Understanding the hydrodynamic effect of groynes at intertidal flats in Estuaries

A case study at Baalhoek and Knuitershoek in the Western Scheldt

Master Thesis

Tim van den Broek

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Understanding the hydrodynamic effect of groynes at intertidal flats in estuaries: a case study at Baalhoek and Knuitershoek in the Western Scheldt

Author information:
Tim van den Broek
University of Twente
Faculty of Engineering Technology
Student number: s1012223
Contact: tim_broek90@hotmail.com

Graduation Committee:

Dr. K.M. Wijnberg	University of Twente
Dr. ir. J.J. van der Werf	University of Twente/Deltares
Ir. H. Holzhauer	University of Twente/Deltares
Ir. P.L.M. De Vet	Deltares

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Abstract

Land reclamations, dredging activities, dike reinforcements and sea level rise caused the habitats of birds and benthic species in the Western Scheldt to decrease in surface area with approximately 3200 ha. The ecological value is classified as an insufficient condition of conservation. To increase the ecological value of the Western Scheldt, 600 ha estuarine nature is planned to be created. One of the projects contributing to this goal is creating ecological valuable low-dynamic intertidal area by the construction of groynes at Baalhoek and Knuitershoek. The design of these groynes consists of two heightened groynes and one new groyne at Knuitershoek, and one heightened groyne and one new groyne at Baalhoek.

The main objective of this thesis is *to understand how the newly-constructed groynes at Baalhoek and Knuitershoek in the Western Scheldt affect the hydrodynamics and sediment-dynamics at the intertidal flats and nearby tidal channels.* First, data analysis on the situation before the implementation of the groynes is performed. This analysis showed that the flow velocities at both locations are too high for the areas to be classified as low-dynamic, and that the flow velocities on the flats are flood dominated by means of maximum flow velocities. Next, the data is used to set-up a depth averaged numerical model (Delft3D Flexible Mesh) to simulate the impact of the design and perform a scenario study to investigate the impact of changing the groyne height, the length of the high water resting areas as seen at Knuitershoek, and the number of groynes.

The KnuBa-Delft3D Flexible Mesh model, that simulates the flow caused by tidal influences, river discharge, and wind, is able to predict the water levels and flow velocities and directions accurately enough to study the impact of the newly implemented groynes. The flow velocity predictions at Baalhoek are more accurate compared to the predictions at Knuitershoek. At Knuitershoek the flow velocities during ebb drop too early. Since the flats are flood dominated this was not a problem in estimating the amount of low-dynamic surface area by means of maximum flow velocities.

The implementation of the designed groynes showed that the demand of 57 ha extra low-dynamic area is not fulfilled. The low-dynamic surface area increases with a total of 15.5 ha for a critical velocity of 0.6 m/s and 23.5 ha for 0.8 m/s. The results at Knuitershoek are more promising compared to those at Baalhoek since a larger proportion of the intertidal area changed to low-dynamic at Knuitershoek. The flow velocities between the groynes at Baalhoek did not decrease enough to create low-dynamic area. The results for the sediment transport and bed level changes showed less sediment transport capacity between the groynes at Knuitershoek and caused possible accretion after the implementation of the designed groynes. At Baalhoek the flood channel in front of the western groyne possibly will fill up, but the groyne seem to block the sediment transport onto the flat. At the tip of al groynes, scour holes will possibly develop.

The groyne height is positively related to the amount of low-dynamic area. Graphs for the amount of low-dynamic area as a function of the groyne height showed similarities between the two cases. Although the numerical values are case dependent, the similarities in the shape of the curves provide confidence in a more general application after some further research. A tipping point was seen in both graphs. For groyne heights beyond that tipping point, the increase of low dynamic area becomes smaller and the velocities in the channel increase.

The same graphs for ‘high water resting area length’ showed that the effects of these resting areas are case dependent. At Baalhoek, in the same configuration as in the design at Knuitershoek, high water resting areas increase the velocities and create less low dynamic area compared to the original design. In general, the high water resting area lengths show an increasing effect on the amount of low dynamic area, but the flow velocities close to the dike are increased by narrowing the cross section between the resting areas and the dike.

The number of groynes showed to have a positive relation with the amount of low dynamic surface area. This means that the distances between the groynes have a negative relation with the amount of low dynamic surface area.

This study showed that DELFT3D Flexible Mesh (the KnuBa-model) reproduced the flow at intertidal flats accurate after local refinement of the grid. This spared a lot of time and work compared to older software because no separate domains have to be created. It also showed that the design at Baalhoek and Knuitershoek was less effective as expected in terms of initial low-dynamic area and it showed the impact of three design parameters (groyne height, high water resting area length and the distance between groynes) on the hydrodynamics and the amount of low-dynamic area.

After this study it is recommended to reconsider the design at Baalhoek. The results of this study could be used as a guide during the redesigning of the groynes. The scenario study showed that increasing the groyne heights can have beneficial effects on the amount of low dynamic area. Adding an extra groyne also showed promising results.

For further research, validation of the KnuBa-model with measurements after the implementation of the groynes is advised. This model could also be extended with waves, sediment transport and bed level changes. Furthermore an extension of the definition of low-dynamic area should be considered. It should be extended with waves and the percentage of time that critical velocities are exceeded. At last, the design graphs for the amount of low-dynamic area as function of the groyne height, high water resting area length, and distance between groynes should be studied further for general applicability.

Preface

The topic of my master thesis is: ‘Understanding the hydrodynamic effect of groynes at intertidal flats in Estuaries’. This thesis is the final project of my study Civil Engineering and Management with the focus on Water Engineering and Management (River and Coastal Engineering). This master thesis is done on behalf of Deltares in combination with the department Water Engineering and Management of the University of Twente. I really enjoyed living in Enschede during my Bachelor and Master study and I am really going to miss the atmosphere of the student life that the city has to offer.

The creation of higher nature value in the Western Scheldt is a hot topic at the moment. The creation of the groynes at Baalhoek and Knuitershoek are one of many projects that will contribute to this goal and working on this project was a very nice experience. I hope the results of my work can contribute to this project and to future projects.

I would like to thank some people in special for their time and help during this master thesis. At first I would like to thank Jebbe van der Werf for being my supervisor. His expert vision on this topic was of great value. I would also like to thank my supervisor Harriëtte Holzhauer for her help and support during this master thesis. The feedback sessions were really helping me in writing the report. I want to thank Lodewijk de Vet for being my supervisor. His help with modelling issues and analysis of the results was very helpful and informative. I enjoyed going on fieldwork in the Western Scheldt for his research, which was a great experience and gave me a very different look on measurement data. I would also like to thank Kathelijne Wijnberg for being my supervisor and for the feedback during this graduation project. I also want to thank all the other people at Deltares who helped me. Everyone was very open minded and willing to help, which creates a very nice working atmosphere. I want to thank the students at Deltares for their help, the coffee breaks, the lunches and good conversations.

Furthermore I want to thank my parents. Without your support I would have never been able to finish my study. I would also like to thank my friends for giving me an unforgettable student life. At last I want to thank my girlfriend Suzanne. We started our master thesis’s at the same time. This period, which was sometimes a very stressful period for both of us, became so much better because of living together in Den Haag. Her support really helped me through the most difficult parts during my thesis.

Tim van den Broek
Den Haag, August 2017

Contents

1. Introduction

This chapter starts with the motivation for this study, followed by the problem definition, objective and research questions. Furthermore an overview of the research method is given. The chapter ends with an outline of this thesis.

1.1. Motivation for this study

The Western Scheldt is designated as Natura 2000 (N2000) region. This means that it is a protected nature area. Breeding and non-breeding birds, fish, shrimps, shellfish and other benthic species find their habitats here. Land reclamation, dredging activities, dike reinforcements and sea level rise caused the habitats to decrease in surface area with approximately 3200 ha (Sistermans & Nieuwenhuis, 2004). That caused the ecological value to be classified as an insufficient condition of conservation (Geerts, 2016).

To increase the ecological value of the Western Scheldt an extra 600 ha estuarine nature is planned to be created (Ontwikkelingsschets, 2005). One of the projects contributing to this goal is a project at Baalhoek and Knuitershoek (Figure 1.1). At these locations groynes were constructed to reduce flow velocity in order to create an extra 57 ha low–dynamic intertidal area. An area can be classified as low-dynamic if the flow velocity is lower than a certain critical velocity. In the past the threshold velocity was set at 0.8 m/s (Maris et al., 2014), but for modelling that value has to be lowered and specified per area to match with the area specific characteristics (Dam et al., 2008). These low-dynamic areas will be flooded and exposed during each tidal cycle. Because of the low flow velocities a new layer of silt will be left behind after each tidal cycle and the flats will increase in height (De Smet et al., 2016). This will create a habitat for benthic species and birds.

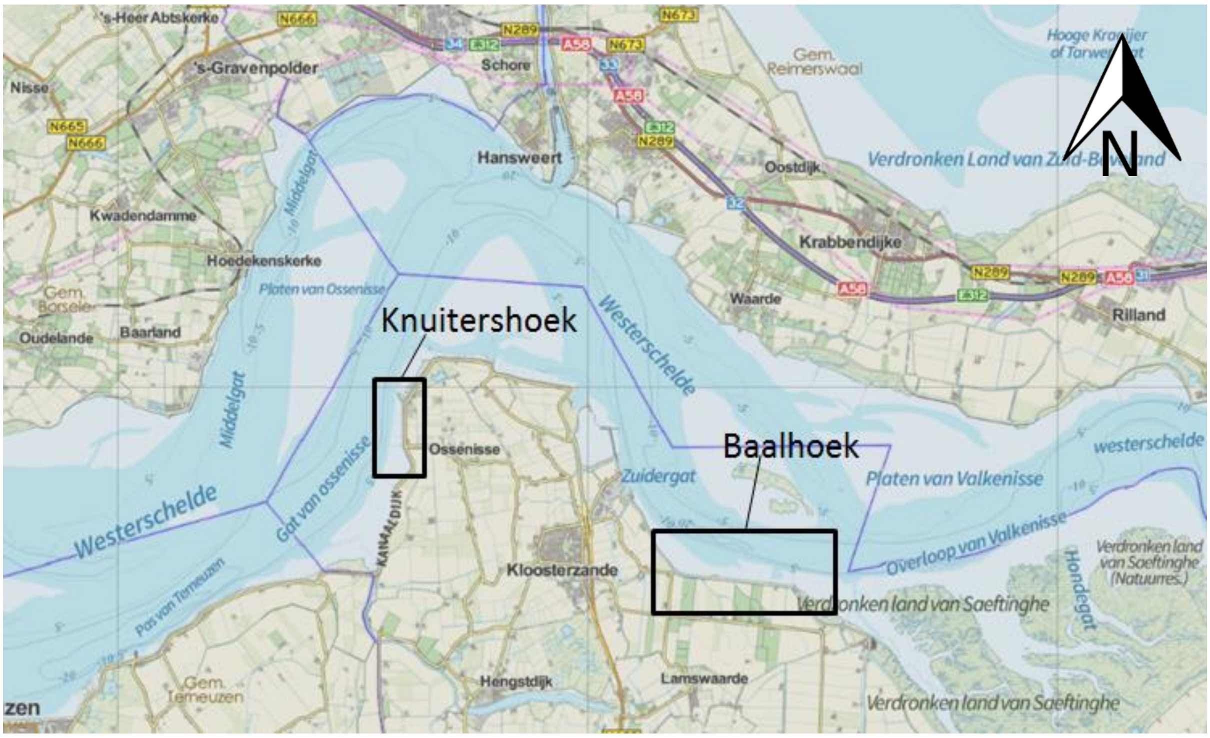

Figure 1.1 - The locations of the two sites 'Knuitershoek' (left boxed area) and 'Baalhoek' (right boxed area). Background image: Provincie Zeeland (2017b).

The aim of the Province of Zeeland is to create low-dynamic areas with the help of groynes at Baalhoek and Knuitershoek without negative effects on the nearby channels and flats. Three existing groynes were heightened and two new groynes were constructed. Navigation, safety and nature may not be influenced negatively by the groynes. The implementation of the groynes at Baalhoek and Knuitershoek will affect the hydrodynamics and sediment dynamics of the intertidal flats and the nearby channels Zuidergat and Gat van Ossenisse. An in depth description of the areas and the groyne design is given in chapter 2.

Besides the creation of more low-dynamic area, this project is a pilot project. It is used to learn about the effects of groynes and to improve future projects involving the creation of low-dynamic areas and the use of groynes in estuaries. This project is executed by the Centre of Expertise Deltatechnology[1] consortium on behalf of the Province of Zeeland. To predict the development of the intertidal areas and the nearby channels research needs to be done. This research requires knowledge of the hydrodynamic development (flow velocity and patterns), the morphological development (sediment transport, sedimentation and erosion) and effects on navigation. The description of these topics can be found in the literature study done prior of this master thesis (Van den Broek, 2017) and are summarised in chapter 2.

1.2. Problem definition

To create low-dynamic areas in estuaries using groynes, insight in the effects groynes on hydrodynamics on intertidal flats and the nearby located channels is required. A groyne is a small dam constructed at an angle to the flow, meant to deflect the flowing water away from critical zones (Yossef, 2005). The effects of groynes on the hydrodynamics in rivers and sandy coastlines are well known. In rivers they reduce the flow velocities, cause flow circulation and increase the flow velocity in the navigation channel. On the coast they create circulations due to the longshore flow in the same way as in rivers, but they also reduce the impact of waves approaching the shores in an angle (Roos, 2016).

In estuaries additional influences are present compared to rivers: change in flow direction and tidal ranges. Two times a day the groynes will be flooded and exposed and the directions changes four times. To study the changes in hydrodynamics due to newly implemented groynes in estuaries, a case study at Knuitershoek and Baalhoek in the Western Scheldt Estuary is done.

It is not yet known what the flow velocities at Baalhoek and Knuitershoek are after the implementation of the designed groynes. The flow velocities are expected to be lowered. If the flow velocity (and/or the wave action) is too low the bottom becomes too rich in silt (>25%) and the bed level increases too fast. When the flow velocities get too high the sedimentation probably is insufficient. According to the province of Zeeland (Geerts, 2016) the increase of the bed level between the groynes should not be larger than 15 cm/year and should be on average 10 cm/year. They expect that a flow velocity between 0.2 m/s and 0.5 m/s at springtide will lead to the preferred result.

The flow patterns around the designed groynes are unknown. Cross-flows can develop in the channel, which are undesirable for navigation. At the tip of the groynes, in the channel, the flow velocity possibly will increase because of flow contraction. This can lead to local erosion which is not desirable since the groynes are close to the channel (Dam et al., 2008).

In exposing parts outside of the study area close to Baalhoek and Knuitershoek it is not desirable that the flow velocities change significantly. It can lead to sedimentation or erosion and ecologically less desirable abiotic circumstances. The Province of Zeeland demands that the maximum change during Springtide is 0.1 m/s and that the maximum flow velocity is 0.5 m/s at the exposing parts of the side areas (Geerts, 2016). These demands are important criteria when evaluating the design of the groynes.

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[1] Centre of Expertise Deltatechnology consortium for this project consists of: Deltares, NIOZ, HZ University of Applied Sciences, and Wageningen Marine Research.

The groynes are constructed close to the channel. Because of shipping, which is an important function of the Western Scheldt, the flow velocities in the channel at springtide should not increase with more than 0.2 m/s (Province of Zeeland: (Geerts, 2016)) and the cross section of the channel has to be wide enough for navigation.

Besides the effects of groynes on navigation, there are effects of navigation on the groynes. Container ships cause waves because of their size. Van Rooijen et al. (2015) concluded in their study that these ship-waves are not of a significant height to be of influence in the Western Scheldt. The bottom shear stress caused by the ship waves are generally relatively low and are not expected to cause resuspension of sediment.

The case study at Baalhoek and Knuitershoek is used to get insight in the effects groynes on intertidal flats in estuaries. During this study the focus is on the initial effects of newly implemented groynes on the hydrodynamics and sediment dynamics at intertidal flats. Especially impact of groynes on the creation of low-dynamic surface area is studied.

1.3. Objective & research questions

The main objective of this research is:

> *To understand how the newly-constructed groynes at intertidal areas like Baalhoek and Knuitershoek in the Western Scheldt affect the hydrodynamics and sediment-dynamics at the intertidal flats and the nearby tidal channels.*

The focus of this project is on the change in hydrodynamics due to the designed groynes at Baalhoek and Knuitershoek. The initial changes in bed level and sediment transport due to the newly implemented groynes are also studied. Based on the research objective the following research questions are defined:

RQ1: What are, according to the measurement data, the flow patterns on the intertidal areas Baalhoek and Knuitershoek and in the nearby tidal channels before construction of the groynes?

RQ2: How well can a depth-averaged (2DH) Delfd3D Flexible Mesh model simulate the hydrodynamic processes near the groynes at Baalhoek and Knuitershoek?

RQ3: What are, according to the model, the effects on the flow, the initial sediment transport and bed level changes on the intertidal areas Baalhoek and Knuitershoek and in the nearby tidal channels before and after construction of the groynes?

RQ4: How do design parameters affect the hydrodynamic impact of groynes in intertidal areas like Baalhoek and Knuitershoek, and the nearby tidal channels?

1.4. Methodology

Research question 1 is answered using water levels and velocity data measured at Baalhoek and Knuitershoek. The focus of the data analysis is on the water levels in the Western Scheldt and the flow velocities at the intertidal flats Baalhoek and Knuitershoek. The T0 flow measurements at Baalhoek are executed between 20 January and 24 February 2016 and at Knuitershoek between 8 March 2016 and 28 April 2016. T1 measurements are planned for at August 2017 and were therefore not available for the current study.

To simulate the effect of groynes at Knuitershoek and Baalhoek on the hydrodynamics, a 2d-depth-averaged numerical model is created using Delft3D - Flexible Mesh: the KnuBa-model. Delft3D Flexible Mesh is a software package created by Deltares. The boundary conditions for the KnuBa-model are generated by the Delft3d NeVla-Model (Consortium Deltares-IMDC-Svasek-Arcadis, 2013). A grid is needed with a valid orthogonality, smoothness and aspect ratio (Deltares, 2017c).

To answer research question 2, the results of the data analysis are used to calibrate the model. The model is based on the situation before the new groynes are constructed. This gives the opportunity to calibrate the model with the T0 flow measurements done at Baalhoek and Knuitershoek and to find out to what extent the model can simulate the hydrodynamic processes across the intertidal flats and neighbouring channels.

For research question 3, the bathymetry and sediment availability in the model are adjusted such that it represents the situation where all the groynes are constructed. Running this model can be used to predict how the hydrodynamics will develop. Also initial sediment transport changes and bed level changes are discussed based on the model. By comparing the results of both versions of the model, the impacts of the groynes on hydrodynamics are evaluated.

Once the effects of the designed groynes on the hydrodynamics are known the next step is to find out how parameters affect the changes in hydrodynamics with the focus on low-dynamic surface area. To answer research question 4, different scenarios are run with the model. These scenarios exist of changes in the heights of the groynes, changes in the length of the ‘High Water Resting area’ (in Dutch: Hoogwatervluchtplaats) and changes in the number of groynes. By using the results of the different scenario runs possible relations between the characteristics of the areas, characteristics of the groynes and the development of the area can be found.

During this study a low-dynamic area is defined as an area where the maximum flow velocity magnitudes are below a critical velocity magnitude. Two critical velocities are used during this study: the critical velocity of 0.8 m/s as used by Rijkswaterstaat (Graveland, 2005) and the critical velocity of 0.6 m/s as used by Dam et al. (2008). For the long term development of an area the exceeding time is also important, but during this study the main interest is on the initial development so the maximum velocity is leading.

1.5. Outline

This thesis starts with a description of the study area and the background in Chapter 2, where the designs at Knuitershoek and Baalhoek are described. Next, the data analysis of flow velocity and water level field measurements is discussed (Chapter 3). In Chapter 4 the set-up and calibration of the KnuBa - Delft3D - Flexible Mesh model is described. The results of implementing the designs in the model are discussed in Chapter 5 followed by the effects of different scenarios in Chapter 6. The findings during this master thesis are discussed in Chapter 7. The conclusions and recommendations are presented in Chapter 8.

2. Description of the study area

2.1. The Western Scheldt Estuary

The Western Scheldt is the Dutch part of the Scheldt Estuary (Figure 2.1). The Western Scheldt estuary is approximately 60 km long and the width varies between two kilometres at the border between The Netherlands and Belgium and five kilometres near Vlissingen. The estuary is an important shipping route to the harbour of Antwerp, and ports along the Western Scheldt (Vlissingen, Terneuzen), but is also a large nature reserve. Another important function is the safety against flooding and overtopping by the dikes and intertidal areas (Graveland et al., 2002).

Figure 2.1 - The Western Scheldt estuary (Google Earth, 2017)

Characteristic for the Western Scheldt is the multiple channel system (Figure 2.2). Apart from the main channel (red arrow) also side-channels (green arrows) and connection channels (black arrows) are present. The navigation channel follows the main channel. The multiple channel system has an important function in safety and nature. Between and around these channels shallow water areas, intertidal areas and salt marshes are present. In these areas a lot of species find their habitat, but these areas also protect for instance the dikes from eroding and overtopping by reducing wave energy.

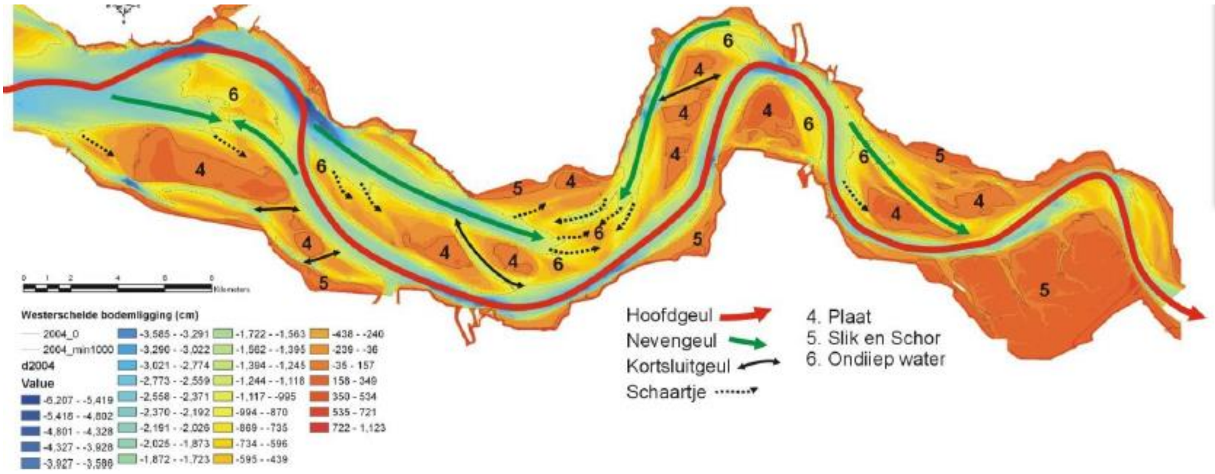


Figure 2.2 - Multiple channel system of the Western Scheldt (Alkyon & Rijkswaterstaat, 2006). The colour contours indicate the 2004 bathymetry (cm+NAP). The red arrow indicates the main channel (Navigation channel). The green arrows indicate side-channels and the black arrows indicate connection channels. The dotted lines represent ebb and flood channels (in Dutch: schaartje). These are open to the relevant tide and closed at the end. The numbers 4, 5 and 6 represent respectively flats, salt marches and shallow water areas.

2.2. General hydrodynamic characteristics of the Western Scheldt

Tidal range

Tides play an important role in the development of the estuary by causing the water to flow in and out of the estuary and shaping the channels and the tidal flats. The tidal cycle in the Western Scheldt can be characterised as a mixture of a semi-diurnal (M2 and S2) and M4 tide with a period of 12h42m and 6h21m respectively (Kuiper & Lescinski, 2013; Roos, 2016; Van Rijn, 2011). The average tidal range of the Western Scheldt varies from 4.0 m at Vlissingen to 5.0 m at Bath (Jeuken et al., 2007). At Baalhoek and Knuitershoek the tidal range is approximately 4.5 m. The difference between high and low water causes large spatial and temporal variation in current velocity and direction. Sediment transport therefore also varies between high and low tide.

Waves

Waves and especially wind induced waves are an important factor for erosion of the tidal flats. Resuspension of sediment due to wind-waves is a significant phenomenon in the morphological development of flats (Dronkers, 1986). Due to wave action and orbital motion grains on flats start to move and are transported away from the tidal flat by the current. This causes the area to erode. Waves that approach flats become higher due to shoaling and can eventually break and therefore cause erosion by causing extra mobility of sediment grains. A modelling study by Van Rooijen et al. (2015) showed that wind waves in the Western Scheldt can develop such that they result in significant bottom shear stress causing erosion. Even at average wind conditions (ZZW-ZW 5 m/s) wind waves show significant effects on the hydrodynamics and morphodynamics. The extreme heights of waves in the Western Scheldt vary throughout the estuary. In the western part of the estuary (near Breskens) the 1/4000 year wave height is between 4.5 and 5 meter, but the areas Knuitershoek and Baalhoek have a 1/4000 year wave height between 1.5 and 2.0 meter (Ministerie van Verkeer en Waterstaat, 2007).

Wind

Wind also causes water level set-up and currents. Due to storms from the west on the North Sea, in combination with a high tide, a lot of water can be pushed inside the Western Scheldt estuary. That can cause the water level to rise to 5 m above Dutch Ordnance Datum NAP along the Dutch coast (Deltacommissie, 2008). In Vlissingen the wind set-up during a storm can cause the water level to rise 2.7 m higher compared to the situation without the storm (Chbab, 2015).

Sediment grain size and silt

According to Sistermans & Nieuwenhuis (2004) relatively fine sediment is found in the Western Scheldt. In general the D_{50} of the bed varies between about 150 µm and 300 µm in the channels and the deeper parts of the shoals. At the higher parts of the shoals, as well as at salt marshes, the sediment size is generally smaller than 200µm. Additionally, a significant percentage of silt (>10%) can be found at the intertidal areas. In the main channels, the percentage of silt is smaller than 10% (Sistermans & Nieuwenhuis, 2004). The percentage of silt on the flats Baalhoek and Knuitershoek even reaches more than 75 % on some locations (Van Eck, 1999).

2.3. Groynes on intertidal flats

Groynes at the 'Schaar van Waarde'

It is expected that the flow velocity magnitudes and the wave energy will decrease due to the newly implemented groynes. This will result in a decrease in transport capacity, which will result in deposition of sediment. This phenomenon was also seen at the 'Schaar van Waarde'. Here two groynes (Figure 2.3) were constructed in 2002 to prevent the intertidal area from eroding (Dam & Bliek, 2013). The groynes resulted in lower tidal velocities which resulted in accretion between the groynes. This created a mud flat between the groynes.

Figure 2.3 - Groynes at the 'Schaar van Waarde' (Google earth, 2016)

At Schaar van Waarde a large scour hole developed due to increased velocities at the tips of the groynes (Dam & Bliek, 2013). The construction of the groynes at Schaar van Waarde also caused migration and narrowing of the channel due to an increase of flow velocities. It is unknown if these effects will happen at Baalhoek and Knuitershoek since the influence of the flow can differ at different locations.

Exploratory study for groynes at Baalhoek and Knuitershoek

In 2008 an exploratory study on potential areas for nature recovery in the Western Scheldt was conducted by Dam et al. (2008). For this study they created a FINEL2d model of the Western Scheldt. The impact of groynes at Baalhoek and Knuitershoek were also studied. The groynes were modelled as dams with an infinite height so could not be flooded, which is not the case in the final design.

The model showed that there is potential for the design to create the low-dynamic area at Baalhoek (Dam et al., 2008). By implementing the groynes in the FINEL2d model, the flow velocities decreased on the flats (Appendix A). It showed some velocity increases in the channel next to the western groyne and close to the dike. The low-dynamic surface area (with flow velocities lower than 0.6 m/s) almost doubled in size (68 ha to 129 ha) in comparison with the reference situation. This is more than the increase of 57 ha that is expected by the Province of Zeeland, but the design changed after the modelling study by Dam et al. (2008). In the main channel, during flood, a strong cross flow developed, but it was not studied whether that has negative effects for shipping.

For Knuitershoek the model also showed that there is potential for the design to create the low-dynamic area (Dam et al., 2008) (Appendix A). The design they used had an extra heightened groyne in the south at K2 (Figure 2.7), but gave a good idea of the situation. The maximum flow velocities decreased by implementing the groynes in the model. Some circulations in the flow occurred which increased the flow velocities near the dike. The calculations showed that the low-dynamic surface area (with flow velocities lower than 0.6 m/s) increased from 43 ha to 65 ha.

Models used to study possibilities in nature improvements in the Western Scheldt predicted lower velocities compared to the measurements (Nolte et al., 2011; 2012). They deliver useful information to make a prediction, but, in order to predict final effects of nature restoration measurements, the outcome of models should be completed in combination with expert judgement (Nolte et al., 2012). This should be kept in mind during the analysis of the modelling results during this study.

2.4. Baalhoek and Knuitershoek

Baalhoek and Knuitershoek are intertidal flats in front of the dike, which are inundated twice a day. At both locations the flow velocities are too high for the desired sedimentation (Dam et al., 2008). This caused the area to erode and now only a peat-layer is left where during low water birds cannot find enough food to live on that location. To improve these areas the Province of Zeeland aims to reduce flow velocities to create an extra 57 ha of low-dynamic area. A low-dynamic intertidal area is defined as an area that is flooded and exposed throughout the tidal period with low flow velocities (Dam et al., 2008; Graveland, 2005). The critical velocities used during this study are set at 0.6 and 0.8 m/s.

Design of the groynes at Baalhoek and Knuitershoek

The intertidal flats Baalhoek and Knuitershoek and the groyne designs are described below. The new groynes are designed by the 'water board Scheldestromen'. At both locations groynes are already present. Three groynes were heightened in 2016 (Phase 1) and two new groynes were constructed between April and July 2017 (Phase 2). An overview of the major events is shown in Figure 2.4.

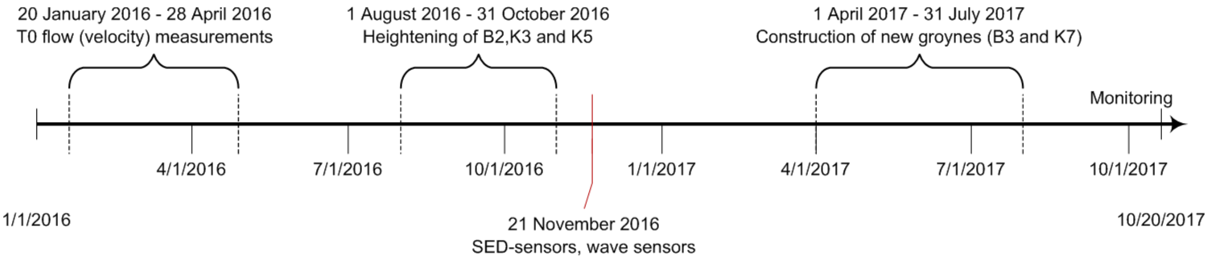


Figure 2.4 - Time line of the construction of the groynes and monitoring at Baalhoek and Knuitershoek.

Baalhoek

Baalhoek is located in the east of Kloosterzande and at the southern bank of the 'Zuidergat'. In Figure 2.5 the low tide situation of December 2005 is shown. The bottom elevation on the intertidal flats varies mostly between -2.0 m+NAP and 0.0 m+NAP. Two groynes (B1 & B2) are present at Baalhoek and are connected with a longitudinal dam. The area between the groynes is exposed during low tide (Figure 2.5), while during high tide it is flooded, including the groynes and the longitudinal dam. The longitudinal dam was constructed in 1990 to prevent the Zuidergat from eroding and moving further to the shore (Dam et al., 2008). An opening in the west of this longitudinal damn created a flood channel (in Dutch: vloed schaartje) on the flat.

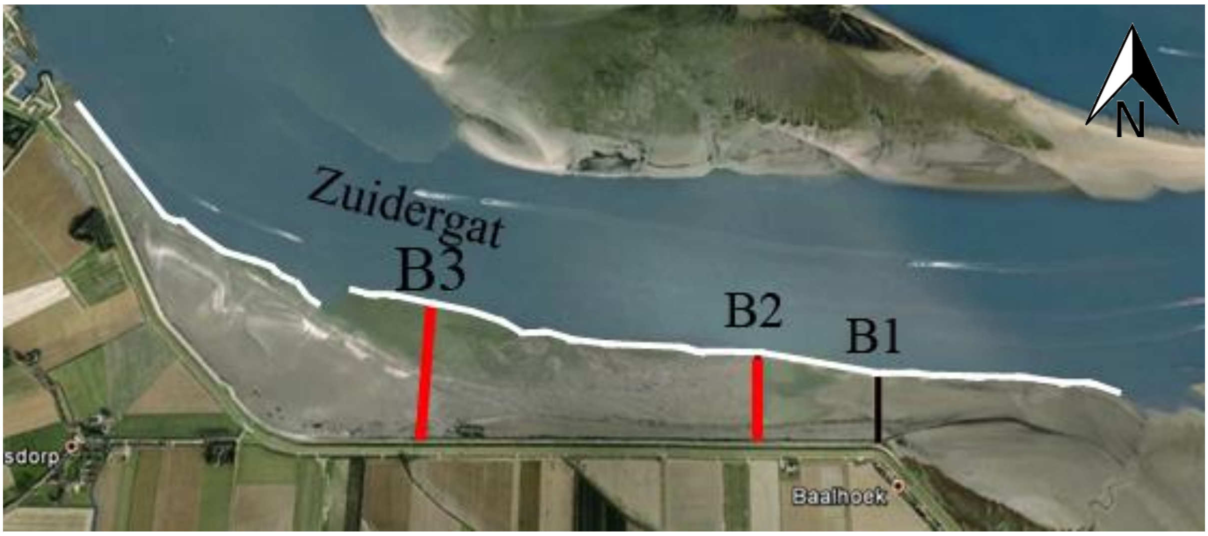


Figure 2.5 - The design at 'Baalhoek'. The red lines represent the new groyne (B3) and the heightened groyne (B2). The white line represents a higher part in the longitudinal dam (Background picture: Provincie Zeeland, 2016).

At this location one groyne was heightened between August and October 2016 (B2, Figure 2.5). A new groyne (B3) was constructed between April and July 2017 at the west of the flat (Figure 2.5). The properties of the new and heightened groynes are shown in Figure 2.6 and Table 2.1. The groynes are constructed with rubble stones (40-200 kg) and have a uniform height of 0.30 and 0.60 m+NAP respectively. The slope on al edges is 1:1.75.

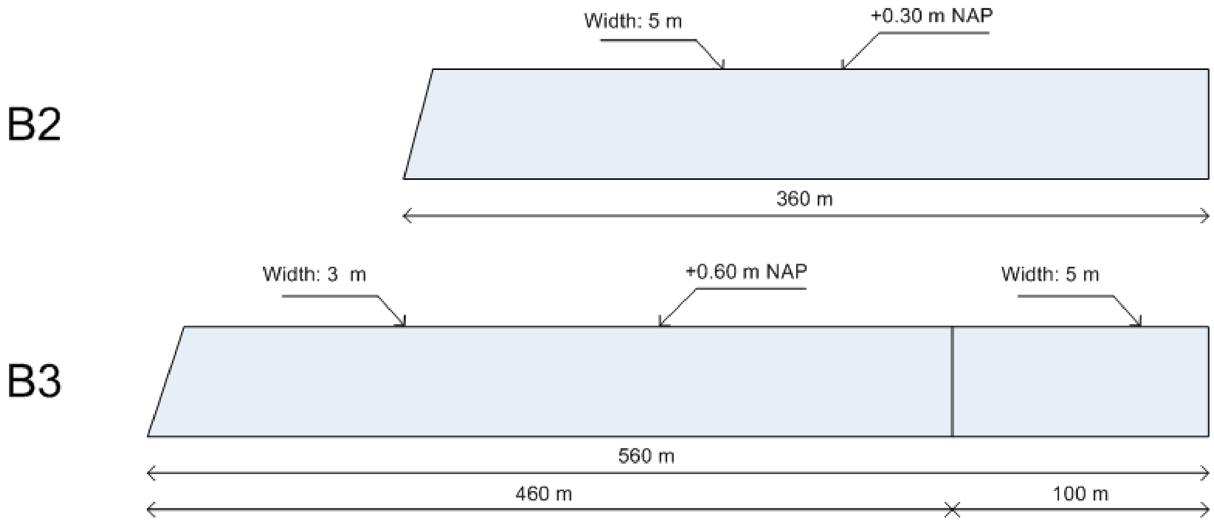


Figure 2.6 – Schematised length profiles of groynes B2 and B3, the channel is located at the left. These are not on scale. The width shown is the width at the top of the groynes.

Table 2.1 – Properties of the groynes at Baalhoek, details for heightened and new groynes.

Groyne	Length (m)	Height (m+NAP)	Width Top (m)	Slope
B1	290			
B2	360	0.30	5	1:1.75
B3	560	0.60	5 (3)	1:1.75

Knuitershoek

Knuitershoek is located west of Kloosterzande on the eastern bank of the ebb-dominated tidal channel 'Gat van Ossenisse.' Six dams are present (K1-6) and are connected with a longitudinal dam (in white) (Figure 2.7). During low tide the area between the groynes is exposed and during high tide it is flooded. The bottom elevation of the intertidal area varies mostly between -2.0 and -1.0 m+NAP. Groynes K1 until K5 and the longitudinal dam are also flooded during high tide. Only dam K6 is high enough to stay above the water surface. The groynes and longitudinal dam were constructed to prevent the channel from eroding further to the shore (Dam et al., 2008).

Figure 2.7 - The design at 'Knuitershoek'. The red lines represent the heightened groynes (K3 & K5) and the new groyne (K7) (Background picture: Provincie Zeeland, 2016).

In the design at Knuitershoek (Figure 2.7), two groynes (K3 and K5) were heightened between August and October 2016 and a new groyne (K7) was constructed between April and July 2017. The properties of the designed groynes are shown in Figure 2.8 and Table 2.2. Groyne K7 has a uniform height of 3 m+NAP. K3 and K5 are divided in two parts (Figure 2.8). The first part starts at the channel with a top at 3.00 m +NAP and a width at the top of 3.00 m. This part is called the High-Water-Resting area and is designed as a safe dry place for birds during high tide. The second part has a top at 0.20 m +NAP and a width at the top of 5 meters. The slope on al edges is 1:1.75.

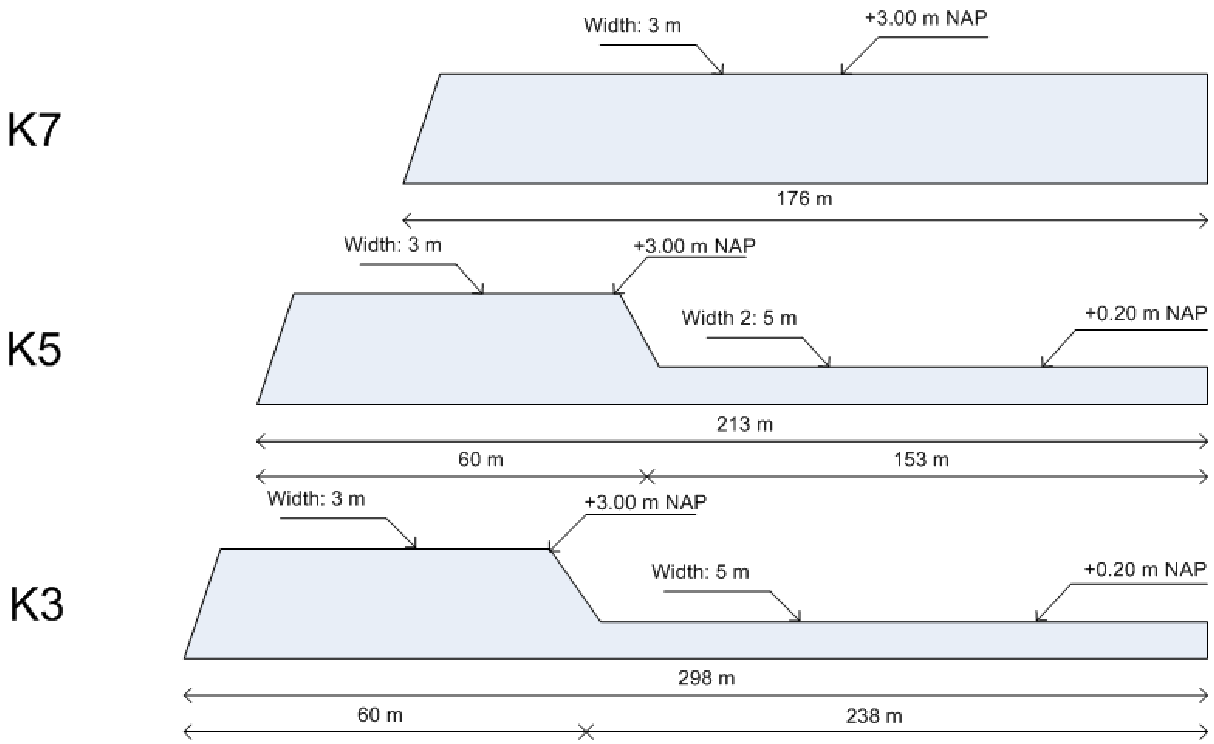


Figure 2.8 – Schematised length profiles of groyne K3, K5 and K7, channel at the left. These are not on scale. The width shown is the width at the top.

Table 2.2 – Properties of the groynes at Knuitershoek, details for heightened and new groynes.

Groyne	Length/length HWR (m)	Height (m +NAP)	Width 1/width 2 Top (m)	Slope
K1	150			
K2	380			
K3	298/60	3.00/0.20	3/5	1:1.75
K4	170			
K5	213/60	3.00/0.20	3/5	1:1.75
K6	370			
K7	176	3.00	3.00	1:1.75

2.5. Conclusion

The Western Scheldt is an estuary consisting of a multiple channel system where tidal flows, waves and wind are processes to keep in mind during this study. The results of an exploratory study for the groynes at Baalhoek and Knuitershoek were promising. The final design is changed after that study and consists of one new groyne and one heightened groyne at Baalhoek and one new groyne and two heightened groynes with high water resting areas at Knuitershoek. This study provides more insight in the initial effects of the final design and the impact of the design parameters of the groynes on the amount of low-dynamic area.

3. Data analysis

3.1. Available data

To get a good understanding of the system at Baalhoek and Knuitershoek data analysis was performed. T0 flow measurements were conducted on 25 locations and 3 transects. These measurements provide reference values for the situation prior to the heightening of the existing groynes and the construction of the new groynes.

The following data was used:

- Transects parallel to the longitudinal dams for flow velocities and directions
- 13 measurement points at Baalhoek for flow velocities and directions (10 min. interval)
- 12 measurement points at Knuitershoek for flow velocities and directions (10 min. interval)
- water levels at four stations in the Western Scheldt (10 min. interval)

Waterlevels:

The water levels stations used for this master thesis are Baalhoek (Baal), Overloop van Hansweert (OVHA), Hansweert (HANS) and Walsoorden (WALS) at the locations shown in Figure 3.1.

Figure 3.1 - Water levels station used during this master thesis.

Flow measurements: Baalhoek

The flow measurements done at Baalhoek were conducted on 14 locations; 5 locations in the channel and 9 locations on the intertidal flats. Unfortunately one measurement point in the channel did not record. The measurement stations used during this master thesis are shown in Figure 3.2. Measurement point 6 only recorded for a short period. The rest of the points recorded between 20 - 1-2016 and 24-2-2016 with a sampling rate of 10 minutes.

A transect parallel to the longitudinal dam is sailed for 13-hours on February 26th to measure the flow velocities and directions in the channel during one tidal cycle Figure 3.2. The transects were sailed with an ADCP (RDI Workhorse Monitor 600 kHz) mounted below a boat.

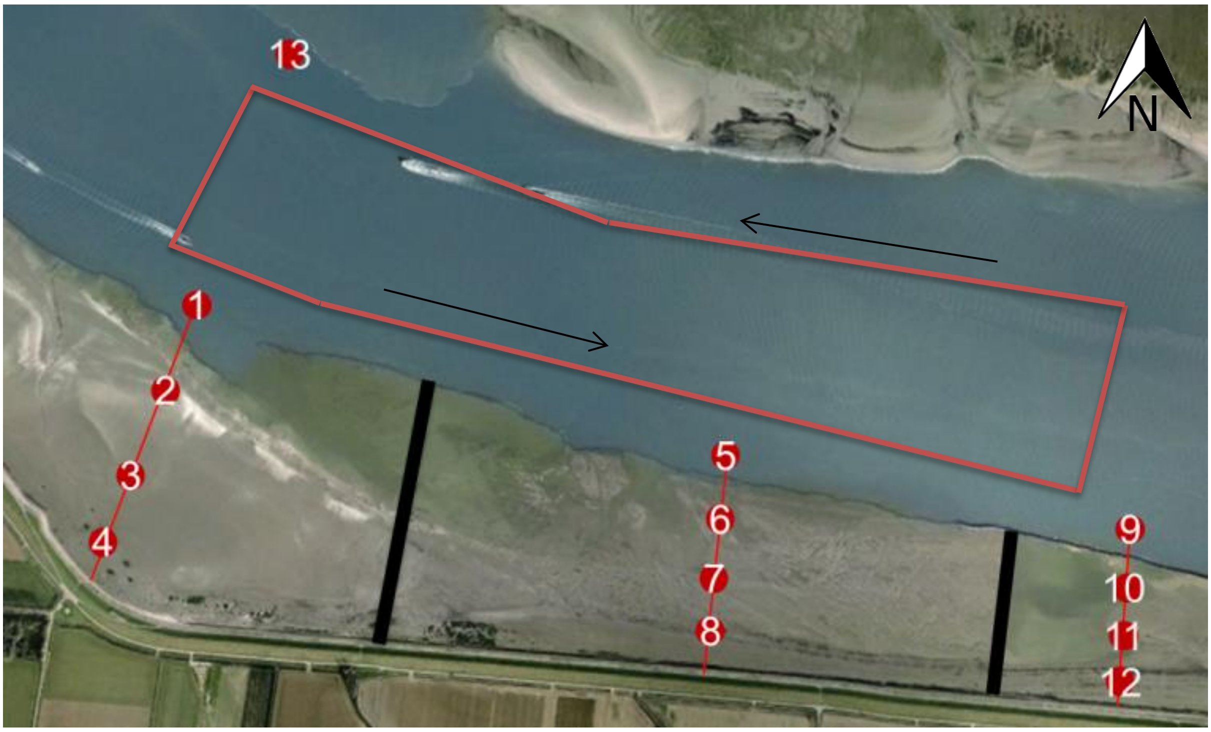


Figure 3.2 - Flow measurement points at Baalhoek. The flow measurement transect is shown by a red line. The black lines represent the groynes as designed by water board Scheldestromen.

Figure 3.3 - Flow measurement points at Knuitershoek. The flow measurement transect is shown by a red line.

Flow measurements: Knuitershoek

The flow measurements done at Knuitershoek were planned on 14 locations; 4 locations in the channel and 11 locations on the intertidal flats. Unfortunately one measurement point in the channel was not set out because of safety reasons. Another measurement point on the flat, between measurement point 6 and 7, did not record. The measurement stations used during this thesis are shown in Figure 3.3. Measurement point 6 only recorded for a short period and measurement point 8 only recorded until a depth of -4.0 m+NAP. The rest of the points recorded according to plan between 8-3-2016 and 28-4-2016 with a sampling rate of 10 minutes. The points in on the flats recorded unit 5-4-2016.

A transect parallel to the longitudinal dam is sailed for 13-hours on March 22nd to measure the flow velocities and directions in the channel during one tidal cycle Figure 3.3. The transect was sailed with an ADCP (RDI Workhorse Monitor 600 kHz) mounted below a boat.

Processing the data

To process the data at first the water levels at measurement stations Baalhoek, Overloop van Hansweert, Hansweert and Walsoorden were obtained for 2016 with a 10 minute interval. Next the flow data obtained from the T0-flow measurements was visualised and processed. In combination with the water levels depth averaged velocities and directions were calculated. An example of the visualisation is shown in Figure 3.4. With the help of this visualisation the difference between ebb and flood flows become visible. The depth averaged values were calculated by using the direction and magnitudes of all depth layers for velocity vectors in U and V direction. The direction was calculated using the average U and V. The depth averaged velocity magnitudes and directions for measurement point 1 at Knuitershoek are plotted in (Figure 3.5). The first layer at the bed, where no data can be obtained, is only 0.1 m high. The overestimation of the depth averaged velocities therefor is limited. This first layer in the channel is approximately 1.0 m, but the channel also has a greater depth. With the depth averaged velocity components U and V, 2d-vector-plots were created to study the development of the flow throughout the tidal cycle.

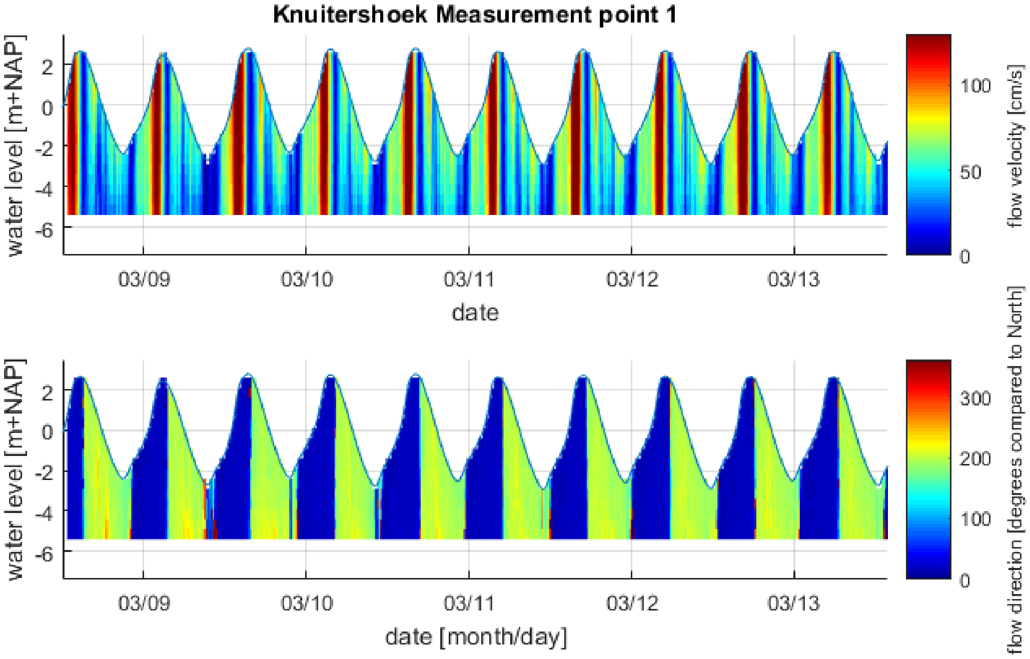


Figure 3.4 – Example of visualisation of the raw data, Knuitershoek measurement point 1. The upper figure shows the flow velocity magnitudes and the water level over time. The lowering of the velocity magnitudes during ebb are probably caused by the higher velocities that occur at the same time on the tip of groyne K6. This forces the main channel flow away from the intertidal flat. The lower figure shows the directions and the water level over time.

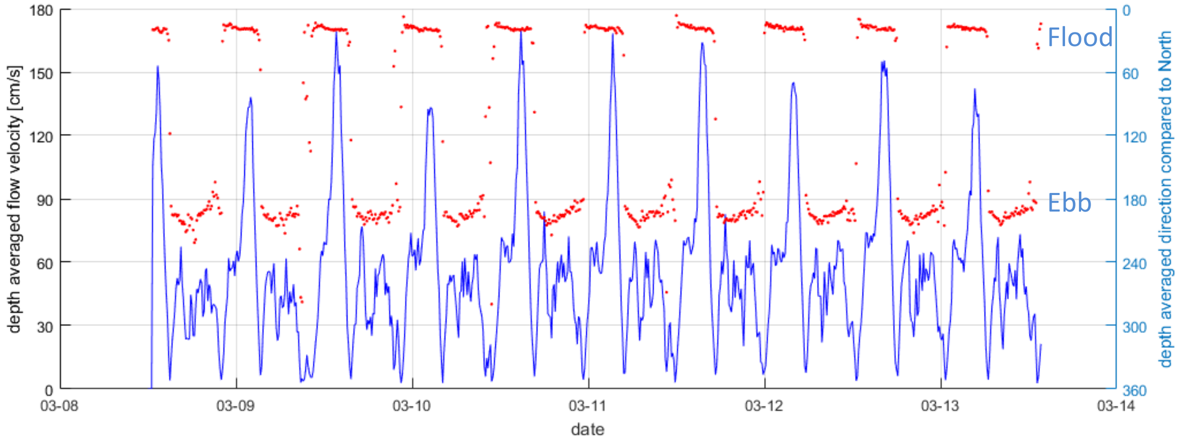


Figure 3.5 – Example of depth averaged velocities (Blue) and directions (Red), Knuitershoek MP01. The flood flows have a direction off approximately 20 degrees compared to North and the ebb flows 200 degrees compared to North.

The 13-hour transect flow measurements were processed by Rijkswaterstaat (Schrijver & Van ’t Westende, 2016a, 2016b). The data was already presented in figures and is used to see how the flow velocities and directions develop in front of the longitudinal dam during a tidal cycle. This data was not processed in the same way as the point measurements because the data was not available during this study.

At first the results for water levels are described, followed by the flow velocity magnitudes and directions.

3.2. Water levels

During this study, four water level stations were used. The water levels of measurement stations Baalhoek and Overloop van Hansweert are described below. These are the stations used for calculation of the depth averaged flow velocities. The water levels during the measurement periods are plotted in Figure 3.6. Both measurement periods include two full spring-neap cycles.

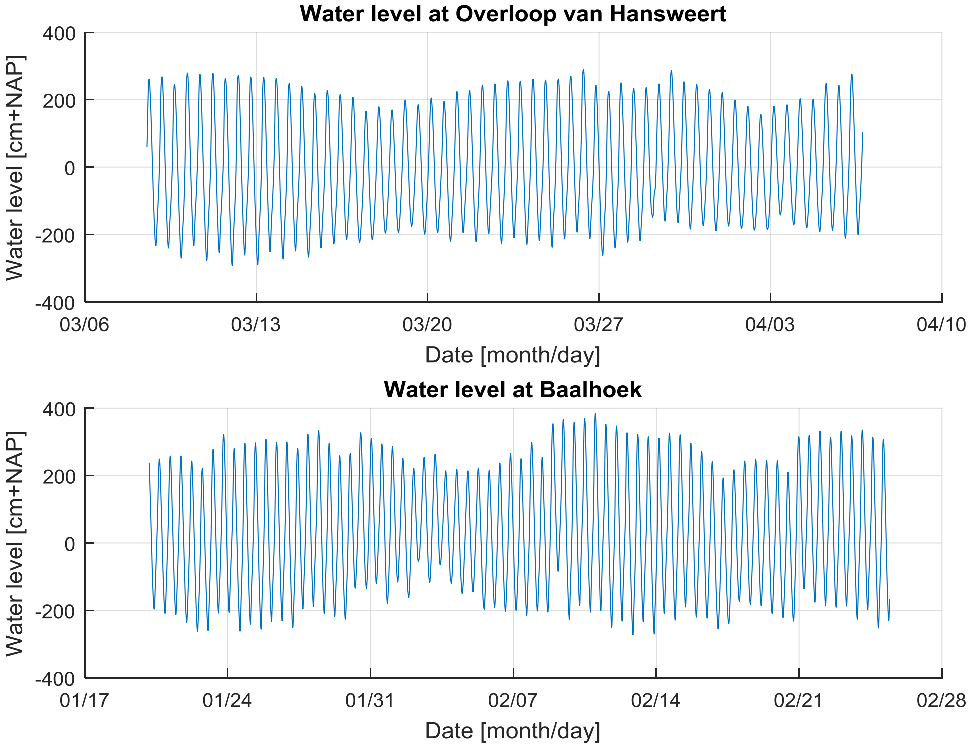


Figure 3.6 - Water levels at Overloop van Hansweert (for Knuitershoek) and Baalhoek during the corresponding flow measurements.

With the water level data from Rijkswaterstaat (2016) the statistics of the water levels at the measurement point Baalhoek (BAAL) are calculated. The results are shown in Table 3.1. The measurements at Baalhoek are done from 20 January 2016 until 24 February 2016 so that period should be used to calibrate the model. During this period the water level seems to be higher compared to the average situation during 2016.

Table 3.1 - Statistics of the water levels in 2016 at Baalhoek. The standard deviation (Std) can be used to compare the tidal range during a period with another period.

Month	Mean [cm+NAP]	Min [cm+NAP]	Max [cm+NAP]	Std [cm+NAP]
Jan	23	-262	393	162
Feb	29	-273	385	165
Mar	8	-306	323	165
Apr	21	-290	360	166
May	17	-269	335	164
Jun	22	-265	321	164
Jul	21	-264	329	163
Aug	21	-263	338	162
Sep	22	-260	351	159
Oct	12	-277	357	159
Nov	21	-273	347	157
Dec	17	-262	323	156

Period	Mean [cm+NAP]	Min [cm+NAP]	Max [cm+NAP]	Std [cm+NAP]
Year	19	-306	393	162
Period (20-1/24-2)	30	-273	385	165
Average spring neap	19	-306	393	162

For Knuitershoek the closest water level measurement station is Overloop van Hansweert (OVHA). The properties for 2016 at OVHA are shown in Table 3.2. The average water level in January seems to be very high in comparison with the rest of the water levels, but this might be because of missing data in the beginning of January. The flow velocity measurements on the intertidal flat at Knuitershoek were carried out between 8 March and 5 April 2016. In this period the mean water level seems to be lower compared to the rest of the year. This is also seen in the water levels at Baalhoek.

Table 3.2 - Statistics of the water levels in 2016 at Overloop van Hansweert

Month	Mean [cm+NAP]	Min [cm+NAP]	Max [cm+NAP]	Std [cm+NAP]
Jan	32	-225	291	148
Feb	19	-261	344	152
Mar	0	-293	290	152
Apr	13	-274	327	153
May	10	-252	298	152
Jun	10	-250	285	153
Jul	14	-249	294	151
Aug	14	-247	305	151
Sep	16	-244	318	149
Oct	6	-261	321	148
Nov	15	-259	314	146
Dec	10	-245	290	145
Year	12	-293	344	150
Period (8-3/5-4)	-3	-293	290	153
Average spring neap	12	-293	344	150

Both measurement periods show a little higher standard deviation compared to the average in a year and an average spring neap cycle. This means that the water levels were varying more during these periods. No extraordinary water levels were reached during one of the periods. The minimum water level was seen at Overloop van Hansweert during the measurement period at Knuitershoek, but that is not a problem for this study.

The water level measurements showed that for the flow measurement period at Baalhoek the water levels are higher and at Knuitershoek lower compared to the average water levels. This means that the calibration of the model is based on both lower and higher water levels. For the model study (design implementation and scenario study) April will be used, since the water levels are comparable with the yearly average values.

No essential water level data is missing during the flow measurement periods. Only the water levels of Overloop van Hansweert are missing (until 27 January) in the measurement period for Baalhoek. This is no problem since the depth averaged velocities at Baalhoek are calculated with the water levels at measurement location Baalhoek (BAAL) and there is still sufficient available data for the calibration.

3.3. Flow velocities and directions

3.3.1. Knuitershoek

Transect measurements

The flow transects measurements done parallel to the longitudinal dams gave insight in the difference between flood and ebb currents. The maximum flow velocity during flood is 1.76 m/s and the maximum flow velocity during ebb is 0.88 m/s. In contradiction with what was found in the literature the flow seems to be flood dominated and not ebb dominated (Dam et al., 2008). This means that the flow velocities during flood are higher than the flow velocities during ebb. This might be due to the location of the transect that is measured. The transect is located in the outer bend of the Zuidergat. Generally, the flow velocity in the outer bend is stronger during flood than in the inner bend as shown in Figure 3.7 (Sukhodolov, 2012). This does not mean that the channel is flood dominated because the flow velocities of the total cross section have to be known to conclude whether the total channel is flood or ebb dominated.

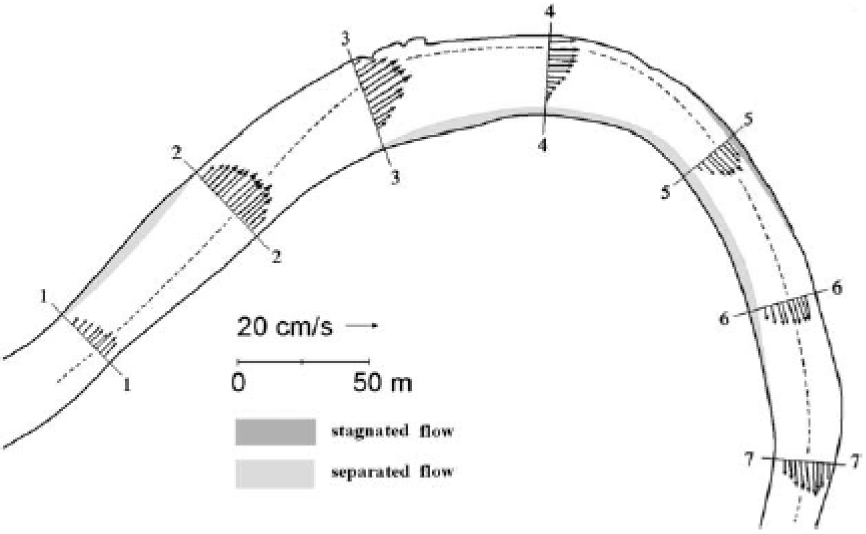


Figure 3.7 - Flow velocities in the outer bends are higher compared to the inner bend. The biggest difference is seen in cross section 4-4 (Sukhodolov, 2012).

In the north of the transect the flow direction seems to be slightly different than in the south of the transect. This is due to the existing groyne in the north of Knuitershoek enforcing the flow direction to change (Figure 3.8). The water is flowing against the groyne and causes contraction of flows and a change in direction towards the channel. This contraction of flows resulted in higher flow velocities and bed shear stresses. This resulted in a scour hole at the end of the existing groyne K6 (Figure 3.9).

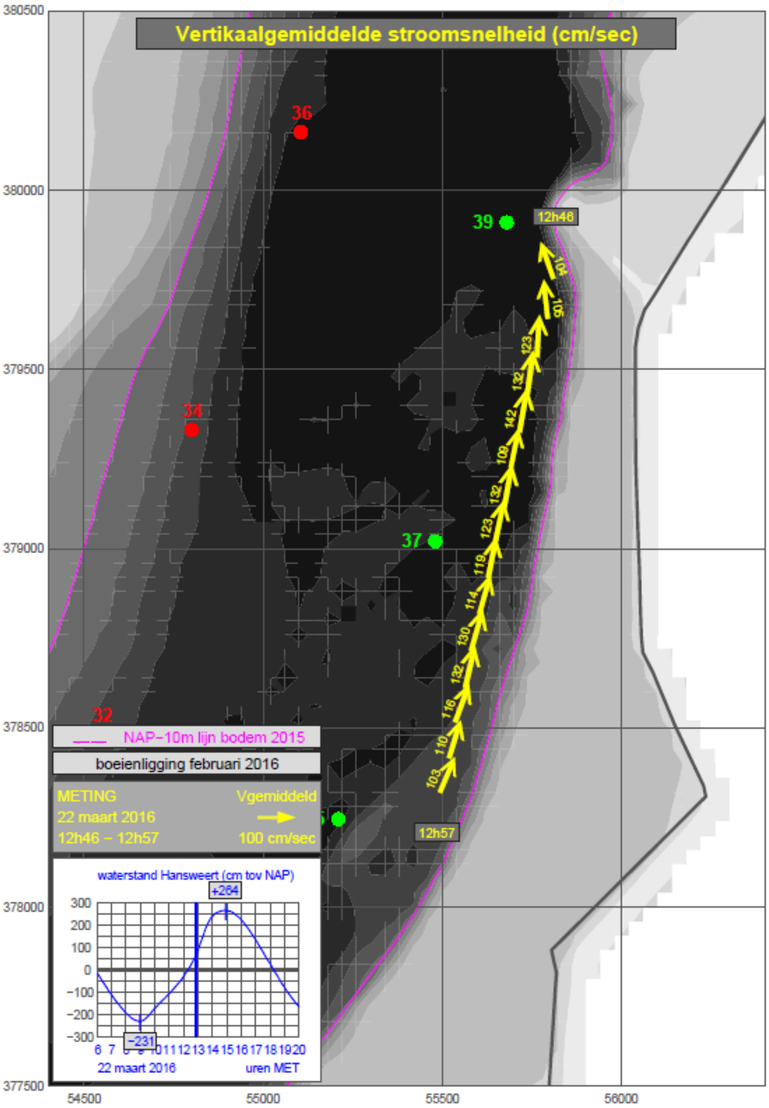


Figure 3.8 - Depth average flow velocities at Knuitershoek parallel to the longitudinal dam. In the north the flows bend towards the channel (Schrijver & Van 't Westende, 2016b).

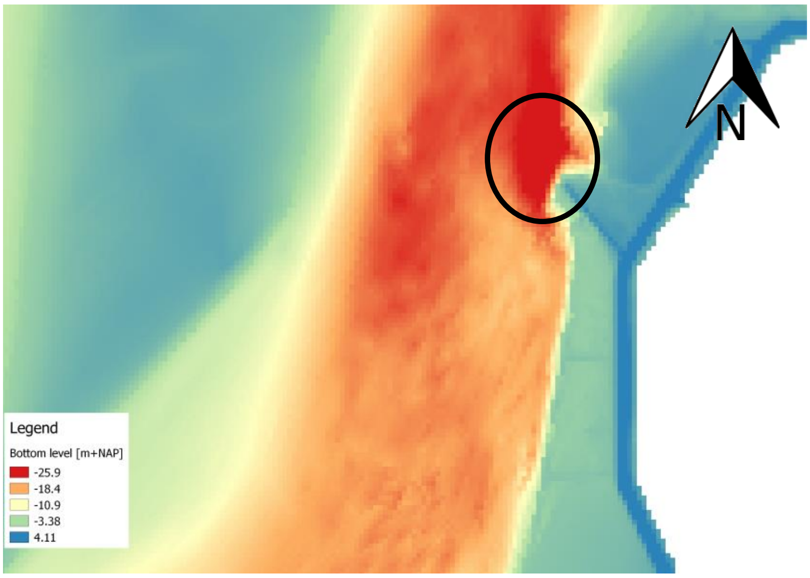


Figure 3.9 - Scour hole (black circle) in the channel at the end of the existing groyne K6 at Knuitershoek.

Point measurements

When the water level is rising the northern part of the flat starts to inundate first. In the beginning the flow is directed in the opposite direction of the channel flow (Figure 3.10, left). This has to do with the height difference on the flat, and with the height of the longitudinal dam and existing groynes. The northern part of the flats has a lower bed level compared to the southern part. The longitudinal dam blocks the flow from the channel and there is an opening in near the existing groyne in the north (K6). The flow on the flat becomes parallel to the flow in the channel when it is fully inundated and the existing dams are completely flooded (Figure 3.10, right).

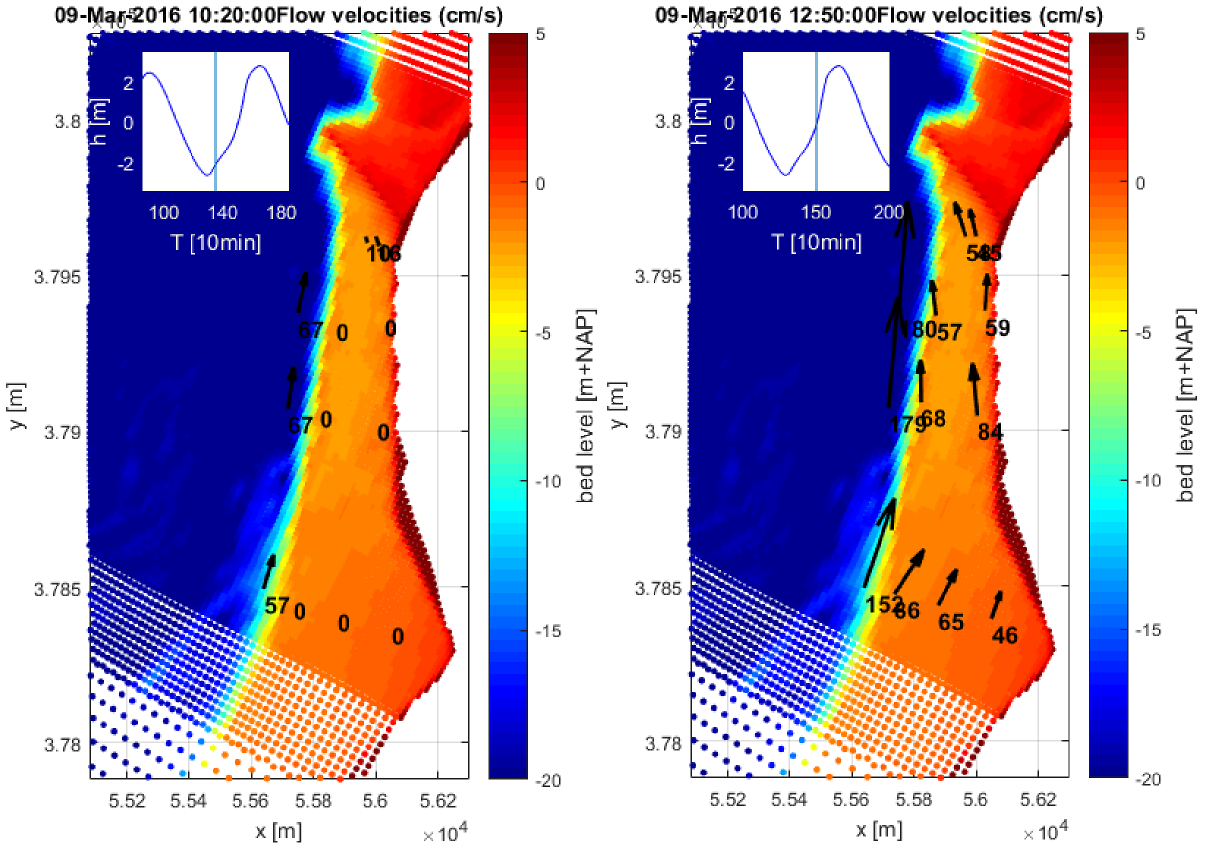


Figure 3.10 - Flow velocities at Knuitershoek when the flat starts inundating (left), and when the entire flat is flooded (right).

When the water level is lowering, the flow in the channel is mainly directed to the south, but on the flat the directions are varying. At first all the flow is parallel to the channel, but when the water level lowers to 2.0 m +NAP the northern measurement points show a flow directed to the north (Figure 3.11, left). This is again caused by bed level differences on the flat and the opening in the longitudinal dam in the north. When the water level is approximating the bed level of the flats, the flow is directed towards the channel in the south and the rest of the water flows to the opening of the longitudinal dam in the north (Figure 3.11, right). This division is caused by a lower bed levels in the northern part of the flat and the existing groynes (K3, K4 and K5).

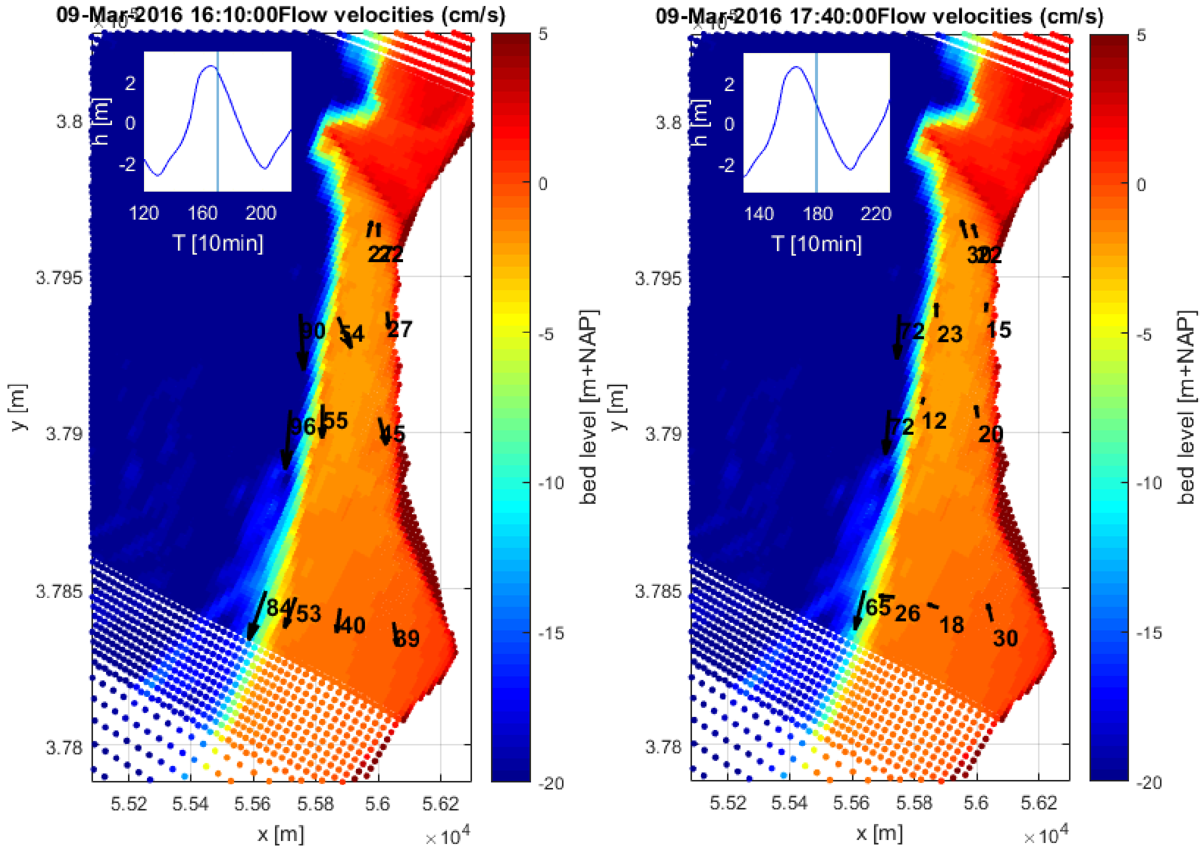


Figure 3.11 - Flow velocities at Knuitershoek when the water level is lowered to 2m+NAP (left). When the water level lowers further, the flow directions change to the north and towards the channel (right).

All measurement locations that were analysed are flood dominated according to the maximum peak flows. Only measurement point 6 is ebb dominated when looking at maximum velocity (Table 3.3), although the difference between the ebb and flood peak is only 4 cm/s. A clear difference can be seen between the measurement points in the channel (1, 5 and 9, in blue) and the measurement points on the flat (the remaining points). The difference between ebb and flood velocities in the channel is larger than the difference between ebb and flood velocities on the flats. This means that the velocities in the channel are more flood-dominant than on the flats.

Table 3.3 – Maximum ebb and flood peak flows of at the measurements points (mp), in blue the points located in the channel.

mp	**dominance based on maximum velocities (flo/ebb)**	**max ebb peak [cm/s]**	**max flood peak [cm/s]**	**mp**	**dominance based on maximum velocities (flo/ebb)**	**max ebb peak [cm/s]**	**max flood peak [cm/s]**
1	flo	78	159	7	flo	57	98
2	flo	53	100	8	flo	74	216
3	flo	46	67	9	flo	55	96
4	flo	44	53	10	flo	75	84
5	flo	77	210	11	flo	45	83
6	Ebb	106	102	12	flo	45	77

To create a depth averaged model the flow velocity profile of the measurements should be close to a logarithmic profile (Deltares, 2017b). To see if this is true for the measurement data at Knuitershoek, the natural logarithm of the height above of the bed level (ln(z)) is plotted against the flow velocities at four moments in time during a tidal cycle (Figure 3.12). This should give a straight line if the velocity profile is logarithmic. The points in the channel (1, 5, and 8) show a very good logarithmic profile since the lines are approximately straight. The points 2, 3, 6, 7 and 9 also show a nearly logarithmic behaviour. The other points are varying more in depth, but do not show very large deviations such as a switch in flow direction (if the velocity was 0 at some point in depth). This could give some deviation between the model and the observed values since a 2dh depth-averaged delft3d Flexible Mesh model assumes logarithmic velocity profiles.

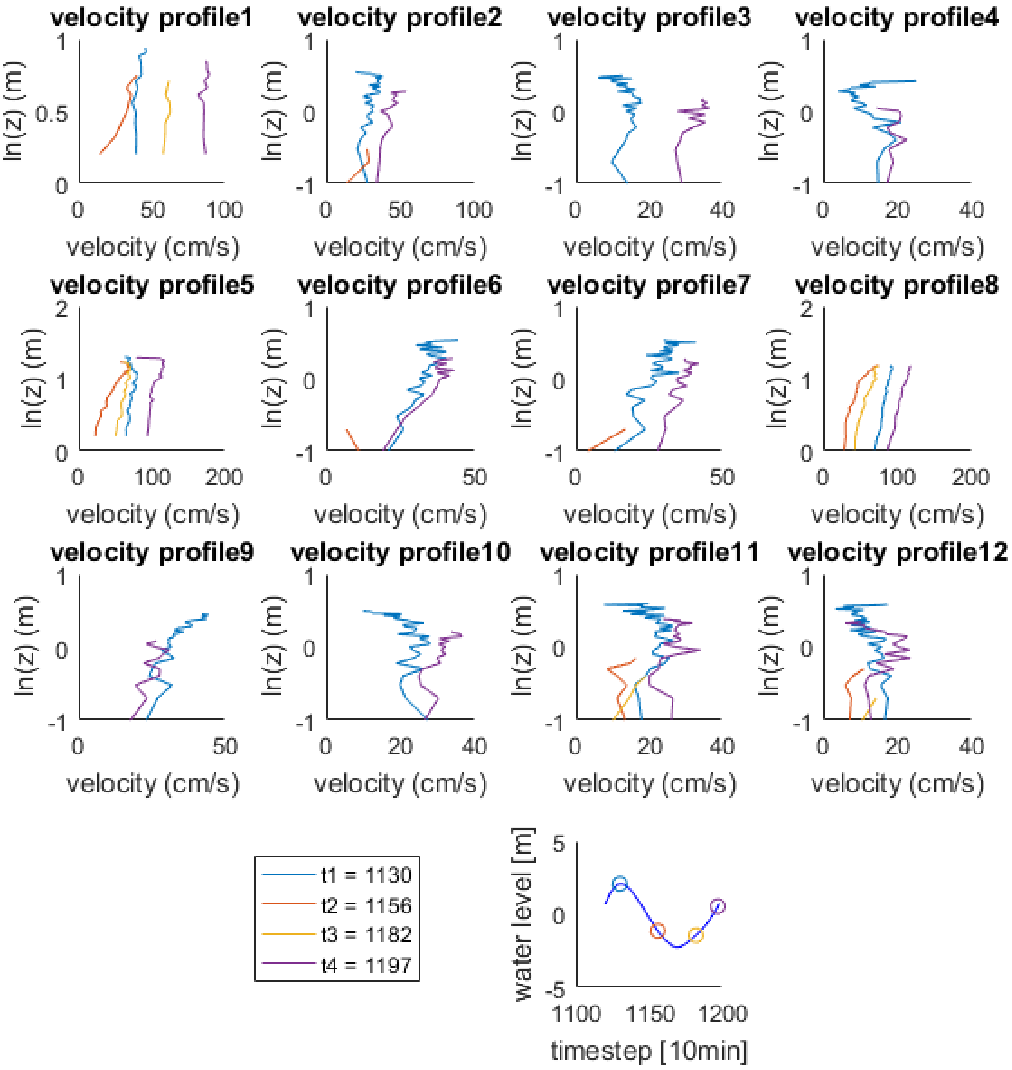


Figure 3.12 – Velocity profiles of the point measurements at Knuitershoek. Velocity plotted against the logarithmic height above the bed level (ln(z)). The bottom right figure shows the moment in the tidal cycle.

Low/high-dynamic

At Knuitershoek and Baalhoek an area is defined as low-dynamic during this data analysis if the flow velocities are below 0.60 m/s (Dam et al., 2008). In Figure 3.13 the depth averaged flow velocities of the measurement points at Knuitershoek are plotted over time in blue. In red the critical velocity is plotted. What can be seen is that all measurement points have velocities higher than 0.60 m/s except for MP4. This means that Knuitershoek cannot be specified as a low-dynamic area according to the flow measurements. The exact surface area that is low-dynamic cannot be concluded directly out of the measurements.

The percentages of time steps with a velocity higher than 0.6 m/s are given in Table 3.4, which shows that the channel measurement locations(MP 1, 5, and 8) have the longest period with high-dynamic flows. A percentage higher than 1.4% means that on average every tidal cycle the critical velocity is exceeded.

Table 3.4 - Percentage of time steps (10 minutes) with a velocity higher than 0.6 m/s.

Measurement point	**1**	**2**	**3**	**4**	**5**	**6**	**7**	**8**	**9**	**10**	**11**	**12**
>0.6 m/s	35.8%	5.5%	0.6%	0.0%	45.8%	6.3%	5.3%	36.7%	5.8%	4.4%	4.1%	2.1%

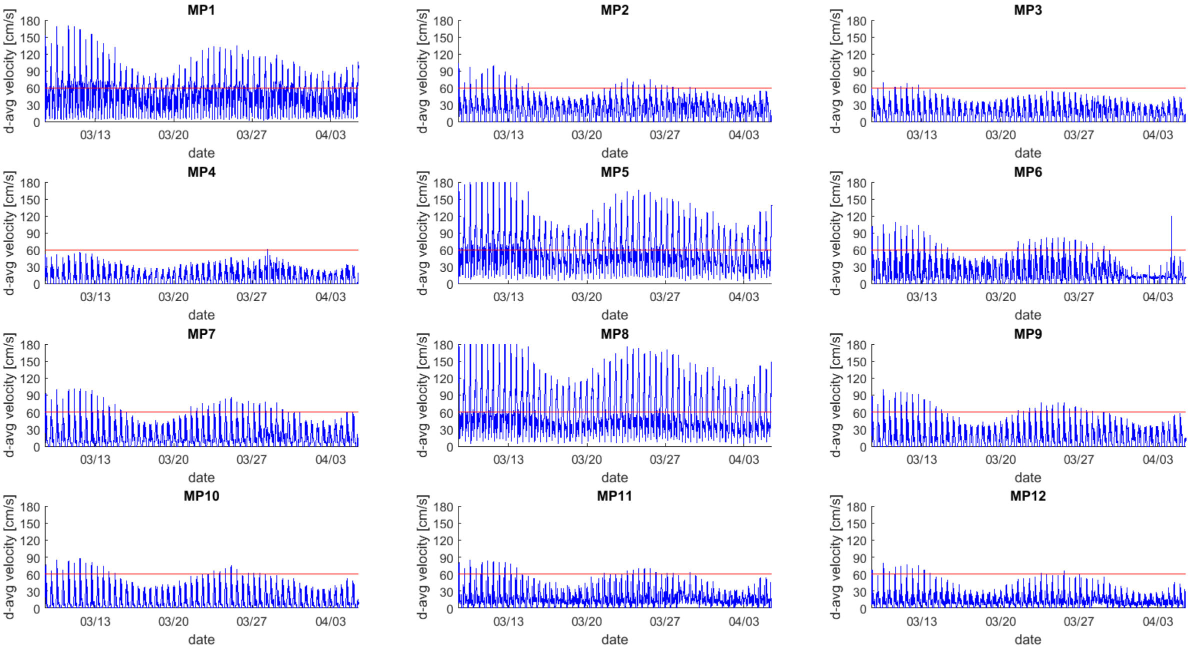

MP1 MP2 MP3 MP4 MP5 MP6 MP7 MP8 MP9 MP10 MP11 MP12

Figure 3.13 - Depth average flow velocities at Knuitershoek (blue) and the critical velocity for low-dynamic area (60 cm/s, red)

3.3.2. Baalhoek

Transect measurements

The two flow measurement transects sailed at Baalhoek show differences in dominance during ebb and flood currents. The northern transect is clearly ebb dominated. The maximum velocity measured during ebb is 1.49 m/s, where the maximum flow velocity during flood is 1.35 m/s. In the southern transect the maximum ebb flow velocity is 1.51 m/s and the maximum flood velocity is 1.94 m/s. This makes the southern transect flood dominated. This does not mean that the channel is flood dominated because the flow velocities of the total channel cross section have to be known to conclude that. The difference in dominance is caused by the location of the transect. During flood, the southern transect is located in the outside of the bend where the northern transect is located in the inside of the bend. In the outside of the bend the flow velocities are generally larger than on the inside of the bend.

In the western part of the transect the flow during flood is directed more to the south in comparison with the rest of the transect (Figure 3.14). This is caused by the flow that is coming from the north. The rest of the flows are directed parallel to the channel. During ebb the all measured flows are directed parallel to the channel (Figure 3.15).

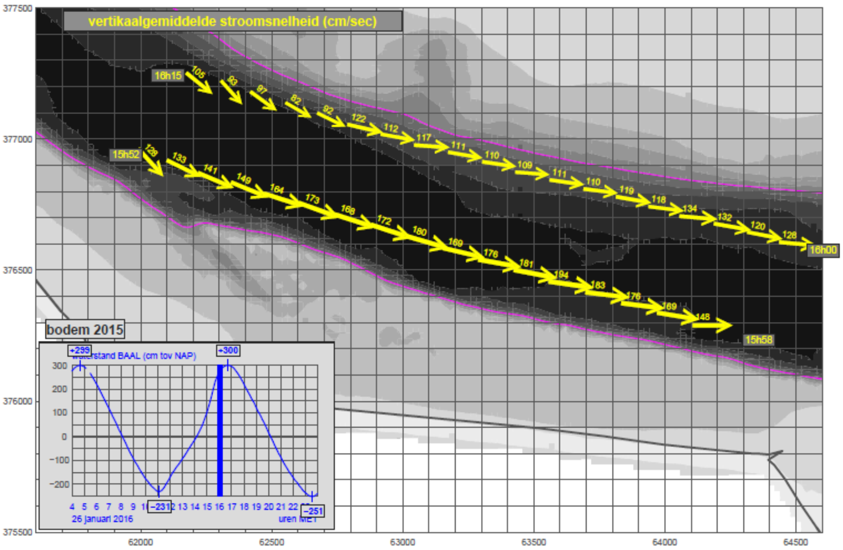


Figure 3.14 – Southward flow in the west of the transects at Baalhoek during flood (Schrijver & Van ’t Westende, 2016a).

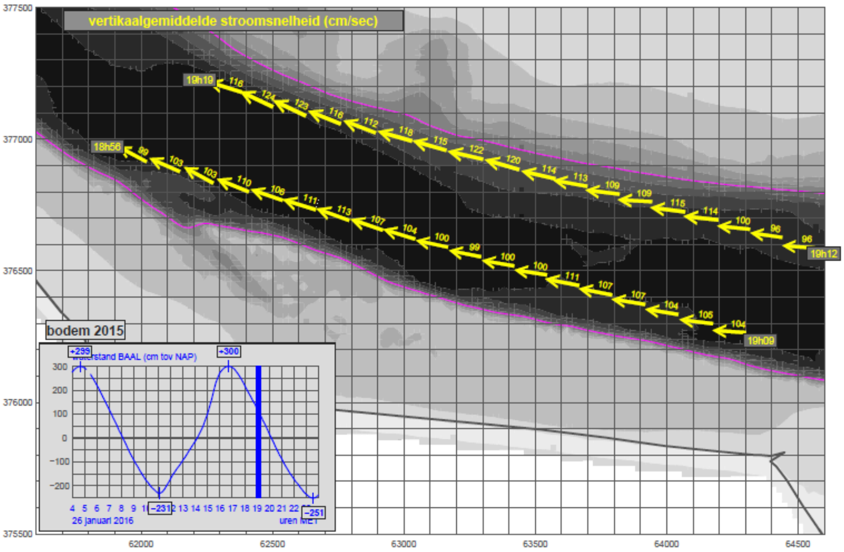


Figure 3.15 – Parallel flow in the channel at Baalhoek during ebb (Schrijver & Van ’t Westende, 2016a).

Point measurements

After low tide, when the flat is exposed, the water starts rising and starts flowing through small flood channel in the west of the flat. This causes the centre of the flat to be flooded first (Figure 3.16). During higher tide all flows are directed in the same direction as the channel flow (Figure 3.17, during spring tide), which means that no circulation cells are visible in the situation before the construction of the groynes. The velocities during high tide (spring tide in this case) are too high to be low-dynamic. On the flats, during spring tide, velocities even reach up to 1.2 m/s.

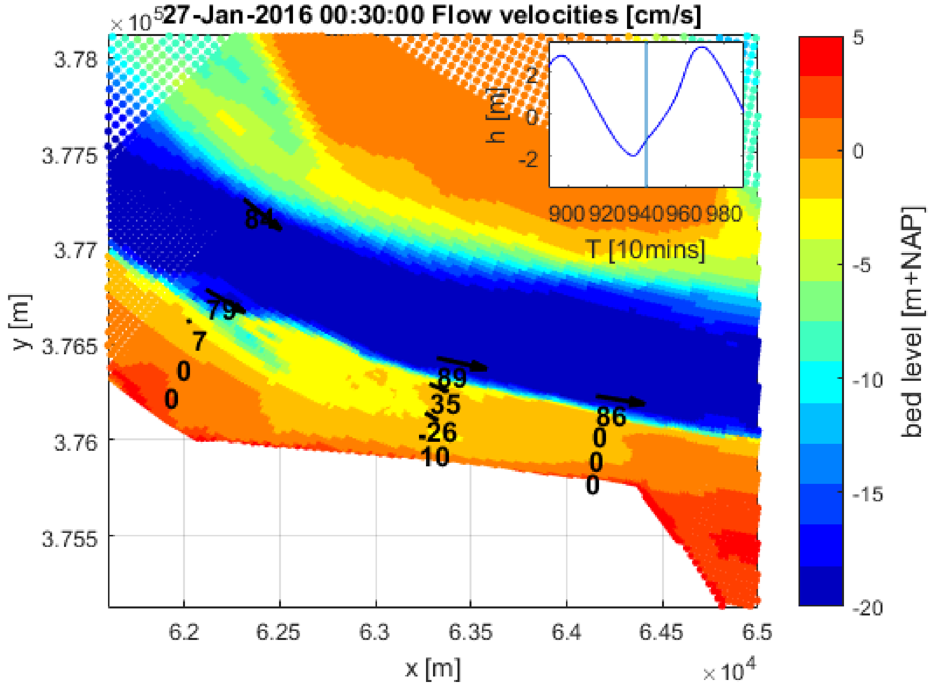


Figure 3.16 - Flow velocities at Baalhoek at the start of flood. The centre part of the flat starts inundating and flowing as first.

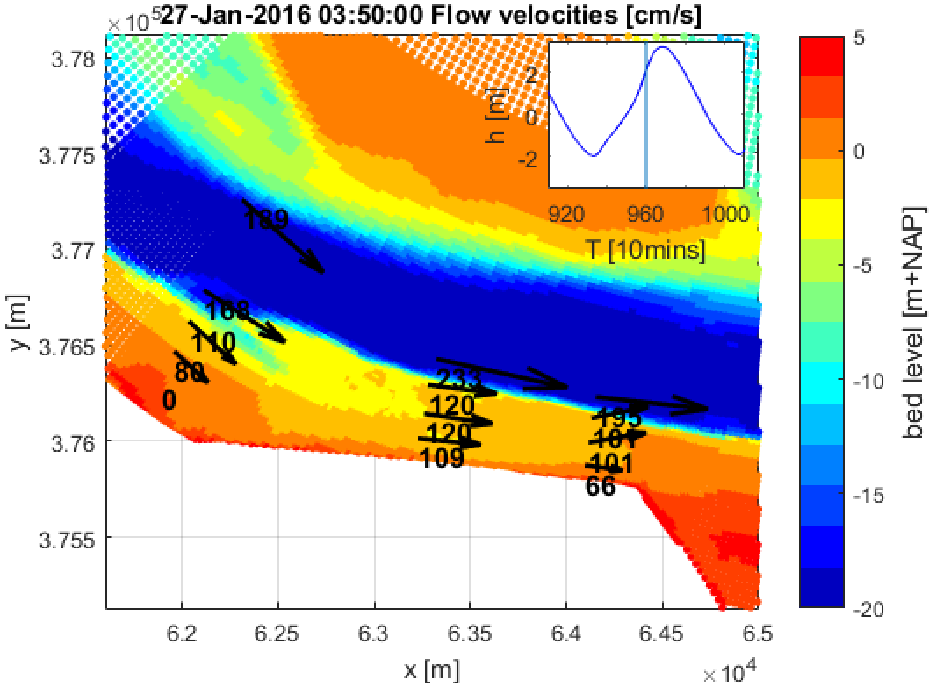


Figure 3.17 - All flows directed parallel to the channel. The bathymetry shown here is the same bathymetry as used for the KnuBa-model (Chapter 4).

At the start of the ebb flows, the flow on the flats is parallel to the direction of the channel (Figure 3.18). The water level is high enough for the water to flow over the existing groynes and longitudinal dam.

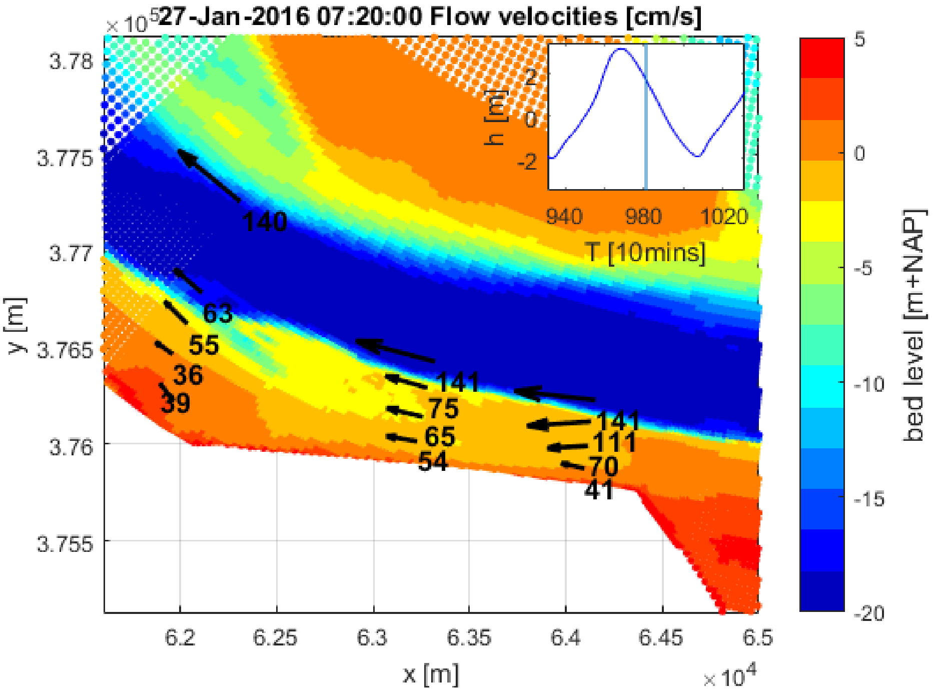


Figure 3.18 - Flow velocities at Baalhoek at the start of ebb. The flow is directed parallel to the channel.

After the flats starts exposing, the water exits the flat through the flood channel in the west. This can be seen in the flow velocities in the centre of the flat and close to the opening in the longitudinal dam (Figure 3.19).

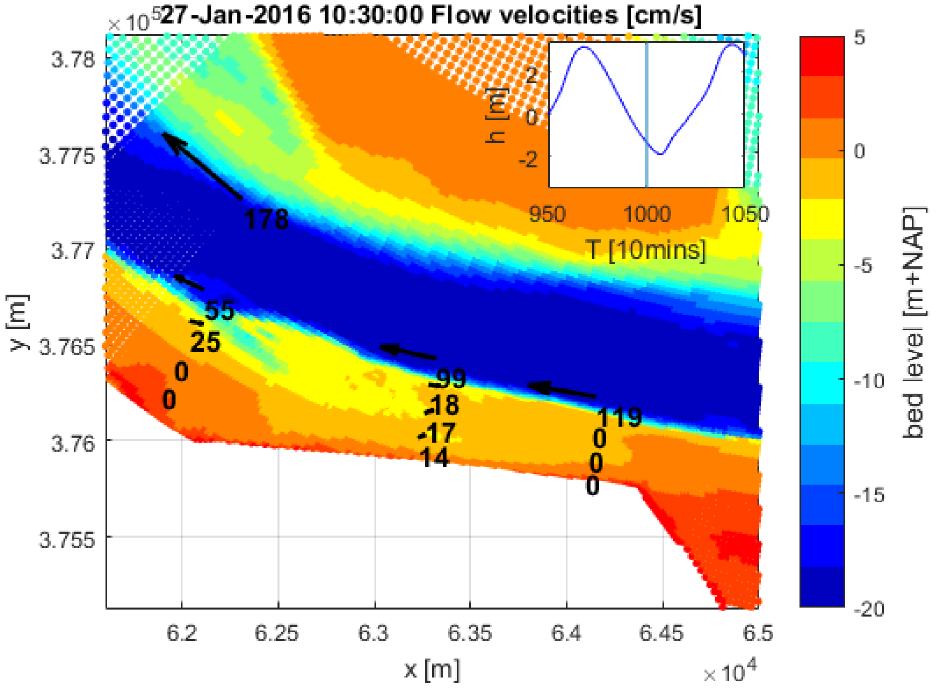


Figure 3.19 - Flow velocities at Baalhoek at the end of ebb. Only the centre in the centre of the flat the water is flowing.

The depth-averaged flow velocities calculated from the measurement points at Baalhoek showed that on the flats, based on the maximum flow velocity, the dominant tide mainly is flood (Table 3.5). Only measurement point 4 shows to be ebb dominated. This point is located close to the dike and the difference between the maximum flows is only 1 cm/s.

Table 3.5 - Properties of the Peak flows at the measurements points (In blue the points located in the channel).

Mp	dominance based on maximum values	max ebb peak [cm/s]	max flood peak [cm/s]	Mp	dominance based on maximum values	max ebb peak [cm/s]	max flood peak [cm/s]
1	flo	77	135	8	flo	58	110
2	flo	84	98	9	flo	136	159
3	flo	54	71	10	flo	97	108
4	ebb	49	48	11	flo	59	106
5	flo	148	186	12	flo	48	94
6	flo	63	91	13	flo	177	201
7	flo	61	106				

To study if the velocity profiles at Baalhoek are close to a logarithmic profile the velocities are plotted against the logarithmic height above the bed level (ln(z), Figure 3.20). The profiles are plotted of four moments during the tidal cycle. Nearly all plots approximate straight lines. This means that the velocity profiles are close to a logarithmic profile and can be simulated in a depth averaged model.

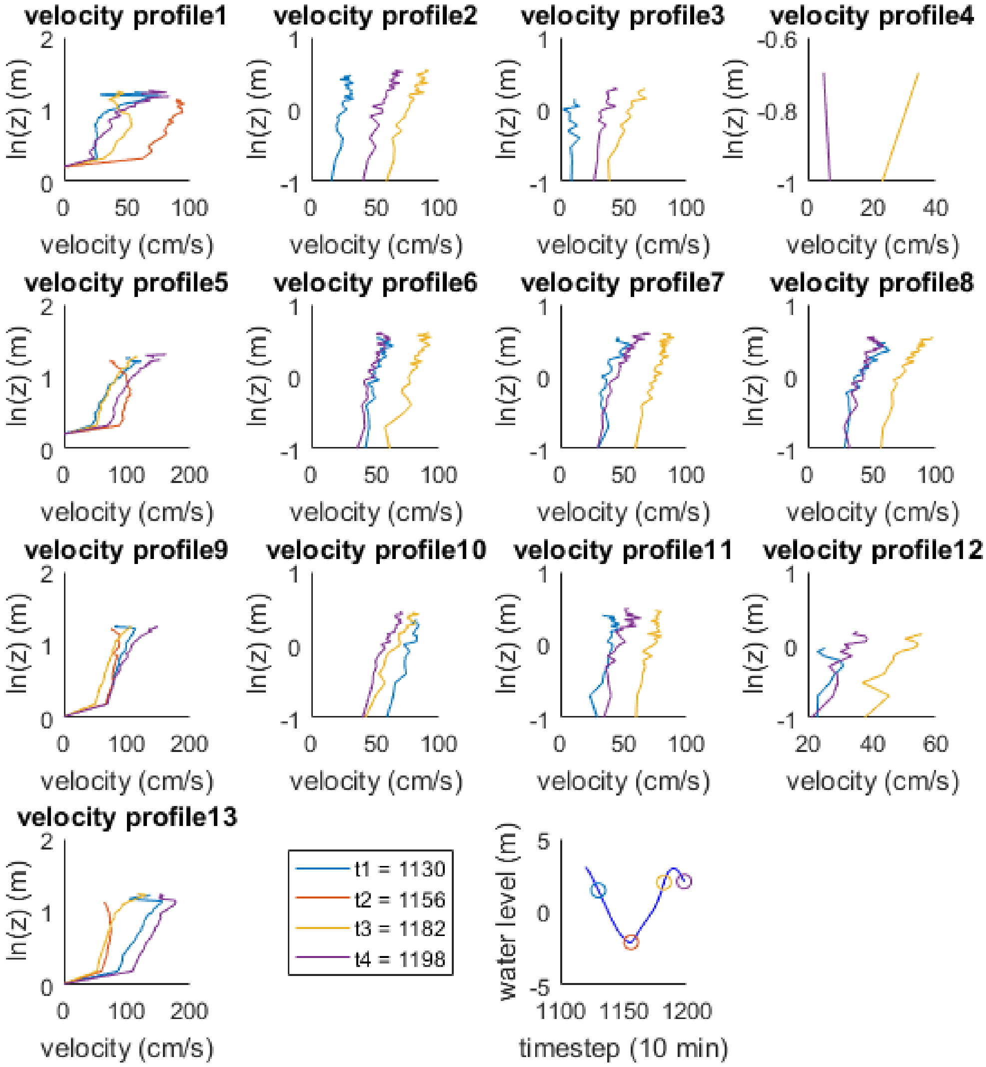


Figure 3.20 - Velocity plotted against the logarithmic height above the bed level (ln(z)). Velocity profiles of the point measurements at Baalhoek. The bottom right figure shows the moment in the tidal cycle.

Low/high-dynamic

In Figure 3.21 the depth averaged flow velocities of the measurement points at Baalhoek are plotted over time in blue. In red the critical velocity is plotted. What can be seen is that all measurement points have velocities higher than 0.60 m/s except for MP 4. This means that Baalhoek cannot be specified as a low-dynamic area according to the flow measurements. The percentage of time steps (10 min) that has velocities higher than 0.60 m/s is given in Table 3.6. Same as at Knuitershoek the velocities in the channel (MP 1, 5, 9 and 13) show a higher percentage of high-dynamic flow than the points on the flat.

The point measurements show that the flow velocities on the flats are too high for a low-dynamic area. Also the closer a measurement point is to the dike, the lower the flow velocities. The western measurement points show that the higher the bed level, the lower the flow velocity.

Table 3.6 - Percentage of time steps (10 minutes) with a velocity higher than 0.6 m/s.

Measurement Point	**1**	**2**	**3**	**4**	**5**	**6**	**7**	**8**	**9**	**10**	**11**	**12**	**13**
>0,6m/s	34.2%	5.7%	0.5%	0.00%	69.0%	1.3%	5.1%	3.5%	66.0%	7.5%	3.8%	0.6%	63.9%

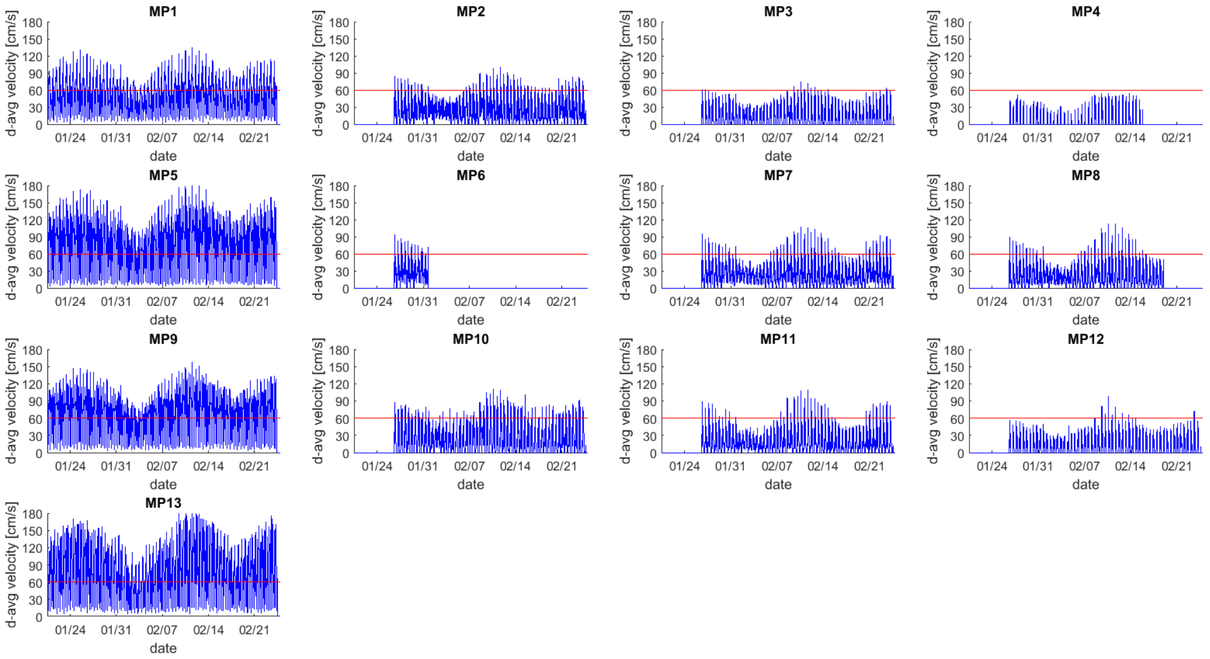


Figure 3.21 - Depth average flow velocities at Baalhoek (blue) and the critical velocity for low-dynamic area (60 cm/s, red).

3.4. Conclusion

The quality of the measurement data is good enough to be used in this study. The flow measurement time series are detailed enough on the flats and long enough to calibrate the model for this study. No essential water level data is missing for the rest of this study.

Based on the velocity depth profiles it can be concluded that an approximation by a 2 dimensional horizontal depth-averaged model can be made. The set-up of this model is described in the next chapter.

The data analysis showed that the intertidal flats are mostly flood dominated based on maximum flow velocities. This is relevant for the rest of this study because for low-dynamic surface area the maximum flow velocities are the most important. The focus during the analysis of the modelling results should be on flood flows, although the ebb flows should not be ignored.

The data analysis also showed that the flow velocities on the flats Baalhoek and Knuitershoek are too high to be classified as low-dynamic area. Almost all measurement points showed that on average during every tidal cycle the flow velocity exceeds the critical velocity.

At Baalhoek the opening in the longitudinal dam (the flood channel) is important for the rest of this study, since it guides the water onto the flat. At Knuitershoek the bed level difference between the northern and the southern part, and the opening in the longitudinal dam in the north is important for the rest of this study.

4. Delft3D FM model of Baalhoek and Knuitershoek: The KnuBa-model

4.1. Set up of the KnuBa-model

The steps for setting up the KnuBa-model are described in this paragraph. An overview of the steps needed for the KnuBa-model is given in Figure 4.1. The Delft3D – NeVla-model was used to create downstream (west) and upstream (east) boundary conditions. These boundary conditions are the input for the nested KnuBa-model where a flexible mesh was created with a higher resolution at the locations Baalhoek and Knuitershoek. The water level and velocity data as described in Chapter 3 were used to calibrate the model.

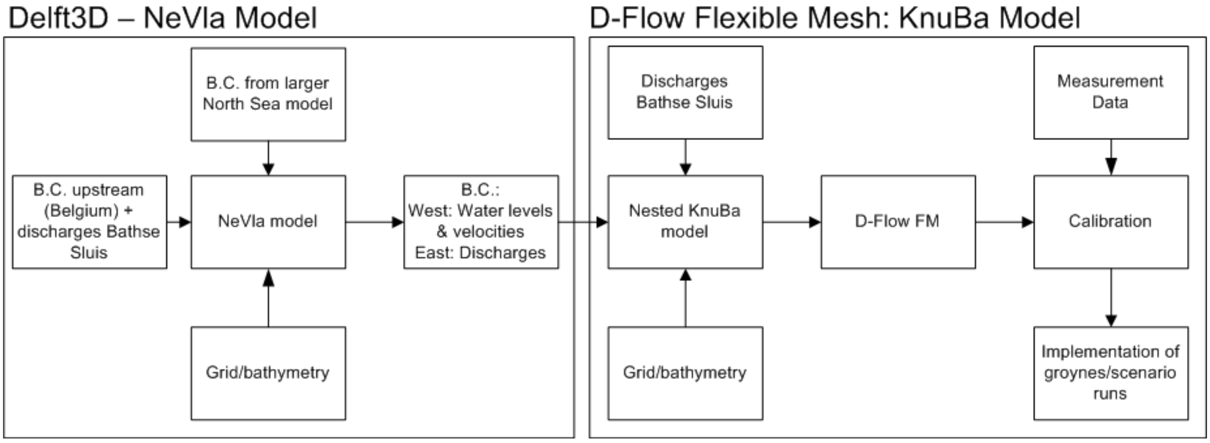


Figure 4.1 - Modelling approach: KnuBa-model. The boundary conditions for the KnuBa-model were generated by the NeVla-model (left). These boundary conditions were put into the KnuBa-model together with the refined grid, bathymetry and the discharges at Bathse Sluis. When the input was complete the Flow module of Delft3D Flexible Mesh was run. Next, the measurement data was used to calibrate the model. After the calibration was finished, the model was used to study the effects of the designed groynes and to perform a scenario study.

4.1.1. Model Assumptions

Before the model is set up, assumptions and model choices need to be made. The choice for Flexible Mesh (FM) is made because two areas need to be modelled in detail. Because FM is able to compute with different spatial resolutions within 1 model domain, lots of work and time is saved. The KnuBa-model is a 2 dimensional horizontal (2DH) depth-averaged model. The 2DH model created for Schaar van Waarde has proven to be a useful tool to predict morphological impacts in systems with groynes (Dam & Bliek, 2013). A 2DH model does not include vertical flows, but since between groynes the most important flows are horizontal (Yossef, 2005), and the velocity profiles at the locations are close to logarithmic, this should not be a problem.

Salinity is not included in the model because the estuary is well mixed (Van der Spek, 1997). The salt/fresh water density differences are not significant enough to influence the hydrodynamics and morphodynamic development in the Western Scheldt in modelling (Van der Wegen & Roelvink, 2012).

Waves are not included in this version of the KnuBa-model, because the focus of this thesis is on the tidal influences and waves are not included in the definition of low-dynamic area. By excluding waves from the model the tidal influences become visible. The amount of low-dynamic surface area of this modelling study therefor is a maximum approximation. Including waves will make the area more dynamic and will increase the amount of sediment in motion. This means that when waves are added, the total low-dynamic surface area will probably be smaller.

The bed level of the KnuBa-model did not change during the computations of the hydrodynamics, because the main focus is on the initial effects of the groynes and the creation of low-dynamic surface area. One additional sediment transport run was made for a first insight of the effects of the newly implemented groynes on the bed level change.

4.1.2. Grid and Domain

The grid for this model was built from the existing grid of the Delft3D NeVla-model. It is converted to a flexible mesh and adjusted in order to be used as a basis for the KnuBa-model. At first the ratio of the cells next to the flats was adjusted to 1x1 so the progress for refining the grid is easier and cleaner. Next, two steps of refinement were executed, which resulted in a curvilinear grid that is detailed at two locations (Figure 4.2). Important bathymetrical features should be covered by a minimum of 5 - 10 grid cells (Deltares, 2017a). The shortest designed groyne has a length of 176 m so the resolution of a cell at the Baalhoek and Knuitershoek of 15m x 15m is considered small enough. The groynes have a width of 5 m. To implement these in the model, the bed level in the cells was increased. So in the model they are represented as groynes with a width of 15 m.

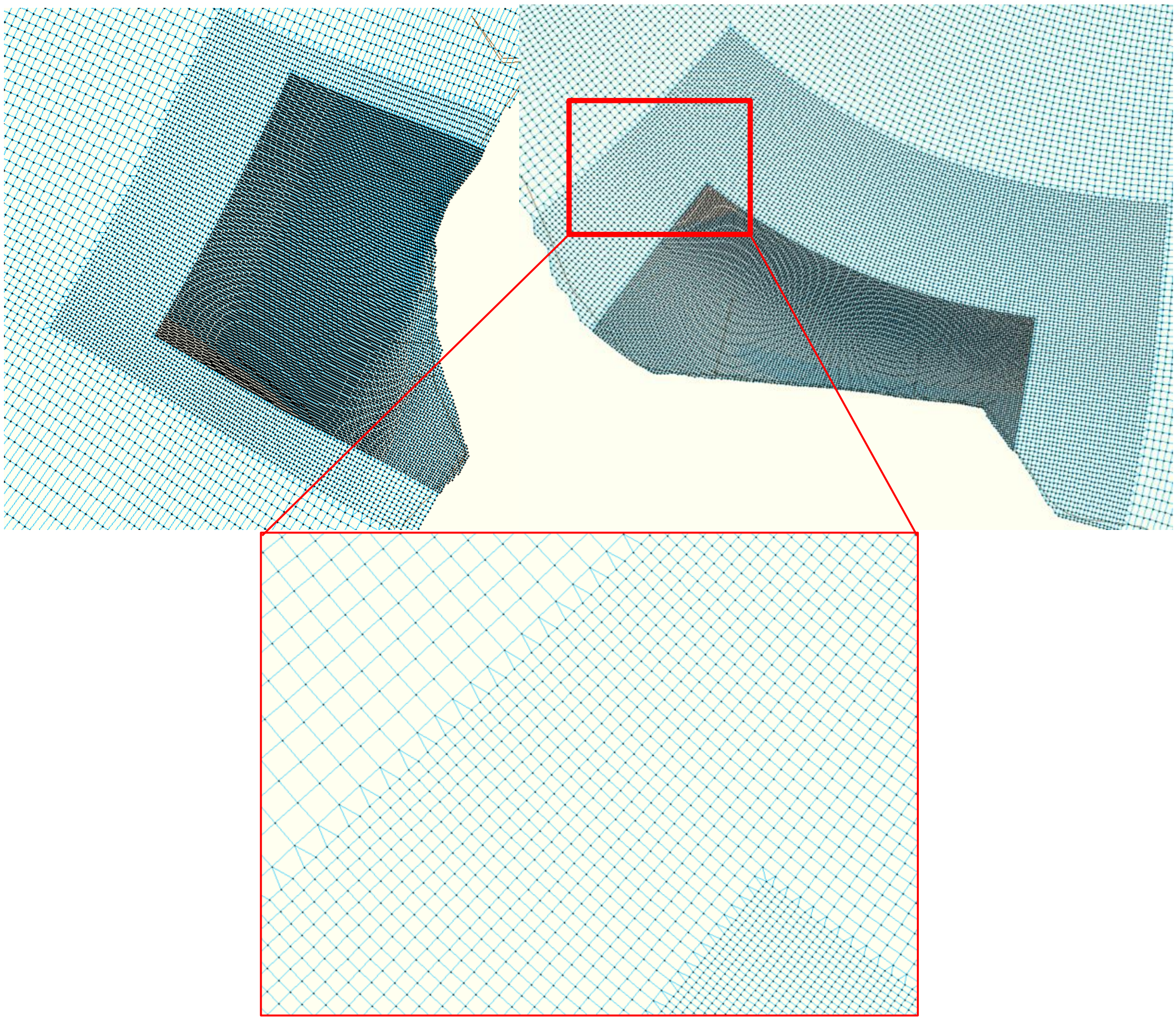


Figure 4.2 - Grid refinement at Knuitershoek (left) and Baalhoek (right). The enlarged figure (bottom) shows how the refinement was implemented.

Besides the curvilinear grid also a triangular grid and a combination of both were tested. The choice for a curvilinear grid was made because the boundary conditions coming out of the NeVla-model can be easily applied and the computation will be more accurate. A curvilinear grid also is more efficient in terms of calculation time (Kernkamp et al., 2011). The flow parallel to the channel is bigger than in the channel cross direction. Since the calculation time step is dependent on the distance and the flow velocity, less cells are needed in the parallel direction than in the cross direction.

Another problem with a triangular grid is that advection terms are not always calculated accurately (H. Kernkamp, personal communication, March 14, 2017). Especially in deeper parts of a domain this can lead to differences. In shallow parts, where the bottom friction is the dominant term in the computations, the problem will be smaller. The main reason for that is that the calculations in the model assume that the grid is perfectly orthogonal, but in practice there are deviations.

To set the domain for the KnuBa-model, the NeVla-model grid was used to make a rough computation with and without groynes. In this way the effect of the groynes upstream (in Belgium) can be seen to make sure no upstream effects are missed by cutting of the domain at a certain position. The groynes in these explorative computations were implemented as thin dams that are infinitely high, which means that they cannot be inundated and will give an overestimation of the effects. The results of these computations showed that the observation points upstream (away from the North Sea) of the groynes were affected negligible. When comparing the simulations with and without groynes the water levels at all stations only differed a few millimetres. When comparing the results of both versions, the R^2-values are 1.000 for all points. It can be concluded that the upstream boundary can be set at the border between Belgium and The Netherlands.

To determine the downstream boundary, two versions of the model were created: one with the boundary just downstream of Knuitershoek and one with the boundary at the mouth of the Western Scheldt at Vlissingen. This is done to be sure that sufficient distance between the boundary and the areas of interest is present. Another influence of the choice between the two is the presence of tidal areas at the cross-section of the boundary. After running the model with the boundary at Vlissingen the choice is made to keep that boundary. This boundary crosses no exposing areas and the flow is perpendicular to the boundary. The results of the water levels are predicted very accurate in comparison with the observed water levels (chapter 4.2.3). The running time of the model, approximately 15 hours for simulation of 1 month, is short enough to work with. The domain is shown in Figure 4.3.

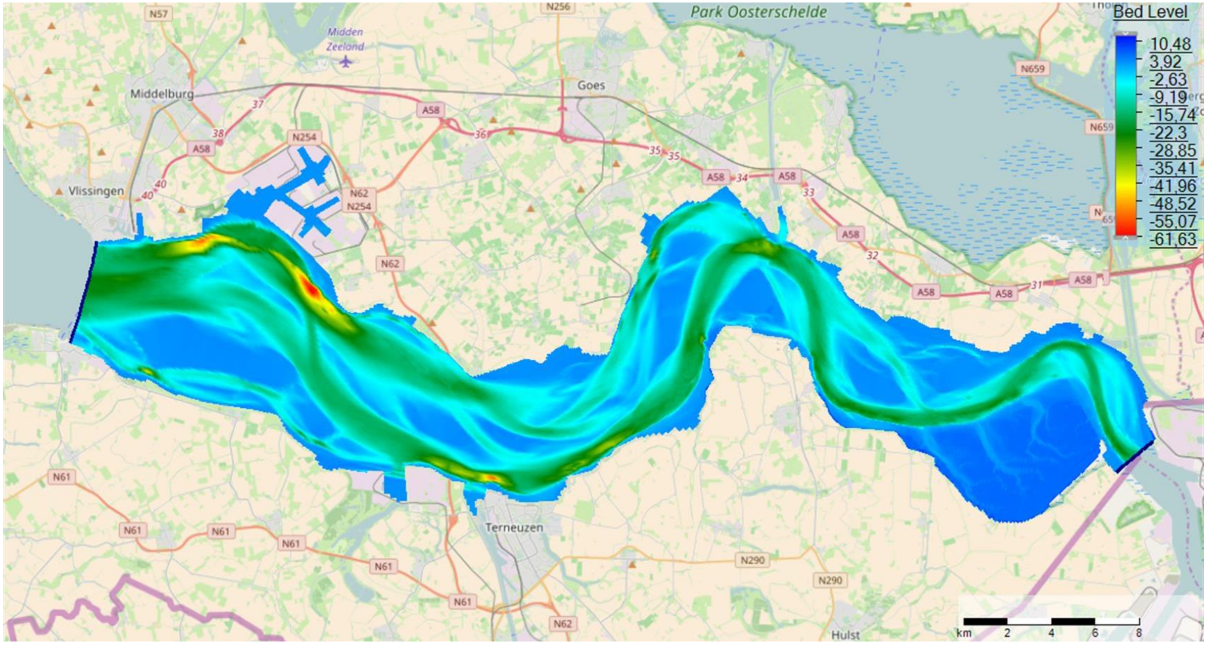


Figure 4.3 - Domain of the KnuBa-model. The dark blue lines represent the boundaries coming from the NeVla-model. The boundary on the left includes water levels and velocities (Riemann) and the boundary on the right includes discharges.

4.1.3. Boundary conditions

To create boundary conditions for the KnuBa-model, the model is nested in the NeVla-model (Delft3d) using the NEST HD software (Van der Kaaij, 2012). Discharge is used as upstream boundary condition at the border. The western boundary is completed by water level and flow velocities, which combine as a Riemann boundary. The Riemann boundary is automatically calculated by Delft3d Flexible Mesh (Deltares, 2017b). By placing observation points and observation cross sections in the NeVla-model, the data can be saved and translated to input at the boundaries.

At the 'Bathse sluis' in the north-eastern part of the Western Scheldt discharges up to 178 m^3/s are measured. This is in the same order of magnitude as the discharge coming from Belgium so the discharges at the Bathse sluis are also included in the KnuBa-model.

4.1.4. Bathymetry

For the bathymetry three data sources were used. For the channels and the areas outside of the study area single-beam bed level measurements from 2016 were interpolated on the grid. The gaps in these data were filled with the Vaklodingen of 2014. For the study areas, the intertidal areas Baalhoek and Knuitershoek, LiDAR data of 2016 was used. LiDAR data is more detailed than Vaklodingen so the intertidal areas can be modelled with more precision. The bed level used for the entire KnuBa-model is shown in Figure 4.3. The bathymetry at Baalhoek is shown in Figure 4.4 and the bathymetry of Knuitershoek in Figure 4.5.

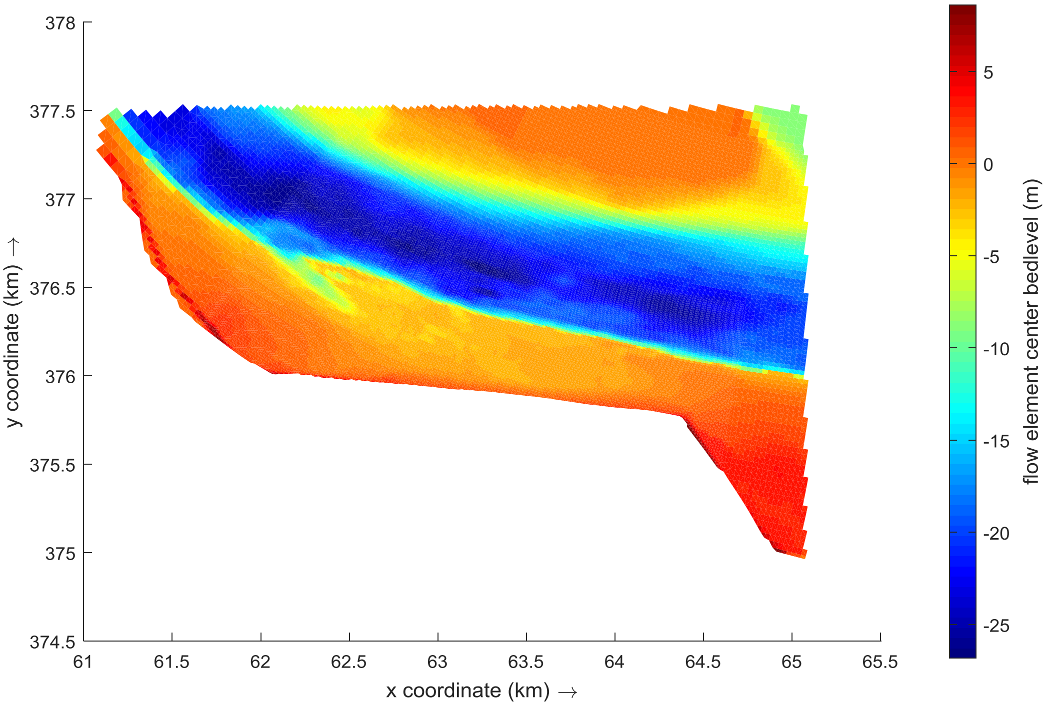


Figure 4.4 - Bathymetry in the KnuBa-model at Baalhoek

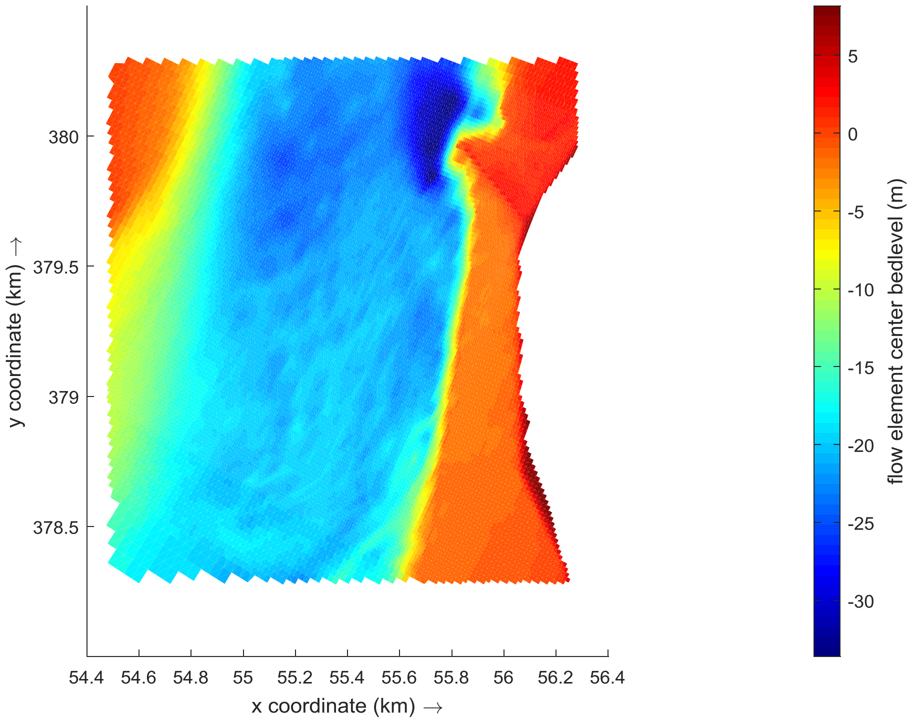


Figure 4.5 - Bathymetry in the KnuBa-model at Knuitershoek.

4.1.5. Additional parameters

The additional model parameters and settings are summarized in Table 4.1. The bed roughness was set at 0.023 s/$m^{1/3}$, which is the default value for flexible mesh. The Western Scheldt model of Tiessen et al. (2016) uses values between 0.022 and 0.028 s/$m^{1/3}$ and this model predicted the water levels and flow velocities and direction accurate. Around Baalhoek and Knuitershoek the value they used was set at 0.023 s/$m^{1/3}$.

Table 4.1- Additional parameter/model settings

Parameter/setting	Value
Reference date	2014-01-01 00:00:00 [yyyy-mm-dd hh:MM:ss]
Bed roughness (Manning's n)	0.023 s/$m^{1/3}$ (Default value)
Horizontal eddy viscosity	1 m^2/s (Default value)
Initial water level	1 m+NAP
Maximum Courant nr.	0.7
Water density	1000 kg/m^3

4.2. Calibration of the KnuBa-model

4.2.1. Introduction

To predict the influences of the implementation of the new groynes the model had to be calibrated. This was done by using the water level measurements of Rijkswaterstaat and the flow measurements done at Baalhoek and Knuitershoek. At first the water levels of the KnuBa-model were compared to the observed values of 2016. This step showed if the nesting of the KnuBa-model inside the NeVla-model was correct. It also showed whether the model is stable in computing water levels in the area around Baalhoek and Knuitershoek.

As second calibration step the flow velocities and direction weerecompared with the observed values. To compare the results the bias and the unbiased Root-Mean-Square-error, as used in (Tiessen, et al., 2016), and the R-squared value (explained variance) were used for Water level and velocity magnitudes. For the directions of flow also the Overall Mean Absolute Error (Tiessen et al., 2016) was used. These methods are explained below.

1. Bias and unbiased Root-Mean-Square-Error:

$$bias = \bar{M} - \bar{D}$$

$$uRMSE = sign(\sigma_M - \sigma_D) * \sqrt{\frac{\sum_{n=1}^{N}[(M_n - \bar{M}) - (D_n - \bar{D})]^2}{N}}$$

Where:

- M = model result
- D = Observation
- N = number of observations
- n = the nth observation
- σ = the standard deviation.

A positive bias means that the mean water level of the model is higher than the water level in the measurements. When the uRMSE is positive the water level variance in the model is bigger than the water level variance in the measurements. The value should be as small as possible; a value of 0 will mean no difference between the model and the measurements. For flow velocities the same approach is used.

2. R^2: Explained variance:

$$R^2 = \frac{SS_{reg}}{SS_{Total}}$$

Where:

- $SS_{reg} = \text{regression sum of squares} = \sum(D_n - \bar{M})^2$
- $SS_{Total} = \text{total sum of squares} = SS_{res} + SS_{reg}$
- $SS_{res} = \sum(M_n - D_n)^2$

The value for R^2 shows the ratio between the modelled variance and the total variance. When the value is 1 the model results are a perfect representation of the measurements. The value should be as close to 1 as possible.

3. Overall Mean Absolute Error:

$$OMAE = \frac{1}{N} * \sum_{n=1}^{N} \sqrt{\left(M_{x,n} - D_{x,n}\right)^2 + \left(M_{y,n} - D_{y,n}\right)^2}$$

Where:

- M = the modelled flow velocities
- D = the measured flow velocities,
- n = the nth time step
- x = flow in x direction

- y = flow in y direction

The OMAE is the average difference between the measured and modelled velocity vectors in x and y directions and should be as small as possible.

4.2.2. Overview calibration steps and results

This paragraph shows the results of the most important calibration steps. The results of the final version are explained in paragraph 4.2.3., 4.2.4. and 4.2.5. The calibration of the KnuBa-model was an iterative process, so for every model version made, first the water levels were checked and then the flow velocities and directions. This means that sometimes the scores for water levels can get a little worse compared to the previous step, but the score for the flow velocities can be higher. After every change, the model had to be run two times in order to simulate for both areas.

In Table 4.2 the model versions with the changes applied are shown. It starts with version V013, which was the first version of the model that used the final boundary conditions from the NeVla-model, the final bathymetry and the final grid. Table 4.3 shows the scores for the calibration of the water levels and Table 4.4 show the scores for the flow velocity magnitudes and directions. The wind roses used during the calibration are shown in Appendix B.

Table 4.2 - Versions of the KnuBa-model after the final boundary conditions from the NeVla-model are obtained. The simulated period for Knuitershoek is (9-3-2016 – 6-4-2016) and for Baalhoek (21-1-2016 – 20-2-2016).

Version	Area/period	Change
V013	Knuitershoek	-
V014	Baalhoek	-
V0150	Baalhoek	Discharge Bath
V0160	Knuitershoek	Discharge Bath
V0151	Baalhoek	WL boundaries +0.05m
V0161[2]	Knuitershoek	WL boundaries +0.05m
V0152	Baalhoek	WL boundaries +0.10m
V0162	Knuitershoek	WL boundaries +0.10m
V0153	**Baalhoek**	**Added wind (HAWI)**
V0164	**Knuitershoek**	**Added wind (HAWI)**
V0165	Knuitershoek	Added wind(TNWS)

Table 4.3 - Water level calibration: Averages of the Bias, uRMSE, RMSE and R^2 -values of the four water level stations (Baalhoek, Walsoorden, Overloop van Hansweert and Hansweert).

Version	Bias [cm]	uRMSE [cm]	R^2 [-]
v013	-10.2	7.9	0.994
v014	-10.2	8.8	0.994
v015	-10.1	8.8	0.994
v016	-10.2	7.9	0.994
v0151	-5.1	8.8	0.996
v0152	-0.1	8.8	0.997
v0162	-0.1	8.0	0.998
v0153	**1.0**	**8.8**	**0.997**
v0164	**-0.1**	**8.1**	**0.998**
v0165	-0.2	8.0	0.998

---

[2] KnuBa-model version V0161 was intentionally planned, but has not run. The difference between v0151 and v0152 made clear that +0.10 m on the water level boundaries predicted the water level more accurate. The results for V0151 and V0152 were used in combination with V0162 to decide which boundaries are used.

Table 4.4 - Velocity and direction calibration: Averages over all measurement points.

Version:	**V013**	**v014**	**v015**	**v016**	**v0151**	**v0152**	**V0162**	**v0153**	**v0164**	**v0165**
Velocity:										
bias [cm/s]	-0.8	-1	0.9	-0.9	-1.1	-0.8	-0.2	**-0.5**	**-0.2**	-0.1
uRMSE [cm/s]	4.8	3.4	-3.4	4.8	3.4	-3.3	4.8	**-3.3**	**5**	5.1
R^2 [-]	0.774	0.858	0.858	0.774	0.860	0.861	0.775	**0.867**	**0.79**	0.785
Direction:										
bias [degr]	-2.7	-1.4	-1.3	-2.7	-1.5	-1.7	-2.8	**-0.2**	**-2.4**	-2.7
OMAE [cm/s]	10.9	9.3	9.3	10.9	9.2	9.2	10.9	**8.8**	**10.6**	10.7

Based on the calibration of the water levels, model versions v0152 and v0162 looked the most promising. But when comparing the scores for the flow velocities and directions version v0153 and v0164 came out better. Since for this thesis the flow velocities and directions are more important than water levels, these were chosen for the final and reference version of the KnuBa-model. That means that the results based on the design and the scenarios will be compared to the results of this final version.

Based on the scores it was decided not to calibrate further by changing the roughness or other parameters. Some extra models were run, but these did not deliver more accurate results. These runs exist of: an extra refinement of the grid at Knuitershoek, higher viscosity and a run with infinite groyne heights. This last model was used to see the impact of the groynes on the water level downstream. The other models did not show significant differences. The results of model version v0153 and v0164 were accurate enough to perform a scenario analysis and to simulate the initial effects of the newly implemented groynes.

4.2.3. Calibrated water levels

The model simulated for two periods: for Baalhoek (21-1-2016 – 20-2-2016) (Figure 4.6) and for Knuitershoek (9-3-2016 – 6-4-2016) (Figure 4.7). For both periods the water levels are predicted with an R^2 value of at least 0.994. The values for the period of Knuitershoek are all higher than 0.997. What can be concluded on the R^2 value is that the variability of the water level is predicted accurate.

The bias of the water levels is between -1.9 cm and 3 cm for all locations on both runs, which is small compared to the tidal range of 4.5 m. At Baalhoek the bias in both periods is negative, which means that the water levels are underpredicted. At 'Overloop van Hansweert' (OvHA) the water levels are predicted between 2.3 cm and 3.0 cm higher than the observed values.

The variability of the water levels predicted by the KnuBa-model is generally higher than the variability of the observed data. This is mainly seen in low water levels that are predicted lower than the observed values. High water levels are predicted more accurate. An example of the observed water levels compared to the predicted water levels is shown in Figure 4.8.

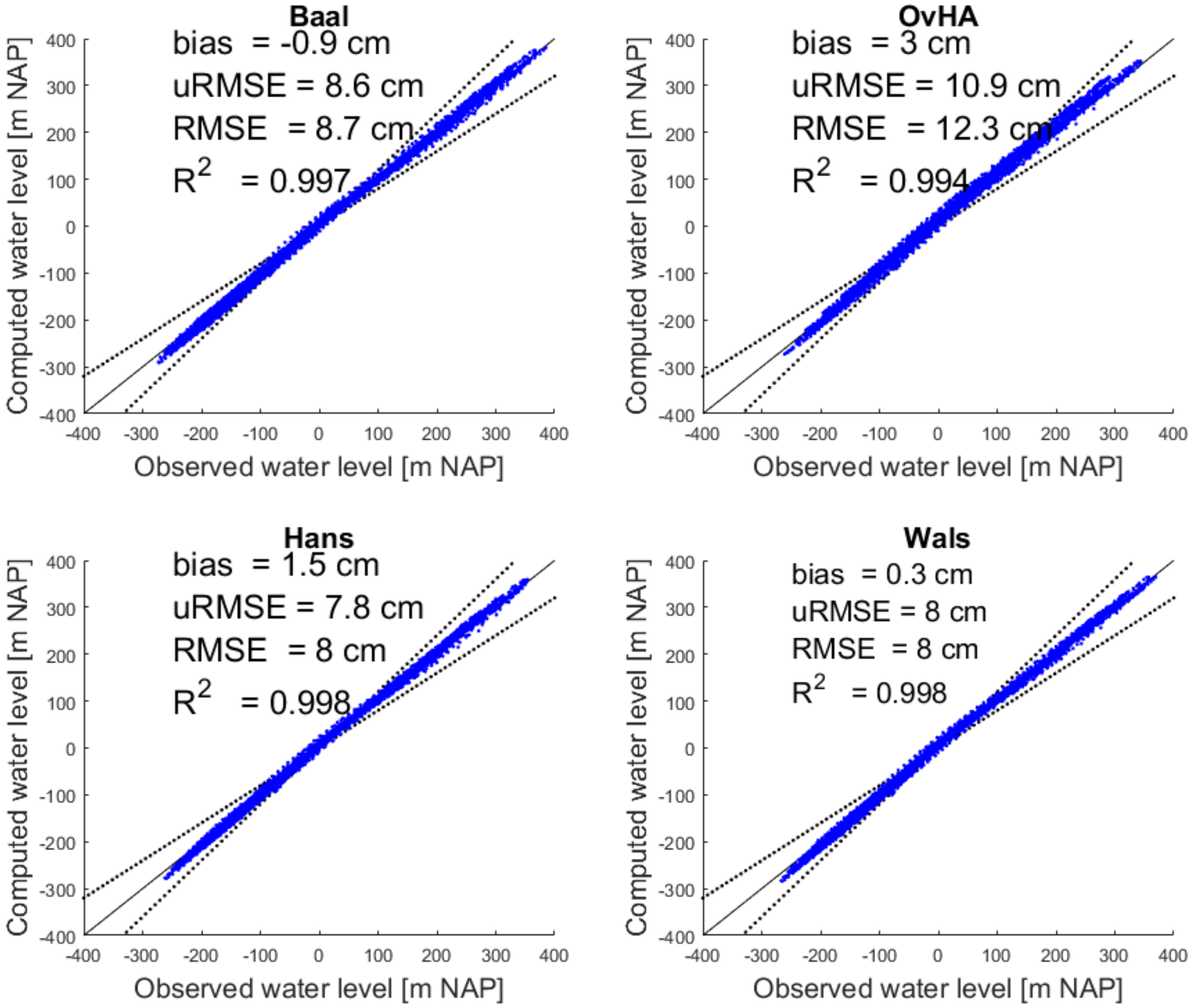


Figure 4.6 – Scatterplot of the observed and the computed water levels. (21-1-2016 - 20-2-2016)

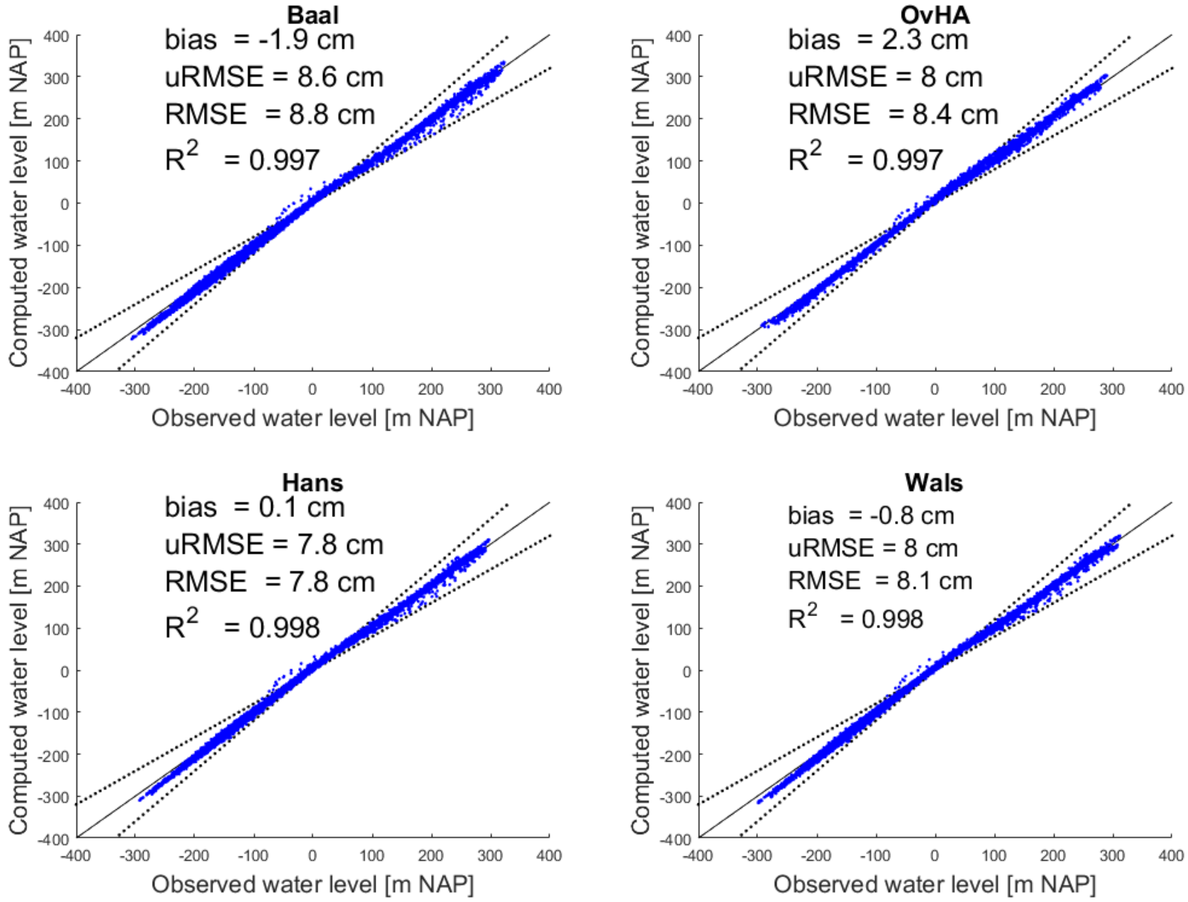


Figure 4.7 - Scatterplot of the observed and the computed water levels. (9-3-2016 - 6-4-2016)

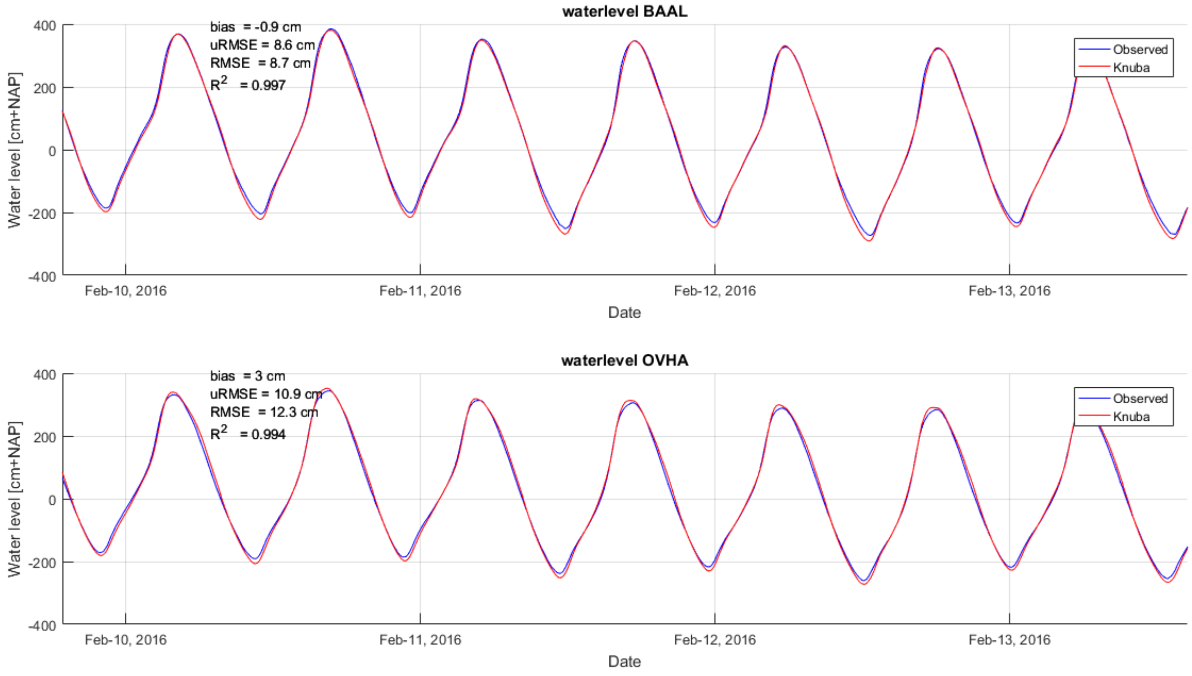


Figure 4.8 - Observed water levels (blue) compared to predicted water levels (red). This example shows the outcomes during spring-tide at Baalhoek and 'Overloop van Hansweert'. The values shown in the left upper corner are for the complete period (21-1-2016 – 20-2-2016). The low water levels are predicted lower than the observed values.

4.2.4. Calibrated flow velocities

The figures in this chapter are zoomed in on a period of 2 full days during spring tide. The overall score and the scatterplots are shown in Appendix C.

Baalhoek

The results for the flow velocities during spring tide at Baalhoek are plotted in Figure 4.9. In this figure two observation points in the channel (BLHK MP1 and BLHK MP5) and two observation points on the flat (BLHK MP3 and BLHK MP 7) are shown. What can be seen is that the peak flows are simulated accurately. In the channel the maximum flows during flood are a little overestimated but in general are a good representation of the maximum flows. During ebb the maximum flow is comparable with the observations.

On the flats the exposing of the area is simulated accurate. This can be seen in the parts where there is no flow velocity at BLHK MP 3 and 7. The velocities simulated on the flats are an accurate representation of the observed values. At some measurement points the predicted maximum flow velocity during flood is too high and the maximum velocities during ebb a too low. This means an overestimation of the asymmetry between ebb and flood flows and sediment transport capacity.

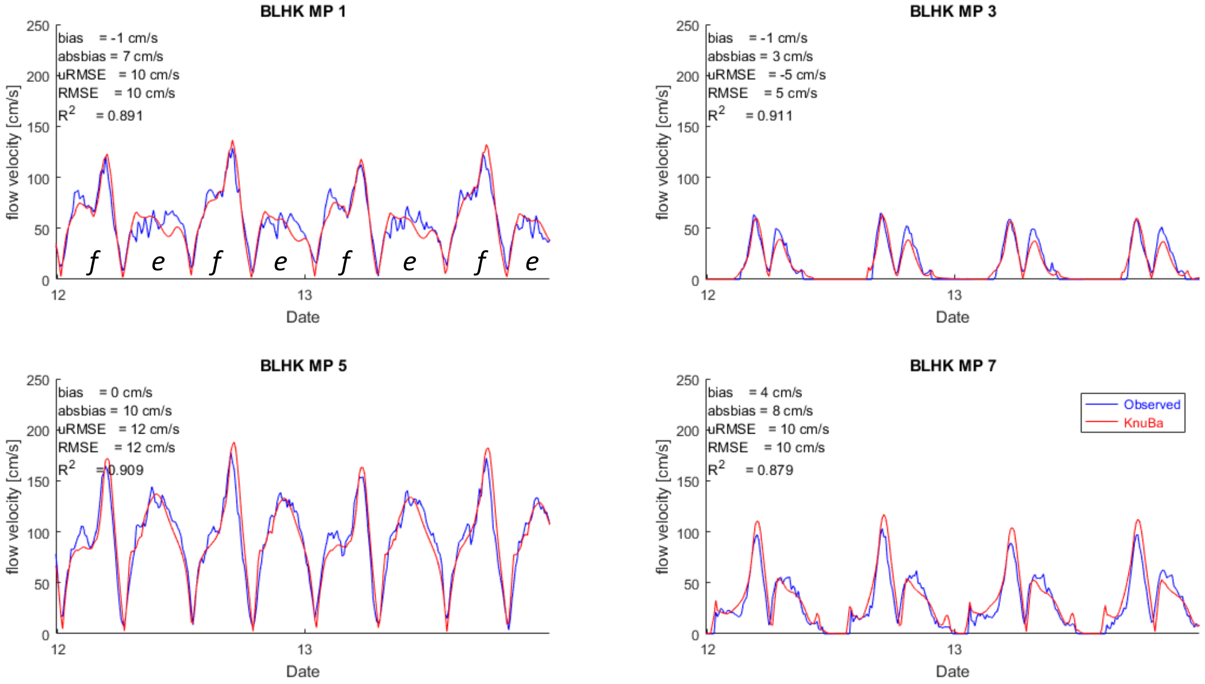


Figure 4.9 - Observed (blue) and modelled (red) flow velocity magnitudes at Baalhoek measurement points 1, 3, 5 and 7. The values shown are for the period 12-2-2016 00:00 – 14-2-2016 00:00, during spring tide when the highest velocities are present. *f* indicates the flood flow and *e* indicates the ebb flow. 1 and 5 are located in the channel. Points 3 and 7 are located on the intertidal area.

Knuitershoek

The flow velocities on the intertidal flat at Knuitershoek (Figure 4.10) are simulated with a comparable accuracy as at Baalhoek. The exposing of the area is seen in the observations as well as in the simulation. Although the measurement points at the flat expose in the simulation a little later than observed. The results of the flow velocities in the channel near Knuitershoek are a little less accurate than the results at Baalhoek. The R^2-values are lower for this area, which is mostly caused by a different behaviour during ebb. During ebb a drop in the modelled velocity is seen in the channel. Also the increase of the velocity during flood starts earlier than the observations. The exact reason for this is not known.

It could possibly be caused by the bathymetry, the grid, or parameter settings. The bathymetry used in the KnuBa-model is a combination of three data sources interpolated on the grid. No further calibration was done on the parameter settings, because the results are assumed to be accurate enough for comparing the effects of the designed groynes with the reference situation. This difference might be explained by the presence of groyne K6 in the north of Knuitershoek. At Baalhoek no groyne comparable to K6 is present. The exact reason is not known, but it is not considered a problem during this study.

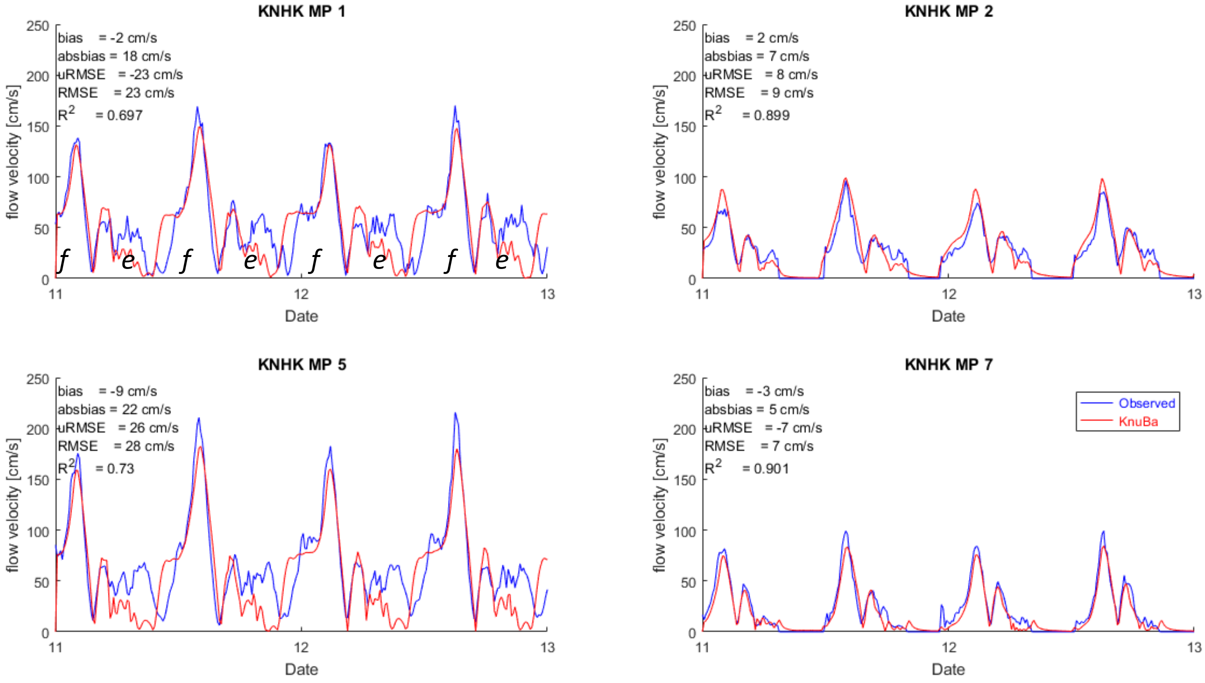


Figure 4.10 - Observed (blue) and modelled (red) flow velocities at Knuitershoek measurement points 1, 2, 5 and 7. The values shown are for the period 11-3-2016 00:00 – 13-3-2016 00:00, during springtide when the highest velocities are present. *f* indicates the flood flow and *e* indicates the ebb flow. 1 and 5 are located in the channel. Points 2 and 7 are located on the intertidal area.

4.2.5. Calibrated flow directions

The flow directions of the KnuBa-model represent the observed flow directions accurate for both locations and periods (Baalhoek: Figure 4.11 and Knuitershoek: Figure 4.12). In the channel a very clear separation between ebb and flood can be seen. This is also seen on the flats, although the figures show that during exposing of the area a constant flow direction is present at Baalhoek. At Knuitershoek the direction of these small flows are varying. For both areas this has to do with very small flow velocities which are not measured in the field, because the water depth is too small for the equipment, but are simulated by the model.

At KNHK MP 7 at Knuitershoek the direction looks inaccurate, but this has to do with the small difference in the direction around 360 degrees. A small difference in direction can cause big difference in the plot since 360 degrees is the same as 0 degrees. That is why during calibration the Overall Mean Absolute Error was used, which uses the U and V components of the flow.

What can be concluded is that the KnuBa-model can predict the flow direction accurate and that it is able to predict the directions of both flood and ebb flows. The flow directions on the intertidal flats for both locations are predicted with comparable scores. The flow directions in the channel at Baalhoek are more accurate than at Knuitershoek. The simulated flow directions in the channel at Knuitershoek change in direction earlier than the observed values. This was also seen in the velocity magnitudes (Figure 4.10).

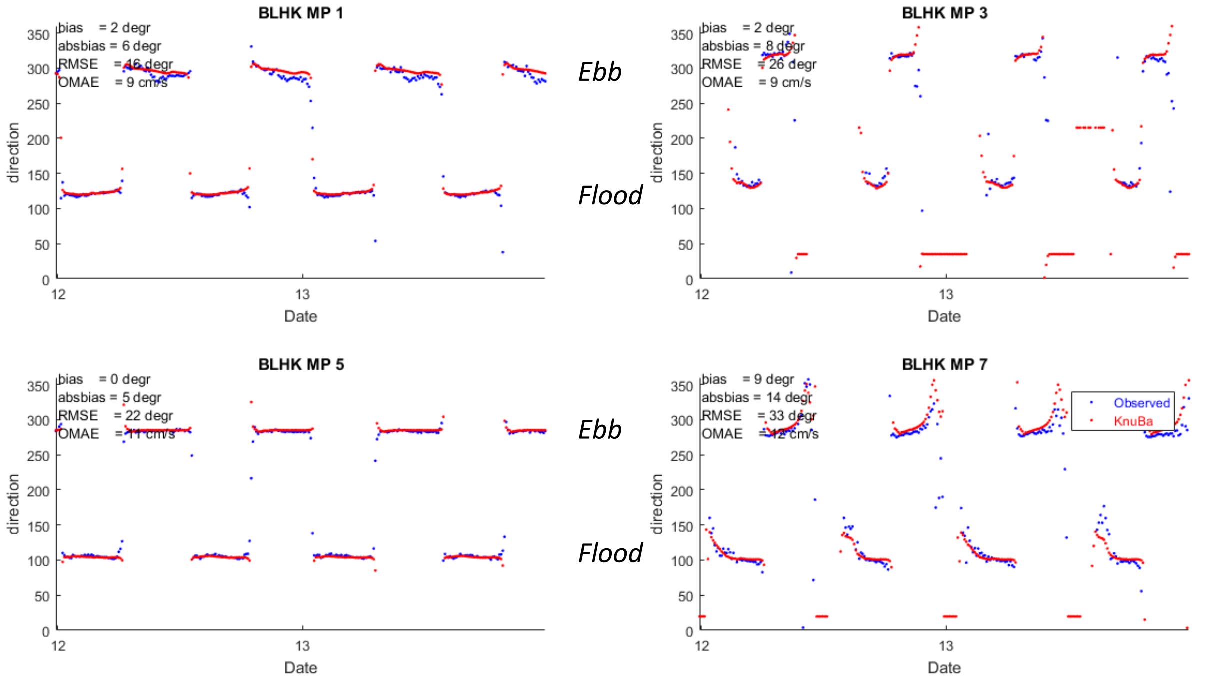


Figure 4.11 - Observed (blue) and modelled (red) flow directions at Baalhoek. The values shown are for the period 12-2-2016 00:00 – 14-2-2016 00:00, during spring tide. 1 and 5 are located in the channel. Points 3 and 7 are located on the intertidal area.

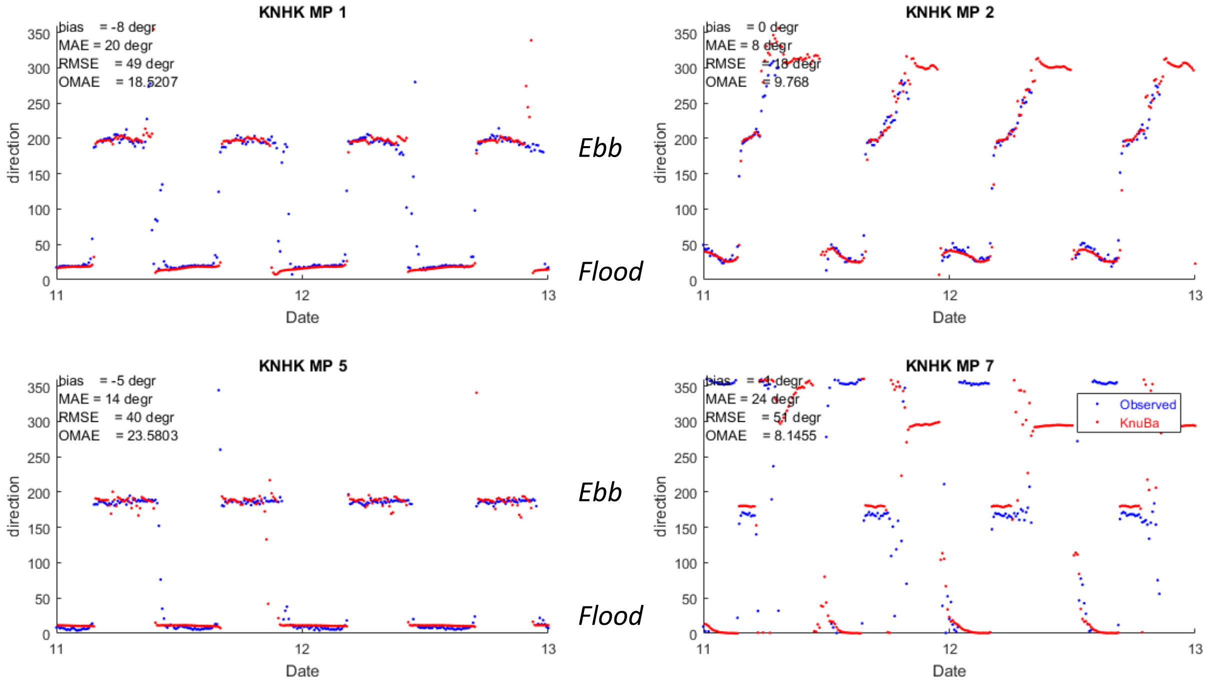


Figure 4.12 - Observed (blue) and modelled (red) flow directions at Knuitershoek. The values shown are for the period 11-3-2016 00:00 – 13-3-2016 00:00, during springtide. 1 and 5 are located in the channel. Points 2 and 7 are located on the intertidal area.

4.3. Conclusion

The KnuBa-model proved to simulate the hydrodynamics at Knuitershoek and Baalhoek accurately. Although the results in the channel for Baalhoek are more accurate compared to the results in the channel at Knuitershoek, both the areas are predicted good enough to study the effects of the designed groynes and to perform a scenario study. The asymmetry overestimation should be kept in mind during the analysis of sediment transport.

5. Effects of the groynes at Baalhoek and Knuitershoek

5.1. Introduction

In this chapter the KnuBa-model will be used to study the hydrodynamic effects and the initial sediment transport and morphologic effects of the designed groynes at Knuitershoek and Baalhoek. The month April is taken as simulation period, because during this month the water levels were close to the average values of 2016 and is in the range of the available boundary conditions (Jan 2016 – Jul 2016). This month covers two full spring neap tidal cycles, so both maximum and minimum tides are used to compute the effects. For analysis the period April 8th, 2016 00:00 until April 11th, 2016 00:00 is used, because this is during spring tide and the maximum velocities occur.

The design is implemented in the model by adjusting the bathymetry file of the KnuBa-model. At the locations of the new groynes the heights as designed by 'Waterschap Scheldestromen' (see section 2.4) were used as input on the coordinates that represent the groynes. These groynes are not erodible in the model. In this chapter the most relevant figures are shown, additional figures are shown in Appendix D.

5.2. Impact on Hydrodynamics

The impact of the groynes on the hydrodynamics is analysed below. First the change in magnitudes are discussed, followed by the flow patterns and concluded by the amount of low-dynamic area that is created based on a critical velocity of 0.6 m/s and 0.8 m/s.

5.2.1. Change in magnitude

By subtracting the flow velocities of the reference version form the design version, the change in magnitude per time step was calculated. The figures in this paragraph show the moment where the flow velocities during high ebb and flood on the flats are highest and where the difference is best visible.

Knuitershoek:

Figure 5.1 shows the relative velocity differences during ebb and flood. It can be seen that the 'high water resting areas' (black circles) cause a decrease in flow velocity downstream to the flow direction in the channel. The flow on the flat in the reference model is generally higher during flood. In the design model the flow behind the high water resting areas during flood is decreased by more than 0.9 m/s. What can be concluded is that the implementation of high water resting areas can have a positive effect in creating low-dynamic area. They block the downstream flow completely in both directions.

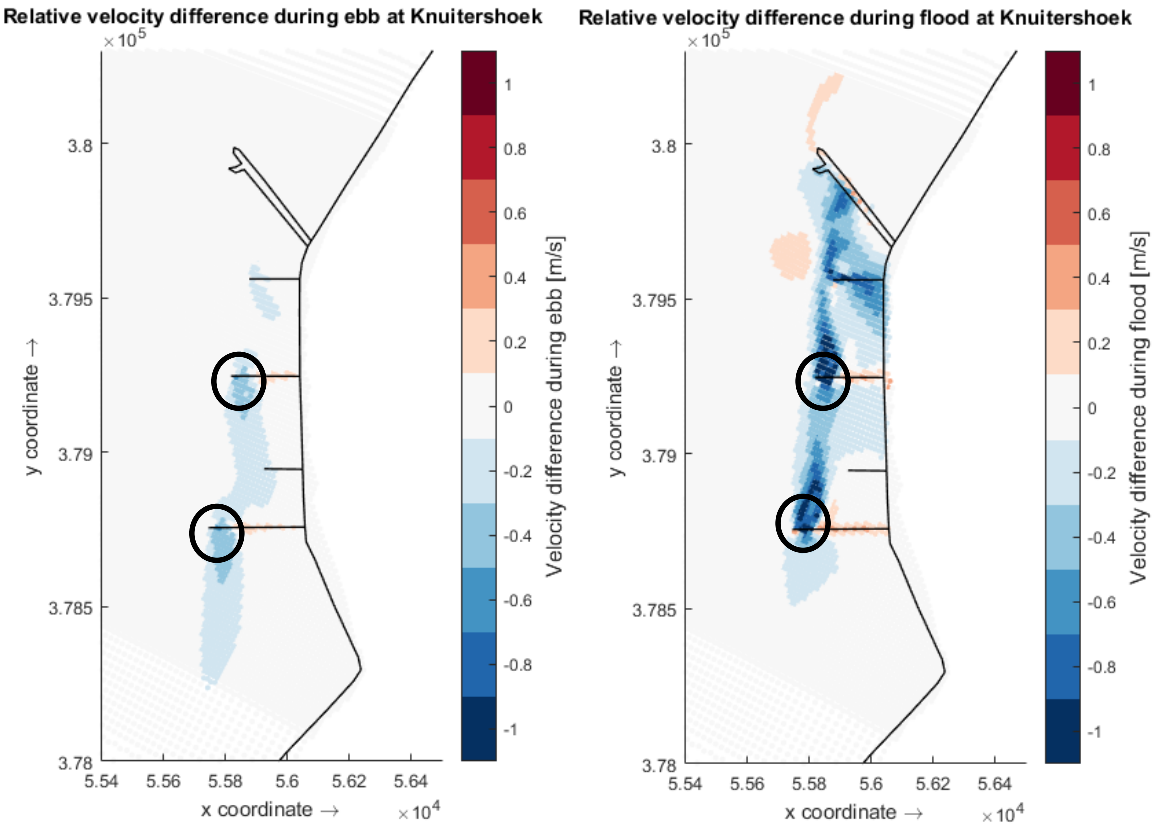


Figure 5.1 - Left: Velocity difference during maximum ebb flows over the intertidal flat at Knuitershoek. Right: The velocity difference during maximum flood flows over the intertidal flat at Knuitershoek. Red indicates a velocity increase due to the groynes, blue a decrease. The circles indicate the location of the high water resting areas.

The flow velocity over the southern two groynes (between the dike and the high water resting area) increases during ebb and during flood. This is caused by a lower water column where the water is forced to flow over groynes. It is possible that this effect is enlarged by blocking that occurs due to the high water resting areas.

The groyne in the north increases the flow velocity in the channel. Because it is impermeable it narrows the cross-section of the channel and it directs the current from the flat to the channel. This increase in velocity is only seen during flood. A possible explanation is that the flow velocities during ebb are lower and the contraction of flows near the tip of the groyne is smaller.

Baalhoek:
At Baalhoek similarities with Knuitershoek can be seen concerning the effect of the groynes on the velocity magnitudes. The velocities between the groynes decrease compared to the reference model (Figure 5.2).

The flow velocity increases over the groynes and in the channel an increase in velocity is seen during flood flows. The increase of flow velocity in the channel is mainly upstream of the western groyne during flood. This might be caused by the height which is 0.6 m+NAP compared to 0.3 m+NAP for groyne B2. Another explanation is that the flow velocity is already lowered by groyne B3 before reaching groyne B2 (during flood). This could mean that the influence of groyne B2 is smaller and that the flow from the flat to the channel is not big enough to cause an increase in the channel.

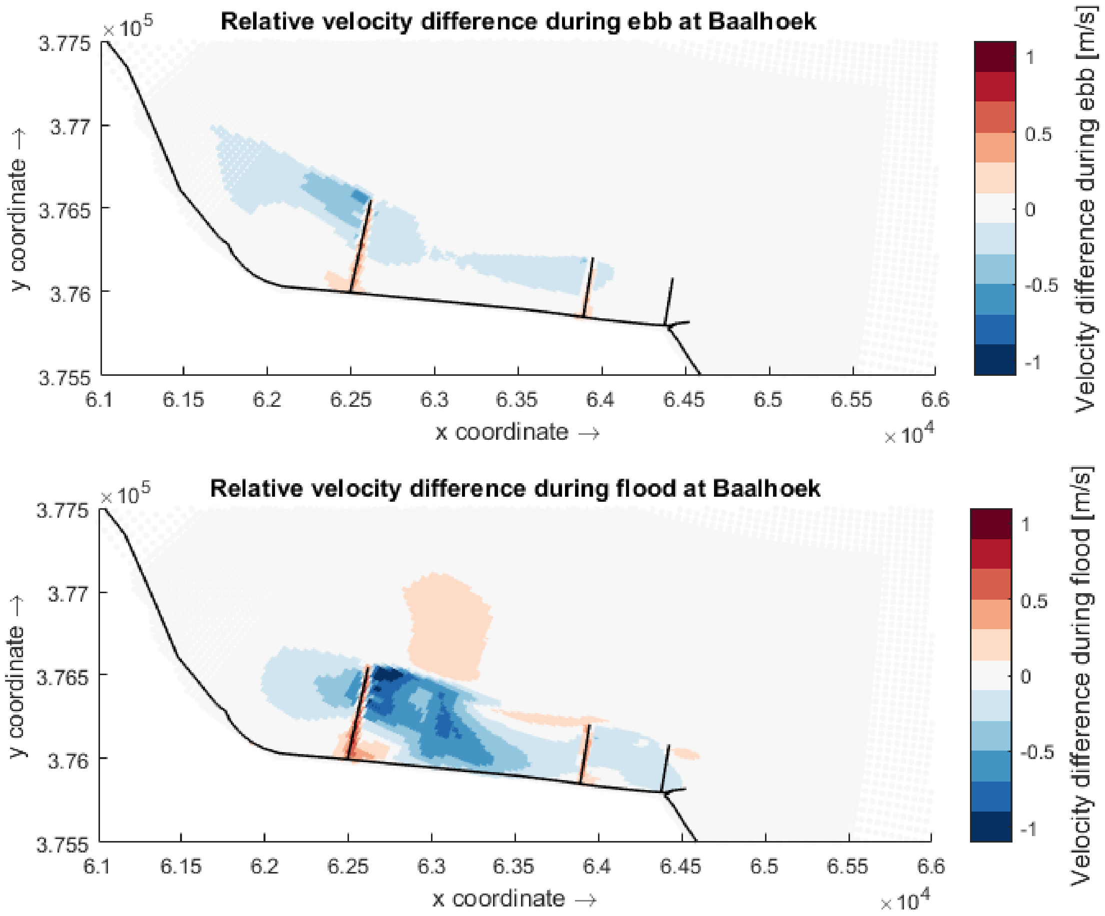


Figure 5.2 – Upper figure: The relative velocity differences during maximum ebb flows over the intertidal flat at Baalhoek. Lower figure: The relative velocity differences during maximum flood flows over the intertidal flat at Baalhoek.

The part with increased velocity in the channel develops over time. The area starts at the tip of the groyne (B3) and slowly moves towards the east with the flood flow. This phenomenon should be kept in mind for the shipping route and for erosion at the 'Plaat van Walsoorden', but is not further discussed during this thesis.

The differences in absolute maximum velocities between the reference and the design (Figure 5.3 and Figure 5.4) show similar patterns as for moments in time as shown before (Figure 5.1 and Figure 5.2). The difference in absolute maximum velocities in the channel seems to be smaller compared to the results on the time steps shown before. This is also seen in the comparison between the transects as measured (Appendix D). When comparing separate time steps changes can be seen, but the changes in maximum velocities are smaller.

At Knuitershoek the new groyne in the north (K7) causes the most increase of velocities in the channel, but no increase of velocities over the groyne. This might be due to the height of the groyne, which makes it impermeable. The same is seen for the high water resting areas; these have the same height as K7 and are not flooded. The remaining parts and the groynes at Baalhoek are lower and have no high water resting areas, which make them completely flooded during high tide. The velocities over these parts and groynes increase.

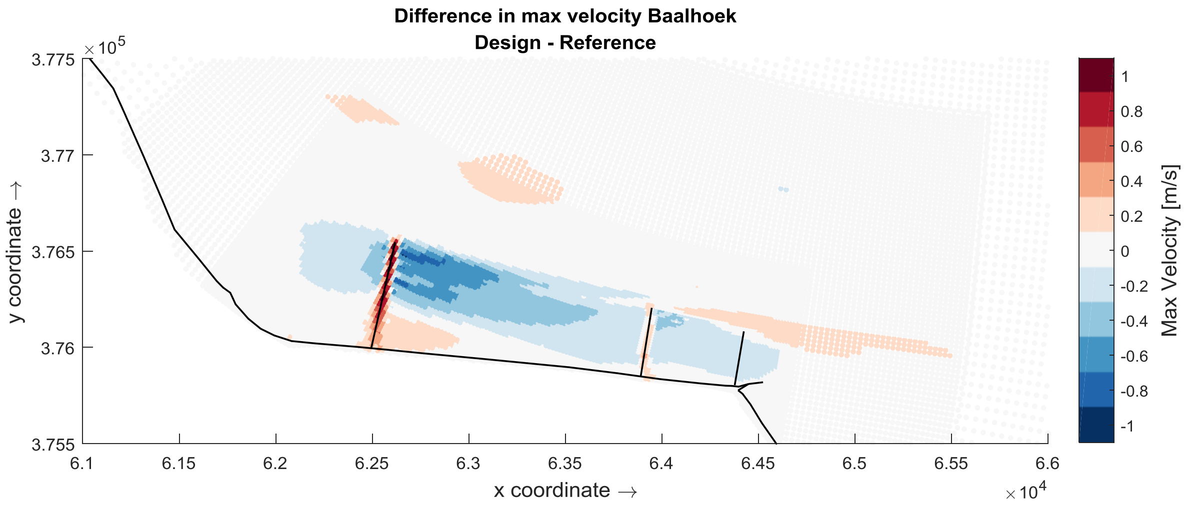


Figure 5.3- Difference in maximum velocity at Baalhoek between the reference and the design

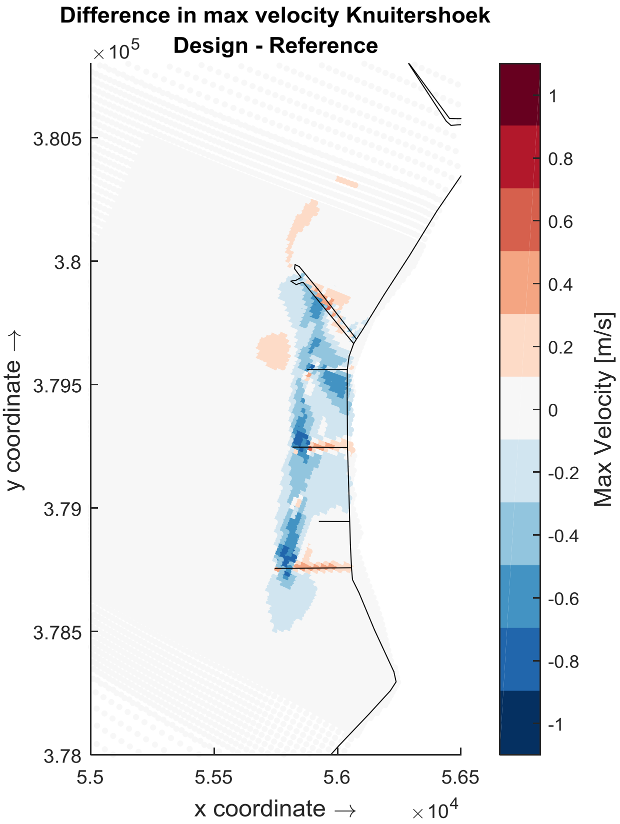


Figure 5.4 - Difference in maximum velocities at Knuitershoek between the reference and the design

At both locations the velocities over the groynes increase. This was also seen at ‘Schaar van Waarde’ and resulted in erosion next to the dams (Dam & Bliek, 2013). The increase of velocities in the channel was also seen at ‘Schaar van Waarde’. This caused the channel to migrate and caused scour holes against the tip of the groynes near the channel. At Knuitershoek and Baalhoek this phenomenon should be monitored since it is expected that it will develop in the same way. Groynes K7 and B3 have priority, because the increase in velocities are largest there.

5.2.2. Flow patterns

The effect of the designed groynes is largest during flood flows (see previous section 5.2.1). The velocities on the intertidal flats are the highest during flood. The changes in flow patterns during flood are described below.

Knuitershoek

At Knuitershoek the most important changes due to the new groynes are circulation in the north and the contraction of flow due to the high water resting area. The new groyne in the north (K7) stays exposed during high water. This creates an obstruction in the flow over the intertidal flat. Where the flow is parallel to the channel in the reference scenario (Figure 5.5, left figure), the flow is forced around the groyne in the design scenario (Figure 5.5, right figure). This creates a circulation cell between groynes K7 and K6 and a flow towards the channel south of K7 (red arrows). This happens during every tide, although the velocities are highest during spring tide.

In the same pictures the effects of the high water resting areas can be seen. Because the height is 3 m+NAP they stay exposed during high tide. The flow is forced around it which creates an area with low flow velocities behind it. The flow in front of the high water resting areas is contracted around the high water resting areas, which increases the flow velocities over the rest of the groyne (between the high water resting area and the dike).

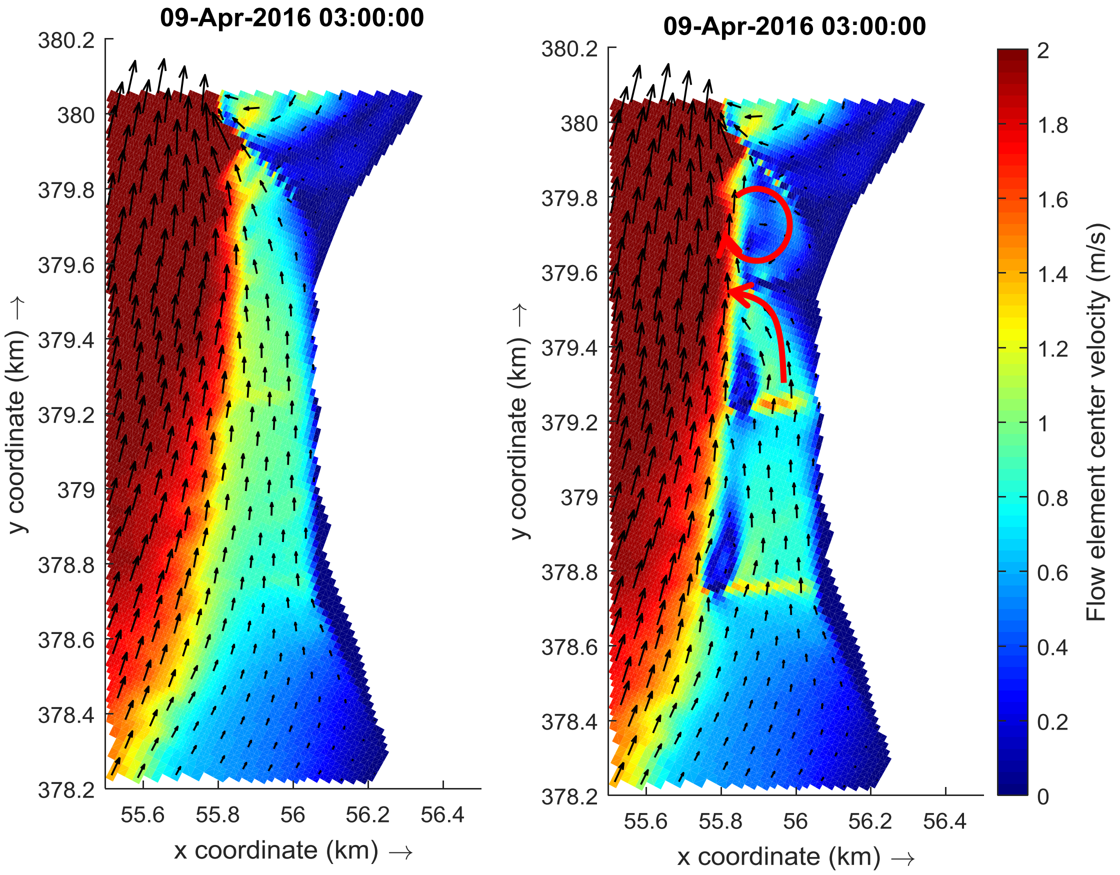


Figure 5.5 - Flow velocities and direction during maximum flood flows at Knuitershoek, left: the reference situation without the designed groynes, right: after the implementation of the groynes. The red arrow indicates circulation between groyne K6 and K7.

Baalhoek

At Baalhoek during flood two periods can be distinguished: the period when circulations are visible and the period when the flow is parallel to the channel. In the situation without the groynes the flow is parallel to the channel (Figure 5.6 and Figure 5.7). The implemented groynes are fully submersible which can also be seen in the results (Figure 5.9), since the water flows over the groynes. At first the groyne works as a barrier and creates a circulation (Figure 5.8, red arrow). But when the water level rises further, the flow starts going over the groynes and becomes parallel to the channel flow (Figure 5.9). This behaviour can be coupled with the water level variation in an estuary due to the tidal differences.

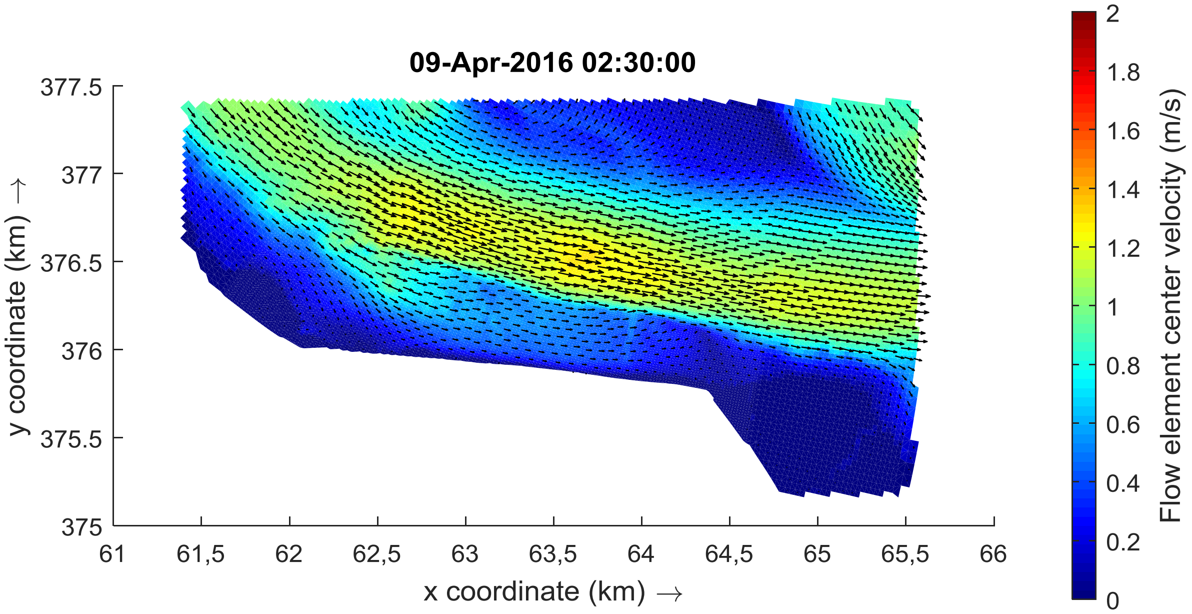


Figure 5.6 - Parallel flow during flood before implementation of the groynes at Baalhoek

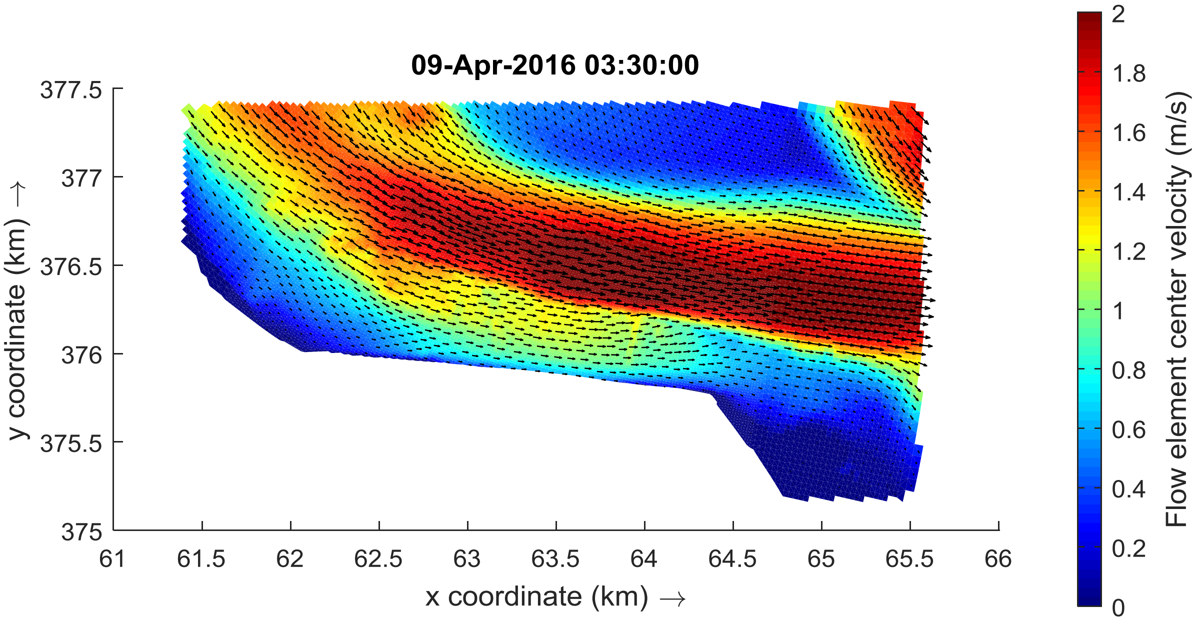


Figure 5.7 - Parallel flow during flood before the implementation of the groynes at Baalhoek

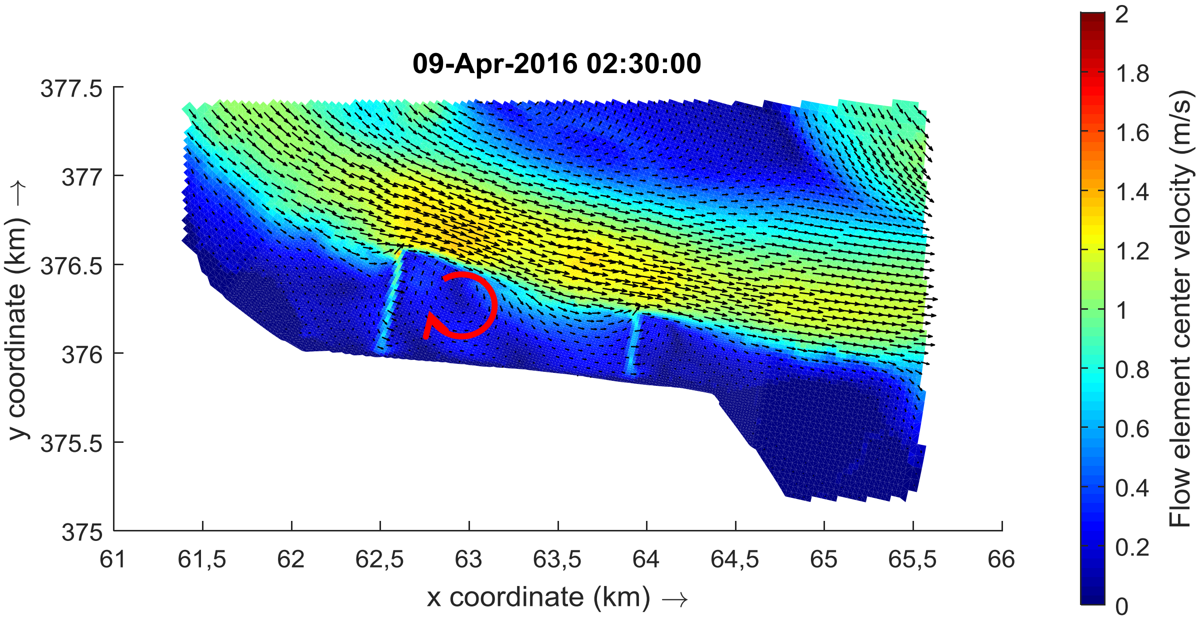


Figure 5.8 - Circulation during flood after implementation of the groynes at Baalhoek

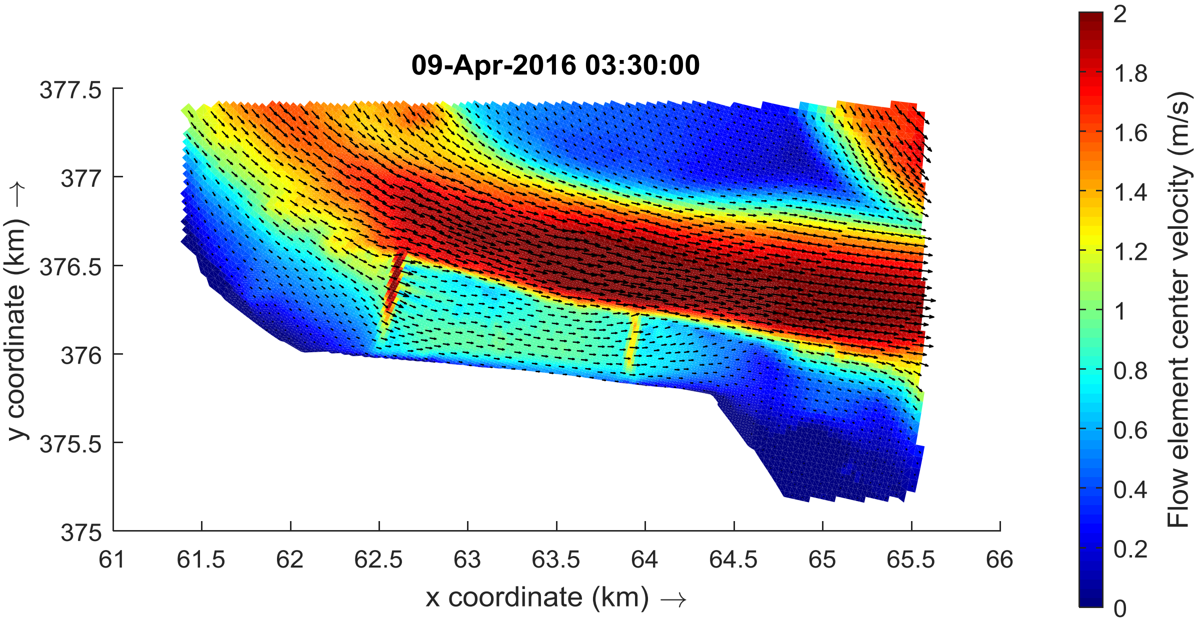


Figure 5.9 - Parallel flow during flood in after the implementation of the groynes at Baalhoek

The flow over the groynes reaches velocities over 2.0 m/s and on the flat 1.1 m/s. The velocities on the flats are higher between the groynes than outside the groynes. This area has decreased in flow velocity but still the velocities are too high to create low-dynamic area. To see if these velocities can be reduced further, the height of the groynes is changed during the scenario study.

5.2.3. Low-dynamic area

The maximum flow velocity is determining the dynamic state of the area. For determining the amount of low-dynamic surface area two critical velocities are used: 0.6 m/s (Dam et al., 2008) and 0.8 m/s (Maris et al., 2014). When the maximum velocity in a cell is below the critical velocity, the surface area of that cell is added to the amount of low-dynamic surface area. The areas used for calculating the low-dynamic surface area is shown in Appendix E. The total surface area of the flat at Baalhoek is 240 ha and at Knuitershoek 65 ha. The results in this paragraph are based on the situation during spring tide.

Knuitershoek

For Knuitershoek the design resulted in 7.2 ha extra low-dynamic area based on the critical velocity of 0.6 m/s (Table 5.1). When looking at 0.8 m/s the low-dynamic surface area increases with 11.2 ha. This means that, based on both the critical values the low-dynamic surface area increases according to the KnuBa-model. The contours of the low-dynamic areas based on the critical velocities based on the situation before and after the implementation of the designed groynes are plotted in Figure 5.10.

Table 5.1 - Low-dynamic area at Knuitershoek for the reference model and the design for a critical velocity of 0.6 m/s and 0.8 m/s.

Knuitershoek – Low-dynamic surface area

Critical velocity:	**0.6 m/s**	**0.8 m/s**
Reference	28 ha	38 ha
Design	35 ha	49 ha
Increase	+ 7 ha	+ 11 ha

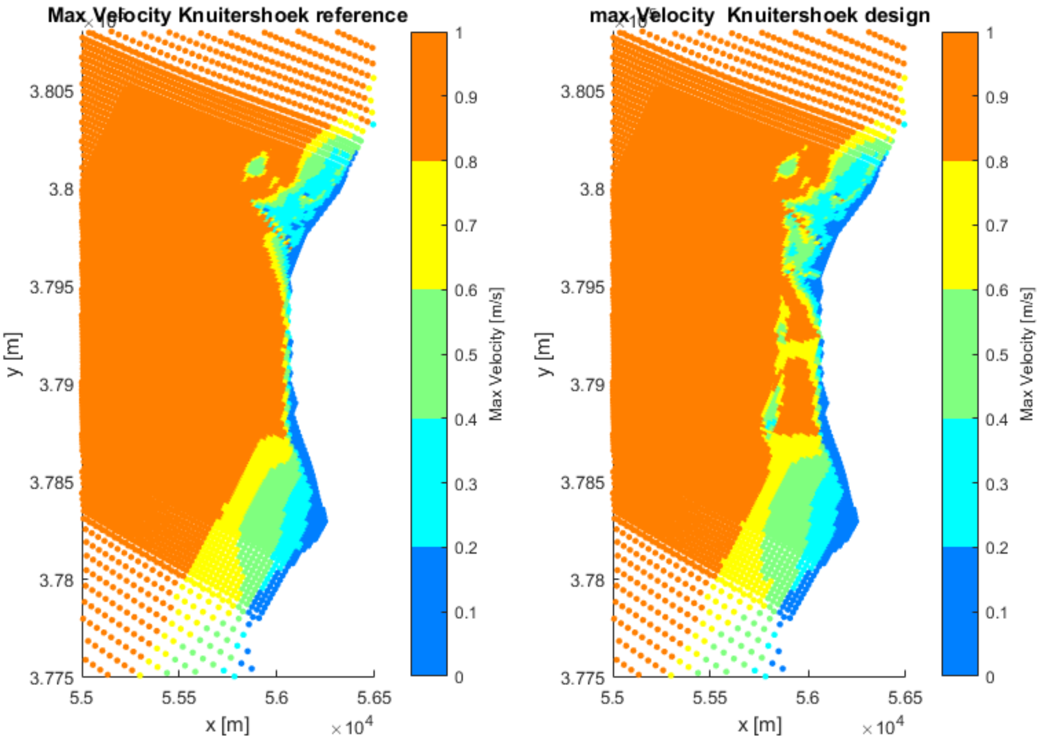


Figure 5.10 - Absolute maximum velocities at Knuitershoek. The left map shows the reference situation. The right map shows the situation after the new groynes are implemented. The orange area indicates where the flow is high-dynamic. Yellow is for critical velocity 0.8 m/s. The other colours indicate low-dynamic area for the critical velocity 0.6 m/s.

The new groyne in the north (K7) has the most effect on the creation of low-dynamic area (Figure 5.11). Because of the height of the groyne, it is not flooded during high water and blocks the flow completely. This causes circulations, contraction of flows on the flats and an increase of flow velocities in the channel, but lowers the velocities between K7 and K6. The high water resting areas have the ability to change high dynamic area into low dynamic area for even a critical velocity of 0.6 m/s.

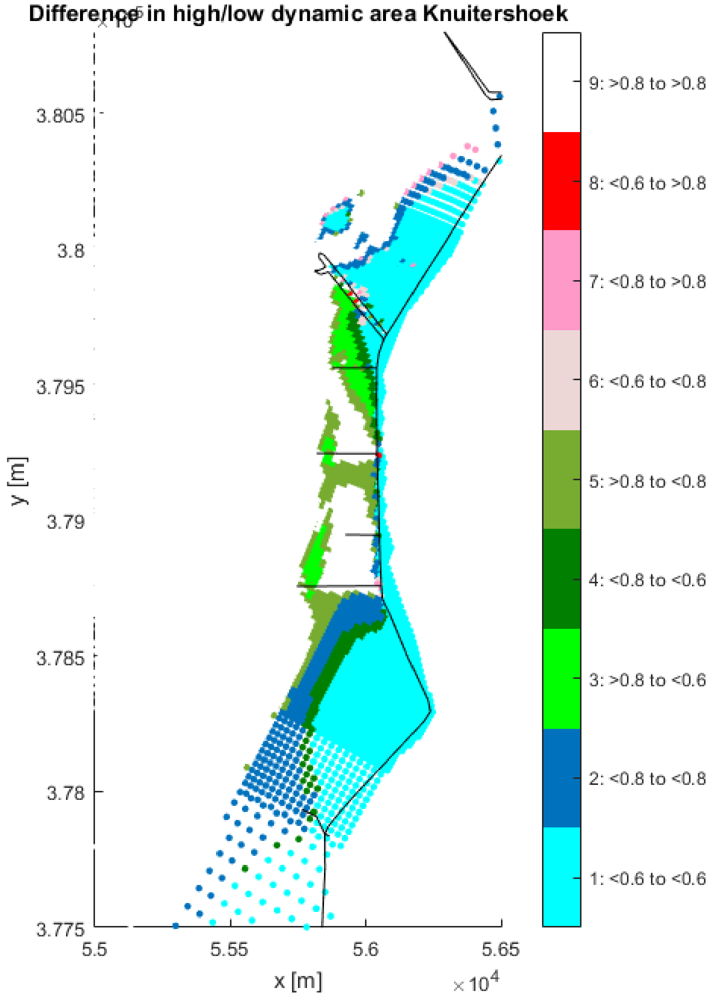


Figure 5.11 - Change in low/high-dynamic area after implementation of the groynes. The critical velocities (0.6 and 0.8) are in m/s. The blue colours indicate low-dynamic areas that did not change. The green colours indicate an improvement in low-dynamic area or a change from <0.8 to 0.6. The red colours indicate a decrease in low-dynamic area or a change from <0.6 to <0.8.

The 'High water resting areas' have significant abilities to lower the flow velocities. In flood direction low-dynamic areas are created behind the higher parts. During the scenario runs the length of the high water resting areas is changed to see the influence on the amount of low-dynamic surface area.

Baalhoek

For Baalhoek the design resulted in 8.3 ha extra low-dynamic area based on the critical velocity of 0.6 m/s (Table 5.2). The increase is higher when looking at the critical velocity of 0.8 m/s, which gives an increase of 12.3 ha of low-dynamic surface area. The contours of the areas with their maximum velocities are plotted in Figure 5.12. The changes in the dynamics of the area are plotted in Figure 5.13.

Table 5.2 - Low-dynamic area at Baalhoek for the reference model and the design for a critical velocity of 0.6 and 0.8 m/s.

Baalhoek – Low-dynamic surface area		
Critical velocity:	**0.6 m/s**	**0.8 m/s**
Reference	111 ha	148 ha
Design	119 ha	160 ha
Increase	+ 8 ha	+ 12 ha

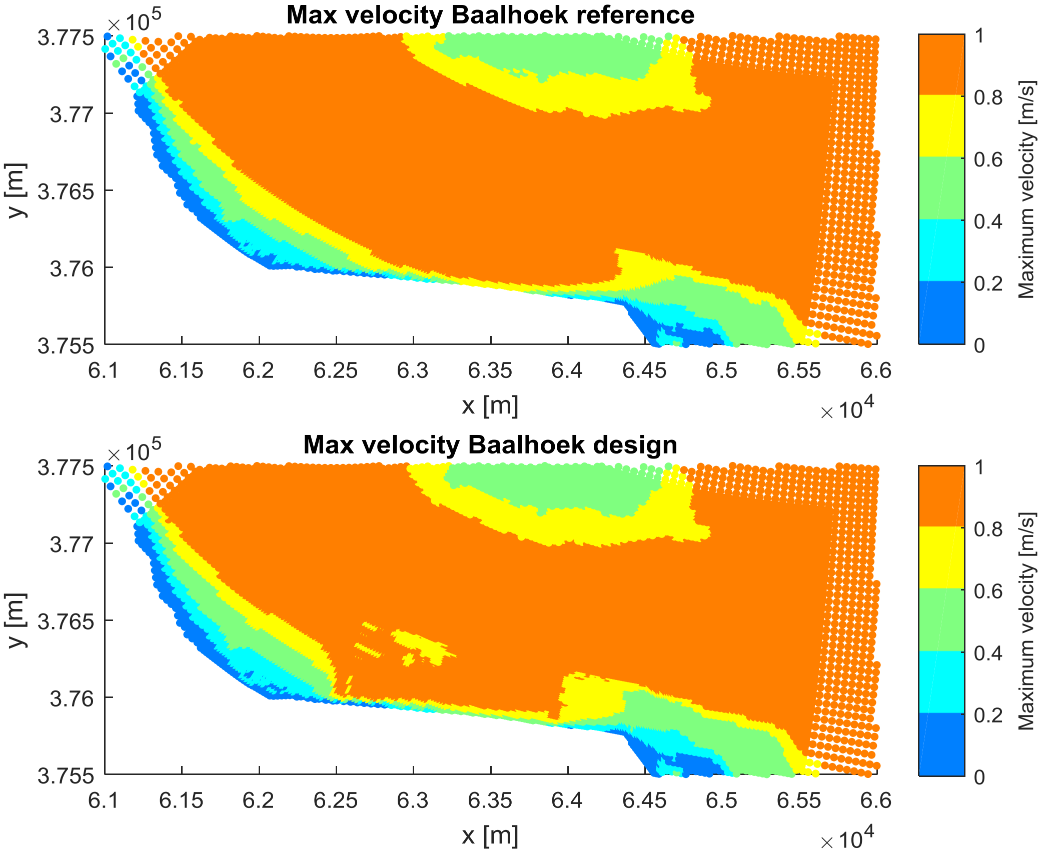


Figure 5.12 -Absolute maximum velocities at Baalhoek. The upper map shows the reference situation. The lower map shows the situation after the new groynes are implemented. The orange area indicates where the flow is high-dynamic. Yellow is for critical velocity 0.8 m/s. The other colours indicate low-dynamic area for the critical velocity 0.6 m/s.

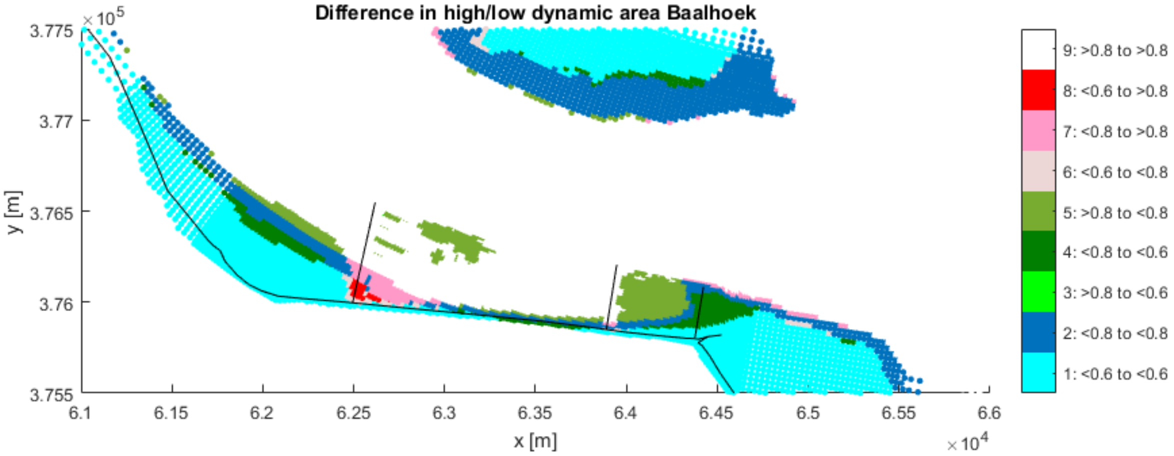


Figure 5.13 - Change in low/high-dynamic area after implementation of the groynes. The critical velocities (0.6 and 0.8) are in m/s. The blue colours indicate low-dynamic areas that did not change. The green colours indicate an improvement in low-dynamic area or a change from <0.8 to 0.6. The red colours indicate a decrease in low-dynamic area or a decrease from <0.6 to <0.8.

At Baalhoek the effect of the groynes is mainly seen outside the new groynes (Figure 5.12). Between the groynes the maximum flow velocities are still above the critical velocity of 0.6 m/s. This is the area where the most low-dynamic area is expected, but the velocities are in general even higher than 0.8 m/s. Close to the dike, near groyne B3, low-dynamic area has disappeared after implementation of the new groynes (Figure 5.13, red colours). This is due to the increased velocities in the flow over the groyne. What can be concluded is that the groynes at Baalhoek probably should be higher in order to block more flow. That is why the height of the groynes is looked into during the scenario runs. The distance between the groynes at Baalhoek (1400 m) is larger than at Knuitershoek (400m). This could possibly have influence on the creation of low-dynamic area and therefor the number of groynes is changed during the scenario analysis.

5.3. Initial sediment transport and morphological changes

Additional model runs were made to see initial sediment transport pattern changes and to get an idea of the development of the flats after the implementation of the designed groynes. To see the direct effects of the groynes and to eliminate the effects of errors in the model, the modelling results of the reference run were subtracted from the results of the design run. It has to be noted that the sediment transport and the bed level changes are not calibrated and validated. These runs are for additional insights on the possible development of the flats. The analysis therefore will be qualitative and not quantitative.

The D_{50} used in the model is 200 µm. For the sediment transport the transport formula of Van Rijn (1993) was used. The bed level was updated during the simulation which means that the hydrodynamics react to the change in bed level. The interest is on the initial changes so the morphological factor was 1. The results shown in this chapter are of the second 14 days of April to cover a full spring-neap tidal cycle.

Knuitershoek

The change in bed level change after 14 days due to the implemented groynes is plotted in Figure 5.14. On the flat the change in bed level change is mainly positive. This means that there is more accretion or less erosion compared to the situation without the designed groynes. In both directions the high water resting areas resulted in more accretion or less sedimentation since the change in bed level changes is positive. This means that the transport capacity on the leeward side of the high water resting areas is smaller. At the tip of all groynes the change in bed level change is negative, which could mean the creation of scour holes in the channel.

The residual sediment transport in the situation after implementation of the designed groynes is plotted in Figure 5.15 on the left and the change in residual transport compared to the situation before the implementation of the groynes on the right. The channel near Knuitershoek is divided in an ebb dominated and a flood dominated part based on the residual sediment transport. The part close to the flat is flood dominated as was also found in the data analysis (section 3.3.1). On the intertidal flat the sediment transport is close to 0 kg m^{-1} s^{-1} except for the areas in the flood direction between the high water resting areas and the dike. The increased velocities over the groynes, as seen in section 5.2.1, cause more sediment transport. The effect of the high water resting areas is also seen in de difference in residual sediment transport. In the left figure no transport is visible where in the right figure (the difference) changes to the ebb direction are visible. This means that there was sediment transport before the implementation of the designed groynes.

Still some unexplainable things are happening in the channel. The change in residual transport in the flood direction further in the channel (Figure 5.15, right) cannot be explained by the hydrodynamic results of the model. The flow velocities that far from the flat do not change by the implementation of the designed groynes (section 5.2.1).

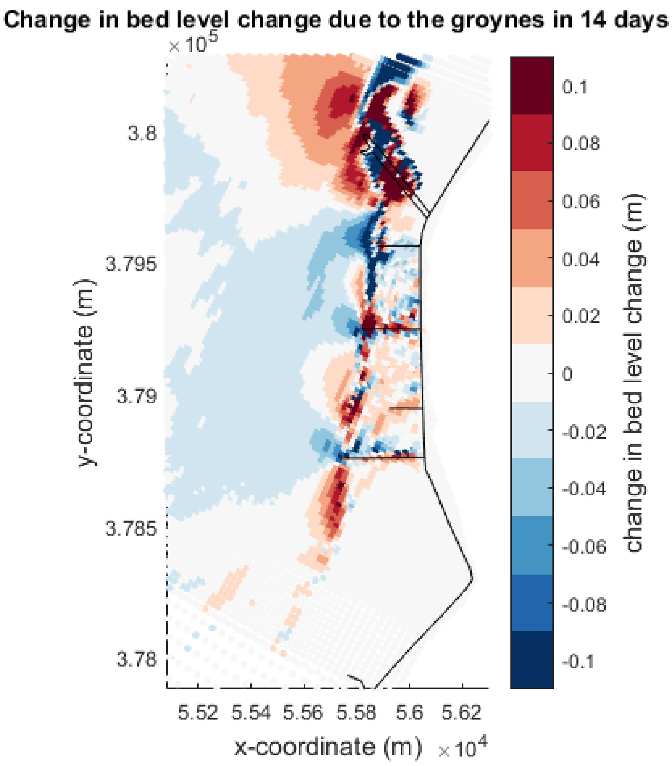
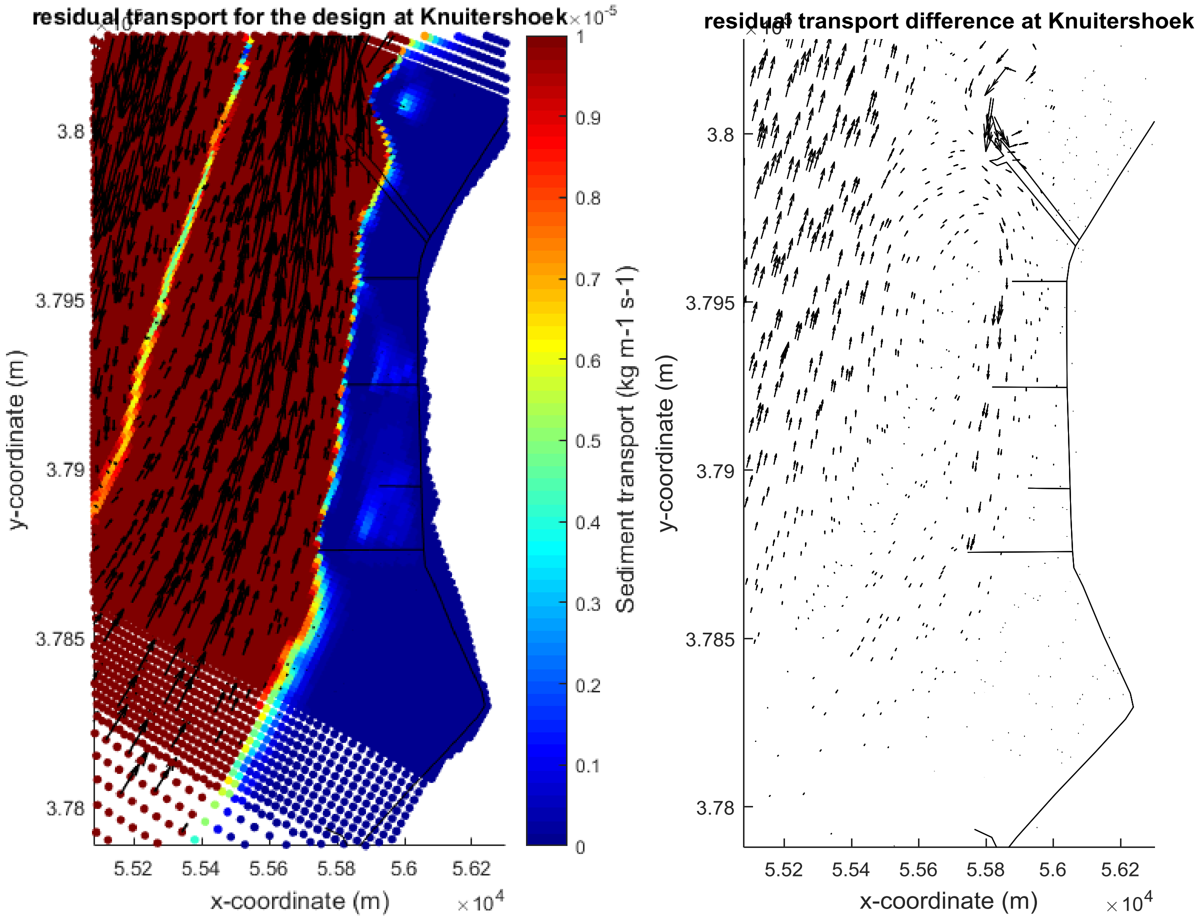

Change in bed level change due to the groynes in 14 days

Figure 5.14 – Change in bed level change in 14 days due to the designed groynes at Knuitershoek. Red indicates a bed level increase, blue a decrease.


residual transport for the design at Knuitershoek

residual transport difference at Knuitershoek

Figure 5.15 – Left: Residual sediment transport after 14 days at Knuitershoek for the situation after the implementation of the designed groynes. Right: Residual transport difference compared to the situation without the new groynes.

Baalhoek

The change in bed level change due to the groynes at Baalhoek (Figure 5.16) shows a decrease at the tip of groyne B3. This means that there is less accretion or more erosion. This is caused by a bigger transport capacity due to higher flow velocities that are caused by the new groynes. The increased velocities at the tip of the new groyne (B3) during flood were mainly found during flood (section 5.2.1). The difference in residual sediment transport therefore is directed in the flood direction (Figure 5.17, lower figure). What can be concluded is that residual sediment transport in the channel has become less ebb dominated due to the groynes. The parts of the channel at the tips of groynes even have become flood dominated based on the residual sediment transport (Figure 5.17, upper figure: black ellipses).

Another negative change in bed level change is seen between the groynes close to groyne B3. This means more erosion or less accretion. Almost no sediment transport, compared to the channel, is visible on the intertidal flat at Baalhoek (Figure 5.17, upper figure). The difference in residual transport between the situation before and after the implementation of the groynes (Figure 5.17, lower figure) shows that there was transport before the groynes were implemented. It can be concluded that the implemented groynes block the sediment transport on the flat.

West of groyne B3 positive change on the flat is seen. This is the location of the flood channel at the opening of the longitudinal dam. Due to the decreased flow velocities caused by the new groyne the sediment transport capacity is lower and the flood channel will probably fill up on the long term.

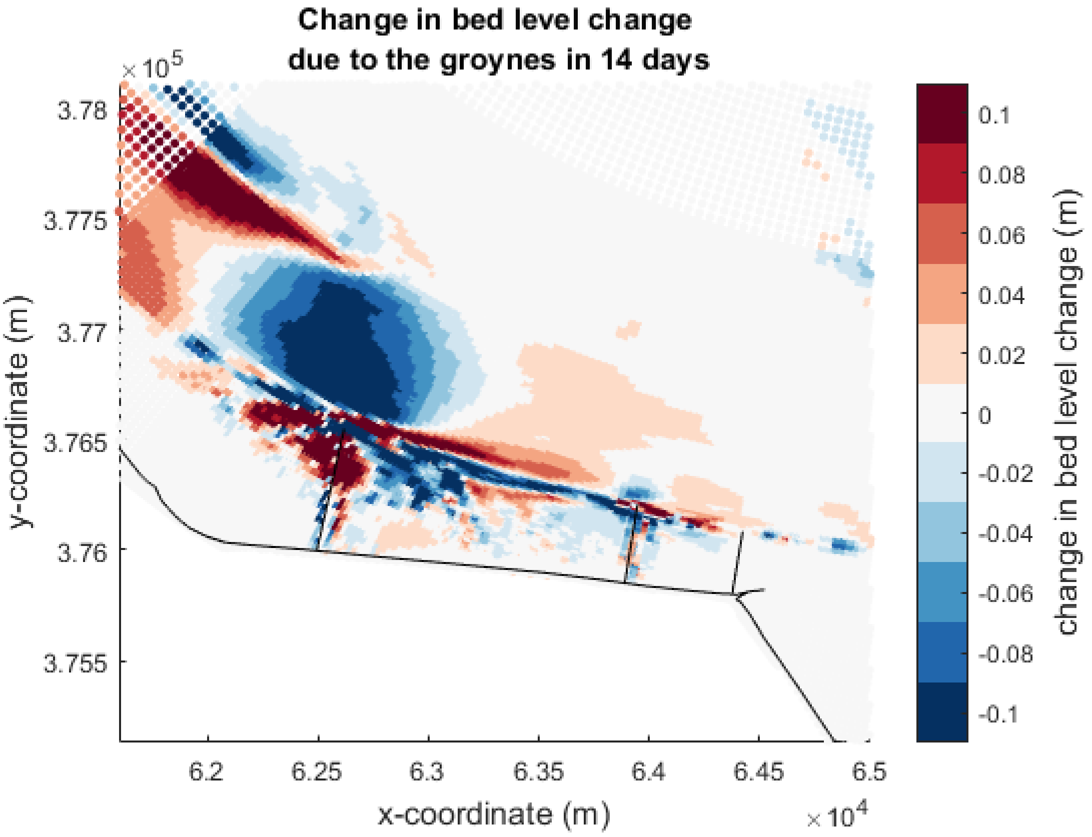


Figure 5.16 - Bed level change in 14 days due to the designed groynes at Baalhoek. Red indicates a positive change in bed level change, blue a negative change in bed level change.

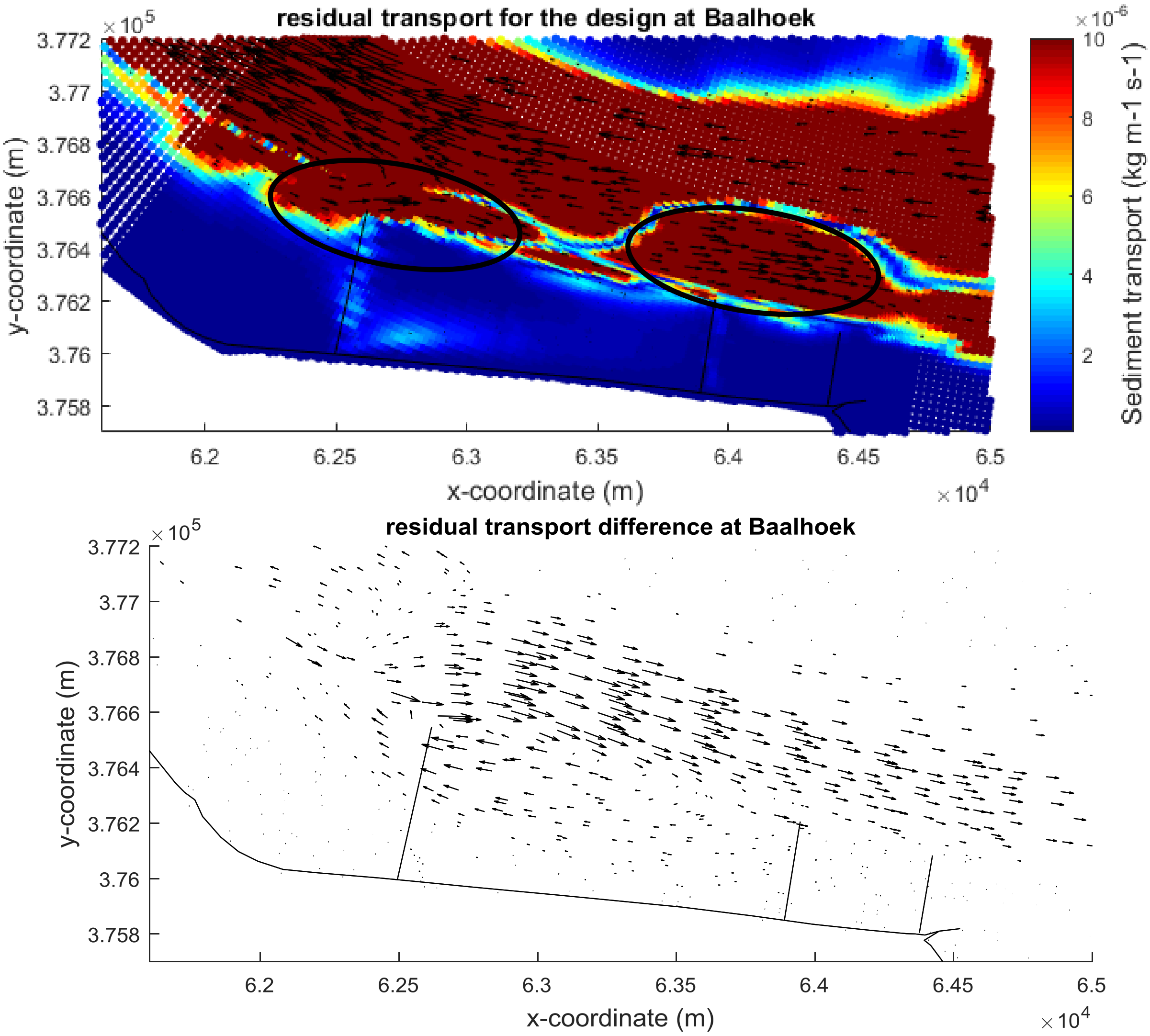


Figure 5.17 – Upper figure: Residual sediment transport after 14 days at Baalhoek for the situation after the implementation of the designed groynes. The black ellipses indicate flood dominated sediment transport. Lower figure: Residual transport difference compared to the situation without the new groynes.

5.4. Conclusion

Combining the low-dynamic surface area increases of both cases gives a total of 15 ha initial increase for a critical velocity of 0.6 m/s and 23 ha increase for 0.8 m/s according to the model simulations. The aim of the Province of Zeeland was to create an extra 57 ha of low-dynamic area. This means that, according to the KnuBa-model, the design in these dimensions will not be enough to fulfil the demand of the Province of Zeeland based on the low-dynamic surface area. It has to be stated that the results are the initial effects based on the situation during spring tide. On the longer term the bed level can increase and velocities can decrease, resulting in more low-dynamic surface area. The first sediment runs of the KnuBa-model showed possible increase of the bed level between the groynes at Knuitershoek and of the flood channel at Baalhoek. These increases could have positive effect on the amount of low-dynamic area on the long term.

The designed groynes only have effect on the flats where the groynes are created and the channel is only affected close to the intertidal flats. In both areas the flood flow velocity magnitudes in the channel directly upstream from the groynes increase between 0.1 and 0.3 m/s. At Knuitershoek the flow velocity magnitudes close the new groyne in the north (K7) increase due to the contraction of flows. At Baalhoek an increase in flow velocity magnitudes is mainly shown near the western new groyne (B3).

6. Generalized system understanding

A scenario study was done to study the effect of the design parameters of the groynes on the hydrodynamics and the amount of low-dynamic area. The design showed three interesting features which could be changed to see the effects on the hydrodynamics. The first and most obvious is the height of the groynes. The second interesting feature is the high water resting area. These were successful in creating low-dynamic parts on the flat. Another interesting feature is the number of groynes. The groynes at Knuitershoek are located much closer to each other compared to the groynes at Baalhoek. To see the possible effects of changing distance between the groynes the number of groynes at the locations is changed.

The following scenarios were tested with the KnuBa-model:

- Changing the heights of the groynes (0.5 – 4.0 m+NAP, 0.5 m interval)
- Changing the length of the High water resting areas (0 – 100 %, 20 % interval)
- Add one groyne at Baalhoek and remove one groyne at Knuitershoek

The effects of these scenarios on the amount of low-dynamic area based on the critical velocities of 0.6 m/s and 0.8 m/s were tested. The maximum velocities during the scenarios are decisive in determining the low-dynamic surface areas. During these model simulations no sediment transport and morphologic changes are computed.

6.1. Height of the groynes

The effect of the height of the groynes on the amount of low-dynamic surface area is assessed by varying the height from 0.5 m until 4.0 m +NAP. The height is uniform over all five groynes (K3, K5, K7, B2 and B3). This means that there are no high water resting areas present during these scenario runs. The results of the variation in height are plotted in Figure 6.1. The surface area of the intertidal flats at Baalhoek and Knuitershoek are 240 ha and 65 ha, respectively.

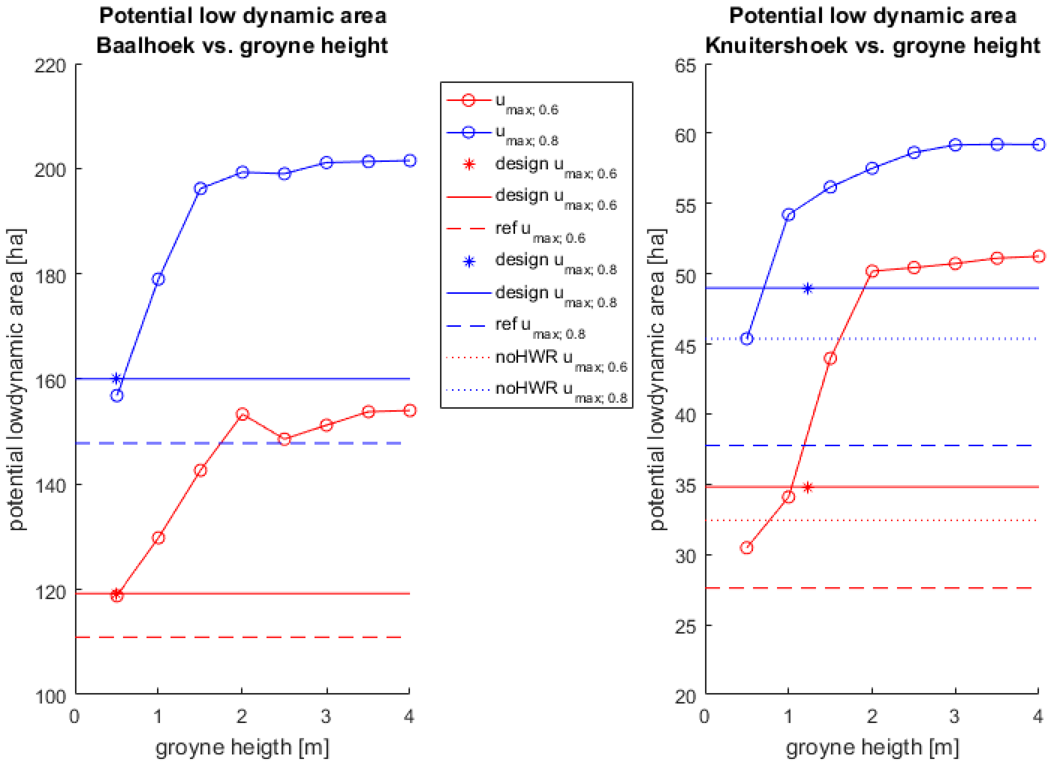


Figure 6.1 - Results of the different groyne height scenario runs. The left figure shows the results at Baalhoek and the right figure shows the results for Knuitershoek. The blue colour represents the results for a critical velocity of 0.80 m/s and the red colour represents a critical velocity of 0.60 m/s. The solid horizontal lines indicate the amount of low-dynamic area of the designs where the dashed lines represent the references. The dotted line in the right figure is a scenario run where the high water resting areas are removed from the design.

Baalhoek
The maximum amount of low-dynamic area using a critical velocity of 0.6 m/s is obtained with a groyne height of 2.0 m+NAP. After that there is no further increase. The decrease in low-dynamic surface area when increasing the height further is caused by circulation during high water. The groynes become too high for the water to create significant flow to cancel the circulation and cause parallel flow. For a critical velocity of 0.8 m/s a tipping point is reached at 1.5 m+NAP groynes height. Increasing the height further only slightly increases the amount of low-dynamic surface area.

A groyne height of 1.0 m+NAP or higher increases the maximum velocities in the channel by more than 0.1 m/s (Figure 6.3). The area in the channel that has higher maximum velocities increases with increasing groyne height (Appendix F.1.1.) When the groynes get higher than 1.5 m+NAP the increase in maximum velocity is even higher than 0.3 m/s on some locations in the channel (Figure 6.2). These increases are important to keep in mind for managing navigation in the channel. In the east of the area at Baalhoek the velocities also increase when the groyne heights get higher. This is not preferred since that area is close to Saeftinghe, a large nature reserve.

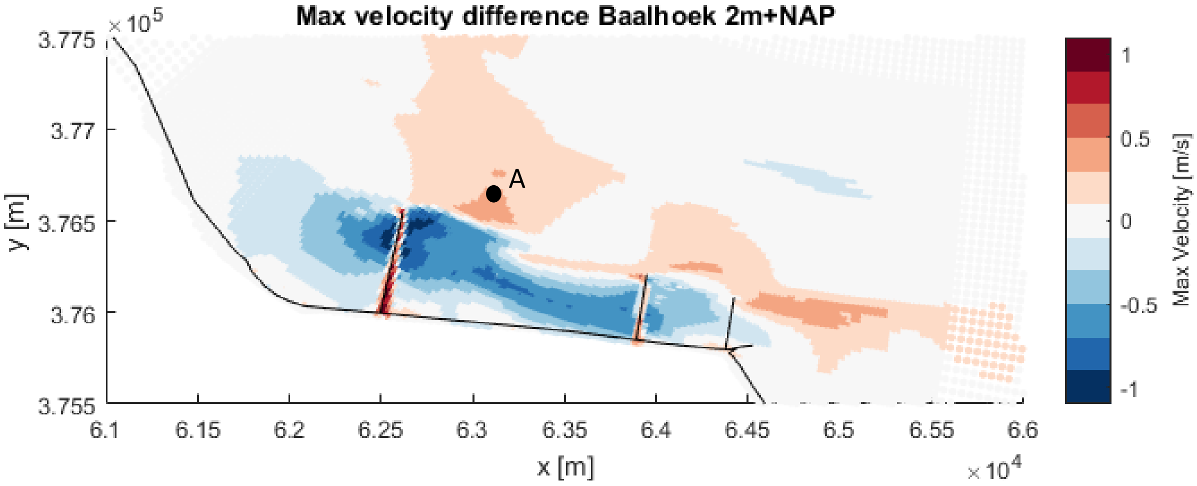


Figure 6.2 - Increase of more than 0.3 m/s in the channel caused by a groyne height of 2.0 m+NAP. The maximum flow velocities in point A due to the different groyne heights are plotted in Figure 6.3.

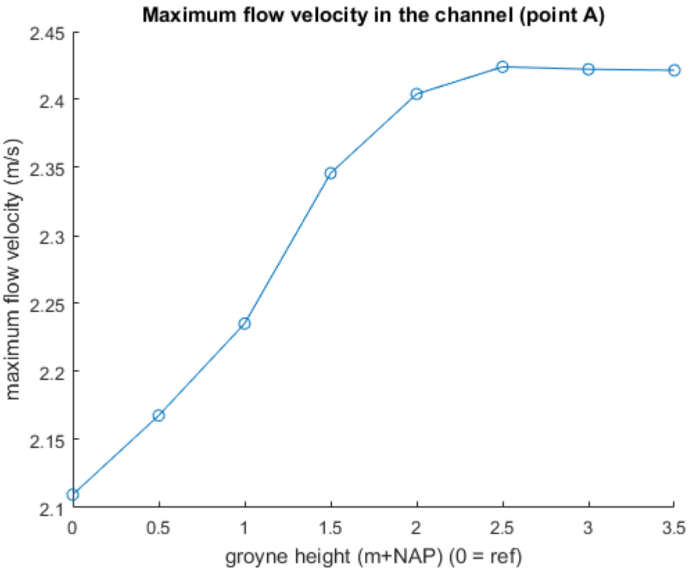


Figure 6.3 – Maximum flow velocity in the channel due to different groyne heights at point A as shown in Figure 6.2. A groyne height of 0m+NAP represents the situation without groynes.

Groyne heights above 1.5 m+NAP create circulation cells reaching to the dike. Figure 6.4 shows the situation for a groyne height of 2.5 m+NAP. The circulation cells between the groynes and upstream from groyne B2 (during flood) create high velocities (higher than 0.8 m/s) close to the dike. This is not preferred since the nature should develop close to the dike and grow towards the channel.

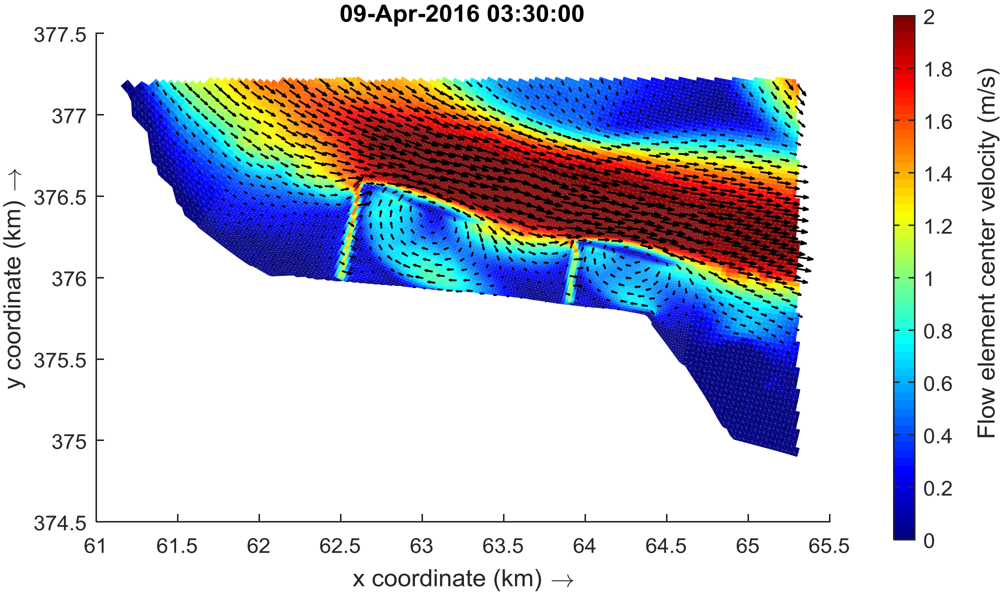


Figure 6.4 – High velocity (>0.8m/s) close to the dike due to circulation cells caused by the groynes with a height of 2.5 m+NAP

Because the increase of velocities in both the channel and close to the dike, the tipping points in Figure 6.1 could be seen as the best configuration for the groyne height. Increasing the height further does not increase the amount of low-dynamic area significantly, but increases the maximum velocities in the channel and close to the dike.

Knuitershoek

At Knuitershoek (Appendix F.1.2) the amount of low-dynamic surface area increases with increasing groyne height. The tipping point for a critical velocity of 0.6 m/s is found at a groyne height of 2m+NAP. For the critical velocity of 0.8 m/s the tipping point is fount at 1.0 m+NAP.

The groynes at Knuitershoek have less effect on the channel compared to the groynes at Baalhoek. At Knuitershoek an increase in flow velocity in the channel is seen next to the southern groynes (K3) after the groyne height is bigger than 1.5 m+NAP (Figure 6.5 and Figure 6.6).

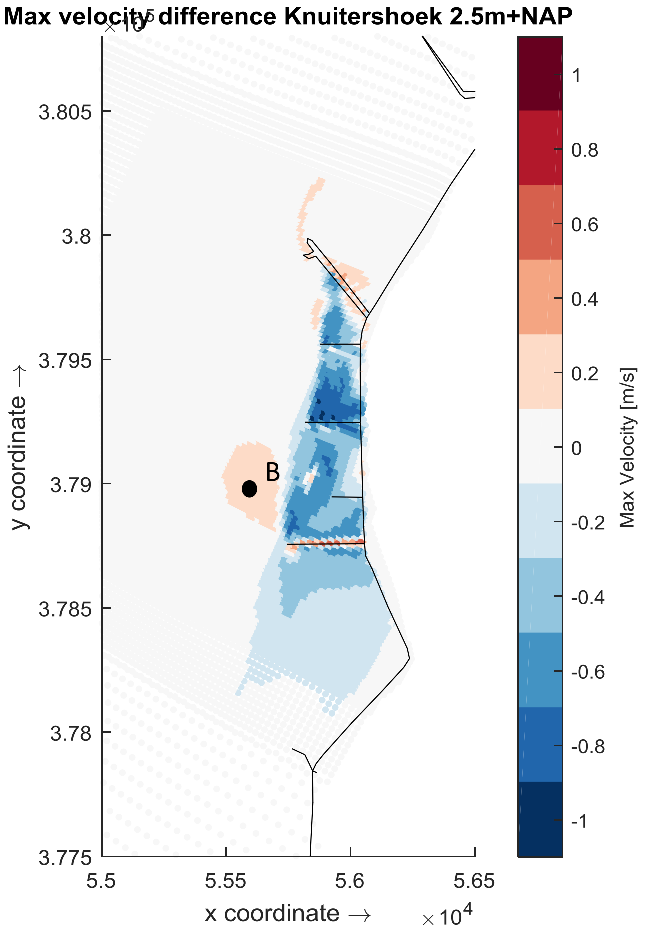


Figure 6.5 - Maximum velocity difference at Knuitershoek compared to the situation before the implementation of the designed groynes. The maximum flow velocities in point B due to the different groyne heights are plotted in Figure 6.6.

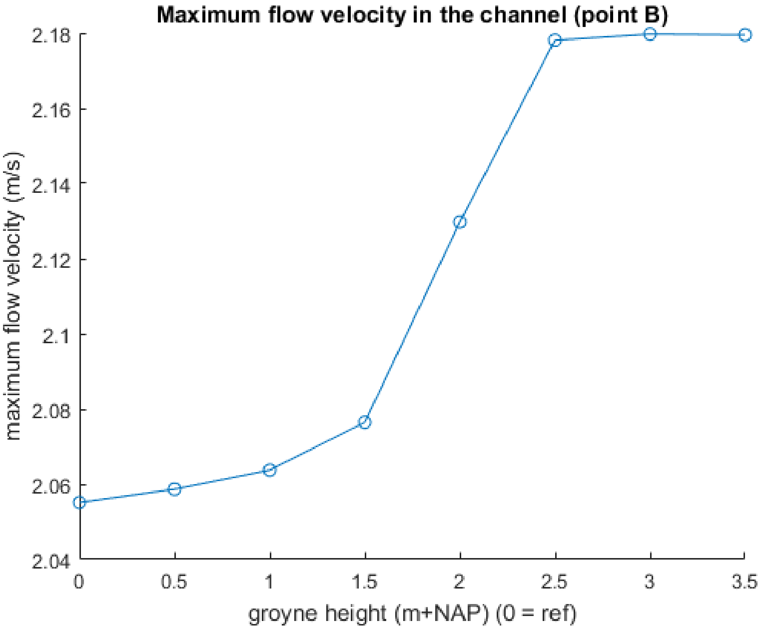


Figure 6.6 - Maximum flow velocity in the channel due to different groyne heights at point B as shown in Figure 6.5. A groyne height of 0m+NAP represents the situation without groynes.

The height of the groynes has more impact on the channel velocities at Baalhoek compared to Knuitershoek. This might be caused by the narrower channel at Baalhoek compared to Knuitershoek. Also the ratio between the width of the intertidal flat and the width of the channel at Baalhoek is higher. The relative narrowing because of the groynes therefore is bigger at Baalhoek compared to Knuitershoek.

Groynes that are constructed higher than the tipping point height cause more circulation compared to parallel flow. This increases the flow velocities close to the dike and is not preferred since the development of nature is preferred to start close to the dike and grow from there to the channel.

Varying critical velocity

The tipping point for the critical velocity of 0.6 m/s is at lower groyne height compared to 0.8 m/s. This is an interesting feature when designing groynes for a specific area, because the critical velocity for low-dynamic area is different for each location and should be based on the desired morphologic and nature development and (Dam et al., 2008). To see the impact of different critical velocities on the amount of low-dynamic surface area, the critical velocity is varied between 0.1 m/s and 1.0 m/s. The results are plotted in Figure 6.7.

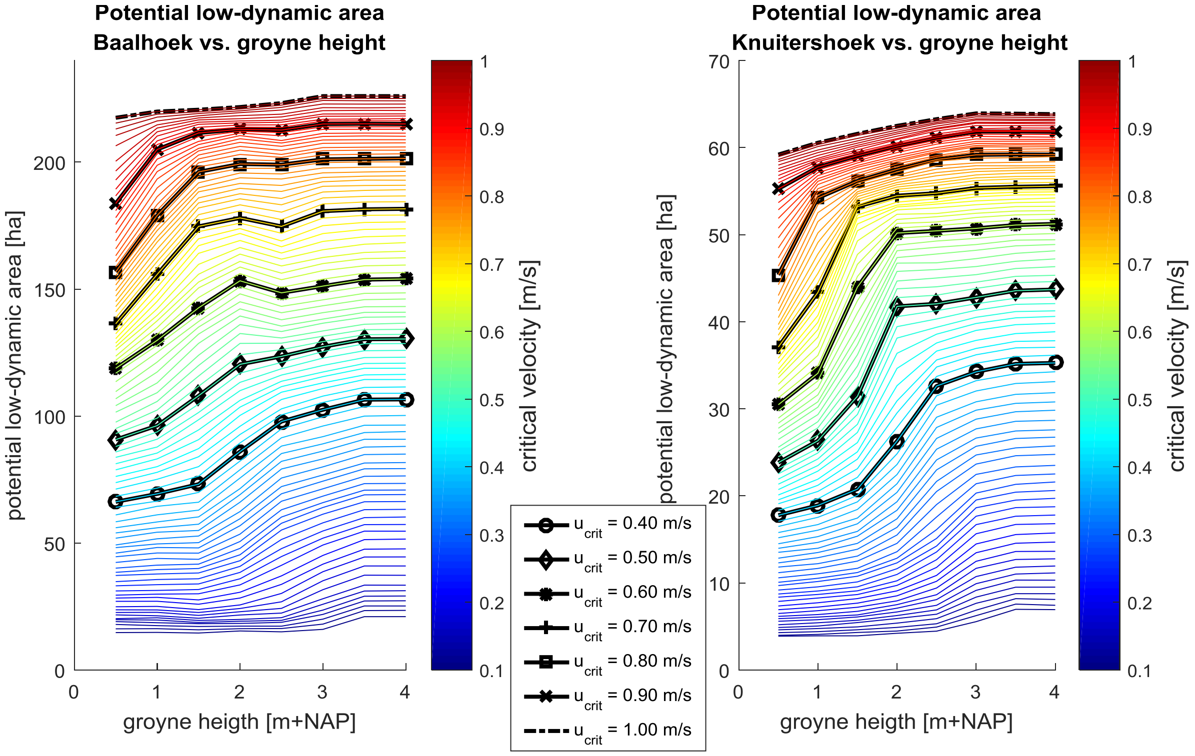


Figure 6.7 - The amount of low-dynamic surface area for the different groyne height scenario runs using varying critical velocities. The left figure shows the results for Baalhoek and the right figure shows the results for Knuitershoek.

Figure 6.7 shows that the tipping point for higher critical velocities moves to lower groynes heights. This principle can be used for future designs. Based on the desired nature development a critical flow velocity can be chosen and the desired groynes height can then be estimated.

6.2. Length of the ‘High Water Resting area’

The results of the designed groynes at Knuitershoek showed that the high water resting areas had an increasing effect on the low-dynamic surface area (section 5.2.3). To assess the effect of high water resting areas in general they are added to both locations, starting at the channel, and varied in length between 0% and 100% of the total groyne length with intervals of 20%. The height of the remaining parts of the groynes is the same as in the design. The high water resting areas were added to both groynes at Baalhoek (B2 and B3) and to the southern two groynes at Knuitershoek (K3 and K5). The results of these scenario runs are plotted in Figure 6.8. The maximum velocities that occur during these scenarios are shown in Appendix F.2.

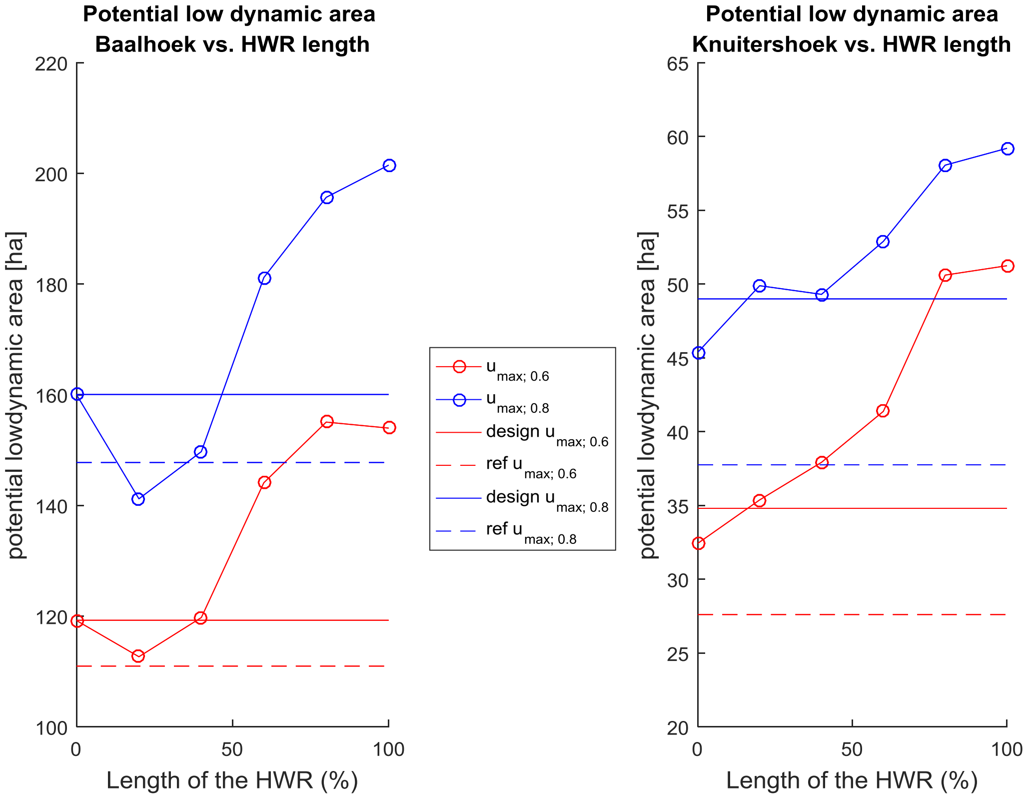


Figure 6.8 – Results of the different high water resting area runs. The left figure shows the results for Baalhoek and the right figure shows the results for Knuitershoek. The blue colour represents the results for a critical velocity of 0.80 m/s and the red colour represents a critical velocity of 0.60 m/s. The solid horizontal lines are the amount of low-dynamic area of the designs where the dashed lines represent the situation without the designed groynes.

Baalhoek

Adding the high water resting areas to the design at Baalhoek showed negative effect on the low-dynamic surface area. This is caused by blockage of water near the channel which forces the water to flow through the flood channel (‘vloed schaartje’) on the flat during flood flows (Figure 6.9).The small decrease of flow velocities behind the high water resting areas do not weigh up against the increase of velocities between the dike and the high water resting areas.

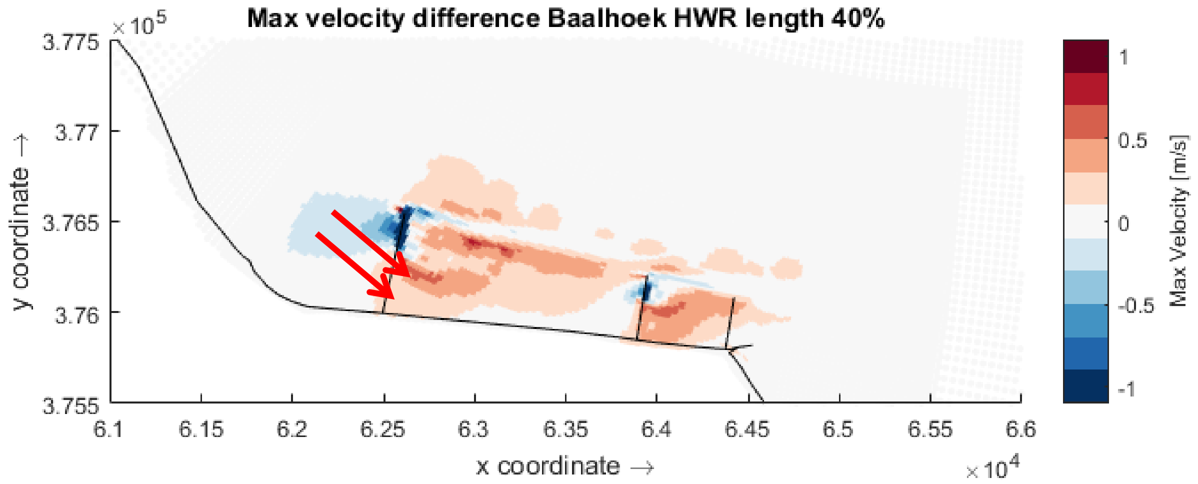


Figure 6.9 - Increased flow velocities compared to the designed groynes at Baalhoek caused by the high water resting area length of 40%. The flood channel guides the flow onto the intertidal flat (red arrows).

The amount of low-dynamic area is only increased after the length of the high water resting areas is 60% or higher. Still the implementation should be doubted. They result in an increase of flow velocities over the intertidal flat close to the dike.

Another downside of the implementation of the high water resting areas at Baalhoek is the increase of velocity in the channel (Appendix F.2.1). The increase of flow velocity in the channel increases with the length of the high water resting areas. Since the navigation channel is close to the flat this effect could be a problem when the velocity increases too much.

Knuitershoek

When the high water resting areas are removed from the design at Knuitershoek, the design is less effective in terms of the low-dynamic surface area. Increasing the length of the high water resting areas has a beneficial effect on the amount of low-dynamic area; the amount of low dynamic area increases with the length. A side effect of increasing the length of the high water resting area is the decrease of the distance between the high water resting area and the dike. This narrows the cross-section between the high water resting area and the dike and increases the flow velocity close to the dike (Figure 6.10).

The effect of the high water resting areas on the channel starts at a length of 60% (Figure 6.10). It causes an increase of velocity in the channel north of the southern groyne (K3) and an increase north of the new groyne (K7). The flow velocity increases close to the dike seem to create a stronger flow around the northern groyne (K7) (black arrows, Figure 6.10). After 80% a small decrease in velocities is seen west of the new groyne (K7).

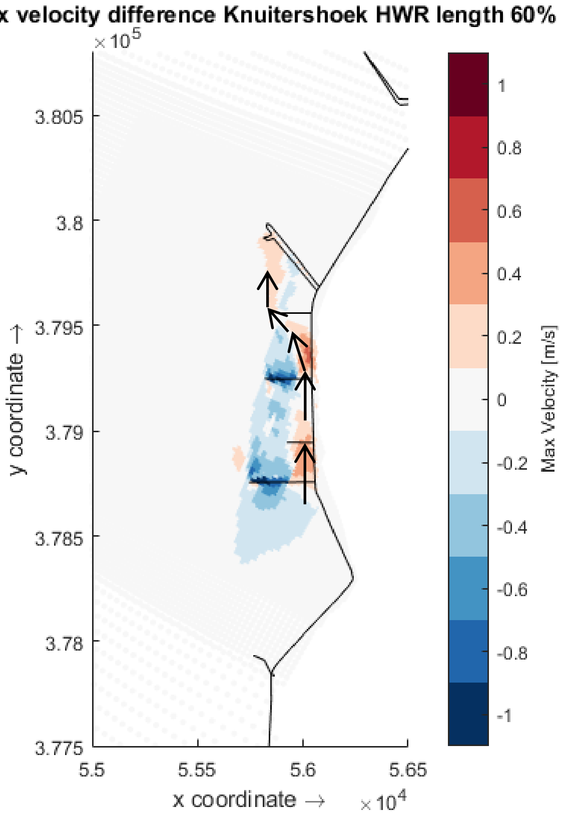


Figure 6.10 - Increased flow velocities compared to the designed groynes (without the high water resting areas) at Knuitershoek caused by the high water resting area length of 60%. The black arrows indicate an increased flow velocity stream.

The impact of the high water resting area is different for both areas. At Baalhoek implementation of a high water resting areas has a decreasing effect on the amount of low-dynamic area where at Knuitershoek the implementation is increasing it. This might be due to the orientation of the intertidal flats compared to the channel flow direction. They both are located in the outer bend of the channel, but the channel at Baalhoek make a sharper turn. That causes the flow to be pushed onto the flat. The flood channel at the opening in the longitudinal dam in the west of the groyne (B3) might also guide the flow onto the flat. This increases the flow velocities between the high water resting area and the dike. At Knuitershoek no opening in the longitudinal dam like at Baalhoek is present close to the high water resting areas.

It can be concluded that the implementation of high water resting areas can be beneficial for the amount of low-dynamic area on intertidal flats, but that with the wrong configuration it can lead to flow velocity increases close to the dike and in the channel.

Varying critical velocity

The negative effect of the high water resting areas at Baalhoek can be seen clearly when changing the critical velocities (Figure 6.11: Left). A drop in potential low-dynamic surface area can be seen even in velocities higher than 0.8 m/s. This indicates that the flow in the channel is guided onto the flat by the implementation of high water resting areas. At Knuitershoek (Figure 6.11: right) the length of the high water resting areas seem to have a positive effect on the amount of low-dynamic area. High water resting area lengths of 40% and 60 % result in an increase of surface area with velocities above 1 m/s at Knuitershoek.

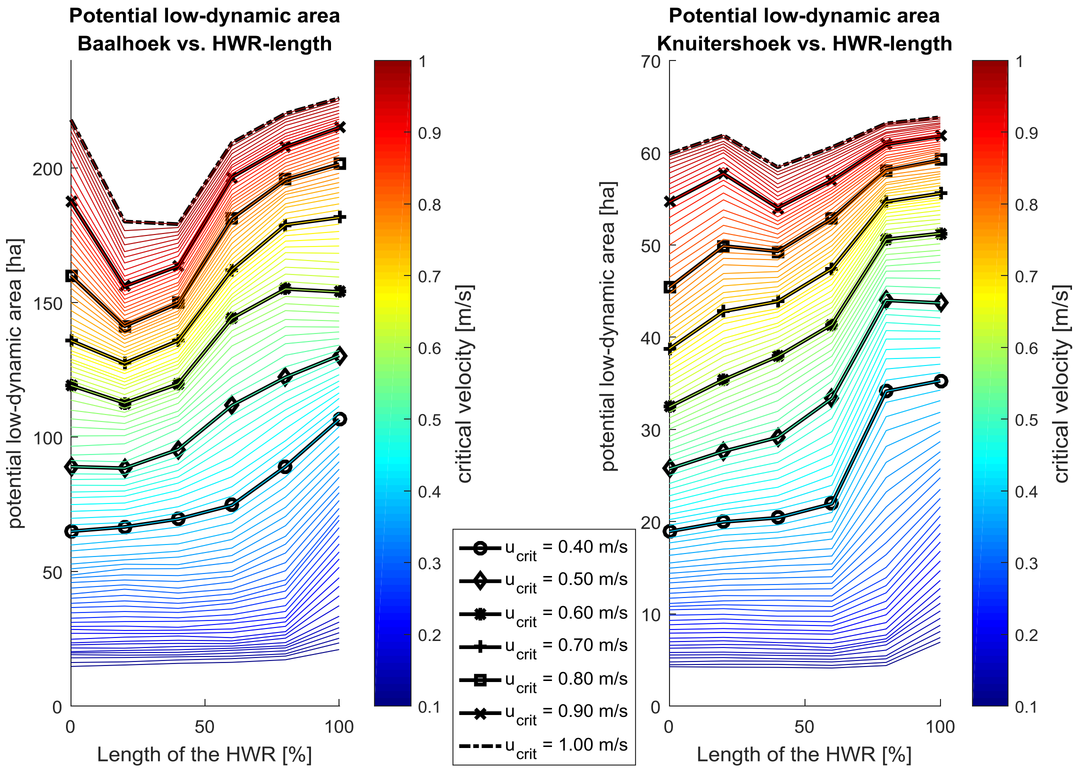


Figure 6.11 - The amount of low-dynamic surface area for the different high water resting area lengths runs using varying critical velocities. The left figure shows the results for Baalhoek and the right figure shows the results for Knuitershoek.

6.3. Number of groynes

As a first impression of the effect of the number of groynes and the distance between the groynes one groyne is added at Baalhoek to decrease the distance between the groynes and one groyne is removed at Knuitershoek to increase the distance between the groynes. This is done in one scenario model run, which is possible because the areas have no influence on each other.

Baalhoek

At Baalhoek one extra groyne is added in the middle of the two new groynes (B2 and B3). This decreased the distance between the groynes from 1400 m to 700 m. The extra groyne has a height of 0.6 m+NAP, which is the same as groyne B3. The extra groyne at Baalhoek increases the circulations seen on the flat during flood. During high water the flow is again parallel to the channel. The maximum velocities shown in the flat are lower compared to the design. Especially the flow velocity between the extra groyne and the eastern groyne (B2) has decreased (Figure 6.12). This created extra low-dynamic area compared to the design (Table 6.1) by lowering the maximum velocities between the extra groyne and groyne B1.

Table 6.1 - Low-dynamic surface area and the change compared to the reference at Baalhoek for the reference, design and the extra groyne model.

Baalhoek: Low-dynamic area

Critical velocity	0.6 m/s	Change	0.8 m/s	Change
Reference	111 ha		148 ha	
Design	119 ha	+ 8 ha	160 ha	+ 12 ha
Extra groyne	122 ha	+ 11 ha	178 ha	+ 30 ha

Max Velocity [m/s]

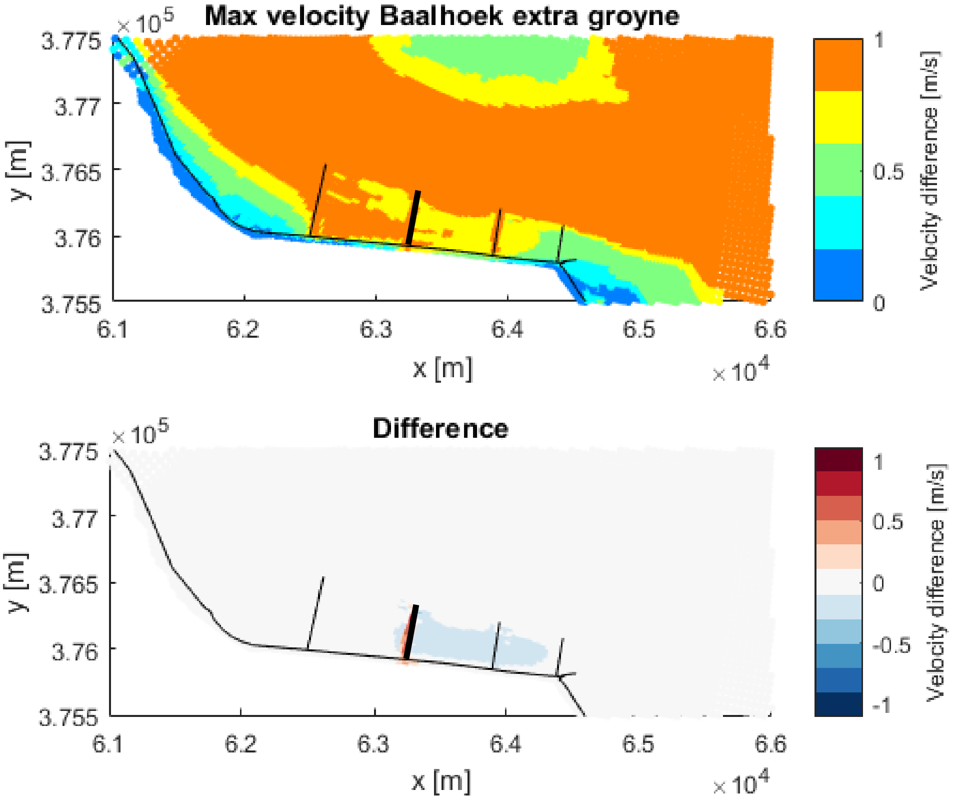


Figure 6.12 – Upper figure: Maximum velocity at Baalhoek in the extra groyne scenario. Lower figure: difference in maximum velocity between the scenario with an extra groyne and the designed groynes. The bold black line indicates the extra groyne.

Knuitershoek:
At Knuitershoek the middle groyne (K5) is removed to see the impact of decreasing the number of groynes and increasing the distance between the groynes from 310m/490m to 800m. The effects on maximum flow velocities are shown in Table 6.2 and Figure 6.13. For both critical velocities, although the difference is small, the low-dynamic area decreases. This is mainly caused by the low-dynamic area that disappears by removing the middle groyne. The flow between the high water resting area and the dike on the southern groyne (K3) can now freely flow without being interrupted by the high water resting area and is not increased by the middle groyne (K5).

Table 6.2 - Low-dynamic surface area and the change compared to the reference at Knuitershoek for the reference, design and the one less groyne model.

Knuitershoek: Low-dynamic area

Critical velocity	0.6 m/s	Change	0.8 m/s	Change
Reference	28 ha		38 ha	
Design	35 ha	+ 7 ha	49 ha	+ 11 ha
Remove middle groyne	35 ha	+ 7 ha	47 ha	+ 9 ha

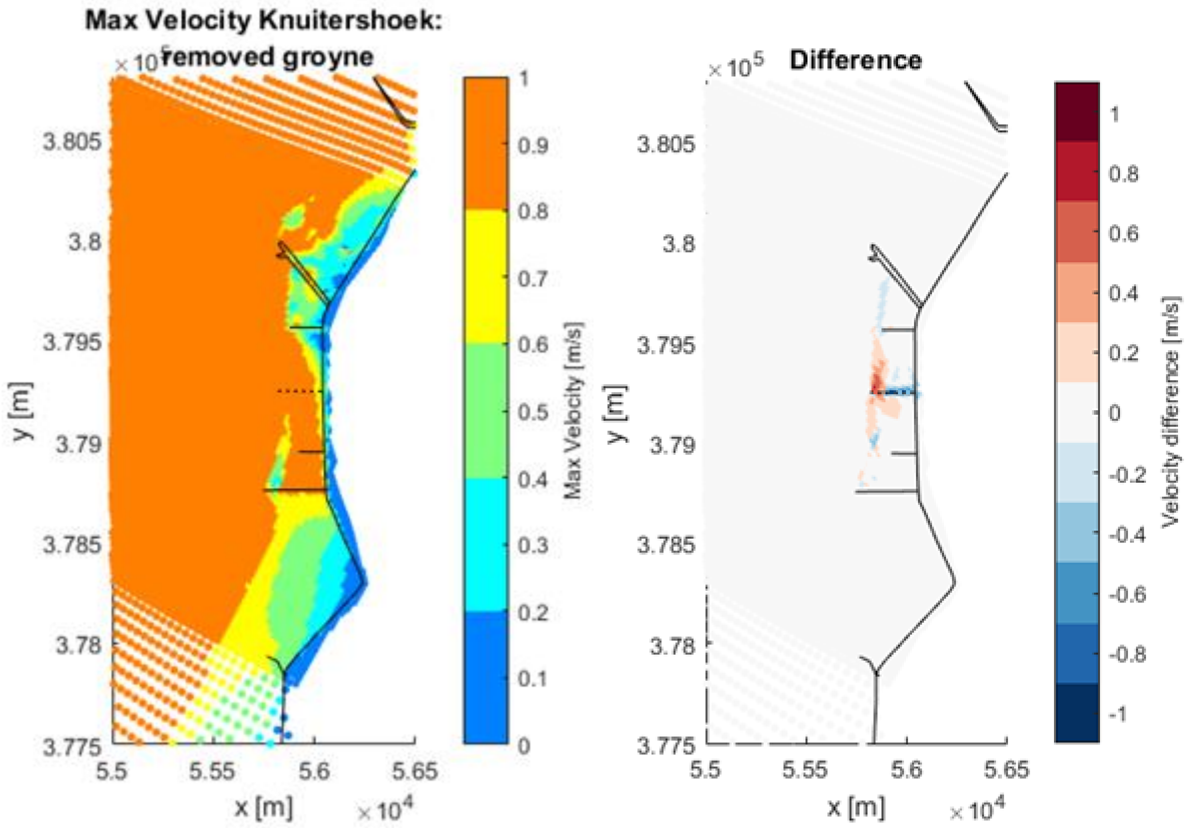


Figure 6.13 – Left: Maximum velocity at Knuitershoek in the removed groyne (dashed line) scenario. Right: Difference in maximum velocity due to the removal of the groyne K5.

For both areas the first groynes that encounter flood flow (K3 and B3) lower the flow velocities the most. This is also seen in the increase of flow velocities in the channel. The flow velocities over those groynes are also higher than over the other groynes. What can be concluded is that the first groyne is taking away flow velocities that make the next groynes more effective in creating low-dynamic area. This is also seen by adding the extra groyne at Baalhoek. Without the extra groyne the design did not create low-dynamic area between the groynes. The extra groyne caused the maximum flow velocity to decrease even further which created low-dynamic area (when looking at a critical velocity of 0.8 m/s). It should be stated that the effect of the first groyne on the next groynes wears of if the distance between the groynes is too large.

6.4. Conclusion

The amount of low-dynamic area is positively related to the groyne height. For the groyne height the tipping points can be seen as an optimum. Groyne heights higher than the tipping point height give no significant increase of low-dynamic area, but increase the flow velocities in the channel and close to the dike.

The implementation of high water resting areas can be beneficial for the amount of low-dynamic area on intertidal flats, but depending on the characteristic of the area the wrong configuration can lead to flow velocity increases close to the dike and in the channel.

The amount of low-dynamic area is positively related to the number of groynes. The distance between groynes has a negative relation with the amount of low dynamic area; the smaller the distance between the groynes, the larger the low dynamic area.

7. Discussion

The findings during this master thesis are discussed and reflected in this chapter.

Modelling assumptions

The model was calibrated using the available measurements carried out before groyne construction (T0). This means that the modelled effects of the designs could not directly be validated by observations. However, as the model accurately reproduced water levels and flow velocities for the T0 situation, it is expected to reliably predict hydrodynamics during the period after the construction as well.

The use of a depth averaged model did not affect the capabilities of the model. The water levels, and the flow velocities magnitudes and directions were simulated accurate, although the velocities during ebb drop too soon compared to the observed flow at Knuitershoek. The drop in velocities during ebb was no problem for this master thesis because the focus was on maximum velocities. The maximum velocities were predicted accurate enough. For sediment dynamics and morphological development the drop might be a problem. The total transport during ebb might be predicted too low since the flow velocities are predicted to low. This should be taken into account during further research.

The bathymetry of the KnuBa-model is based on three datasets: Vaklodingen2014, Single-beam measurement data and LiDAR-data 2016. These are interpolated over the grid of the model. This interpolation could cause inaccuracies compared to reality. The model results showed that the model using this bathymetry could simulate the water levels and the flow accurate. Only at Knuitershoek the ebb velocities drop too early. After testing the model using the vaklodingen of 2016, which came available in the end of this master thesis, the problem was not resolved. During every model run (reference, design and scenario runs) the same bathymetry is used. This made it possible to compare the results of the different groynes.

During this study waves were not taken into account, because as first step only the effects of flow are studied. The focus in this study was on the flow, which is determining if an area is low or high dynamic from definition. This assumption means that the results during this study are the 'worst-case' scenario. Adding waves will make the area more dynamic by causing higher bed shear stress and cause erosion of the flats (Van Rooijen et al., 2015). In future research, waves should be taken into account.

Definition of low-dynamic area

Low-dynamic areas are defined by maximum flow velocities, 0.6 and 0.8 m/s during this study. Based on the maximum velocities an estimation of the development of the area can be made, but in the future it is interesting to extent the definition of low-dynamic area. By adding a percentage of time that threshold velocities are exceeded, more insight in the development of the area can be gained. Waves, as discussed before, also play a role in the dynamics by increasing the bed shear stress. A next step could be the extension of the definition of low-dynamic area with waves.

Initial effect

The results in this study are mainly based on the initial hydrodynamic effects of the newly implemented groynes on intertidal areas. Sediment transport and morphological changes are only discussed for the design groynes based on an exploratory model run. The rest of the study is purely based on hydrodynamics. There is no interaction between flow, waves, sediment transport and changes in the bed level. The interaction between these factors possibly causes more low-dynamic area over time because of accretion. The bed level will rise because of this and flow velocities will possibly be lowered, creating more low-dynamic area.

Application knowledge on different locations

At the ‘Schaar van Waarde’, north of Baalhoek, erosion on the tips and parallel to the groynes was observed (Dam & Bliek, 2013). This was caused by the contraction of flows close to the channel and increased velocities during the flooding of the groynes at high tide. The same can be expected at Knuitershoek and Baalhoek since the velocities over the groynes increased in the situation after implementation of the designed groynes. Based on the results in these three cases it can be concluded that submersible groynes increase velocities and cause erosion parallel to the groynes and at the tips in the channel.

This study delivered useful insights on the effects of groynes on intertidal flats in estuaries. The height of the groynes should be studied for each area individually. Both areas during the case study at Knuitershoek and Baalhoek showed that increasing the height to not submersible heights has negative effects on the channel and on areas close to the dike. In the study of Dam et al. (2008) of the groynes at Baalhoek and Knuitershoek were implemented with an infinite height. They also found the circulation cells which causes high velocities close to the dike. The increase in the channel was also observed in their modelling results.

The tipping point in the curves of the amount of low-dynamic area as a function of the groyne height, as seen during this study (section 6.1) indicates a change in behaviour at a certain groyne height. The increase of low dynamic areas for heights beyond that tipping point does not weight up against the increase of flow velocities in the channel and close to the dike due to circulation cells. This knowledge can be useful for the creation of low dynamic areas in other locations, by indicating a possible preferred groyne height. Although the numeric values of these curves are case dependent, the similarities in shape between the curves between both areas, provides much confidence in a more general applicability after some further research.

Implementation of high water resting areas does not guarantee an increase in low-dynamic area. At Knuitershoek the implementation of the designed groynes increase the amount of low-dynamic surface area, but in the same configuration at Baalhoek they resulted in an increase of velocities and a decrease in low dynamic area. This is due to the flood channel located in the west on the intertidal flat at Baalhoek and the orientation of the flat compared to the channel. It is located in front of the western groyne and guides the flow coming from the channel onto the flat and pushed it passed the wrong side of the high water resting area. Increasing the length of the high water resting areas can be beneficial for the amount of low dynamic area. As the length increases more flow is blocked and the leeward side of the groyne becomes low-dynamic. A downside of increasing the length is the increase of flow velocities between the high water resting areas and the dike by narrowing the cross-section between the two. What can be concluded is that high water resting areas should not be implemented without analysing the characteristics of the area first. The principle that can be used when designing groynes is that increasing the length has a positive effect on the amount of low dynamic area, but creates higher velocities close to the dike when the cross section between the two gets too narrow.

The number of groynes showed to have a positive relation with the amount of low dynamic surface area. This means that the distances between the groynes has a negative relation with the amount of low dynamic surface area. This principle can be used when designing groynes at intertidal areas.

8. Conclusions and recommendations

8.1. Conclusions

The goal of this master thesis was to understand how groynes affect the hydrodynamics and sediment-dynamics at intertidal flats in estuaries. The four research questions are answered below.

RQ1: What are, according to the measurement data, the flow patterns on the intertidal areas Baalhoek and Knuitershoek and in the nearby tidal channels before construction of the groynes?

During ebb, the flow velocities over the flats are lower compared to the flow velocities during flood, which makes the flats flood dominated. In the channel the flow is also flood dominated when looking at the maximum velocities, but the high velocities during ebb are present for a longer period. The velocity profiles of the point measurements showed to be close to a logarithmic profile in depth, so a depth averaged model should be capable of simulating the flow on these locations.

The flow measurements confirmed that the velocities on the case locations were too high to create low-dynamic areas. The flow directions on the flats are mainly parallel to the channel and little to no circulation is seen. The longitudinal dams are important for the flow patterns on the flats. The openings in these dams guide the flow on (during flood) and off (during ebb) the intertidal flats.

RQ2: How well can a depth-averaged (2DH) Delfd3D FM model simulate the hydrodynamic processes near the groynes at Baalhoek and Knuitershoek?

The Delft3d Flexible Mesh KnuBa-model uses the grid of the NeVla-model converted to a flexible mesh with a resolution of approximately 15x15 m near Knuitershoek and Baalhoek. The boundary conditions were created by the NeVla-model and exist of Riemann boundaries in the west and Discharges in the east. The model uses a uniform manning roughness coefficient of 0.023 $s/m^{1/3}$ in the entire domain. Waves are not included during this study.

The KnuBa-model proved to simulate the hydrodynamic processes near the groynes at Baalhoek and Knuitershoek accurately. The water levels were predicted with an average R^2-value of 0.997 and 0.998 compared to the observed values. The predicted (depth-averaged) flow velocities and directions at Baalhoek are accurate in both the channel and on the intertidal flat. At Knuitershoek the flow velocities on the flat are predicted accurate too, but in the channel the flow velocity during ebb drops too early. The hydrodynamic processes were simulated accurate enough to predict the impact of the new groynes at Baalhoek and Knuitershoek, and to assess a scenario study on the design parameters of the groynes at intertidal flats in estuaries.

RQ3: What are, according to the model, the effects on the flow, the initial sediment transport and bed level on the intertidal areas Baalhoek and Knuitershoek and in the nearby tidal channels before and after construction of the groynes?

The groynes affect the intertidal velocity magnitudes and directions. At Baalhoek the flow velocities decrease on the flats, but between the groynes the flow velocities are still too high to be classified as low-dynamic area. The groynes caused the low-dynamic area to increase initially by 8 - 12 ha, depending on the chosen critical velocity for Baalhoek and 7-11 ha for Knuitershoek. The goal for the groynes was to create 57 ha extra low-dynamic area. The initial increase of low-dynamic area due to the designed groynes therefore is considered too low.

The groynes in intertidal areas in estuaries influence the flow directions in two stages. At first, when the water level is rising, the groynes create circulation cells. At high tide the flow direction becomes parallel to the flow in the channel. This is due to the combination of a large tidal range and maximum water levels that exceed the groyne height.

The designed groynes only have effect on the intertidal flats where the groynes are created and the channel is only affected close to these intertidal flats. In both areas the flood flow velocity magnitudes in the channel directly upstream from the groynes K7 at Knuitershoek and B3 at Baalhoek increase between 0.1 and 0.3 m/s.

The results for the sediment transport and bed level changes showed less sediment transport capacity between the groynes at Knuitershoek and caused possible accretion after the implementation of the designed groynes. At Baalhoek the flood channel in front of the western groyne possibly will fill up, but the groyne seem to block the sediment transport onto the flat. At the tip of al groynes, scour holes will possibly develop. It should be stated that the sediment transport is not calibrated.

Three characteristic differences between the different groynes showed effects; the high water resting areas, the height differences and the distance between groynes. The high water resting areas at Knuitershoek increase the amount of low-dynamic area. Downstream of these resting areas the maximum flow velocities are below 0.6 m/s. Increasing groyne height seems to have an increasing effect on the amount of low-dynamic surface area.

RQ4: How do design parameters affect the hydrodynamic impact of groynes in intertidal areas like Baalhoek and Knuitershoek, and the nearby tidal channels?

During the scenario study three design parameters of the groynes at Baalhoek and Knuitershoek were investigated: groyne height, length of high water resting areas and the number of groynes (distance between the groynes).

The groyne height has an increasing effect on the low-dynamic surface area, but also increases the maximum flow velocities in the channel. The curves for the amount of low-dynamic surface area as function of the groyne height showed similarities for both areas. Although the values are case dependent, a tipping point is clearly visible. For groyne heights beyond this tipping point the increase of the amount of low dynamic area does not weight up against the velocity increases in the channel and on the flat.

The effect of the high water resting areas is case dependent. At Knuitershoek they create more low dynamic area, but in the same configuration at Baalhoek they increase the velocities. They are sensitive to the presence of channels and the orientation of the channel flow. The general conclusion of the effect of high water resting areas is that increasing the length has a positive effect on the amount of low dynamic area, but creates higher velocities close to the dike when the cross section between the two gets too narrow.

The number of groynes showed to have a positive relation with the amount of low dynamic surface area. This means that the distances between the groynes has a negative relation with the amount of low dynamic surface area.

The goal of this study was to understand how groynes affect the hydrodynamics and sediment-dynamics at intertidal flats in estuaries. Three design parameters showed significant impacts on the hydrodynamics when looking at the designed groynes. The impact of each parameter was studied and the relation between three design parameters and the amount of low-dynamic area became clear. This understanding of the hydrodynamics can be used in future projects but also in the current project to improve the design at Baalhoek. The understanding of the sediment dynamics were only studied qualitatively in an exploratory model run and should be looked at in further research.

This study showed that DELFT3D Flexible Mesh (the KnuBa-model) reproduced the flow at intertidal flats accurate after local refinement of the grid. This spared a lot of time and work compared to older software because no separate domains have to be created. It also showed that the design at Baalhoek and Knuitershoek was less effective as expected in terms of initial low-dynamic area and it showed the impact of three design parameters (groyne height, high water resting area length and the distance between groynes) on the hydrodynamics and the amount of low-dynamic area.

8.2. Recommendations

Groyne design at Baalhoek and Knuitershoek

The design at Knuitershoek showed promising results for the creation of low-dynamic area. At Baalhoek the results, based on the initial hydrodynamic impacts, are less promising. The flow velocities between the groynes are not decreased sufficient to create low dynamic area and even increase the amount of high dynamic area between the groynes. The groyne design at Baalhoek should be reconsidered. The results of this study could be used as a guide during the redesigning of the groynes. The scenario study showed that increasing the groyne heights can have beneficial effects on the amount of low dynamic area. Adding an extra groyne also showed promising results.

Further research

The first step in further research is the validation of the KnuBa-model once new measurement data (T1) becomes available. The KnuBa-model is currently only calibrated on the situation before the implementation of the designed groynes. From September 2017 new measurements will be conducted, on both Baalhoek and Knuitershoek, which can be used to validate the model and to test if the impacts of the designed groynes are predicted as accurate as the situation before the implementation.

Next, the KnuBa-model can be extended with waves, sediment transport and bottom update. This would require wave measurements and sediment measurements and bed level measurements to calibrate and validate the model. By implementing the sediment transport and using bottom updates in the process, long term development of the flats can be predicted. It should be stated that, when looking at sediment transport, it is important to find the reason for the drop in ebb flow velocities close to the intertidal flat at Knuitershoek. This drop in velocities will cause an overestimation of the asymmetry between flood and ebb transport.

Furthermore an extension of the definition of low-dynamic area should be considered. It should be extended with waves and the percentage of time that critical velocities are exceeded.

At last, further research on the general application of the graphs for low-dynamic area as function of groyne height and 'high water resting area' length should be done. This can be done with for example a Monte-Carlo analysis on the design parameters of groynes. By creating multiple scenarios, relationships between the parameters become visible.

9. References

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Appendix A: Potential of the designs at Knuitershoek and Baalhoek

Relative flood and ebb velocity changes due to the groynes as modelled by Dam et al., 2008.

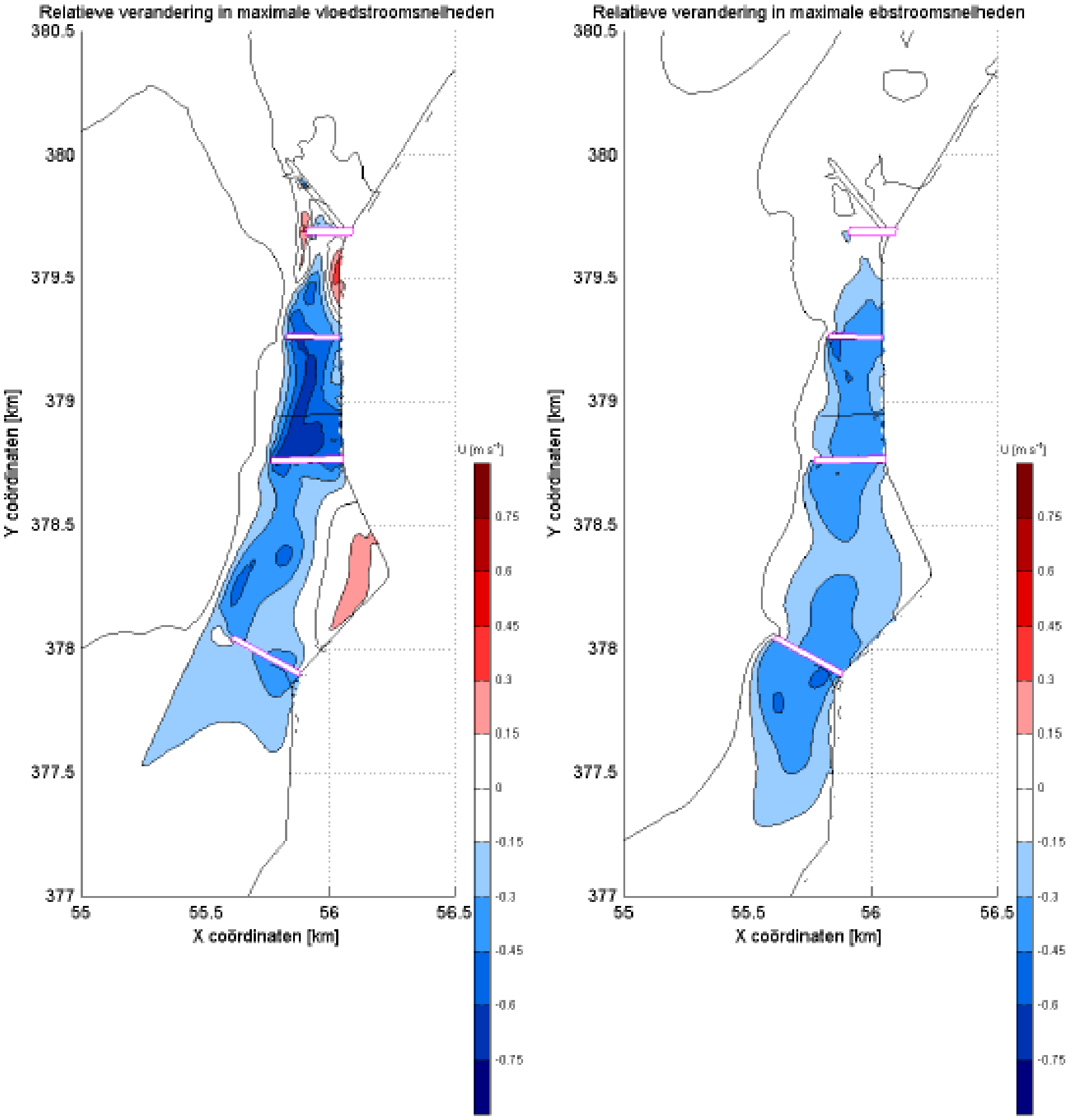


Figure A 1 - Relative maximum flood flow velocity changes (left) and maximum ebb flow velocity changes (right) at Knuitershoek as modelled by Dam et al. (2008).

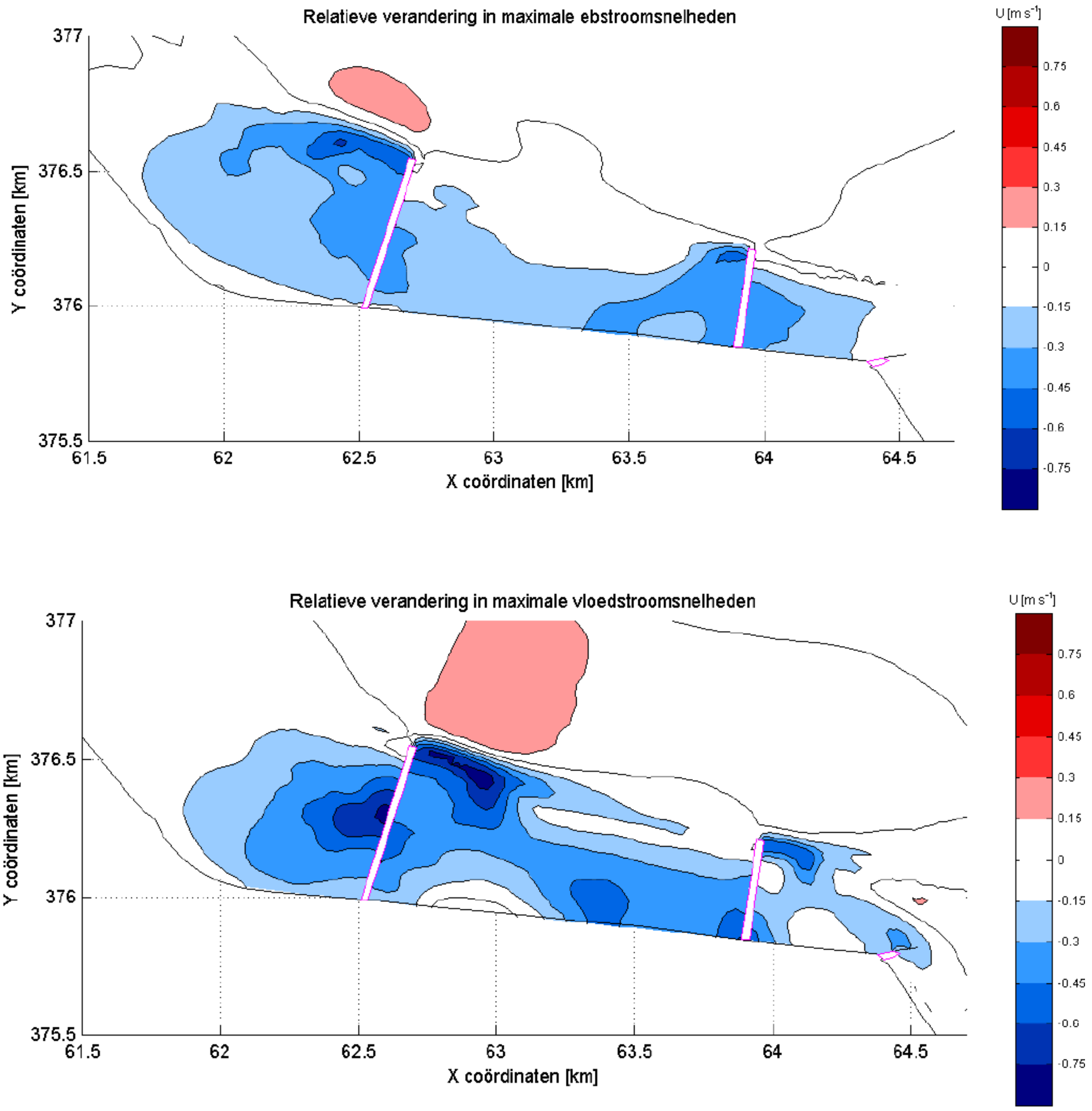


Figure A 2 - Relative maximum flood flow velocity changes (below) and maximum ebb flow velocity changes (above) at Baalhoek as modelled by Dam et al. (2008).

Appendix B: Wind roses used for the KnuBa-model

The wind rose for measurement location Terneuzen Westsluis (TNWS) is shown in Figure A 3.

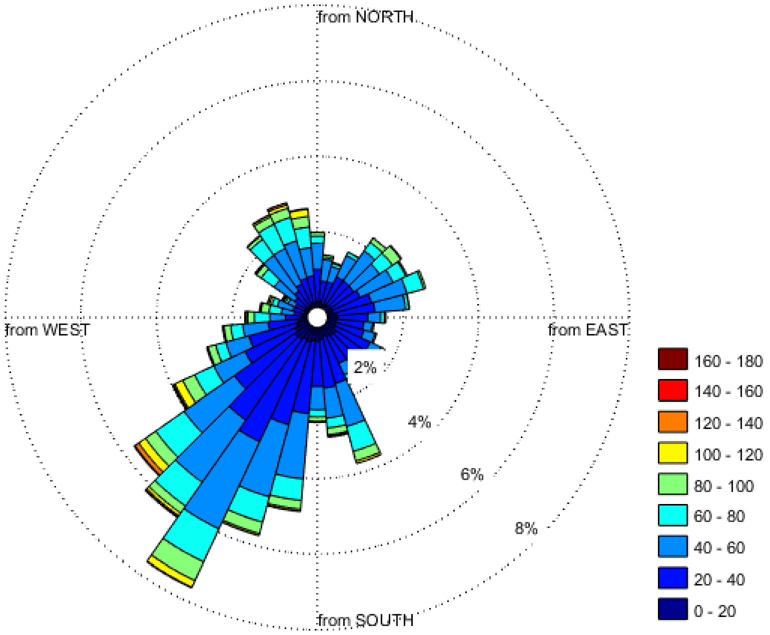


Figure A 3 - Wind rose of measurement location Terneuzen Westsluis TNWS.

The wind rose for measurement location Hansweert Wind (HAWI) is shown in Figure A 4.

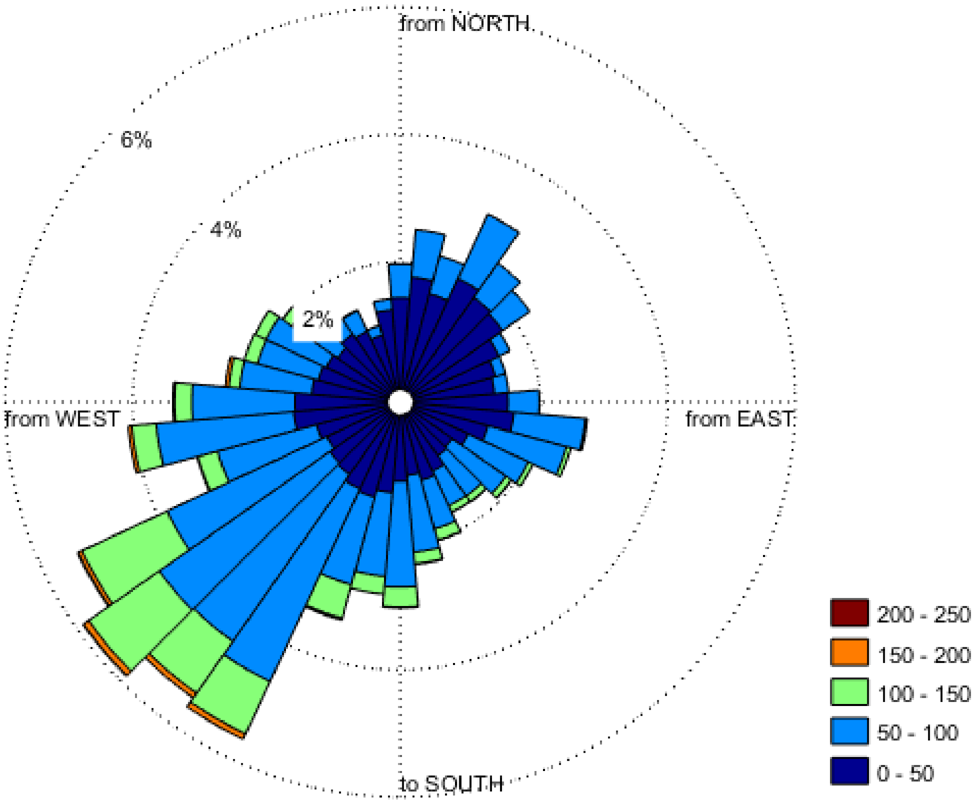


Figure A 4 - Wind rose of measurement location HAWI.

Appendix C: Flow velocities calibration scores

On the next two pages the scores and the scatterplots of the flow velocity measurements and model results at Baalhoek and Knuitershoek are shown.

Scatterplots of the flow velocity measurements and model results at Knuitershoek

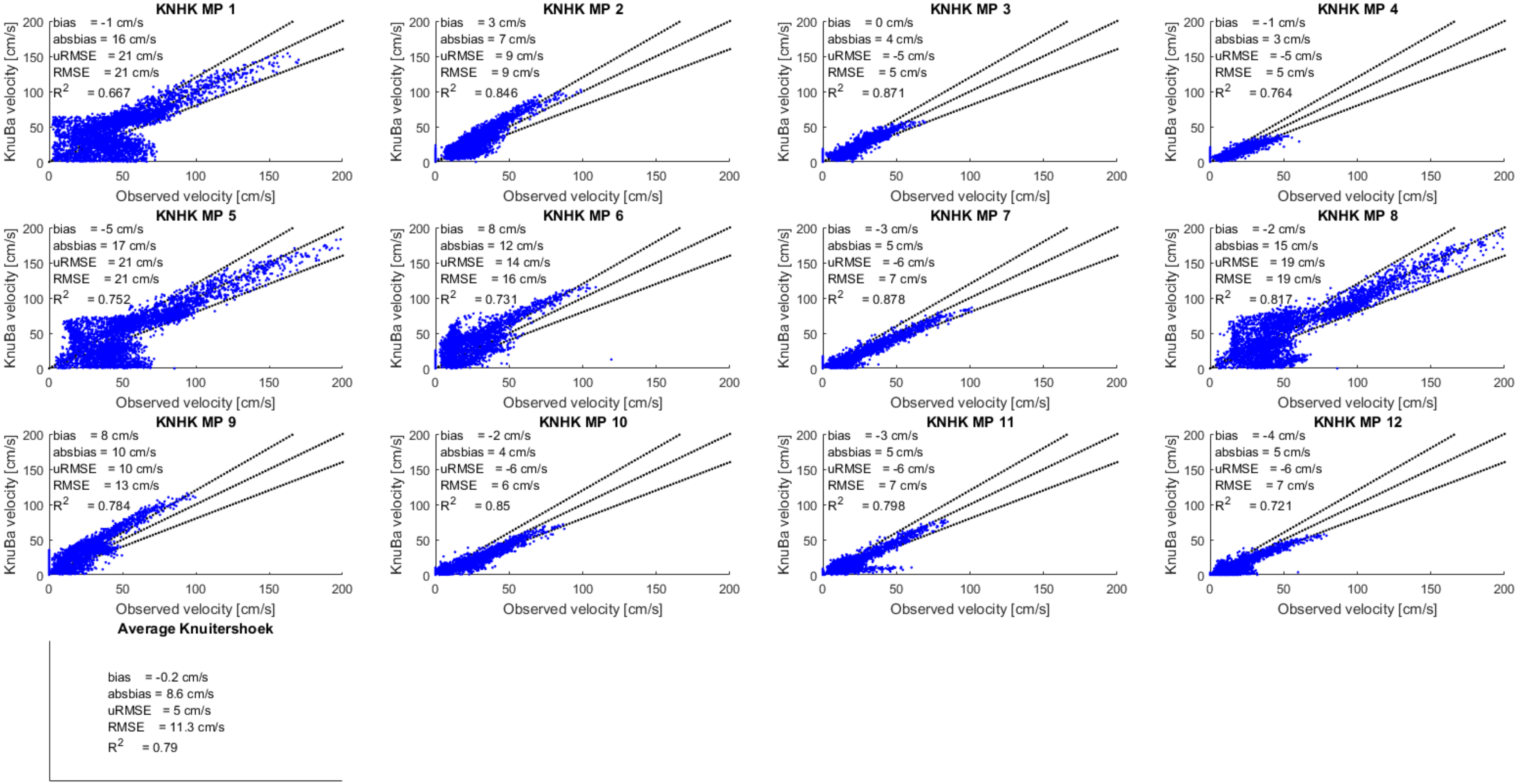


Figure A 5 - Scatterplots of the flow velocity measurements and model results at Knuitershoek

Scatter plots of the flow velocity measurements and model results at Baalhoek

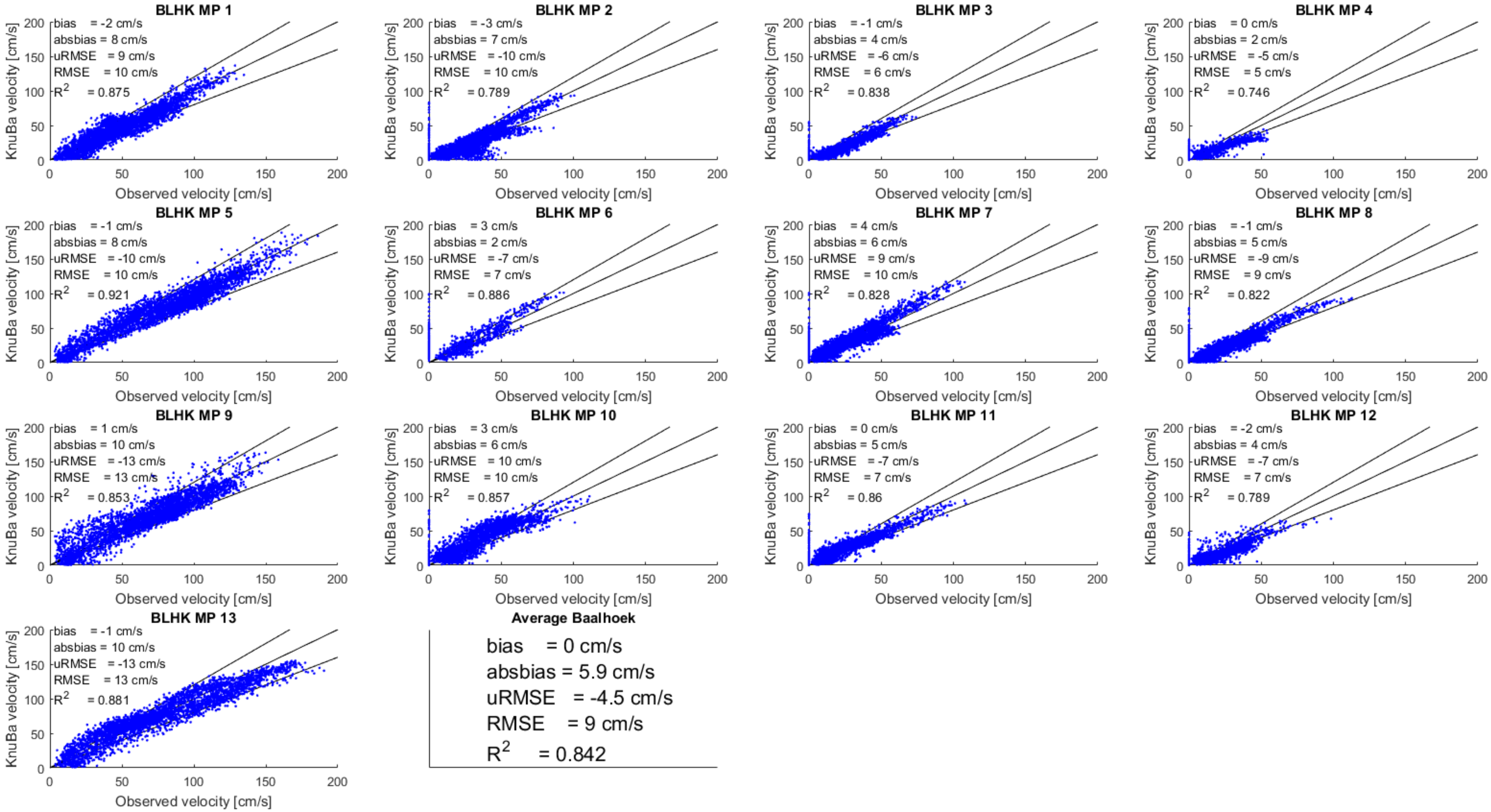


Figure A 6 - Scatterplots of the flow velocity measurements and model results at Baalhoek

Appendix D: Modelled flow velocity transects

This appendix shows the results of the KnuBa-model on the transects as sailed during the measurements.

Baalhoek northern transect:

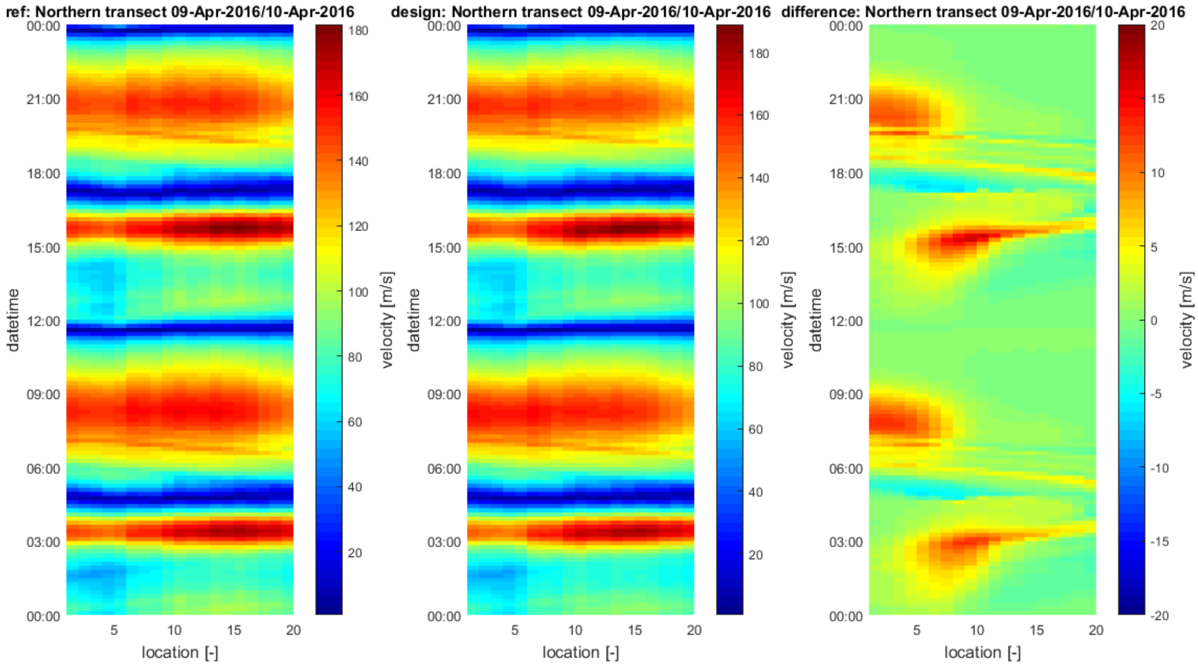


Figure A 7 - Modelling results for the northern transect at Baalhoek. Left: the reference model, middle: the design model and right: the difference (Design- Reference)

Baalhoek southern transect:

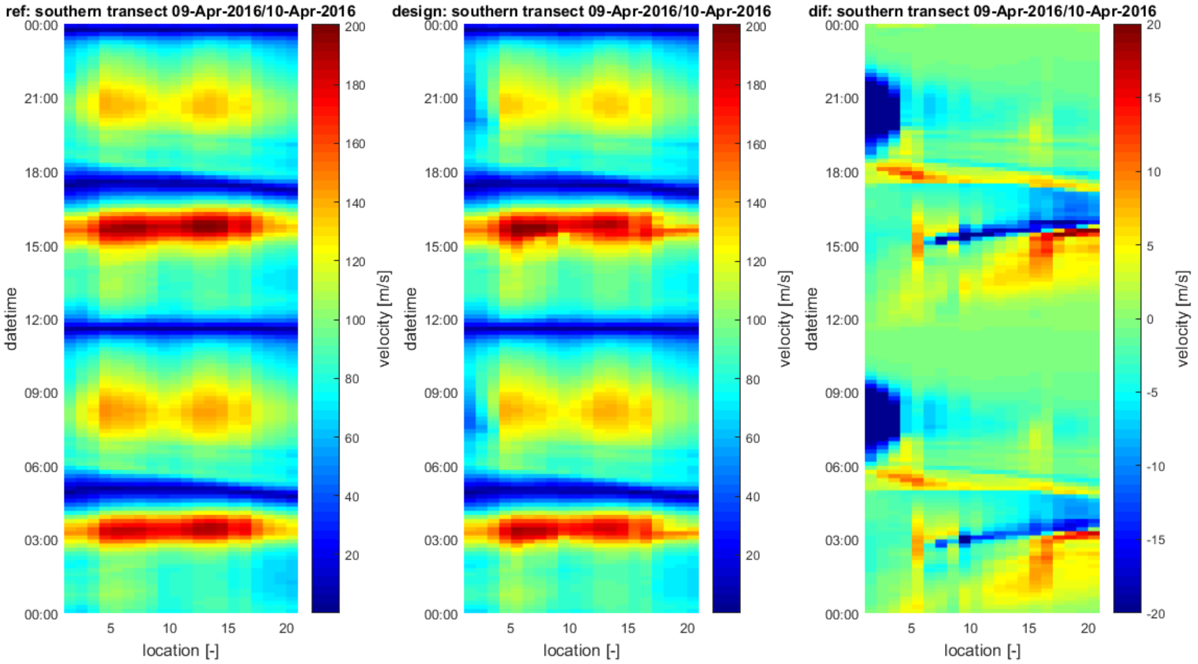


Figure A 8 -Modelling results for the northern transect at Baalhoek. Left: the reference model, middle: the design model and right: the difference (Design- Reference)

Knuitershoek:

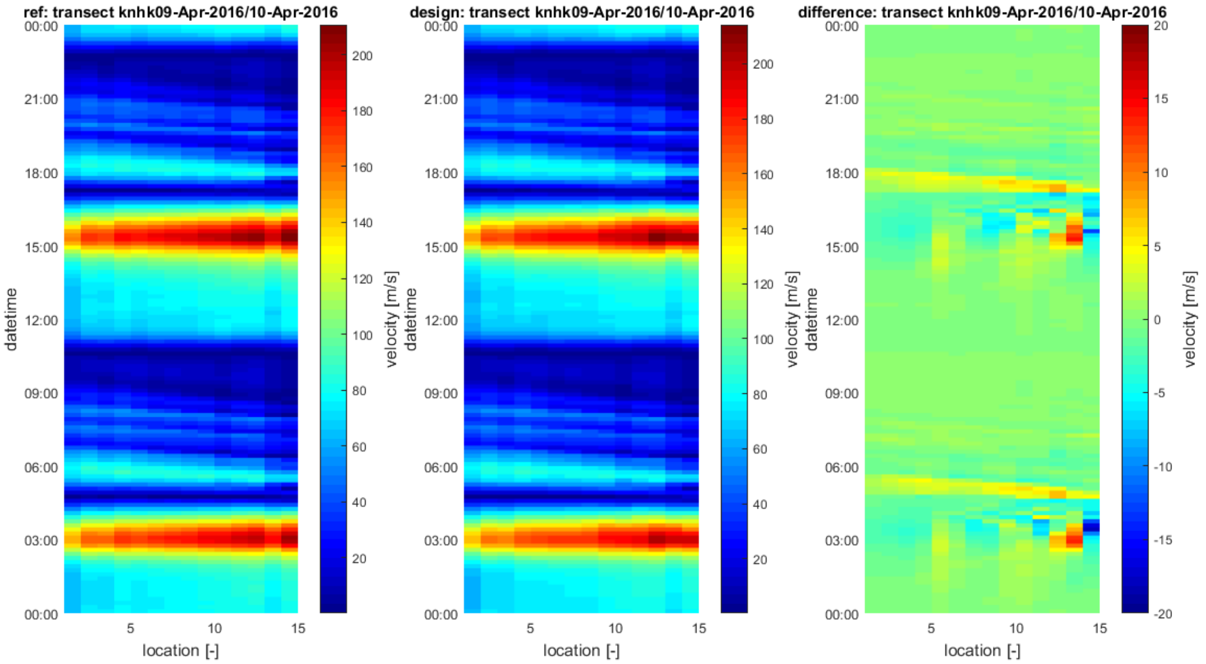


Figure A 9 -Modelling results for the transect at Knuitershoek. Left: the reference model, middle: the design model and right: the difference (Design- Reference)

Appendix E: areas for low-dynamic surface area

Baalhoek:

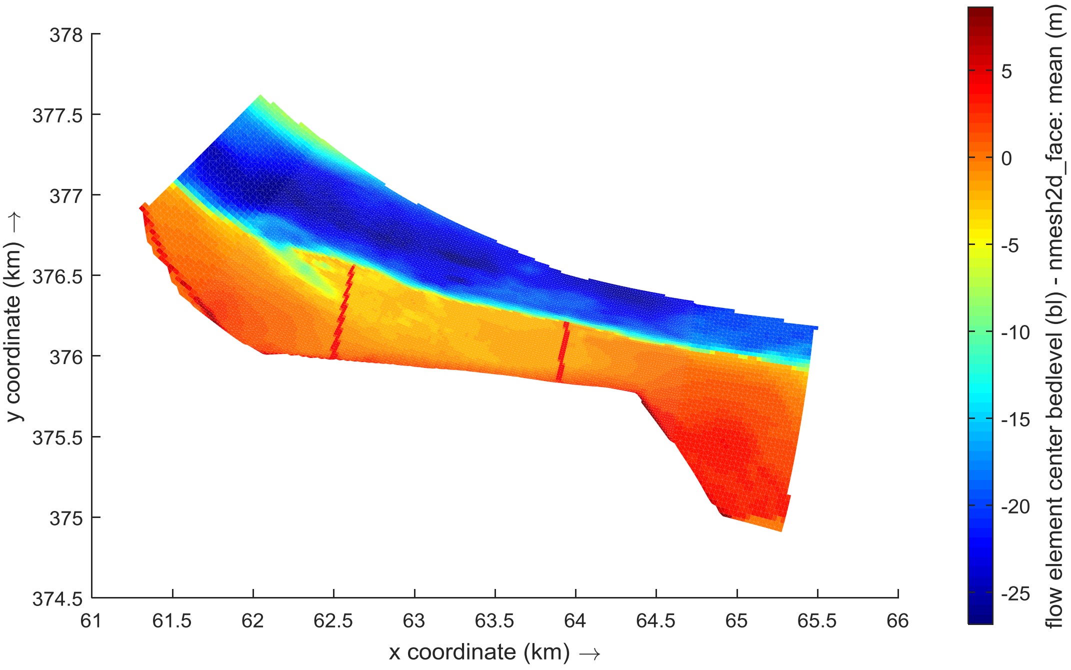


Figure A 10 - Area used to determine the amount of low-dynamic area at Baalhoek

Knuitershoek:

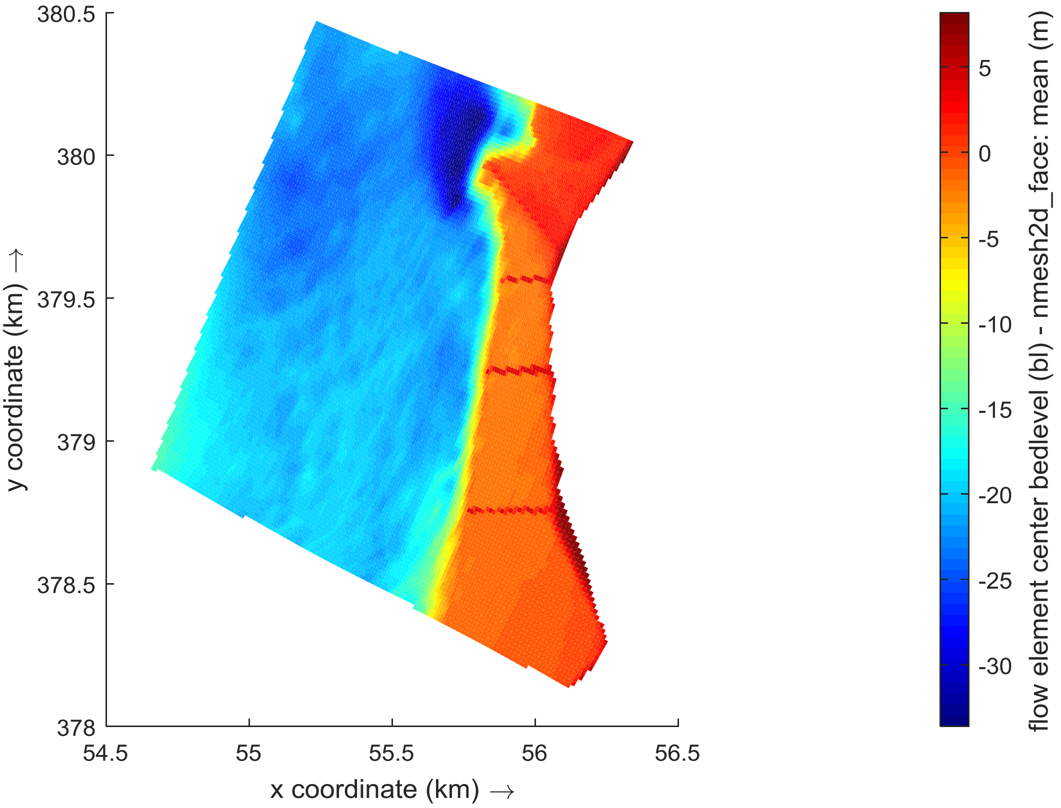


Figure A 11 - Area used to determine the amount of low-dynamic area at Knuitershoek

Appendix F: Results of the scenario runs

F.1. Scenario runs: Groyne heights

F.1.1. Baalhoek

This appendix shows the maximum velocities at Baalhoek during the groynes height scenario runs followed by differences compared to the reference scenario.

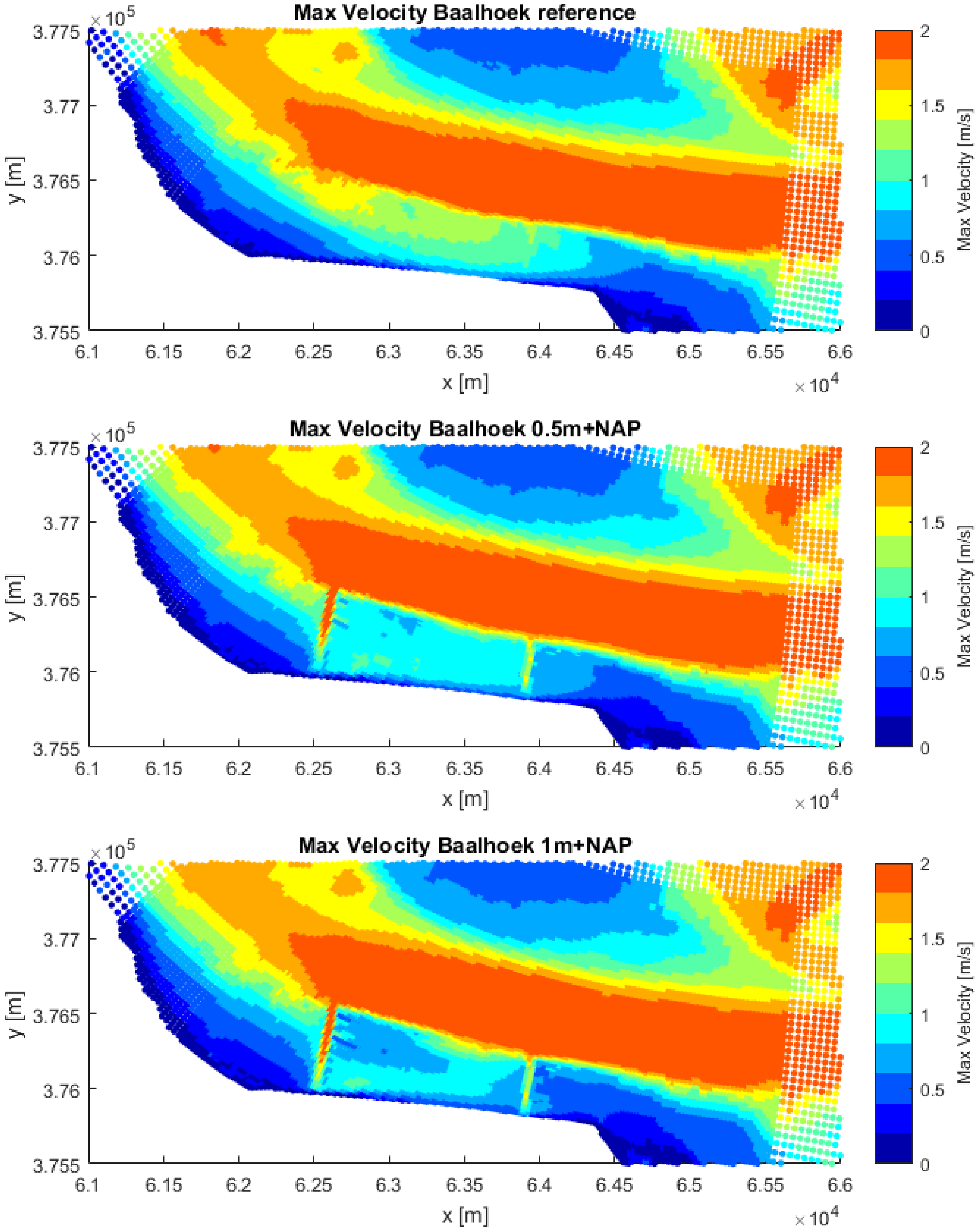


Figure A 12 - Maximum velocities for the groyne height scenario runs at Baalhoek (Reference, 0.5 and 1.0 m+NAP).

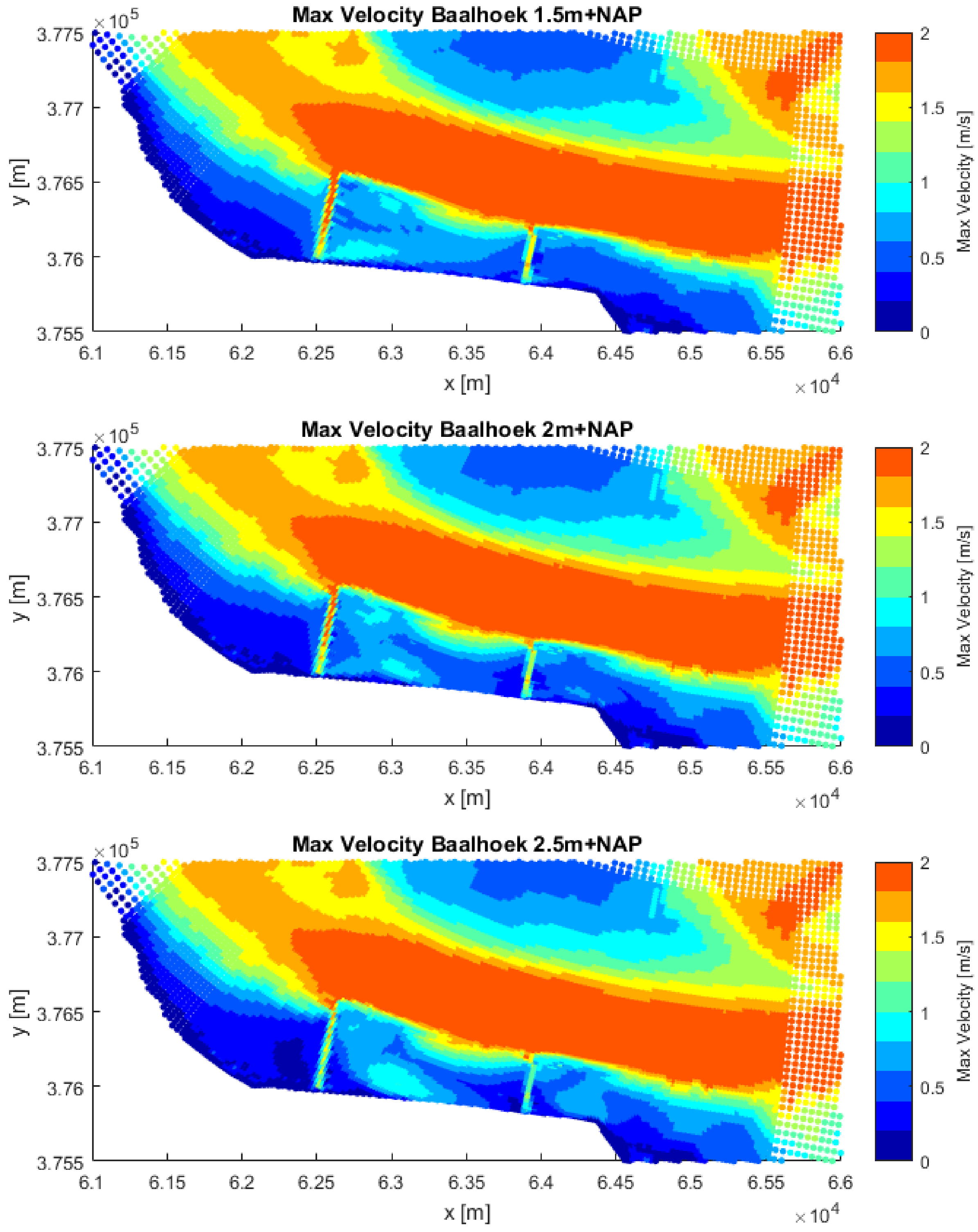


Figure A 13 - Maximum velocities for the groyne height scenario runs at Baalhoek (1.5 - 2.5 m+NAP).

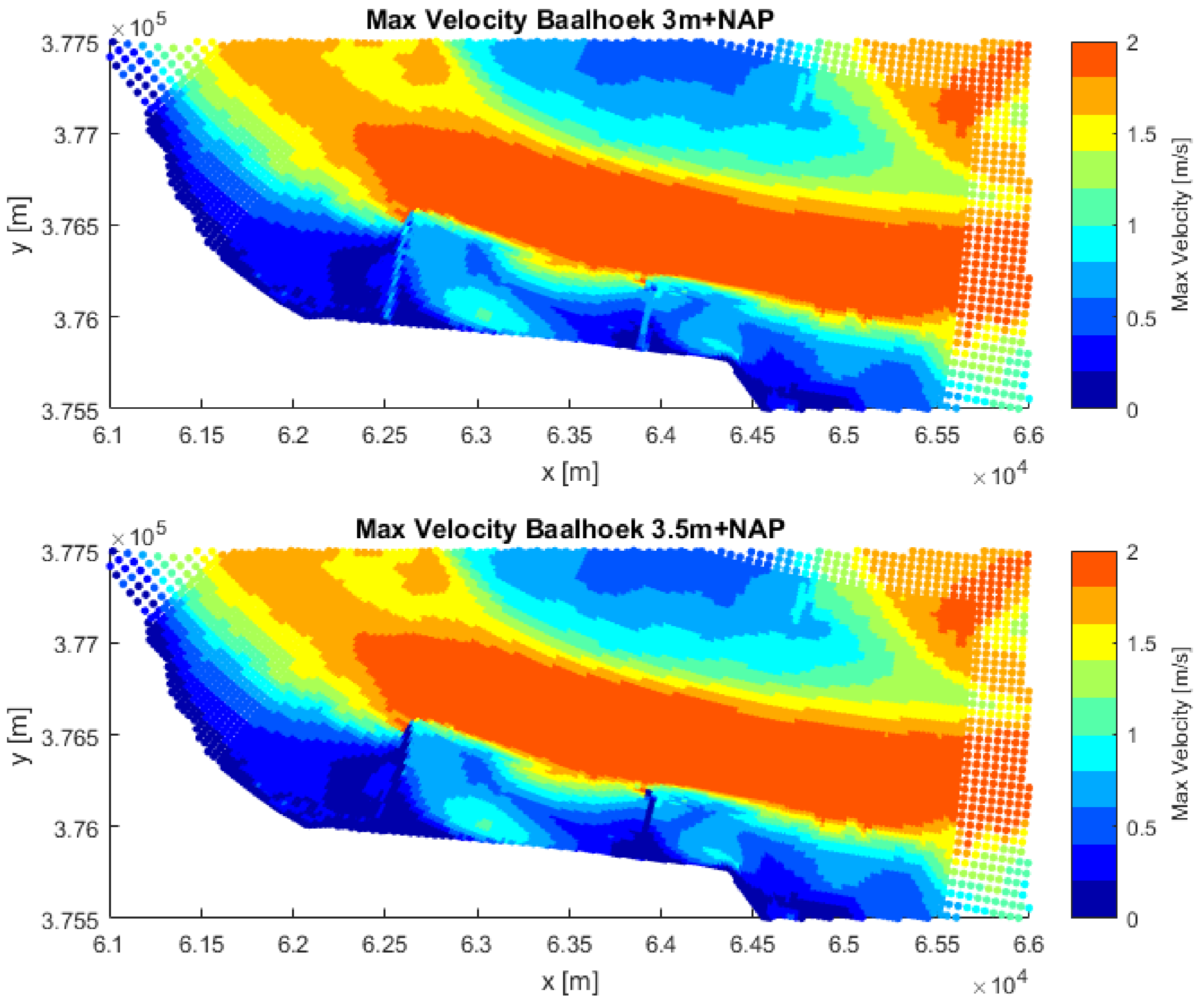


Figure A 14 - Maximum velocities for the groyne height scenario runs at Baalhoek (3.0 and 3.5 m+NAP).

Differences in maximum velocity compared to the reference scenario during the groyne heigth scenario runs:

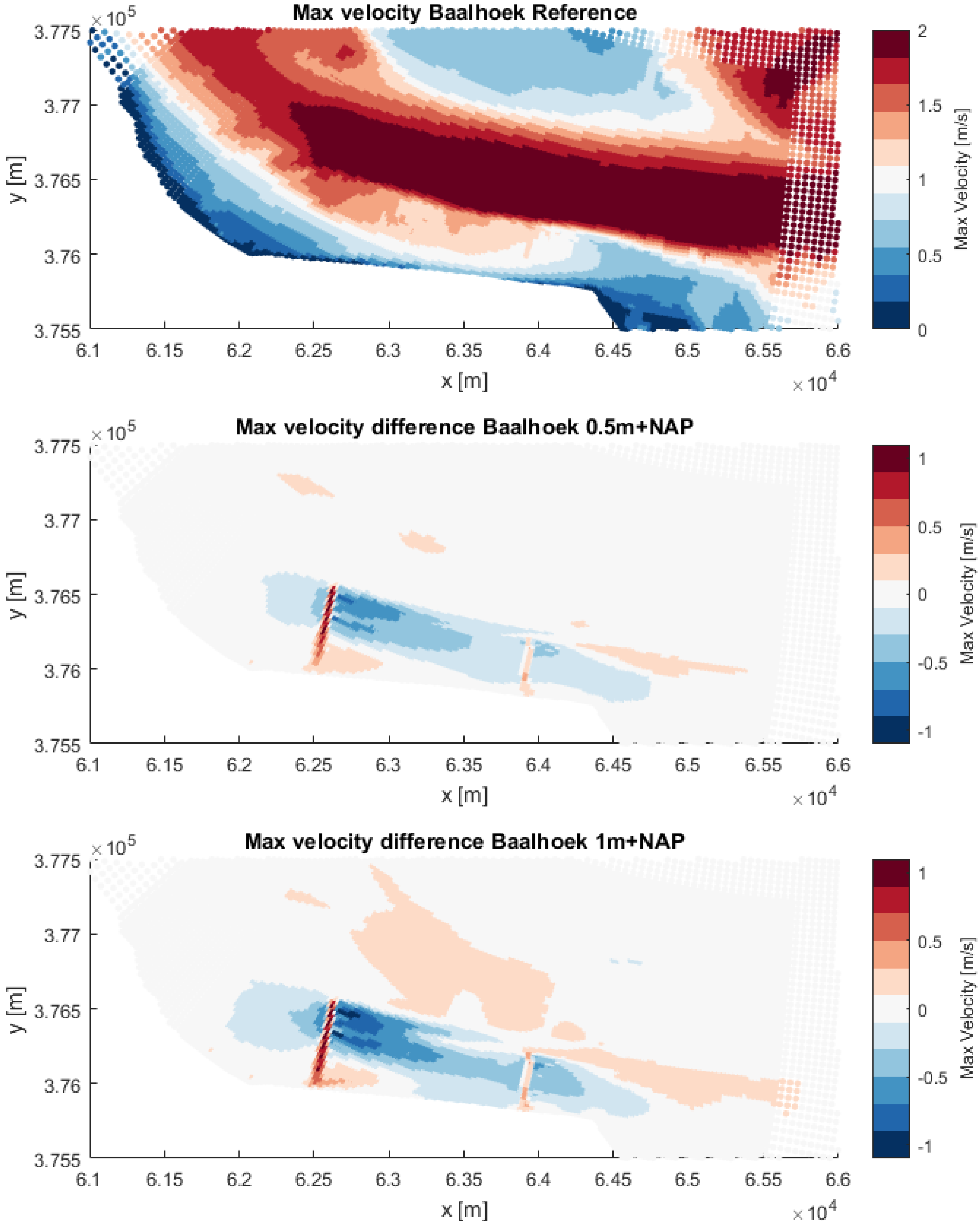


Figure A 15 - Differences in maximum velocities for the groyne height scenario runs at Baalhoek (Reference, 0.5 and 1.0 m+NAP)

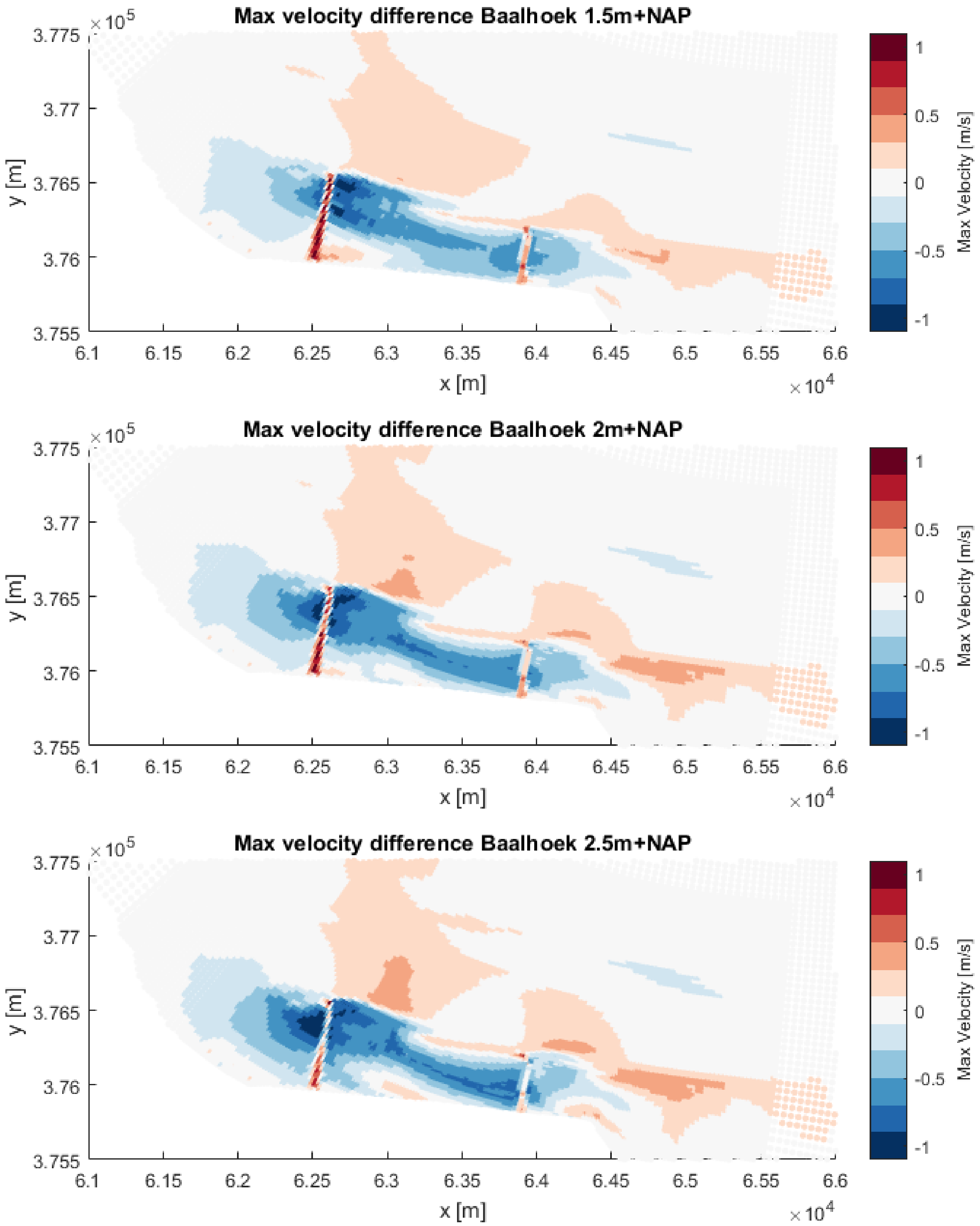


Figure A 16 - Differences in maximum velocities for the groyne height scenario runs at Baalhoek (1.5 - 2.5 m+NAP)

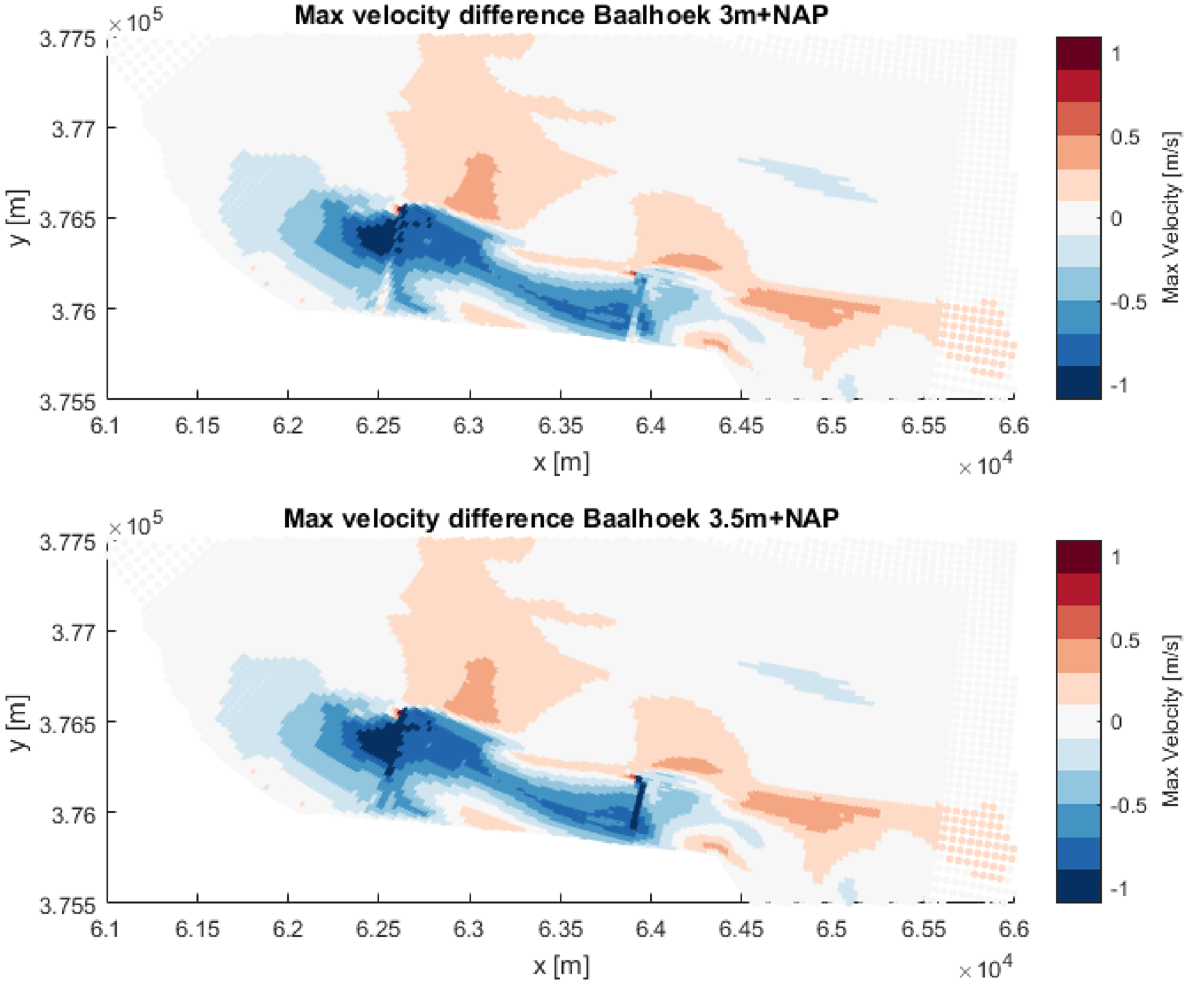


Figure A 17 - Differences in maximum velocities for the groyne height scenario runs at Baalhoek (3.0 and 3.5 m+NAP)

F.1.2. Knuitershoek

This appendix shows the maximum velocities at Knuitershoek during the groynes height scenario runs followed by the difference compared to the reference scenario.

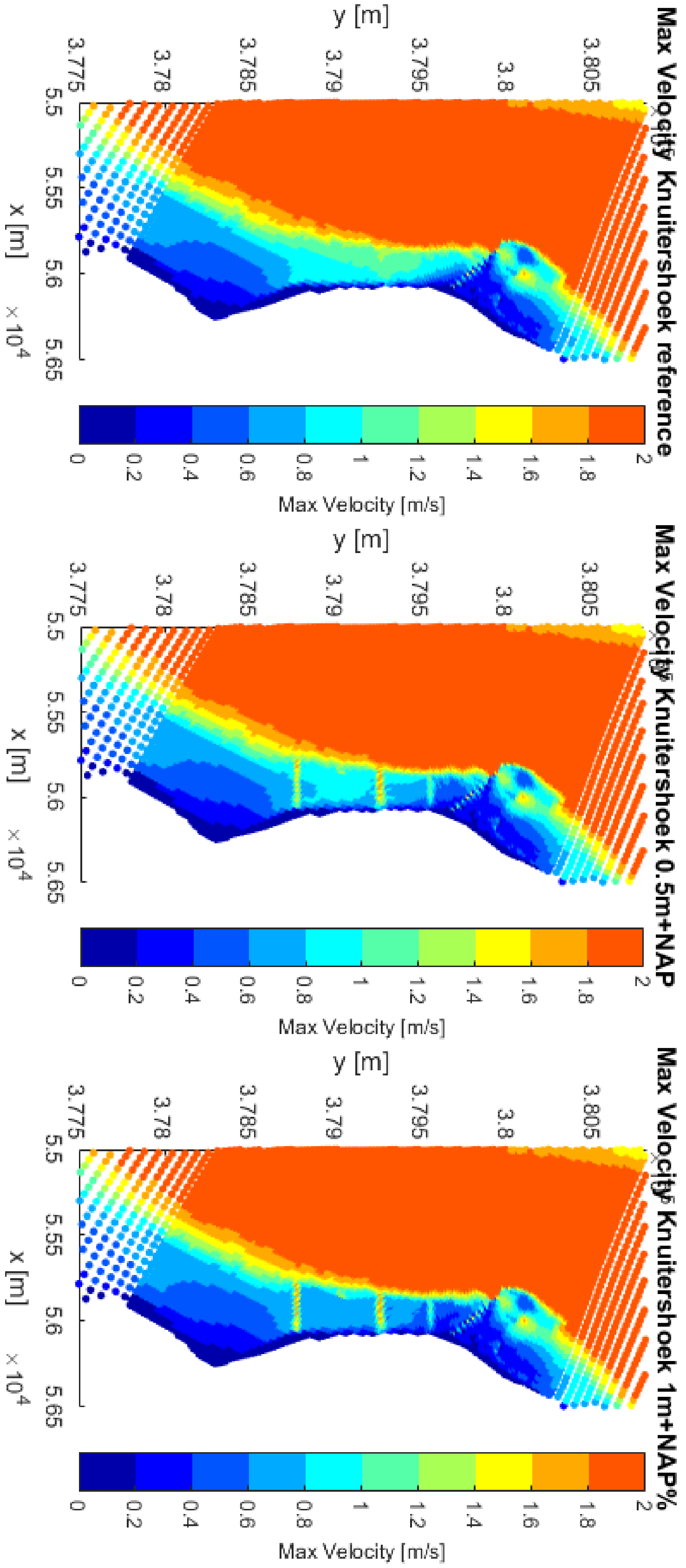


Figure A 18 - Maximum velocities for the groyne height scenario runs at Knuitershoek (reference, 0.5 and 1.0 m+NAP).

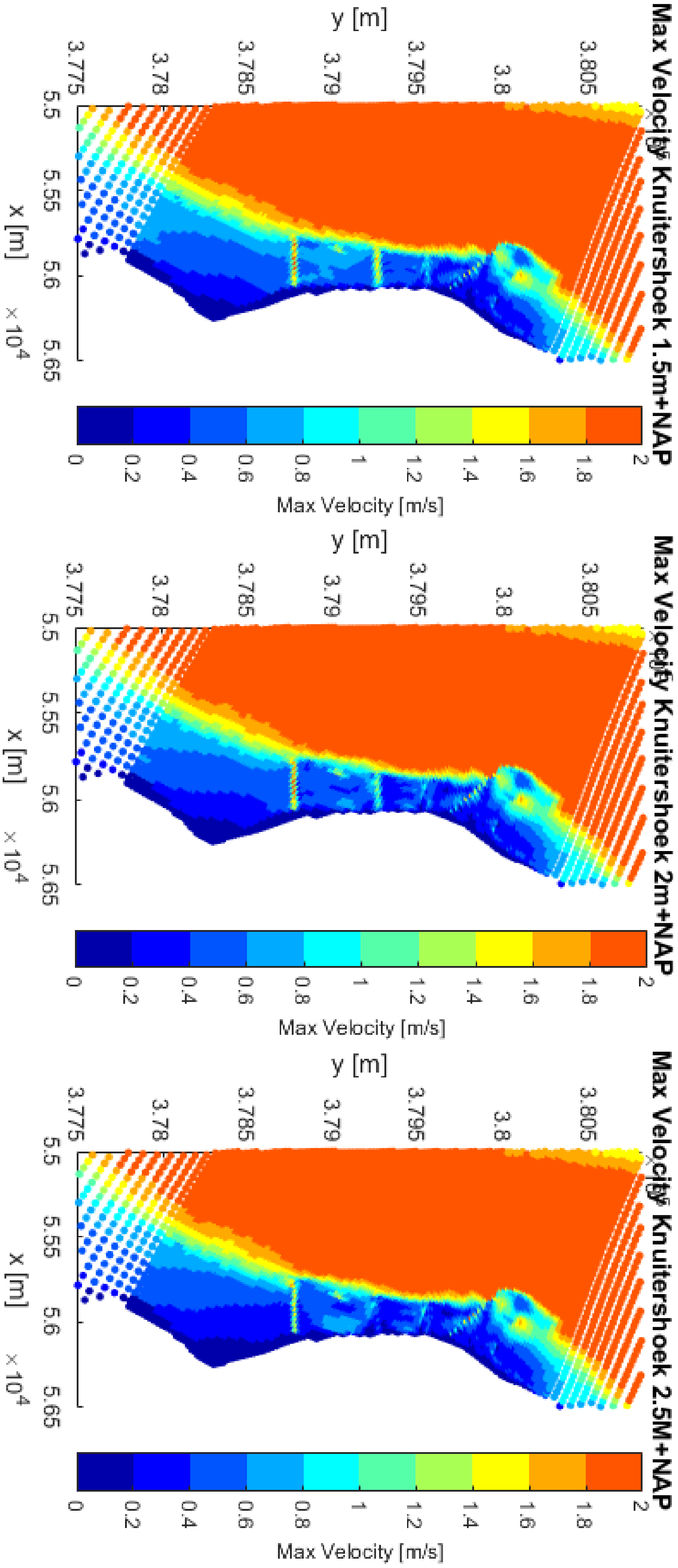


Figure A 19 - Maximum velocities for the groyne height scenario runs at Knuitershoek (1.5 - 2.5 m+NAP).

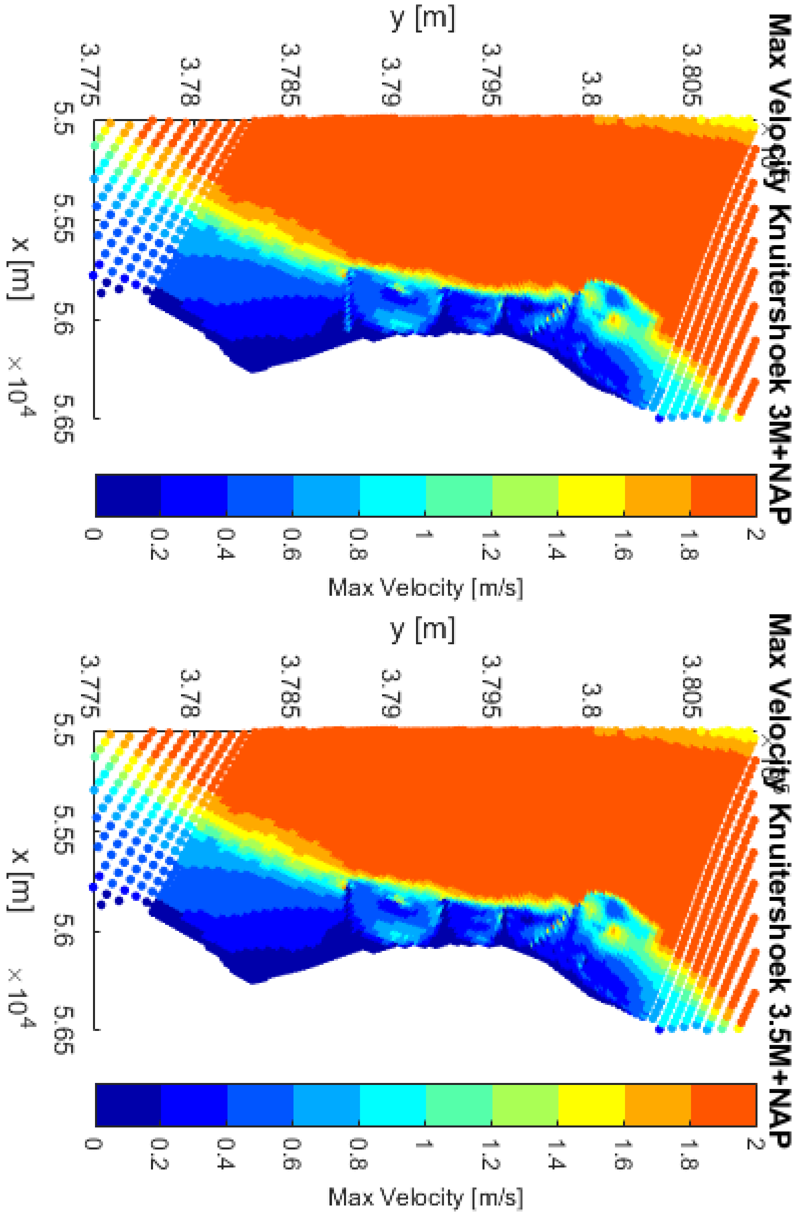


Figure A 20 - Maximum velocities for the groyne height scenario runs at Knuitershoek (3.0 and 3.5 m+NAP).

Differences in maximum velocity of different groyne heigths compared to the reference scenario.

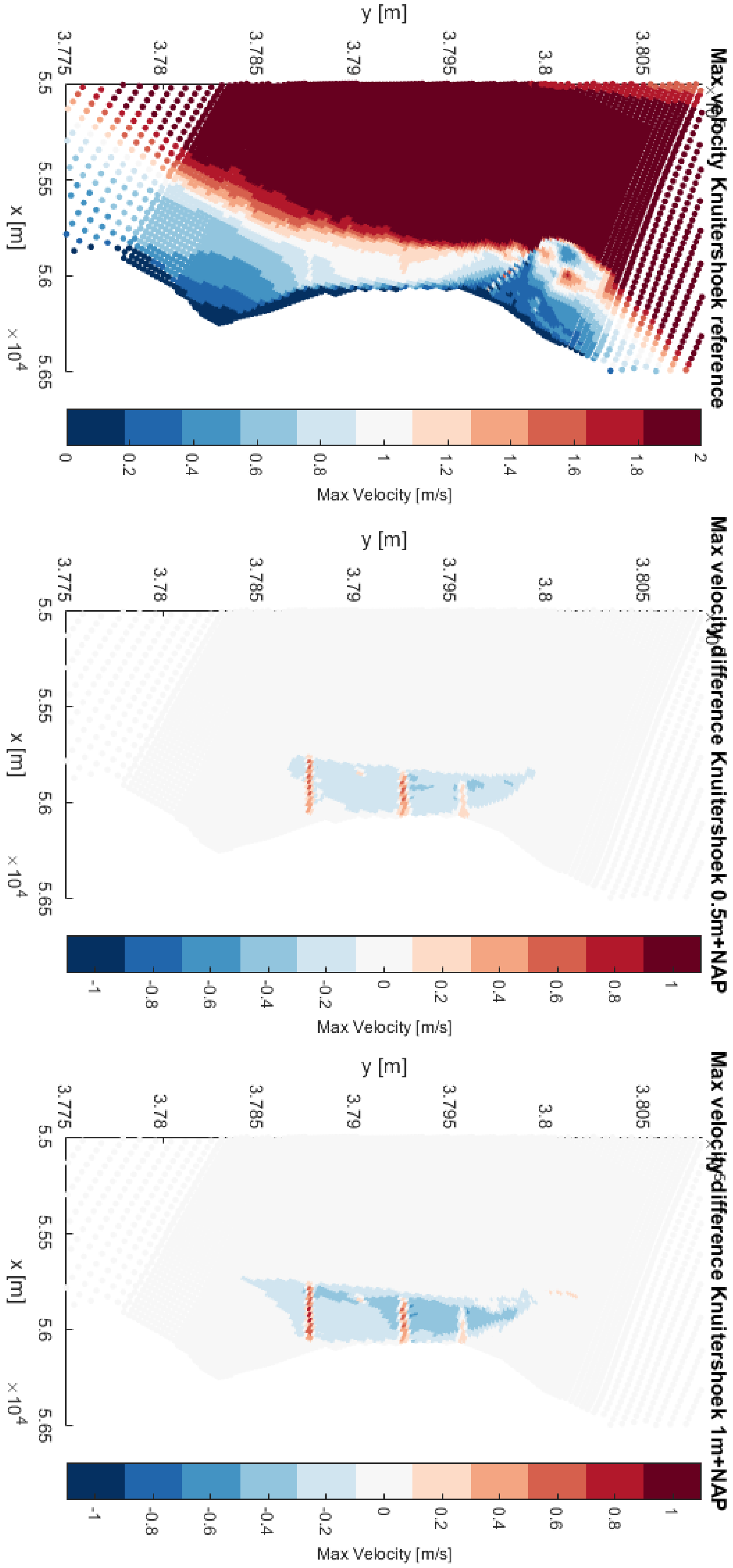


Figure A 21 - Differences in maximum velocities for the groyne height scenario runs at Knuitershoek (reference, 0.5 and 1.0 m+NAP)

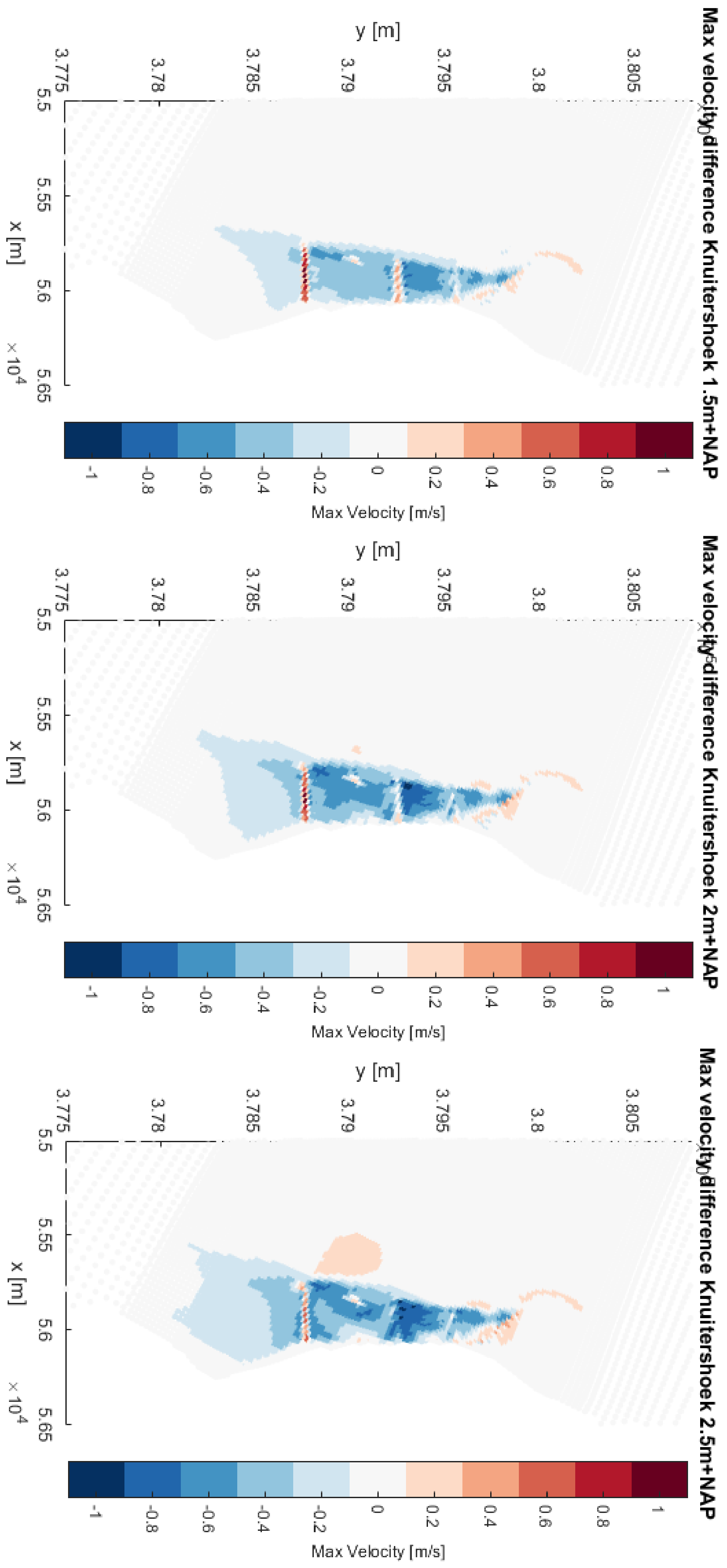


Figure A 22 - Differences in maximum velocities for the groyne height scenario runs at Knuitershoek (1.5 - 2.5 m+NAP)

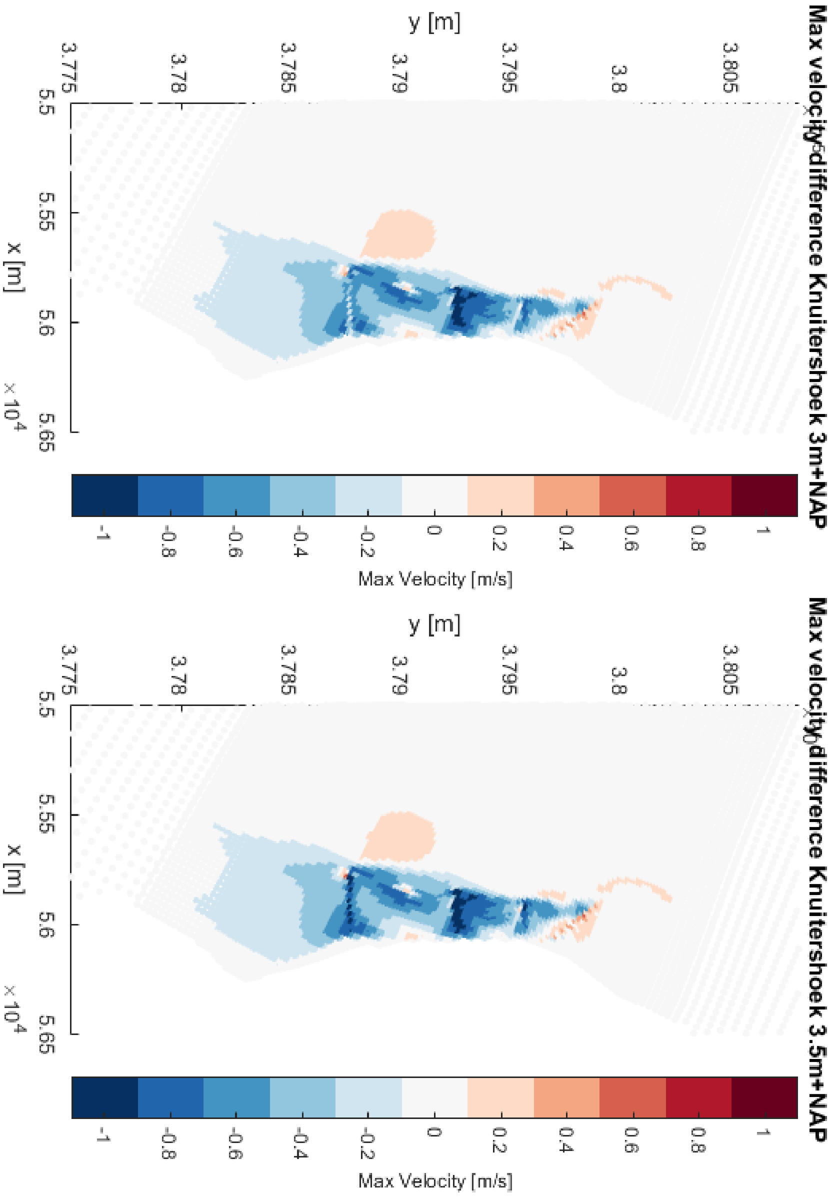


Figure A 23 - Differences in maximum velocities for the groyne height scenario runs at Knuitershoek (3.0 and 3.5 m+NAP)

F.2. Scenarios: High water resting areas

F.2.1. Baalhoek

This appendix shows the maximum velocities at Baalhoek during the high water resting area scenario runs followed by differences compared to the reference scenario.

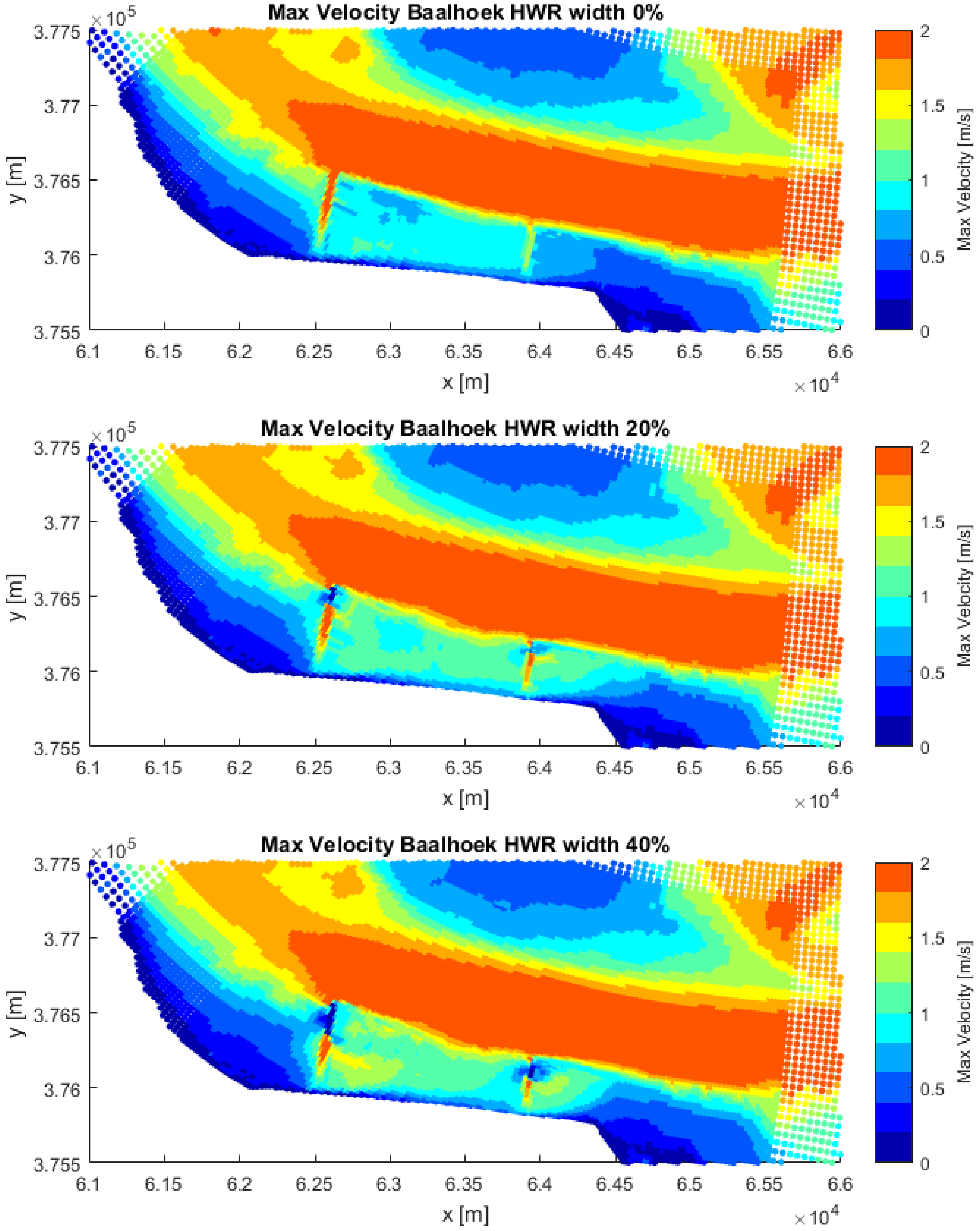


Figure A 24 - Maximum velocities for the high water resting area length scenario runs at Baalhoek (0 %, 20 % and 40 %)

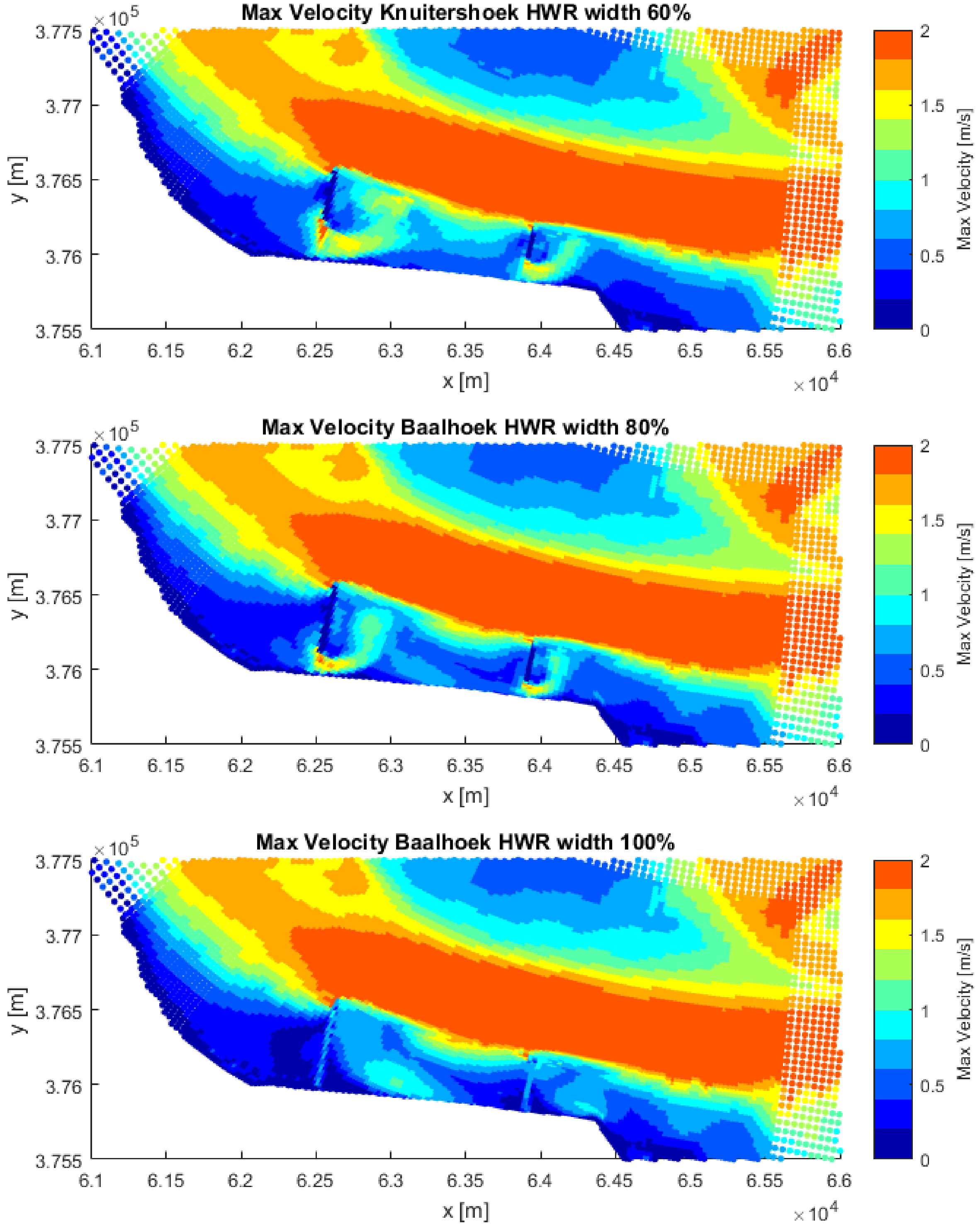


Figure A 25 - Maximum velocities for the high water resting area length scenario runs at Baalhoek (60 %, 80 % and 100 %)

Maximum velocity difference compared to no high water resting area.

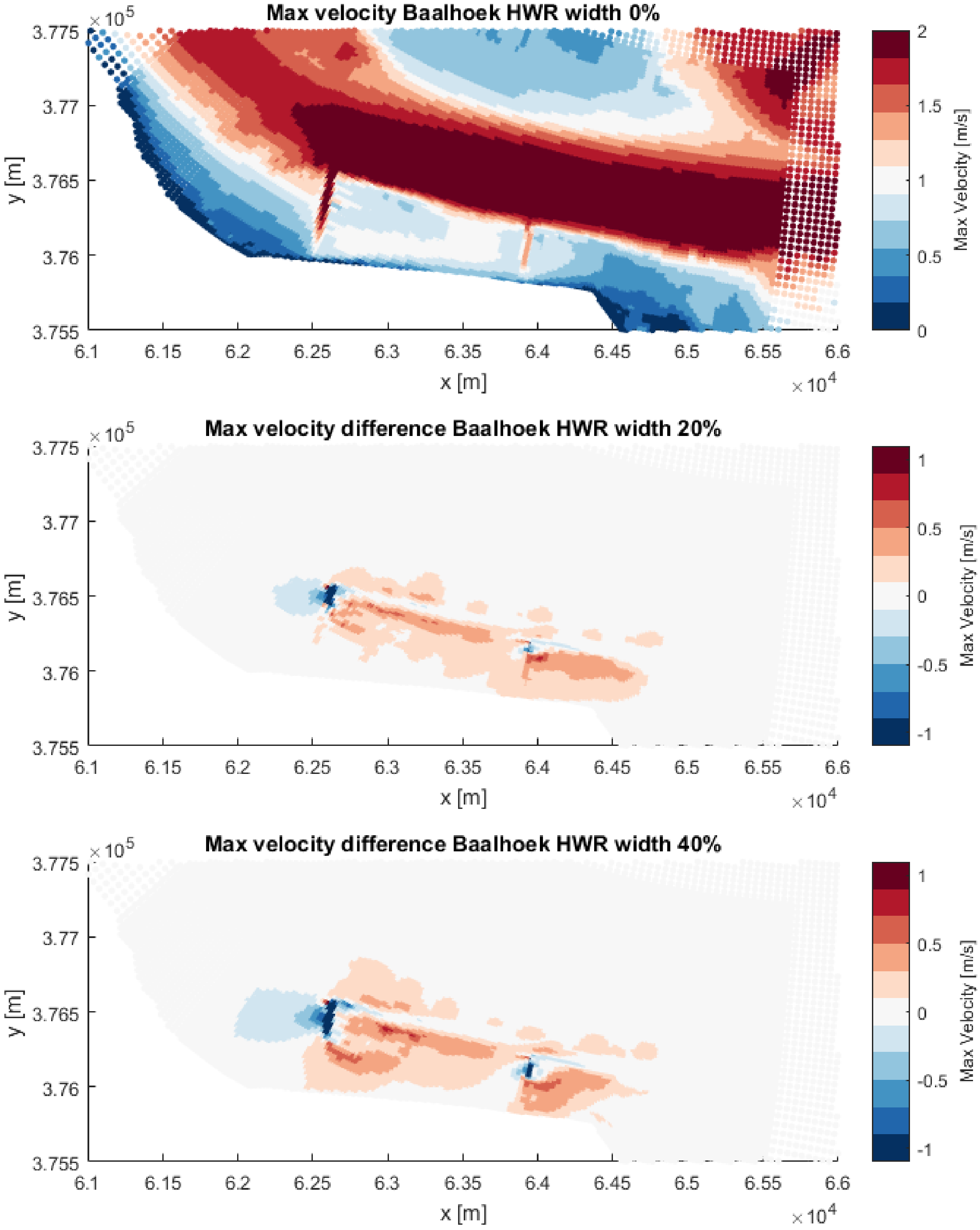


Figure A 26 - Difference in maximum velocities for the high water resting area length scenario runs at Baalhoek (0 %, 20 % and 40 %)

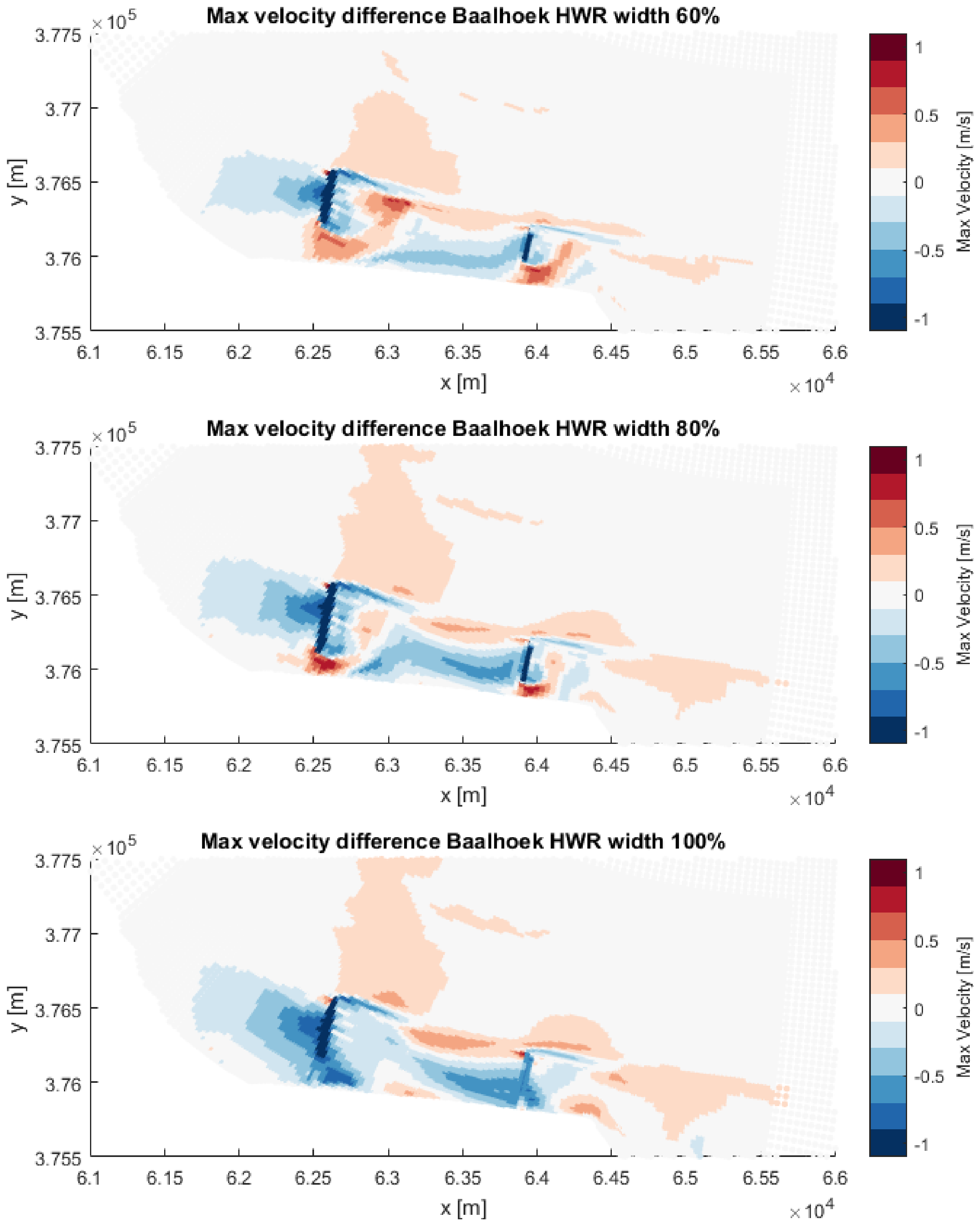


Figure A 27 - Difference in maximum velocities for the high water resting area length scenario runs at Baalhoek (60 %, 80 % and 100 %)

F.2.2. Knuitershoek

This appendix shows the maximum velocities at Knuitershoek during the high water resting area scenario runs followed by differences compared to the reference scenario.

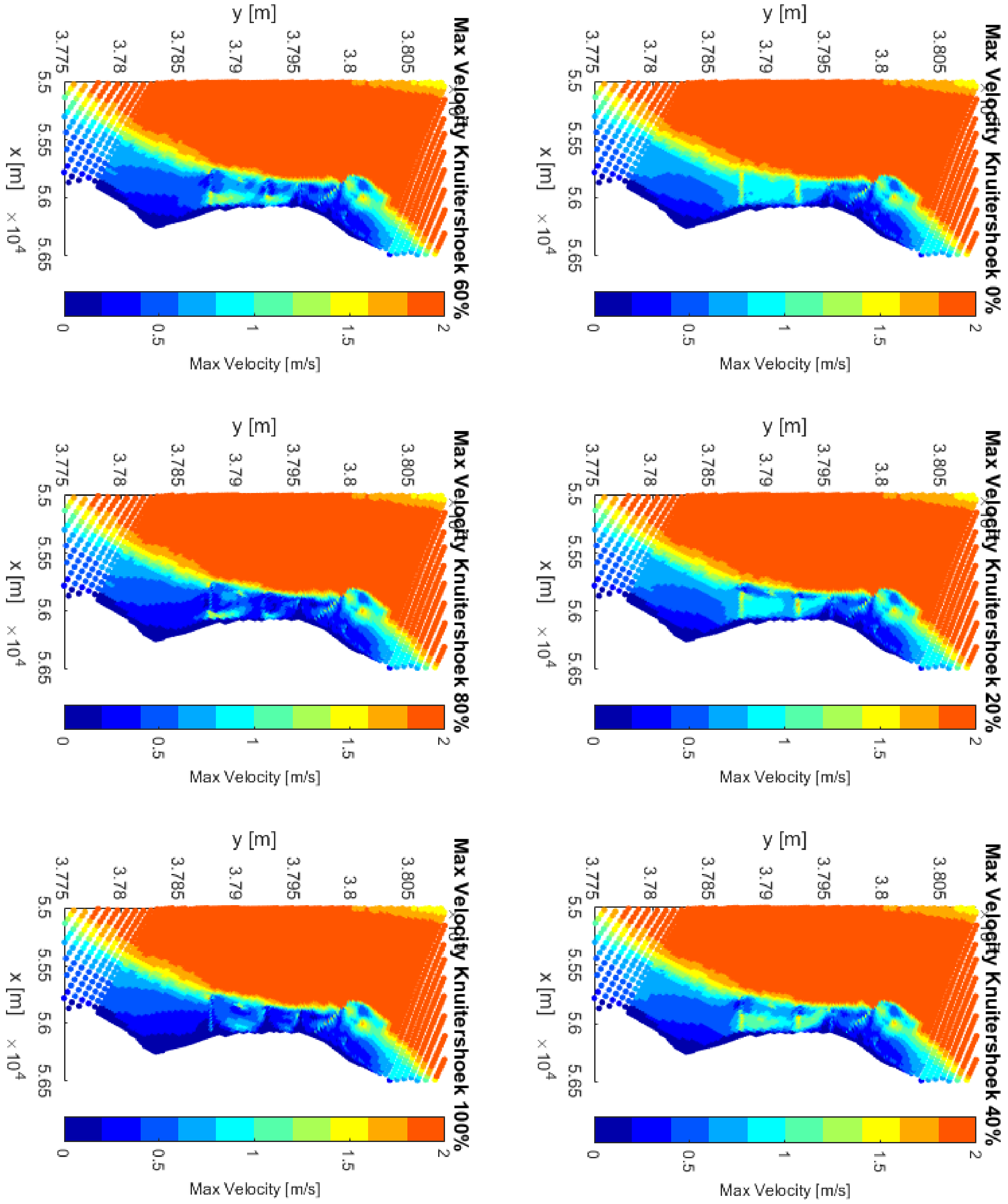


Figure A 28 - Maximum velocities for the high water resting area length scenario runs at Knuitershoek (0 % - 100 %)

Maximum velocity difference of changing high water resting area length scenarios scompared to no high water resting area.

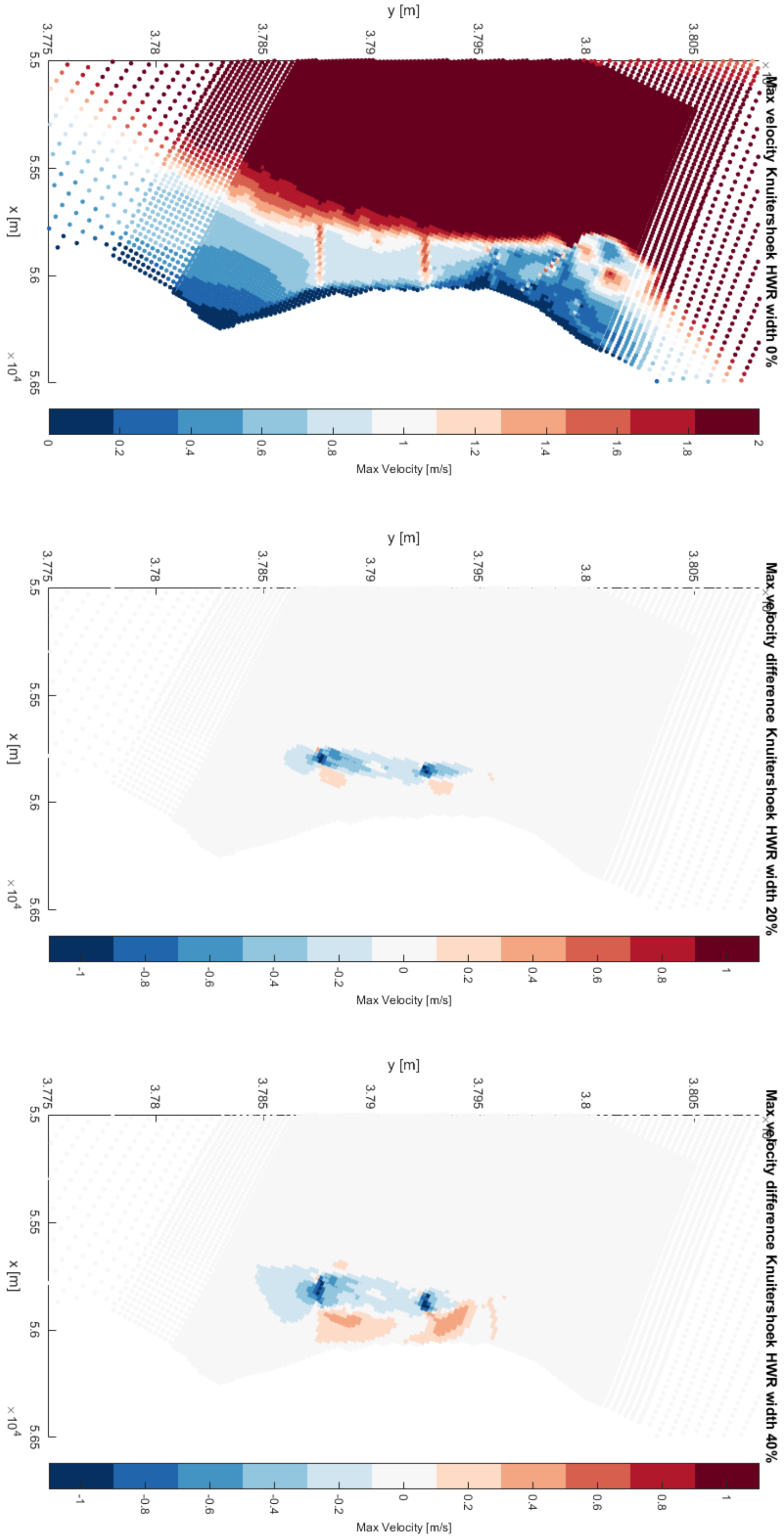
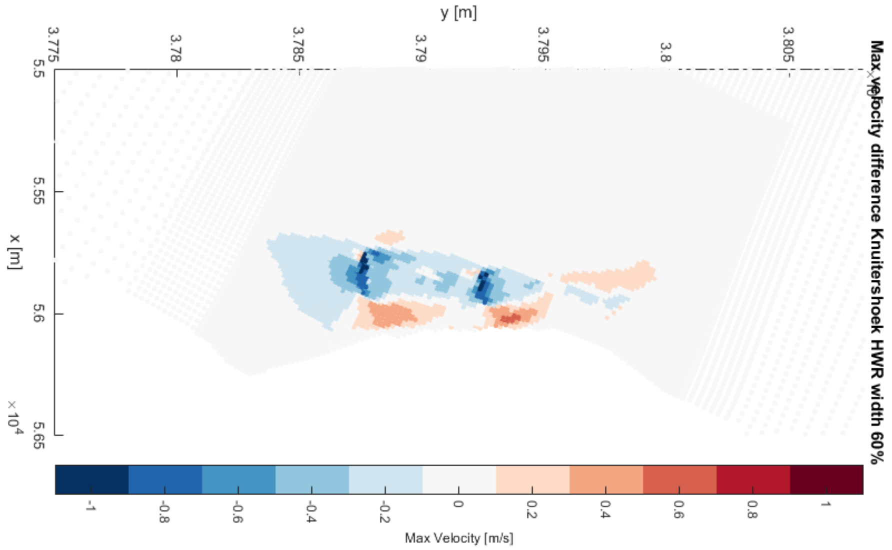
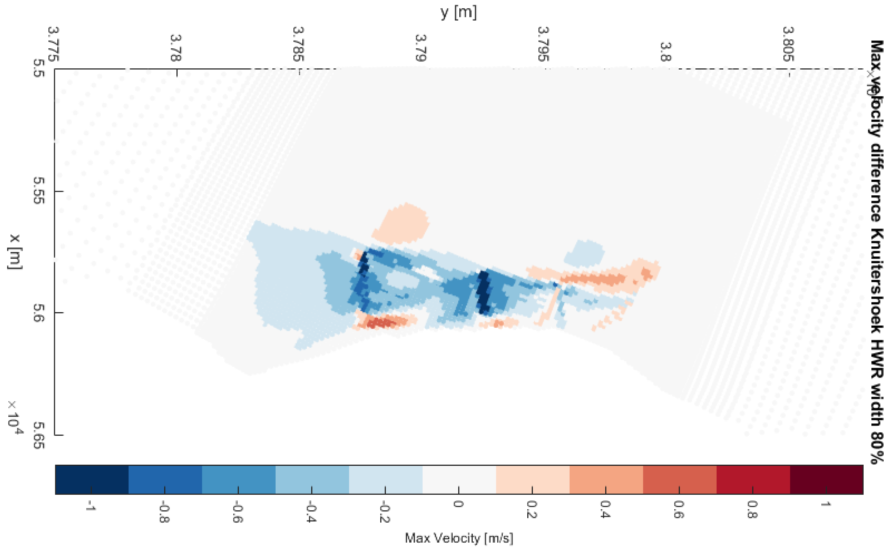


Figure A 29 - Difference in maximum velocities for the high water resting area length scenario runs at Knuitershoek (0 %, 20 % and 40 %)





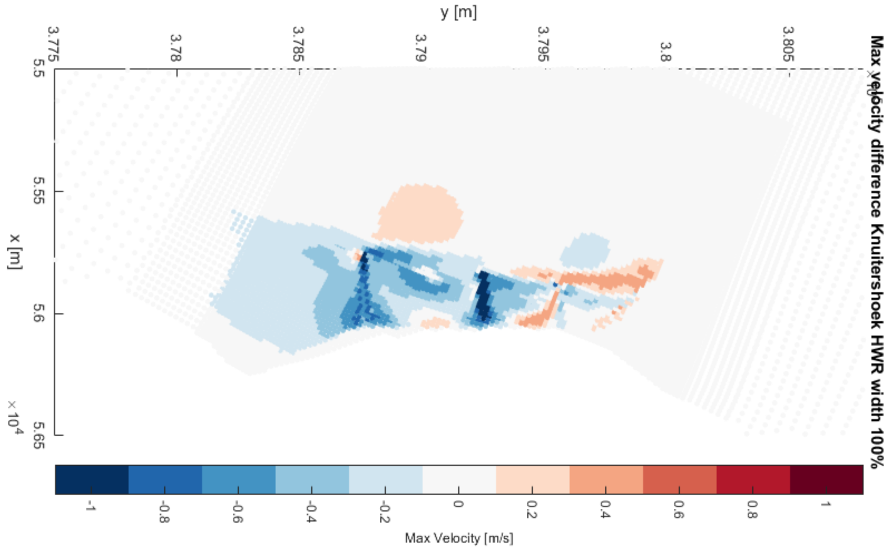


Figure A 30 - Difference in maximum velocities for the high water resting area length scenario runs at Knuitershoek (60 %, 80 % and 100 %)