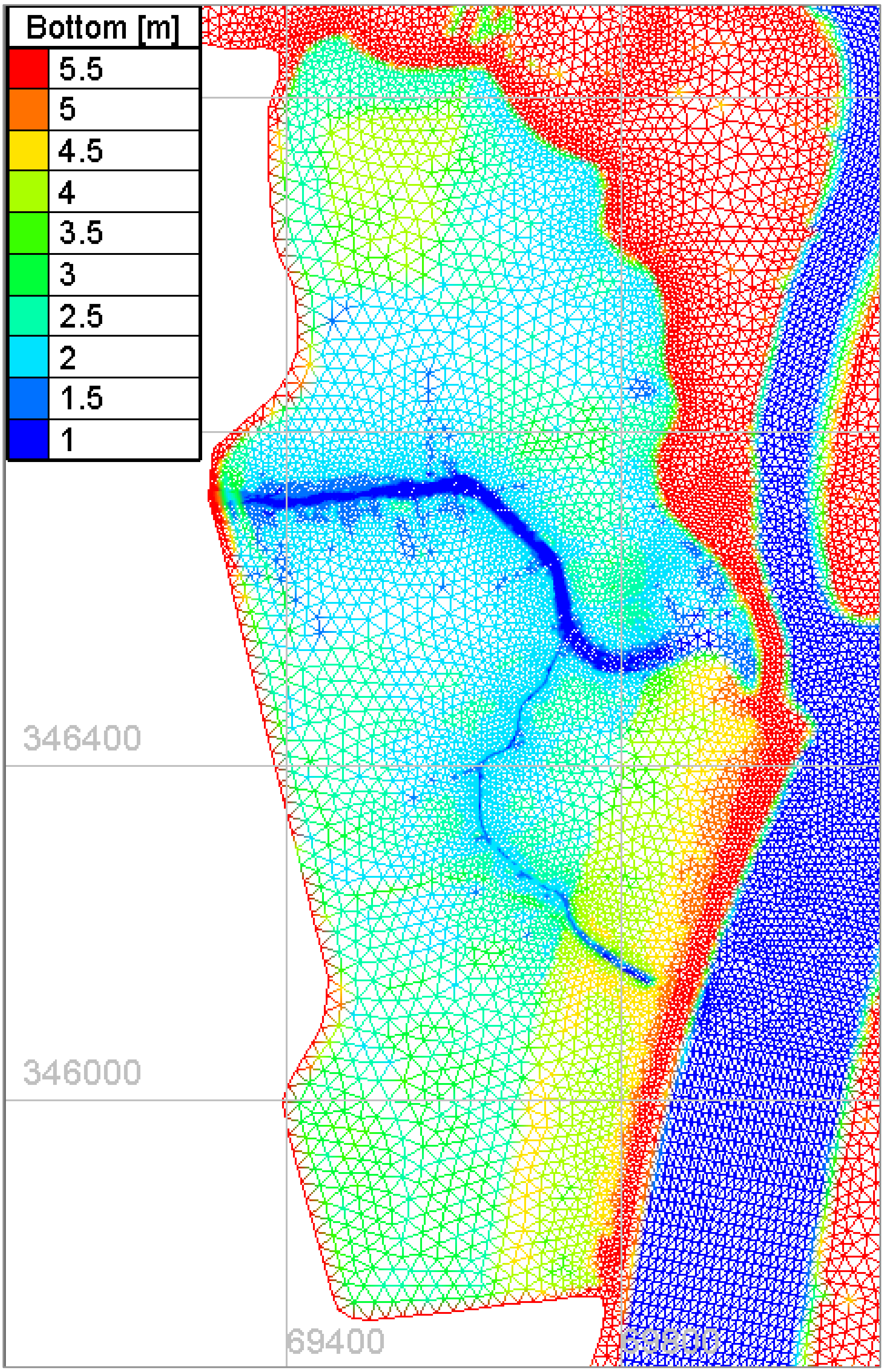


Figure 12 – Grid at FCA De Bunt: finer grid along ditches and dikes

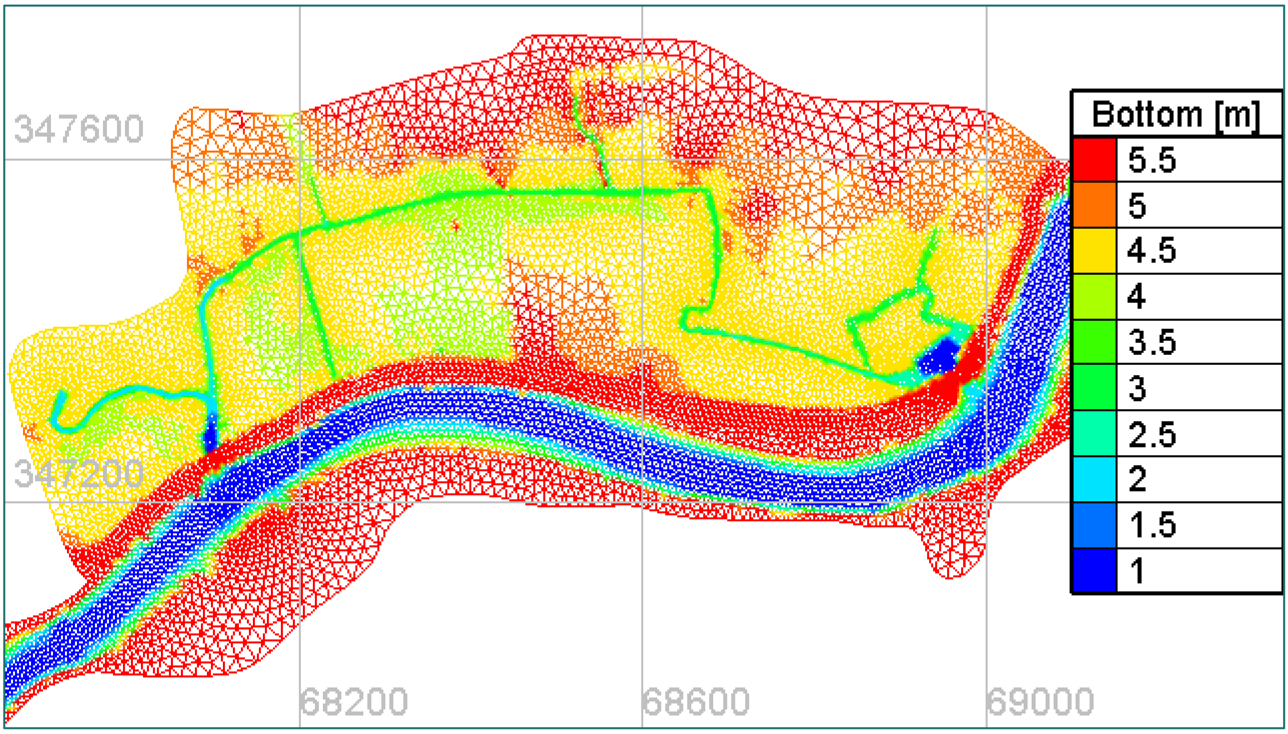


Figure 13 – Grid at the polder Klein Broek: finer grid along ditches and dikes

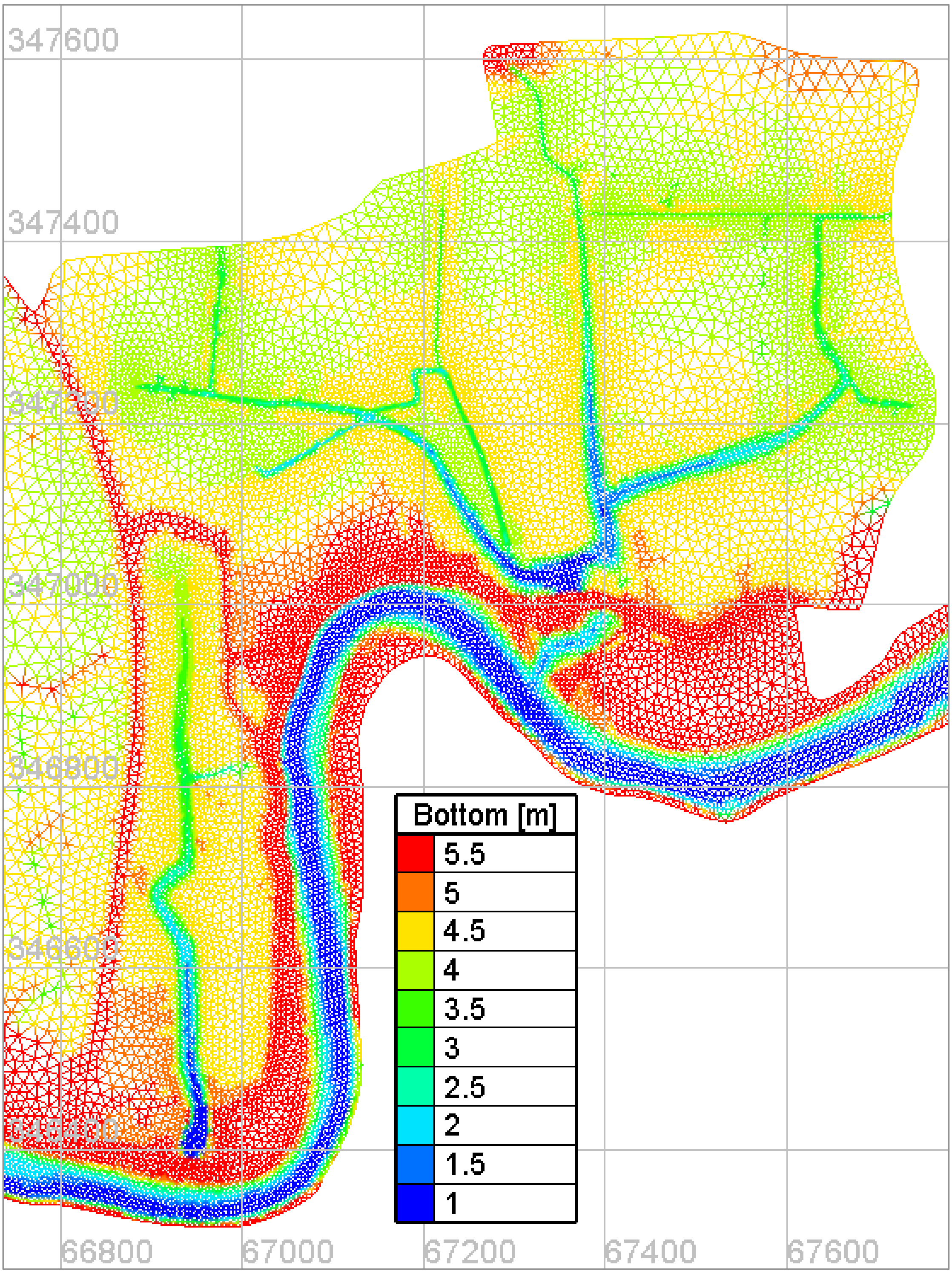


Figure 14 – Grid at the polder Groot Broek: finer grid along ditches and dikes

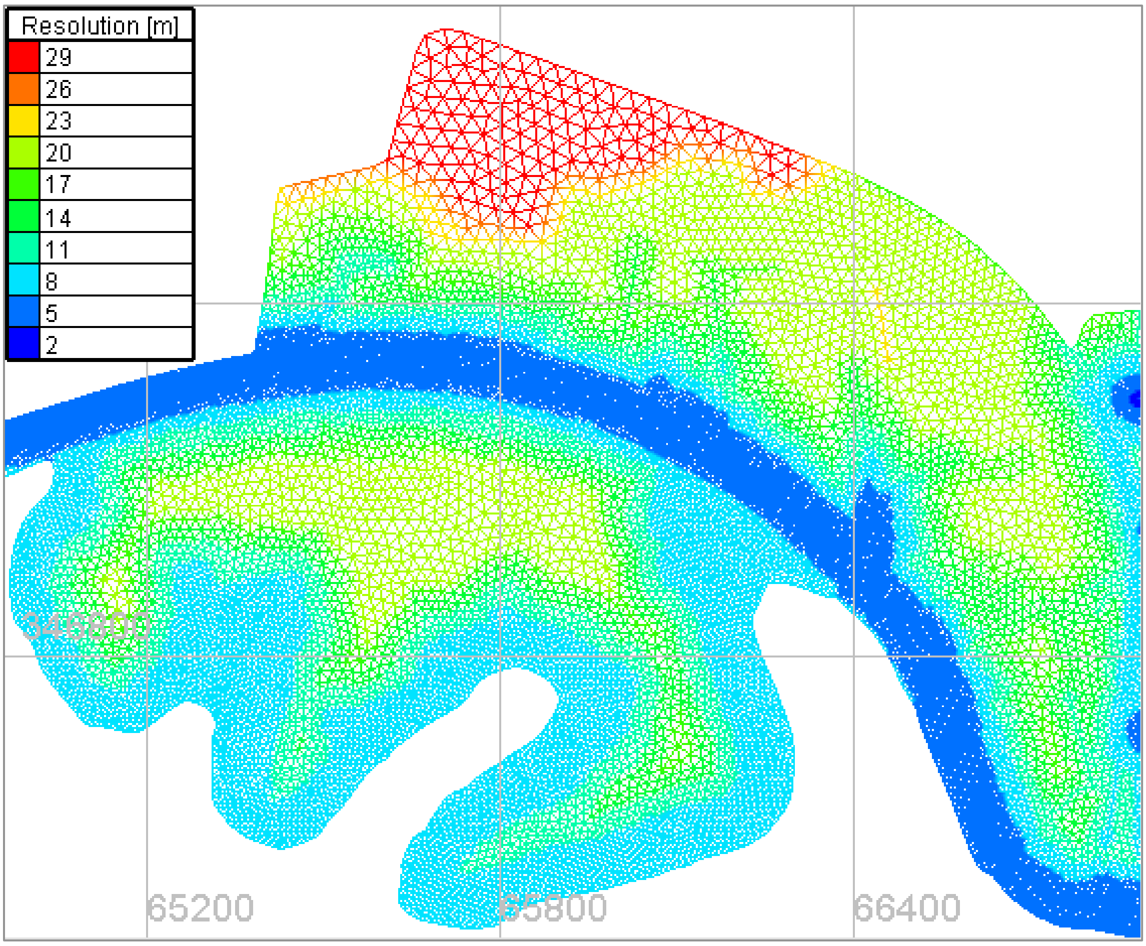


Figure 15 – Grid resolution at Potpolder I and Weijmeerbroek – Oude Durme channel

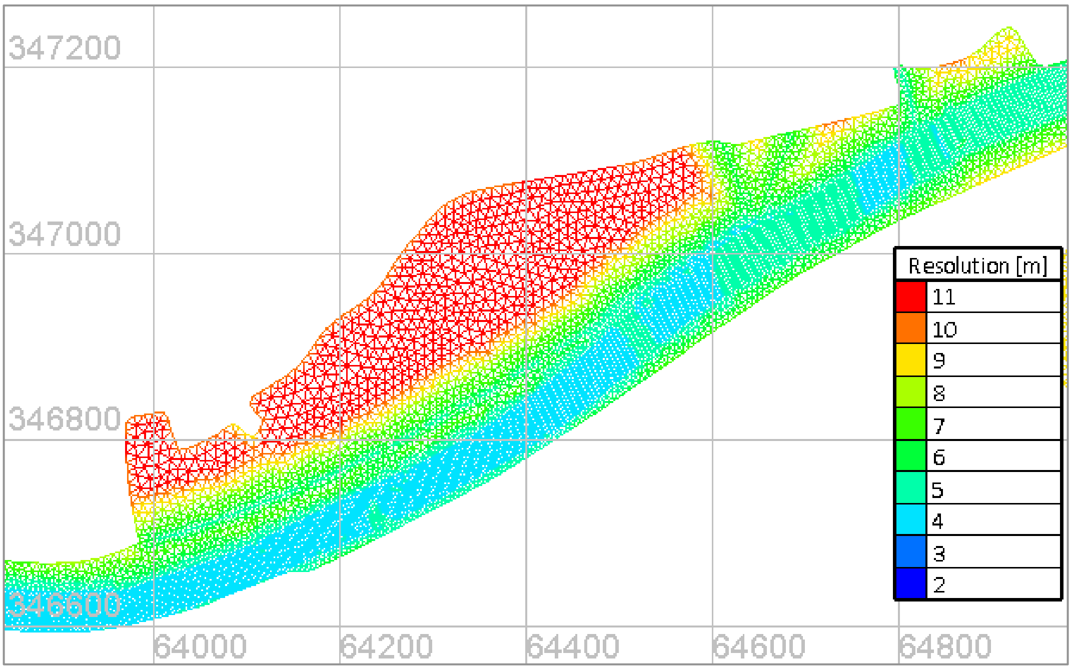


Figure 16 – Grid resolution at Polder van Waasmunster

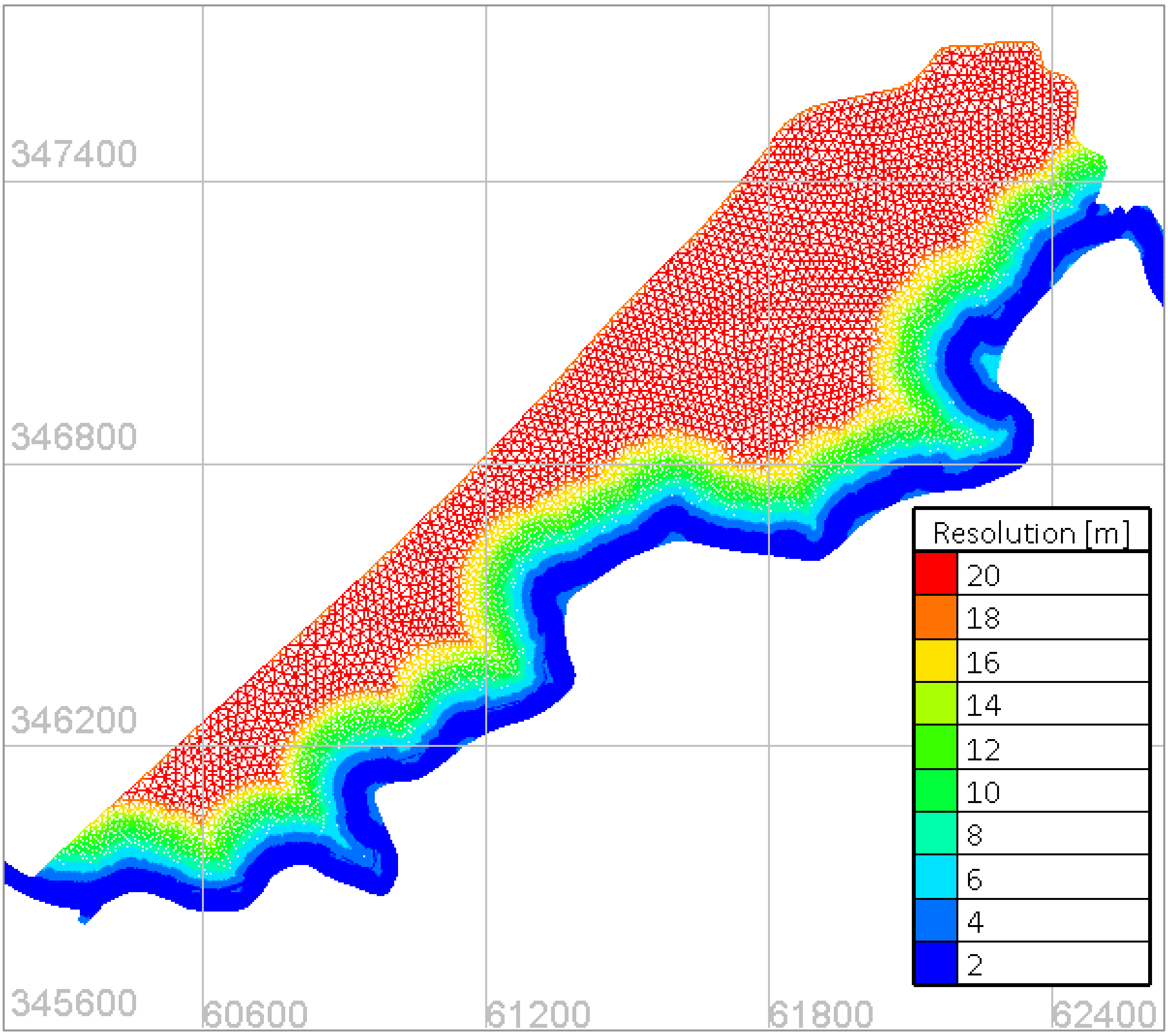


Figure 17 – Grid resolution at Potpolder IV

5.2 Bathymetry

The constructed model has been calibrated for two periods (explained in more detail in §7): one spring-neap period within the year 2010 (situation before dredging), the second period covers a spring-neap cycle in 2019 (situation after dredging). Therefore, two bathymetries were constructed: a “2010” and “2019“ bathymetry.

5.2.1 Bathymetry for 2019 runs

The model bathymetry for runs in the year 2019 was constructed using several data sets (see Table 6 and Figure 18). The Durme model was constructed in RD Paris coordinate system and uses TAW as a vertical reference. All the data that is in other projections or vertical references was converted to RD Paris and TAW.

Most of the used data sets were measured in 2019. Along the Durme river, the available bathymetry data in 2020 and 2018 was used at the downstream and the upstream section, respectively (Table 6 and Figure 18). At the most upstream part, the data at the deeper part of the river is missing. This part was filled with the data constructed from the measured bathymetry along several transects in December 2018.

The polders Klein Broek and Groot Broek were included in the model and the design bathymetries provided by IMDC were used. They are however not yet active in the 2019 model runs. The bathymetry at the dike sections where a breaching or lowering of the dike has been proposed in the planned bathymetry, was replaced with a similar elevation as the dike nearby (Figure 19, Figure 20).

The model covers also the wetland areas Weijmeerbroek-Oude Durme for future scenarios (not active in the calibration runs). The bathymetry data for the Oude Durme channel is not available, a bottom value of 1 mTAW was assigned. The missing data within Potpolder IV was filled/interpolated with the bathymetry nearby.

In order to implement the boundary condition and guarantee stable numerical results, some adjustments were made to the bathymetry at the two boundaries. Near the bridge of Temse, a smoothing of the bathymetry at the Scheldt was performed. At the upstream boundary of the Durme, the dike was lowered. These adaptations are shown in Figure 21 and Figure 22.

The resulting model bathymetry for the year 2019 is presented in Figure 23.

Table 6 – Topo-bathymetric data used for construction of model bathymetry for the year 2019 runs (see also Figure 18)

Location (Background colors correspond to colors in Figure 18)	**Measured year**	**Data source**	**Data file**
Scheldt + de Bunt + Tielrodebroek	2019		boz_dtm_taw_mt_2019_1m_mean_RD_negativeDepth
Durme river downstream	2020		dhm_2020_negativeDepth
Durme river upstream	2018		dhm_2018_RD_TAW_ook_opwaarts_negativeDepth
Durme river most upstream, deeper part	2018	DVW	raster_171218 (interpolated from transect measurements)
Klein Broek		IMDC	D3_KleinBroek_Mesh15_09_RD_mTAW.xyz
GrootBroek		IMDC	D4_GrootBroek_Mesh15_09_RD_mTAW.xyz
Potpolder I	2019		Lidar_2019_Potpolder_1_RD_TAW_negativeDepth
Polder_van_Waasmunster	2019		Lidar_2019_Polder_van_Waasmunster_RD_TAW_negativeDepth
Weijmeerbroek	2019		Lidar_2019_Weijmeerbroek_RD_TAW_negativeDepth
Potpolder IV	2019		Lidar_2019_Potpolder_4_RD_TAW_volledig_negativeDepth
Oude Durme channel 3 ponds within Potpolder IV			Missing data

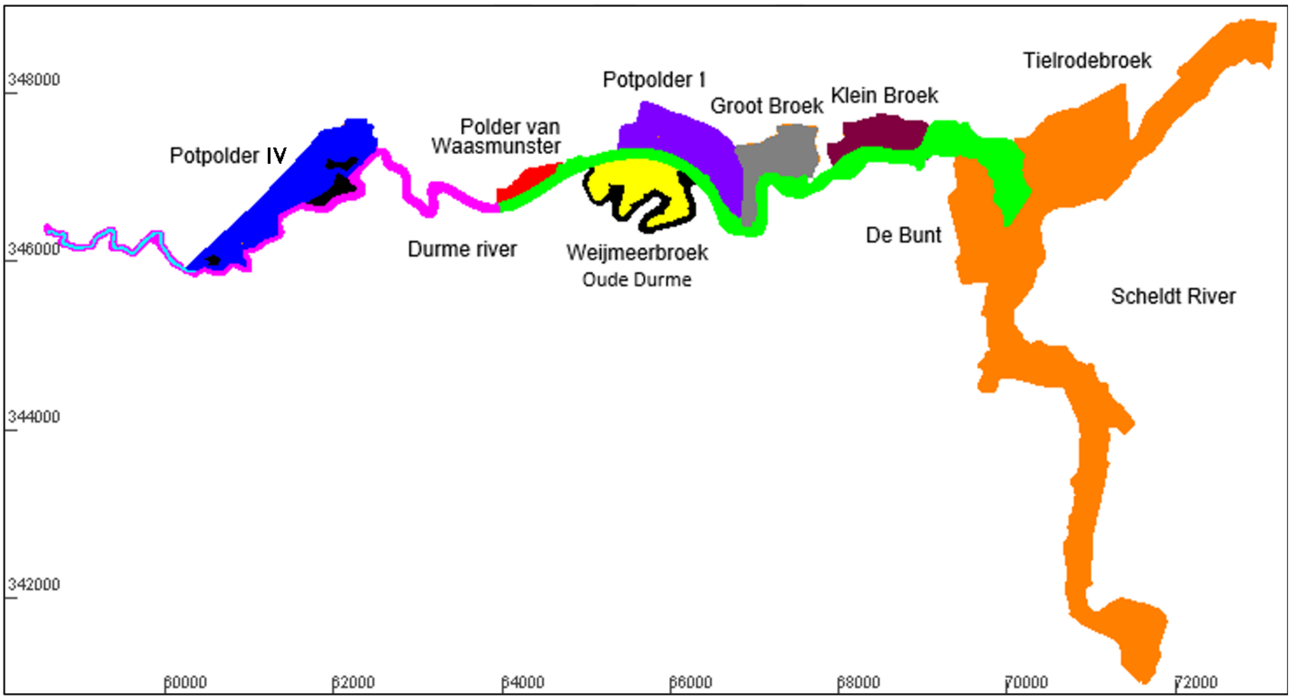


Figure 18 – The coverage of topo-bathymetric data used for construction of model bathymetry for the year 2019. Different colours show different data sets used (see Table 6)

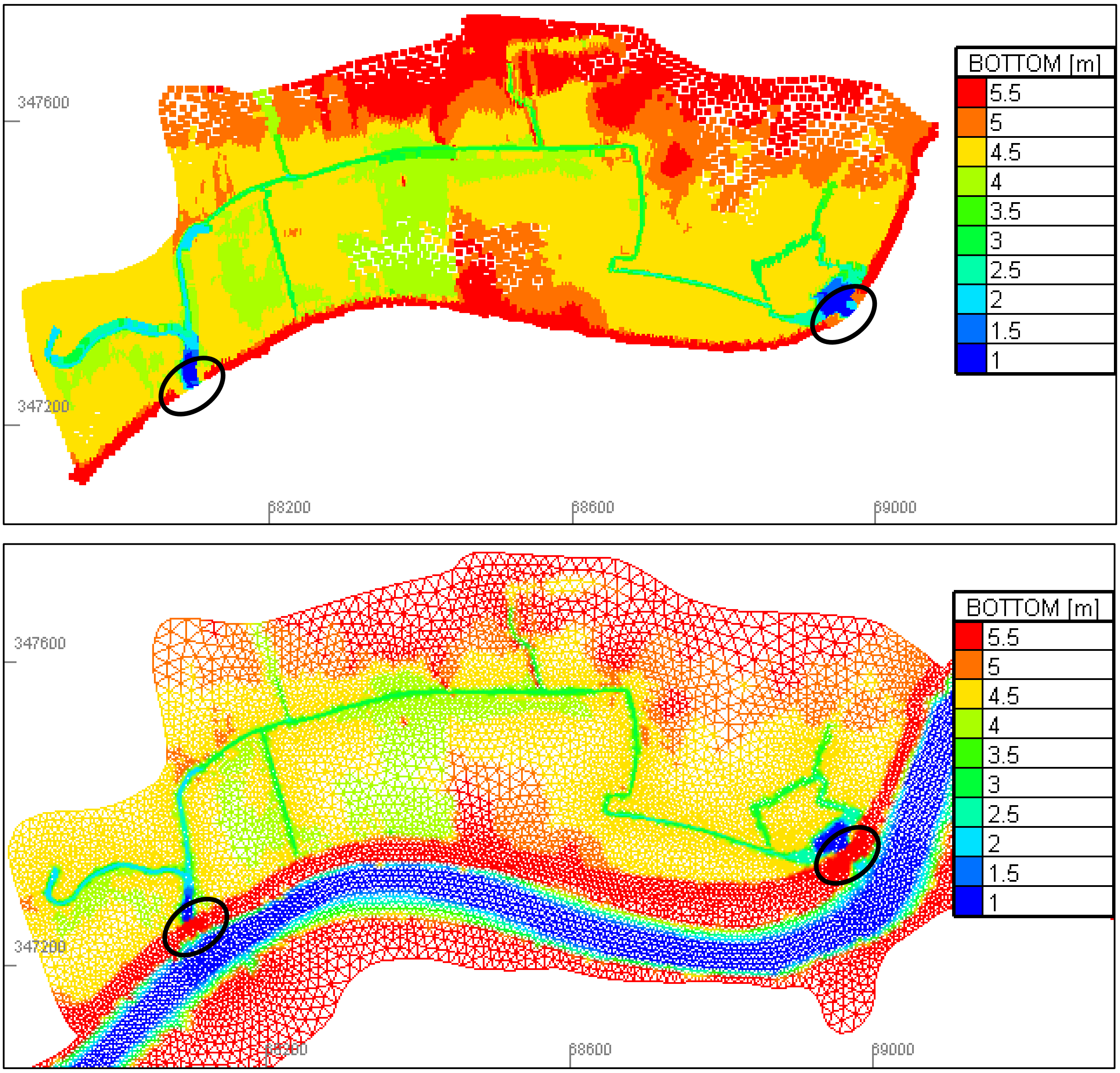


Figure 19 – Bathymetry adjustment at polder Klein Broek. Upper: planed bathymetry (IMDC), lower: reconstructed dike sections

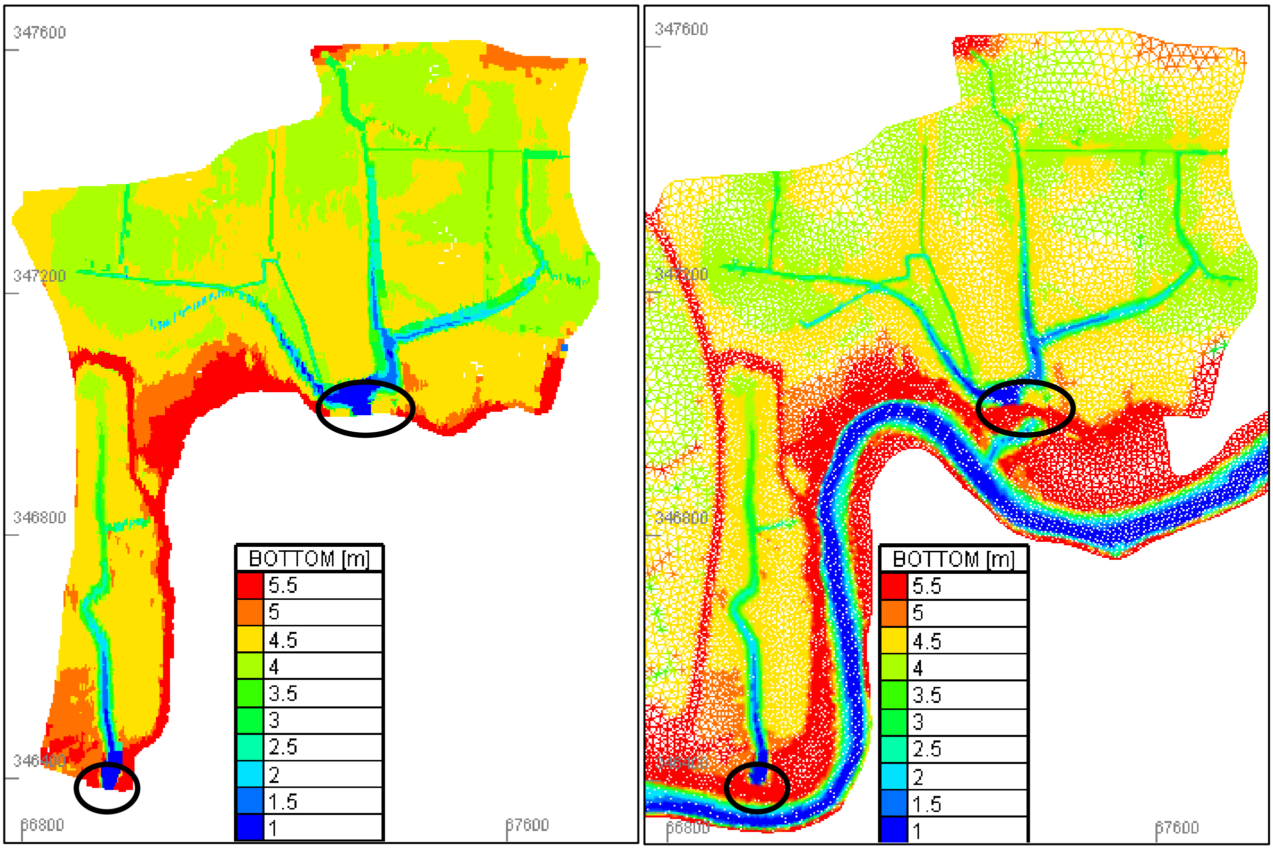


Figure 20 – Bathymetry adjustment at polder Groot Broek. Left: planed bathymetry (IMDC), right: reconstructed dike sections

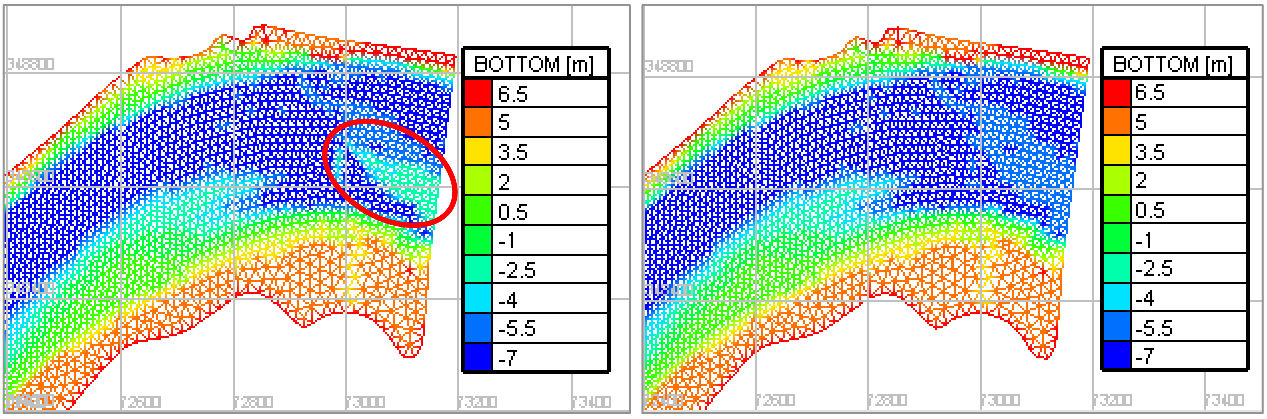


Figure 21 – Bathymetry adjustment at Scheldt downstream boundary. Left: original bathymetry, right: smoothed bathymetry

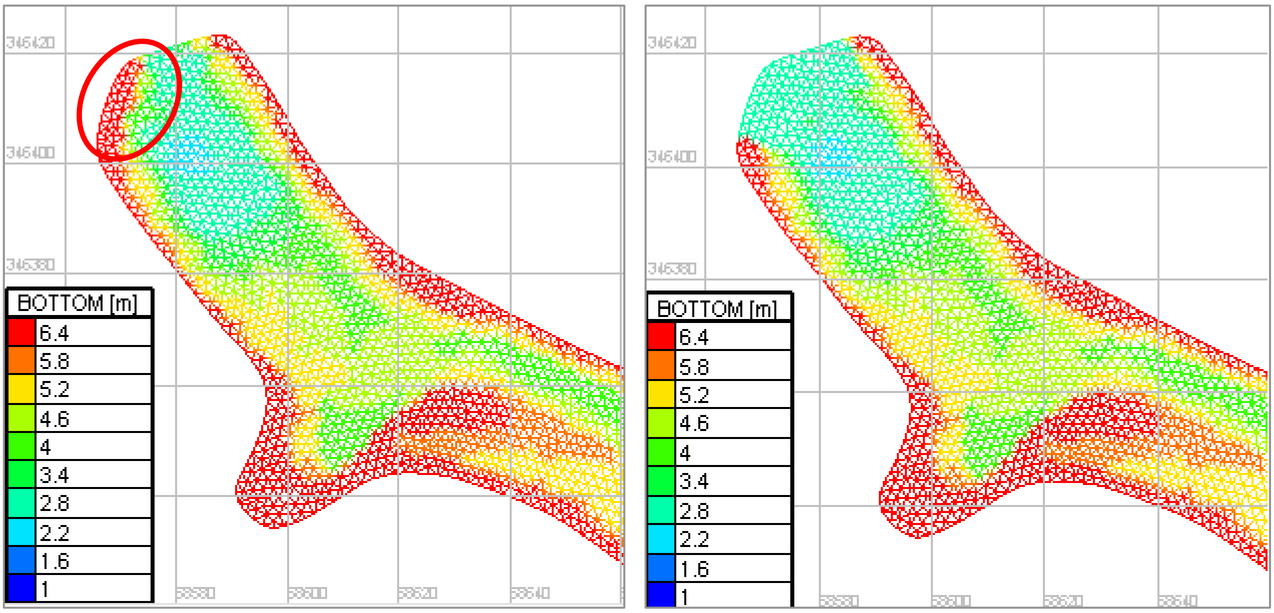


Figure 22 – Bathymetry adjustment at Durme upstream boundary. Left: original bathymetry, right: lowering the dike

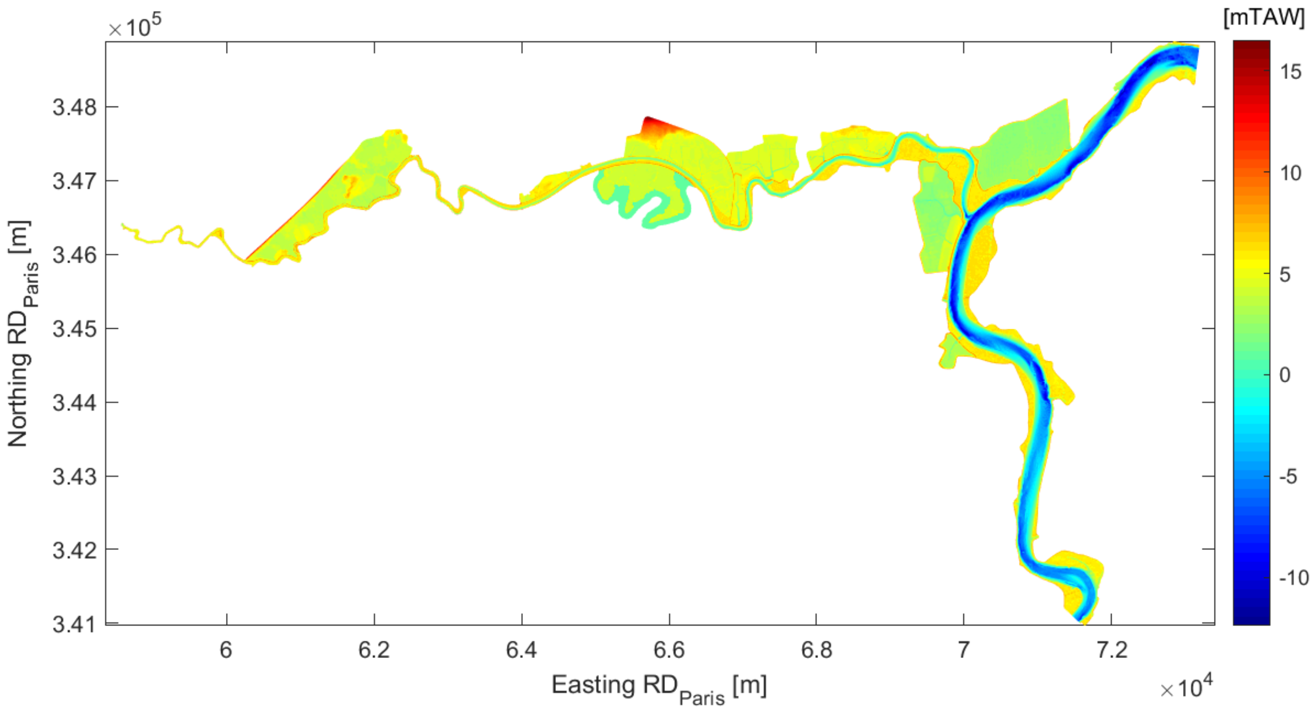


Figure 23 – The Durme model bathymetry, for the “2019” runs

5.2.2 Bathymetry for 2010 runs

Similar to the case in 2019, no complete topo-bathymetric data set is available for the year 2010. Several data sets were used to construct the bathymetry for 2010 model runs (see Table 7 and Figure 24). The resulting model bathymetry for the year 2010 is presented in Figure 25.

Table 7 – Topo-bathymetric data used for construction of model bathymetry for the year 2010 runs (see also Figure 24)

Location (Background colors correspond to colors in Figure 24)	**Measured year**	**Data source**	**Data file**
Scheldt + de Bunt + Tielrodebroek	2011		boz_dtm_taw_mt_2011_1m_mean_RD_negativeDepth.xyz
Klein Broek, Groot Broek, Potpolder I, Polder van Waasmunster, Weijmeerbroek, Potpolder IV	2011		Clip_boz_dtm_lidar1_negativeDepth.xyz
Durme river downstream	2010 & 2011		dhm_2010_zonderbruggen_negativeDepth.xyz
Durme river upstream, deeper part	2013		dhm_2013_RD_TAW_ook_opwaarts_negativeDepth.xyz
Durme river most upstream, deeper part	2013?	DVW	raster_c1352_04179.xyz (interpolated from measured transects)
Oude Durme channel 3 ponds within Potpolder IV			Missing data

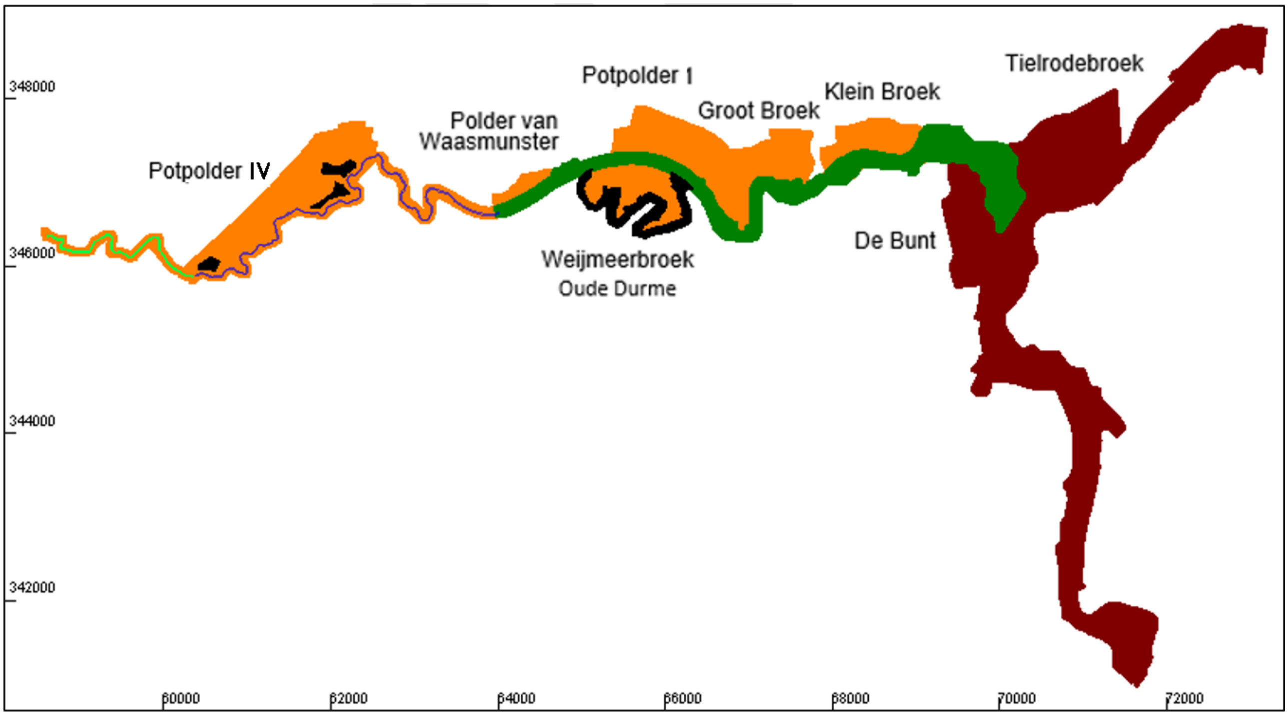


Figure 24 – The coverage of topo-bathymetric data used for construction of model bathymetry for the year 2010. Different colours show different data sets used (see Table 7)

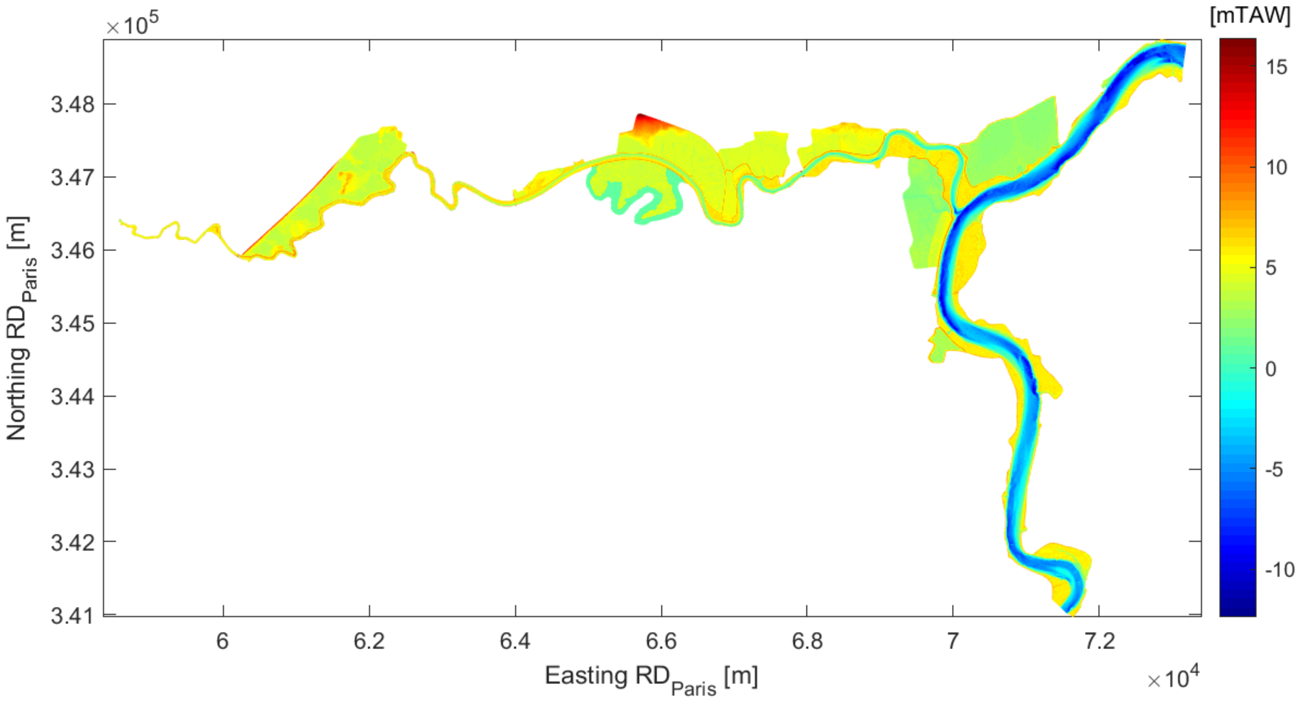


Figure 25 – The Durme model bathymetry for the "2010" runs

5.3 Boundary Conditions

The model has three open boundaries (see Figure 7). Two boundaries at the Scheldt river were prescribed with measured water levels at the stations Temse and Sint-Amands (see Figure 4 for the location).

The boundary upstream at the Durme river was imposed with the discharge along the boundary segment.

5.4 Parameter settings

In Table 8 the general settings of the model are listed. The hydrodynamic model was constructed in 2D. Salinity was not included in the model, as it is considered not to influence the hydrodynamic calculations. Both bed roughness and the turbulence model have been tested and calibrated, as described in more detail in §6, §7.

Table 8 – Parameter settings of the Durme model

Parameter	Value
Time step	Sensitivity analysis (1s, 2s)
Initial condition	2 days spin-up from constant water level
Number of vertical levels	1 (2D)
Version TELEMAC	v7p2r2
Salinity	Off
Wind	Off
Roughness formula	Manning
Bed roughness value	*Calibration:* 0.01, 0.012, 0.014, **0.016**, 0.018, 0.02, 0.022 s/m$^{1/3}$
Option for the treatment of tidal	1: equations solved everywhere with correction on tidal flats
Treatment of negative depths	1: smoothing the negative depths
Free surface gradient compatibility	0.9
Turbulence model	*Sensitivity analysis/calibration:* Constant viscosity: 0.01, 0.1, 1 m^2/s), **Elder model (al = 6: at = 0.6)**
Scheme for advection of velocities	1: method of characteristics, not mass-conservative
Scheme for advection of depth	conservative scheme
Solver	7: Generalised Minimum RESidual (GMRES) method

6 Model sensitivity

Before carrying out model calibration in §7, some sensitivity analyses were performed. From a first notice, some instabilities occurred in the upstream region of the Durme in case of imposing high discharge upstream. As such the sensitivity of the model to the time step was examined. In a second step, the sensitivity of the model results to the imposed upstream discharge was investigated. This was done as no measurements of the discharge are available. In the end, the sensitivity to the turbulence model and its parameter was performed as it determines the dissipation of energy in the model.

6.1 Sensitivity to the model time step

Two model runs were carried out with a model time step of respectively 2 s and 1 s. The results show almost identical computed water levels using the time step of 1 s and 2 s. However, an instability in the computed water levels is observed at Waasmunster-Brug and Waasmunster-Manta (see Figure 4 for the location) with the time step of 2 s, for the case of a higher upstream discharge of 7.5 m^3/s (the capacity of the pump station at the dam of Lokeren, at upstream boundary, see Figure 5). An example for the station Waasmunster-Manta in Figure 26 shows clearly the instability of the computed water levels at low tide for the time step of 2 s. The time step of 1 s was therefore applied in further simulations.

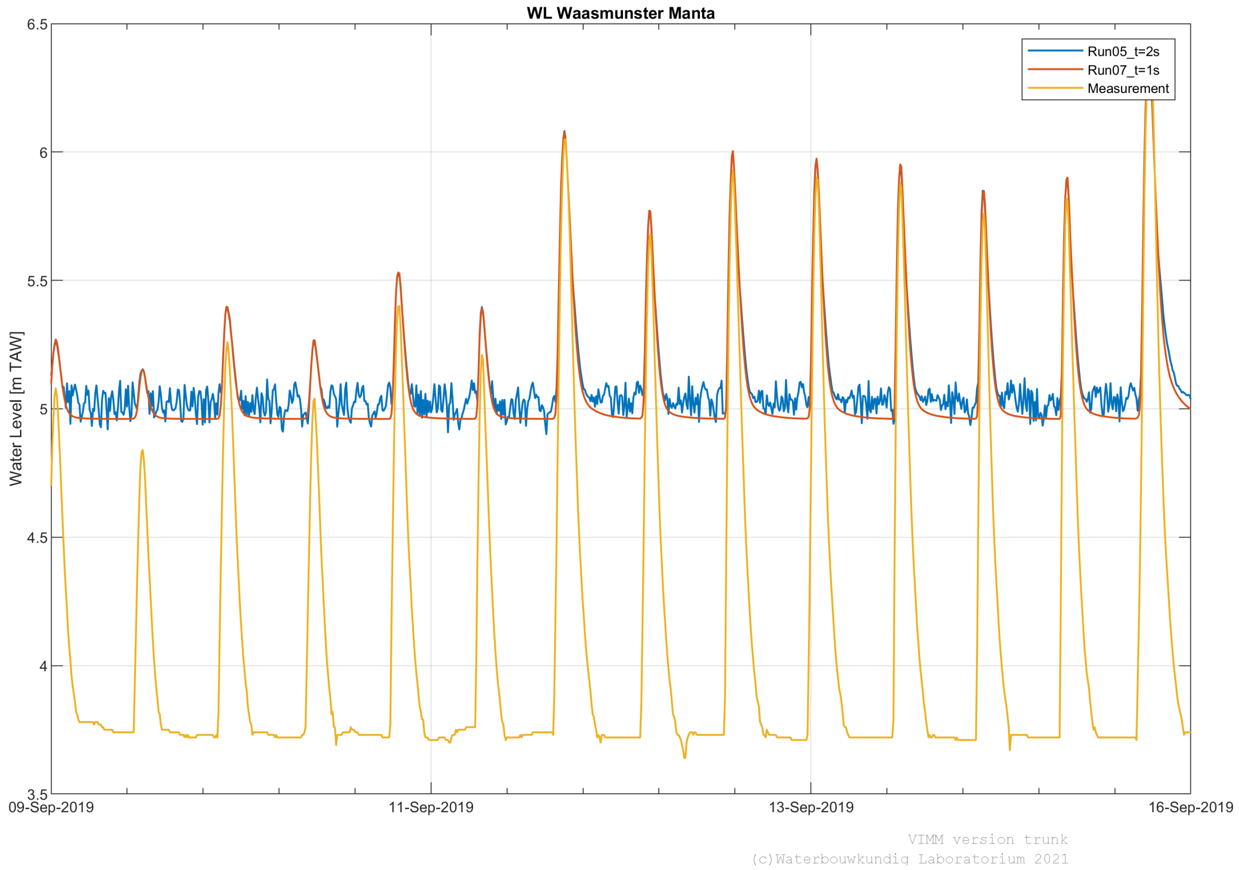


Figure 26 – Measured and modeled water levels at Waasmunster-Manta, with the model time step of 1 s and 2 s and the imposed upstream discharge of 7.5 m^3/s

6.2 Sensitivity to the upstream boundary discharge

As presented in Chapter 5, the Durme model has three open boundaries. On the two boundaries at the Upper Sea Scheldt, water levels were imposed as boundary conditions. At the upstream of the Durme river, a discharge should be imposed. However, only discharge data of the wastewater treatment plant (RWZI) is recorded, available on a daily basis. The discharge data for the pump station at the Dam of Lokeren (between Moervaart and Durme) and the pumping station of the Ledebeek is not available.

To examine the influence of the upstream discharge on the water levels in the area, seven model runs were caried out with different discharge values imposed at the upstream boundary, ranging between 0 and 20 m^3/s (see Table 9). The discharge value of 15 m^3/s is the combined theoretical pumping capacity of the Durme dam and Ledebeek pumping station and Q_{RWZI}. The highest chosen value of 20 m^3/s corresponds to a summation of all theoretical discharge capacities, in the upstream part of the tidal Durme. In each model run, the discharge was kept constant throughout the simulation period.

Table 9 – Sensitivity runs of the flow model to the upstream boundary discharge

RunID	$Q_{upstream}$ [m^3/s]
Run02	0
Run03	0.25
Run04	0.75
Run16	2.5
Run07	7.5
Run08	15
Run09	20

Figure 27 presents the lowest low water level (LLW) and highest high water level (HHW) during one week simulation, 09/09/2019 till 16/09/2019, for the seven sensitivity runs. The HHW corresponds to a tide on 15/09/2019 with the high water of ~6.2 mTAW at Tielrode. The analysis was done for the six water level stations along the Durme and Scheldt river: Lokeren, Zele, Waasmunster-Manta, Waasmunster-Brug, Tielrode and Driegoten (see Figure 4 for the locations). The timeseries of the water levels at these locations calculated for different upstream discharges are compared in Appendix 2.

The upstream discharge $Q_{upstream}$ influences significantly the low water levels upstream (at Lokeren, Zele Waasmunster-Manta, and Waasmunster-Brug). Without imposing any discharge upstream, the water level at Lokeren drops to 5 mTAW during low tide while the LLW reaches to 7 mTAW for the case of 20 m^3/s forcing (Figure 27, upper). Even very small increments of the discharge have significant effect on the low water levels here. The influence of the discharge decreases further to the downstream of the Durme river as expected. No change in the water level can be observed for Driegoten, located in the Upper Sea Scheldt.

Compared to low waters, the high waters are less affected by upstream discharge $Q_{upstream}$ (Figure 27). However, the effect is still significant for the two most upstream stations at Lokeren and Zele with the difference of 1.5 m for Lokeren between the case without discharge and maximum forcing of 20 m^3/s.

At very high discharge (15-20 m^3/s), the water levels at the two most upstream stations are almost constant at the level of about 6.7 mTAW (Zele) and 7 mTAW (Lokeren) (Figure 43).

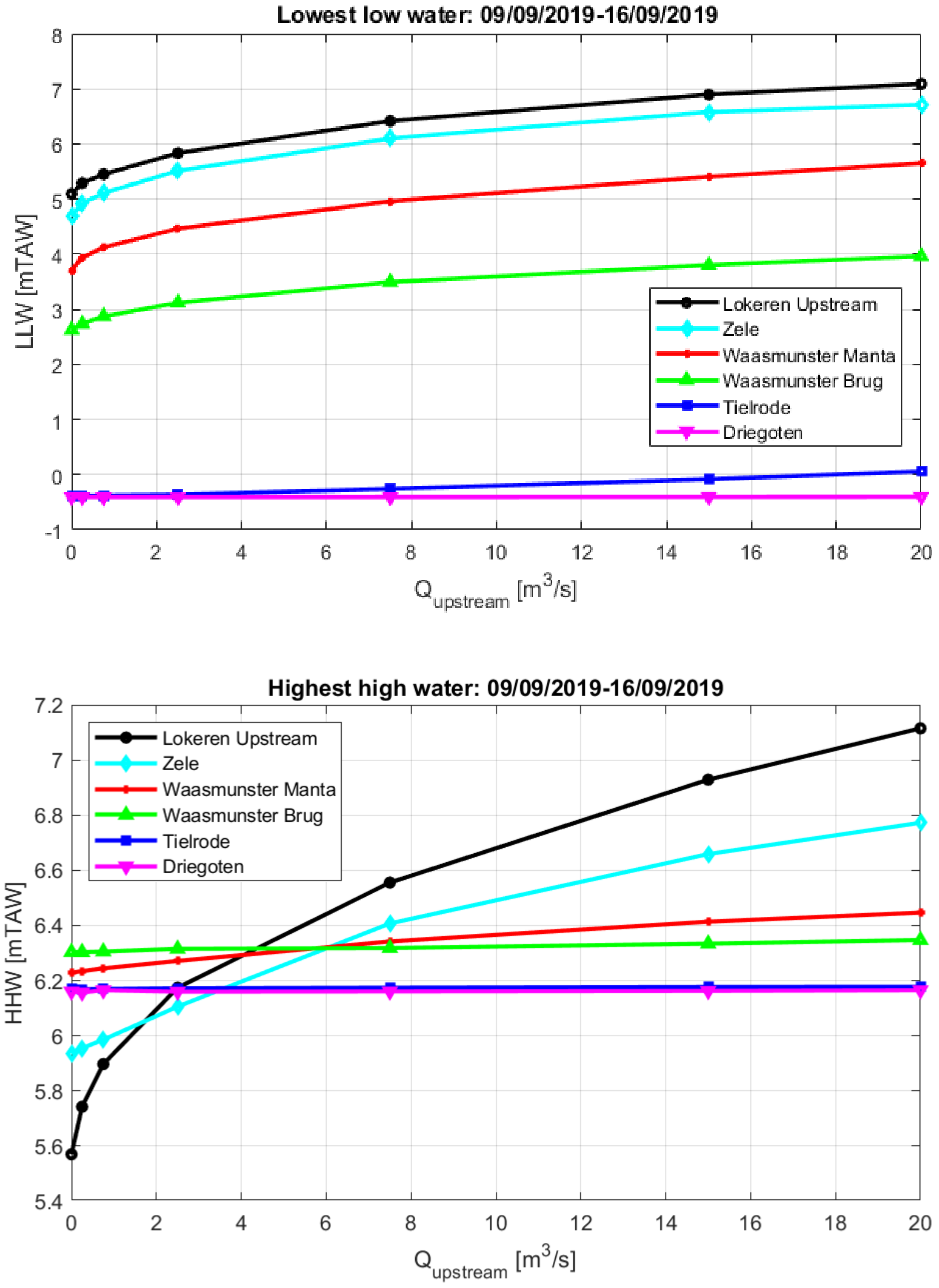


Figure 27 – Influence of upstream discharge on the lowest low water (LLW) and highest high water level (HHW) during the simulation period (09 – 16/09/2019)

6.3 Sensitivity to turbulence model

The sensitivity of the model to the turbulence model has been investigated. Both a constant viscosity coefficient and the Elder turbulence model were considered (see overview in Table 10).

The constant viscosity coefficient represents the molecular viscosity, turbulent viscosity and dispersion (EDF-R&D, 2014). In Smolders (2016), the value 0.01 m^2/s was chosen for the case of constant viscosity. In this study, three values were selected: 0.01, 0.1, and 1 m^2/s.

In the Elder model, the viscosity is calculated from the characteristics of the flow and the value is determined separately along and across the current direction. In TELEMAC, it is possible to assign a coefficient for each direction:

$$Kl = al\ U^* h$$

$$Kt = at\ U^* h$$

with:

Kl, Kt	viscosity in the longitudinal and transversal current direction [m^2/s]
al, at	dispersion coefficient in the longitudinal and transversal current direction [-]
U*	friction velocity [m/s]
h	water depth [m]

The Elder turbulence model has been examined with the default settings: al = 6, at = 0.6.

Table 10 – Sensitivity runs of the flow model w.r.t turbulence settings

Run ID	Turbulence model	Parameter values
Run18	Constant viscosity	1 m^2/s
Run17	Constant viscosity	0.1 m^2/s
Run19	Constant viscosity	0.01 m^2/s
Run20	Elder model	al = 6; at = 0.6 (default)

Among the four runs, Run18 with the viscosity value of 1 m^2/s results in a flattening of the water level signal at the upstream locations of Durme river (see Figure 28 for stations Zele and Lokeren). This observation (a flattening out of the tidal signal) is also observed at the most upstream station Lokeren with the viscosity of 0.1 m^2/s. Run19 (constant viscosity of 0.01 m^2/s) and Run20 (Elder model) give similar water levels. However, Run19 shows numerical instabilities of the computed water levels at the station Driegoten and Tielrode (see Figure 28 for Driegoten). The Elder turbulence model was selected for further simulations

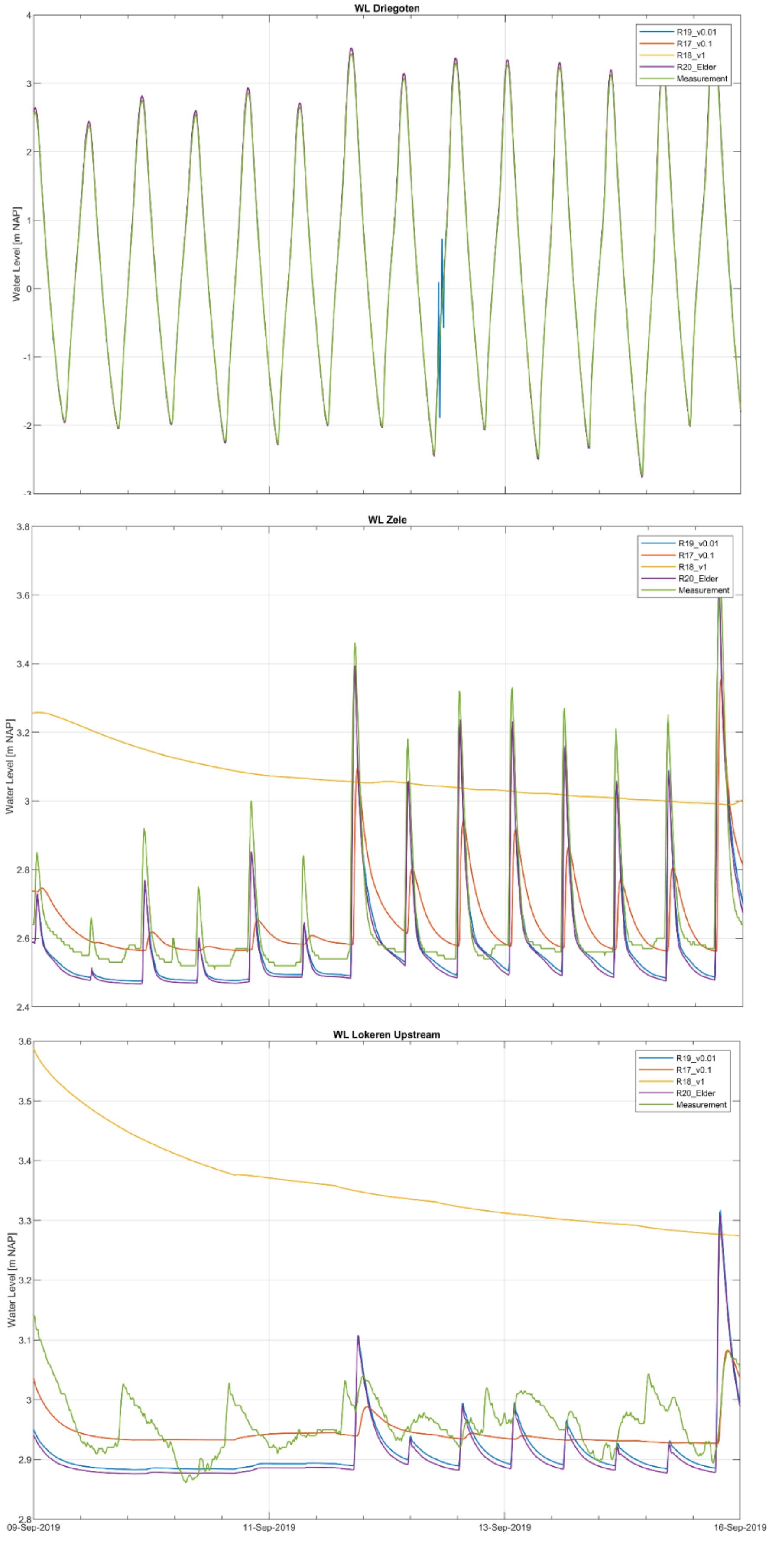


Figure 28 – Measured and modeled water levels at Driegoten, Zele and Lokeren with different turbulence model settings

7 Model calibration

7.1 Calibration strategy

No accurate discharge data is available for the Durme. The only data available is the daily effluent of the wastewater treatment plant in Lokeren for the year 2019. As shown in §6.2, the discharge has a clear influence on the water levels. To avoid this influence as much as possible, a period for calibration was selected with almost no rainfall and hence limited fresh water discharge (and variation) in the Durme.

In the study area, dredging of the fairway was carried out during the period 2012 - 2014 (Meire et al., 2024b)). To ensure robust model settings, calibration has been carried out both before and after this major dredging work. As stated in the model goals (§1.2) the aim of the calibration is to find one parameter setting that works both for the situation before and after dredging, and both for high and low discharge conditions. This aim is achieved by constructing a cost function that is minimized (see §7.4).

7.2 Calibration period selection

7.2.1 Calibration period after dredging (2019)

As presented above, the calibration period is chosen in such a way to avoid periods with high runoff. In Figure 29, the precipitation in the year 2019 at Zele (plu17a – 1066) is plotted together with the water levels at the two most upstream stations Lokeren and Zele (see Figure 4 for the locations). The measured RWZI discharge is also presented. The figure shows a correlation of the precipitation with water levels upstream as well as with the RWZI discharge.

Based on the availability of the data of water level, ADCP current velocity, and the upstream discharge from wastewater treatment plant (RWZI), a period in 2019 was selected as a calibration period for the post dredging case. In this year, three ADCP sailed measurement campaigns are available: one at Weert/Driegoten on 02/09/2019 and one at Waasmunster Brug and one at Tielrode on 16/09/2019 (see Figure 6 for the location). The precipitation and RWZI discharge were small during these two days. Within the month 09/2019, a continuous period of 14 days, from 09/09/2019 to 23/09/2019 shows the limited precipitation, low discharge from the RWZI and relatively low water level at the upstream measurement locations (Zele, Lokeren). These two weeks (09/09/2019 - 23/09/2019) were therefore selected for the calibration of the model considering the water levels. To make use of the ADCP data for Weert on 02/09/2019 as well, the model runs were started on 31/08/2019, in which the first two days are the model initialization period (Table 11).

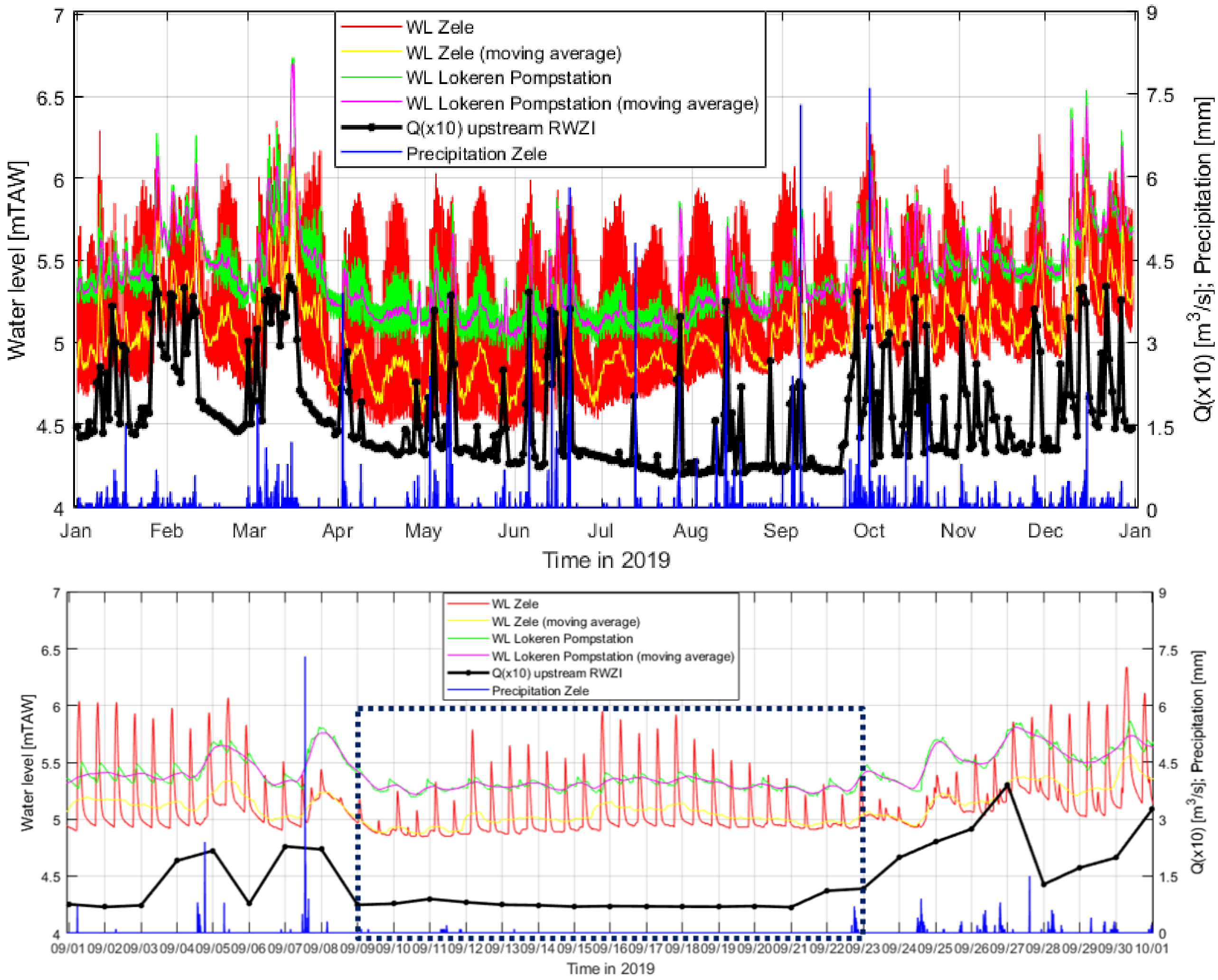


Figure 29 – Water level and precipitation at Zele and Lokeren and discharge RWZI (discharge is multiplied by 10) for the whole year 2019 (upper) and in 09/2019 (lower). The black dotted line shows the selected calibration period

Table 11 – Calibration period for the 'after dredging' case

Calibration period w.r.t water level	Calibration period w.r.t ADCP velocity	Total calibration period
09/09/2019 – 23/09/2019 (14 days)	02/09/2019 16/09/2019	02/09/2019 - 23/09/2019 (+2 days initialization)

7.2.2 Calibration period before dredging (2010)

Similar to the case after dredging, a dry period was chosen to perform the simulations for the "before dredging" case. Figure 30 presents the precipitation at Zele station for the year 2010, together with the water levels at Waasmunster Manta. This tidal station was chosen instead of Zele and Lokeren (as in Figure 28 for the case in 2019) because the water levels are not available at these two stations for 2010. The period of 14 days (12/04/2010 - 26/04/2010) shows low rainfall and was selected to carry out the calibration runs.

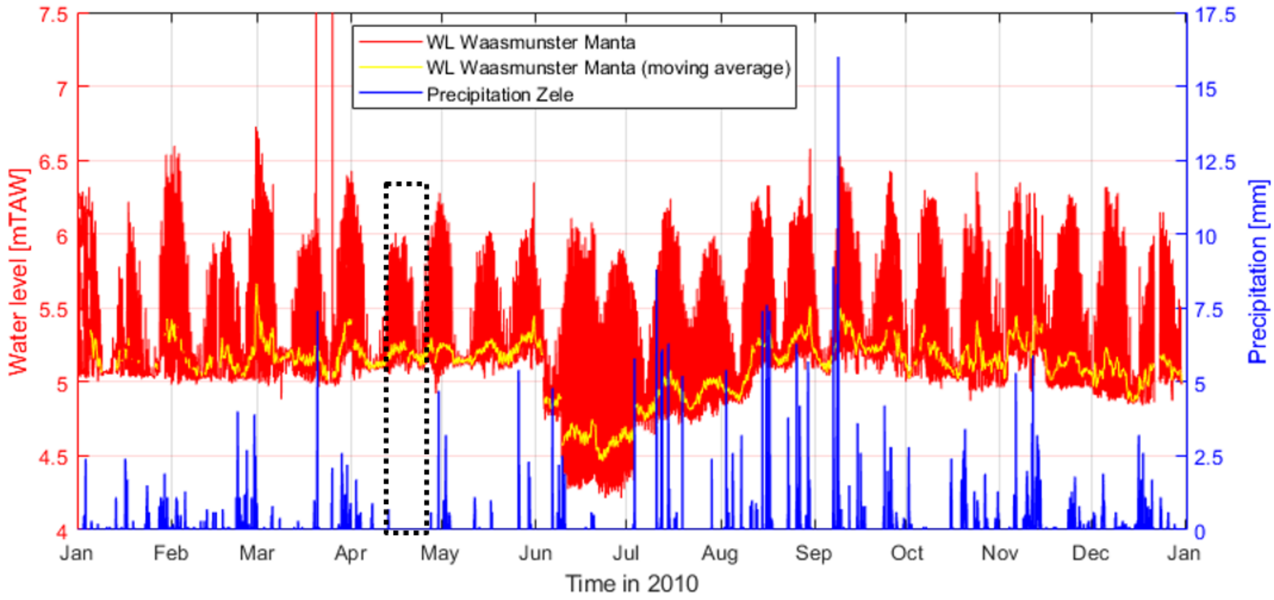


Figure 30 – Precipitation at Zele and water level at Waasmunster-Manta in 2010. The black dotted line shows the calibration period

Table 12 – Calibration period for the 'before dredging' case

Calibration period w.r.t water levels	Calibration period w.r.t ADCP velocity	Total calibration period
12/04/2010 – 26/04/2010 (14 days)	15/04/2010	12/04/2010 – 26/04/2010 (+2 days initialization)

7.3 Calibration runs

For each calibration period before dredging (in 2010) and after dredging (2019), seven model runs were carried out with the roughness values of 0.01, 0.012, 0.014, 0.016, 0.018, 0.02 and 0.022 s/m$^{1/3}$ (see Table 13). The Elder turbulence model with default settings was used. The other parameters are found in Table 8.

Table 13 – Overview of model calibration runs

Manning coefficient [s/m$^{1/3}$]	Run ID year 2019 - after dredging	Run ID year 2010 - before dredging
0.010	Run32	Run33
0.012	Run25	Run26
0.014	Run24	Run27
0.016	Run23	Run28
0.018	Run20	Run29
0.020	Run21	Run30
0.022	Run22	Run31

7.4 Calibration method - Cost function

To select one set of the model parameters that can produce good results spatially and temporarily, a cost function was used. This cost function is defined to get one objective value that represents the quality of the model performance, and as such makes it possible to compare different model runs (Smolders et al., 2016). One run is selected as a reference run, the cost is calculated for each run based on the chosen factors (model statistical parameters), thresholds (expected observation errors) and the associated weights:

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

The cost for the reference run equals 1. A run with a cost < 1 indicates a better model performance compared to the reference run, whereas a cost > 1 implies worse model performance.

The factors (statistical parameters) included in the cost function, together with the thresholds and weights selected in this study are given in the Table 14. For water levels (HW, LW), BIAS and RMSE0 were chosen and RMSE was used considering current velocity and discharge (see the formulation of these parameters in Appendix 1).

In Smolders et al. (2016), the threshold for the RMSE of water levels was selected as 0.03 m, this value was applied to the BIAS and RMSE0 in this study. The threshold for the RMSE of HW and LW phase was selected as 3 minutes. The threshold for the RMSE of discharge is 13 m^3/s, which is the value used in Smolders et al. (2016) for the Upper Sea Scheldt. The threshold for the RMSE of current velocity was chosen as 0.05 m/s, which is the measurement error for current velocity suggested in Van Rijn et al., (2003).

The general aim of the Durme model is to represent the tidal wave within the Durme, which the water is getting shallower and very undeep in the upstream section and the area here is characterized by very asymmetric tides. The general sinusoidal tidal curve is only seen in the downstream part and as such no harmonic components are used in the cost function.

The water levels are very sensitive to the applied upstream discharge (see §6.2), which is unknown, and to the bathymetric data. Furthermore the definition of low water (time and level) is difficult in the most upstream part, as the water levels remain almost constant, except for a short period around high water. Therefore the error statistics of the low waters in the upstream part was not integrated in the cost function and focus was put on the high waters. As there is a good distribution of the water level stations over the Upper Scheldt and Durme, an equal weight over the different stations was chosen.

For the horizontal tides, only a limited number of data is available and as such, the weight in the cost function is smaller compared to vertical tide measurements.

In total, 28 high waters, 27 low waters for each water level station, 2 ADCP measurements (30 transects at Weert and 16 transects at Waasmunster-Brug) and 1 discharge time series (177 data points) were used in the calculation of the cost function for the situation in 2019. The data for the period in 2010 includes 27 high waters, 27 low waters for each water level station and 50 ADCP transects at Driegoten.

To assure a robust calibration, both situations after and before dredging in 2019 and 2010, respectively were assessed. As the amount of data available in 2019 is higher, both bathymetric data and calibration data (water level and velocity measurements), higher weights were assigned to the period in 2019.

Table 14 – Factor, weights and thresholds used in the cost function for calibration

		Factor	Threshold	Stations	Weight [%]	
2019						**70**
Vertical tide (water level)	HW	|BIAS| HW level [m]	0.03	Driegoten Tielrode Waasmunster-Brug Waasmunster-Manta Zele	10	40
		|BIAS| HW time [min]	3		10	
		RMSE0 HW level [m]	0.03		10	
		RMSE0 HW time [m]	3		10	
	LW	|BIAS| LW level [m]	0.03	Driegoten Tielrode	1.25	5
		|BIAS| LW time [min]	3		1.25	
		RMSE0 LW level [m]	0.03		1.25	
		RMSE0 LW time [m]	3		1.25	
Horizontal tide (current velocity, discharge)		RMSE ADCP current velocity [m/s]	0.05	Weert Waasmunster-Brug	20	25
		RMSE discharge [m^3/s]	13	Tielrode	5	
2010						**30**
Vertical tide	HW	|BIAS| HW level [m]	0.03	Tielrode Waasmunster-Brug Waasmunster-Manta	4	16
		|BIAS| HW time [min]	3		4	
		RMSE0 HW level [m]	0.03		4	
		RMSE0 HW time [m]	3		4	
	LW	|BIAS| LW level [m]	0.03	Tielrode	1	4
		|BIAS| LW time [min]	3		1	
		RMSE0 LW level [m]	0.03		1	
		RMSE0 LW time [m]	3		1	
Horizontal tide (current velocity)		RMSE ADCP current velocity [m/s]	0.05	Driegoten	10	10

7.5 Calibration results

The comparisons of the water level, ADCP current velocity and discharge from the measurements and model with different Manning coefficients for the two periods are presented in Figure 44 to Figure 50 (Appendix 2). The results were integrated in a cost value to select one optimal model setting (see §7.4 for the implementation of the cost).

Figure 31 shows the cost values resulted from 14 calibration runs with 7 values of Manning coefficient. The runs with smallest value of n = 0.01 s/m$^{1/3}$ were selected as a reference runs. Therefore this value coincides with a cost value of 1. The cost decreases slightly with the increase of the coefficient up to 0.016 s/m$^{1/3}$, indicating better model performance compared to the reference runs. Further increase of the Manning coefficient results in a cost higher than 1, showing worse model quality. It should be mentioned however that the difference in the cost function for n in the range of 0.012 to 0.016 s/m$^{1/3}$ is very small. The Manning coefficient of 0.016 s/m$^{1/3}$ gives the best model performance (the lowest cost value). The following section presents the results of the model applying n = 0.016 s/m$^{1/3}$, for both situations: after dredging (Run23) and before dredging (Run28).

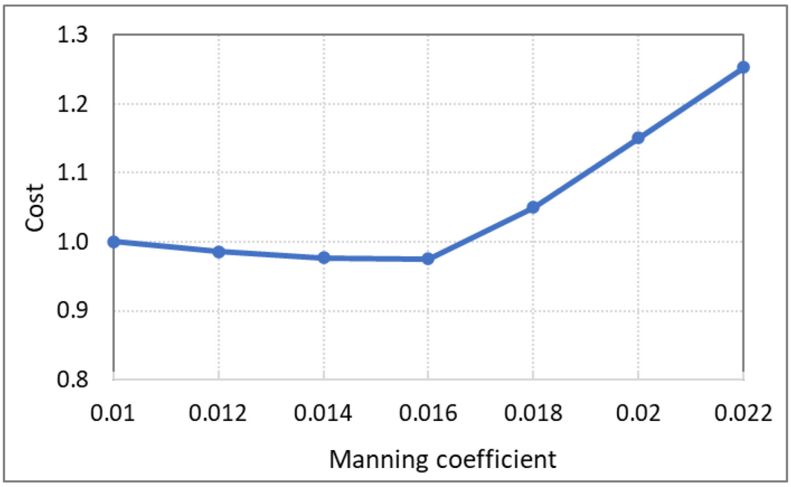


Figure 31 – Cost value for different Manning coefficients computed for both cases before and after dredging

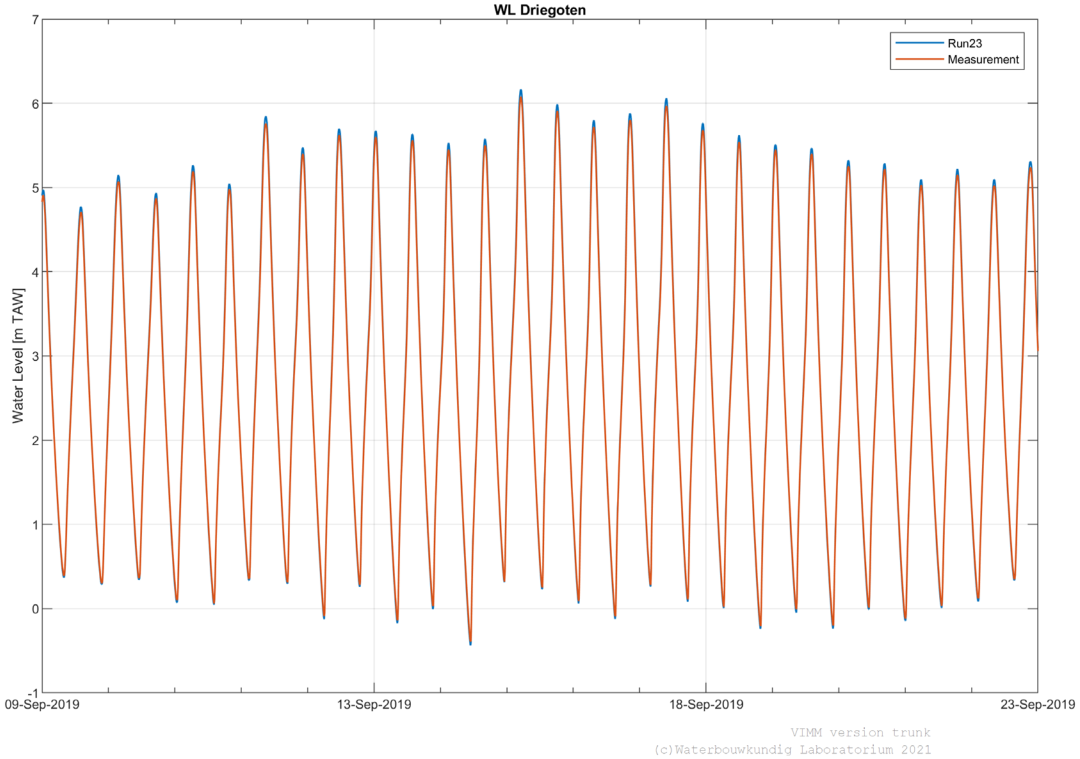
7.6 Evaluation of calibrated model

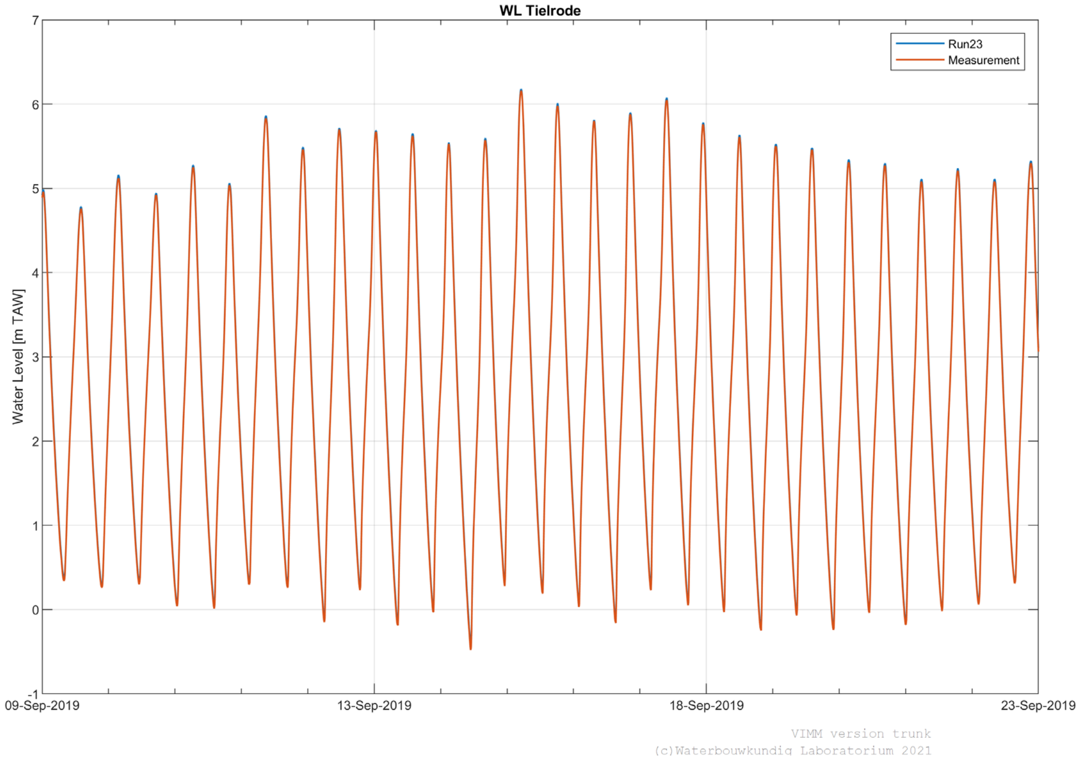
7.6.1 Calibration period in 2019: after dredging

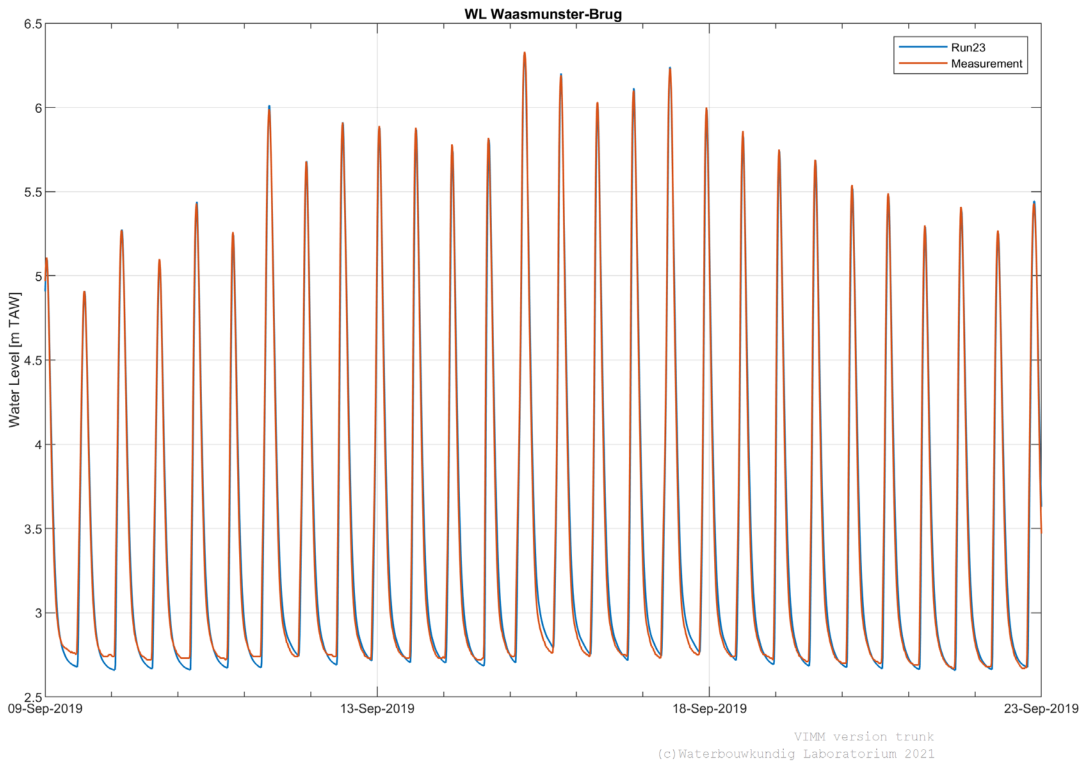
7.6.1.1 Time series of water level

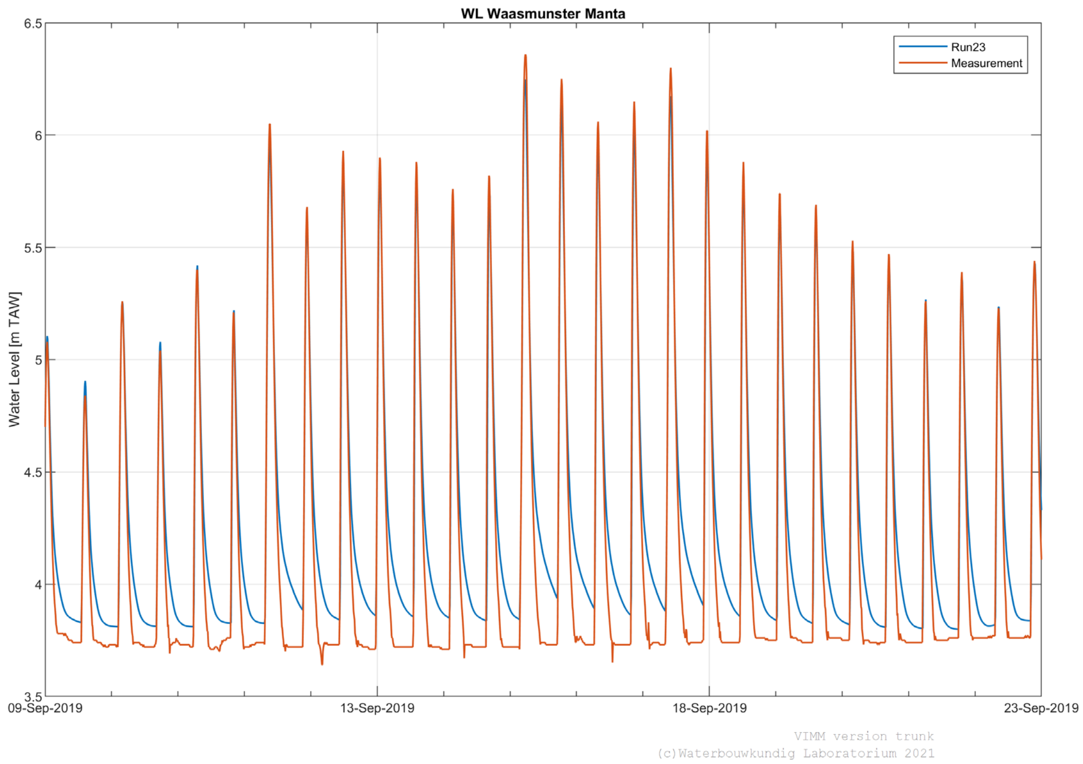
Figure 32 presents the measured and modeled water levels at Driegoten, Tielrode, Waasmunster-Brug, Waasmunster-Manta and Zele for the calibration period in 2019 (see Figure 4 for the locations). Both measured and modeled water levels show clearly spring-neap tidal variation. A deviation in the simulated water levels is observed around low water moments at locations upstream of the Durme river (Waasmunster-Brug, Waasmunster-Manta and Zele). This is mainly due to the uncertainty in the bathymetry and unknown discharge at the upstream end of the Durme river. Therefore, the statistical errors for these locations are presented for only high waters (Figure 33). For other two stations Driegoten, Tielrode the whole timeseries is also considered in the statistical analysis. The formulations of the statistical parameters are presented in Appendix 1.

The underestimation of the modelled HW (negative BIAS) upstream of Durme river, at Zele is probably mainly due to lack of inflow discharge imposed at the model upstream boundary. The RMSE of modelled HW for this location is 12 cm. For other four stations, the model represents the water level measurements very well. RMSE is quite small, in the range of 1.5-7.5 cm






WL Waasmunster-Brug
Run23
Measurement
Water Level [m TAW]
6.5
6
5.5
5
4.5
4
3.5
3
2.5
09-Sep-2019
13-Sep-2019
18-Sep-2019
23-Sep-2019
VIMM version trunk
(c)Waterbouwkundig Laboratorium 2021


WL Waasmunster Manta
Run23
Measurement
Water Level [m TAW]
6.5
6
5.5
5
4.5
4
3.5
09-Sep-2019
13-Sep-2019
18-Sep-2019
23-Sep-2019
VIMM version trunk
(c)Waterbouwkundig Laboratorium 2021

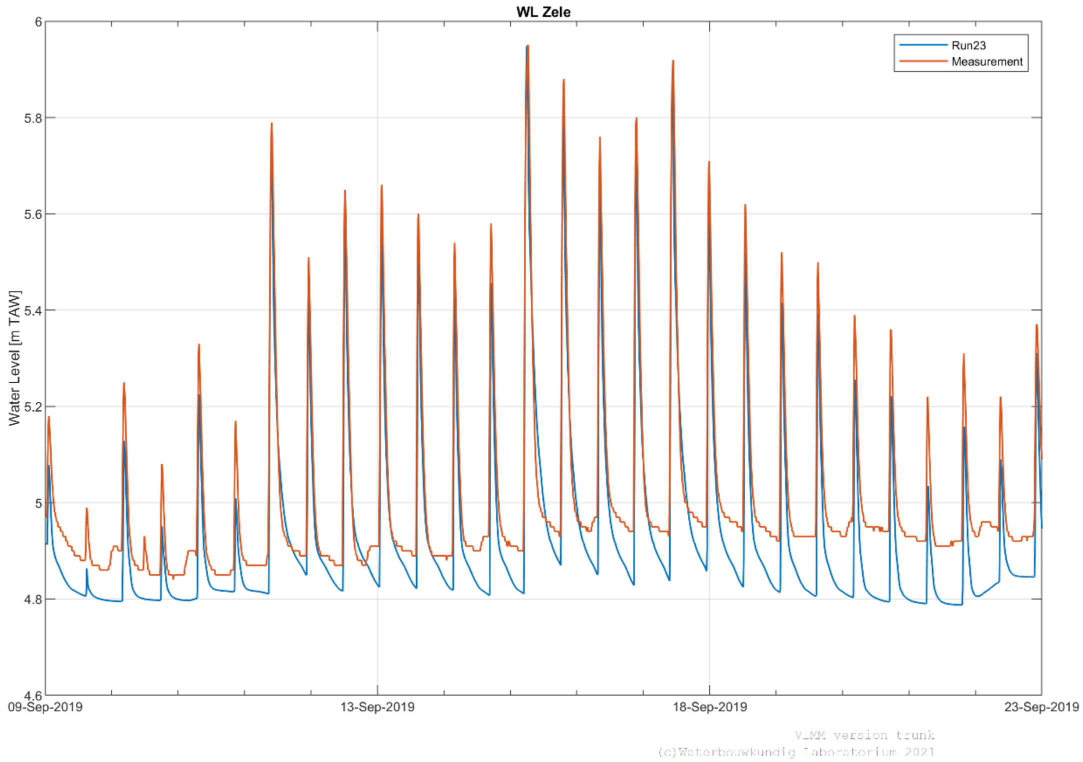
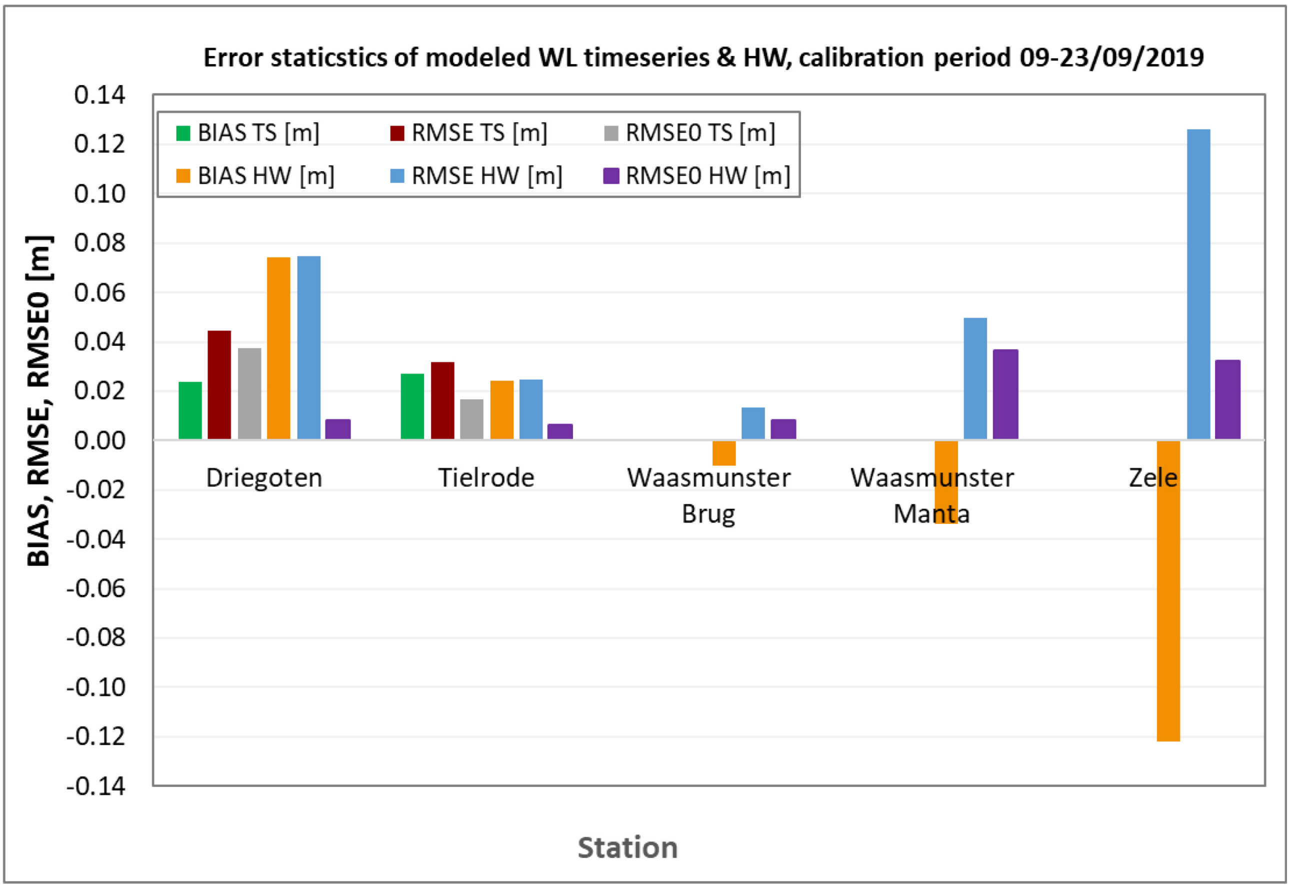


Figure 32 – Measured and modeled water levels at Driegoten, Tielrode, Waasmunster-Brug, Waasmunster-Manta and Zele during the calibration period in 2019 - after dredging

Figure 33 – BIAS, RMSE and RMSE0 of the computed water level, calibration period in 2019: after dredging



7.6.1.2 ADCP sailed current velocity

Figure 34 and Figure 35 compares of the depth-averaged current velocity along the transects Weert at the moment around maximum ebb and Waasmunster-Brug around maximum flood (see Figure 6 for the location). The timeseries of measured and modeled mean velocity is compared in Figure 36 and Figure 37 for Weert and Waasmunster-Brug, respectively.

The model reproduces very well the velocity magnitude and direction along Weert. The averaged RMSE and RMAE for this cross-section are 0.18 m/s and 0.21. Once adjusted RMAE (i.e. ARMAE, see Equation 5 in Appendix 1) is used in which the measurement error is considered in the calculation of the parameter, the model is ranked as excellent, according to the qualification of Sutherland et al., (2004) (see Table 15).

For Waasmunster-Brug, deviation in the direction can be found around the turning moment of the tide. This contributes to a high value of RMAE (0.64) for this cross-section. The calculated RMSE of 0.17 m/s is quite small.

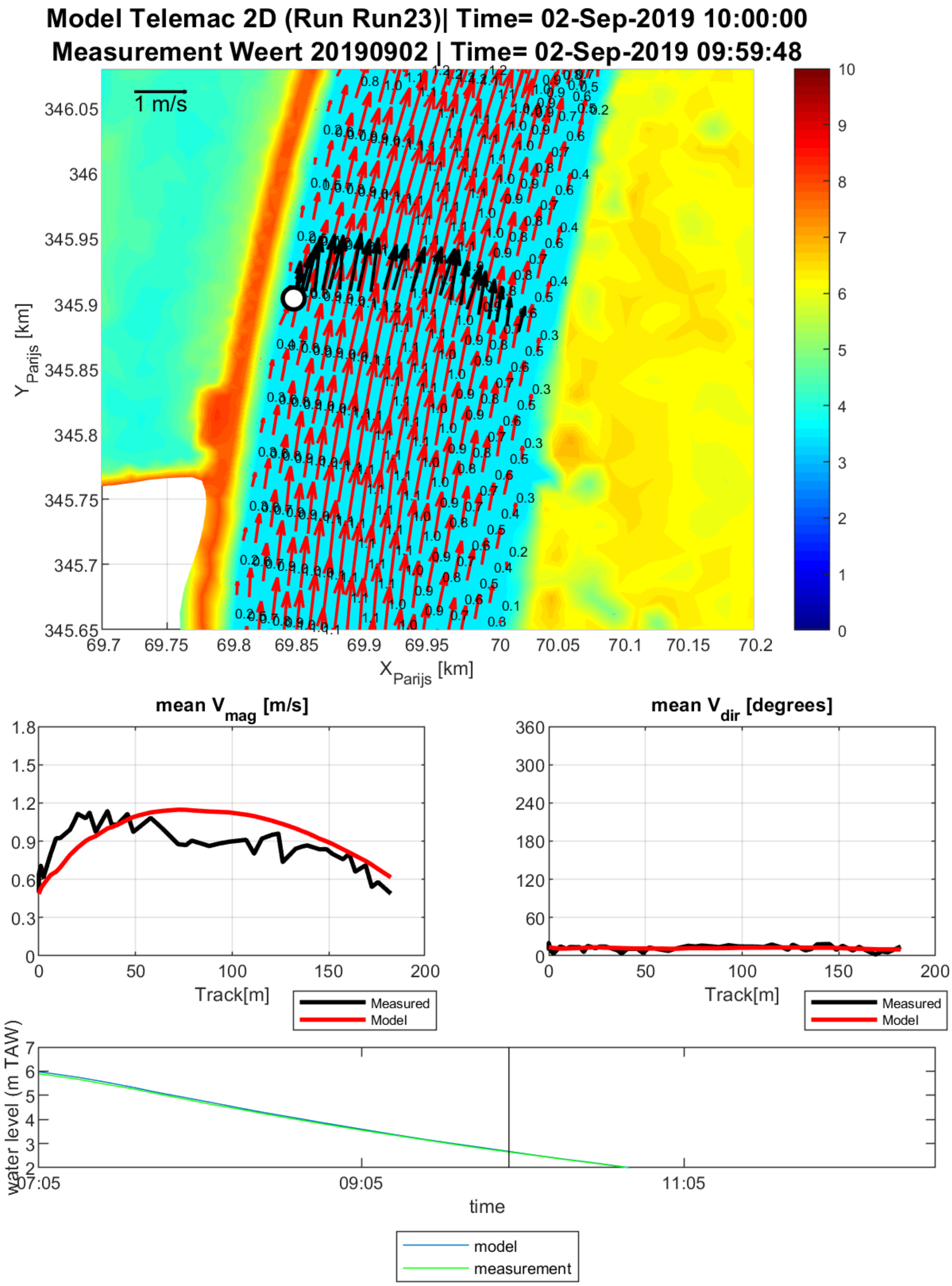


Figure 34 – Measured and modeled depth-averaged current velocity at cross-section Weert around maximum ebb

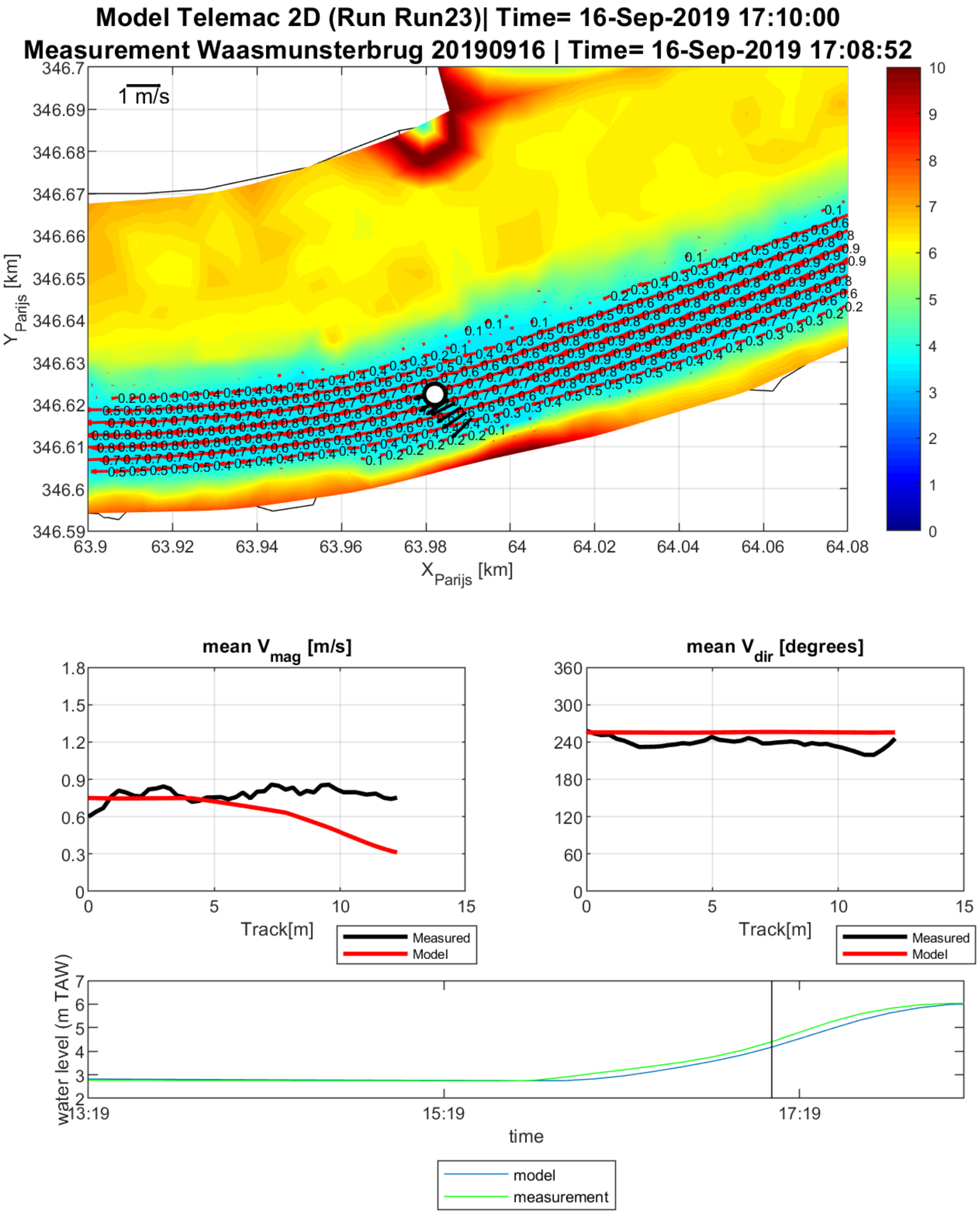


Figure 35 – Measured and modeled depth-averaged current velocity at cross-section Waasmunster-Brug around maximum flood

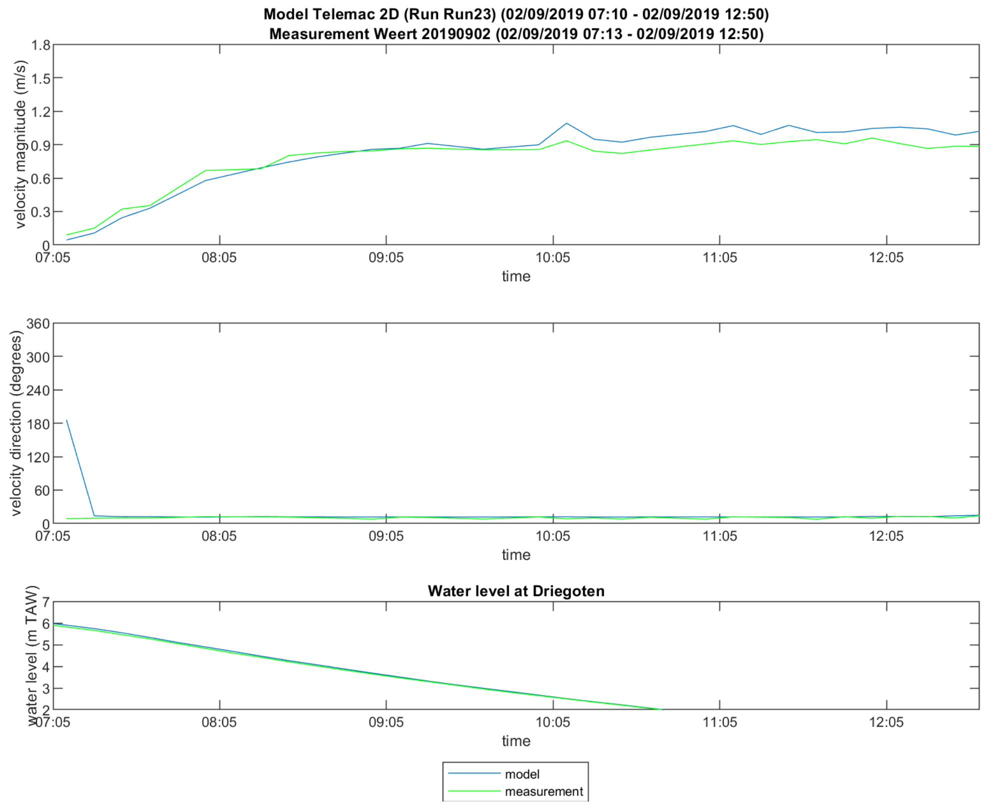


Figure 36 – Timeseries of measured and modeled mean velocity magnitude and direction at cross-section Weert on 02-09-2019

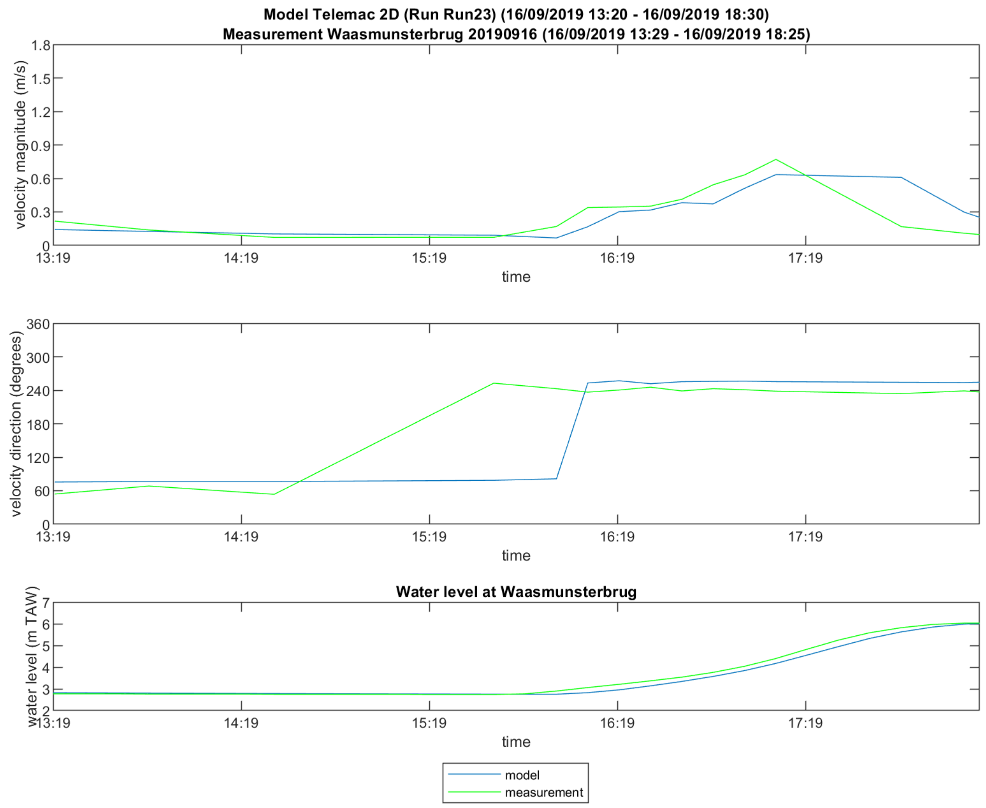


Figure 37 – Timeseries of measured and modeled mean velocity magnitude and direction at Waasmunster-Brug on 16-09-2019

7.6.1.3 Flow dischange

Figure 38 compares the discharge through the Tielrode cross-section from measurement and model on 16/09/2019 (see Figure 6 for the location). The phases and values are well captured by the model. Both measurement and model show higher discharge peak during the rising phase than the falling phase of the tide. The model underestimates the lower peak in the ebb phase. The RMSE is 15 m^3/s, which is considered quite small.

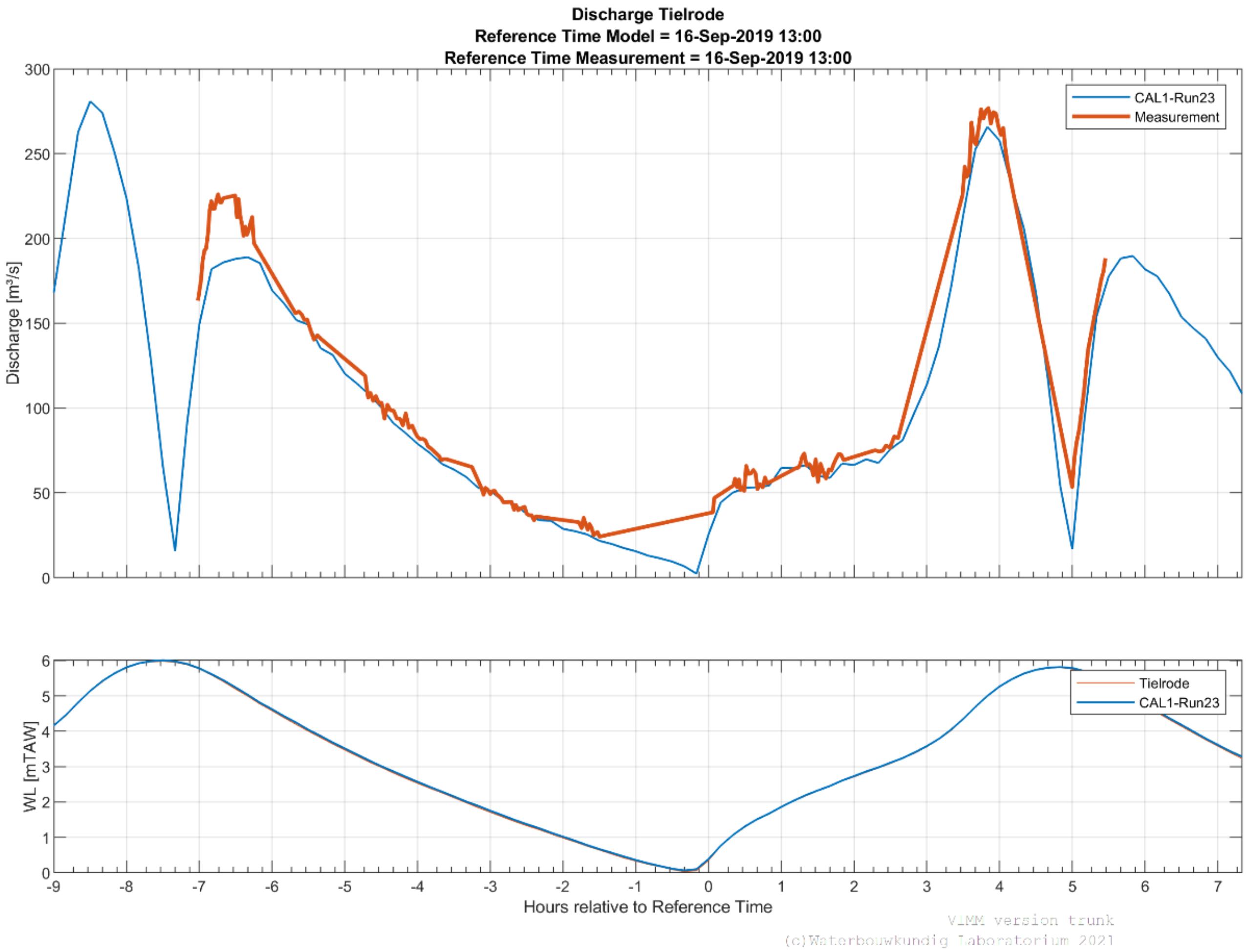


Figure 38 – Measured and modeled discharge across transect Tielrode

7.6.2 Calibration period in 2010: before dredging

In the calibration period in 2010, the water level measurements are available at three stations Tielrode, Waasmunster-Manta and Waasmunster-Brug. In Figure 39, BIAS, RMSE and RMSE0 of the modeled high water levels are presented. The error statistics of the complete time series is calculated for the location Tielrode. All errors are smaller than 3 cm, which indicate very good model performance.

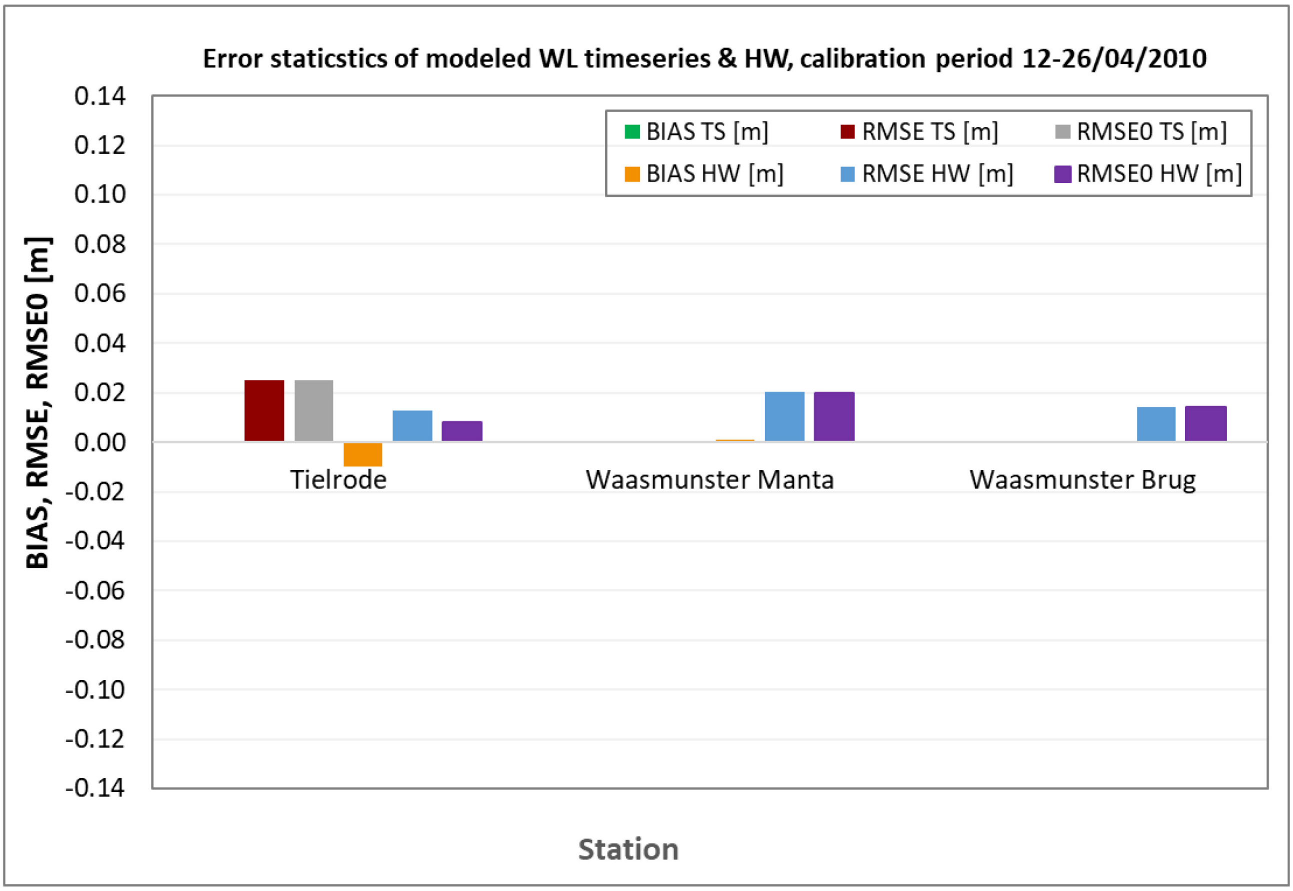


Figure 39 – BIAS, RMSE and RMSE0 of the computed water level, calibration period in 2010: before dredging

7.6.2.1 ADCP sailed current velocity

In the calibration period in the 2010, one ADCP measurement available at the cross-section Driegoten. This data covers the whole tidal cycle on 15/04/2010. The measured and computed velocity magnitude and direction along the transect are compared in Figure 40 and Figure 41, respectively for the moments around maximum ebb and maximum flood. The comparison of timeseries velocities over the whole tide cycle is presented in Figure 42.

It is clear in the figures that the peak flood velocity is higher than peak ebb velocity. However, the ebb duration lasts longer (~7 h vs. 5.5 h) (Figure 42). The figures show a good agreement between measurement and model, both during ebb and flood phases. The RMSE and RMAE of 0.2 m/s and 0.25, respectively. Employing the ratio RMAE/ARMAE of about 1.5 as found in Sutherland et al., (2004), the model performance is ranked as excellent (see Table 15).

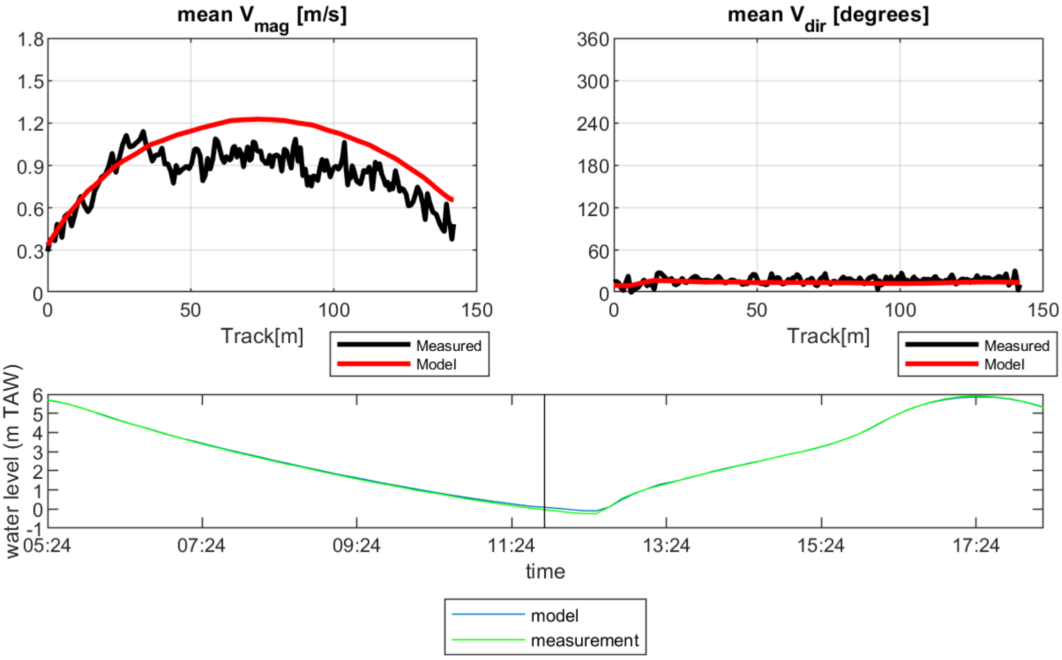


Figure 40 – Measured and modeled depth-averaged current velocity at cross-section Driegoten around maximum ebb

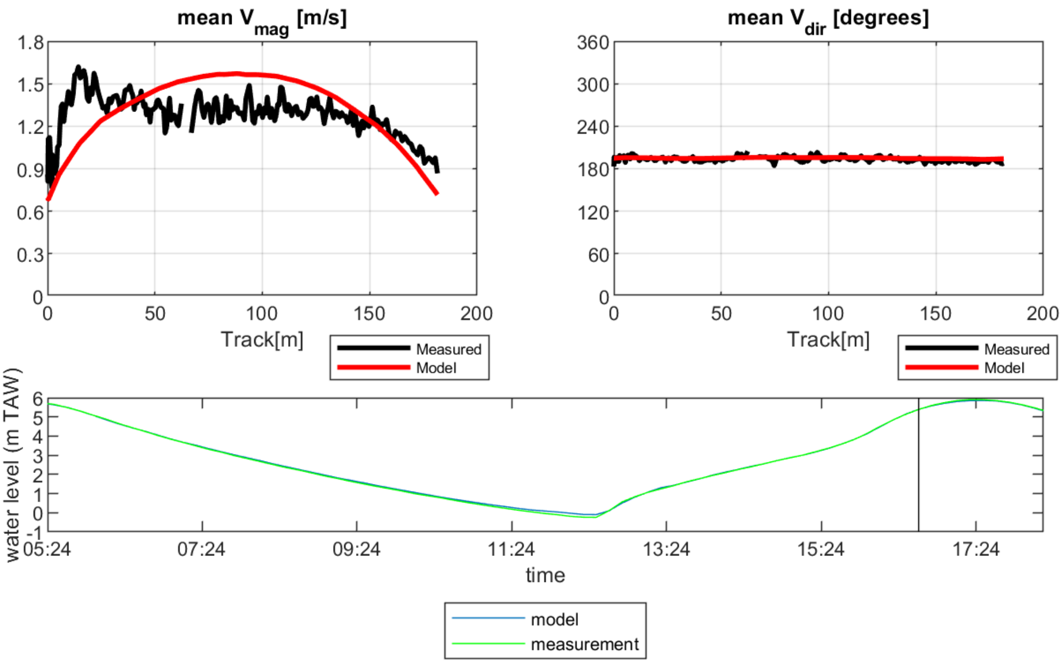


Figure 41 – Measured and modeled depth-averaged current velocity at cross-section Driegoten around maximum flood

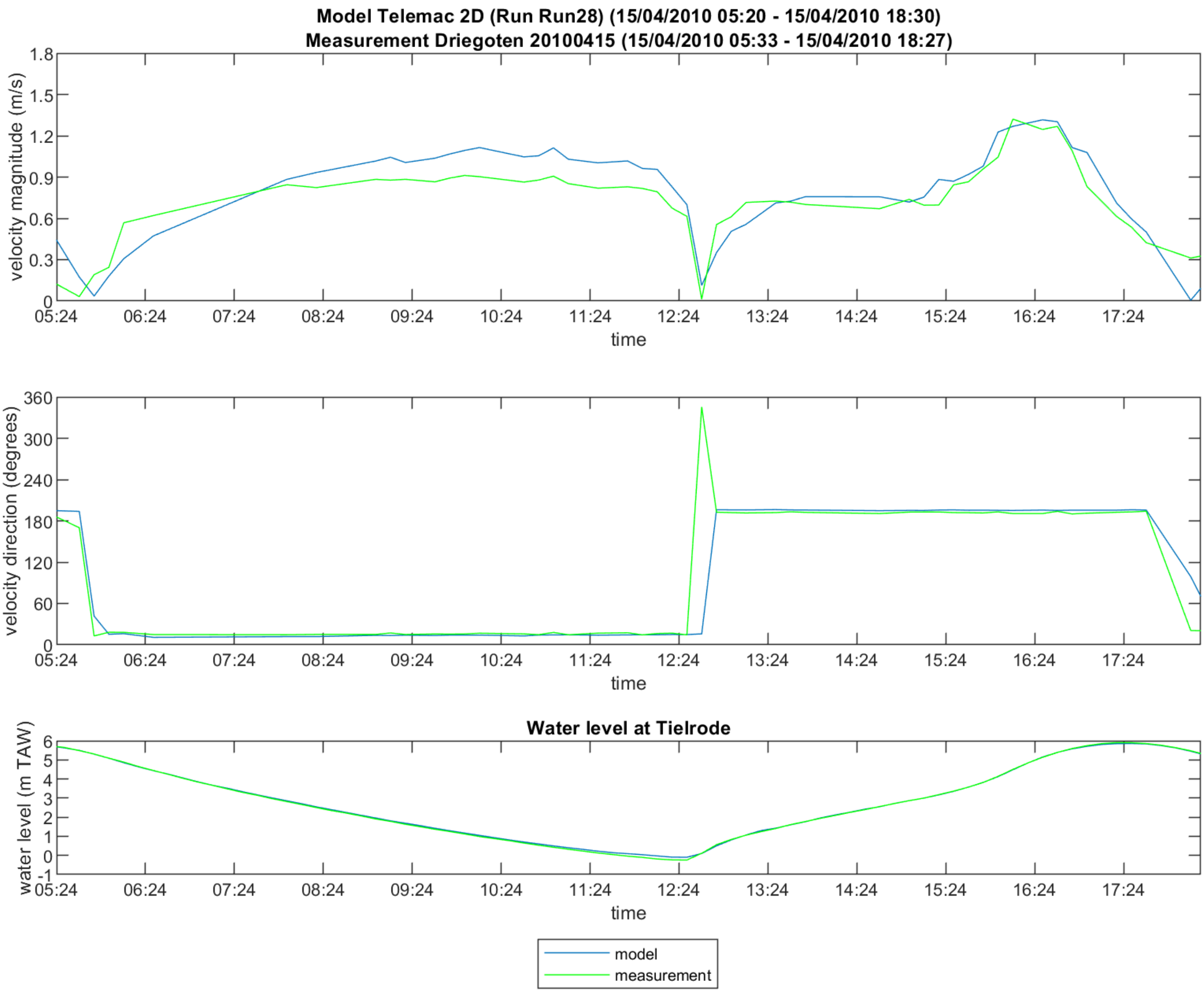


Figure 42 – Timeseries of measured and modeled mean velocity magnitude and direction at Driegoten on 16-09-2019

7.6.3 Effect of the reduction of water level at northern boundary at Temse

At the reporting phase, we were informed about the correction in the water level measurements at several stations in the Scheldt due to an error in the recorded data (see also in Vereecken et al., 2023). Within the Durme model domain, the correction of -4 cm is applied to the water levels at Temse and -5 cm at Driegoten during the period 2011-2021. The reduction of the water levels would have an effect on the hydrodynamic result in the Durme area because the model applies measured water levels at Temse at its northern boundary. In this section, the effect of this correction is studied by carrying out a simulation with the water level at the northern boundary (at Temse) being reduced by 4 cm. This run was conducted for the period after dredging 09/09/2019 – 23/09/2019 (+2 days initialization). The results of high water along the Durme river from the two simulations (with and without water level correction at Temse) are compared for a spring tide and neap tide in Figure 51 (Appendix 3).

Figure 51 shows that with the correction (reduction of 4 cm) of water levels at Temse, high water along the Durme river is reduced by about 3 cm. The effect is less for the most upstream section of the river (about 4 km length), especially for the neap tide.

8 Conclusions and recommendation

8.1 Conclusions

In this study, a detailed model was constructed for the Durme area using TELEMAC modelling software. To answer the addressed research questions, the model should be able to simulate the hydrodynamics accurately, both in a historical situation and in the current situation. Furthermore, it should be able to implement different model scenarios that the Sigma areas are active and the old Durme tributary is reconnected. Therefore, the model has been implemented with high grid resolution to simulate in detail the hydrodynamics in the area. In addition, the model domain covers all existing and foreseen Sigma areas, following the MeWA contour of the Sigma plan.

Sensitivity runs have been performed on the upstream discharge at the Lokeren Dam. The water levels in the upstream part, upstream Waasmunster-Brug, are very sensitive to the applied discharge. Even a small increase of the value has a significant effect on the water levels. As the upstream discharge is unknown, this has been taken into account in the calibration strategy by selecting dry periods with low expected fresh water discharges. Based on the model sensitivity to viscosity settings, and based on theoretical considerations, the Elder viscosity model was selected for this application.

Two calibration periods have been selected: one before dredging (2010), and one after dredging (2019). For each situation, a period of two weeks (spring - neap cycle) was selected with almost no rainfall. The model was calibrated using the available data of water levels (Driegoten, Tielrode, Waasmunster-Brug, Waasmunster-Manta, Zele, Lokeren), ADCP sailed current velocity (Driegoten, Waasmunster-Brug) and discharge (Tielrode). In total, 14 calibration runs were carried out for the two calibration periods with 7 values of Manning bottom roughness.

To select one set of the model parameters that can produce good results spatially and temporarily, a cost function is used, which integrates the model errors for different locations and parameters. A lower cost indicates better model performance. A uniform Manning value of 0.016 $m^{1/3}/s$ was selected as the optimal setting, as it produces the lowest cost value.

The calibrated model was evaluated for both situations in 2010 and 2019. The modeled water levels agree well with the measurements with quite a small error. The RMSE of HW is smaller than 8 cm for all locations, except the value of 12 cm for the most upstream location Zele, which might be explained by unknown upstream discharge and the increased uncertainty in the model bathymetry in the upstream part. Considering the whole timeseries at Driegoten, Tielrode, the total RMSE is smaller than 5 cm.

The evaluation of model horizontal tide is done with ADCP measurements or discharge measurements, where available. For the calibration period 2019, ADCP measurements are available for half a tidal cycle at cross-sections Weert and Waasmunster-Brug. The model reproduces very well the velocity magnitude and direction along Weert. The resulted RMSE and RMAE are 0.18 m/s and 0.21. Once measurement error is considered in the calculation of error statistics, the model is ranked as excellent, according to the qualification of Sutherland et al., (2004). The RMAE for Waasmunster-Brug cross-section is rather high, which is contributed by the deviation in the velocity direction between model and measurement around the turning moment of the tide. The calculated RMSE is still small (0.17 m/s).

The measured discharge through the Tielrode cross-section from 2019 is also used for model calibration. Both measurement and model show a higher discharge peak during the rising phase than during the falling phase of the tide. The model underestimates the (lower) discharge peak after HW. Generally, the model represents well the measured discharge, both phases and values. The RMSE is 15 m^3/s, which is considered as quite small.

For the calibration period in 2010, the ADCP measurement at Driegoten is available over the whole tidal cycle. The measured and modelled velocities show clearly asymmetry of the tide. The peak current velocity is higher during flood than during ebb, but the ebb duration lasts longer. Similar to the calibration period in 2019, the current velocities at this cross-section are well represented by the model. The RMSE and RMAE of 0.2 m/s and 0.25, respectively indicates very good model performance.

8.2 Recommendation

The information of the water level correction was provided at the finalizing phase of the report. All model runs had been carried out applying recorded water levels at the Temse to the northern model boundary that are 4 cm higher than the corrected values. With the correction (i.e. reduction of water levels at Temse by 4 cm), high water along the Durme river is reduced by about 3 cm. Future simulation studies should take this correction into account.

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Appendix 1 Statistics parameters

Let n be the total number of time points in a time series; x_i and y_i respectively be simulated and measured values at time point i (i = 1:n); $\overline{x}$ be the mean simulated values $\bar{y}$ be the mean measured values. Several statistical parameters used in the report are defined as follow:

BIAS:

$$\text{BIAS} = \bar{x} - \bar{y} \quad (1)$$

Root Mean Square Error (RMSE):

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

Unbiased root mean square error (RMSE0):

$$RMSE0 = \sqrt{\frac{1}{n}\sum_{1}^{n}[(x_i - y_i) - (\bar{x} - \bar{y})]^2} \quad (3)$$

Relative Mean Absolute Error (RMAE):

The RMAE is applied to horizontal current velocity which is two-dimensional vector. The formulation of RMAE for the current velocity reads:

$$\text{RMAE} = \frac{\frac{1}{n}\sum_1^n \|\vec{x}_i - \vec{y}_i\|}{\frac{1}{n}\sum_1^n \|\vec{y}_i\|} = \frac{\sum_1^n \sqrt{(x_{1i} - y_{1i})^2 + (x_{2i} - y_{2i})^2}}{\sum_1^n \|\vec{y}_i\|} \quad (4)$$

x_1, x_2: calculated velocity in first and second direction

y_1, y_2: measured velocity in first and second direction

|| || indicates vector magnitude

Sutherland et al., (2004) adjusted RMAE (named ARMAE), which the error of measured parameter is considered. The authors also proposed the qualitative ranking based on the value ranges of ARMAE as shown in the Table 15.

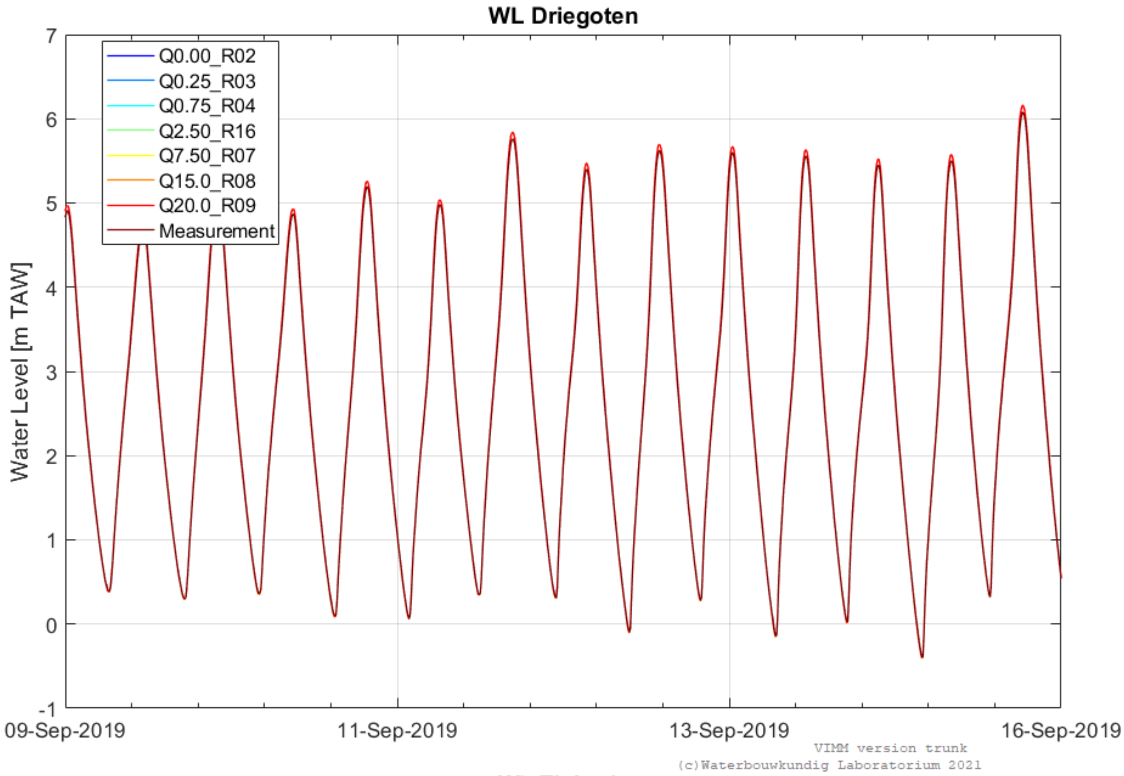
$$\text{ARMAE} = \frac{\frac{1}{n}\sum_1^n \|\vec{x}_i - \vec{y}_i\| - \Delta y}{\frac{1}{n}\sum_1^n \|\vec{y}_i\|} \quad (5)$$

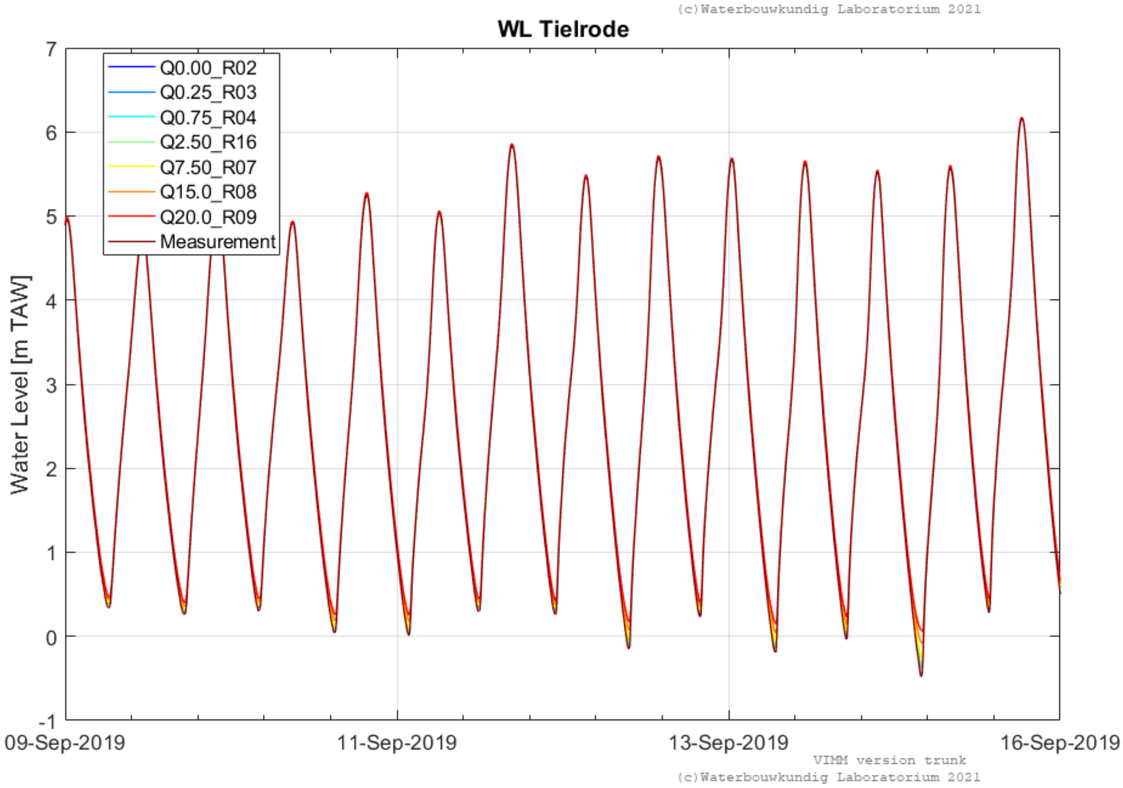
with the measurement error Δy = 0.05 m/s for current velocity.

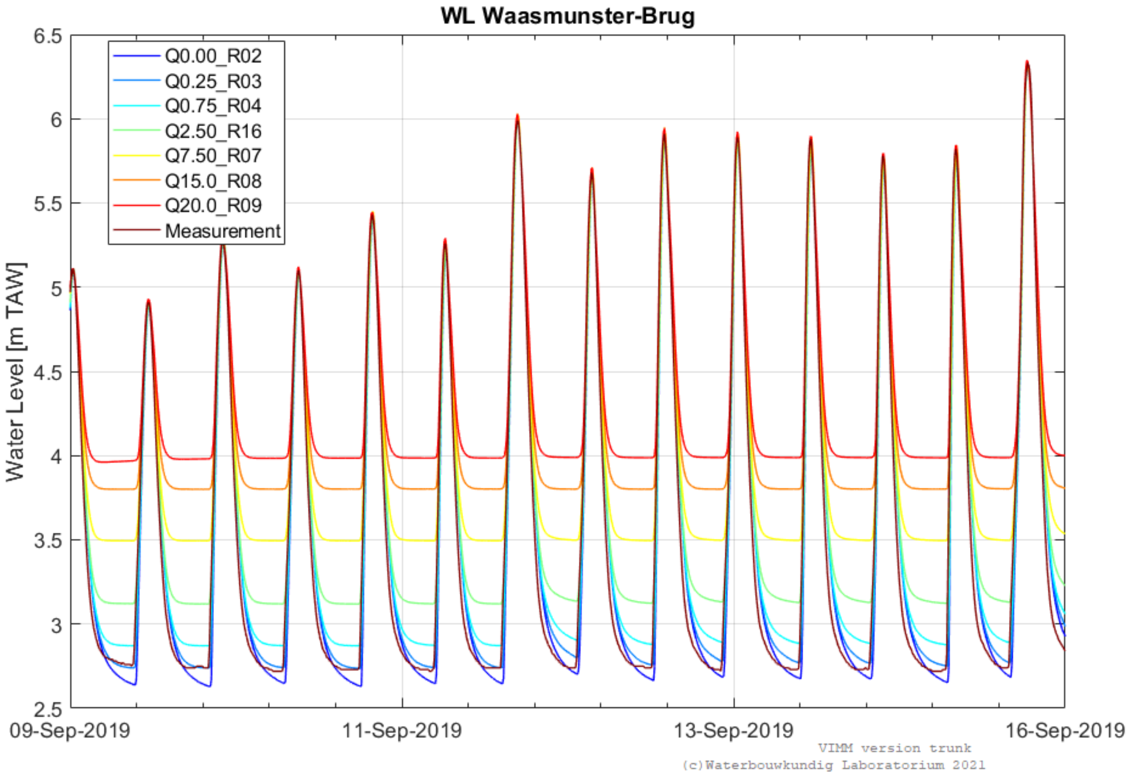
Table 15 – Error classification of current velocity (Sutherland et al., 2004)

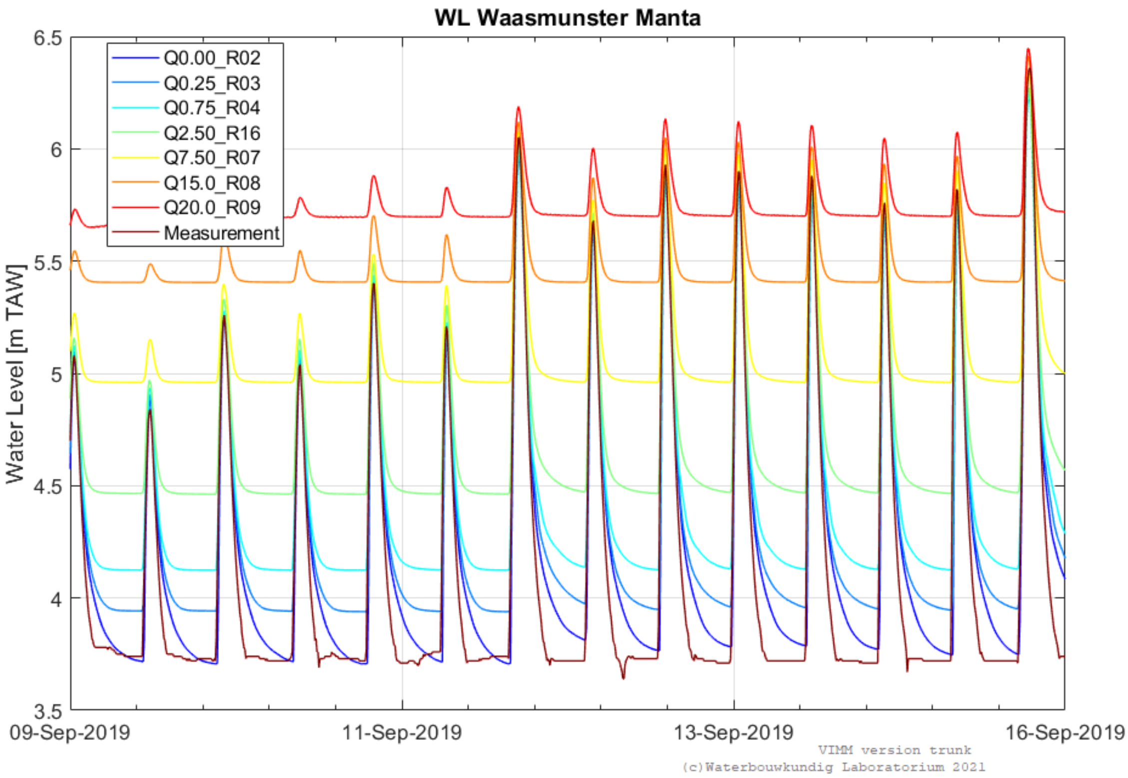
Classification	Current velocity ARMAE
Excellent	< 0.2
Good	0.2 – 0.4
Reasonable/fair	0.4 – 0.7
Poor	0.7 – 1.0
Bad	> 1.0

Appendix 2 Sensitivity/Calibration Figures






WL Waasmunster-Brug
Water Level [m TAW]
6.5
6
5.5
5
4.5
4
3.5
3
2.5
Q0.00_R02
Q0.25_R03
Q0.75_R04
Q2.50_R16
Q7.50_R07
Q15.0_R08
Q20.0_R09
Measurement
09-Sep-2019
11-Sep-2019
13-Sep-2019
16-Sep-2019
VIMM version trunk
(c)Waterbouwkundig Laboratorium 2021


WL Waasmunster Manta
Water Level [m TAW]
6.5
6
5.5
5
4.5
4
3.5
Q0.00_R02
Q0.25_R03
Q0.75_R04
Q2.50_R16
Q7.50_R07
Q15.0_R08
Q20.0_R09
Measurement
09-Sep-2019
11-Sep-2019
13-Sep-2019
16-Sep-2019
VIMM version trunk
(c)Waterbouwkundig Laboratorium 2021

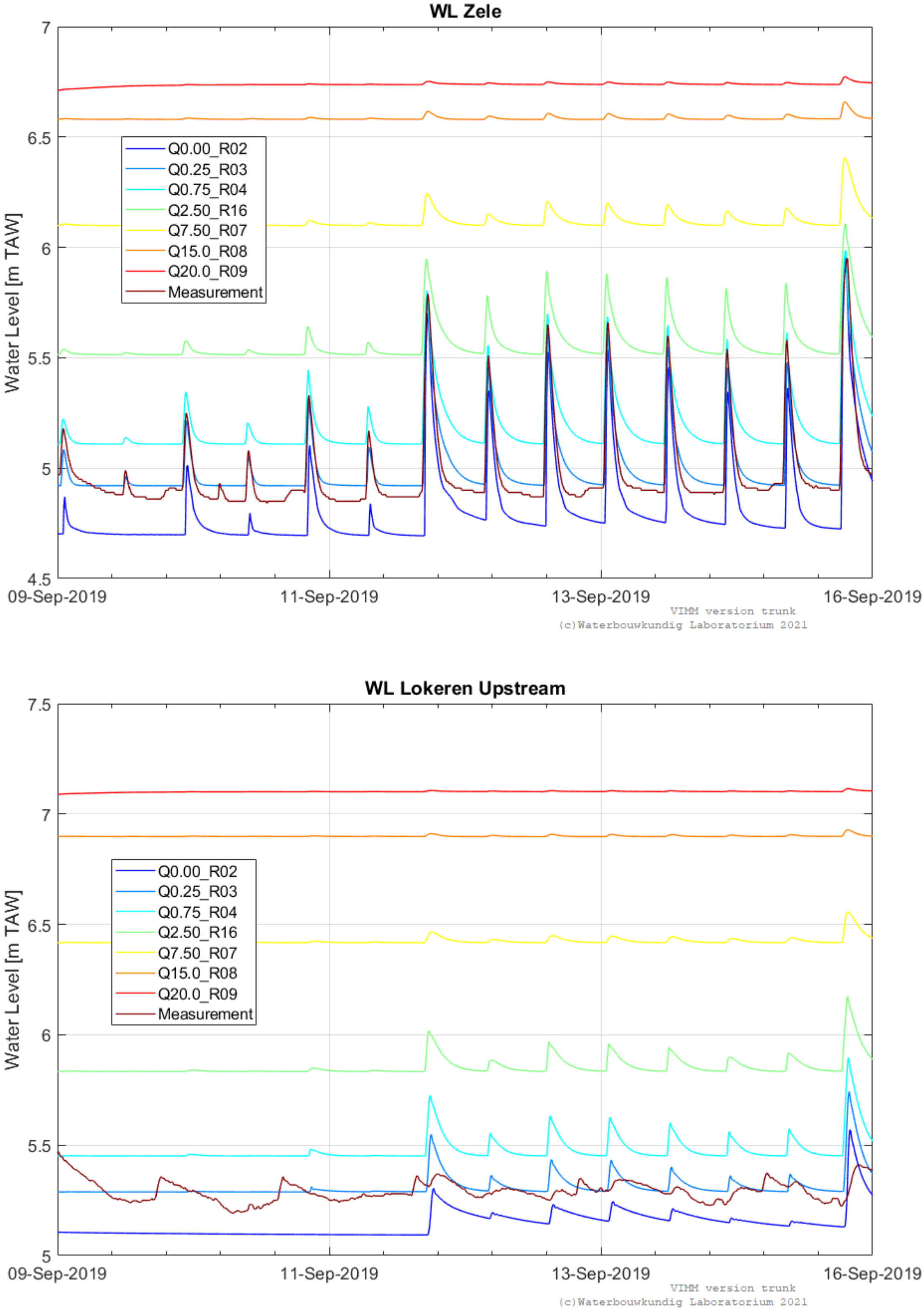
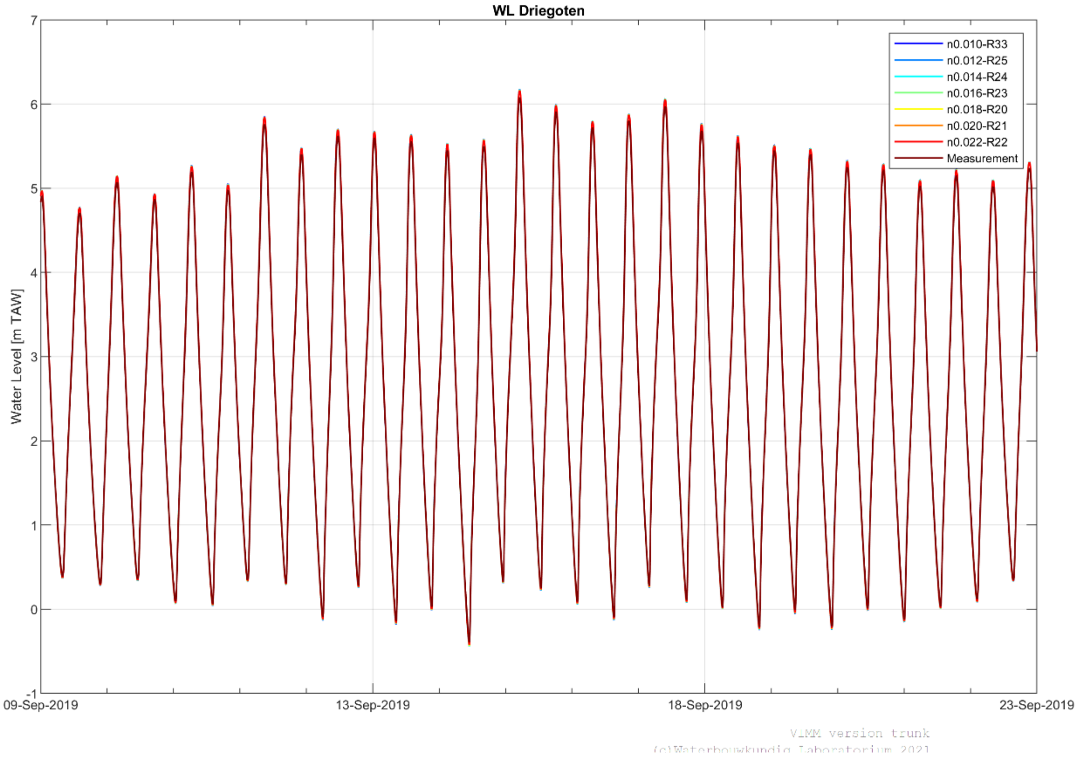
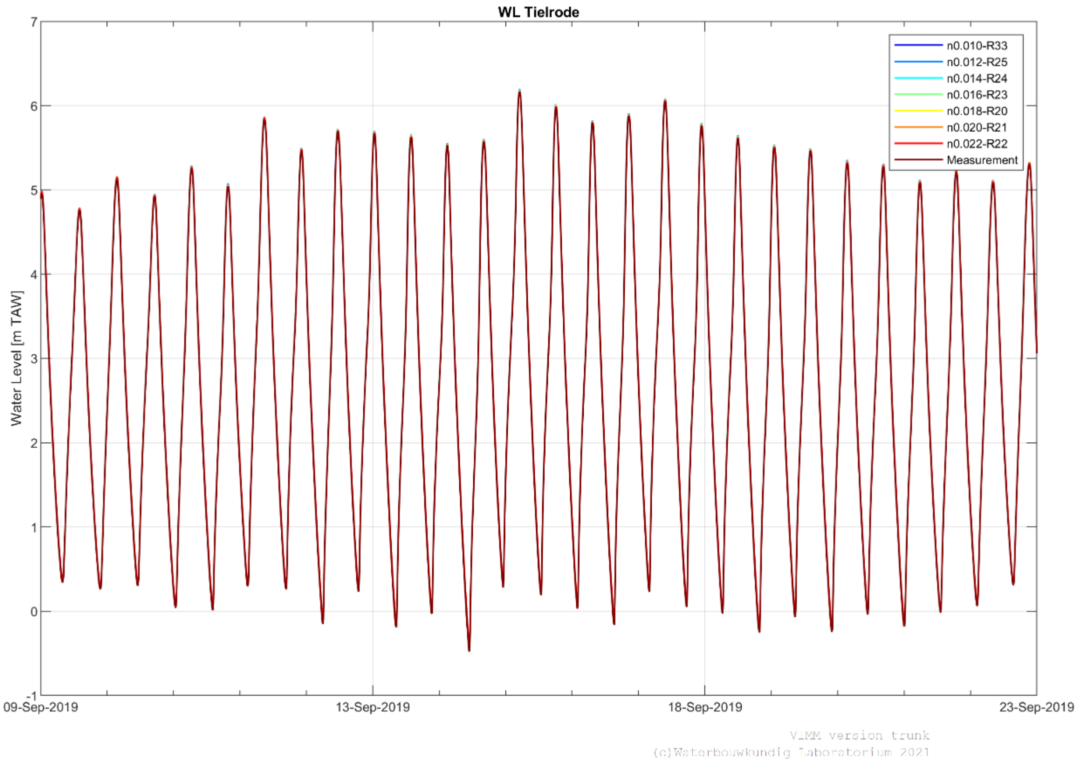
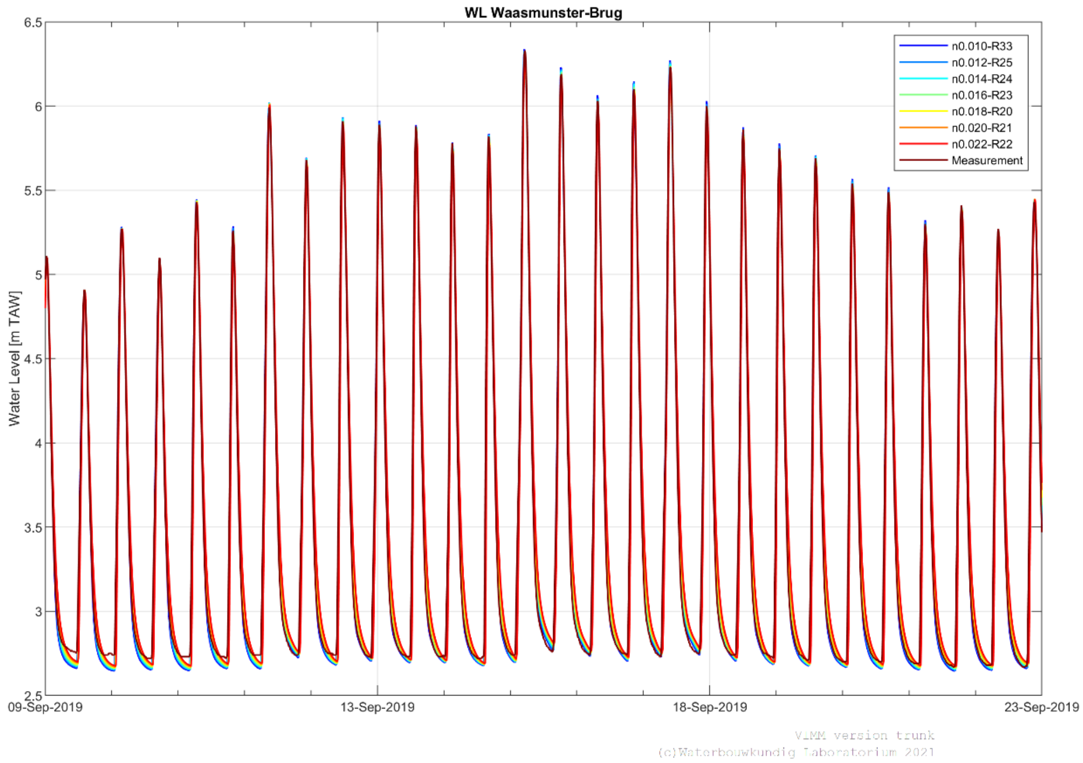


Figure 43 – Sensitivity of modeled water levels to the upstream boundary discharge Q [m³/s]


WL Driegoten
Water Level [m TAW]
7
6
5
4
3
2
1
0
-1
09-Sep-2019
13-Sep-2019
18-Sep-2019
23-Sep-2019
n0.010-R33
n0.012-R25
n0.014-R24
n0.016-R23
n0.018-R20
n0.020-R21
n0.022-R22
Measurement
V_MM version trunk


WL Tielrode
Water Level [m TAW]
7
6
5
4
3
2
1
0
-1
09-Sep-2019
13-Sep-2019
18-Sep-2019
23-Sep-2019
n0.010-R33
n0.012-R25
n0.014-R24
n0.016-R23
n0.018-R20
n0.020-R21
n0.022-R22
Measurement
V_MM version trunk
(c)Waterbouwkundig Laboratorium 2021


WL Waasmunster-Brug
Water Level [m TAW]
6.5
6
5.5
5
4.5
4
3.5
3
2.5
09-Sep-2019
13-Sep-2019
18-Sep-2019
23-Sep-2019
n0.010-R33
n0.012-R25
n0.014-R24
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Measurement
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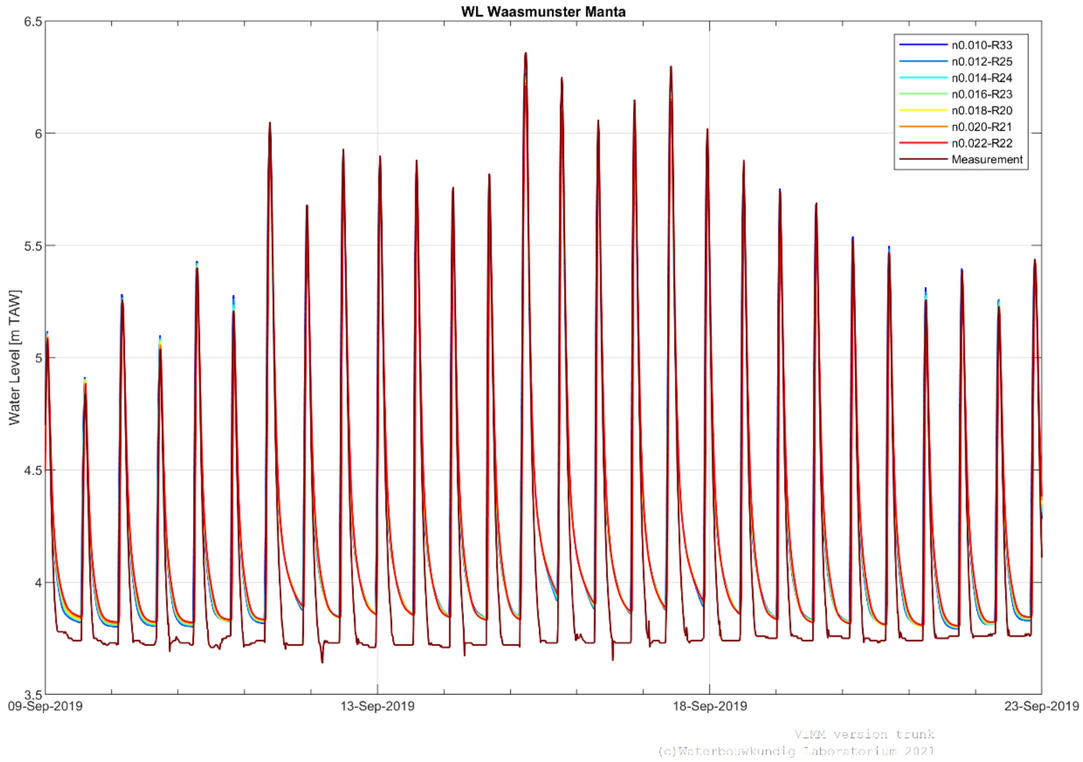
(c)Waterbouwkundig Laboratorium 2021


WL Waasmunster Manta
Water Level [m TAW]
6.5
6
5.5
5
4.5
4
3.5
09-Sep-2019
13-Sep-2019
18-Sep-2019
23-Sep-2019
n0.010-R33
n0.012-R25
n0.014-R24
n0.016-R23
n0.018-R20
n0.020-R21
n0.022-R22
Measurement
V_MM version trunk
(c)Waterbouwkundig Laboratorium 2021

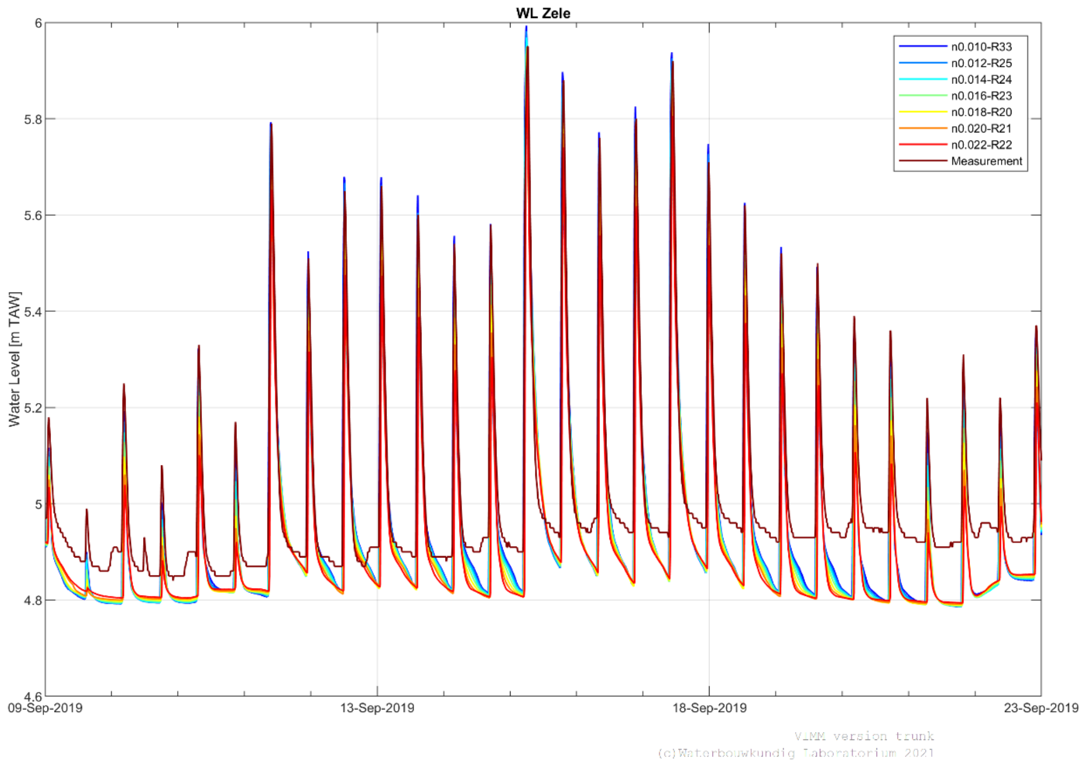


Figure 44 – Measured and modeled water levels at Driegoten, Tielrode, Waasmunster-Brug, Waasmunster-Manta and Zele with different Manning coefficients, calibration period in 2019: after dredging

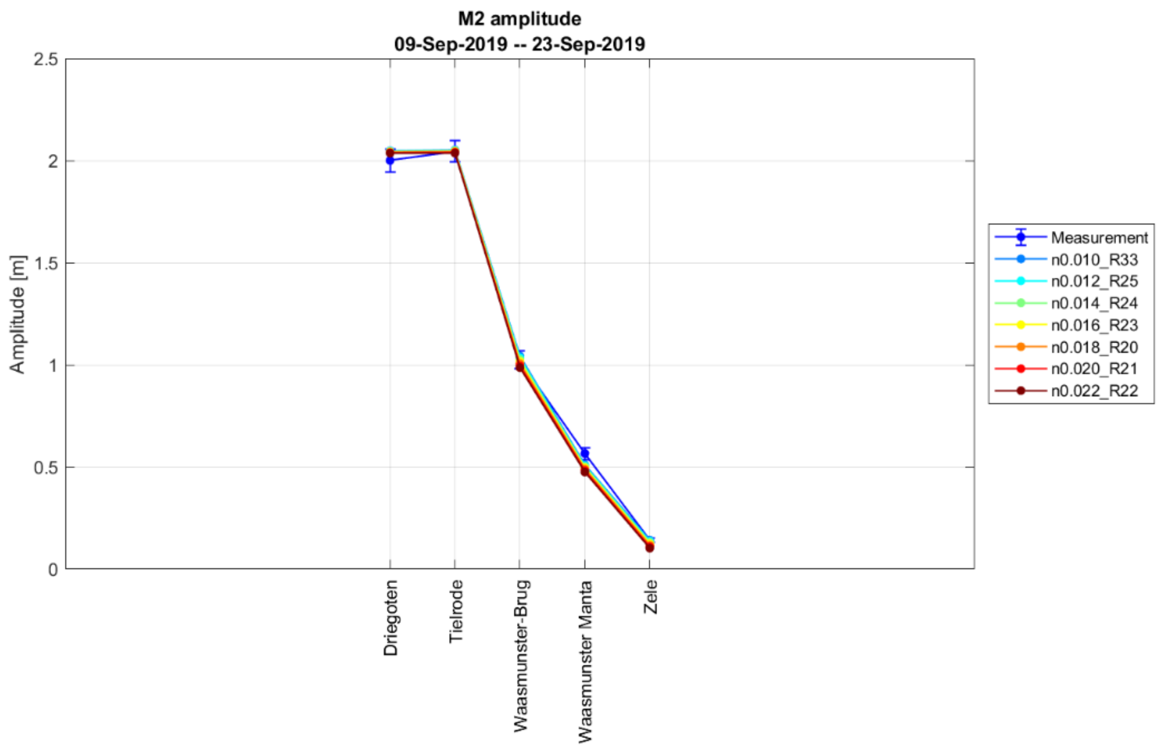
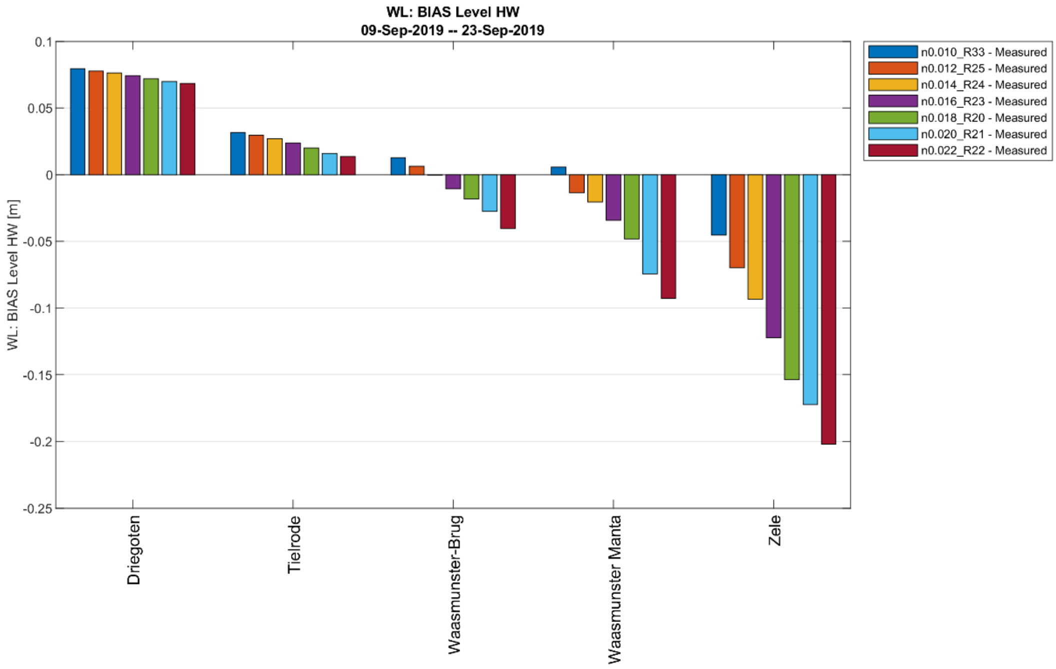
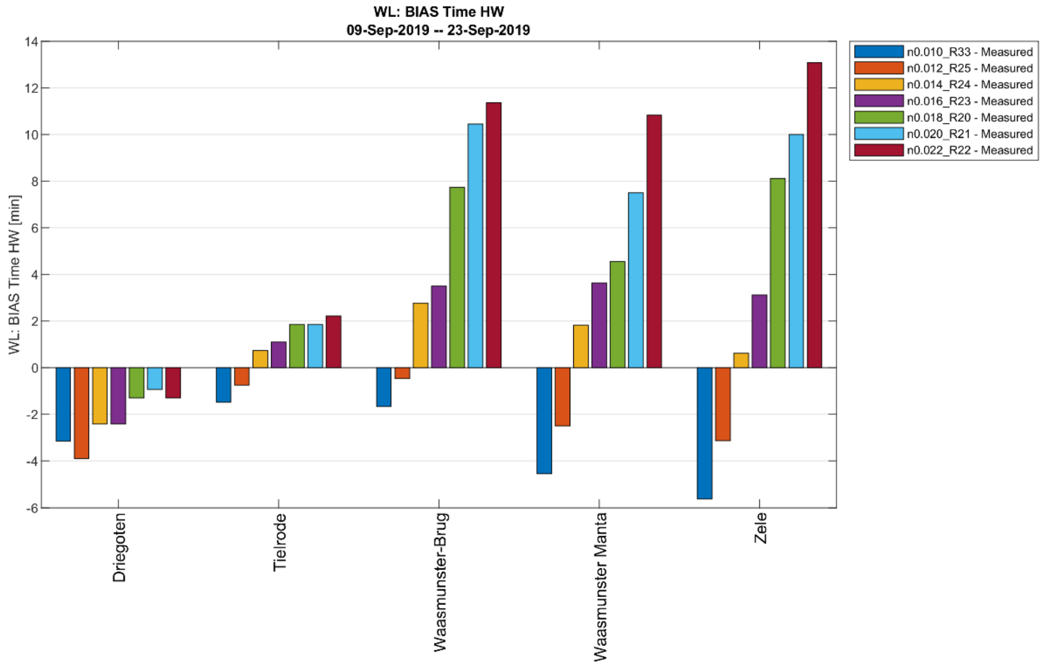
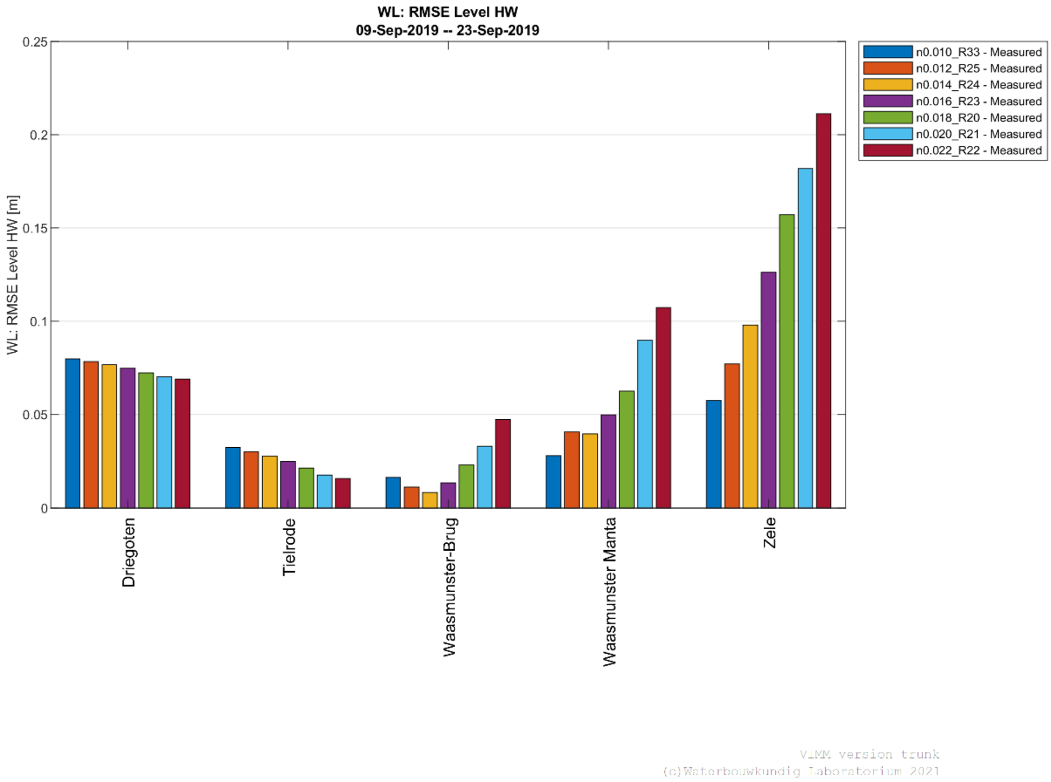
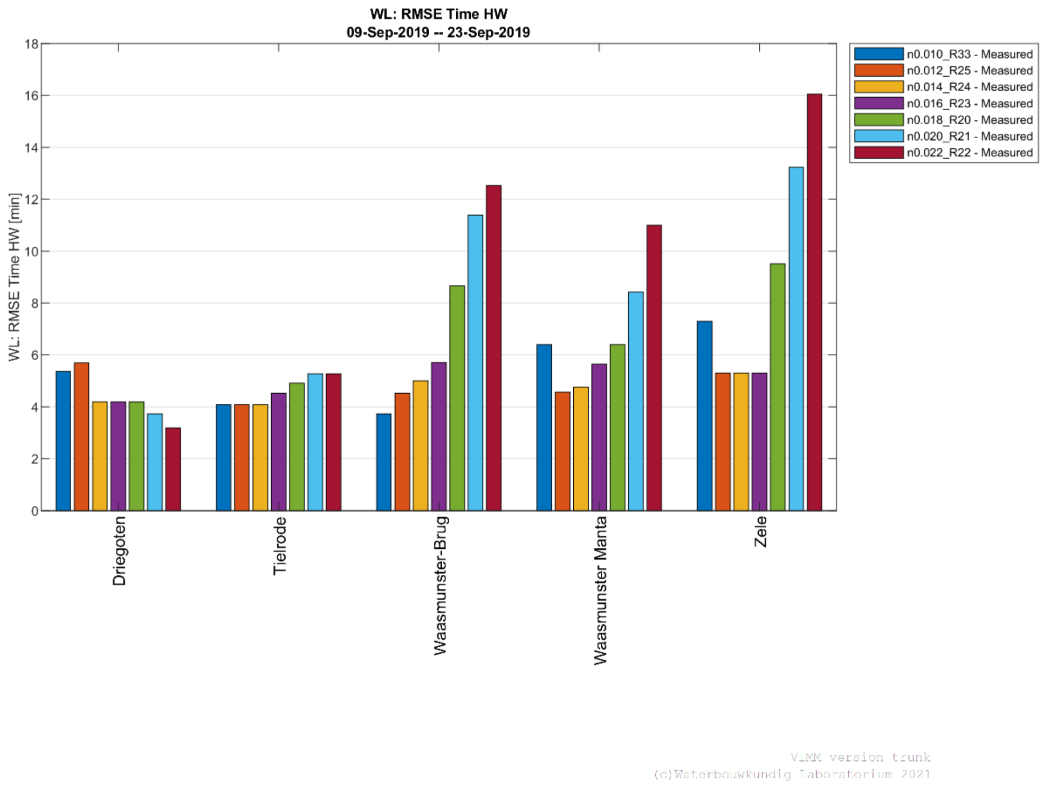


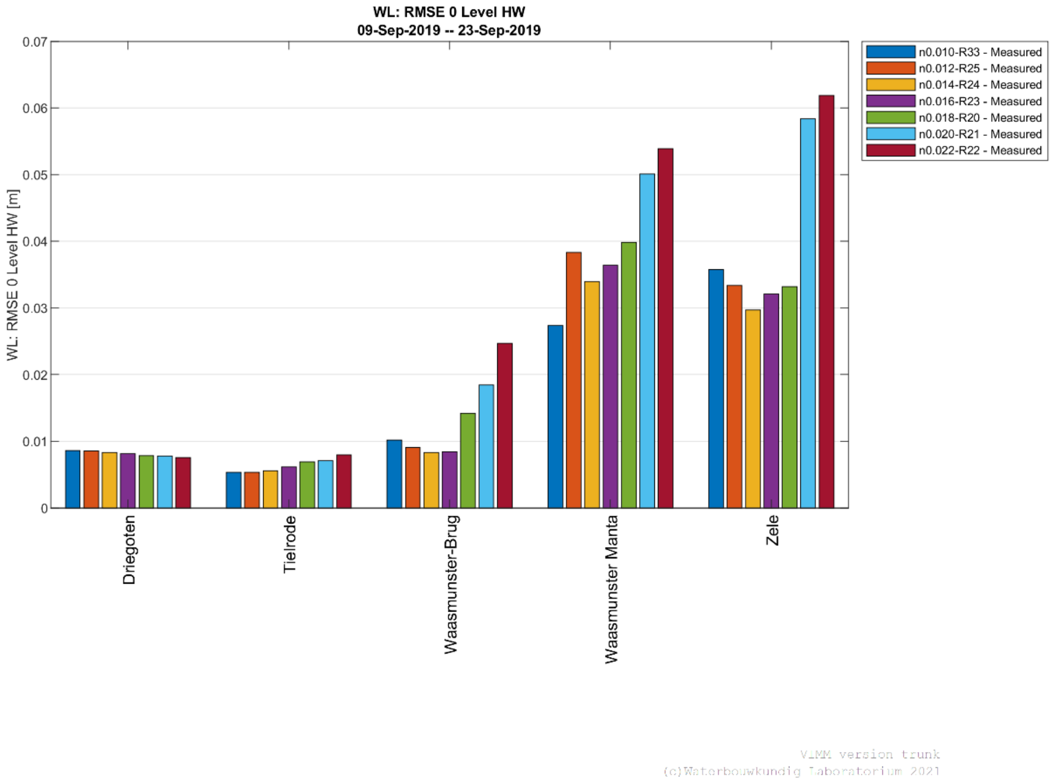
Figure 45 – M2 amplitude, calibration period in 2019: after dredging


WL: BIAS Level HW
09-Sep-2019 -- 23-Sep-2019
WL: BIAS Level HW [m]
n0.010_R33 - Measured
n0.012_R25 - Measured
n0.014_R24 - Measured
n0.016_R23 - Measured
n0.018_R20 - Measured
n0.020_R21 - Measured
n0.022_R22 - Measured
Driegoten
Tielrode
Waasmunster-Brug
Waasmunster Manta
Zele


WL: BIAS Time HW
09-Sep-2019 -- 23-Sep-2019
WL: BIAS Time HW [min]
n0.010_R33 - Measured
n0.012_R25 - Measured
n0.014_R24 - Measured
n0.016_R23 - Measured
n0.018_R20 - Measured
n0.020_R21 - Measured
n0.022_R22 - Measured
Driegoten
Tielrode
Waasmunster-Brug
Waasmunster Manta
Zele


WL: RMSE Level HW
09-Sep-2019 -- 23-Sep-2019
WL: RMSE Level HW [m]
0.25
0.2
0.15
0.1
0.05
0
Driegoten
Tielrode
Waasmunster-Brug
Waasmunster Manta
Zele
n0.010_R33 - Measured
n0.012_R25 - Measured
n0.014_R24 - Measured
n0.016_R23 - Measured
n0.018_R20 - Measured
n0.020_R21 - Measured
n0.022_R22 - Measured
V_MM version trunk
(c)Waterbouwkundig Laboratorium 2021


WL: RMSE Time HW
09-Sep-2019 -- 23-Sep-2019
WL: RMSE Time HW [min]
18
16
14
12
10
8
6
4
2
0
Driegoten
Tielrode
Waasmunster-Brug
Waasmunster Manta
Zele
n0.010_R33 - Measured
n0.012_R25 - Measured
n0.014_R24 - Measured
n0.016_R23 - Measured
n0.018_R20 - Measured
n0.020_R21 - Measured
n0.022_R22 - Measured
V_MM version trunk
(c)Waterbouwkundig Laboratorium 2021



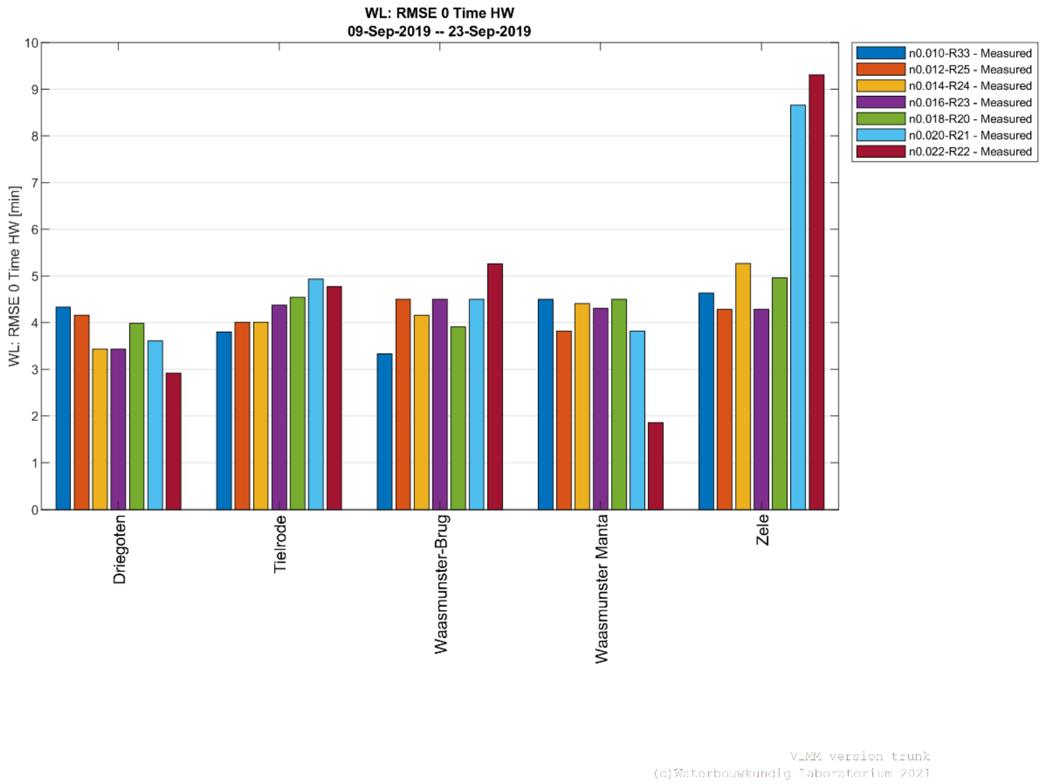


Figure 46 – BIAS, RMSE and RMSE0 of the model HW for different Manning coefficient values, calibration period in 2019: after dredging

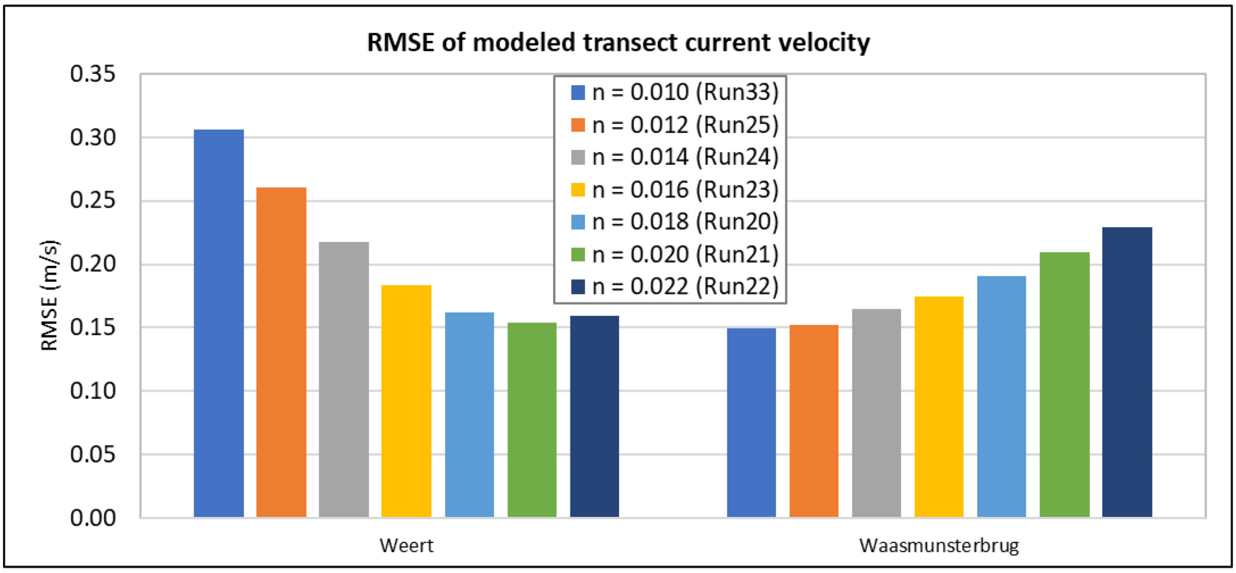


Figure 47 – RMSE of model velocity along Weert and Waasmunsterbrug transect for different Manning coefficient values, calibration period in 2019: after dredging

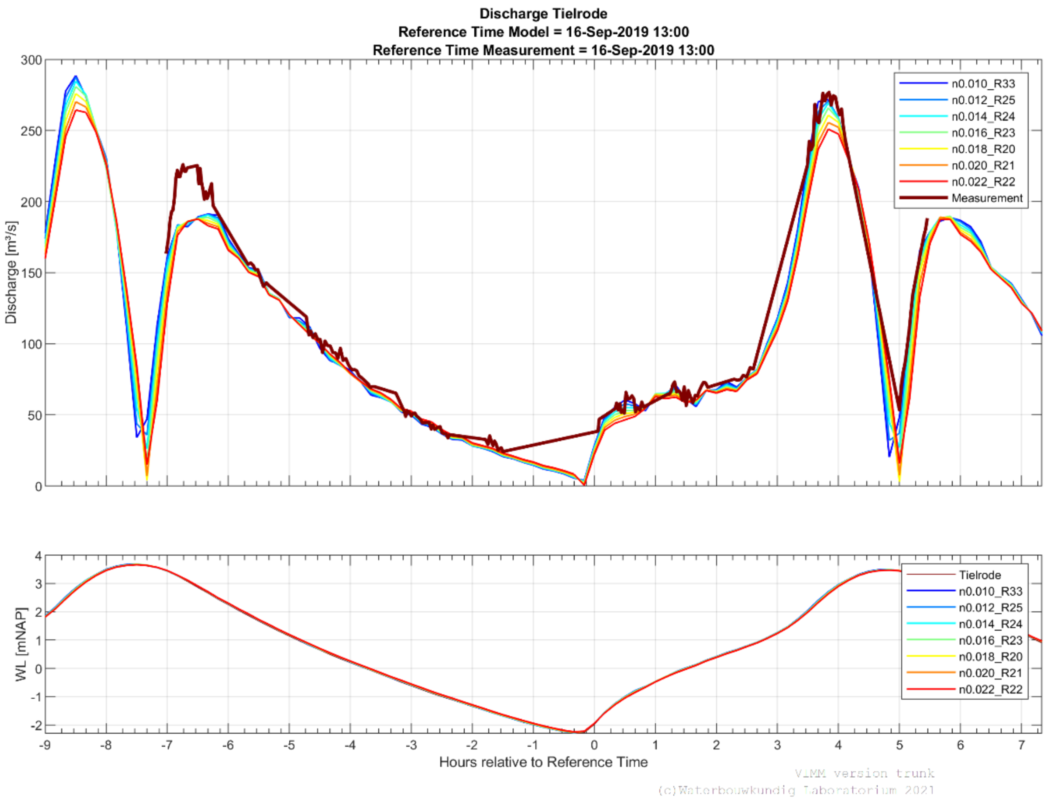
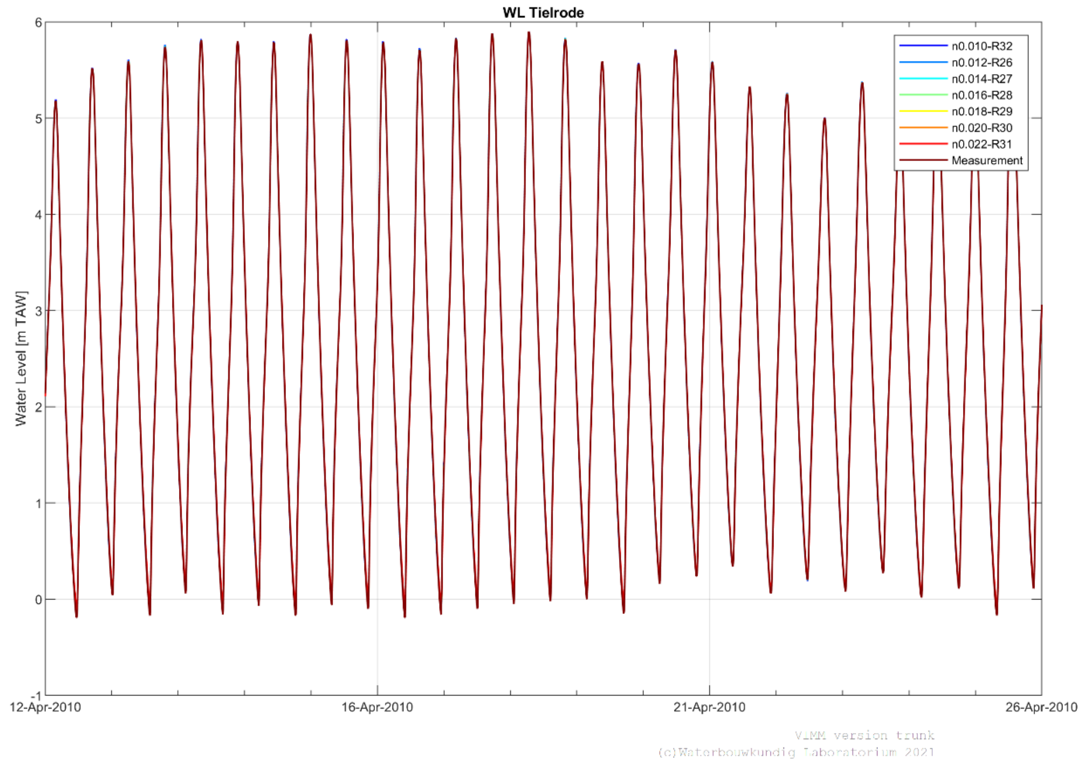


Figure 48 – Comparison of flow discharge on 16-09-2019 at Tielrode transect from measurement and model with different Manning coefficients, calibration period in 2019: after dredging



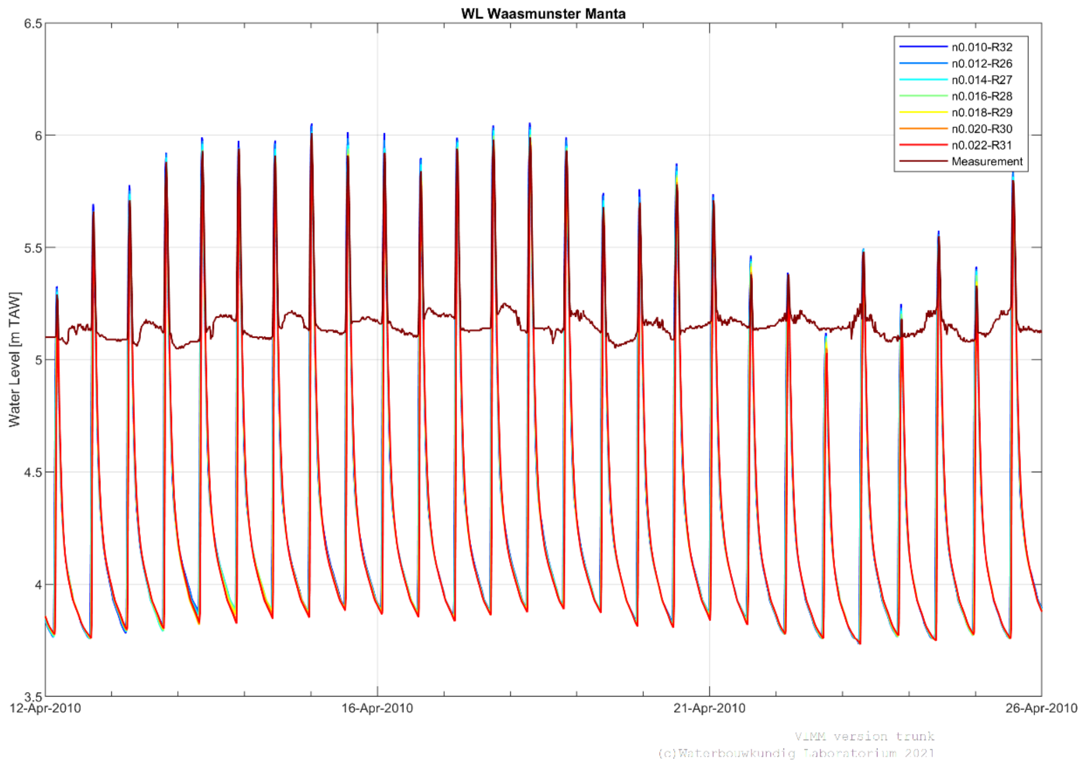


Figure 49 – Measured and modeled water levels at Tielrode, Waasmunster Manta with different Manning coefficients, calibration period in 2010: before dredging

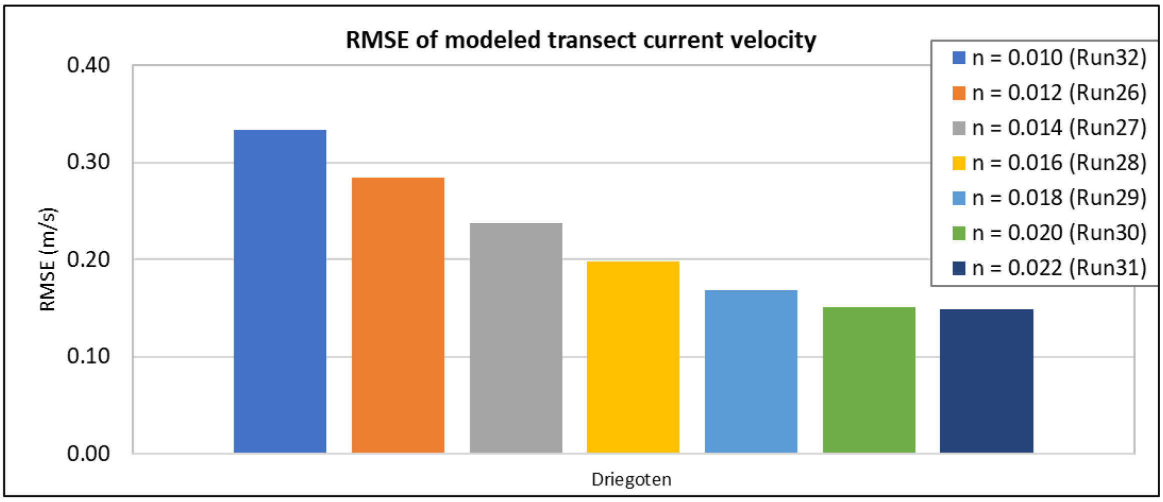


Figure 50 – RMSE of model velocity along Driegoten transect on 15-04-2010 for different Manning coefficient values, calibration period in 2010: before dredging

Appendix 3 Effect of WL reduction at northern boundary on high water along the Durme river

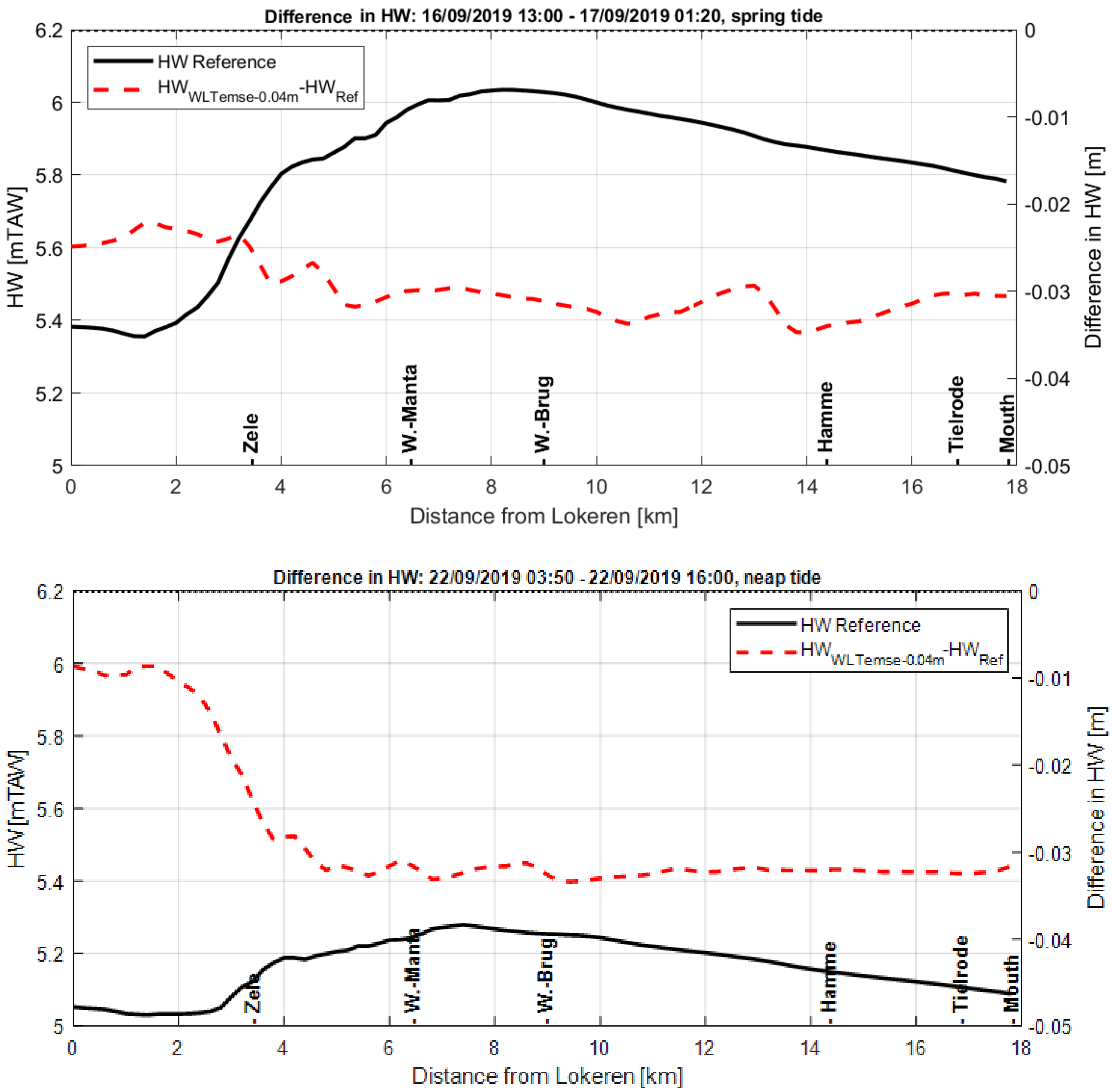


Figure 51 – Effect of WL reduction at northern boundary (Temse) on high water. Upper: spring tide, lower: neap tide

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