The effect of vessels on the flow pattern inside a groyne field

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S.V. (Steven) Brouwers

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by

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Preface

Dear reader,

This master thesis is the final product of my master Hydraulic Engineering at the TU Delft. A year ago I contacted my daily supervisor, Kees Sloff, whether he knew of an interesting research topic to dedicate my master thesis to. He informed me about this new approach to possibly stop or reduce the amount of erosion inside the Waal, groyne field nourishments. The practical applicability of this possible solution interested me so much, I decided this was the subject I wanted to do master thesis about.

The past year I investigated the effect of vessels on the flow inside a groyne field. To spice up my master thesis, I performed an actual measurement campaign inside a real groyne field. Connecting the practical side of my study with the theoretical side of my study. By actually standing inside the water, feeling the water flow around my feet, the actual flow pattern inside a groyne field and the effect of a vessel became much clearer to me.

I would like to thank my thesis committee for helping me and guiding me in the right direction. Furthermore, I would like to thank the people from the lab and especially Tors, with whom I performed the actual measurements and with whom I investigated the capabilities of the different measurement instruments. Of course, I would also like to thank my family for their continuous support during my study and my friends who made my time as a student unforgettable.

S.V. (Steven) Brouwers
Delft, November 2022

Abstract

Due to river training in the past centuries, the bed level of the Waal started and is still decreasing by several centimetres a year. Erosion of the riverbed causes problems for objects underneath the riverbed like cables, pipelines and foundations of structures. Furthermore, some parts of the river are eroding at a higher velocity compared to other parts due to a difference in the composition of the bed material. This can result in a jump in the bed level while the water level cannot follow this jump. This results in less available draught for inland vessels. If no mitigation measures are applied and the bed level keeps decreasing, more problems are likely to occur resulting in less transport over the Waal. A possible solution to reduce bed erosion inside the Waal locally is the use of groyne field nourishments.

The objective of this research is to obtain more knowledge about the flow in a real-life groyne field and the effect of vessels on this flow. The research question formulated for this research is, therefore: *what is the influence of vessels on the flow properties inside a groyne field and in what way do the characteristics of the vessels influence this?* To answer this research question a literature study is done first. Secondly, a measurement campaign is performed and finally, the results are analysed to investigate the effect of the characteristics of the vessels.

The literature study is done to obtain more knowledge about the flow properties inside a groyne field. The distinction is made between emerged and submerged groynes and the scenario with and without vessels. The situation where the groynes are emerged is dominant for the erosion inside the groyne field. In this scenario, the flow inside the groyne field consists out of one or two circulation patterns. The first circulation pattern is a large eddy in the downstream part of the groyne field, referred to as the primary eddy. When the groyne field is long enough, a second eddy is present in the upstream part of the groyne field, the secondary eddy. This eddy has a flow direction opposite to the primary eddy and a smaller flow velocity. When a vessel passes a groyne field, the flow pattern inside the groyne field changes due to the primary waves created by the vessel. Firstly, the water level inside the groyne field is raised due to the bow wave. Secondly, due to depression in the water level caused by the primary wave the water level inside the groyne field is lowered. Finally, the water level inside the groyne field is increased again due to the stern wave.

To investigate the effect of vessels on a groyne field, a measurement campaign is performed. The flow direction, flow velocity and water level inside the groyne field are measured with the use of several measurement instruments for two weeks. The obtained data by the measurements is analysed and visualised. The results show that the primary eddy remains partly intact when a vessel sails past the groyne field. Since the primary eddy remains partly intact, the water is guided towards the upstream part of the groyne field. In the upstream part of the groyne field, the secondary eddy does disappear and the flow is directed out of the groyne field. This results in the water, and sediment, flowing out of the groyne field mainly in the upstream part of the groyne field. This has resulted in a scour hole present in the upstream part of the groyne field.

In this research the effect of multiple vessel characteristics on the water level and flow velocity inside the groyne field is investigated. The vessel characteristics investigated are the draught, the sailing speed, the vessel length, the vessel width and the distance of the vessel towards the measurement instrument. The effect of vessels on the water level and flow velocity inside the groyne field differs for each vessel. Information about the vessels has been obtained by using AIS (Automatic Identification System) data. During the processing of the AIS-data, irregularities and errors were found and mostly removed from the AIS-data. According to the final results, the draught of a vessel does not influence the water level and flow velocity inside the groyne field. An increase in the sailing speed of a vessel and a decrease in the distance of a vessel towards the groyne field does have an enlarging effect on the water level difference and the flow velocity inside a groyne field. The combined effect of increasing the length and the width of a vessel also has an enlarging effect on the water level difference and the flow velocity inside the groyne field. It should be noted that the results show a large variance and it is impossible to predict the effect of a single vessel based on the vessel characteristics.

The measurement campaign showed that a constant water level fluctuation is present inside the groyne field even when no vessel is affecting the flow inside the groyne field. Multiple explanations for this fluctuation are given with transverse oscillations between both riverbanks being the most likely.

The measured flow pattern inside the groyne field without vessel is according to the literature. When the flow is affected by a vessel, the flow pattern differs from the flow pattern described in the literature. Furthermore, the effect of a vessel is likely not only depending on the characteristics of a vessel but also on the flow mechanism inside the river system such as the helical flow, the angle of the groyne field with respect to the main channel and the constant water level fluctuation inside the groyne field.

This research adds to the already existing knowledge about the flow in groyne fields. To investigate the effectiveness of groyne field nourishments, a pilot is planned where the actual nourishment will take place at the same location as the measurement campaign. Therefore, this research can be used to better prepare the planned nourishment pilot to investigate the effectiveness of groyne field nourishments. Furthermore, this research contains data about the flow pattern inside the groyne field without nourishment which can be compared to the situation during and after the nourishment pilot. In the end, this research can be a part of the answer to whether groyne field nourishments can reduce or stop the erosion inside the Waal river.

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1 Introduction

Due to river training in the past, the main channel of the Waal is eroding. Several normalisation measures like the construction of groynes and the cut-off of certain bends in the river have disturbed the equilibrium slope of the river in the past, which is now resulting in erosion of the riverbed. Rijkswaterstaat, which is responsible for the rivers in the Netherlands, is now looking for solutions to reduce this erosion and to avoid problems like insufficient sailing depth in the future. A possible measure is the appliance of sediment nourishments in groyne fields. These groyne field nourishments supply sediment to the river's main channel due to the waves of vessels sailing past the groyne fields, resulting in a possible solution to deal with the erosion of the main channel.

1.1 Context

The Rhine River is the main waterway connecting the inland of the Netherlands and Germany to the harbour of Rotterdam. The Rhine enters the Netherlands at Lobith and bifurcates into the Waal and the Pannerdensch Kanaal at the Pannerdensche Kop. The Pannerdensche Kop is designed such that about 2/3 of the Rhine discharge flows into the Waal and about 1/3 into the Pannerdensche Kanaal. Due to the connection with the harbour of Rotterdam, the Waal is the most important river for navigation in the Netherlands.

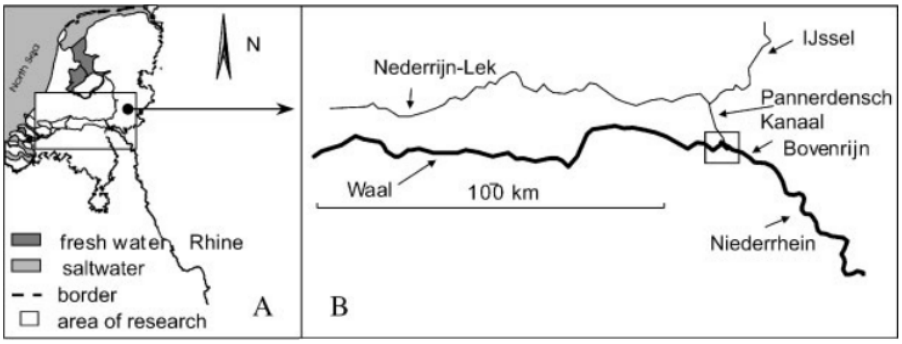

Figure 1.1: The Rhine river system in the Netherlands (Ten Brinke et al., 2004)

The Waal river used to be a free-flowing river before the twelfth century. Around the year 1100, people started the construction of dikes to prevent their land from being flooded. In the next centuries, the first normalisation measures were applied to the Waal. Many river bends were cut off and groynes and dams were built to prevent erosion of the banks and to capture the sediment deposited between the groynes to create agricultural land. The intention of these measures was to increase the flow velocity in the river and prevent the formation of sand bars. Around the year 1870, more width normalisations were conducted to guide the flow into a fixed channel with a constant width. These normalisations were realised by the construction of groynes at regular distances to guide the flow into a fixed path during low discharges and to prevent bank erosion. From 1879 to 1890, the second width normalisation took place reducing the width of the channel to 360 meters during low discharge. Between 1912 and 1916, the third normalisation took place reducing the width of the main channel to 260 meters during low discharge with a minimum sailing depth of 2.5 meters. The water level during low discharge is also called the agreed low water level (OLR), meaning that 95% of the time this water level is exceeded to ensure enough water depth for navigability. In the past, the response of the river to certain measures was not always understood. Due to all these measures, like the normalisation of the river and the decrease of the length of the river due to the cutoff of bends, the bed level of the river has decreased over the past two centuries.

The navigability of the Waal river is improved by the construction of groynes in the past centuries. However, the cross-sectional area of the Waal is also reduced due to the construction of these groynes. The consequence of this decrease in cross-sectional area is an increase in flow velocity if the same discharge flows through the system. The consequence of this increase in flow velocity is an increase in the bed shear stress resulting in erosion and deepening of the main channel. Another consequence of the reduction of the cross-sectional area is the reduction of the equilibrium slope necessary to transport the sediment supplied from upstream. Since the downstream boundary condition is the sea level, the change in slope will result in more erosion further land inwards (Ylla Arbos et al., 2019). In figure 1.2 the bed elevation for the years 1950 and 2018 is visible. The decrease of the bed level and the decrease of the slope of the Waal can be seen.

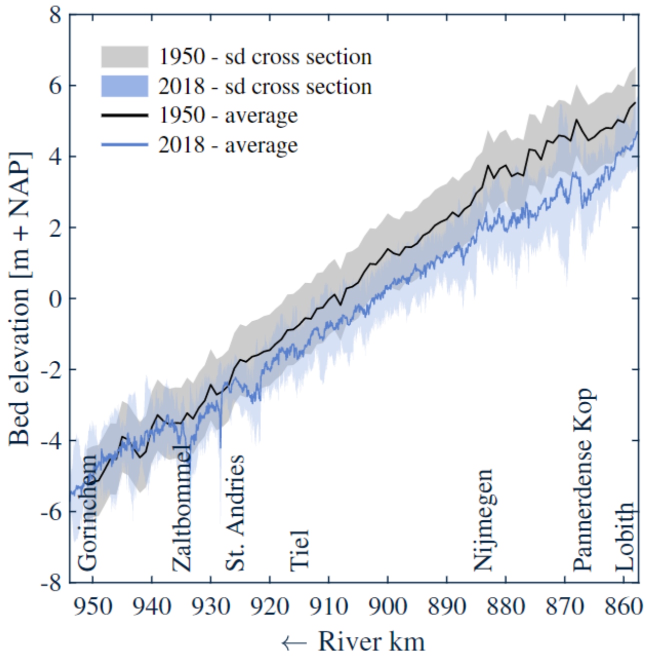

Figure 1.2: Bed level degradation of the Waal from 1950 till 2018 (Ylla Arbos et al., 2019)

At the end of the 20th century the upcoming trend of the six-barge push tows was a reason to increase the fairway dimensions of the Waal. Therefore, Rijkswaterstaat introduced the Waal program in 1994. The Waal program can be summarised by these three points (Havinga et al., 2006):

- Increase the main channel dimensions from 150 meters wide and 2.50 meters deep to 170 meters wide and 2.80 meters deep at OLR (agreed low water level)
- Stop bed degradation which was equal to several centimetres per year at that time
- Obtain surplus values for the river's eco-system by integrating floodplain rehabilitation plans

To enlarge the width of the Waal in the bend at Nijmegen a non-erodible fixed layer is constructed in 1988. This non-erodible layer is constructed to avoid the transport of sediment from the outside of the bend to the inside of the bend due to the helical flow which results in a larger sailing depth at the outer bend and a lower depth at the inner bend. This erosion in the outer bend and aggradation in the inner bend results in a smaller width for the vessels which is unfavourable for navigability. The non-erodible layer consists of gravel and sand, protected by a layer of riprap to avoid erosion. Due to this fixed layer, the flow velocity in the inner bend is increased such that sediment can pass the bend. At the end of the fixed layer, the flow conditions return to the situation without a fixed layer. This means that at the end of the fixed-layer erosion will occur since the sediment concentration in the flow is low. At the end of the inner bend the sediment concentration is larger compared to the situation without a fixed layer, so aggradation will take place (Havinga, 2016). A visualisation of the fixed layer is visible in figure 1.3. In the right picture, the fixed layer is visible. Furthermore, the erosion at the end of the fixed layer and the aggradation at the end of the fixed layer in the inner bend are visible.

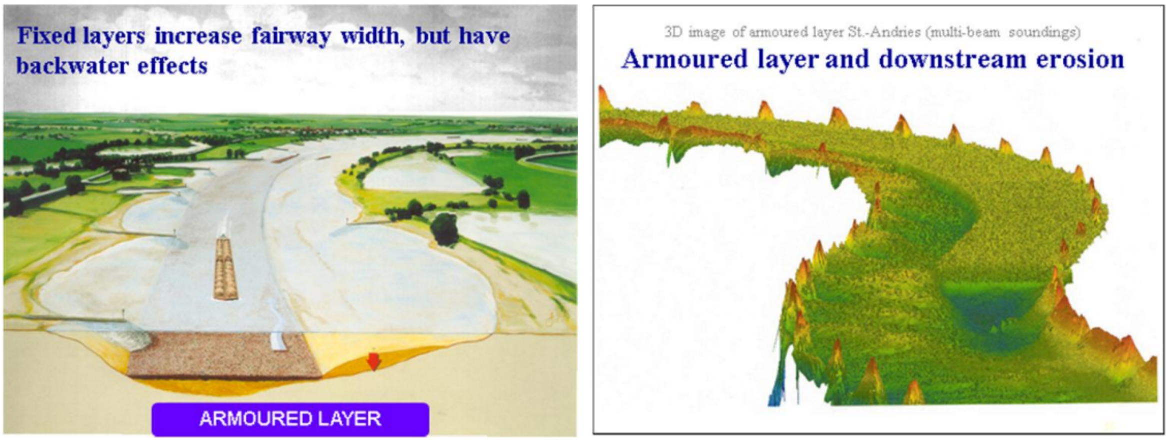

Figure 1.3: Armoured layer at the outside corner (left picture). Morphological effects downstream of the fixed layer (Right picture) (Havinga, 2016)

Due to the fixed layer at Nijmegen the width of the waterway in the bend is increased by 50 meters (Havinga, 2016). Unfortunately, the fixed layer also resulted in some problems. This problem is a local reduction of the sailing depth since the fixed layer does not erode. Over the years, the bed level around the fixed layer has been decreasing and, therefore, also the water level, while the bed on top of the fixed layer has remained at the same level resulting in a decrease in the water depth on top of the fixed layer. According to a recent MIRT research from 2019, the bed level downstream of the fixed layer is decreasing with a velocity of 2.3 cm/year. This decrease in available draught will results in hindrance for vessels during low discharge in the future since they will not be able to pass the fixed layer if the water level on top of the fixed layer keeps decreasing.

As part of the program "Ruimte Voor de Rivier" the groynes between Pannerdensche Kop and Gorinchem are lowered by an average of one meter. This is done to enlarge the cross-sectional area of the river during high flow conditions resulting in a decrease in the water depth which increases flood safety. A result of lowering the level of the groynes is aggradation or a reduction of the erosion in the main channel and erosion of the groyne fields (Busnelli et al., 2011).

Current mitigation measures

The continuing bed degradation in the Waal is a severe problem. If no effective measures are applied, pipelines, cables, foundations of structures and other objects covered beneath the bed will become exposed. Furthermore, several points in the river like the fixed layer at Nijmegen can become serious bottlenecks and limit the available draught of vessels sailing up the Rhine due to their incapability to erode.

In a MIRT report published in 2019 the current measures to deal with bed degradation and some future solutions are presented. It is stated that there is a shortcoming of 50000 m^3/year of sediment from Germany. The current solution to deal with this shortcoming of sediment is dredging. The sediment is moved from places where aggradation takes place to places where erosion occurs. The effectiveness of this solution depends on multiple factors like the amount of sediment, the location of the sediment and the composition of the sediment. By moving the sediment, however, there is still a deficit of 50000 m^3/year. The report mentions a few short-term solutions to deal with the fixed layer at Nijmegen like removing the fixed layer, lowering the fixed layer and performing regular nourishments downstream of the fixed layer to decrease the jump in the water level. Furthermore, some long-term measures are mentioned to deal with the bed degradation inside the Waal. First, it is mentioned to continue the current way of dealing with erosion by dredging at places where aggradation takes place and depositing this sediment where erosion occurs. The next solution mentioned is to deal with the sediment deficit of 50000 m^3/year by adding extra sediment in the form of nourishments. Also, moving the sediment from downstream parts of the Waal where no erosion takes place to more upstream parts is a solution. However, due to the different grain size distributions, this is only possible within a distance of several kilometres between both places.

The above-mentioned solutions are mostly so-called 'soft measures' which can be adjusted or stopped relatively easily. Other solutions are more fixed, the so-called 'hard measures'. Hard measures mentioned in the MIRT report are lowering the groynes to decrease the flow velocity during high discharge and the construction of longitudinal dams in the river. Longitudinal dams divide the channel into a main channel and a side channel. During low discharge, the water is forced into the main channel increasing the water depth which is beneficial for shipping. During high discharge, the water is divided over the main and side channel resulting in a lower flow velocity in the main channel and, therefore, less erosion. Another solution mentioned is to fix the whole bed by adding coarse material or rocks to the bed. This solution, however, is not durable with respect to the ecology of the riverbed.

The solution to deal with the continuing bed erosion can also be a combination of some of the previously mentioned measures. However, new sustainable solutions are still being looked for. A possible sustainable solution can be groyne field nourishment as will be explained in the next section.

Groyne field nourishments

A possible new solution to reduce the continuous bed erosion of the Waal is to make use of groyne field nourishments. During a groyne field nourishment, sediment is placed in the area between the groynes, the groyne field. Due to vessels sailing past the groyne field and the waves and suction they create inside the groyne field, the sediment is supposed to be mobilised towards the main channel. This can possibly result in a local reduction of erosion in the main channel.

The effectiveness of these groyne field nourishment is not yet known. The most important factors which probably determine the effectiveness of these nourishments are the location of the nourishment in the groyne field, the location with respect to the river (north- or south bank, inner- or outer bend), the grain size distribution of the nourishment and the characteristics of the vessels sailing past the groyne field.

According to research of Czapiga et al. (2022) nourishments do not always reduce erosion but can sometimes even enhance extra bed erosion. To reduce channel erosion, the sediment flux needs to be changed such that the equilibrium channel slope increases. This can be done by coarsening the sediment flux, increasing the sediment flux or both. By coarsening the sediment flux, the grain size distribution of the nourished sediment should be similar to or coarser than the grain size distribution of the bed. This is to avoid downstream erosion. When increasing the sediment flux by nourishing fine sediment, the added sediment flux volume should be large enough. By nourishing a small volume, the coarse sediment becomes more mobile which results in erosion. To determine whether groyne field nourishment can really be effective, these points have to be taken into consideration eventually.

Previous research of Ten Brinke et al. (2004) shows that the erosion in groyne fields differs between the north- and south bank due to the underwater volume of the vessels. Loaded vessels sailing upstream to Germany along the south bank of the river cause close to twice as much erosion compared to the effect that the mostly empty vessels sailing downstream have on the north side. Furthermore, due to the helical flow in the bends, it is likely that erosion takes place at the outer bank of the bends and sedimentation at the inner side of the bends.

1.2 Objective and research questions

Problem definition

Due to river training in the past, the bed level of the Waal is decreasing. Several normalisation measures like the construction of groynes and the reduction of bends in the river have disturbed the equilibrium slope, now resulting in erosion of the riverbed. To deal with this erosion a sustainable solution is required.

Objective

The objective of this research is to gain more insight into how vessels affect the flow inside a groyne field before the actual groyne field nourishment pilot has taken place. This information can be used to better prepare the planned nourishment pilot and to compare the situation with nourishment to the situation without nourishment. This data can be used to eventually determine the efficiency of groyne field nourishments. Eventually, this gives us more information about the question of whether groyne field nourishments can actually stop or decrease the present erosion inside the Waal river.

Research question

The research question for this master thesis is: *What is the influence of vessels on the flow properties inside a groyne field and in what way do the characteristics of the vessels influence this?* The flow properties taken into consideration for this research are the flow velocity, flow direction, water level and sediment concentration. To answer the research question, the following sub-research question will be answered:

- What are the flow properties inside a groyne field with and without vessels according to the already existing literature?
- What are the flow properties inside a designated groyne field and how are they affected by vessels sailing past the groyne field?
- What are the characteristics of the vessels that influence the flow properties inside the groyne field the most?

1.3 Methodology

Sub-research question 1

What are the flow properties inside a groyne field with and without vessels according to the already existing literature?

To obtain information about the flow inside a groyne field an extensive literature study will be performed. The focus is to understand how the flow behaves inside a groyne field, with and without vessels. The focus will be on the flow velocity, the flow direction and how the sediment moves inside the groyne field. This literature study will give an insight into how the flow behaves inside the groyne field. This information will be used in the next sub-research question.

Sub-research question 2

What are the flow properties inside a designated groyne field and how are they affected by vessels sailing past the groyne field?

It will be investigated whether the flow pattern inside a real designated groyne field is in agreement with the flow according to the literature. A measurement campaign will be set up to measure the actual flow properties inside a groyne field. The selected groyne field will be a groyne field which is part of the actual nourishment pilot. The flow properties included in this research are the flow velocity, the flow direction, the water level and the sediment concentration. These measurements give a so-called base case scenario and can be used to better prepare the actual nourishment pilot. The results of the measurements can also be used to compare the situation before the nourishment to the situation during and after the nourishment. By doing this it is possible to investigate the change of the flow properties due to the nourishment. The measurements inside the groyne field will be performed during low discharge when the groynes are emerged since that is the moment the groyne fields are being eroded due to the ship-induced waves.

The literature study in the previous sub-research question will be used to obtain information about the most interesting places to place the measurement instruments. This will result in a more complete overview of the flow properties inside the groyne field with the available instruments.

Multiple measurement instruments are required to obtain a clear view of the flow properties inside the groyne field. Firstly, the flow speed and flow direction need to be measured to gain insight into the exact flow pattern inside the groyne field. Secondly, the water pressure inside the groyne field needs to be measured to gain insight into the change in the water level caused by vessels sailing past the groyne field. Thirdly, the sediment concentration needs to be measured to gain insight into whether the sediment is mobilised or not. Furthermore, at several points inside the groyne field, samples of the bed will be taken to gain insight into the composition of the bed and to link these to the measured sediment concentrations inside the water.

Before starting the measurements a measurement plan will be made. In this measurement plan, the desired measurement results will be described and how to achieve these results. Also, the instruments to perform the measurements and how these instruments are placed inside the groyne field will be mentioned. The final measurement plan should be a complete overview of the planned experiment. After the measurements have been done and the resulting data is obtained, the data need to be analysed to obtain the desired results.

The measurement results will give an overview of the flow properties inside the groyne field and how they are affected by vessels. Furthermore, these results can be used in the future to prepare the actual nourishment pilot and to compare the situation before the nourishment to the situation during and after the nourishment. The results will be written and visualised such that the flow properties inside the groyne field are clear and visible.

Sub-research question 3

What are the vessel characteristics that influence the flow properties inside the groyne field the most?

Vessels have an influence on the flow properties inside a groyne field. However, each vessel has a different influence on the flow properties. In this sub-research question, the data of the measurements will be used to obtain insight into the effect of vessel characteristics on the flow properties inside the groyne field. We will investigate the change in the water level and the maximum flow velocity. The vessel characteristics taken into consideration are the draught of the vessel, the speed of the vessel, the distance to the measurement instrument, the length of the vessel and the width of the vessel.

Firstly, information about the vessels sailing past the groyne field is required. Therefore, the AIS-data of the vessels sailing past the groyne field will be requested at Rijkswaterstaat. This AIS-data includes useful information about the characteristics of the vessels. For example, the moment a vessel sails past the groyne field, the draught of the vessels and the speed of the vessels.

Secondly, a python script will be written which runs through the data and connects the AIS-data with the results obtained by the measurements. This will result in a database where for each vessel the influence on the water level and the flow velocity is visible. By analysing this database, the influence of the vessel characteristics on the measurement results can be visualised.

By taking a large number of vessels into consideration, the results should indicate clearly how the different characteristics influence the flow properties. The different results will be analysed for several separate locations, so it becomes clear what the effect of the different vessel characteristics on the flow properties are.

Finally, it will be investigated whether it is possible to investigate the effect of vessels on the water level inside the groyne field with the use of a frequency analysis.

2

Existing theory on flow and morphodynamics inside a groyne field

This chapter presents information about the flow and morphology inside a groyne field according to the currently available literature. The main focus of this chapter is the flow pattern and the sediment fluxes inside a groyne field. In this research, the focus is on conditions that occur in groyne fields inside the Dutch Rhine branches, notably the Waal river. To obtain an overview of the flow inside a groyne field a distinction is made between two situations. Firstly, the situation where the groynes are emerged and secondly, the situation where the groynes are submerged. In the beginning, the effect of vessels on the flow inside the groyne field is neglected. Later, the effect of vessels on the flow inside the groyne field is investigated to obtain a complete overview of the flow inside a groyne field.

2.1 Emerged groynes

In this section the situation where the groynes are emerged is investigated. When the groynes are emerged, the groyne fields are not part of the conveying cross-section of the river. This means that the flow inside the groyne fields does not contribute to the discharge in the main channel (Yossef, 2002). Firstly, the flow pattern inside the groyne field is investigated and secondly, the morphodynamics inside the groyne field is investigated.

Flow inside an emerged groyne field

The most important factors influencing the flow pattern inside a groyne field are the shape of the groynes and the position of the groyne field with respect to the main channel. For instance, whether the groynes are located in a straight river section, an inner bend or an outer bend, and the orientation of the groynes influences the flow pattern inside a groyne field (Przedwojski et al., 1995). Since the water inside the main channel is not able to follow the sharp bend of the groyne head, the water deflects into the groyne field. This deflected water is deflected such that it flows against the downstream groyne. After hitting the downstream groyne, the water deflects towards the bank and back to the upstream side of the groyne field. This circulation pattern is called the primary eddy. When the length of the groyne field is more than two hundred meters (Ten Brinke et al., 2004) or the groyne field has a groyne length-to-width ratio larger than two (Sukhodolov et al., 2002) an extra secondary horizontal eddy flowing in the opposite direction compared to the primary eddy appears in the upstream part of the groyne field as is visible in figure 2.1. The flow velocity inside the primary eddy is usually about thirty to forty percent of the flow velocity in the main channel while the flow velocity inside the secondary eddy is much smaller. Also visible in figure 2.1 is a dynamic eddy. The dynamic eddy is created downstream of the upstream groyne. When the dynamic eddy is large enough it flows into the primary eddy, causing fluctuations in the size of the primary eddy (Yossef, 2005).

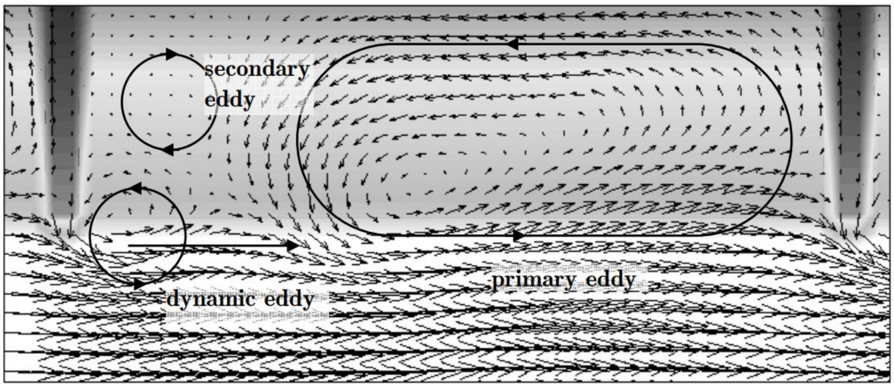

Figure 2.1: Flow pattern inside a groyne field larger than two hundred meters or a length to width ratio larger than two (Yossef, 2005)

According to model tests, Klingeman et al (1984) reported that six different types of eddy patterns can be distinguished as is visible in figure 2.2.

- Type 1: The main flow is deflected outside the groyne field. A single eddy is present and covers the whole groyne field.
- Type 2: The current is again deflected outside the groyne field. In this situation, however, a second eddy is present flowing in opposite direction.
- Type 3: The flow is directed into the groyne field towards the downstream groyne. Due to the water flowing directly into the groyne field, a much stronger eddy appears downstream. Due to the increased spacing between the two groynes also a secondary eddy appears.
- Type 4: The flow is directed into the groyne field towards the downstream groyne. In this case, however, only a single eddy is present since the upstream eddy is not stable enough.
- Type 5: The flow is directed directly towards the bank. At both sides of the groyne field, small eddies are present providing a small amount of protection for the riverbank.
- Type 6: The current is directed straight towards the bank. Due to a larger distance between the two groynes the downstream eddy has disappeared resulting in large amounts of bank erosion.

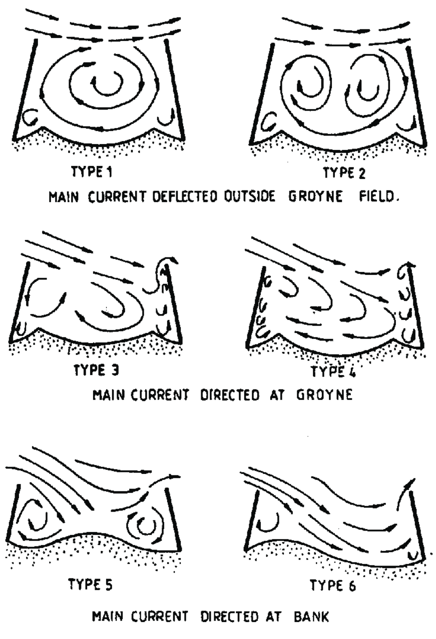

Figure 2.2: Six different types of eddy circulation patterns inside a groyne field (Przedwojski et al., 1995)

Morphodynamics inside an emerged groyne field

In this section, the morphodynamics inside an emerged groyne field is investigated. The morphodynamic flow inside an emerged groyne field in a straight river section without vessel-induced waves is shown in figure 2.3. The water flowing through the main channel of the river has a certain sediment concentration. Since the water flows partially into the groyne field like described in the previous section, the sediment also flows into the groyne field at the downstream side of the groyne field and enters the circulation pattern of the primary eddy. Due to the smaller flow velocities inside the groyne field compared to the flow velocity inside the main channel, the sediment settles inside the groyne field, resulting in sedimentation inside the groyne field (Yossef and de Vriend, 2010).

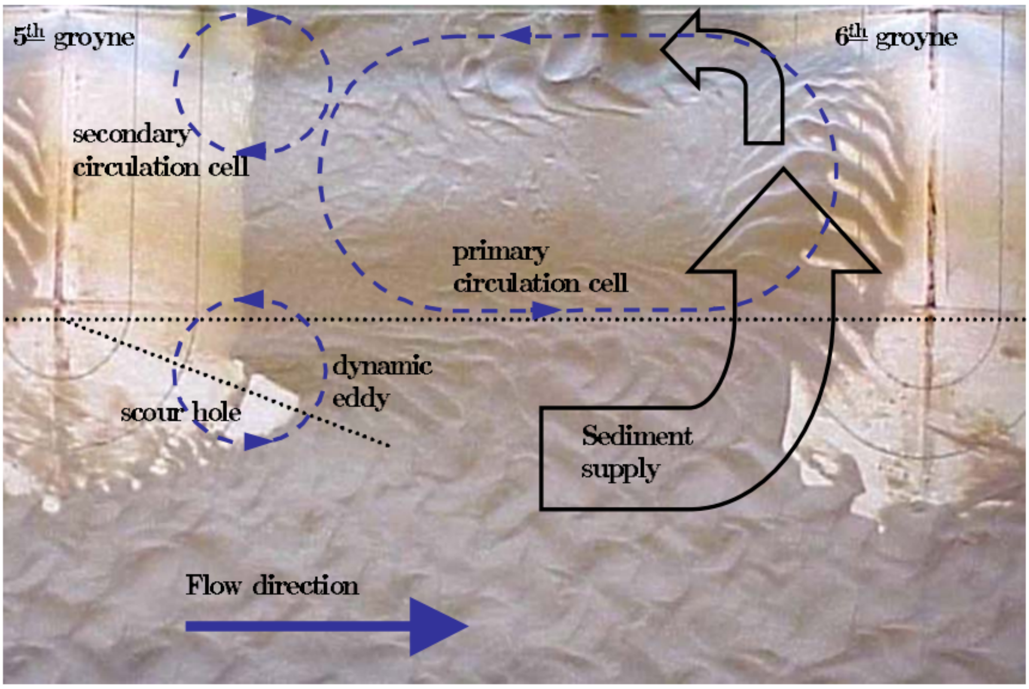

Figure 2.3: Morphodynamics in an emerged groyne field (Yossef and de Vriend, 2010)

Due to the lower flow velocity at the location of the primary eddy and the flow entering the groyne field at the downstream part of the groyne field, the sediment will mainly settle in the downstream part of the groyne field. This can be seen in figure 2.4 where Yossef (2005) investigated the bed profile in a river section with emerged groynes. Yossef started with a uniform bed level of around 0.15 meters and investigated the bed pattern after 40 hours of flow. The flow in the main channel is from left to right. The white parts indicate a higher bed level while the black parts indicate erosion. Also visible are the scour holes, in black, at the tip of the groyne head due to the dynamic eddies (Yossef, 2005).

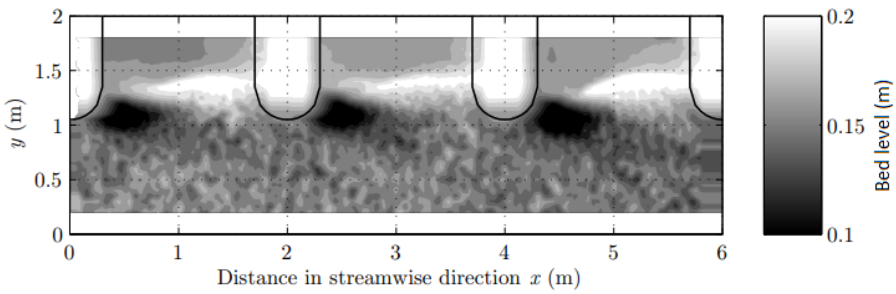

Figure 2.4: Bed profile in an emerged groyne field after 40 hours of flow (Yossef, 2005)

2.2 Submerged groynes

When groynes are submerged, water flows over the top of the groynes. This situation results in the groyne fields being part of the wetted cross-section of the river. Firstly, the flow inside a submerged groyne field is investigated. Secondly, the morphodynamic processes inside a submerged groyne field are investigated.

Flow inside a submerged groyne field

The flow pattern inside a submerged groyne field is highly dependent on the rate of submergence. When the water level raises and the groynes become more submerged, the horizontal eddy generated in the situation for emerged groynes dampens and the unidirectional flow is dominant. Eventually, when the water level raises and the groynes become fully submerged, the horizontal eddy completely disappears and only the unidirectional flow over the groyne crest will (Yossef, 2005). Both situations are visualised in figure 2.5.

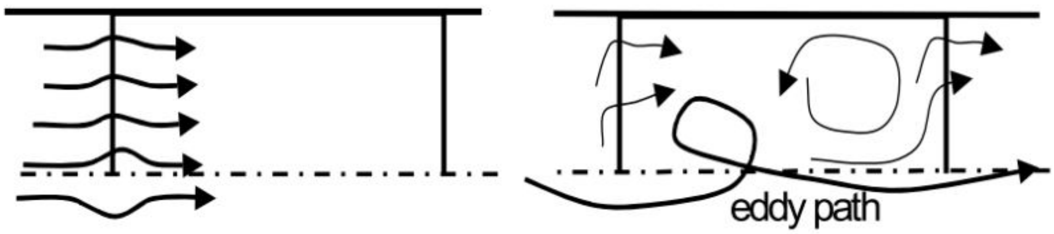

Figure 2.5: Flow patterns in submerged groynes for fully submerged groynes (left) and barely submerged groynes (right) (Uijttewaal, 2007)

Another consequence of the groynes being submerged is the formation of a vertical eddy just downstream of the groyne. This eddy originates from the flow separation on top of the groyne since the flow cannot follow the shape of the groyne exactly. Due to this flow separation, the water level upstream of the groyne is higher compared to the water level downstream of the groyne (Yossef, 2002). When the groynes are not level or the water flow over the groyne is not level, an extra secondary flow pattern can appear, guiding the flow towards the main channel as can be seen in figure 2.6.

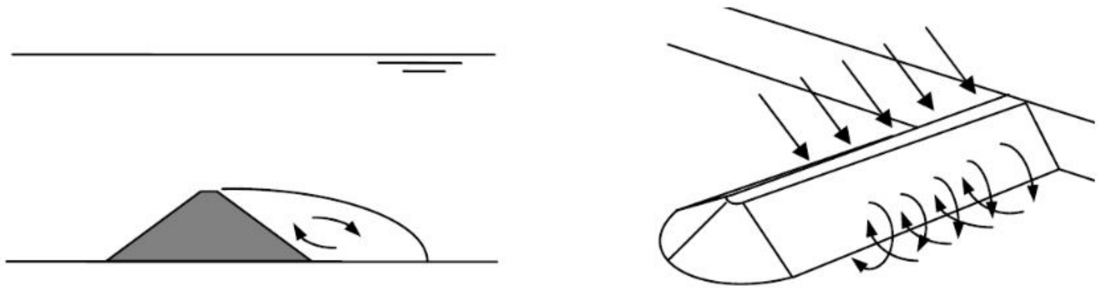

Figure 2.6: Vertical eddy appearing downstream of the submerged groyne (left) and secondary flow guiding the flow towards the main channel (right) (Van Broekhoven, 2007)

Morphodynamics inside a submerged groyne field

The morphodynamic flow pattern inside a submerged groyne field for a straight river section without ship-induced waves is visible in figure 2.7. In this figure the difference between the flow velocity inside the main channel and the groyne field is visible. Due to the lower flow velocity on top of the groyne fields, the sediment supply of a submerged groyne field is directed towards the groyne field. The sediment is transported from the main channel towards the groyne field through the mixing layer between the flow in the main channel and the flow at the edge of the groyne field. Since the flow in this mixing layer is very turbulent, the sediment concentration inside the mixing layer is high (Yossef and de Vriend, 2010).

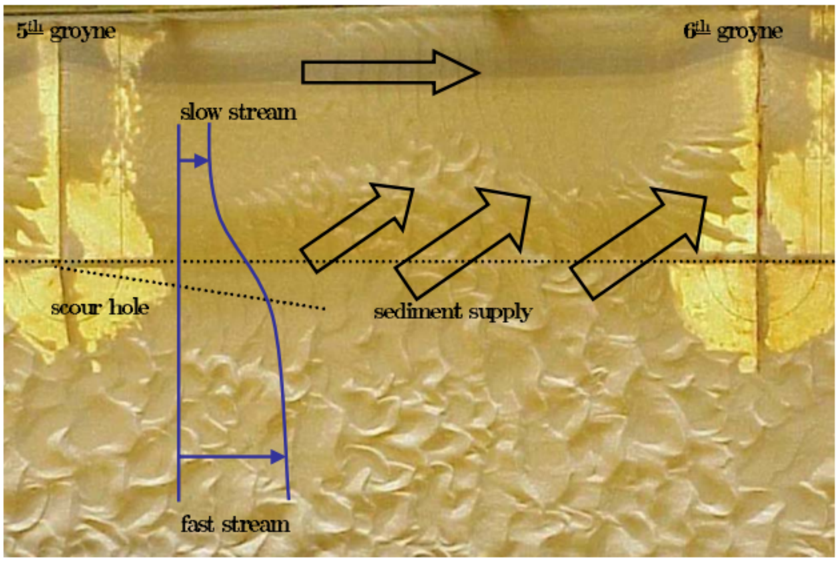

Figure 2.7: Morphodynamics in a submerged groyne field (Yossef and de Vriend, 2010)

In figure 2.8 the bed profile in the case of a set of submerged groyne fields is visible according to research of Yossef (2005). The experiments started with a uniform bed level of around 0.15 meters and investigated the bed profile after 40 hours of flow. The flow in the main channel is from left to right. According to this figure, it can be observed that, contrary to the situation for the emerged groynes, there is sediment deposition over the entire length of the groyne field. Furthermore, the scour holes created by the dynamic eddy downstream of the groyne tips are still present. It can be concluded that, just as for the situation with emerged groynes, the sediment supply is towards the groyne field. Since the direction of the sediment supply is towards the groyne field for emerged and submerged groynes, the equilibrium state in a straight river section would be a completely filled-up groyne field (Yossef and de Vriend, 2010).

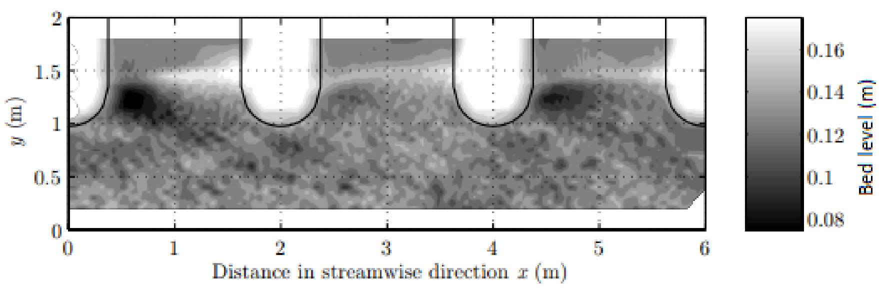

Figure 2.8: Bed profile in a submerged groyne field after 40 hours of flow (Yossef, 2005)

2.3 The influence of vessels

In the previous section it is stated that for emerged and submerged groynes in a straight river section without vessels, the direction of the sediment supply is towards the groyne field. The equilibrium state would be a completely filled-up groyne field. In reality, this is not the case due to vessels passing the groyne field which cause erosion inside the groyne field, resulting in an equilibrium situation. In this section, the effect of vessels on the flow properties and morphodynamics inside a groyne field is investigated.

Flow properties

The passage of a vessel creates waves and currents in a channel. The waves created by a vessel can be separated into two components, the primary and the secondary waves. The primary wave consists of the bow or front wave, a depression in the water level beside the vessel due to the return current and the stern wave. The secondary wave consists of transverse and diverging waves. in figure 2.9 the influence of a vessel on the shoreline is visible. Firstly, the water level raises due to the front wave. Secondly, the water level drops and finally, the water level raises again due to the stern wave. When the vessel has passed, the secondary wave system trailing the vessel causes some smaller, higher frequency fluctuations in the water level.

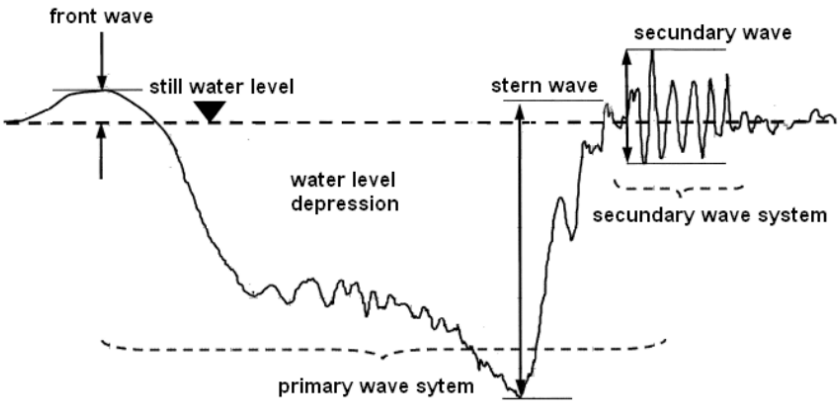

Figure 2.9: Influence of a passing vessel on the shoreline (De Roo and Troch, 2010)

Primary waves

The primary wave system is indicated in figure 2.9 and can be divided into three parts: the bow or front wave, a depression in the water level and the stern wave. The length of the primary wave is about the length of the vessel and the main components influencing the primary waves are the cross-section of the channel, the sailing speed of the vessel, the water depth and the distance between the vessel and the shore (De Rijck et al., 2010).

The raise and depression in the water level due to the passage of a vessel can be explained by comparing them with the streamlines around a Rankine body in a uniform flow as can be seen in figure 2.10. The first point where the vessel cuts through the water is the bow. As can be seen in the figure, the streamlines are expanding when the vessel starts cutting through the water, meaning that there is more distance between the streamlines. This results in a lower flow velocity and, therefore, a raise in the water level, the bow wave. In the middle part of the vessel, the haul of the vessel is wider and, therefore, the streamlines lay closer to each other. This results in an increase in the flow velocity around the vessel and a decrease in the water level. At the stern of the vessel, the streamlines expand again, leading to a lower flow velocity and a higher water level, the stern wave. The bow wave, the depression in the water level due to the return current and the stern wave are visible in figure 2.9. The magnitude of the increase and decrease in water level depends on the size of the vessel with respect to the water level, the draught of the vessel and the speed of the vessel (De Rijck et al., 2010).

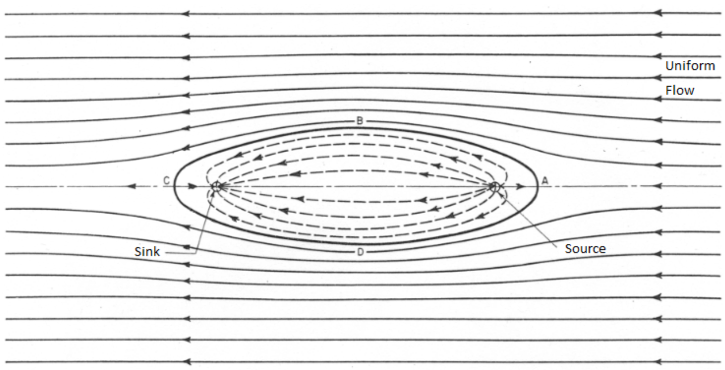

Figure 2.10: Flow around a Rankine body in a uniform flow (De Rijck et al., 2010)

Secondary waves

The secondary wave system is also indicated in figure 2.9 and are the waves produced at the bow and stern of the vessel due to the discontinuity of the water level at the hull of the vessel. The discontinuities cause pressure differences resulting in a wave pattern. The secondary waves can be distinguished between transverse waves and converging waves and are visible in figure 2.11. Each disturbance creates a circular wave, these circular waves are enveloped by the diverging waves. The transverse waves are the remains of the circles trailing the vessel. The transverse waves travel in the same direction and with the same speed as the vessel while the diverging waves travel at a lower speed (Schiereck and Verhagen, 2012).

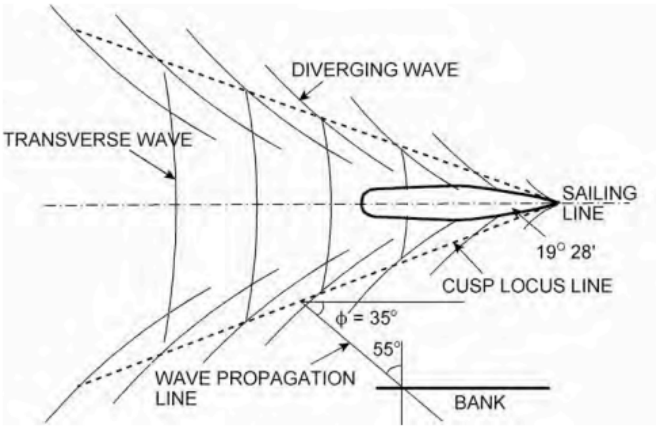

Figure 2.11: Secondary wave pattern around a vessel (Schiereck and Verhagen, 2012)

Flow inside a groyne field due to the passage of a vessel

The passage of a vessel results in a change of the flow pattern inside a groyne field. Figure 2.12 shows a schematic view of the changes in the flow pattern due to the passage of a push-convoy beside a groyne field near Druten according to research of Ten Brinke et al. (2004). The passage is divided into seven phases. Each phase is explained below::

- Phase 0: This is the base reference case. The flow pattern inside the groyne field consists of a primary eddy in the downstream part of the groyne field and a secondary eddy in the upstream part.
- Phase 1: A push-barge vessel is approaching the groyne field and sailing next to the head of the downstream groyne. Due to the bow wave, there is a gradient in the water level, causing the water to flow out of the groyne field at the downstream groyne.
- Phase 2: The secondary eddy disappears and the primary eddy reduces in strength. Due to the return current, a vortex is created at the downstream groyne head. At this point, the water level in the groyne field is lowered due to the return current.
- Phase 3: At this point, the stern of the vessel has passed the head of the downstream groyne resulting in the ending of the return current at the downstream part of the groyne field and the beginning of the supply flow as is visible by the change in flow direction in the downstream groyne field.
- Phase 4: The return current along the vessel is pulling the water out of the upstream groyne field while the supply flow is pulling the water towards the upstream groyne resulting in two streams coming together. This coming together of flows results in an eddy in the upstream part of the groyne field. At this moment, the water level in the groyne field is rising again.
- Phase 5: The supply flow is still forcing the water out of the upstream part of the groyne field while the normal flow situation is slowly restored in the rest of the groyne field.
- Phase 6: The original situation with a primary and a secondary eddy is restored.

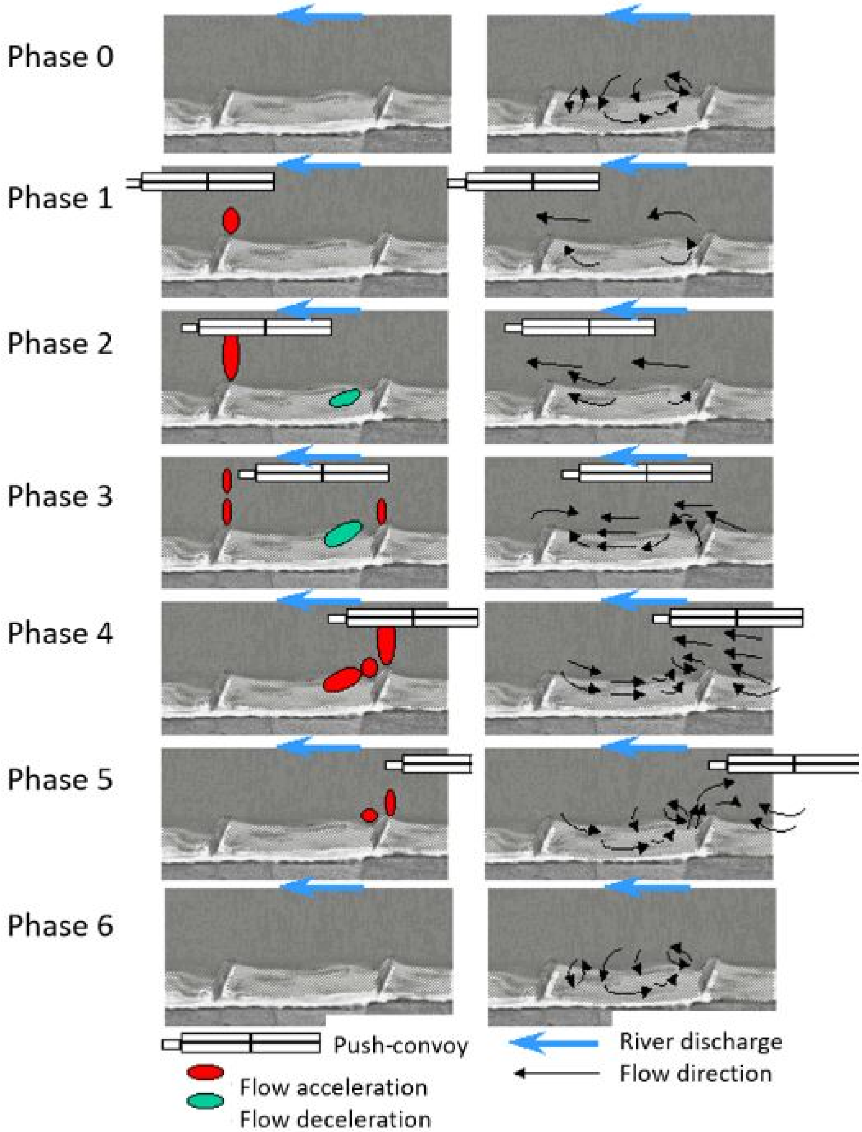

Figure 2.12: Influence of a vessel on the flow pattern inside a groyne field (Ten Brinke et al., 2004)

Morphodynamics

The changes in the flow pattern inside a groyne field due to the passage of vessels induce a change in the morphodynamics. In the previous section, it is stated that in a situation without vessels the direction of the sediment supply is towards the groyne field, indicating that the equilibrium state would be a completely filled-up groyne field. The passage of a vessel, however, induces erosion during low and medium discharge when the groynes are emerged. This creates an equilibrium between the erosion induced by vessels and the aggradation due to the natural flow during high discharge when the groynes are submerged. Research of Ten Brinke et al. (2004) shows this 'breathing' phenomenon of the groyne fields along the Waal from 1970 until 2000 based on the hydrograph of that period. It is visible that erosion due to shipping takes place during periods with relatively low discharge. When the discharge increases during a peak flood, sediment is deposited into the groyne fields resulting in an equilibrium. It should be noted, however, that this data dates from 50 to 20 years ago and the average vessel dimensions have changed as have the groyne dimensions.

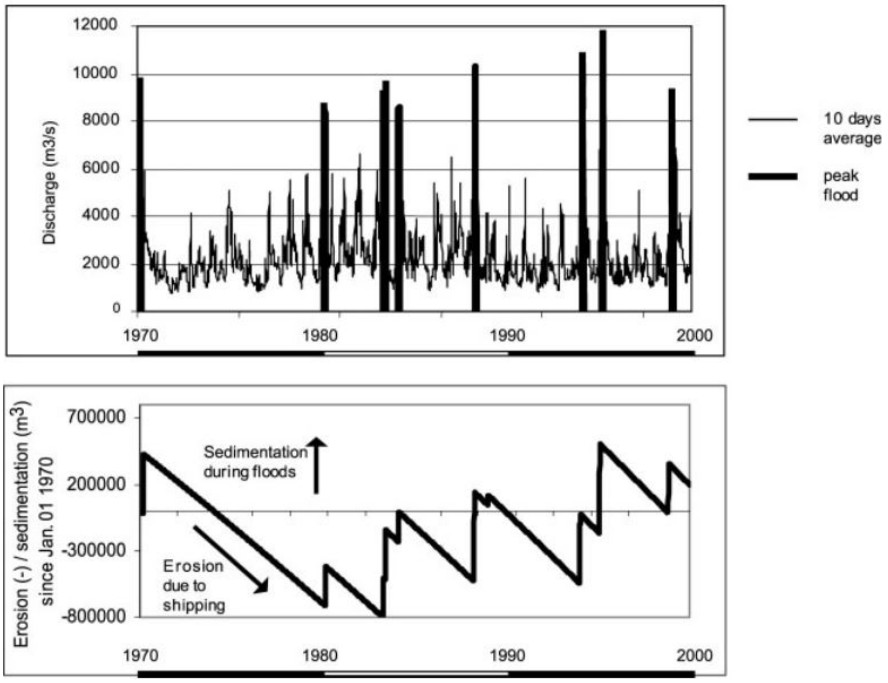

Figure 2.13: Erosion and sedimentation of the groyne-field beaches in the Waal during the period 1970-2000 according to the hydrographs of that period ((Ten Brinke et al., 2004)

Ten Brinke (2003) also found a difference between the erosion and sedimentation at the north- and south bank of the Waal during the period 1995-1998 as is visible in figure 2.14. He explained this difference in erosion due to the different conditions of the vessels sailing past the groyne field. The loaded ships sailing at the south side of the river sailing upstream have a larger draught compared to the mostly empty ships sailing downstream at the north side of the river. According to the results of Ten Brinke (2003), the difference in erosion between the north- and the south banks is a factor two. During high discharge, however, the sedimentation in the northern groyne field is two times higher compared to the south side. This restores the equilibrium. An explanation for the higher rate of sedimentation on the north side of the river has not been found

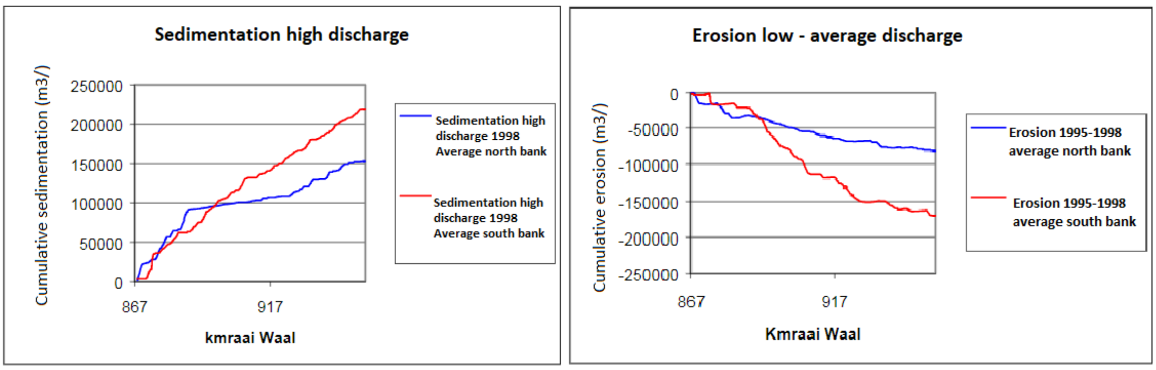

Figure 2.14: Cumulative erosion and sedimentation of the Waal during the period 1995-1998 during low/average and high discharge (Ten Brinke, 2003)

According to research of Ten Brinke (2003), erosion inside a groyne is mainly due to the primary waves. He measured the shear stress of the passage of 29 barge-tow combinations and the contribution of the primary and secondary waves to the total shear stress at two different locations inside a groyne field. One location is near the bank of the groyne field and one is at the riverside of the groyne field. The results are visible in figure 2.15. The blue part is the contribution of the primary waves on the shear stress and the red part is the contribution of the secondary waves. On average seventy percent of the shear stress is induced by the primary waves and the remaining thirty percent by the secondary waves. The drawdown and return current are therefore dominant. In the remainder of this research, the focus will be on the primary waves.

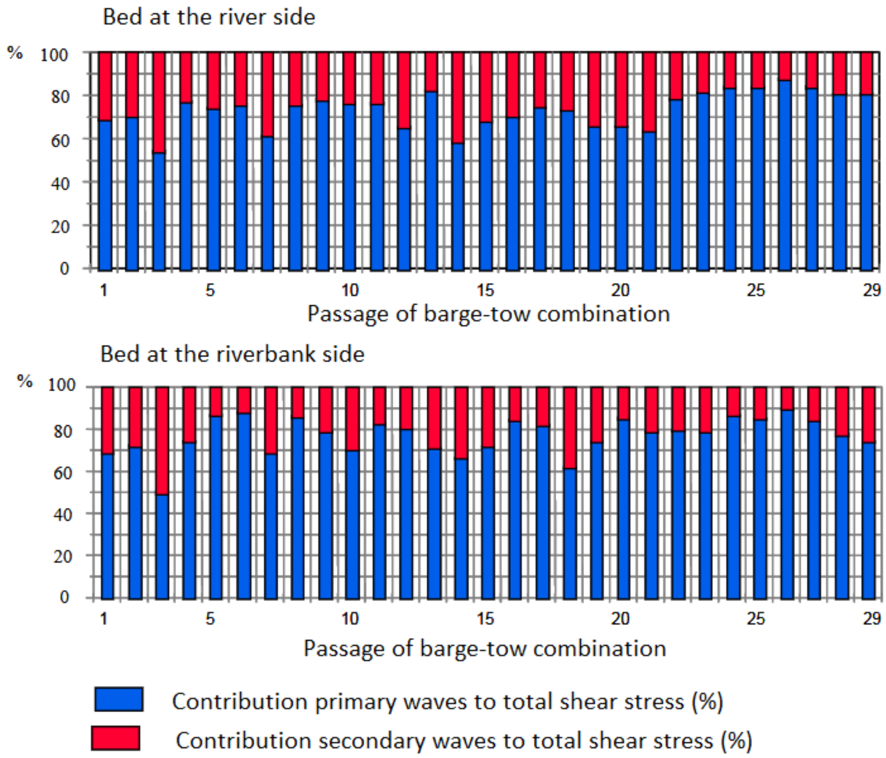

Figure 2.15: Influence of the primary and secondary waves on the total shear stress inside a groyne field for the riverside (top) and bank side (bottom) (Ten Brinke, 2003)

2.4 Chapter conclusion

In this chapter the flow pattern in an emerged and submerged groyne field is presented. During the period when the groyne field is emerged, the flow pattern inside the groyne field consists of a primary and an optional secondary eddy when the groyne field is longer than 200 meters or has a groyne field to width ratio larger than two. Furthermore, a dynamic eddy is present just downstream of the upstream groyne. When the groyne field becomes submerged, the horizontal eddy pattern dampens and the unidirectional flow becomes more dominant. When the groynes become fully submerged, only the unidirectional flow will remain. For both situations, the direction of the sediment supply is towards the groyne field. The equilibrium state is therefore a completely filled-up groyne field. This equilibrium state is however never reached due to the presence of vessels. Due to the passage of a vessel, the flow pattern inside the groyne field changes. This change in flow pattern is induced by the primary waves created by a vessel. When a vessel passes the groyne field the front wave raises the water level inside the groyne field first. Secondly, the water level inside the groyne field is lowered and finally, the water level is increased again by the stern wave. These fluctuations in water level, flow direction and flow velocities induce erosion inside the groyne field when the groynes are emerged. Eventually, this erosion and aggradation create a breathing effect where the groyne field is eroded by the vessels when the groyne field is emerged and sedimentation occurs when the groynes are submerged. Furthermore, next to the primary waves, also secondary waves are created by a vessel. The contribution of these secondary waves on the total shear is significantly lower compared to the contribution of the primary waves.

3

Measurements of flow and morphodynamics inside a groyne field in the Waal river

In this chapter, the flow properties and the morphodynamics inside a real designated groyne field are investigated. This data is obtained by performing a measurement campaign where the flow direction, flow speed, water level and sediment concentration inside a groyne field are measured. In the first part of this chapter, a brief explanation of the measurement plan is given, containing information about the location of the groyne field, the locations of the instruments, information about the measurement instruments themselves, the desired results and the measurement setup. In the second part of this chapter, the results of the measurement campaign are presented.

3.1 Measurement plan

In this section the measurement plan is briefly explained. The measurement plan contains the location of the measurements, the desired results, the instruments used and the setup of the instruments. The complete measurement plan can be found in appendix A.

Measurement location

The measurements took place in a groyne field near Haalderen at the northern side of the Waal, just upstream of Nijmegen. The location is indicated by the red circle in figure 3.1. Since one of the nourishment pilots will take place at this location, this location is chosen to perform the measurements for this research. By choosing a location which is actually part of the nourishment pilot, the results before the nourishment can be compared to the results during and after the nourishment to investigate the actual effect of the nourishment.

Figure 3.1: Measurement location

Desired results

Multiple properties are measured to investigate the flow properties and morphodynamics inside the groyne field. The properties included in this measurement campaign are:

- Bathymetry
- Water level
- Flow speed
- Flow direction
- Sediment concentration

With these properties it is possible to obtain a clear view of the flow inside the groyne field.

Instrument list

The following instruments are used during the measurement campaign:

- 4x Acoustic Doppler Velocimetry (ADV)
- 4x RBR solo
- 4x Seapoint Turbidity Meter (STM)

Instrument locations

The instruments are placed at four different locations inside the groyne field. The instruments are mounted to poles which are placed into the ground. This results in four different poles placed inside the groyne field with all instruments attached to it. After placement, the exact location of all instruments was measured with GPS. The exact coordinates of the measurement instruments are presented below:

	N (degrees)	E (degrees)	ADV number	RBR serial number
Location 1	51.87497	5.93120	ADV TUD001	202439
Location 2	51.87486	5.93227	ADV TUD002	202440
Location 3	51.87468	5.93288	ADV TUD004	202441
Location 4	51.87463	5.93346	ADV TUD005	208681

Table 3.1: Instrument GPS-locations including ADV numbers and RBR serial numbers

The exact locations of the measurement instruments with respect to the groyne field are plotted in figure 3.2. It is important to note that the flow direction in the main channel of the river is from right to left. Location one is therefore near the downstream groyne and location four is near the upstream groyne. To gather information about the location where the primary eddy ends and the secondary eddy begins, locations two and three are placed more towards the upstream groyne.

Next to the exact GPS location of the instruments, the exact height of all the different instruments and the angle of the ADV heads with respect to the shore is measured.

Figure 3.2: Exact GPS locations of the measurement instruments inside the groyne field

The left figure in figure 3.3 shows a schematic setup of one of the poles. The STM is placed closest to the bed to measure the sediment concentration. On top of the STM, the ADV head is placed to measure the flow velocity and flow direction. The RBR is placed above the ADV head to measure the water level. Finally, the ADV canister is placed which includes the batteries of the ADV and an extra water pressure sensor. All instruments are placed beneath the water's surface. The ADV canister is the only instrument which is partially above the water level as is visible in the right figure of figure 3.3.

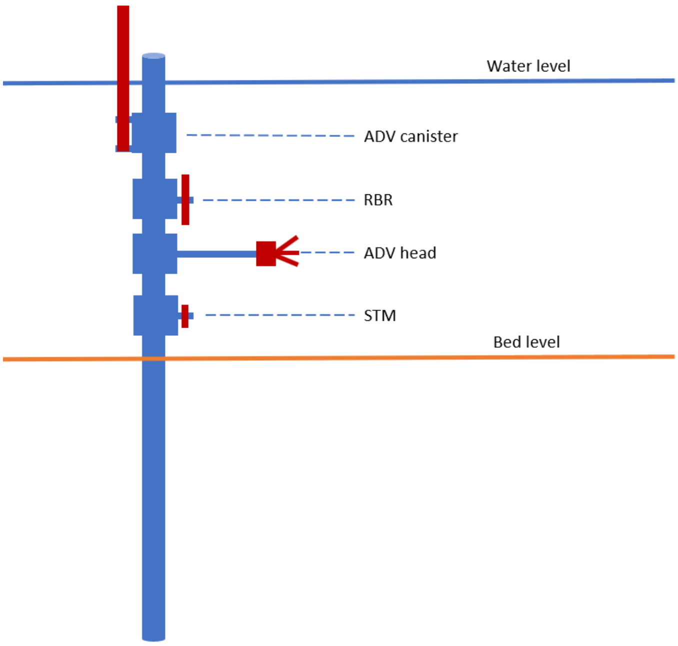

Figure 3.3: schematised view of the measurement setup, not to scale (left), and real measurement setup (right)

Measurement duration

The instruments were placed inside the groyne field on the 20th of April and removed on the fourth of May. The total measurement duration was therefore fourteen days. In the measurement plan, found in appendix A, a minimum measurement duration of seven days is stated. Since the batteries of the measurement instruments were capable of measuring more than one week, it was decided to leave the instruments inside the groyne field for a longer period to gather more data.

During this two-week period the vessel movements were monitored three times. Once on the 21st of April, the day after the instrument placement, by means of a visit to the project site, and on the 26th of April and the third of May by means of the my ship tracking tool. During the first physical observation, multiple quantities were noted. The time the vessel sailed past the upstream and the downstream groyne, depending on the direction of the vessel, the direction of the sailing vessel, whether the ship was sailing at the inside or the outside of the bend, the name of the vessel, the type of the vessel and the amount of waves and suction produced by the vessel. During the online observations, the time the vessel sailed past the upstream and downstream groyne was noted, the sailing direction of the vessel, whether the ship was sailing at the inside or the outside of the bend, the name of the vessel, the type of the vessel and the velocity of the vessel. Later, a complete overview of all vessels passing the groyne field is requested at Rijkswaterstaat. More about this in chapter 4. The data obtained during these observations is used to determine the effect of vessels on the flow properties inside the groyne field.

3.2 Measurement results

In this section, the results of the measurement campaign are presented. The results of the measurement campaign are processed and visualised with Python. Firstly, the bathymetry of the groyne field is presented. Secondly, the flow velocity and flow direction inside the groyne field measured with the ADVs are presented. Thirdly, the RBR results and finally, the STM results are presented.

3.2.1. Bathymetry

The first groyne field property investigated is the bathymetry of the groyne field. Unfortunately, the exact bathymetry of the groyne field was not measured during the measurement campaign due to a lack of the right measurement equipment and time. Therefore, already existing information about the bathymetry of the groyne field is used. To investigate the bathymetry of the groyne field and the influence of the bathymetry on the flow and morphodynamics inside the groyne field, the GeoWeb tool of Rijkswaterstaat is used. One of the maps available in the GeoWeb tool contains the bathymetry of the river the Waal and most of its groyne fields, including the groyne field used for the measurements.

Unfortunately, it is not possible to select an area and obtain all depth values for the coordinates inside that area with the GeoWeb tool. Therefore, the data of the latest measurements inside the groyne field and the measurements in the last decade have been requested at Rijkswaterstaat. Before investigating the complete bathymetry, a single cross-section is investigated with the GeoWeb tool. in figure 3.4 the location and profile of a cross-section of the chosen groyne field is visible. The measurements visible in this plot date from January 2018.

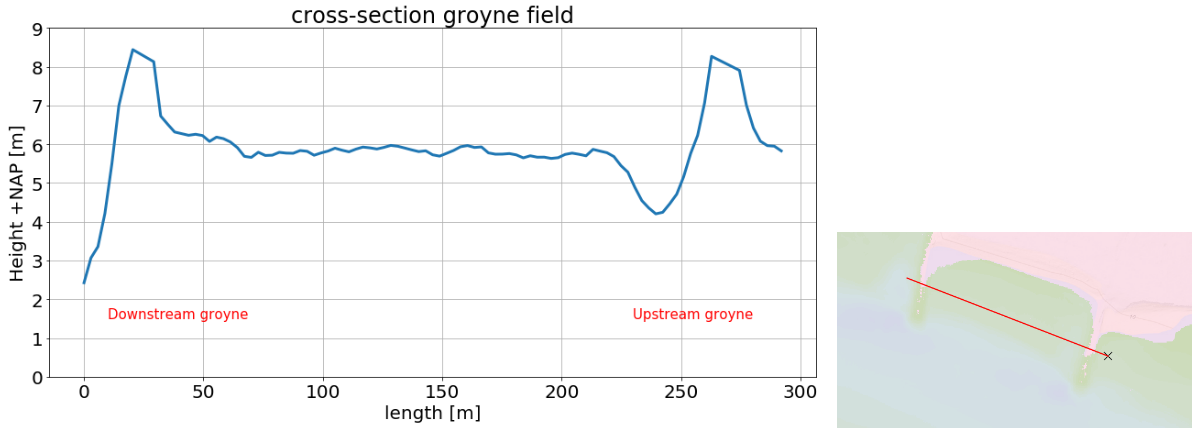

Figure 3.4: Depth profile (left) and location (right) of cross-section groyne field according to the GeoWeb tool

Visible in figure 3.4 are the two groynes reaching a height of eight meters above NAP. Between both groynes, there is a constant bed level of around 5.8 meters until the upstream part of the groyne field is reached. Visible is a decrease in the bed level inside the groyne field just downstream of the upstream groyne. Inside this hole, the bed level drops around 1.6 meters until it reaches a level of 4.2 meters above NAP.

According to the cross-section, a scour hole is present just downstream of the upstream groyne. To obtain more information about the bed inside the groyne field, the bathymetry of the groyne field was requested at Rijkswaterstaat. Unfortunately, only limited amount of data was available. The most recent data dates from January 2018 and is visible in figure 3.5. By selecting an extreme colour scale, it is possible to see the relative differences in the bed level. The pink colour indicates the location of the groynes reaching a level of eight meters above NAP. The yellow part indicates the location of the main channel at a level equal to around zero meters +NAP. The locations of the ADVs are also plotted in the figure.

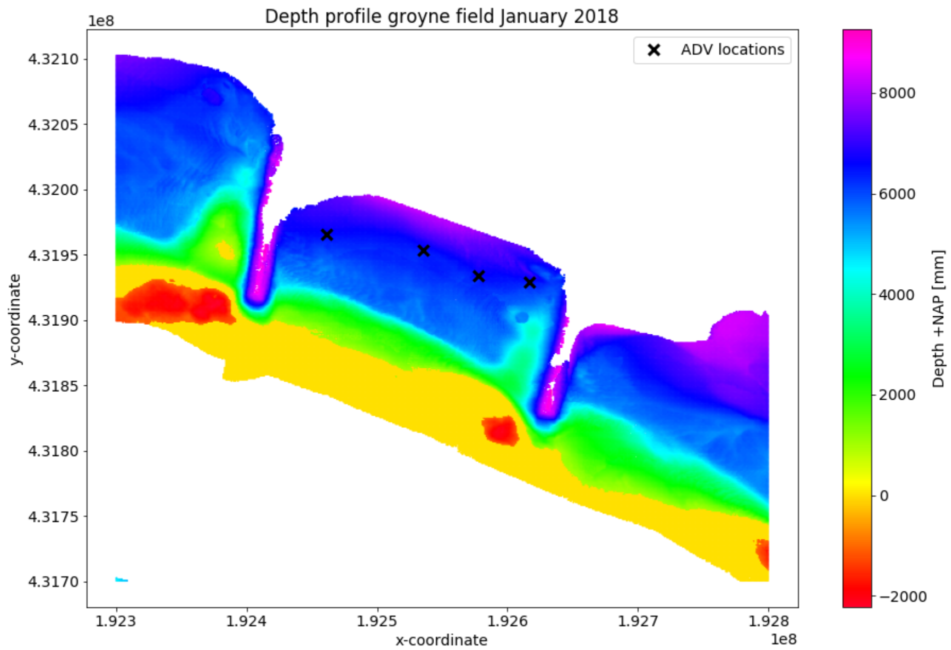

Figure 3.5: Bed profile inside the groyne field in January 2018

According to the figure, a scour hole is indeed present just downstream of the upstream groyne. A possible explanation for the location of this scour hole should be found in the results of the measurements. Beside the scour hole inside the groyne field, an extra deep scour hole just outside the groyne field is visible. This scour hole is around two meters deeper compared to the bed level of the main channel and is located at the location of the dynamic eddy. By investigating the groyne field downstream of the chosen groyne field, another even larger scour hole is present over there. These scour holes are created due to the dynamic eddy present at the tip of the groyne (Yossef, 2005).

By using the GeoWeb tool it is possible to look at the profile of the main channel perpendicular to the groyne field. The location and the cross-section are visible in figure 3.6. The cross-section is plotted such that the left part represents the northern groyne field and the right part represents the southern groyne field. Visible is the effect of the helical flow inside the river due to the groyne field being located in a bend. The helical flow causes the bed level slope at the northern side of the main channel to be steeper compared to the southern side of the main channel.

Also visible in figure 3.6 is the sudden steep decrease in bed level at two-thirds of the northern groyne field. The bed level slowly decreases until it reaches a level of approximately 5.8 meters above NAP with a gradient of around 0.0175 m/m. Suddenly, the bed level decreases till it reaches a level of 0.8 meters above NAP with a gradient of around 0.120 m/m. This difference in gradient is likely to be caused by a combination of the discharge of the main channel eroding the outer side of the groyne field and the helical flow eroding the outer part of the groyne field. The helical flow is not able to reach the inner part of the groyne field with as much force as the outer part of the groyne field. Therefore, the slope remains more gentle at the inner part of the groyne field.

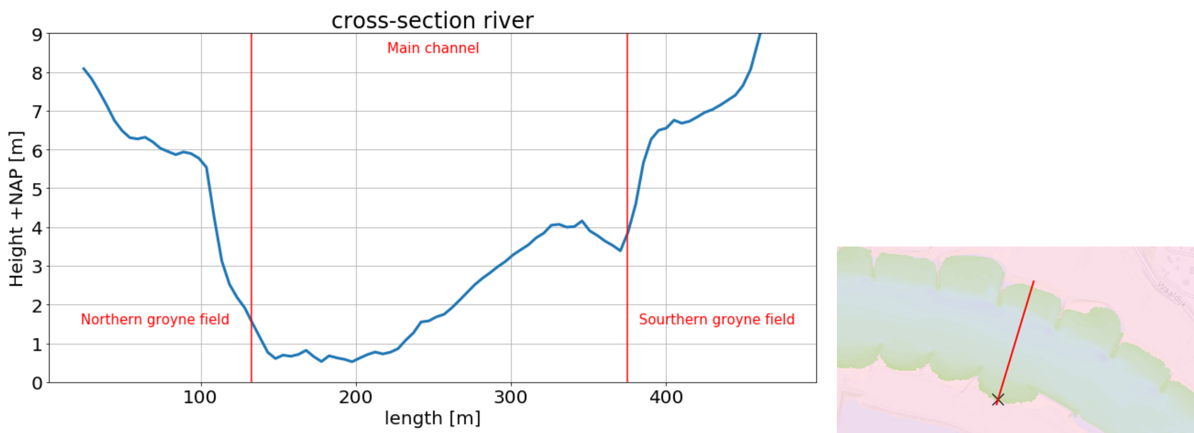

Figure 3.6: Depth profile (left) and location (right) of cross-section river according to the GeoWeb tool

Beside the bed profile of the groyne field, the bed profile of the main channel was requested at Rijkswaterstaat. For the bed profile of the main channel more data is available as is visible in figure 3.7. In this figure, the bed profile of the main channel in front of the groyne field is visible for measurements in the year 2014 (left), 2019 (middle) and 2021 (right). According to the figures, the bed is indeed deeper in the outer part of the bend due to the helical flow as was also visible in the cross-section. Comparing the bed level over the years a small decrease in the bed level is visible. Furthermore, the scour hole downstream of the groyne field appears to be growing. Since the decrease of the bed level is in the range of around two centimetres per year, a decrease of around fourteen centimetres (140 mm) is expected in the seven years between 2014 and 2021. To investigate whether the actual decrease of the bed level is indeed equal to fourteen centimetres, the obtained data need to be investigated further.

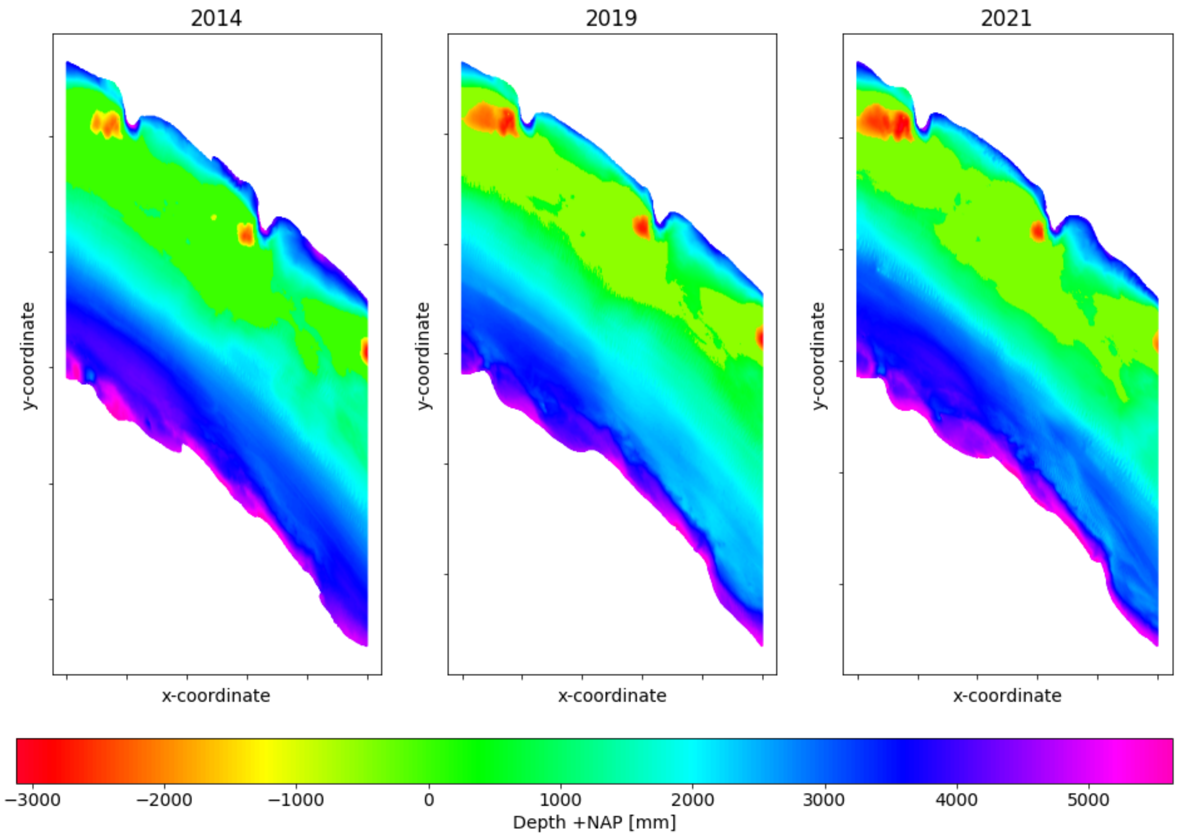

Figure 3.7: Bed level of the main channel in 2014 (left), 2019 (middle) and 2021 (right)

3.2.2. ADV results

In this section the results of the Acoustic Doppler Velocimetries (ADVs) are presented. The results are divided into two parts, the results of the situation without a vessel and the results of the situation with a vessel. The heads of the ADVs are positioned such that they are pointing out of the groyne field and perpendicular to the shore as can be seen by the arrows in figure 3.8. For the numbering of the ADVs, the numbers 1,2,4 and 5 are used. This is done because ADV number 3 was out of use and to avoid problems there has been chosen to skip number 3 and refer to the numbers visible on the ADVs. The ADV heads were placed at the following heights above the bed:

	Height above the bed (m)
ADV1	0.400
ADV2	0.404
ADV4	0.356
ADV5	0.353

Table 3.2: ADV head height above the bed [m]

Figure 3.8: Location and direction of the ADV heads

Situation without vessel

The results are divided into parts of ten minutes to be able to see the exact results. In figure 3.9 the results of the flow velocity at all ADV locations and in figure 3.10 the results of the water level at all locations are visible for the period from 13:00 until 13:10 on the 21st of April. A positive Z-velocity means a flow directed toward the shore and a positive Y-direction means a flow directed in the upstream direction, as can be seen in figure 3.8. The period from 13:00 until 13:10 is chosen because during this period no vessels were sailing past the groyne field and the flow inside the groyne field was therefore relatively stable. Since the ADVs were programmed to measure with a frequency of 8Hz, a lot of data is collected. To make the figures more clear, for each data point the average water level and velocity are calculated by adding up all water levels and velocities in the four seconds before and after the chosen measurement point and dividing by the number of data points in this interval. This removed the unrealistic values and smoothed the lines inside the graph to make the figures clearer. In figure 3.11 the flow pattern is visible by looking towards the groyne field from above. It is important to note that the flow direction in the main channel is from left to right. According to the figure, the direction of flow inside the groyne field is contrary to the flow outside the groyne field in the main channel. Also visible is the formation of the primary eddy and a 'shadow zone' where the flow velocity is almost reduced to zero, directly downstream of the upstream groyne. At the location of the shadow zone, the smaller secondary eddy is probably located. The primary eddy covers almost the entire groyne field as can be seen by the direction of the flow of ADV1, 2 and 4. At the location of ADV5, the flow velocity is significantly smaller compared to the other locations.

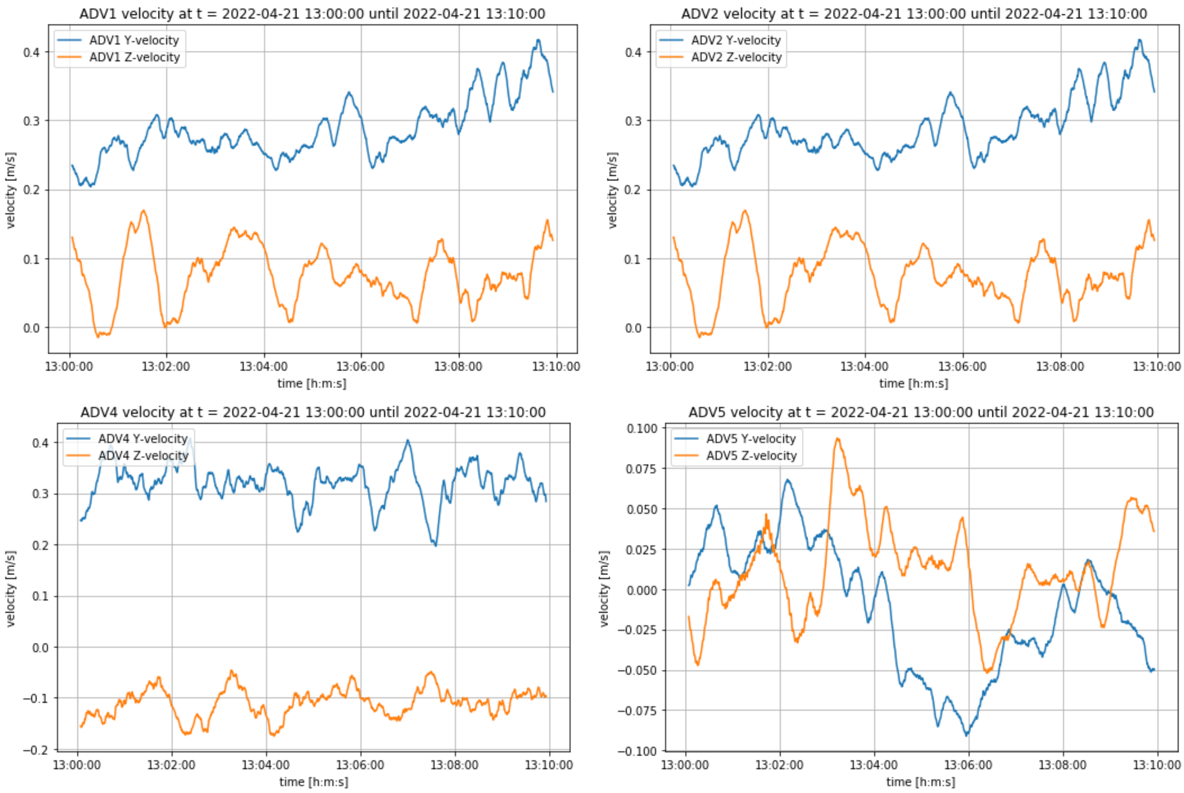

Figure 3.9: ADV flow velocities inside the groyne field at all locations on the 21st of April from 13:00 until 13:10

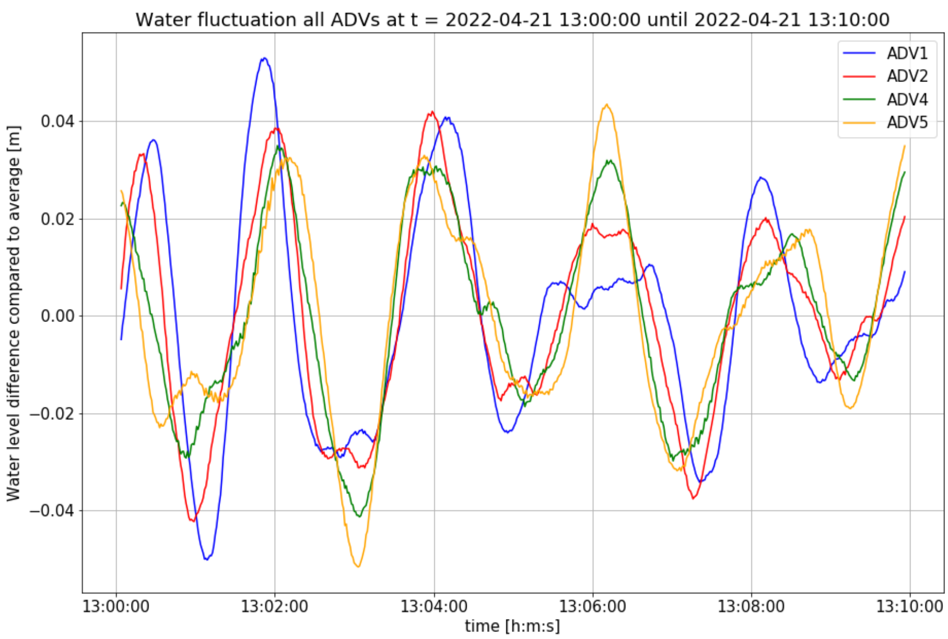

Figure 3.10: ADV water level fluctuation at all location on the 21st of April from 13:00 until 13:10

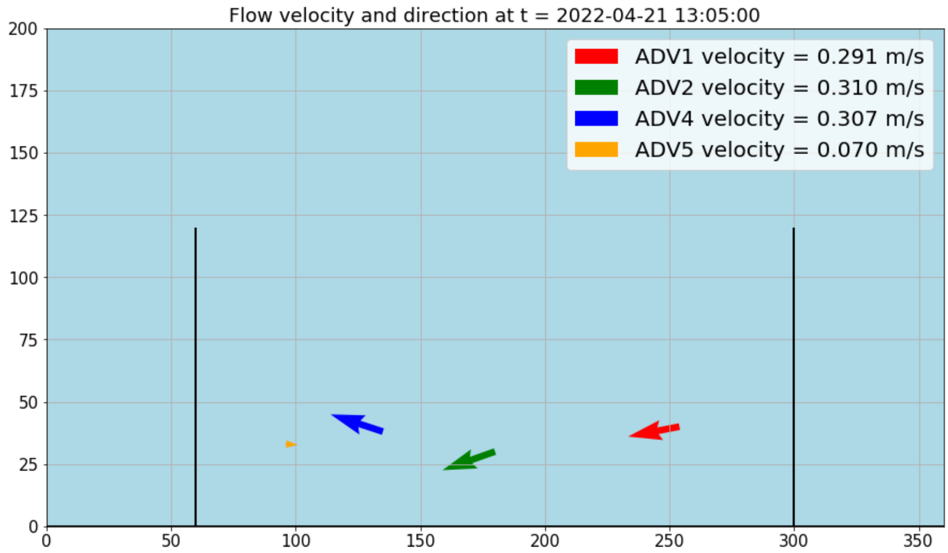

Figure 3.11: Flow velocity and direction inside the groyne field at 21-04-2022 13:05:00. The flow inside the main channel is from left to right

By investigating figure 3.10, which represents the water level inside the groyne field, it is visible that there is a constant fluctuation in the water level of several centimetres. The water level is raising several centimetres in a period of around 40 seconds after which it lowers again over a period of around 40 seconds. This constant fluctuation of water level is visible throughout the whole measurement period. Later, there will be more extensively investigated what the cause of this fluctuation might be.

In figure 3.12 the flow pattern which is likely to be present inside the groyne field is plotted. It should be noted that the extra arrows are not to scale with the flow velocity. Due to the bend in the river, the water flows directly into the groyne field against the downstream groyne. The water is deflected due to the groyne and flows in opposite direction along the shore towards the upstream groyne. Due to the groyne field being too long, the flow is not able to cover the full length of the shore and detaches to flow back towards the main channel. This is the primary eddy. In the remaining part of the groyne field, just downstream of the upstream groyne, a smaller, less strong eddy flowing in opposite direction is formed. This is the so-called secondary eddy.

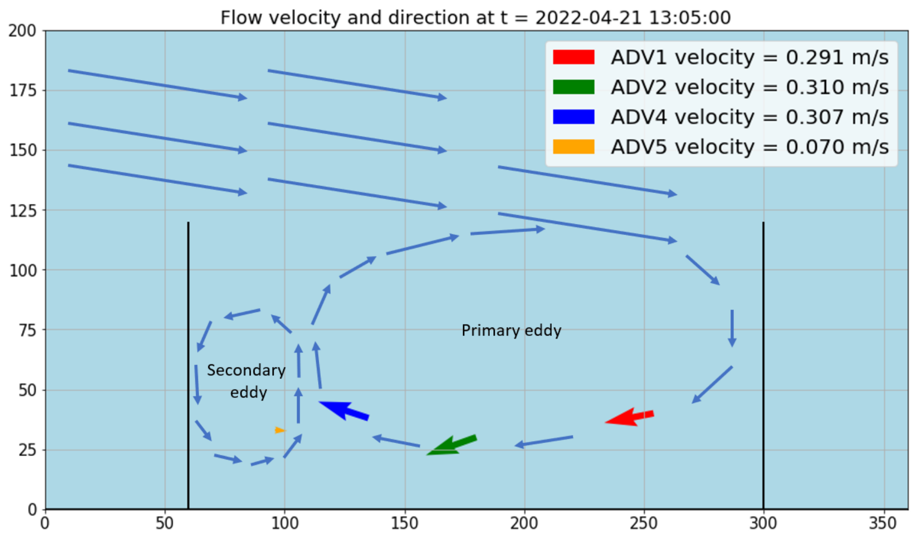

Figure 3.12: Expected flow inside the groyne field at 21-04-2022 13:05:00. The blue arrows suggest the flow pattern and are not scaled to the velocity

Situation with vessel

In this section the flow pattern when a vessel passes the groyne field is investigated. After investigating the results obtained by the ADVs, two vessel movements are chosen which represent the average effect of a vessel on the flow pattern inside the groyne field. The first vessel passage is on the 24th of April at 22:38. The second vessel passage is on the 24th of April at 22:57. In figure 3.13 the water level at all ADV locations is visible from 22:30 until 23:00 on the 24th of April. The green dotted line represents the moment a vessel enters the area between both the upstream and downstream groyne and the red dotted line represents the moment a vessel leaves the area between the upstream and downstream groyne.

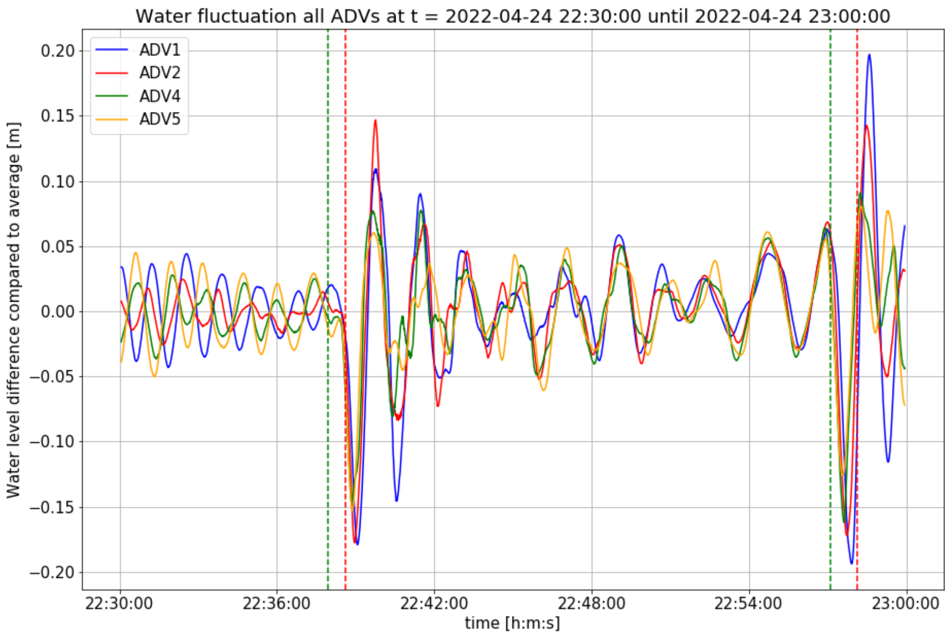

Figure 3.13: ADV water level fluctuation at all location on the 24th of April from 22:30 until 23:00

According to AIS-data later obtained, the first vessel enters the groyne field at 22:37:57 by sailing past the upstream groyne and takes 39 seconds to leave to the groyne field at the downstream groyne. This means the vessel had a relatively high velocity. The vessel had a length of 135 meters and a width of twelve meters. In figure 3.14 the water level fluctuation from 22:35 until 22:45 is visible. According to the figure, the water level starts decreasing when the vessel has left the area between both groynes which is not in agreement with the literature. There are two possible explanations for this. The first explanation is that due to the large velocity of the vessel, the effect of the vessel on the bank has a certain delay. The second explanation is that there is an error in the timing of the AIS-data. The second vessel passes the upstream groyne at 22:57:06 and the downstream groyne 61 seconds later. The vessel has a length of 172 meters and a width of 23 meters. In figure 3.15 the water level fluctuation from 22:53 until 23:03 is visible. According to this figure, the water level starts decreasing the moment the vessel enters the area between both groynes which is in agreement with the literature.

In figure 3.16 and 3.17 the velocities at the different ADV locations for both vessels are visible. Visible is the change of velocity when the vessel passes the groyne field. Especially at the location of ADV5, the velocity increases from almost zero to values of around 0.2 m/s.

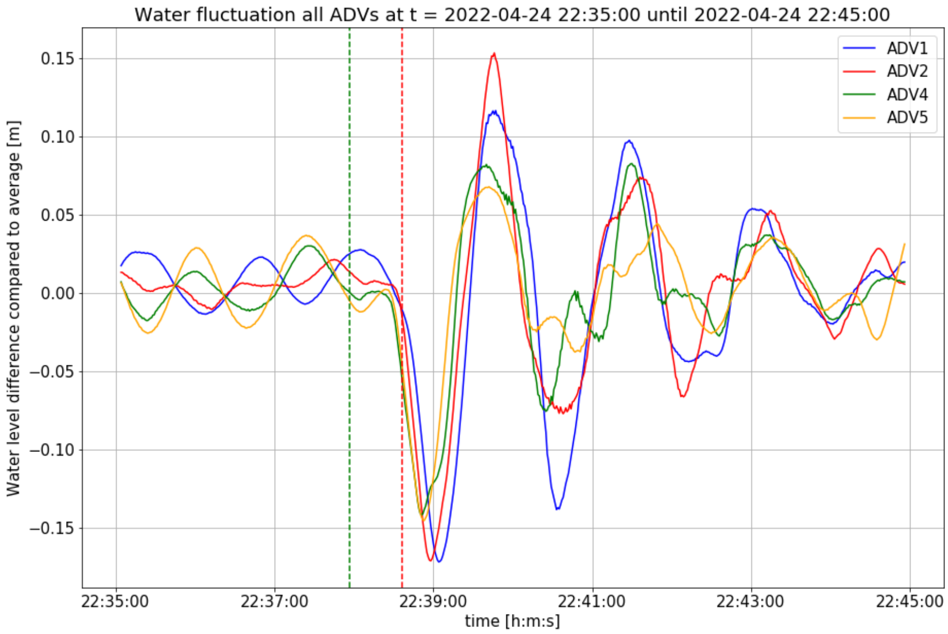

Figure 3.14: ADV water level fluctuation at all location on the 24th of April from 22:35 until 22:45

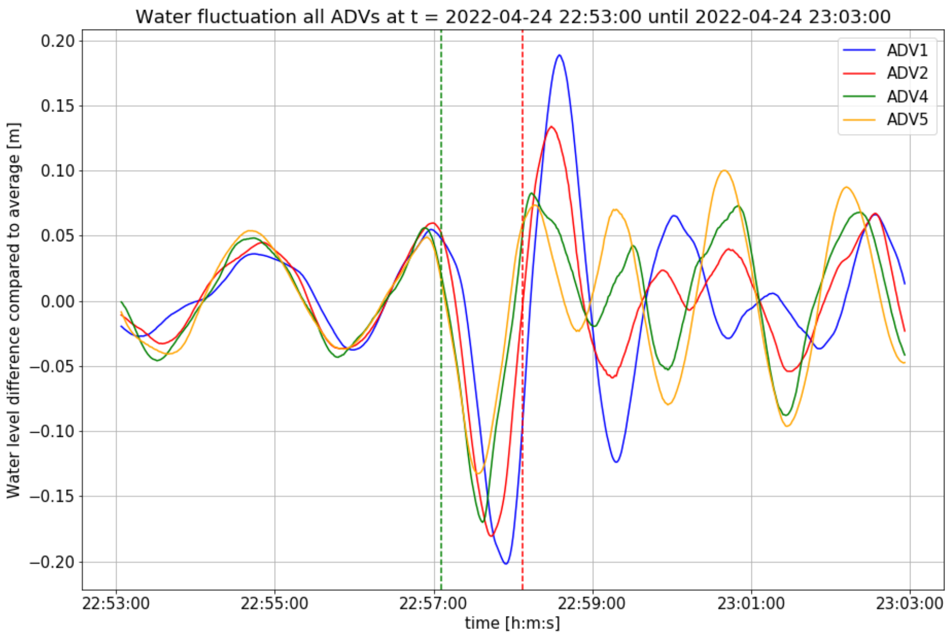

Figure 3.15: ADV water level fluctuation at all location on the 24th of April from 22:53 until 23:03

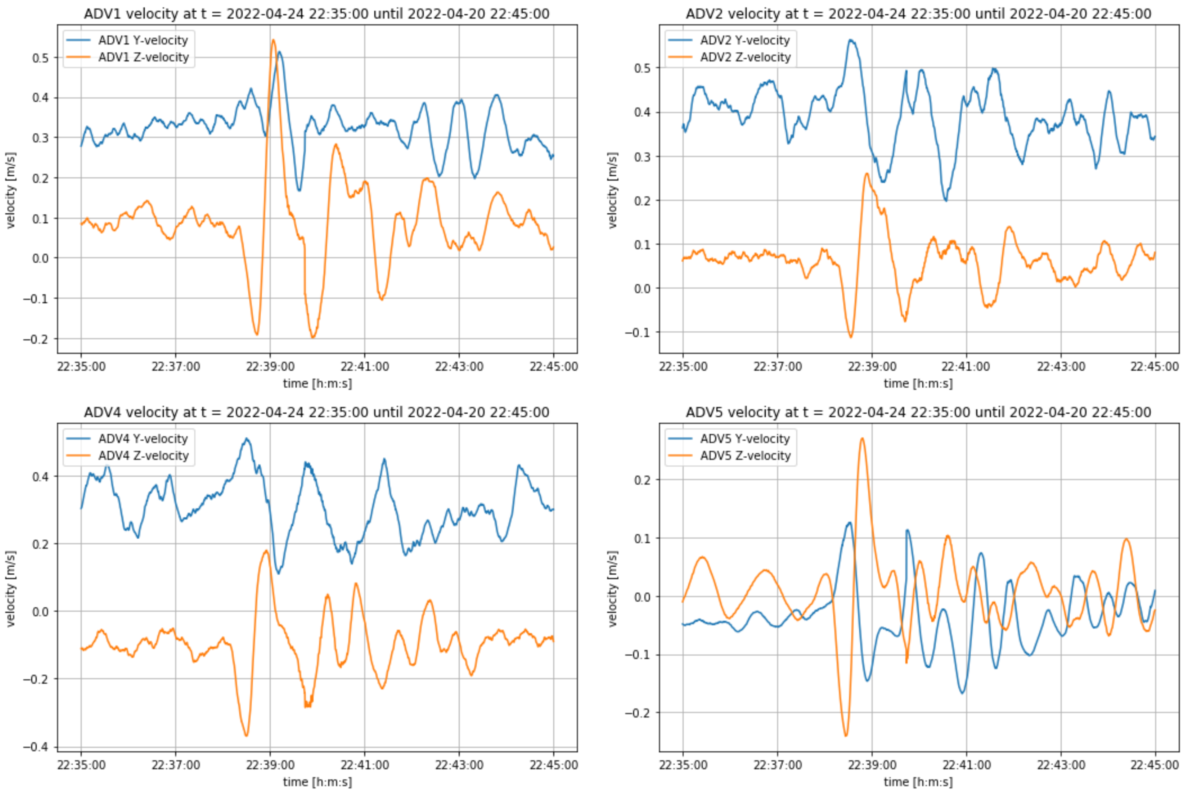

Figure 3.16: ADV flow velocities inside the groyne field at all locations on the 24th of April from 22:35 until 22:45

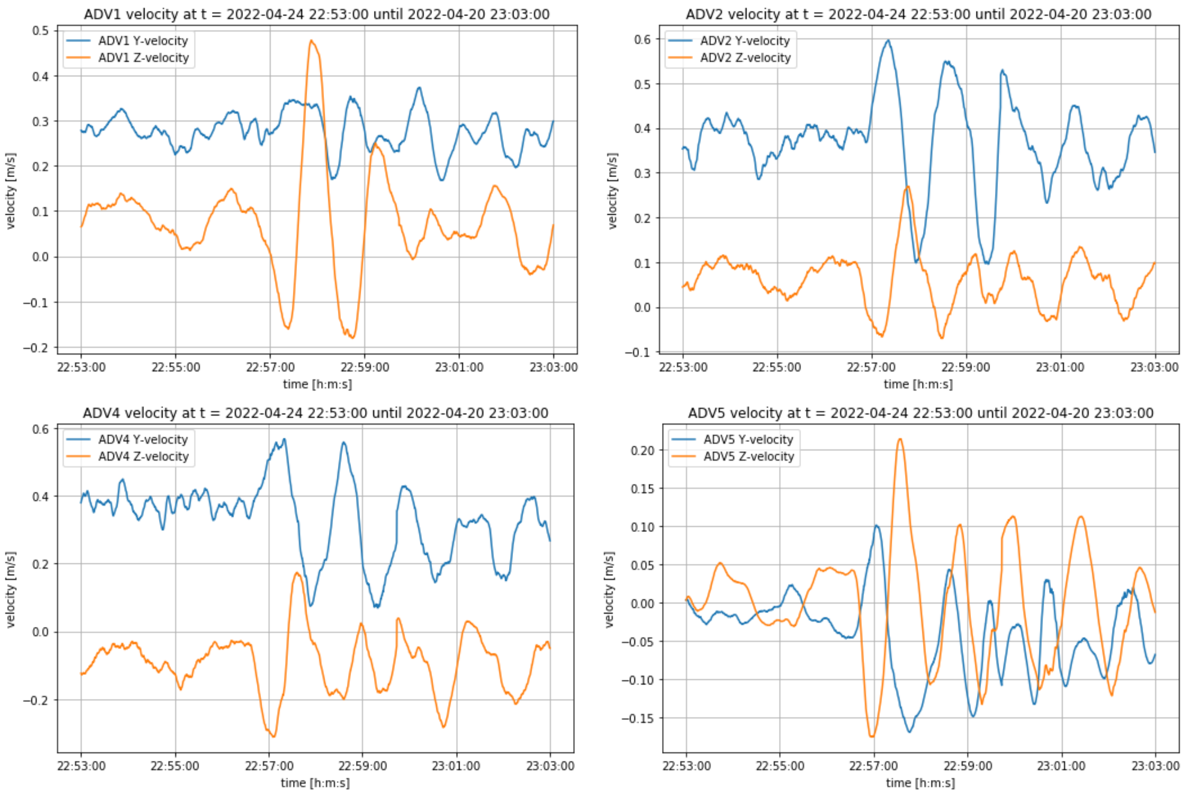

Figure 3.17: ADV flow velocities inside the groyne field at all locations on the 24th of April from 22:53 until 23:03

The influence of the vessel arriving at the groyne field at 22:57 is further inspected by investigating the flow pattern inside the groyne field. This is done by plotting a schematic top view of the groyne field including the flow direction and velocities at the four measurement locations. Before the arrival of the vessel, the flow pattern is equal to the flow pattern in figure 3.11. In figure 3.18 the flow pattern inside the groyne is visible when the vessel is sailing past the upstream groyne. The return current around the vessel is lowering the water level by forcing the water out of the groyne field. At the location of ADV5, the flow velocity increases from almost zero to a flow velocity of almost 0.2 m/s. At the location of ADV4, the flow velocity is also increased and the flow direction is directed out of the groyne field towards the upstream groyne. At the location of ADV1 and ADV2, the flow pattern remains unchanged, indicating that at these locations the flow pattern remains intact, guiding water towards the upstream part of the groyne field where the water leaves the groyne field. In figure 3.19 the flow pattern inside the groyne field is visible when the vessel has passed the middle of the groyne field. At this moment, the water level inside the groyne field is increasing again. The flow direction at the locations of ADV4 and ADV5 has turned around and is now directed towards the bank of the groyne field. Furthermore, at the locations of ADV1 and ADV2, the flow is also supplying more water towards the groyne field.

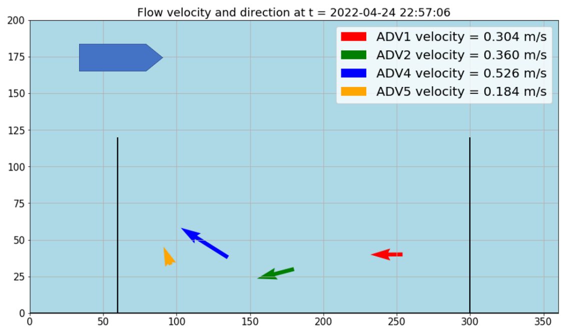

Figure 3.18: Flow velocity and direction inside the groyne field at 24-04-2022 22:57:06

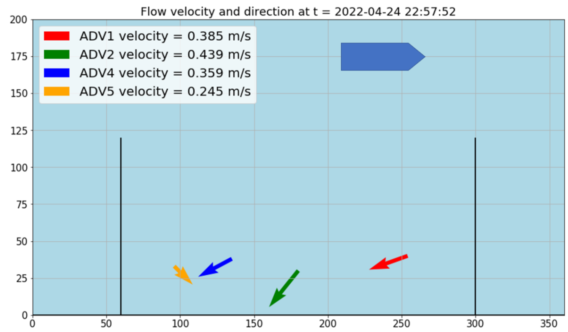

Figure 3.19: Flow velocity and direction inside the groyne field at 24-04-2022 22:57:52

In figure 3.20 the flow pattern inside the groyne field is visible when the vessel is leaving the groyne field. At the location of ADV1 and ADV2, the flow is still supplying water towards the groyne field. At the locations of ADV4 and ADV5, the flow has come to a rest. According to the literature, the return current around the vessel should decrease the water level inside the upstream part of the groyne field when the vessel is sailing past the downstream groyne field. In reality, this is not the case for this particular groyne field. In figure 3.20 the flow pattern when the vessel has left the groyne field is visible. The water level inside the groyne field is still fluctuating as can be seen in figure 3.15 but will eventually return to the standard flow pattern.

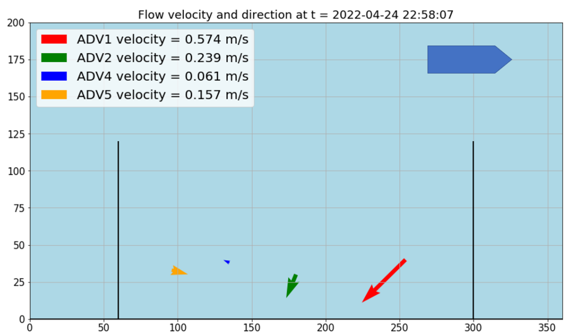

Figure 3.20: Flow velocity and direction inside the groyne field at 24-04-2022 22:58:07

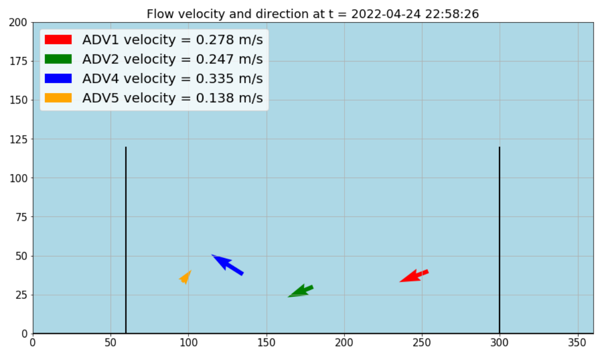

Figure 3.21: Flow velocity and direction inside the groyne field at 24-04-2022 22:58:26

It can be concluded that the vessel changes the flow pattern and the water level inside the groyne field significantly. Especially the flow in the part downstream of the upstream groyne, at the location of ADV5, experiences a substantial change in flow velocity and flow direction compared to the stable situation.

The influence of this vessel on the flow inside the groyne field can be summarised as follow: At the beginning, the standard flow pattern consisting of a primary and a secondary eddy is present inside the groyne field. At the moment the vessel sails past the upstream groyne, the primary wave created by the vessel start decreasing the water level inside the groyne field, forcing the water out of the groyne field. At the location of ADV5, the secondary eddy disappears and the water starts flowing directly out of the groyne field. At the location of ADV4, the flow velocity also increases, guiding more water towards the upstream groyne and out of the groyne field. The flow pattern in the downstream part of the groyne field remains intact, meaning that it supplies more water towards the upstream groyne. At the moment the vessel is sailing halfway beside the groyne field, the water level inside the groyne field starts to increase again due to the stern wave. The flow inside the groyne field is pointing towards the bank meaning the water level inside the groyne field is increasing. When the vessel is leaving the groyne field by sailing past the downstream groyne, the flow at the locations of ADV1 and ADV2 is still supplying water towards the groyne field. At the upstream part of the groyne field, the flow has come to a rest. When the vessel has passed the groyne field entirely, the water level keeps fluctuating for a few minutes. Eventually, the standard flow pattern returns inside the groyne field.

After investigating the other results obtained by the ADVs, not all vessels have the same influence on the water level inside the groyne field. By investigating a different time period it is possible to observe the effect of other vessels on the water level inside the groyne field. The water level at the location of ADV5 for the period between 12:30 and 13:00 on the 24th of April is plotted in figure 3.22. During this period, seven vessels passed the groyne field. The green dotted lines indicate again the moment a vessel enters the area between both groynes and the red dotted line is the moment a vessel leaves the area between both groynes. Information about these vessels is presented in table 3.3. The first vessel that passes the groyne field, vessel one, has almost no influence on the water level inside the groyne field. The second vessel does have a large effect on the water level by reducing the water level by several centimetres. The next two vessels, vessel three and four, pass the groyne field at the same time. This combining effect, or the effect of one of the two vessels, causes a decrease in the water level. the next vessel, vessel five, has again a minor effect on the water level inside the groyne field. The final two vessels, vessel six and seven, pass the groyne shortly after each other. their effect on the water level inside the groyne field is average. This figure shows that the effect created by a vessel differs for each vessel. Furthermore, when two vessels are sailing past the groyne field at the same time, the effect of a single vessel is impossible to predict.

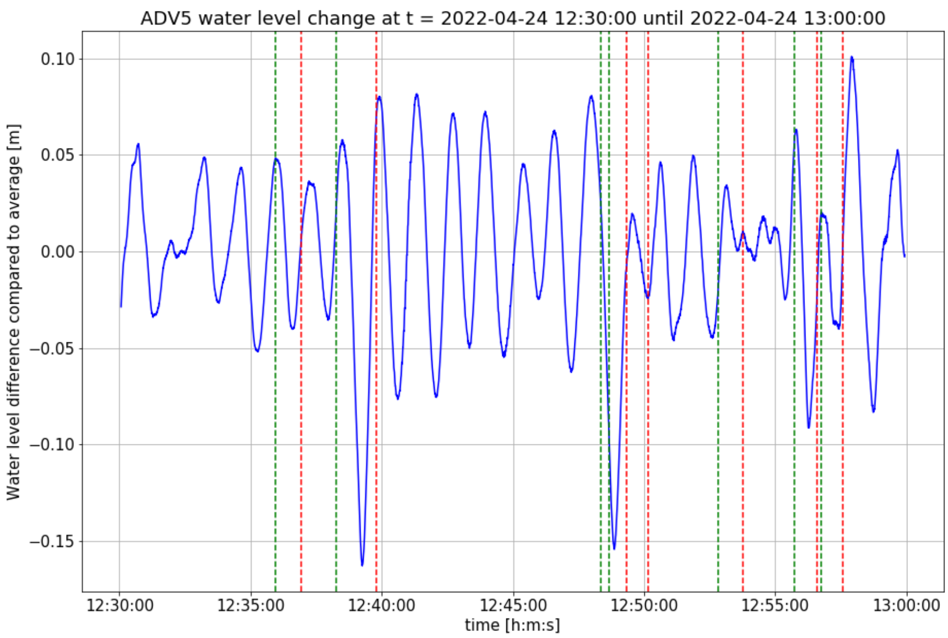

Figure 3.22: ADV5 water level fluctuation on the 24th of April from 12:30 until 13:00

	Time entering groyne field	Time leaving groyne field	Sailing direction	Sailing speed [knots]	Length [m]	Width [m]	Draught [m]
Vessel 1	12:35:57	12:36:56	Downstream	7.6	85	6	2.4
Vessel 2	12:38:17	12:39:47	Upstream	8.8	110	11	-
Vessel 3	12:48:22	12:49:21	Downstream	6.5	110	12	-
Vessel 4	12:48:40	12:50:10	Upstream	8.5	135	12	2.5
Vessel 5	12:52:49	12:53:46	Downstream	8.4	110	12	1.6
Vessel 6	12:55:45	12:56:35	Downstream	7.8	135	14	-
Vessel 7	12:56:46	12:57:34	Downstream	8.5	85	8	1.7

Table 3.3: Information about vessels passing the groyne field on the 24th of April from 12:30 until 13:00

The instruments were placed inside the groyne field for a duration of two weeks. Therefore, more data is collected than shown in this section. With the help of a Python script, it is possible to look through the remaining data. According to this data, the majority of the vessels passing the groyne field have barely any influence on the flow inside the groyne field like visible in figure 3.22. The few exceptions, like the vessels presented in figure 3.14 and 3.15, cause the major changes in flow velocities and water level inside the groyne field. The vessels that cause these major differences in flow velocity and water level inside the groyne field induce the largest amount of erosion.

3.2.3. RBR results

The RBRs should produce the same results as obtained by the pressure sensor of the ADV. However, since the RBRs were programmed to measure at a frequency of only 1 Hz the results should look slightly different. The numbering of the RBRs is the same as for the ADVs. Plotting the results for the 24th of April from 22:53 until 23:03, the same period as in figure 3.15, gives the results visible in figure 3.23. Since the RBRs are programmed to measure at a frequency of 1 Hz, compared to the 8 Hz of the ADVs, the results look slightly different. Investigating the shape of the line and the amount of decrease and increase in the water level the results are almost identical. Since the water pressure sensors of ADV1 and ADV2 were partly above the water level due to a decrease in the water level inside the groyne field visible in Appendix A.10, they were not able to measure the water level inside the groyne field during the whole measurement period. Therefore, the data of the RBRs is used to visualise the water level difference in the remainder of this report. The results of the water pressure sensors of the ADVs are used to confirm these water levels.

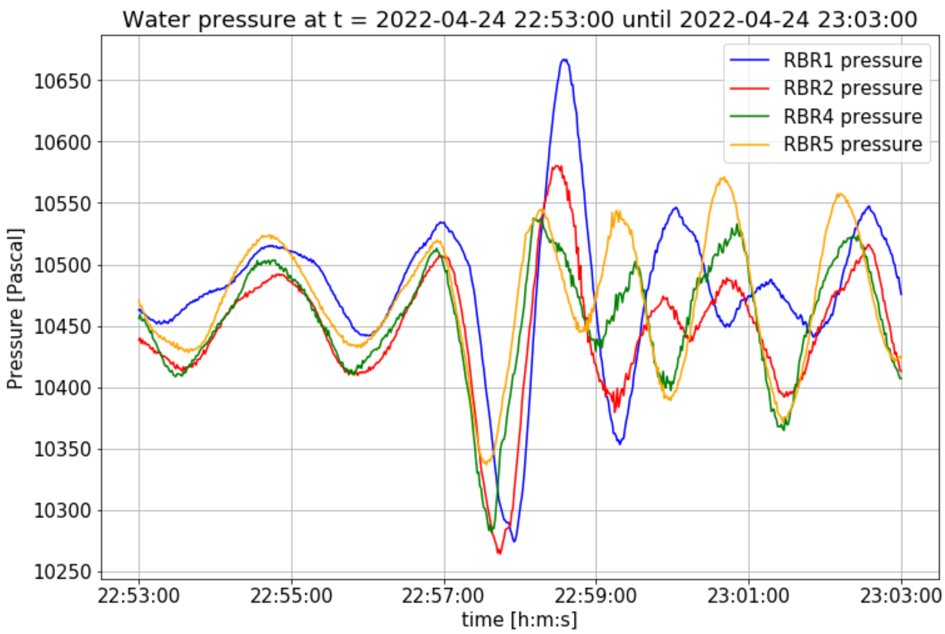

Figure 3.23: RBR water pressure at all locations from 24-04-2022 22:53 until 23:03

3.2.4. STM results

In this section, the STM results are presented. Before analysing the results, the composition of the bed at multiple locations inside the groyne field is investigated. The STMs are powered by the batteries inside the ADV canister. This means that the locations of the STMs are the same as the locations of the ADVs visible in figure 3.8. For the numbering of the STMs, the same numbers as for the ADVs are used. The STMs are placed at the following heights above the bed:

	Height above the bed (m)
STM 1	0.12
STM 2	0.07
STM 4	0.09
STM 5	0.05

Table 3.4: STM height above the bed [m]

It should be noted that it was hard to measure the exact height of the STMs. The STMs were located at a depth of around one meter below the water level and since the flow velocity inside the groyne field was high, these numbers should be interpreted with a range of several centimetres.

Sediment properties

Before analysing the results, it should be noted that the substance of the sediment at each location was different. To investigate the substance of the sediment at the various locations inside the groyne field three samples were taken and sieved. In figure 3.24 the sieve curves for three different locations are shown. The first sample was taken near the location of ADV1, the second sample was between the location of ADV2 and ADV4 and the final sample was taken near the location of ADV5. In the figure five different areas are distinguished. The area smaller than 0.063 mm is classified as silt, the area between 0.063 and 0.250 mm as fine sand, the area between 0.250 and 0.500 mm as medium sized sand, the area between 0.500 and 2.000 mm as coarse sand and the area larger than 2.000 mm as pebbles.

At the location of ADV5 the sediment is finer compared to the other locations according to the blue sieve curve in figure 3.24. Almost 50 percent of the sample can be classified as fine sand while it contained almost no sediment larger than 2.000 mm. At the location of ADV1, the sediment is coarser. This is visible by the red sieve curve in figure 3.24. Around 50 percent of the sample is larger than 0.500 mm and 50 percent smaller. Fifteen percent of the sample is even larger than 2.000 mm. At the location between ADV2 and ADV4, the sediment is even coarser. In figure 3.24 this is visible by the purple sieve curve. Around 66 percent of the sample is larger than 0.500 mm and around 25 percent is even larger than 2.000 mm.

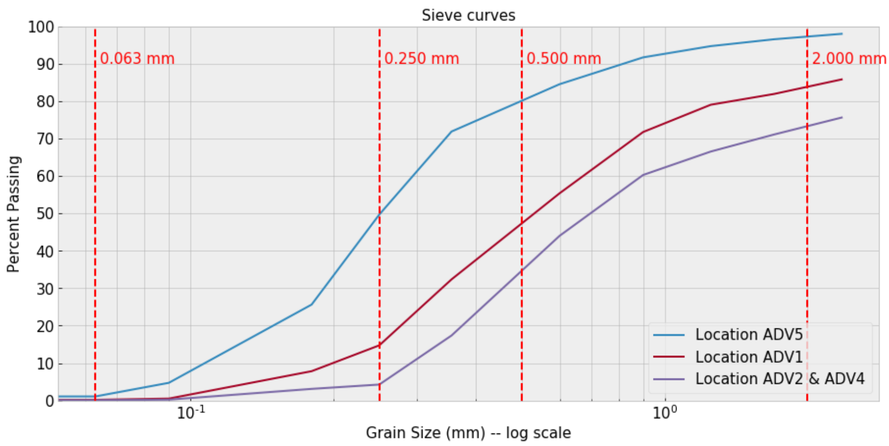

Figure 3.24: Sieve curves of three different locations inside the groyne field

Results

In this section the results of the STMs are presented. When the instruments were removed from the groyne field, the measurement instruments were covered with algae, including the STM sensor. Since the STM sensors use light to measure the sediment concentration inside the water this resulted in unreliable results due to the algae blocking the light signal. Therefore, only part of the data can be used to measure the sediment concentration inside the water. Furthermore, the results of the STMs are not calibrated. Therefore, the results only indicate a linear magnitude of the sediment concentration inside the water reaching from zero to 60.000. The situation without vessels on the 21st of April from 13:00 until 13:10, visual in figure 3.10, is investigated first. Since the STMs measure the sediment concentration inside the groyne field with the same frequency as the ADVs, the STMs measure with a frequency of 8 Hz. To make the results more clear, the results are averaged by computing the average sediment magnitude in the four seconds before and the four seconds after the data point of interest, just like the water level and velocity results. After averaging, The STM results of this period are visible in figure 3.25. According to the results, a relatively constant magnitude of the sediment concentration inside the groyne field is present at all locations. This suggests that when there is no vessel influencing the flow inside the groyne field a constant amount of sediment is present inside the water.

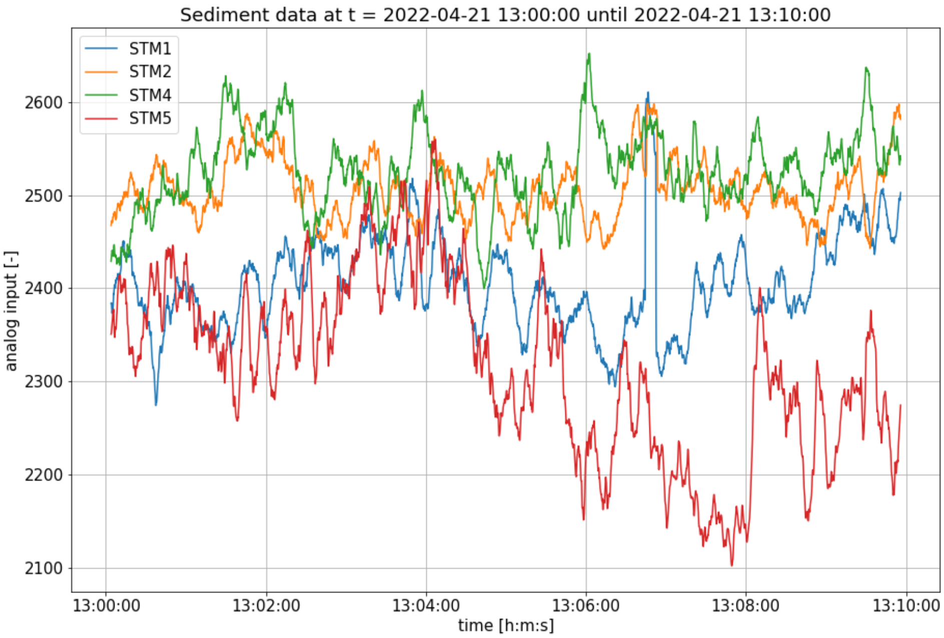

Figure 3.25: Averaged STM measurements of 21-4-2022 13:00 until 13:10

The results when a vessel sails past the groyne field are investigated next. Since the STMs were covered with algae, resulting in a large part of the measurement results being unreliable, the sediment concentration during the vessel movements visible in figure 3.14 and 3.15 cannot be investigated. Therefore, the influence of a vessel passing the groyne field on the 21st of April at 14:33 is investigated. In figure 3.26 the effect of this vessel on the water level is visible. According to this figure, the water level starts lowering before the vessel has even arrived at the groyne field. At the moment the vessel enters the area between both groynes, the water level starts increasing again. A possible reason for this is an inaccuracy of the AIS-data. Furthermore, a second vessel passes the groyne field at 14:36. This vessel has, however, no significant effect on the flow inside the groyne field.

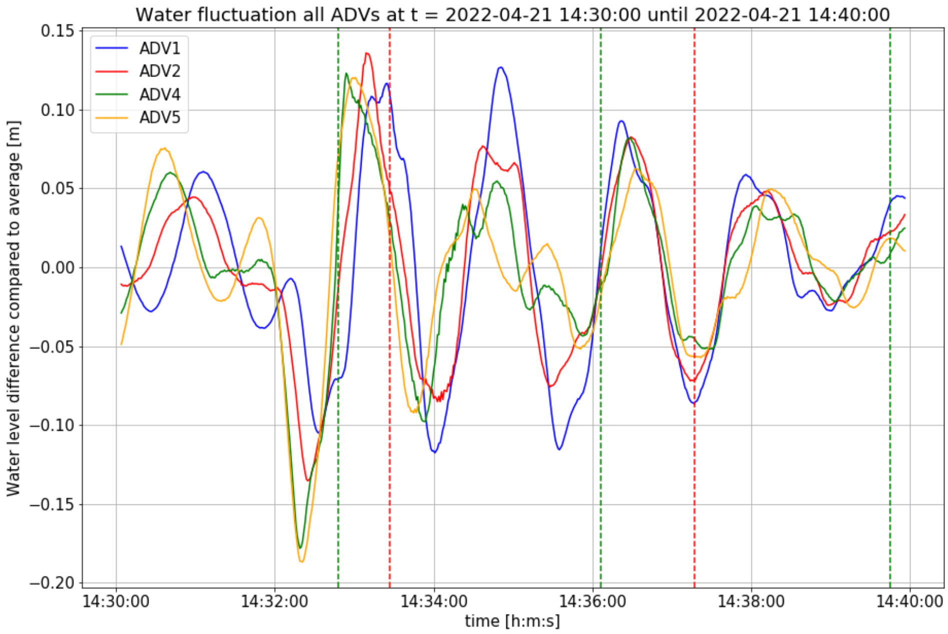

Figure 3.26: ADV water level fluctuation at all location on the 21st of April from 14:30 until 14:40

In figure 3.27 the results are visible. According to this figure, the sediment concentration at the location of STM5 increases significantly when the vessel sails past the groyne field. At the locations of the other STMs, the sediment concentration remains relatively constant. The peak at the location of STM5 can be explained by a combination of the fine sediment present at this location, visible in figure 3.24, and the low flow velocity at this location when no vessels are passing the groyne field. This combination results in fine sediment settling at this location. When a vessel passes, the flow velocity is significantly increased at this location, resulting in the fine sediment being mobilised. This stirred up sediment remains in the water column for several minutes before it settles again as can also be seen in the figure.

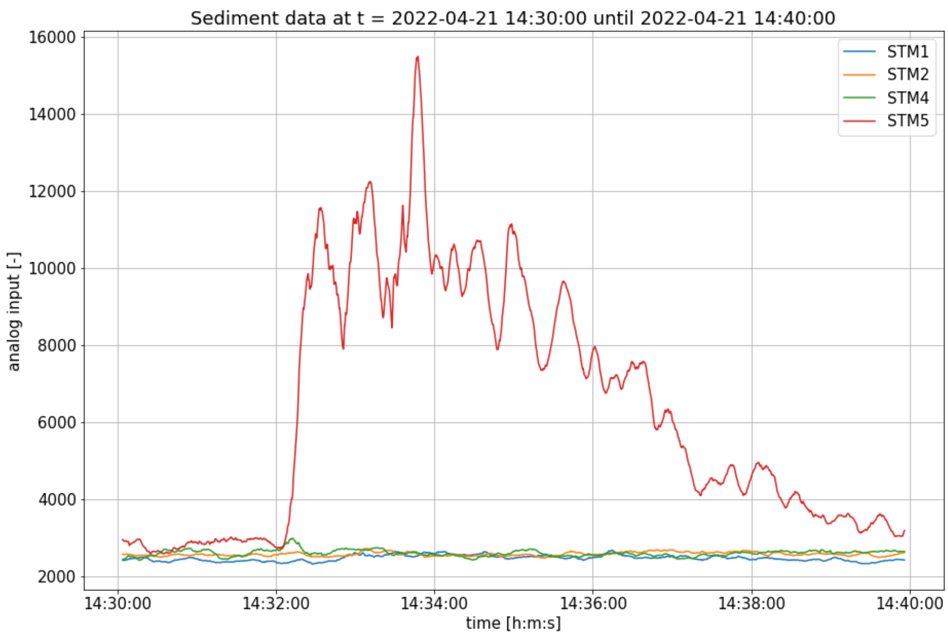

Figure 3.27: STM results of 21-4-2022 14:30 until 14:40

By removing the result of STM5 it is possible to investigate the magnitude of the sediment concentration at the locations of the other measurement instruments. The results are visible in figure 3.28. The magnitude of the sediment concentration at these locations remains relatively constant when the vessel passes the groyne field. A small increase in the sediment concentration at the location of STM4 is visible at 14:32 when the water level starts decreasing in the groyne field. Furthermore, a minor increase in the sediment concentration at the location of STM1 at 14:33 is visible. A possible explanation for the difference in sediment concentration at the location of STM5 compared to the other locations is the composition of the bed. At the location of STM5, the sediment is relatively fine, making it easier to mobilise. Another possible explanation is the transport of the sediment over the bed floor. In combination with the coarser material, it is possible that the sediment is mobilised underneath the STM sensors by rolling over the bed floor. In table 3.4 the heights of the STMs are noted. According to this data, STM5 is placed closest to the ground which could be an explanation for the higher sediment concentration at this location.

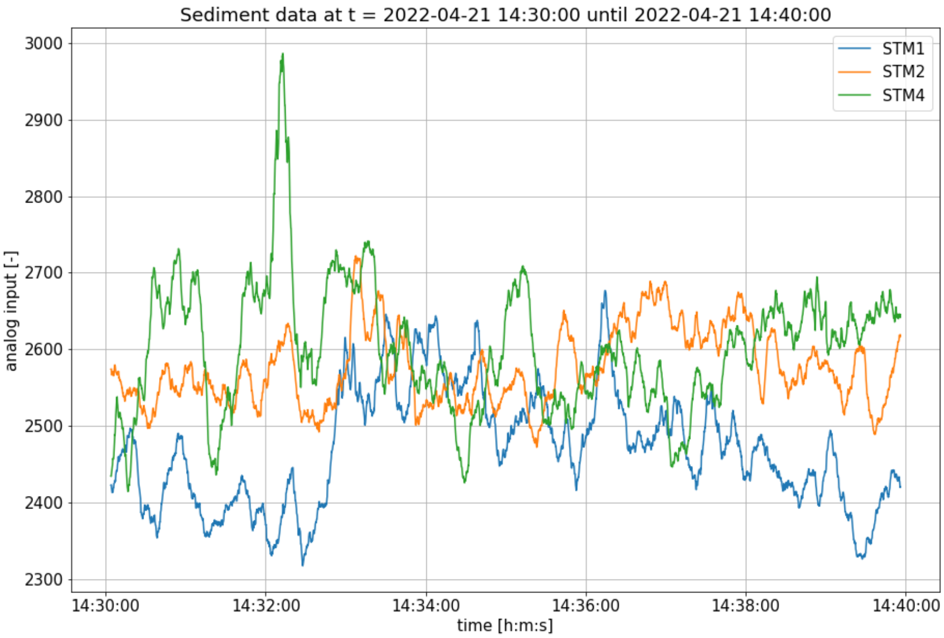

Figure 3.28: STM results of 21-4-2022 14:30 until 14:40 without STM5

3.2.5. Overall observations

In this section, some observations of the measurement campaign are more extensively discussed. Firstly, an overall indication of the quality of the measurement data and of the measurement campaign, in general, is given. Secondly, the different results of all measurement instruments are used to explain the flow inside the groyne field with and without vessels. Finally, the constant fluctuation inside the groyne field is investigated.

Overall measurement data quality

In this section, the quality of the measurement data is discussed. Overall, the measurement campaign gave good, reliable and clear data. By measuring the angles of the ADVs before and after the measurements it can be concluded that the instruments did not move. Furthermore, the batteries of all instruments were placed properly and were still running when the measurements were stopped. The same can be said for the RBRs which kept working properly during the entire measurement period.

After reviewing the data of the STMs, the results became increasingly unrealistic by progressing in time. According to the results, the sediment concentration inside the water kept increasing day by day resulting in extremely large values at the end of the measurement duration. It appeared that the sensors of the STMs were covered with algae. Since the STMs measure the sediment concentration inside the water with the use of light and determine the amount of sediment by the amount of reflection of particles inside the water, the algae resulted in too large values. The results of the STMs can therefore only be used for the first days of the measurement campaign.

Flow inside the groyne field

In this section, the results of all measurement instruments will be used to explain the flow pattern inside the groyne field with and without vessels.

The bathymetry of the groyne field is investigated first. Visible in figure 3.5 is the depth profile of the groyne field in January 2018. Downstream of the tip of the groynes, a scour hole is presented due to the dynamic eddy. Furthermore, a large scour hole is present downstream of the upstream groyne. After investigating the flow velocity at this part of the groyne field it appeared that vessels do have a large influence on the flow velocity in this part of the groyne field. When a vessel passes the groyne field, the primary eddy increases in strength, guiding the sediment towards the upstream groyne with a high flow velocity. Together with the fine sediment at this location, a large amount of erosion in this part of the groyne field is present, causing the bed level to be lowered at this location.

The next properties investigated are the flow velocity and water level for the situation when no vessel passes the groyne field. The flow pattern for this situation is visible in figure 3.12. Visible are the primary eddy in the downstream part of the groyne field and the potential secondary eddy present in the upstream part of the groyne field. The flow velocity in the primary eddy is on average between 0.3 - 0.4 m/s while the velocity inside the secondary eddy is much smaller. By investigating the different flow patterns described in figure 2.2, the flow pattern inside this groyne field is comparable to type 3. Furthermore, a constant fluctuation of the water level is found even when no vessel is influencing the flow. In the next section, this is more extensively investigated.

The situation when a vessel passes the groyne field is investigated next. The results in figures 3.14 and 3.15 clearly show that some vessels have a significant influence on the water level inside the groyne field. According to the results, the water level starts decreasing at the moment the vessel sails beside the groyne field due to the return current around the vessel. When the vessel passes the measurement instrument and starts leaving the groyne field, the stern wave increases the water level. This stern wave can raise the water level inside the groyne field even when the vessel has already left the groyne field. This means the effect of the vessel has a certain delay.

The passage of a vessel also causes a change in the flow velocities and directions inside the groyne field. When the return current is lowering the water level inside the groyne field, the flow at the location of ADV5 is directed out of the groyne field with a relatively large increase in the flow velocity. The flow velocity at the locations of ADV1, ADV2 and ADV4 also increases but their flow direction changes less significantly compared to the change of the flow direction at the location of ADV5. It appears that the primary eddy remains partly intact and the direction of the flow only changes slightly towards the main channel when the groyne field is emptied and slightly towards the bank when the groyne field is filled.

Finally, the sediment transport is investigated with the use of STMs. As previously described, only part of the STM data can be used. It appeared that mainly at the location of STM5 a large amount of sediment transport is triggered when a vessel passes the groyne field. A likely reason for this is the finer sediment present at this location and the height of STM5 above the ground. At the locations of the other measurement instruments inside the groyne field, the sediment concentration remains relatively stable when a vessel passes. A possible explanation for this is the coarse sediment present at the location. Therefore, possibly only transport directly over the bed floor takes place which is difficult to measure with the use of the STMs.

Constant water level fluctuation

In figure 3.10 it can be seen that there is a constant water level fluctuation inside the groyne field even when there is no vessel affecting the flow inside the groyne field. In figure 3.29 the water level fluctuation is shown for the 26th of April at the location of ADV5 for a period of 30 minutes with only one vessel passing the groyne field at 3:19. The last vessel passed the groyne field at 2:57 before this half our period. Clearly visible is the fluctuation of around five to eight centimetres. In this section, some possible explanations for this water level fluctuation are elaborated.

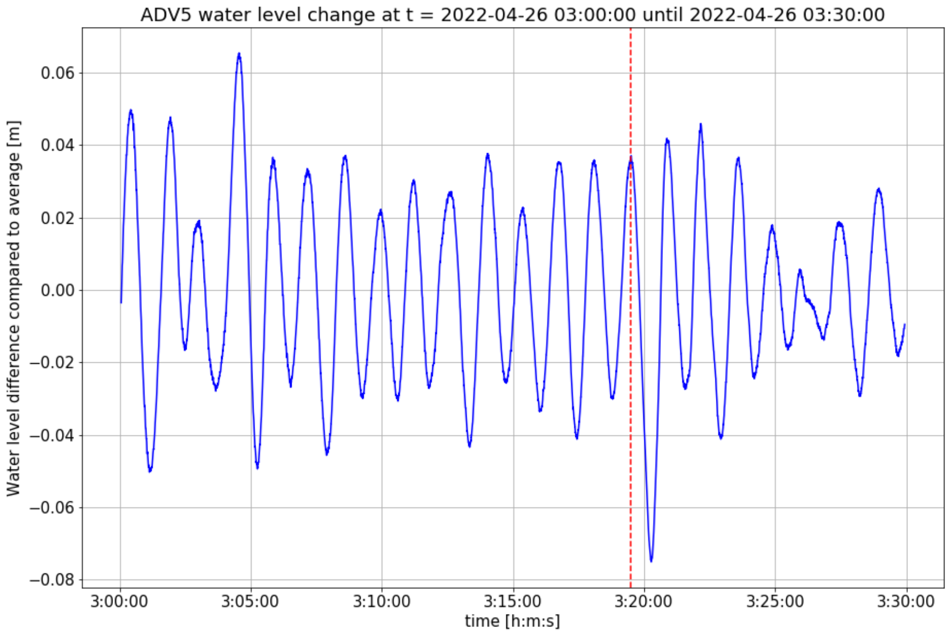

Figure 3.29: Water level fluctuation at the location of ADV5 from 26-04-2022 3:00 until 3:30

Dynamic eddy

The first possible explanation for the constant fluctuation of the water level inside the groyne field is the release of the dynamic eddy which is visible in figure 2.3. According to research of Yossef (2005), the dynamic eddy is formed at the tip of the upstream groyne and detaches regularly. When the eddy is released, it moves downstream into the primary eddy. When the two merge, the size of the primary eddy changes. This change in the size of the primary eddy should result in a fluctuation in the water level. To really determine whether this causes the constant water level fluctuation further research is required.

Oscillation inside the groyne field

Another explanation for the water level fluctuation is the presence of an oscillation inside the groyne field. This suggests that the water is oscillating from the upstream groyne towards the downstream groyne. By plotting the water level of all different locations on top of each other which has been done in figure 3.30 this can be checked.

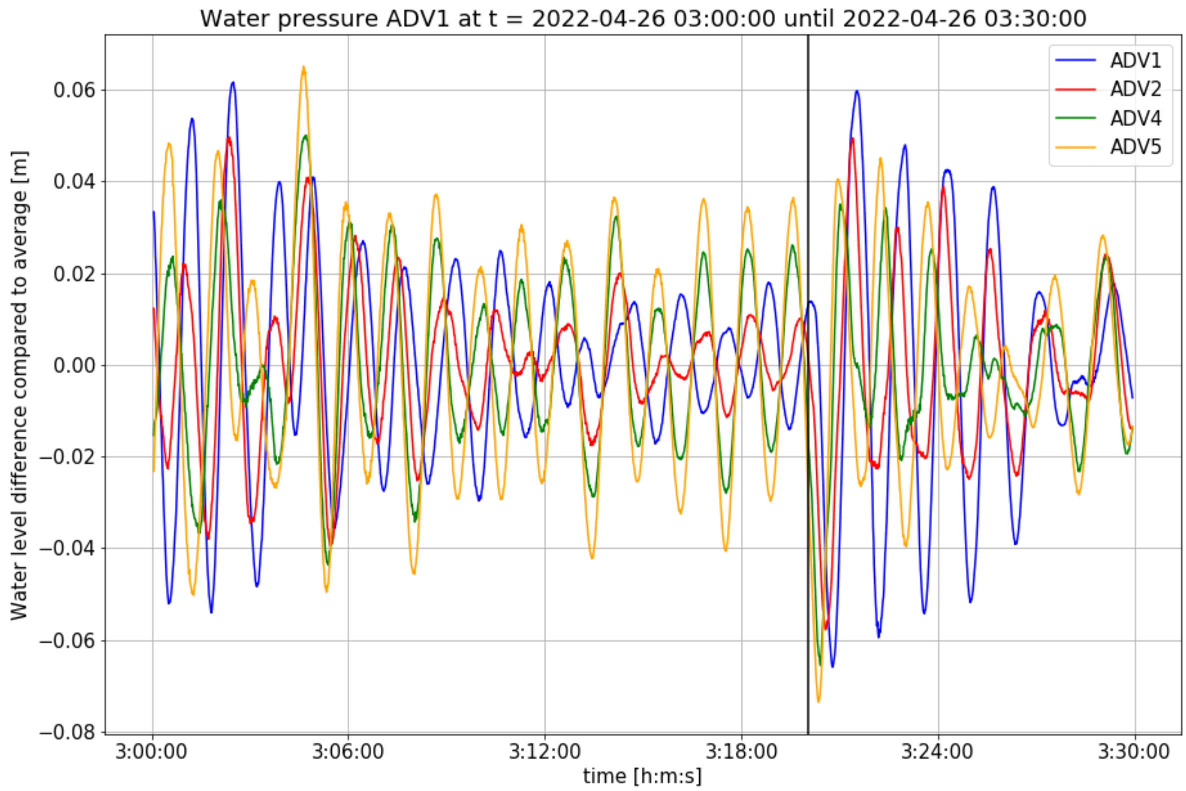

Figure 3.30: Water level fluctuation at all ADV locations from 26-04-2022 3:00 until 3:30

Visible is the passage of a vessel at 3:19, visualised by the black line, which results in a decrease of the water level in the entire groyne field. If oscillation inside the groyne field from the upstream groyne towards the downstream groyne were present, the water level should be out of phase between both sides of the groyne field. At 3:05 the water levels seem to be in phase with each other. However, when proceeding in time, the water level at the location of ADV1 seems to be out of phase with the water level at the other locations. A possible explanation for this is that the passage of the vessel at 2:57 disturbed the flow inside the groyne field which caused the water levels to be in phase with each other. After a certain amount of time, the balance inside the groyne field is restored and the oscillations return inside the groyne field.

In figure 3.31 the period between 3:10 and 3:20 is plotted. According to the figure, the water level at the locations of ADV4 and ADV5 are in phase which is to be expected since they lay close together. The water level at the location of ADV2 is also in phase with ADV4 and ADV5 but with a smaller amplitude. The water level of ADV1 is out of phase with the other locations, indicating an oscillating pattern inside the groyne field.

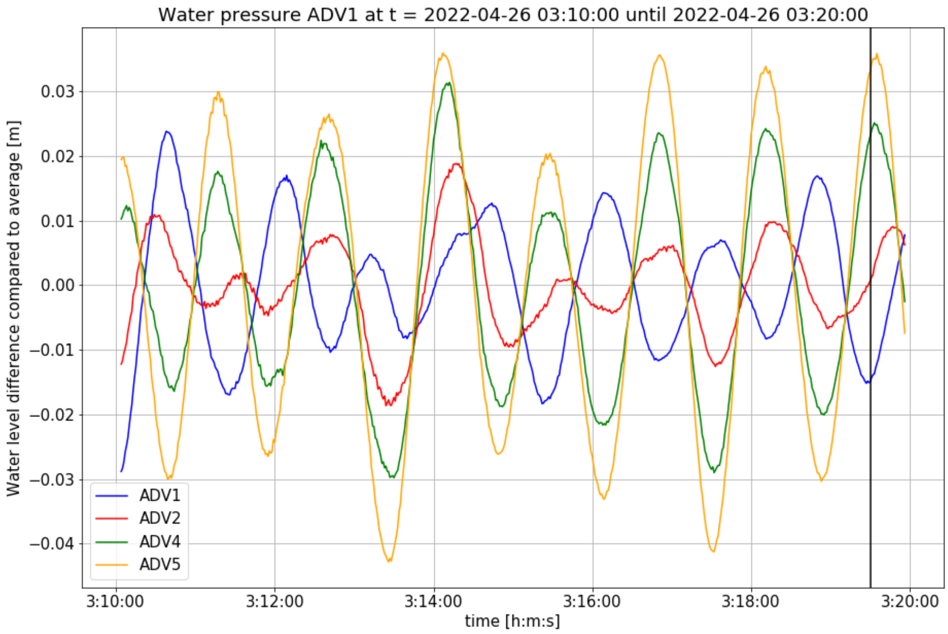

Figure 3.31: Water level fluctuation at all ADV locations from 26-04-2022 3:10 until 3:20

However, by looking at other time periods where no vessel passes the groyne field in a long time, such as in figure 3.32, this oscillating pattern is not clearly visible. In this figure, the last vessel passed the groyne field at 00:58 and the first vessel at 1:25 as can be seen in the figure. After being disturbed by the vessel, between 1:18 and 1:24 the water level at all different locations seems to be in phase and in rest. The same can be said for other time periods. Therefore, it is unlikely that the fluctuations inside the water level are caused by oscillations inside the groyne field.

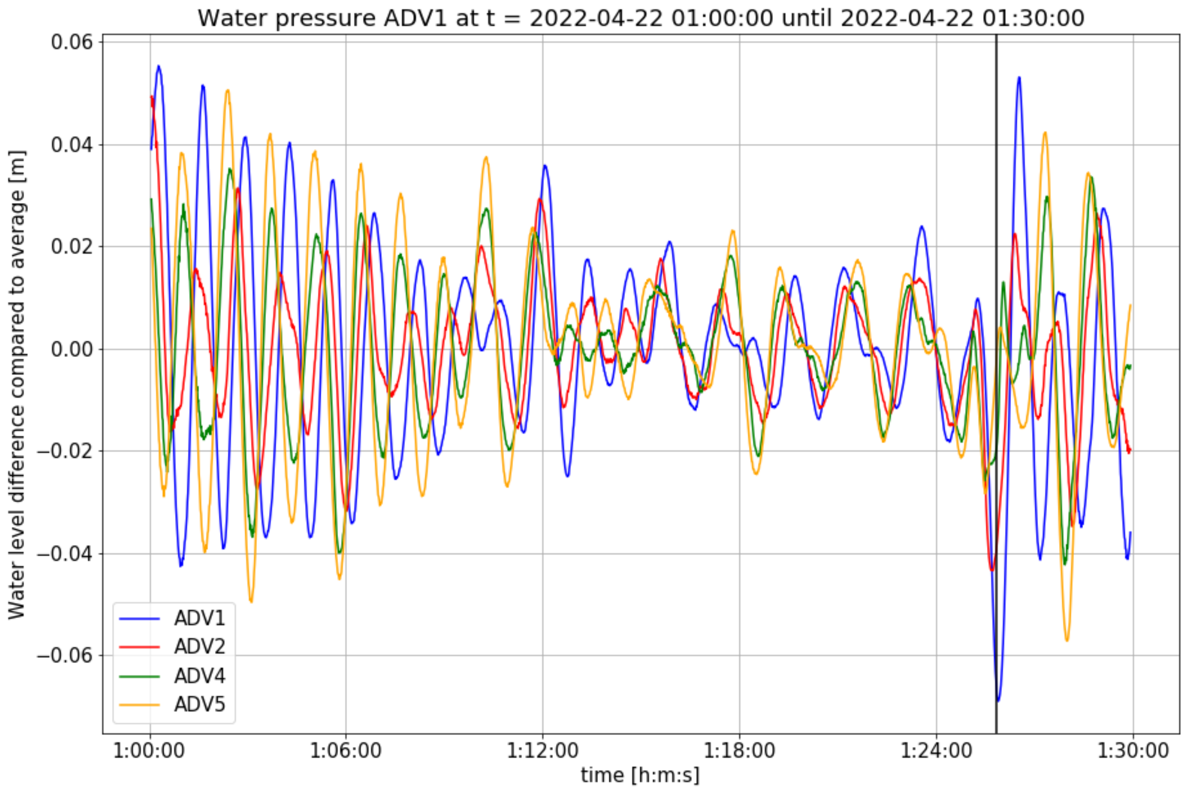

Figure 3.32: Water level fluctuation at all ADV locations from 22-04-2022 1:00 until 1:30

Transverse oscillations between both riverbanks

Another explanation for the fluctuations inside the groyne field is the presence of transverse oscillations between both banks of the river. Previous research of Juez and Navas-Montilla (2022) and Meile et al. (2011) showed the presence of transverse oscillation in a river section with groynes. Like the oscillations inside the groyne field, the presence of these oscillations can be verified by measuring the water level at both banks of the river and validating whether they are out of phase with each other. Unfortunately, no measurements were done at the other bank of the river. However, it is possible to determine what the wave period should be when a standing wave is present between both banks of the river. In figure 3.33 a standing wave is visible with one node. The wave period of the standing wave can be calculated with formula 3.1 visible below. In this formula, L represents the length from bank to bank, d is the depth of the river and g is the gravity constant.

$$T = \frac{2L}{\sqrt{gd}} \tag{3.1}$$

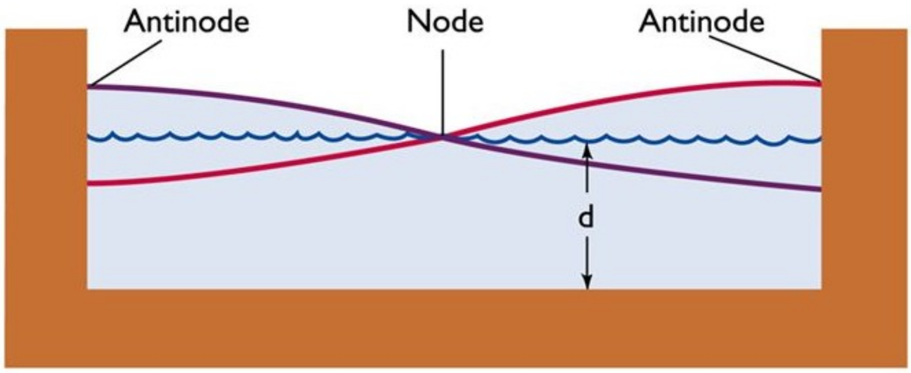

Figure 3.33: Standing wave in a closed basin (Sešek and Trontelj, 2013)

From figure 3.6, the width of the river is estimated to be about 300 - 350 meters wide. The average water depth inside the river, assuming a water level of +750 cm above NAP according to the figures A.9 and A.10, is assumed to be around 6 - 6.5 meters. The wave period can now be computed:

$$T = \frac{2L}{\sqrt{gd}} = \frac{2 * 350}{\sqrt{9.81 * 6}} = 91.2s \tag{3.2}$$

After performing a spectral analysis on the water level visible in figure 3.29 it is possible to determine the wave period of the water level fluctuations inside the groyne field. The results of the spectral analysis are visible in figure 3.34. It should be noted that the middle figure represents the amplitude of the different wave components and the bottom picture the variance. By decreasing the x-axis size in the bottom picture, it is possible to see at which frequency the peak appears. This peak is present at a frequency of 0.012 Hz. The wave period of the oscillations therefore becomes:

$$T = 1/f = 1/0.012 = 83.3s \tag{3.3}$$

This wave period is relatively close to the wave period computed for the standing wave with one node. Therefore, the presence of transverse oscillations between both riverbanks is possible. To really confirm this, however, further research is required.

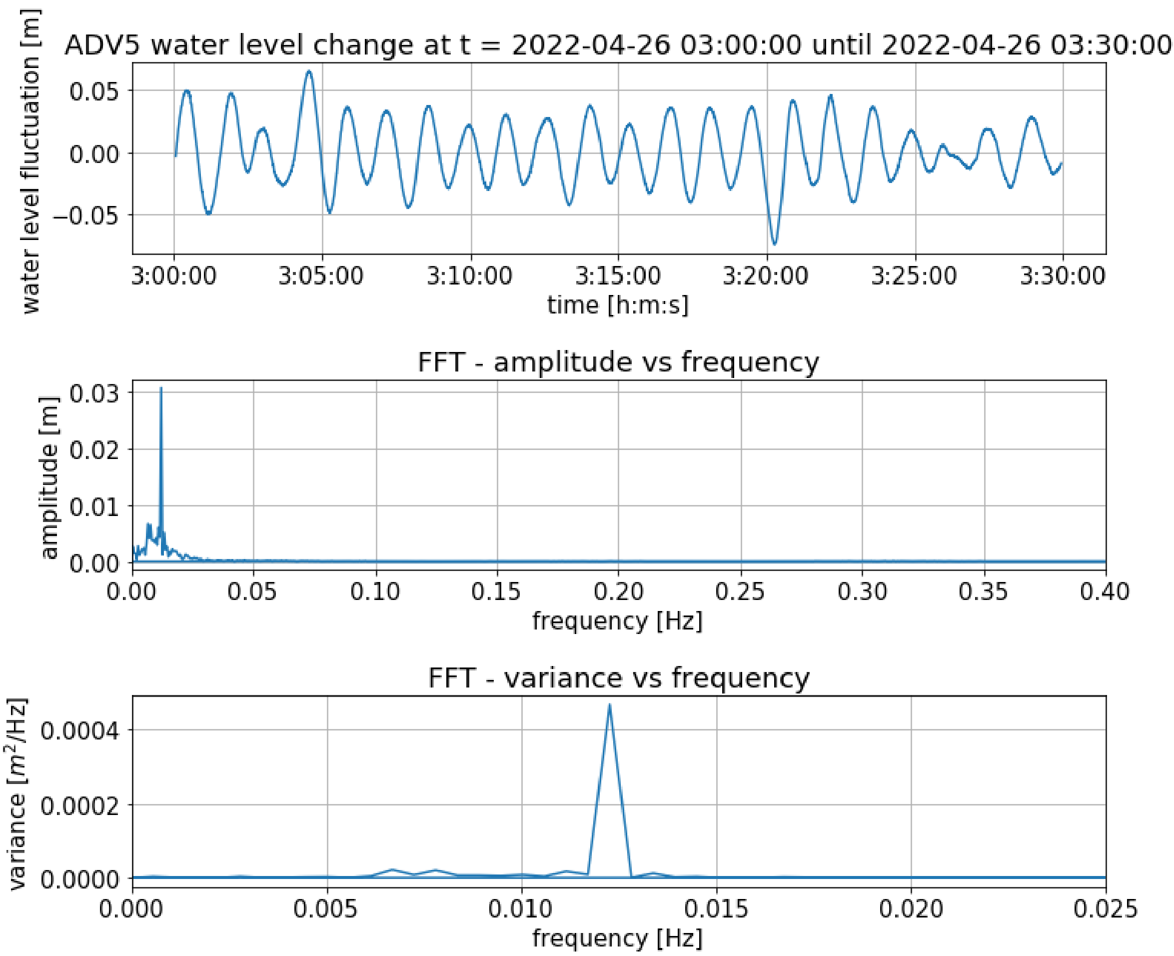

Figure 3.34: Water level fluctuation (top figure), amplitude wave components (middle figure) and variance (bottom figure) from 26-04-2022 3:00 until 3:30

3.3 Chapter conclusion

In this chapter the flow direction, flow velocity, water level and sediment concentration inside a groyne field are investigated. These flow properties are investigated by performing a measurement campaign in a selected groyne field. The flow properties are measured with the use of ADVs (Acoustic Doppler Velocimetry), RBRs and STMs (Seapoint Turbidity Meter). Next to the flow properties, the bathymetry of the groyne field was investigated. Just downstream of the upstream groyne a scour hole is present. This scour hole is created by the vessels sailing past the groyne field and the effect of the primary waves they create. The effect of the primary waves created by vessels on the flow pattern inside the groyne field is extreme at the location just downstream of the upstream groyne.

The flow pattern inside the groyne consists of a primary and a smaller secondary eddy. When a vessel passes the groyne field, the flow pattern changes. Due to the drawdown created by a vessel sailing in downstream direction passing the upstream groyne, the water level inside the groyne field is lowered. The water leaves the groyne field at the upstream part of the groyne field resulting in an increase in flow velocity at this location. The flow pattern inside the downstream part of the groyne field, consisting of a primary eddy, remains intact, forcing water towards the upstream part of the groyne field. When the vessel proceeds sailing past the groyne field, the water level increases again. The flow direction in the upstream part of the groyne field is now directed towards the bank while the primary eddy in the downstream part of the groyne field forces more water inside the groyne field. When the vessel is leaving the groyne field by sailing past the downstream groyne head, the water level is still raising and the primary eddy still forces more water inside the groyne field. When the vessel has entirely passed the groyne field, the standard flow pattern consisting of a primary and a secondary eddy returns again.

The bed composition inside the groyne field differs for all locations. At the downstream part of the groyne field, the bed material is relatively fine, at the upstream part of the groyne field more coarse while the bed is coarsest in the middle part of the groyne field. When no vessels are sailing past the groyne field, the sediment concentration inside the groyne field is stable. When a vessel does pass the groyne field, a large increase in the sediment concentration in the upstream part of the groyne field where the bed composition is finest is measured. At the other locations, a minor increase in sediment concentration is visible. A possible reason for this is the coarser bed material at this location.

When no vessels are sailing past the groyne field, a constant fluctuation in the water level is visible. This water level fluctuation is around five to eight centimetres with a wave period of around 80 seconds. In this chapter, three possible explanations are given. The most likely explanation for this fluctuation is the presence of transverse oscillations between both river banks. The calculated wave period if these transverse oscillations were presented is around 90 seconds. To determine whether these transverse oscillations are really present, further research is required.

4

Influence of vessel characteristics on the flow properties inside the groyne field

This chapter presents the investigated effect of vessels on the flow properties inside the groyne field. The previous chapter showed how the flow inside a groyne field looks without passing vessels, and how passing vessels alter the flow pattern. This change of flow properties inside the groyne field is not the same for each vessel and in this chapter it is investigated how the different vessel characteristics influence these flow properties. For the vessel characteristics the draught, sailing speed, distance to the measurement instrument, length of the vessel and width of the vessel are considered. For the flow properties, the change in water level and flow velocity are investigated.

4.1 AIS-data

To obtain enough information about the vessels sailing past the groyne field AIS-data is used. AIS stands for Automatic Identification System and uses transceivers to track vessels. This tracking is done for multiple reasons. For example, to track vessels and for security reasons (Bhattacharjee, 2022). In the Netherlands, the use of AIS is required for all commercial shipping vessels larger than CEMT class 1 and all recreational vessels larger than 20 meters.

The exact data send out by a vessel depends on whether it is sailing or not. When a ship is sailing, around every ten seconds the following properties important for this research are communicated:

- Navigation status, whether the ship is sailing or at anchor
- Exact time of measurement point
- Position in longitude and latitude of the measurement location
- Speed over ground in knots, also known as SOG (1 knot = 0.51 m/s)
- Course over the ground in degrees, also known as COG

Furthermore, each six minutes extra data is broadcasted about the properties of the vessel. For this research, the following properties are of interest:

- Type of ship and cargo
- Dimensions of the ship
- Location of the GPS antenna on board the vessel
- Draught of the ship

Besides the data previously mentioned, even more data is emitted like numbers corresponding to the identity of a vessel, the name of the vessel and the ETA (Expected Time of Arrival). However, this data is not important for this research. It should be noted that the AIS system also has limitations. The accuracy of the data depends on the accuracy of the transmitted data from the vessel. When the emitted data is not accurate, the received data will also not be accurate.

To be able to say something about the influence of the vessels on the flow properties inside the groyne field, the AIS-data for the whole measurement duration, from the 20th of April until the 4th of May, in front of the groyne field is requested. Due to privacy reasons, the data had to be anonymised. This removed the vessel names and identification numbers. Data like the draught, location, speed over ground and course over ground of the vessels remained available.

The received data set contained 151.151 different measurement points. By filtering the data, this number has been reduced significantly. First, all data was removed outside the reach of the surveyed groyne field (upstream and downstream). Second, unrealistic data points were removed from the remaining data set. This was done by calculating the distance from the data points to the ADVs and removing the points that are unrealistically close to the ADVs and that are positioned on the land. Finally, for each vessel passage, the closest point to the measurement station of interest is chosen. Eventually, 1793 different vessels and 4343 different vessel passages, since some vessels passed the groyne field multiple times during the measurement period, are observed during the measurement period.

4.2 Approach to analyse and visualise the data

To obtain results about the influence of the vessels on the flow properties inside the groyne field, the data obtained by the measurement campaign in the previous chapter and the received AIS-data have been combined. For each vessel passage, the vessel characteristics and the influence of these vessels on the flow properties have been noted. This has been done with the use of Python.

As stated before, the flow properties considered for this research are the water level and flow velocity inside the groyne field. For each flow property, a different approach is used to calculate the effect of the vessels. In the next section, the approach for each flow property is explained. Furthermore, it is explained how the data will be visualised.

4.2.1. Water level fluctuation

Firstly, the change in water level due to the passage of a vessel is investigated. The water level data obtained from the measurement campaign is plotted into 30-minute sections. These 30-minute sections of the water level are smoothed by calculating the average water level in the four-second interval before and after the actual measurement point. This has been done to eliminate large extreme values. Next, the moments a vessel enters the area between both groynes are added to the plot by means of a dashed vertical green line. The moments a vessel leaves the groyne field are indicated by a dashed vertical red line. This gives an overview of all the moments vessels sail past the groyne field and the water level inside the groyne field as can be seen in figure 4.1.

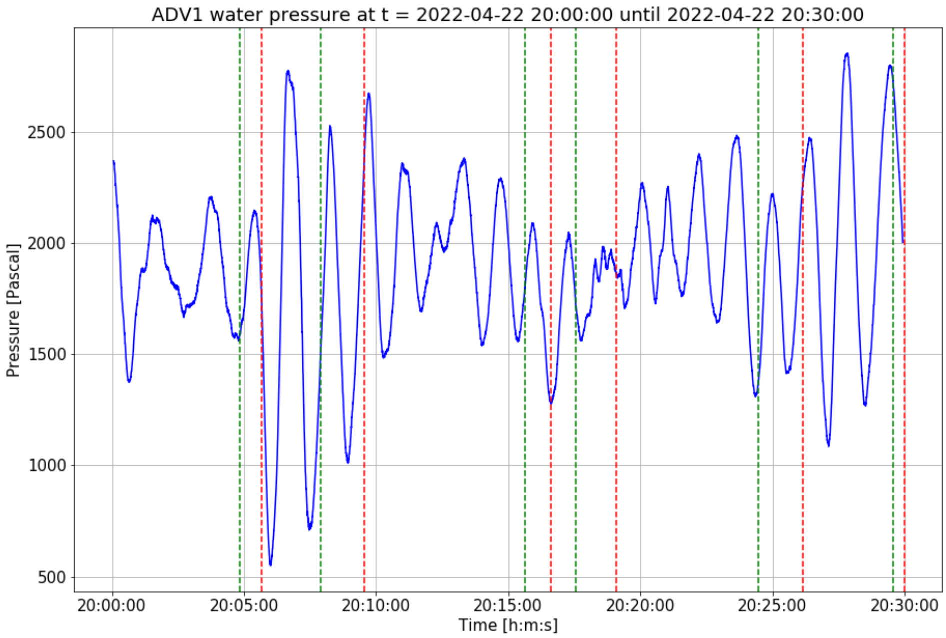

Figure 4.1: Water pressure at the location of ADV1 with the moment a vessel enters the area between both groynes indicated by the green dotted line and leaves the area by the red dotted line

Figure 4.1 shows the water level at the location of ADV1 on the 22nd of April from 20:00 until 20:30. In the Python scripts, it is possible to change the location of the measurement instrument to the four different ADV locations mentioned in the previous chapter. This results in the ability to investigate the effect of the vessels at different locations inside the groyne field.

By measuring the maximum water level difference in a certain interval when a vessel passes the groyne field, the effect of a vessel on the water level inside the groyne field can be measured. This maximum water level difference is calculated by measuring the lowest and the highest water level in this interval. By subtracting the two, the difference between the decrease in water level due to the suction created by the primary wave and the increase in water level due to the stern wave is known and can be used to measure the effect of a vessel on the water level. Since there is a certain delay in the effect of a vessel on the water level inside the groyne field and some inaccuracy in the AIS-data, a certain interval is chosen in which the maximum and minimum water level is measured. In Appendix B this choice of interval is elaborated. The interval chosen is the one which takes the 60 seconds before and the 60 seconds after the closest measurement point into consideration. Since for each AIS measurement point the distance to each ADV is calculated, it is possible to select the AIS data point with the smallest distance to a measurement instrument. The water level difference will be calculated by measuring the difference between the maximum and minimum water level in this 120-second interval. By writing a Python script it is possible to measure for each vessel movement the minimum water level and the maximum water level caused by the vessel and thus the difference in water level caused by the vessel. Eventually, this results in a large file containing the vessel properties in the form of the AIS-data, the calculated distance to the measurement instruments and the measured water level difference caused by the vessel.

4.2.2. Flow velocity

Secondly, the change in flow velocity due to the passage of a vessel is investigated. The approach to investigate the influence of vessels on the flow speed inside the groyne field is comparable to that of the water level change. However, for the flow velocity, two different components are available, the flow speed perpendicular to the edge of the groyne field and the flow speed parallel to the edge. It is chosen to calculate the combined total velocity. The flow velocity is again divided into sections of 30 minutes and smoothed by calculating the average velocity in the four seconds before and after the actual measurement point to remove extreme values. The flow velocity and the vessel movements are again plotted together as can be seen in figure 4.2. In this figure, the flow velocities and the vessel movements on the 22nd of April from 20:00 until 20:30 are plotted. The green dotted lines indicate the moments a vessel enters the groyne field while the red dotted lines indicate that a vessel leaves the area in front of the groyne field.

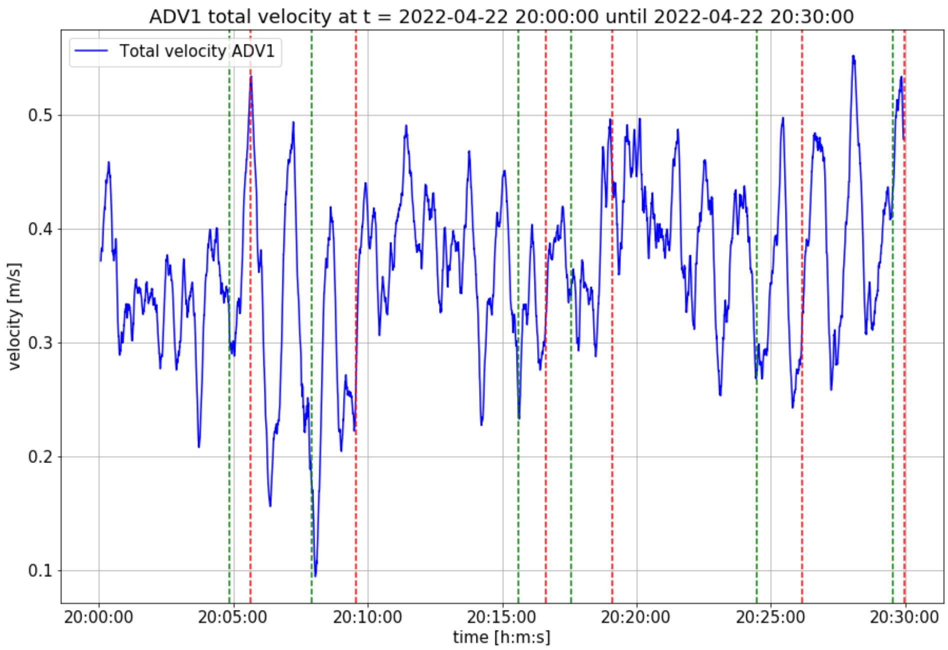

Figure 4.2: Flow velocity at the location of ADV1 with the moment a vessel enters the area between both groynes indicated by the green dotted line and leaves the area by the red dotted line

The effect of a vessel on the flow velocity inside the groyne field is less obvious compared to the effect of a vessel on the water level as can be seen in figure 4.2. The effect of a vessel is a combination of a change in flow direction and a change in the magnitude of the flow velocity. For this research, the effect of a vessel on the flow velocity is measured by calculating the maximum velocity inside a certain interval due to the vessel. In Appendix B the choice of which interval to use is elaborated. There is chosen to use the same interval as previously used for the water level difference. Namely, the closest measurement point with an interval of 60 seconds before and 60 seconds after this measurement point. With the use of a Python script, it is possible to obtain the maximum flow velocity for each vessel movement. To investigate the difference between the four different measurement locations, the effect of vessels on the flow velocity is investigated for all four locations.

The final results are four different CSV files containing all the data necessary to investigate the effect of the vessel characteristics on the water level difference and maximum flow velocity for each location inside the groyne field. The CSV files contain the following information:

- The time a vessel sails closest to the chosen measurement instrument
- Latitude and longitude of the vessel
- Distance of the vessel to the measurement instrument
- SOG (speed over ground) and sailing speed of the vessel in knots
- Draught of the vessel
- Length and width of the vessel
- Maximum water level difference caused by the vessel
- Maximum flow velocity caused by the vessel

4.2.3. Analyse and visualise data

Unfortunately, vessels do not pass the groyne field with a constant interval between each other. Therefore, it is possible that two vessels pass the groyne field at the same interval, making it difficult to analyse the exact effect of both vessels on the flow properties inside the groyne field. To avoid this, the data has been filtered by selecting only vessels which arrive at the groyne field ten minutes after the last vessel arrived at the groyne field. By doing this, the flow inside the groyne field has time to recover from the effect of the previous vessel and the effect of a single vessel can be investigated more accurately. Furthermore, according to research of Ten Brinke (2003), vessels with a length smaller than 60 meters have barely any influence on the flow properties inside the groyne field compared to the longer vessels. Therefore, vessels with a length smaller than 60 meters have been eliminated from the data.

The results are visualised by plotting each variable against the water level difference and maximum flow velocity. Before doing this, it is investigated whether the different variables are correlated to each other. In Appendix D the correlation between all parameters is analysed with the use of Pearson's correlation coefficient. According to this coefficient, the length and width of the vessels are strongly correlated to each other while the other variables are weakly or very weakly correlated. This means that it is possible to plot the draught, sailing speed and distance to the groyne field without taking the other parameters into consideration. For the length and width of the vessel, the relationship between both parameters has to be kept into consideration before taking conclusions.

4.3 Results

In this section, the results of the data obtained in the previous section are visualised. Firstly, a hypothesis about the expected effect of the vessels on the water level change and flow velocity inside the groyne field is made. In this hypothesis formulas about the expected drawdown from present literature are presented. Furthermore, an indication of how this could affect the flow velocity inside the groyne field is made. Secondly, the results of the measured data are presented. For each flow property, all five mentioned vessel characteristics are analysed to obtain a clear view of the different flow properties.

4.3.1. Water level change

Firstly, the change in water level caused by the vessels is evaluated at all different locations. Before plotting the results, a hypothesis is made based on already existing literature.

Hypothesis

A hypothesis for the water level difference can be made by investigating the formulas for the drawdown around a vessel. In Appendix C multiple formulas are presented to calculate the water level drawdown around a vessel. In figure C.2 the input parameters for several formulas are presented. In this hypothesis, the formulas of Hochstein and Adams (C.1), Gelencser (C.2) and Dand and White (C.3) are used. Each formula depends on the draught, sailing speed and width of the vessel. The formula of Gelencser also requires the distance to the shore and the length of the vessel to calculate the drawdown. According to all formulas, an increase in draught and vessel width results in an increase in the underwater surface of the vessels and should therefore result in an increase in the drawdown. An increase in the sailing speed of the vessels should also result in an increase in the drawdown according to all formulas. The formula of Gelencser also depends on the distance between the vessel and the shore. According to the formula, a decrease in the distance should result in an increase in the drawdown. Finally, the formula of Gelencser also depends on the length of the vessel. According to the formula, an increase in the length of the vessel results in an increase in the drawdown. In table 4.1 the complete hypothesis of the effect of vessels on the water level inside the groyne field is visible.

Characteristic	Drawdown
↑ Draught	↑ Increase
↑ Sailing speed	↑ Increase
↑ Distance to bank	↓ Decrease
↑ Length vessel	↑ Increase
↑ Width vessel	↑ Increase

Table 4.1: Water level hypothesis

ADV1

The first location investigated is the location of ADV1. The exact location of ADV1 with respect to the groyne field is visible in figure 3.2. In this section, the effect of the draught, sailing speed, distance to the measurement instrument, vessel length and vessel width is investigated. For this location, 539 vessel movements are registered after filtering the data as previously described.

Draught

In figure 4.3 the draught of the vessels versus the water level difference is plotted. Each blue dot indicates a vessel passage. The dotted black vertical line indicates the water level fluctuation which is present inside the groyne field without vessels passing. At the location of ADV1, this is equal to 0.04 meters. To obtain a better view of the results, three percentile lines are plotted inside the figure. The 10, 50 and 90 percent percentile lines. The percentile lines are made by slicing the data into certain intervals. The 10% percentile line is the level where 10% of the total amount of data points in that certain interval are smaller than that level. The 50% percentile line is the level at which 50% of the data points are smaller and larger than that level. The 90% percentile line indicates the level where only 10% of the data points in that interval are larger. By plotting the percentile lines certain patterns inside the results are more easy to observe. In figure 4.3 the percentile lines are calculated by taking horizontal intervals of 0.5 meters, starting from 0.75 until 3.75 meters.

According to the hypothesis, an increase in the draught of a vessel should result in an increase in the water level difference. An increase in draught results in an increase in the submerged area of the vessel and should therefore result in an increase in drawdown. By investigating the percentile levels it is visible that the draught has no significant influence on the water level difference. Also plotted in figure 4.3 is the expected water level difference according to the drawdown formulas in Appendix C. To plot the formulas, a water level difference of 0.075 meters is assumed at a draught of 0.1 meters. To compute the drawdown at the other draught levels, all other parameters included in the formulas have remained constant and only the draught has been altered.

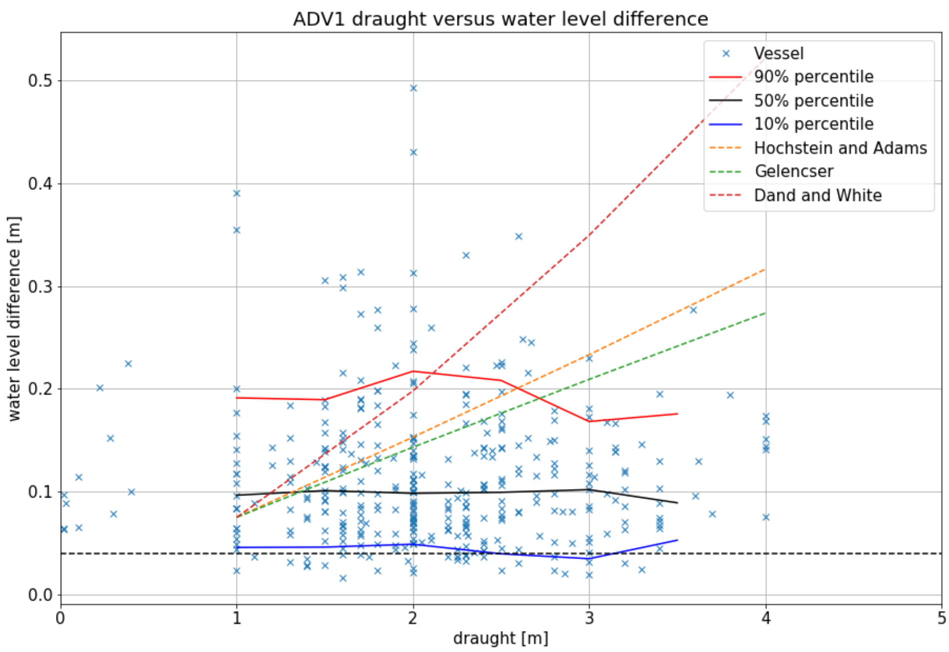

Figure 4.3: ADV1 draught versus water level difference including expected results according to existing formulas

Sailing speed

The sailing speed versus the water level difference is investigated next. The results are plotted in figure 4.4. The sailing speed is given in knots (1 knot = 0.514 m/s) and is the velocity of the vessel compared to the water. The percentile lines are calculated by taking horizontal intervals of 0.5 knots from 6 to 10.5 knots.

According to the hypothesis, the drawdown should increase when the sailing velocity increases. The 50% percentile line, however, shows an almost horizontal pattern indicating that the average effect of the draught has no influence on the water level difference. The 90% percentile line shows a peak when the sailing speed is around 7.0 knots. This is probably due to the low amount of data points in that certain interval. When the sailing speed increases, the 90% percentile line does show an increasing pattern. This indicates that the more extreme water level differences are more likely to happen when the sailing speed is larger. Also plotted in figure 4.4 is the expected influence of the sailing speed on the water level difference according to the formulas shown in Appendix C. To compute the formulas, a water level difference of 0.075 meters at a sailing speed of 6.0 knots is assumed. The formulas of Hochstein and Adams and Dand and White show the same results. To plot these lines all the other parameters are remained constant while only the sailing speed is altered.

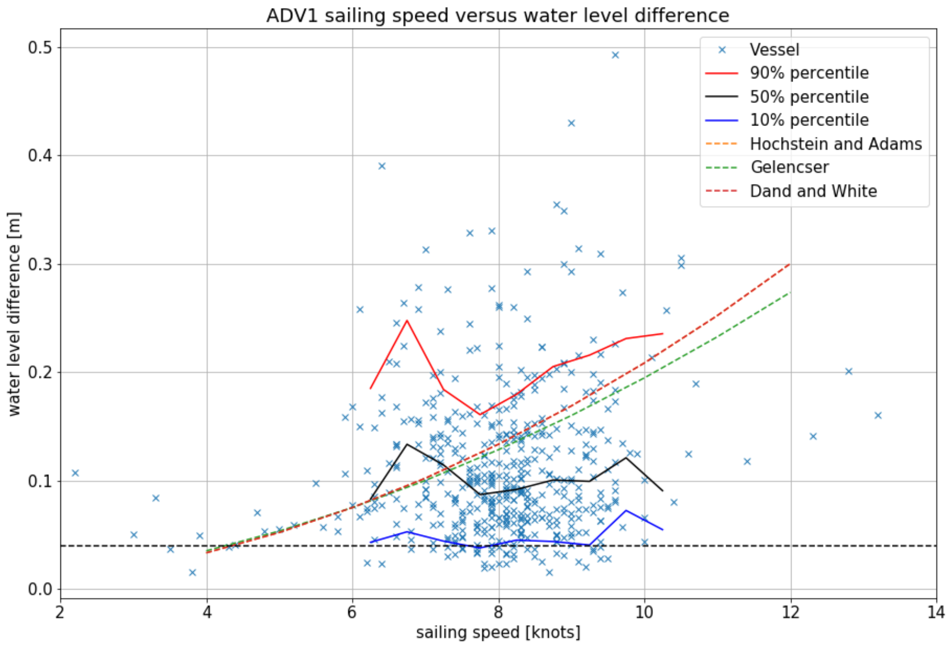

Figure 4.4: ADV1 sailing speed versus water level difference including expected results according to existing formulas

Distance to measurement instrument

The influence of the distance to the measurement instrument versus the water level difference is plotted in figure 4.5. The percentile lines are calculated by taking horizontal intervals of 25 metres from 100 to 250 metres. Beside the dashed horizontal line, a vertical dashed line is visible. This vertical line indicates the minimum sailing distance with respect to the measurement instrument. If the distance were smaller than this level, the vessel would be sailing inside the groyne field which is not realistic for a vessel passing the groyne field.

According to the hypothesis, a smaller distance to the measurement instrument results in a larger drawdown according to the formula of Gelencser. According to the figure, it is visible that a closer distance to the measurement instrument indeed results in a larger water level difference. The 50% and 90% percentile lines both show an increase if the distance to the measurement instrument decreases. Also plotted in figure 4.5 is the expected drawdown with respect to the distance to the measurement instrument according to the formula of Gelencser. To compute this line, a water level difference of 0.07 meters is assumed at a distance of 250 meters. The expected water level difference according to the formula of Gelencser is in agreement with the 50% percentile line.

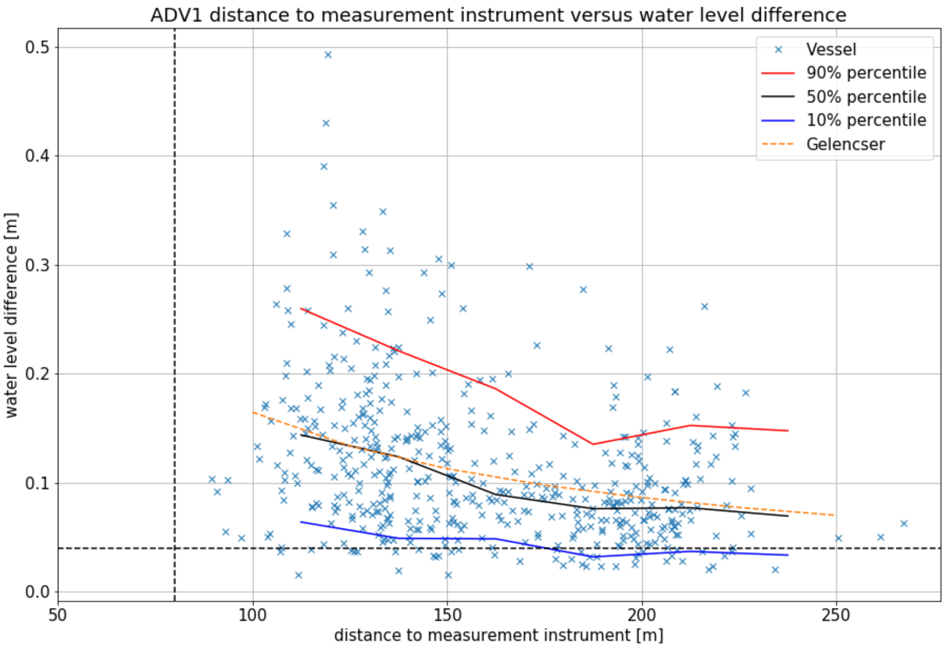

Figure 4.5: ADV1 distance to measurement instrument versus water level difference including expected results according to existing formulas

Length of the vessel

The next parameter investigated is the length of the vessel. As previously noted, the length of the vessel is strongly correlated to the width of the vessel. Therefore, by plotting an increase in length, an increase in the width is plotted at the same time. This can be avoided by plotting only vessels with a certain width. In figure 4.6 the water level difference versus the length is plotted for vessels with a width of twelve meters. Due to this limitation, the number of data points is reduced to 216. The percentile lines are calculated by taking horizontal intervals of 25 meters from 75 to 150 meters. The vessels larger than 135 meters are the so-called push-barge vessels. They do not seem to follow the same increasing pattern as vessels smaller than 135 meters. Later this will be more extensively investigated.

According to the hypothesis and the formula of Gelencser, an increasing vessel length should increase the drawdown of a vessel. According to the results, it is visible that an increase in vessel length results in an increase in the water level difference. Both the 50% and 90% percentile lines clearly show an increasing pattern. Also plotted in figure 4.6 is the expected effect of the vessel length on the water level difference according to the formula of Gelencser. The orange line is plotted by assuming a water level difference of 0.04 meters at a vessel length of 60 meters and by keeping all other parameters constant. Comparing the expected effect of the vessels to the measured effect in figure 4.6, it is visible that the measured effect is smaller than the expected effect.

In figure E.1 the length versus the water level difference is plotted for the whole data set without filtering the effect of the different widths. Again, an increasing pattern is visible. Clearly visible are the push-barge vessels not following the same pattern as the smaller vessels.

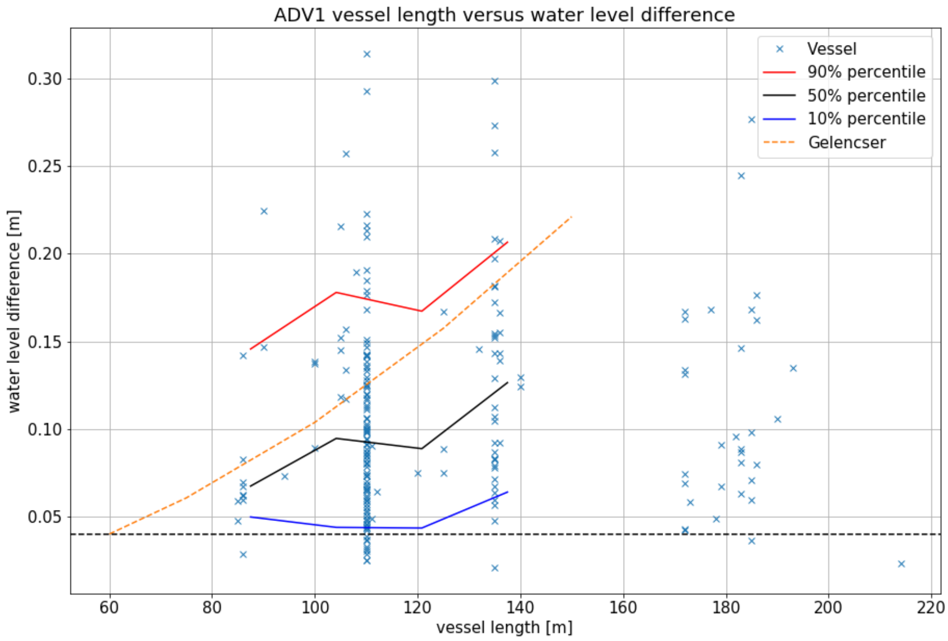

Figure 4.6: ADV1 vessel length versus water level of vessels with a width of twelve meters, including expected results according to existing formulas

Width of the vessel

Finally, the width of the vessels versus the water level difference is investigated. The width of the vessels is strongly related to the length of the vessels. To investigate the effect of the width of the vessels, the length should be eliminated. This can be done by investigating the effect of vessels with the same length. However, the length of the vessels is more variable compared to the width of the vessels. Therefore, a certain interval is chosen to plot the effect of the width. In figure 4.7 the effect of the width on the water level difference for vessels with a length between 110 and 135 meters is plotted. Due to this limitation, 264 data points remained. The percentile lines are calculated by taking horizontal intervals of 2.5 meters from 10.0 to 20.0 meters.

According to the hypothesis an increase in the width of a vessel increases the vessel's underwater cross-section and therefore increases the drawdown. The percentile lines show an increasing pattern when the width of the vessels increases until the width becomes larger than 16 meters. A possible explanation is the low amount of measurement points in this interval. Also plotted in figure 4.7 is the expected effect of the width on the water level difference according to the existing formulas. The lines are calculated by assuming a water level difference of 0.1 meters at a vessel width of ten meters. Comparing the percentile lines and the results of figure 4.7 it is visible that the slope of the percentile lines is comparable to that of the expected results.

In figure E.2 the width versus the water level difference is plotted for the whole dataset without filtering the effect of the different lengths. Visible is the increasing pattern for the vessel with a width between 5.0 and 15.0 meters. Also visible are vessels wider than 20 meters, these vessels are push-barge vessels. They do not follow the same pattern as the smaller vessels. Later this will be more extensively investigated.

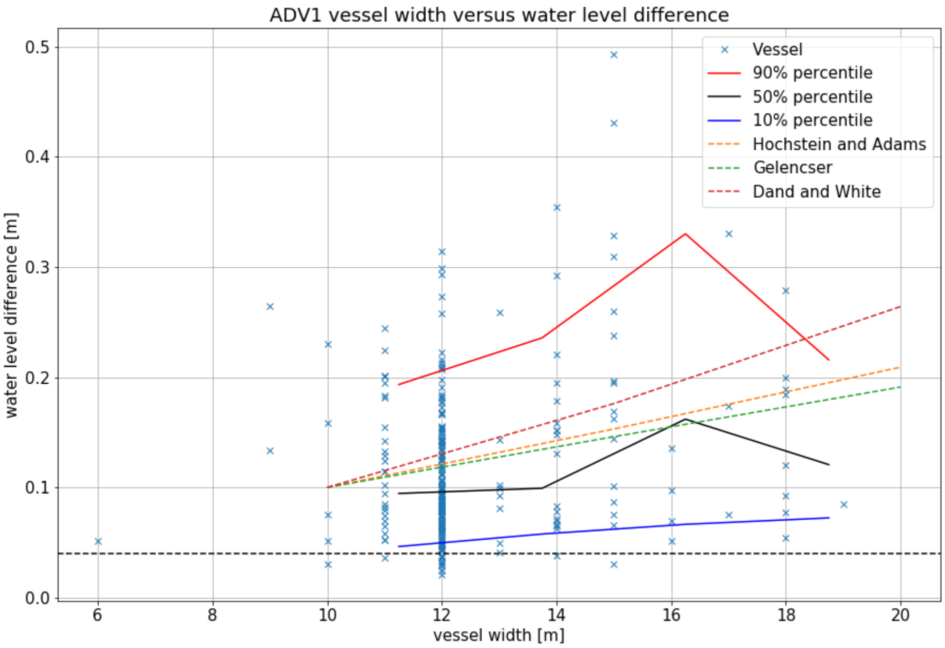

Figure 4.7: ADV1 vessel width versus water level difference results

ADV2, ADV4 and ADV5

The figures of the water level change at the other measurement locations can be found in Appendix E.2. The explanation of the results can be found in Appendix E.1. In this section, only a brief summary of the results at these locations is given.

At all locations, the draught has no influence on the water level difference inside the groyne field according to the results. An increase in the sailing speed did result in an increase in the water level difference at all locations. By decreasing the distance to the measurement instrument, at all locations an increase in the water level difference is visible. At the location of ADV5 however, only the 90% percentile line shows a clear increase when the distance was decreased while the 50% percentile line remained relatively horizontal. By increasing the length of the vessel, the 50% percentile lines show a small increase in water level difference at all locations. The 90% percentile lines do not show a clear pattern, mainly due to a low amount of data points in some percentile intervals. Finally, at all locations, the water level shows an increasing pattern when the width of the vessel increased. In table 4.2 an overview is given of all vessel characteristics at all locations and whether their influence on the water level difference inside the groyne field is in agreement with the hypothesis.

	ADV1	ADV2	ADV4	ADV5
Draught	X	X	X	X
Sailing speed	?	✓	✓	✓
Distance to measurement instrument	✓	✓	✓	?
Length vessel	✓	?	?	?
Width vessel	✓	✓	✓	✓

Table 4.2: Effect of vessel characteristics on the water level difference and whether they are in agreement with the hypothesis. ✓ = yes, ? = questionable, X = no

4.3.2. Flow velocity

In this section, the influence of the vessels on the flow velocity inside the groyne field is evaluated. Before plotting the results, a hypothesis is made to predict the influence of the vessels on the flow velocity inside the groyne field. The vessel characteristics taken into consideration are the draught, the sailing speed, the distance to the measurement instrument, and the length and width of the vessel.

Hypothesis

Unfortunately, no formulas are present to calculate the effect of a vessel on the flow velocity inside a groyne field. However, after investigating the results from the previous chapter, it is visible that there is a strong relationship between the water level difference and the flow velocity inside the groyne field. Therefore, the hypothesis is that the effect of the vessels on the flow velocity inside the groyne field is the same as the hypothesis for the water level visible in figure 4.1.

ADV1

In this section, the influence of the vessels on the flow velocity inside the groyne field at the location of ADV1 is investigated. The exact location of ADV1 with respect to the groyne field can be seen in figure 3.2. For this location, 567 different vessel movements are registered taking into consideration the 10-minute interval. In each plot in the next sections, a horizontal black dashed line is present. This line indicates the average flow velocity inside the groyne at the location of the measurement instrument. For the location of ADV1, this average flow velocity is equal to 0.33 m/s.

Draught

The first vessel characteristic investigated is the draught. The results of the draught versus the maximum velocity at the location of ADV1 are plotted in figure 4.8. The percentile lines are calculated by taking horizontal intervals of 0.5 meters from 0.75 to 3.75 meters.

According to the hypothesis, an increase in draught should result in an increase of the flow velocity inside the groyne field due to an increase in the underwater area. The percentile lines however show a horizontal pattern for the effect of the draught. According to the results, the draught has no significant influence on the flow velocity in this particular groyne field.

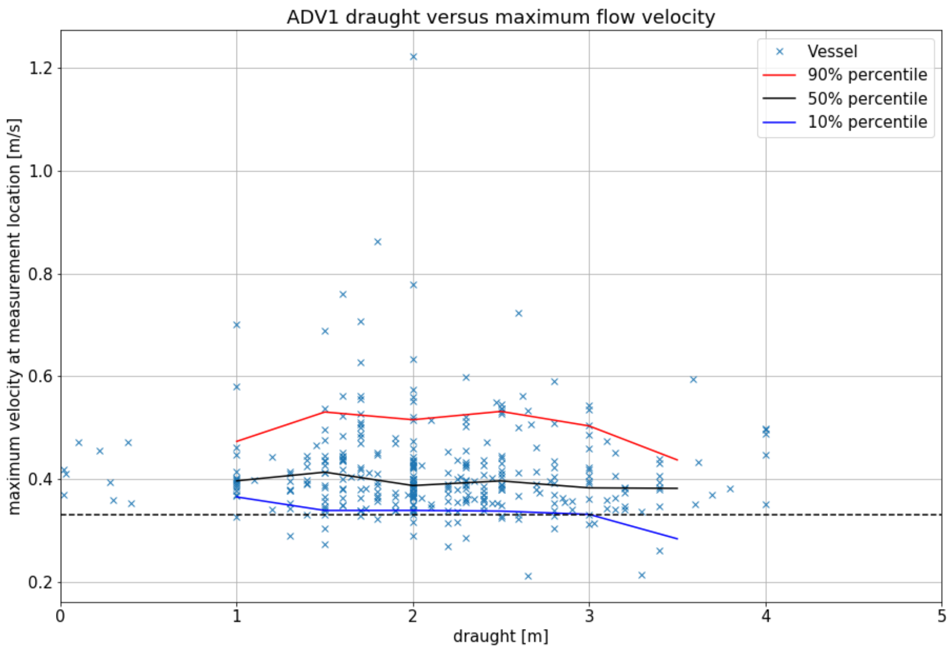

Figure 4.8: ADV1 draught versus maximum flow velocity at measurement location

Sailing speed

The next characteristic investigated is the sailing speed. The sailing speed versus the maximum flow velocity is plotted in figure 4.9. The percentile lines are calculated by taking horizontal intervals of 0.5 knots from 6.0 to 10.5 knots.

According to the hypothesis, an increase in the sailing speed should increase the flow velocity inside the groyne field. It should be noted that due to the measurement point at a flow velocity of around 1.2 m/s, the scale of the plot is different compared to the plots of the water level difference. The 10% and 50% percentile lines show a horizontal effect. The 90% percentile line shows an increase in flow velocity when the sailing speed increases. This suggests that extreme values are more likely to occur when the sailing speed increases.

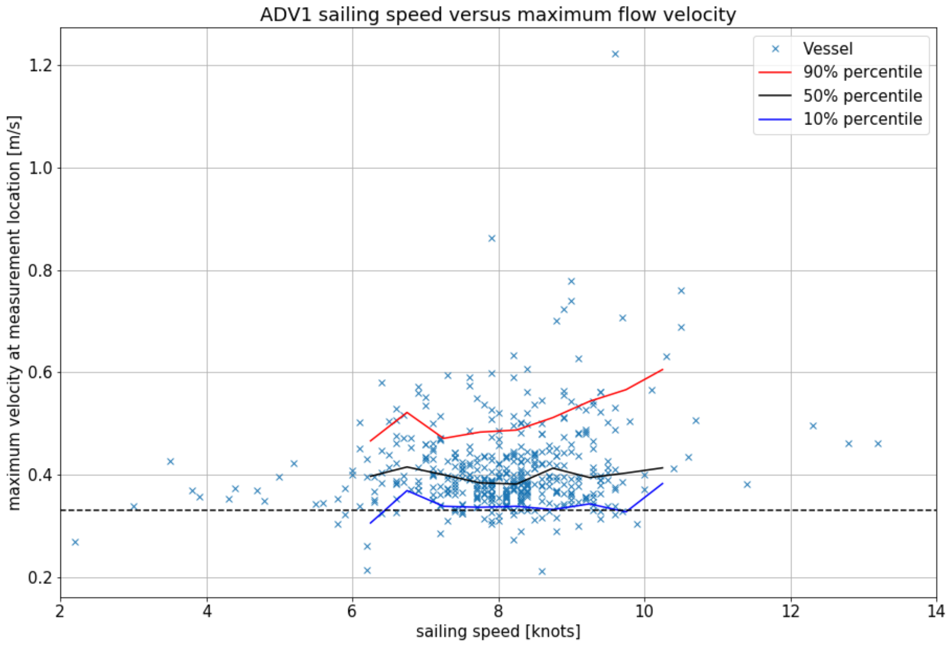

Figure 4.9: ADV1 sailing speed versus maximum flow velocity at measurement location

Distance to measurement instrument

The distance to the measurement instrument is investigated next. The results for the distance to the measurement instruments are plotted in figure 4.10. The percentile lines are calculated by slicing the horizontal data into intervals of 25 meters from 100 to 250 meters.

According to the hypothesis, a smaller distance to the measurement instrument should result in a larger maximum velocity. The percentile lines show that the maximum velocity indeed increases when the distance to the measurement instrument decreases.

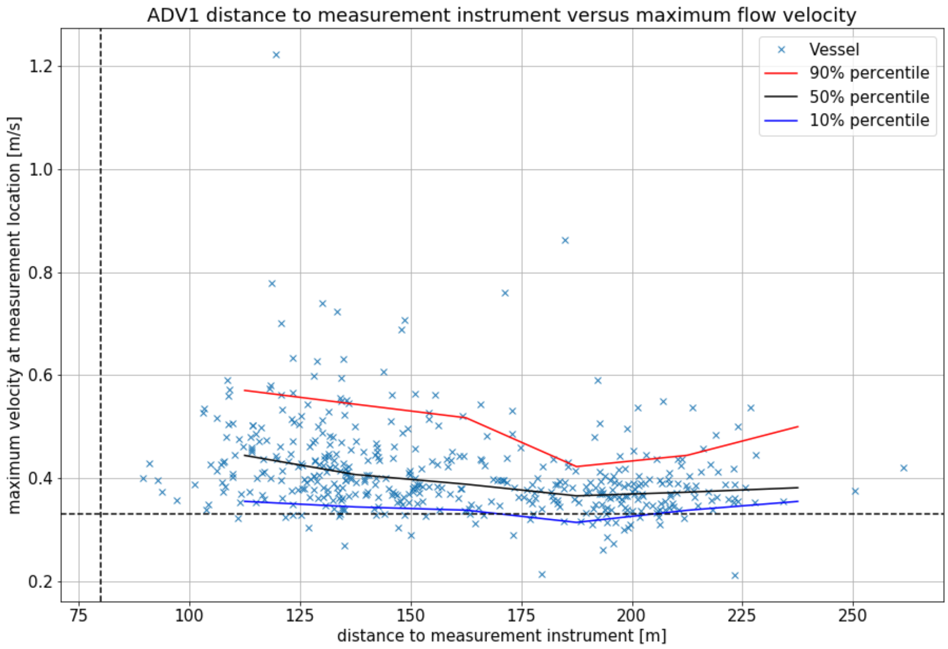

Figure 4.10: ADV1 distance to measurement instrument versus maximum flow velocity at measurement location

Length of the vessel

The next parameter investigated is the length of the vessel. The vessel length is strongly correlated to the width of the vessel as can be seen in Appendix D. The effect of the length of a vessel on the flow velocity inside the groyne field can be investigated by plotting only vessels with a certain width. In figure 4.11 the effect of the vessel length versus the maximum flow velocity for vessels with a width of twelve meters is plotted. By doing this, the number of data points is reduced to 216. The percentile lines are calculated by taking horizontal intervals of 25 meters from 75 to 150 meters. In this figure, the push-barge vessels, which are vessels larger than 135 meters, do again not follow the same pattern as the smaller vessels. This effect will be investigated more extensively later.

According to the hypothesis, an increase in the length of a vessel should result in an increase of the flow velocity inside the groyne field. The 50% percentile line in figure 4.11 shows a minor increase when the vessel length increases. The 90% percentile line shows a steeper increase when the length increases. This suggests that higher flow velocities are more likely to occur when a large vessel passes.

In figure E.24 the length versus the maximum flow velocity for the whole dataset without filtering the effect of the different widths is plotted. The pattern of the percentile lines is comparable to those of the percentile lines in figure 4.11.

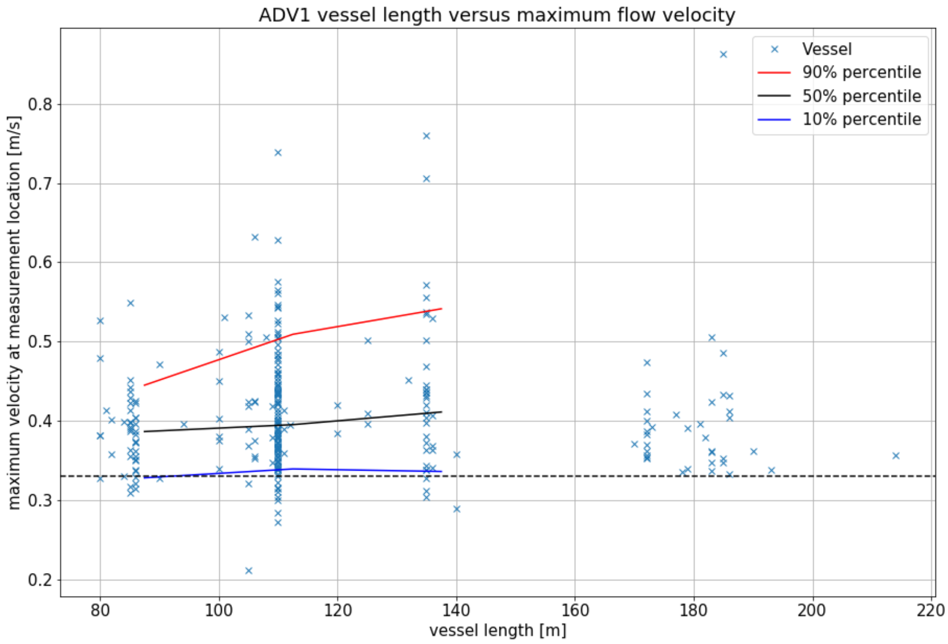

Figure 4.11: ADV1 vessel length versus maximum flow velocity at measurement location

Width of the vessel

Finally, the width of the vessel versus the maximum flow velocity is investigated. As previously described, the width and length of the vessel are strongly correlated. To investigate the effect of the width on the flow velocity inside the groyne field, the same approach is used for the water level. The vessels with a length of 110 to 135 meters have been selected and plotted against the maximum flow velocity in figure 4.12. The number of data points is reduced to 264 by doing this. The percentile lines are calculated by taking horizontal intervals of 2.5 meters from 10.0 to 17.5 meters.

According to the hypothesis, an increase in the width of a vessel should result in an increase of the flow velocity inside the groyne field. The 50% percentile line in figure 4.7 however, shows a horizontal pattern. The 90% percentile line does show an increasing pattern, indicating that the extreme values are more likely to occur when the vessel width increases.

In figure E.25 the width versus the maximum flow velocity for the whole data set is plotted. The percentile lines show a pattern similar to those in figure 4.12. The 50% percentile line is relatively horizontal while the 90% percentile line clearly shows an increasing pattern.

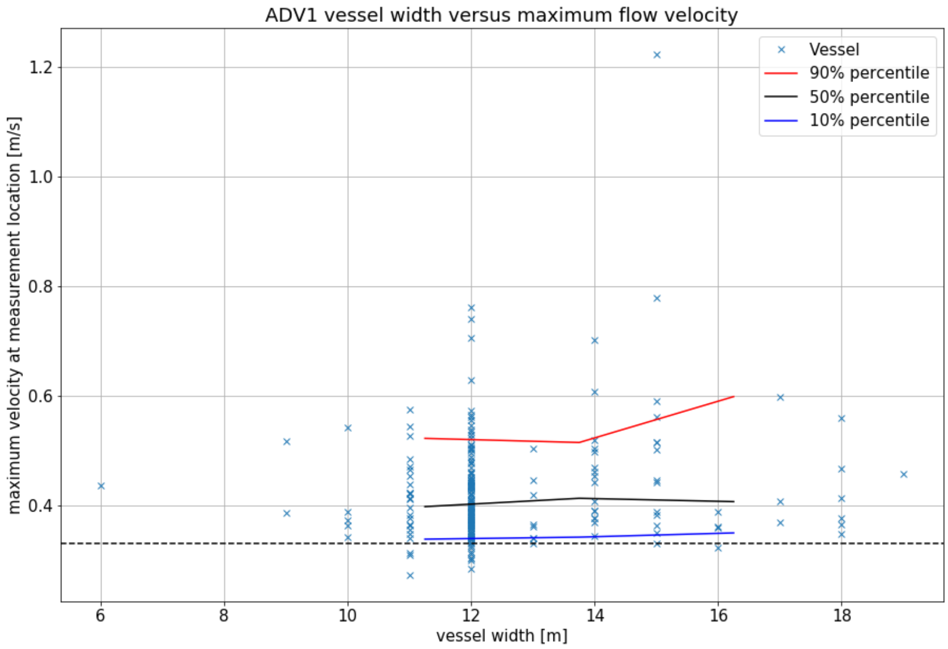

Figure 4.12: ADV1 vessel width versus maximum flow velocity at measurement location

4.3.3. ADV2, ADV4 and ADV5

The figures of the influence of all parameters on the flow velocity at the other locations can be found in Appendix E.4. The explanation of the results can be found in Appendix E.3. In this section, only a brief summary of the results at these locations is given.

The draught of the vessels has again no significant influence on the flow velocity at all locations according to the results. The sailing speed of the vessel clearly shows an increasing pattern in the flow velocity inside the groyne field at the location of ADV4 and ADV5. At the location of ADV2, the pattern is less clear but an increasing pattern is still visible. By reducing the distance towards the measurement instrument an increase in the flow velocity inside the groyne field is visible at the location of ADV2 and ADV4. At the location of ADV5, the effect is less clear. At all locations, the 50% percentile line shows an increasing pattern for the effect of the vessel length. The 90% percentile lines show variable results, mainly due to a low amount of data points in some percentile intervals. Finally, the vessel width has a questionable influence on the flow velocity at all locations. When investigating the results of the total dataset for the width, an increasing pattern is visible. In table 4.3 an overview is given of all vessel characteristics at all locations and whether their influence on the flow velocity inside the groyne field agrees with the hypothesis.

	ADV1	ADV2	ADV4	ADV5
Draught	X	X	X	X
Sailing speed	?	?	✓	✓
Distance to measurement instrument	✓	✓	✓	?
Length vessel	✓	✓	?	?
Width vessel	?	?	?	?

Table 4.3: Effect of vessel characteristics on the flow velocity and whether they are in agreement with the hypothesis. ✓ = yes, ? = questionable, X = no

4.4 Data evaluation

In this section, the data visualised in the previous section is evaluated. Firstly, the results of the water level difference and the maximum flow velocity are analysed and discussed. Secondly, also a general evaluation of the data is made.

4.4.1. Water level difference

Draught

The first characteristic investigated is the draught of vessels. At all four locations, the draught has no influence on the water level difference inside the groyne field which is contrary to the hypothesis. A possible explanation for this is the unreliability of the draught data. The draught of a vessel has to be manually entered into the AIS system database before each departure. It is unlikely, however, that sailors forget to enter the draught of the vessel at each departure. Therefore, it is assumed that this is not the reason the draught has absolutely no influence on the water level difference.

Sailing speed

The sailing speed of the vessel is investigated next. At the location of ADV1, the average sailing speed has a minimal effect on the water level difference inside the groyne. At the other three locations, the sailing speed does show an increasing effect on the water level difference. It should be noted that mainly the 90% percentile line shows an increasing pattern, also at the location of ADV1. This suggests that extreme values are more likely to occur when the sailing speed is larger.

Distance to measurement instrument

The next characteristic is the distance to the groyne field. At the location of ADV1, ADV2 and ADV4, the distance to the measurement instrument shows an effect which is in agreement with the expected results. Especially at the location of ADV1, the effect is comparable to the calculated line according to the existing formula and it is clear that extreme values occur when the distance to the measurement instrument is small. At the locations of ADV5, the effect is less obvious. The 90% percentile does however show an increase when the distance becomes smaller, indicating again that the more extreme values do appear more often when the distance to the measurement instrument is smaller.

Length of vessel

The effect of the length of the vessels shows an increasing pattern at the location of ADV1. At the locations of ADV2, ADV4 and ADV5 the effect is less clear. The 50 % percentile lines show an increasing pattern. The 90% percentile lines, however, do not show a clear effect. A possible reason for this is the low amount of data points due to selecting only a single width. When ignoring the effect of the relation between the length and the width of the vessel at all locations a positive trend is visible.

According to the results, the vessels with a length longer than 135 meters, the so-called push-barge vessels, do not increase the flow velocity with the same trend as the vessels smaller or equal to 135 meters. According to previous research from Ten Brinke (2003) large push-barge vessels do create a larger effect on the flow inside the groyne field compared to the smaller vessels. A possible reason why this is not visible in the results could be the low amount of push-barge vessels measured during the measurement campaign compared to the other vessels. However, when increasing the number of vessels in the results by ignoring the 10-minute difference criteria, the results show the same pattern where the vessels with a length of 135 meters are still creating the largest effect on the flow.

Width of the vessel

Finally, the width of the vessel. At all locations, the water level difference increases by increasing the width of a vessel. Furthermore, the slopes of the percentile lines follow the slope of the expected values according to the existing formulas pretty accurately. When ignoring the relationship between the width and the length of a vessel, the same pattern remains.

The same effect as previously described for the length of the push-barge vessels is present for the width of the vessels. According to previous research of Ten Brinke (2003) the push-barge vessels, the vessels wider than 20 meters, should have a larger effect on the flow inside the groyne field compared to the smaller vessels. As described before, this is not the case and the push-barge vessels do not follow the same trend as the smaller vessels. The wider push-barge vessels, however, do seem to create an effect which is comparable to the effect of the vessels with a width of around 15 meters which is around the maximum width of the motorised vessels sailing in the Waal.

4.4.2. Flow velocity

Draught

The first characteristic is the draught of the vessel. Comparable to the water level difference, there seems to be no significant effect of the draught on the flow velocity at all locations. Since the draught has to be entered manually before each departure, some wrong values could be entered. However, it is unlikely that this has happened for most of the vessels. Therefore, it is assumed this is not the reason the draught has absolutely no influence on the flow velocity inside the groyne field.

Sailing speed

The next characteristic is the sailing speed of the vessel. At the locations of ADV1 and ADV2, the 50% percentile line shows a horizontal pattern, indicating no significant effect of the sailing speed on the flow velocity. At the location of ADV1, the 90% percentile line does show an increasing pattern when the sailing speed increases. This suggests that at this location more extreme values occur when the sailing speed increases. For the locations of ADV4 and ADV5, the 50% percentile line does show an increasing pattern. At the location of ADV5, the effect of an increasing sailing speed is the clearest. All percentile lines increase when the sailing speed increases.

Distance to measurement instrument

Next, the distance to the measurement instrument. At the locations of ADV1, AD2 and ADV4, the flow velocity inside the groyne field increases when the distance of a vessel towards the measurement instrument decreases. At the location of ADV5, the effect is more questionable.

Length of vessel

The vessel length is the next characteristic investigated. At the locations of ADV1 and ADV2, an increasing pattern is visible when the vessel length increases. At the location of ADV4 and ADV5, the effect is less clear. A possible explanation for this is the low amount of data points to compute the percentile lines. This could result in wrong results. When ignoring the relationship between the length and the width of the vessel a clear increase in the flow velocity is visible at all locations.

The effect of the push-barge vessels on the flow velocity is comparable to the effect previously visible for the water level difference. Vessels with a length longer than 135 meters do not increase the flow velocity with the same trend as the vessels smaller than 135 meters which is not in agreement with research from Ten Brinke (2003). A possible reason could be the low amount of push-barge vessels observed during the measurement period. However, when increasing the number of vessels in the results by ignoring the 10-minute difference criteria, the results show the same pattern where the vessels with a length of 135 meters are still creating the largest effect on the flow.

Width of vessel

The final characteristic is again the width of the vessel. The effect of the width of a vessel on the flow velocity inside the groyne field is hard to investigate since the width is strongly related to the length. In this research, it is tried to eliminate the effect of the length by selecting a small range of vessel lengths. It was not possible to select a single vessel length since there were too few data points. At all locations the effect of the width on the flow velocity is questionable. It should be noted that this could be declared due to the decrease in the number of data points. When ignoring the relationship between the length and the width of the vessels, a clear increasing pattern is visible at all locations. This suggests that the combination of an increase in length and an increase in width has a positive effect on the flow velocity inside the groyne field.

Again, the vessels with a width larger than 20 meters, the push-barge vessels, do not follow the same pattern as the smaller vessels. After increasing the amount of data points, the same pattern is still visible.

4.4.3. General evaluation

After analysing the different results for the water level and the flow velocity, the results are evaluated in general. It appears that the variety in all plots is large. At first sight, there seems to be no clear pattern in the data. After computing the different percentile lines, the results became clearer, but the variety remains.

A possible explanation for the variety of the results could be the presence of multiple other factors influencing the flow inside and outside the groyne field. Most of the current research has been done in uniform channels or with the use of computer programs. In this groyne field, the effect of the helical flow is probably affecting the effect of the vessels. Furthermore, due to the location of the groyne field being inside a bend, the flow is flowing inside the groyne field under an angle. Another explanation could be the presence of transverse oscillations between both banks of the river as described in section 3.2.5. If these transverse oscillations are constantly present inside the river section, a vessel sailing past the groyne field could increase this effect by creating a wave with the same wave period as the oscillating wave. This could result in resonance and an increase of the water level difference and flow velocity inside the groyne field. Another possibility could be the timing of the vessel. If the water level is raising inside the groyne field due to the transverse oscillation, the passage of a vessel could reduce this effect by lowering the water level due to the return correct. Another possibility is that these effects increase each other, resulting in a large effect of the vessel inside the groyne field. This effect will be more extensively investigated in section 4.5. Another possibility is that there is still some relation between the different variables influencing the results or the AIS-data being unreliable.

In Appendix E.5 the maximum flow velocity versus the water level difference is plotted for all locations. The results show a relatively linear pattern. Therefore, a straight line is plotted through the data with the use of the least square error method. Furthermore, Pearson's correlation coefficient is calculated for each location. At the location of ADV1 and ADV5, the relation between the flow velocity and the water level difference can be described as strong according to table D.1. At the location of ADV2 and ADV4, the relation can be described as moderate.

4.5 Frequency analysis

In this section, an explanation will be given on how to investigate the effect of vessels on the water level inside the groyne field with the use of a frequency analysis. Furthermore, it is investigated whether the vessels increase the water level difference by resonating the already existing fluctuation of the water level inside the groyne field due to the waves they create.

4.5.1. Eigenfrequency groyne field

During the frequency analysis a Fast Fourier Transform (FFT) is used to convert a signal from its original domain, which is time in this case, to a frequency domain. Since the waves inside the groyne field exist out of the waves creates by vessels and the waves constantly present inside the groyne field, it is possible to recreate these waves by adding multiple waves with different frequencies and amplitudes. An FFT uses this principle to calculate the different frequencies and amplitudes of a certain domain. In formula 4.1 the formula for all different wave components is shown. $\underline{a}_i$ represent the different amplitudes, f_i the frequency and $\underline{\alpha}_i$ the different phase shifts.

$$\underline{\eta}(t) = \sum_{i=1}^{N} \underline{a}_i \cos(2\pi f_i t + \underline{\alpha}_i) \tag{4.1}$$

The effect of a vessel can be investigated by eliminating the frequencies of the waves constantly present inside the groyne field. By doing this, only the waves created by vessels should remain. In Appendix F five 30-minute sections are shown. These figures consist out of the water level fluctuation, the amplitude versus the frequency of the separated harmonic waves and the variance versus the frequency of the harmonic waves.

The variance can be used to calculate the energy of the waves. Four of these five sections are 30-minute sections where no vessel sails past the groyne field. Therefore, these sections are suited to investigate the constant frequencies inside the groyne field. In one of the figures, figure F.2, a vessel passes the groyne field at 3:19. This vessel, however, has a small influence on the water level inside the groyne field. The main frequencies present inside the groyne field when no vessel passes the groyne field are 0.012 Hz on the 26th of April according to figures F.1, F.2 and F.3 and 0.08 Hz on the 1st and 2nd of May according to figures F.4 and F.5. After investigating the other 30-minute sections a frequency of 0.012 Hz is present at most frequency plots and is mainly dominant. Therefore, it is assumed that the eigenfrequency of the waves inside the groyne field is equal to 0.012 Hz.

4.5.2. Influence of the vessels

The influence of the vessels can be investigated by plotting the FFT results for each 30-minute interval. For each 30-minute interval, this results in the amplitude and frequency of all different wave components. This results in the first downside of this approach. The effect of a single vessel cannot be investigated by using this method. When decreasing the interval to investigate the effect of a single vessel, the FFT resolution decreases. The FFT resolution is equal to the frequency of the measurement divided by the number of points in the FFT interval. For the 30-minute interval, this results in a resolution of:

$$F_s/N = 8/(30*60*8) = 8/14.400 = 5.6*10^{-4} = 0.00056\text{Hz} \tag{4.2}$$

This means that in an interval of 0.01 Hz almost twenty frequency bins are plotted. Using the 120 seconds interval to measure the effect of a single vessel as previously described this results in an FFT resolution of:

$$F_s/N = 8/(120*8) = 8/960 = 0.0083\text{Hz} \tag{4.3}$$

Since the wave frequencies are in the order of 0.01 Hz, the resolution is too low to determine the exact frequencies.

The next challenge is to determine which peak in the frequency analysis corresponds to which vessel. In some intervals, more peaks are visible than vessels sailing past the groyne field. In other intervals, fewer peaks are visible compared to the number of vessels. Fewer peaks than vessels can be expected since multiple vessels can create the same wave frequency, but more peaks than expected are hard to explain since they are likely created by other mechanisms affecting the water level inside the groyne field. In the next section, it will be explained how to calculate the frequency of the drawdown wave created by a vessel. Unfortunately, these frequencies are not in agreement with the measured frequencies according to the frequency analysis.

Due to both complications, the effect of the vessels is not measured with the use of a frequency analysis.

4.5.3. Ship wave frequencies

In this section, it is investigated whether certain vessels with a certain drawdown frequency resonate with the constant water level fluctuation present inside the groyne field. To investigate this, it is required to calculate the frequency of the drawdown wave the vessels create.

The length of the drawdown wave is depending on the length and the speed of the vessel. According to previous research of De Rijck et al. (2010), the length of the primary wave can be assumed to be equal to the length of the vessel. The primary wave consists out of the bow wave, the depression in the water level and the stern wave visible in figure 2.9. The wavelength is therefore assumed to be equal to the vessel length. The wave period can therefore be computed by diving the wavelength by the velocity of the vessel and the wave frequency by the inverse of the wave period. Unfortunately, the computed drawdown wave frequency is higher compared to frequencies observed in the FFT. By assuming only the drawdown to be equal to the vessel length, the wavelength is equal to two times the vessel length divided by the velocity. This is because the drawdown is only half of a wave. The calculated wave frequencies after assuming the wavelength to be twice the vessel length are more realistic. The formulas used to compute the ship frequency are shown in formula 4.4. With L the vessel length en U the sailing speed in m/s.

$$T_{ship} = L/2U$$
$$F_{ship} = 1/T = 2U/L \quad (4.4)$$

In figure 4.13 the results of the frequency analysis for the period between 12:30 and 13:00 on the 24th of April are visible. This is the same period as investigated in figure 3.22. In table 4.4 the expected frequencies of the waves created by the vessels are shown. Comparing them to the peaks present in figure 4.13 the peaks do not match. This means that the computed frequencies are not the right frequencies.

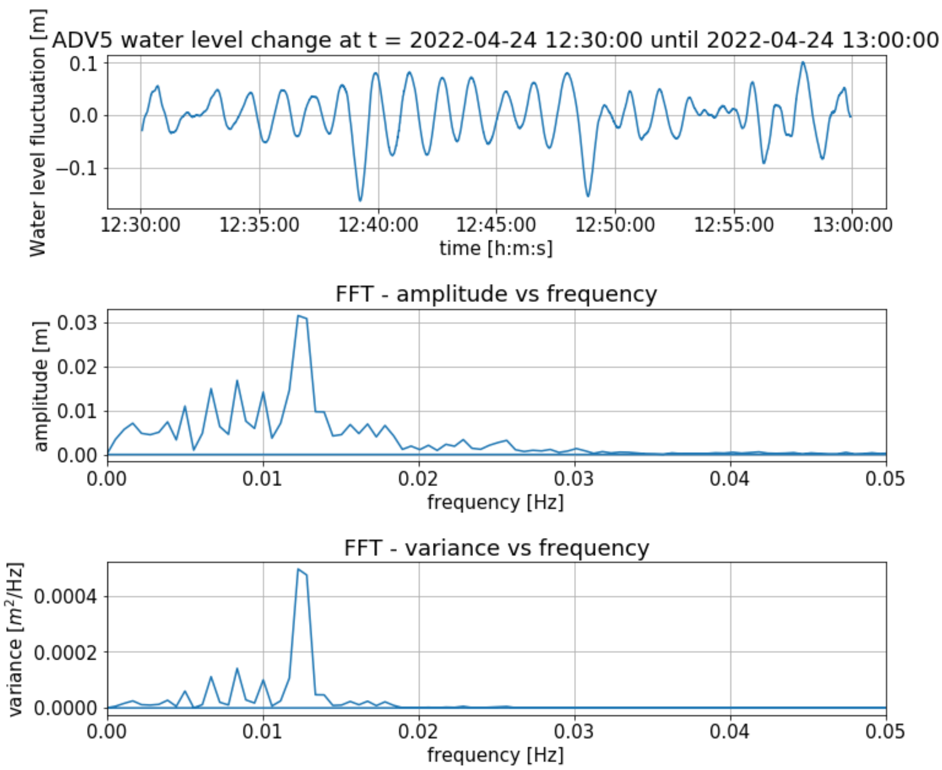

Figure 4.13: Water level fluctuation (top figure), amplitude wave components (middle figure) and variance (bottom figure) from 24-04-2022 12:30 until 13:00

	Time entering groyne field	Time leaving groyne field	Sailing speed [knots]	Velocity [m/s]	Length [m]	Wave frequency [1/s]
Vessel 1	12:35:57	12:36:56	7.6	4.0	85	0.023
Vessel 2	12:38:17	12:39:47	8.8	4.5	110	0.021
Vessel 3	12:48:22	12:49:21	6.5	3.5	110	0.016
Vessel 4	12:48:40	12:50:10	8.5	4.3	135	0.016
Vessel 5	12:52:49	12:53:46	8.4	4.4	110	0.020
Vessel 6	12:55:45	12:56:35	7.8	4.1	135	0.015
Vessel 7	12:56:46	12:57:34	8.5	4.5	85	0.027

Table 4.4: Time entering, time leaving, sailing speed, velocity, length and wave frequency of vessels passing the groyne field on the 24th of April from 12:30 until 13:00

To investigate whether resonance occurs, all vessel frequencies can be plotted versus the water level difference. If resonance would occur, a certain peak in the water level difference at a certain frequency should be visible. In figure 4.14 the produced frequencies of all vessels are plotted versus the water level difference. According to this figure, there is no dominant increase in the water level difference at a certain frequency. At a frequency of 0.02 Hz, a minor peak is visible, but this is mainly due to the high number of data points in that section. In figure 4.15 the frequency versus the water level difference is plotted for the vessels where 10 minutes before arrival no other vessel passes the groyne field. According to this figure also no resonance occurs. The same pattern is visible at the locations of the other measurement instruments.

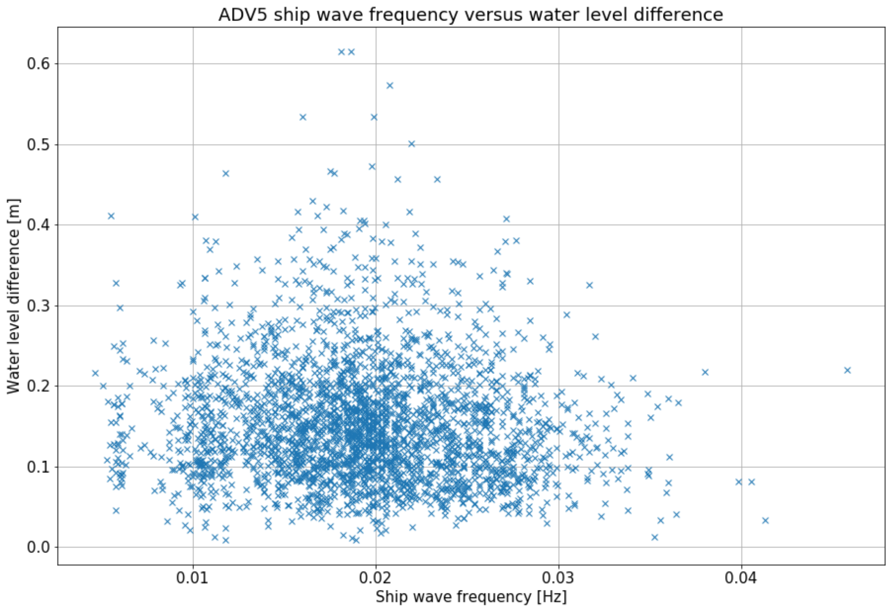

Figure 4.14: ADV5 wave frequency versus water level difference for all vessels

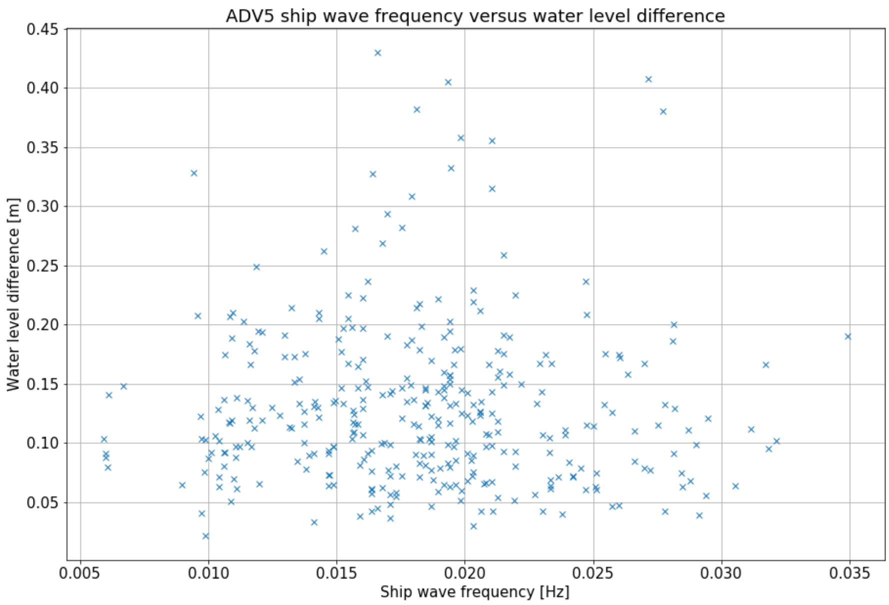

Figure 4.15: ADV5 wave frequency versus water level difference for vessels where ten minutes before arrival no vessels have passed the groyne field

According to this section, the waves created by vessels do not resonate with the constant water level fluctuation inside the groyne field. It should be noted, however, that many assumptions were done during this investigation. The eigenfrequencies of the waves produced by the vessels do not agree with the measured frequencies, which indicates that the eigenfrequencies are most likely depending on more parameters than the length and velocity of a vessel.

4.6 Chapter conclusion

In this chapter the effect of vessels on the flow properties inside the groyne field is investigated. The flow properties taken into account are the water level and the flow velocity. For each flow property, the effect of the different vessel characteristics is investigated. The vessel characteristics taken into account are the draught of a vessel, the sailing speed, the distance to the measurement instrument, the length of the vessel and the width of the vessel.

Data of the vessels is gathered with the use of AIS (Automatic Identification System) data. Around every ten seconds, this system communicates multiple properties of the vessel like the position of the vessel, the speed of the vessel and the direction of the vessel. Furthermore, data like the dimensions of the ship and the draught of the vessel are emitted. It has to be noted that the accuracy of this data depends on the quality of the emitting equipment. After inspecting the data, some inaccuracies have been found and mostly eliminated from the data.

Before analysing the results, a hypothesis has been made to predict the expected results of the vessel characteristics on the water level and flow velocity. An increase in the draught, sailing speed, length and width of the vessel should result in an increase in the water level and flow velocity while an increase in the distance to the measurement instruments should result in a decrease in the water level and flow velocity.

After combining the AIS data with the obtained measurement data, the effect of each vessel on the water level and flow velocity inside the groyne field has been determined. Before plotting the effect of each vessel characteristic it has been investigated whether the different characteristics are correlated with each other. Only the vessel length and vessel width showed a strong correlation with each other. The other characteristics showed a weak correlation.

Firstly, the effect of the vessels on the water level was investigated. The results showed a high variance for all vessel characteristics. By plotting the percentile lines it was possible to investigate the effect of the characteristics on the water level and to spot certain trends. The draught of the vessels had no effect on the water level inside the groyne field. The sailing speed and the distance to the measurement instrument did show an effect according to the hypothesis. The effect of the length and the width of the vessel was less clear. However, by neglecting the effect of the relation between the length and the width of the vessel a clear increasing pattern was visible. It should be noted again that the variance of the results was large, making it hard to predict the effect of a single vessel.

Secondly, the effect of the vessels on the flow velocity was investigated. The draught of the vessels had no effect on the flow velocity inside the water. The sailing speed and distance to the measurement instrument did show an effect according to the hypothesis. The effect of the length and the width of the vessel was again less clear. By neglecting the relationship between the length and the width, a clear increasing pattern was visible. Indicating that the combination of an increase in length and width results in an increase in the flow velocity. It should be noted again that the results showed a high variance, making it hard to predict the effect of a single vessel.

Finally, it was investigated whether it is possible to investigate the effect of vessels with the use of a frequency analysis. It was found that the measured frequency was not large enough to measure the exact influence of a single vessel.

5 Discussion

The objective of this research was to obtain more insight into the effect of vessels on the flow properties inside a real groyne field and in which way the characteristics of vessels influence these flow properties. To investigate this, a literature study and a measurement campaign were performed to obtain data from the real-life situation.

The measurements performed in this research are limited to the shallow part of the groyne field. In the deeper part of the groyne field, no measurements were performed due to a lack of the right measurement equipment. According to the flow direction in the shallow part of the groyne field, which is opposite compared to the flow in the main channel, a large primary and a small secondary eddy should be present inside the groyne field. Furthermore, this is also in agreement with the flow pattern according to the literature.

The results of the measurement campaign furthermore suggest that the effect of vessels on the flow inside the groyne field is dominant in the upstream part of the groyne field, just downstream of the upstream groyne. At this location, the direction and magnitude of the flow velocity is affected the most, while in the downstream part of the groyne field mainly the magnitude of the flow velocity is changed and the primary eddy remains relatively intact. Since the measurements are only performed in the shallow part of the groyne field, the influence of a vessel on the deeper part of the groyne field cannot be investigated. At the deeper area of the upstream part of the groyne field, it is most likely that the water indeed flows out of the groyne field. At the deeper area of the downstream part of the groyne field, the effect of the vessels is more questionable. The combination of an increase in the flow velocity of the primary eddy in the shallow part of the groyne field and the lowering of the water level inside the groyne field suggest, however, that the primary eddy remains intact and that the suction force of the vessel is not strong enough to completely vanish the primary eddy. A possible explanation for the primary eddy remaining intact is the location of the groyne field. Since the groyne field is located at the outer side of a river bend, the flow is directed directly into the groyne field at the downstream part of the groyne field, flowing against the downstream groyne. To counter this flow and to guide the water out of the groyne field at the downstream part of the groyne field, a large force is required. The suction force generated by the vessels is not strong enough to turn this flow around.

The measurement period ranged from the 20th of April until the fourth of May. The water level at the measurement location was around 775 cm +NAP during this period, which is around the average water level and therefore the measurement represents the average results. This water level resulted in an emerged groyne field with sufficient water to measure the effect of the vessels. By measuring in a different period of the year, or to make things more clear, measuring during a period with a different water level, the results can alter from the current results. When the water level exceeds the level of the groynes, and the water level is, therefore, larger than 850 cm +NAP, the groyne field becomes submerged. When the groynes become submerged, the horizontal eddy dampens and the unidirectional flow becomes more dominant. In this situation, the horizontal eddies eventually disappear and therefore the effect of vessels on the flow pattern decreases. When the water level is lower compared to the water level during the measurement period, there is less water inside the groyne field. The size of eddies becomes therefore smaller, resulting in a smaller flow velocity inside the groyne field.

According to the data of the water pressure sensors, a constant water level fluctuation of several centimetres with a constant frequency is present inside the groyne field. A possible explanation for this fluctuation is the presence of transverse oscillation between both riverbanks. The computed frequency of the transverse oscillations, assuming they are present, is close to the observed frequency of the measured water level fluctuation according to the data. The expected wave period of the transverse oscillations has been calculated, however, by assuming a uniform channel with a constant depth. By computing the real wave period and investigating at which angle the transverse waves are propagating from bank to bank, it is possible to determine more accurately whether transverse oscillations are present between both riverbanks.

To investigate the effect of the vessels on the flow properties inside the groyne field, AIS-data is used. In this research, the AIS-data is assumed to be reliable data. However, the quality of the AIS-data is highly dependent on the crew of the vessel, since they have to manually enter several parameters before each departure, and on the quality of the data emitted by the vessel. According to the AIS-data obtained, some of the vessels appeared to be sailing on land due to a lack of GPS accuracy. Furthermore, the AIS-data is not continuously measuring the GPS location of the vessels but only measures the location of the vessel around every ten seconds. This can result in unreliable results when calculating the minimal distance to a measurement instrument.

By assuming the AIS-data to be reliable data, some unrealistic results came out of the vessel characteristics analysis. According to this research, the draught of the vessels has no significant influence on the water level and flow velocity inside the groyne field. This is contrary to the expected results according to the literature. It is unlikely, however, that the draught data is such unreliable that absolutely no influence of the draught is visible in the results.

According to previous literature, push-barge vessels have a large effect on the flow inside the groyne field. However, according to the results of the measurement campaign, the effect of the push-barge vessel is not as dominant as expected. The push-barge vessels induce an effect similar to that of the vessels with a length of 135 meters, which are the largest inland vessels sailing past the groyne field beside the push-barge vessels. In this research, no explanation for this phenomenon has been found.

The results of the effect of the vessel characteristics on the water level and flow velocity inside the groyne field showed a large variance. A possible explanation for the large variance is the influence of multiple other mechanisms on the flow inside the groyne field. Possible mechanisms influencing the flow are the oscillations in the water level, the helical flow inside the river bend and the angle of the groyne field with respect to the main channel. All these mechanisms can influence the effect of a vessel on the flow inside the groyne field. Therefore, it is likely that there are more parameters influencing the flow inside the groyne than the vessel characteristics which results in a large variance of the results.

6 Conclusions

During this research, the flow velocity, flow direction, water level and sediment concentration inside a groyne field in the Waal were measured to investigate the influence of ships on the flow pattern inside the groyne field. The data has been obtained by performing measurements in the shallow part of a groyne field with the use of ADVs (Acoustic Doppler Velocimetry), RBRs and STMs (Seapoint Turbidity Meter). The results of this research add to the existing knowledge on groyne fields and can be used to better prepare the planned nourishment pilot to reduce erosion inside the Waal.

The flow inside the chosen groyne field consist of a primary and secondary eddy when no vessels sail past the groyne field. When a vessel passes the groyne field, the flow pattern inside the groyne field changes. Due to the depression in the water level caused by the primary waves induced by a vessel, the water level decreases inside the groyne field. During this process, the secondary eddy disappears while the primary eddy remains intact, guiding extra water towards the upstream groyne. This results in water flowing out of the groyne field at the location of the upstream groyne. When the vessel has passed the groyne field, water starts to flow back inside the groyne field due to the stern wave. The direction of the flow changes from directing out of the groyne field, towards into the groyne field at the location of the secondary eddy just downstream of the upstream groyne. The primary eddy remains intact and increases in force guiding more water towards the bank of the groyne field and raising the water level.

During the passage of a vessel, the flow velocity inside the groyne field increases. At the location of the secondary eddy, this increase is relatively the largest. Furthermore, the sediment is finest at this part of the groyne field. The large increase in flow velocity at this location results in the fine sediment being mobilised and directed towards the main channel. Due to the flow leaving the groyne field downstream of the upstream groyne, a scour hole is present at this location.

When no vessels influence the flow inside the groyne field, a constant water level fluctuation of several centimetres is visible. This fluctuation has not been observed by previous research which investigated the flow pattern inside a groyne field. The most likely explanation for this fluctuation is the presence of transverse oscillations between both banks of the river. However, as we have monitored the water level only on one side of the river, this cannot be confirmed.

The influence of the characteristics of vessels on the water level and flow velocity inside the groyne field differs from the expected results according to existing formulas. Data about the characteristics of the vessels have been obtained by using AIS (Automatic Identification System) data from Rijkswaterstaat. For all characteristics, the observed variance of the effect of the vessel characteristics on the flow is very large, making it hard to predict the effect of a single vessel. By considering the results of all vessels, the following conclusions can be drawn. From the data, no relation between the draught of the vessels on the water level change and flow velocity inside the groyne field could be found by an individual passing ship. An increase in the sailing speed of a vessel and a decrease in the distance of a vessel towards the groyne field does have an enlarging effect on the water level difference and the flow velocity inside a groyne field. The combined effect of increasing the length and the width of a vessel also has an enlarging effect on the water level difference and the flow velocity inside the groyne field. This increasing effect is only visible until a certain length and width. The large push-barge vessels, vessels longer than 135 meters and wider than 20 meters, do not induce a larger effect compared to the largest inland vessels with a length of 135 meters.

Overall, this research has shown that the effect of vessels on the flow properties inside a groyne field located in a river bend is hard to predict based on analysis of data and the characteristic of the vessels. Multiple mechanisms affect the flow properties inside the groyne field and affect the influence of vessels on these flow properties. It did, however, obtained a clear view of what the flow pattern inside the groyne field looks like with and without vessels. This information can be kept in mind when planning the shape and location of the groyne field nourishments.

7

Recommendations

In this chapter recommendations to improve further research on the effect of vessels on the flow inside the groyne field are presented. Furthermore, a recommendation is given about how to apply the knowledge presented in this research to the nourishment pilot.

Research recommendations

To obtain a better view of the exact flow pattern inside the groyne field it is recommended to also perform measurements in the deeper part of the groyne field. In this research, the water level, flow velocity and sediment data have been acquired by performing measurements in the shallow part of the groyne field. By performing measurements in the deeper part of the groyne field, more information about the exact flow inside the groyne field and the size and flow directions of the primary and secondary eddies will be obtained. To perform these measurements in the deeper part of the groyne field, a method has to be found on how to lower these instruments safely onto the bed and how to make sure they do not move.

During the survey, algae growth on the STMs affected the measured sediment concentration. Furthermore, the measurement instruments were not calibrated. To obtain more knowledge about how vessels affect the sediment concentration inside the groyne field, a better way to measure the sediment concentration or how to avoid the algae from covering the sensors has to be found. Furthermore, placing the measurement instruments at the same height and measuring the height above the bed more accurately would lead to more accurate results. To investigate the sediment concentration at different heights it can also be beneficial to place multiple instruments at the same location but at different heights.

More research has to be done to determine the origin of the constant water level fluctuation inside the groyne field. To investigate the presence of transverse oscillations travelling from riverbank to riverbank, some simple measurements can be performed. By placing multiple water pressure sensors (RBRs) on both sides of the river, it is possible to investigate whether the waves are out of phase with each other or not.

For a better understanding of the three-dimensional flow circulations inside the groyne field, it is recommended to consider building a numerical model. The numerical model can be calibrated with the measured point data. The model runs can provide insight into the gaps in the spatial distribution and time records of the observations. It should however be noted, that a numerical model can never approximate the real situation. Furthermore, by building a model it can be investigated whether the transverse oscillations can be presented inside the channel and what the influence of the helical flow inside the main channel on the flow inside the groyne field is.

To better investigate the effect of the vessel characteristics on the flow properties inside the groyne field, the accuracy of the AIS-data should be further investigated. During the processing of the AIS-data provided by Rijkswaterstaat, some irregularities and errors were found in the accuracy of the AIS-data. Therefore, it is recommended to develop procedures of quality assurance that can eliminate these errors. Specific sources of error may be the manually introduced parameters (such as draught) and the position of the ship.

To investigate the influence of single vessel characteristics, the exact effect of the correlation between all characteristics should be further investigated. During this research, it was found that most of the characteristics had a very weak or weak correlation with each other. It should be investigated further whether this weak correlation can have a significant influence on the results.

Nourishment recommendation

According to the flow pattern observed in this research, the highest amount of erosion occurs when the nourishment is placed in the centre of the groyne field. It should be noted that to ensure maximum erosion, the nourishment should not cover the length of the whole groyne field. By allowing water to flow past the nourishment, the primary eddy is able to flow around the nourishment eroding the nourishment from all sides. This erosion is induced by the vessels since the observations show that most of the highest velocities develop when the ship waves enforce the eddies, rather than by other currents induced by the waves. This should result in more sediment being transported towards the main channel. By altering the size of the nourishment, and thus the area of contact between the water and the nourishment, it is possible to influence the amount of sediment supplied to the main channel. To eventually determine the efficiency of the nourishment, further research about the grain size distribution of the nourishment is required to determine whether the nourishment can decrease the erosion inside the Waal River.

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A

Measurement plan

To gain insight into the flow properties and morphodynamics inside a groyne field, measurements will be done inside a designated groyne field. In this measurement plan, the goal and location of the measurements will be elaborated. Furthermore, the desired results, measurement instruments and measurement set-up will be explained.

A.1 Goal of the measurements

The goal of the measurements is to gain insight into the flow properties and the morphodynamic processes inside a selected groyne field. This information will be gathered to obtain more information about the effectiveness of groyne field nourishments, a pilot organised by Rijkswaterstaat to reduce erosion inside the Waal by adding sediment inside the groyne field. The waves created by vessels sailing past the groyne field should mobilise the sediment and reduce the sediment deficit inside the upper Waal. These measurements will take place before the actual nourishment pilot has taken place. This will be done to be able to compare the situation before the nourishment to the situation after the nourishment. In this measurement campaign, special focus will be on the influence of vessels on the groyne field.

A.2 Measurement location

The location of the measurements will be the same as one of the actual nourishment pilot locations to be able to predict the effectiveness of the nourishments the best. Since the pilot will be done at three different locations, this leaves three possible locations to perform the measurements:

1. Upstream of Nijmegen in the outer bend near Haalderen (river kilometre 878).
2. Downstream of Nijmegen and the Tacitusbridge over the A50 at the south side of the river (river kilometre 894).
3. Little further downstream of the Tacitusbridge over the A50 at the northern side of the river (river kilometre 896).

The locations of the nourishment pilot are visible in figure A.1 below, indicated by the numbers one, two and three.

Figure A.1: Groyne field nourishment pilot locations

To determine the best location for the measurement a few criteria have been taken into account. The criteria are groyne height, accessibility and vessel effect.

The first criterion is the groyne height. After inspection, the groynes upstream of Nijmegen have not yet been lowered, while the groynes downstream of Nijmegen have been lowered. Due to the varying water level inside the Waal, the groynes upstream of Nijmegen are emerged most of the time, while the groynes downstream of Nijmegen are emerged less often. Since the desired effect induced by the vessels is more clear when the groynes are emerged, location one upstream of Nijmegen has a significant preference over the other two locations.

The next criterion is the accessibility of the location. All locations are accessible by foot. At location one a small parking spot is available. From this parking spot, a five-minute walk remains to the project location. At Location two there is no parking spot, which means that the area is more difficult to access by car. Location three is also more difficult to access by car since the land surrounding it is surrounded by a fence. Locations one and two are accessible to the public, while location three is not.

The final criterion is the effect of the vessels. Since the goal is to measure the effect of the vessels on the flow inside the groyne field, it is preferred to have an effect that is as extreme as possible. Since location one is located at the outer bend of a corner, vessels tend to sail close to the groyne field. Locations two and three are similar concerning the effect of vessels. They are both located at a wide, straight section of the river. The only difference is that location two is located on the southern side of the river while location three is located on the northern side of the river. Loaded vessels are mostly sailing upstream to deliver goods to the hinterland, which results in a larger effect of the vessels on the southern side of the river. The effect of the vessel is therefore expected to be larger at location two compared to location three.

Taking all the criteria into account location one is chosen to perform the measurements. Location one is chosen because the groynes have not yet been lowered at this location, resulting in the groyne field being emerged more often compared to locations two and three. Furthermore, at location one the vessels are sailing close to the groyne field resulting in a larger effect of the vessels and the groyne field is relatively easily accessible. A downside of a location in a river bend, however, is the helical flow possibly affecting the flow inside the groyne field. The effect of this helical flow should be taken into consideration when producing the results.

Location groyne field

The nourishment pilot will take place in five different groyne fields at the location near Haalderen. The groyne fields are shown and numbered from one to five in figure A.2. The upstream groyne field, number one, will be used as a reference groyne field. In this groyne field, there will be no nourishment, the other four groyne fields will be used for the nourishment. Since the measurements can only be performed in a single groyne field, due to a lack of measurement instruments and time, a decision has to be made about which groyne field to select. Groyne field number two has eventually been chosen to perform the measurements. This groyne field is chosen since it has the most uniform shape compared to the other groyne fields. In addition, this groyne field is relatively easily accessible compared to the other groyne fields.

Figure A.2: Groyne field pilot locations near Haalderen. Groyne field one will be used as a reference groyne field while groyne fields two to five will be used for the actual nourishments.

Dimensions groyne field

The dimensions of the groyne field are shown in figure A.3. On the day this picture was taken the groynes were emerged and the water line reached 100 meters inside the groyne field at the downstream groyne and 115 meters inside the groyne field at the upstream groyne. This distance varies when the water level raises or lowers, so this distance is not constant. The length of the groyne field is equal to about 230 meters. The groynes reach a height of approximately 950cm +NAP. This means that when the water level exceeds 950cm +NAP, the groynes will be submerged and the desired effect by vessels will be reduced. The measurements will therefore have to take place during a water level lower than 800cm +NAP to obtain the most ideal results. For simplification, the dimensions of the groyne are assumed to be equal to 100 x 230 meters in the rest of the measurement plan.

A.3 Desired results

To goal of these measurements is to gain more insight into the flow and morphodynamics inside the groyne field. Therefore, several quantities at several places inside the groyne field need to be measured. These quantities are:

- Bathymetry of the groyne field
- Water level
- Flow speed
- Flow direction
- Sediment concentration in the water

Firstly, the bathymetry of the groyne field will be measured. This will result in an overview of the bed level inside the groyne field. The bathymetry can be visualised by means of a graph where several colours can indicate the different levels. By measuring the bottom level strange shapes in the flow can possibly be identified.

Secondly, the water level will be measured at several places. Due to the primary waves induced by vessels, the water level inside the groyne field will first be increased by the bow-wave. Next, the water level will be lowered and finally, the water level will increase again. This change in water level will give us some insight into the rate of the water level change due to the vessels. The water level can be visualised by plotting the water level

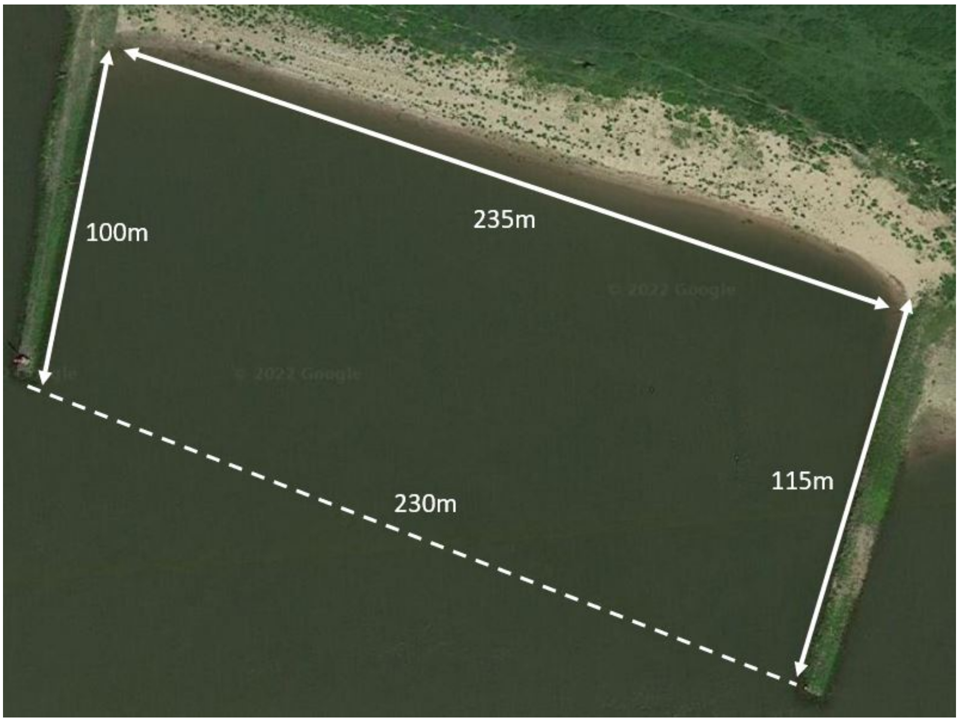

Figure A.3: Groyne field dimensions

over time.

Thirdly, the flow speed and flow direction inside the groyne field will be measured. First, a standard flow pattern without vessels has to be obtained. This can be done by placing several instruments strategically inside the groyne field to create a map of the flow speed and direction in the entire groyne field. Since the amount of measurement instruments is limited, it is important to investigate beforehand which locations are most interesting. Second, different flow patterns will be made of situations when vessels are passing the groyne field. Together with the water depth, this will give insight into how the flow changes when a vessel passes a groyne field. The desired results will be visualised in the form of several maps of the groyne field with arrows indicating the flow direction and magnitude of the flow speed at different times and at different locations inside the groyne field.

Finally, the sediment concentration inside the groyne field will be measured. The sediment concentration inside the water results in information about how much sediment is moved inside the groyne field. Together with the flow speed and flow direction it is possible to get an indication of the direction and amount of transport of the sediment.

A.4 Measurement instruments

The quantities described in the previous section can be measured with the use of several measurement instruments. For each quantity, a suited instrument is chosen and a short description of the instruments will be given in this section.

Deeper Smart Sonar CHIRP+

To measure the bathymetry of the groyne field the Deeper Smart Sonar CHIRP+ can be used. This instrument is actually used to spot fish inside the water column but can also be used to measure the bottom profile. The instrument can be mounted behind a boat or surfboard. Multiple lines can be sailed to create a bathymetry profile of the groyne field.

RBR solo^3 D fast 8

To measure the water level inside the groyne field the RBR solo^3 D fast 8, where the D stands for depth logger, can be used. This instrument measures the water level with a standard sampling frequency of 1 Hz, up to a sampling frequency of 8 Hz. Since there is no interest in the small waves induced by the wind or the vessels, the maximum sampling frequency of the RBRs is sufficient to obtain a clear view of the water level inside the groyne field. RBRs use a piezoresistive pressure sensor. The RBRs can be placed on the bottom of the groyne field connected to a pole or frame to create a continuous data set.

Acoustic Doppler Velocimetry (ADV)

To measure the flow velocity and the flow direction inside the groyne field, ADVs can be used. ADVs are Acoustic Doppler Velocimetry which measure the flow velocity and flow direction at a single point with a relatively high frequency. ADVs measure the flow velocity by using the Doppler shift effect. An ADV exists out of a transmitter which sends out a beam of acoustic waves with a fixed frequency. These acoustic waves are reflected by particles in the water onto the receivers. An ADV has two, three or four receivers. Two receivers can measure a 2D flow pattern while three of four receivers can create a 3D flow pattern. The receivers calculate the change in frequency of the returned signal and calculate the velocity in the x, y and z directions. The actual measured location is usually between five to ten centimetres from the tip of the transmitter (Chanson, 2008). In figure A.4 two examples of ADVs are shown.

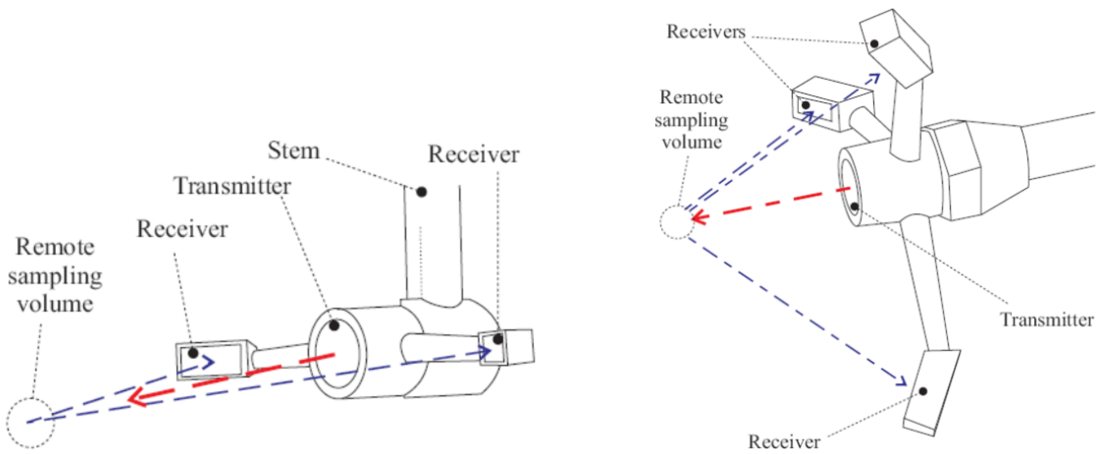

Figure A.4: Examples of ADVs with transmitter and receiver. a The left ADV has two receivers while the right ADV has three receivers (Chanson, 2008).

Just like the RBRs, the ADVs can be connected to a pole or frame and placed on the bottom of the groyne field to measure the flow speed and flow direction inside the groyne field.

Seapoint Turbidity Meter (STM)

To measure the sediment concentration inside the water the STM (Seapoint Turbidity Meter) can be used. An STM measures the sediment concentration inside the water by sending out a light signal from an LED and measuring the reflection of the light caused by small particles inside the water. A high number of particles will result in a high amount of reflections while a small number of particles results in a small amount of reflection. To obtain the best results, the STMs should be calibrated by taking a sample from the project site and measuring the number of particles inside the sample.

A.5 Vessel movements

To couple the changes in the water level and flow velocity with the presence of a vessel it is required to know when a ship passes the groyne field. It is possible to do this by tracking the vessels with their AIS tracking system. With the use of websites like myshiptracking.com, it is possible to check whether and when a vessel passes the groyne field. Unfortunately, to really investigate the influence of vessels sailing past the groyne field the AIS information may not be accurate enough. Since the GPS-data of the AIS may be slightly off, the distance between the vessels and the groyne field and the exact time the vessels sails past the groyne field may not be accurate. Therefore, the best way to really get an indication of the influence of the vessels is to stand next to the groyne field and take notes manually by writing the vessel name, the vessel type, distance to the groyne field, sailing speed and the exact time.

A.6 Measurement duration

Since flow caused by vessels sailing past the groyne field is of interest, only data of a few days is required. It is important to link this data to the specific vessels sailing past the groyne field. Therefore, a visit to the project site to note the vessel information is required. For this reason, a minimum measurement duration of seven days is chosen. In these seven days, the project site will be visited once to note the vessel information manually. Furthermore, due to the large travel time to reach the measurement location, there has been chosen to also monitor the vessel movements with the use of online AIS-data.

A limiting factor can be the water level. Since the groynes are reaching approximately 950cm +NAP the water level should be lower. To measure the influence of vessels, a water level beneath 800cm +NAP is required. Ideal would be a water level of around 700cm +NAP. If the water level exceeds this 800cm +NAP, there should be waited until the water level drops again to start the measurements.

A.7 Instrument placement

In this section, the placement of the measurement equipment will be elaborated. The placement of the equipment was supposed to be divided into two parts. First, the part where the groyne field is shallow and second, the part where the groyne field is deep. Unfortunately, due to a lack of time and testing with the frames which were supposed to be used for the measurements in the deeper part of the groyne field, the measurements in the deeper part of the groyne field were cancelled. Therefore, only measurements were done in the shallow part of the groyne field.

Shallow part of the groyne field

For the shallow part of the groyne field poles can be used. These poles can be placed inside the bed and the equipment can be mounted on these poles. In the shallow part of the groyne field the ADVs, RBRs and STMs will be placed. The locations of the instruments are shown in figure A.5 where the white squares indicate the locations. The STMs should be placed around ten centimetres above the bottom of the groyne field with the ADV head above it. This way, the sediment concentration and flow speed at the bottom of the groyne field is measured. This is important data since the erosion will take place just above the bed of the groyne field. The RBRs will be mounted above the ADV and STM.

Figure A.5: ADV + RBR + STM locations

In total there will be 4 sets of ADVs, RBRs en STMs. The ADVs and STMs will be set to measure at a frequency of 8Hz. The RBRs will be measuring at a frequency of 1 Hz.

A.8 Final instrument settings

In this section, the final instrument settings of the ADV, STM and RBRs are presented.

ADV + STM settings

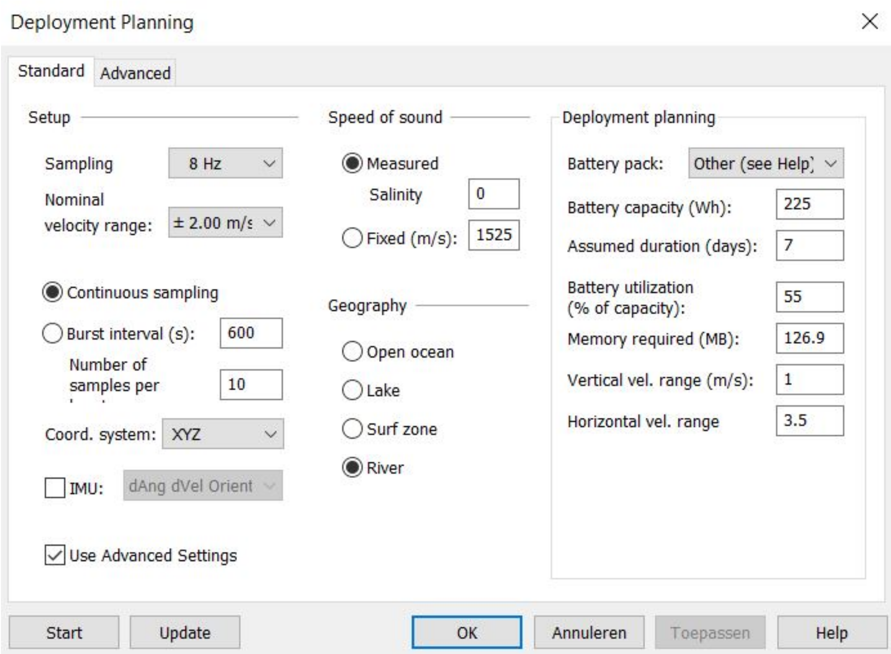

Figure A.6: ADV standard settings

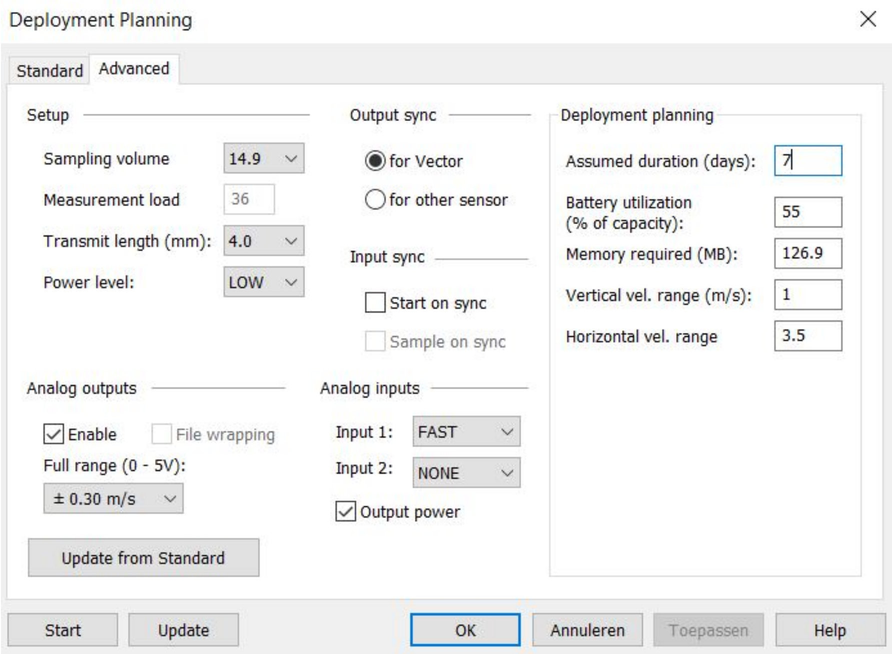

Figure A.7: ADV advanced settings

The ADVs are set to a continuous sampling frequency of 8 Hz and a nominal velocity range of 2 m/s. The salinity is set to zero and the measurement duration to seven days. The coordinate system is set to XYZ. In the advanced menu of the program, the STM settings are set to a fast analog input 1 to make sure the STM is also measuring at a frequency of 8 Hz and the range is set to 30 m/s.

RBR settings

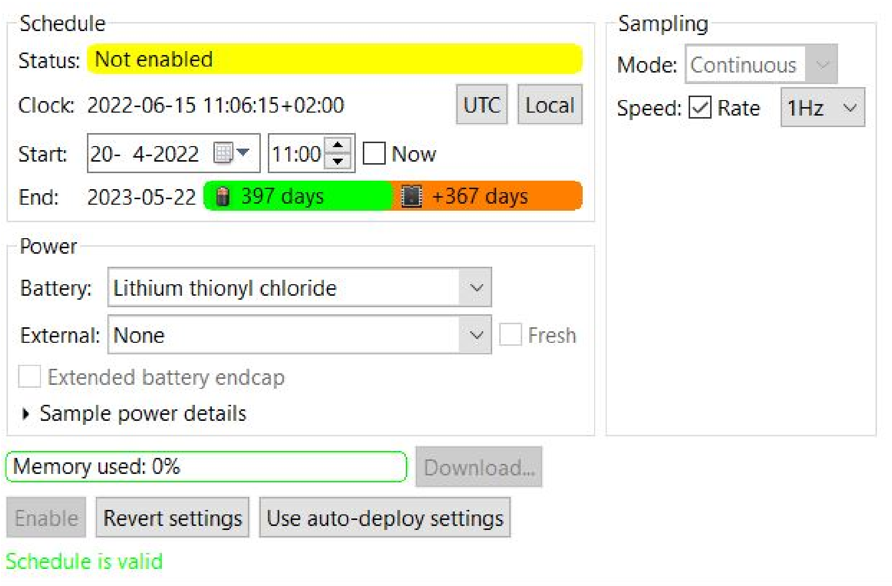

Figure A.8: RBR settings

The RBRs are set to a sampling frequency of 1 Hz to measure the difference in water level.

A.9 Weather data

This section of the measurement plan has been written after the measurement campaign has taken place and contains the weather data during the whole measurement period from the 20th of April until the 4th of may in table A.1. The average wind velocity in April for the period from 1981 until 2010 is 4.0 m/s according to data from Rijkswaterstaat.

Date	Average temperature (degrees)	Average wind direction (degrees)	Average wind velocity (m/s)
20-4-2022	11.3	E-N-E (58)	4.2
21-4-2022	12.3	E-N-E (63)	4.7
22-4-2022	12.2	E-N-E (65)	5.5
23-4-2022	13.0	E-N-E (68)	6.2
24-4-2022	11.7	N-N-E (28)	6.0
25-4-2022	7.8	N-N-E (24)	3.5
26-4-2022	9.2	N (351)	4.5
27-4-2022	7.4	N (356)	2.0
28-4-2022	9.4	N-E (40)	2.9
29-4-2022	8.7	N-N-E (24)	4.0
30-4-2022	7.6	N-N-W (338)	2.2
1-5-2022	9.4	N-E (39)	1.4
2-5-2022	11.0	N (360)	2.3
3-5-2022	9.5	N-E (2)	2.5
4-5-2022	10.4	N-N-W (332)	1.8

Table A.1: Weather data from the KNMI weather station at Eelde

A.10 Water level data

This section has been written after the measurements have taken place and contain the water level data of the whole measurement period in figures A.9 and A.10. The water levels have been measured by Rijkswaterstaat at the measurement station in Nijmegen Haven just downstream of the measurement location and at Lobith, just upstream of the measurement location. The actual water level, therefore, lies between both water levels. During the whole measurement period, the water level remained below the maximum water level of 800cm + NAP.

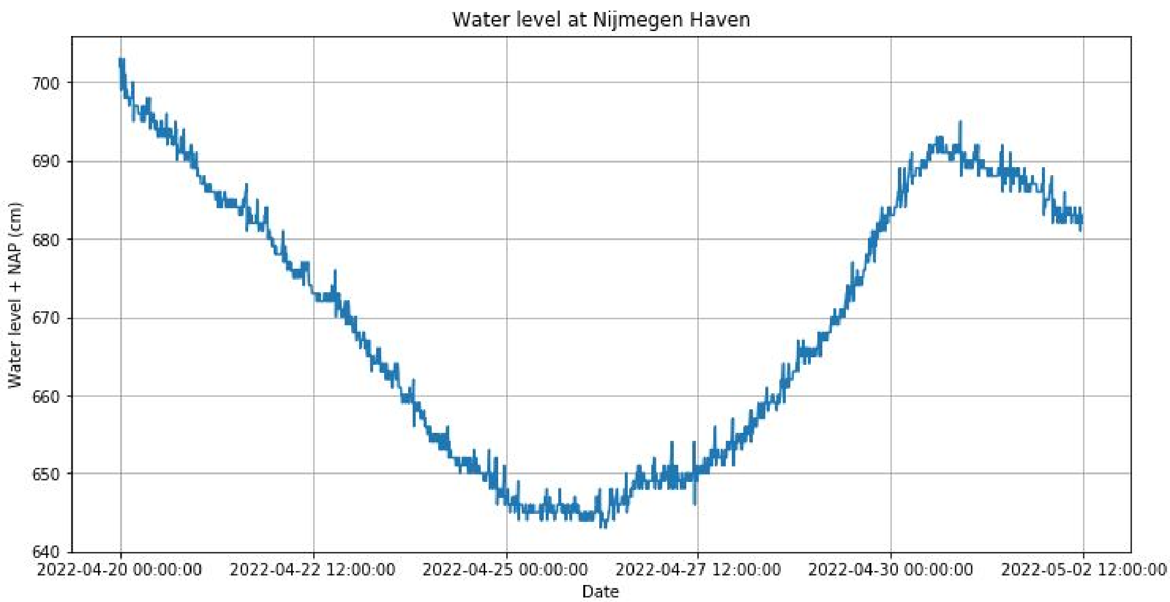

Figure A.9: Water level at Nijmegen Haven during the measurement period

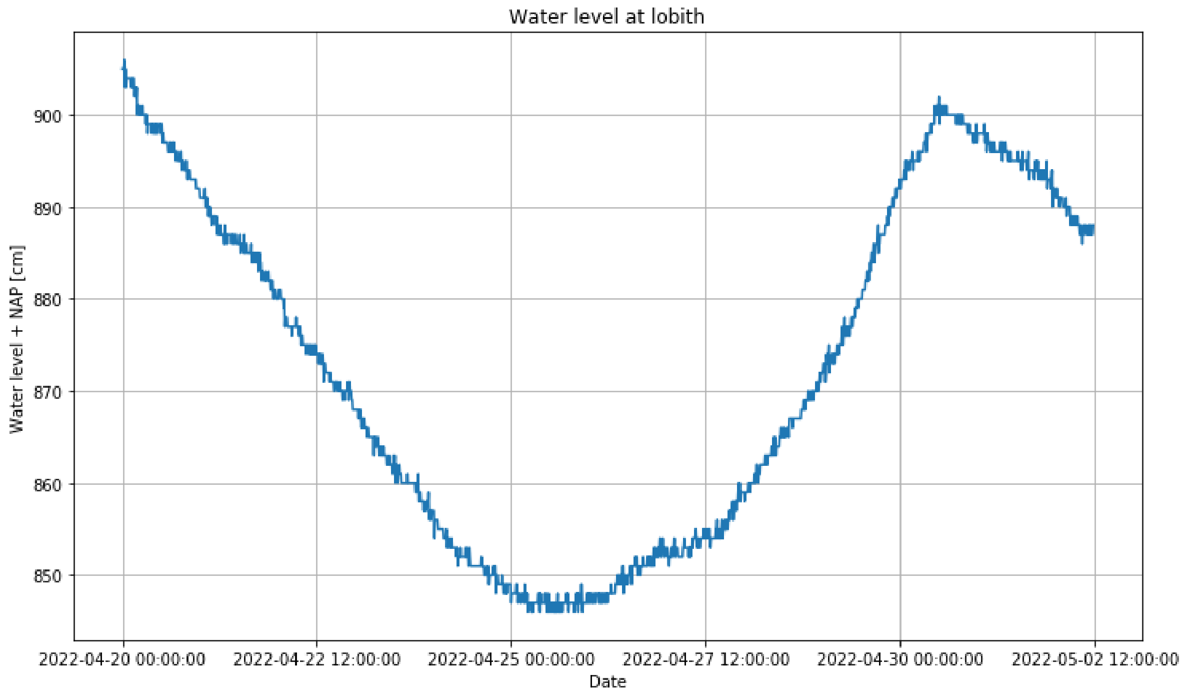

Figure A.10: Water level at Lobith during the measurement period

B
Interval choice

To achieve the most realistic results, certain parameters have to be chosen carefully. This chapter investigates how the water level difference and maximum flow velocity can be extracted from the measurement results in the best way possible.

B.1 Water level difference

According to the results of the measurement campaign, a vessel causes fluctuations in the water level inside a groyne field due to the primary waves. First, the bow wave increases the water level. Second, the water level decreases due to the return current around the vessel and finally, the water level increases again due to the stern wave. To investigate the influence of the vessels on the water level inside the groyne field, the maximum water level difference caused by a vessel needs to be extracted from the data. This can be done by computing the difference between the minimum and maximum water level in a certain interval. In figure B.1, the water level change at the location of ADV1 from 00:00 until 00:30 on the 21st of April is visible. Furthermore, the green dotted vertical lines indicate the moment that a vessel has entered the area between the upstream and downstream groyne. The red dotted vertical line indicates the moment a vessel has left the area between the upstream and downstream groyne.

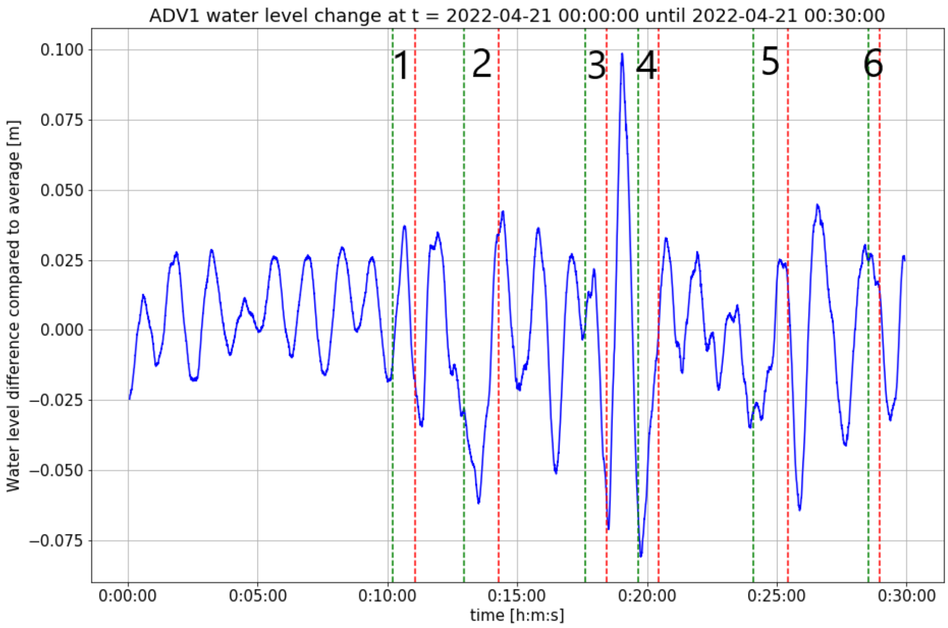

Figure B.1: Water level difference compared to the average water level at the location of ADV1 on the 21st of April from 00:00 until 00:30. The green dotted lines indicate the entrance of a vessel between the upstream and the downstream groyne, the red dotted lines a departure

After investigating the results, a certain delay in the effect of a vessel on the water level inside the groyne field is observed. This delay is likely caused by the inaccuracy of the AIS-data or by the stern wave increasing the water level after the vessel has passed the groyne field. To deal with this delay, a certain interval has to be chosen in which the effect of the vessel is present. A too-small interval results in unrealistic results since the total effect of the vessel has not been taken into consideration. A too-large interval also results in unrealistic results, since the effect of a single vessel is able to influence the results of multiple other vessels due to the intervals overlapping. To investigate which interval gives the most realistic results, multiple intervals are evaluated on the data of a single day, the 21st of April. The average water level difference computed for different intervals on all locations is shown in table B.1.

	ADV1	ADV2	ADV4	ADV5
Closest point +/- 45 sec	0.119	0.098	0.105	0.121
Closest point +/- 60 sec	0.131	0.109	0.115	0.138
Closest point +/- 75 sec	0.136	0.115	0.120	0.138
Between in & out	0.099	0.086	0.094	0.109
Between in & out +/- 10 sec	0.109	0.095	0.105	0.121
Between in & out +/- 20 sec	0.119	0.104	0.113	0.127
Between in & out +/- 30 sec	0.131	0.111	0.118	0.133
Between in & out +/- 40 sec	0.138	0.117	0.122	0.139
Between in & out +/- 60 sec	0.145	0.123	0.128	0.145

Table B.1: Average water level difference according to the different intervals at all locations on the 21st of April in meters [m]

The first choice of an interval is to take the AIS data point where the distance to the chosen measurement instrument is the smallest. Since multiple GPS signals are emitted when a vessel sails past the groyne field it is possible to select the data point when the vessel sails closest to the measurement instrument taken into consideration. The interval takes the 45, 60 or 75 seconds before the closest measurement point and the 45, 60 or 75 seconds after the closest measurement point into consideration. This results in a constant interval of 90, 120 or 150 seconds. The next intervals taken into consideration are the time intervals from the moment a vessel enters the groyne field by passing the upstream or downstream groyne until the moment the vessel leaves the groyne field by passing the downstream or upstream groyne, depending on the sailing direction of the vessel. The length of this interval is variable since it depends on the sailing speed and the sailing direction of the vessel. On the 21st of April, the average time a vessel spends between both groynes is 78 seconds. The slowest vessel, however, spend a time of 219 seconds between both groynes. The next intervals are a variation of the previous interval by enlarging the interval with respectively 10, 20, 30, 40 and 60 seconds before and after the period the vessel was sailing between both groynes. This increases the average interval length to 98, 118, 138, 158 and 198 seconds for the different intervals.

By investigating the results in table B.1 it is visible that the larger the interval, the larger the average water level difference becomes. This is in agreement with what is expected since a larger interval increases the possibility that a larger value is chosen. However, at a certain moment, when the interval becomes too large, the intervals of two vessels could overlap. This can result in two vessels obtaining the same results while only one of the vessels has a large influence on the water level difference. Therefore, the interval should not be too large.

By investigating the results visible in figure B.1, it is possible to see the effect of the different intervals on the results of each vessel. In figure B.1 six vessels pass the groyne field, each indicated by a number. In table B.2 the measured water level difference according to the different intervals are visible.

	Vessel 1	Vessel 2	Vessel 3	Vessel 4	Vessel 5	Vessel 6
Closest point +/- 45 sec	0.070	0.053	0.158	0.113	0.058	0.059
Closest point +/- 60 sec	0.070	0.086	0.168	0.113	0.059	0.061
Closest point +/- 75 sec	0.070	0.098	0.168	0.148	0.059	0.061
Between in & out	0.061	0.099	0.092	0.096	0.057	0.060
Between in & out +/- 10 sec	0.071	0.104	0.093	0.113	0.060	0.061
Between in & out +/- 20 sec	0.072	0.104	0.097	0.114	0.084	0.063
Between in & out +/- 30 sec	0.072	0.104	0.161	0.150	0.090	0.063
Between in & out +/- 40 sec	0.072	0.104	0.170	0.180	0.090	0.063
Between in & out +/- 60 sec	0.072	0.104	0.170	0.180	0.104	0.072

Table B.2: Measured water level difference of the different vessels visible in figure B.1 according to all intervals in meters [m]

The first interval is the closest point +/- 45 seconds. Since these results are from the location of ADV1, the point was chosen when the vessel was closest to this measurement instrument. An advantage of this method is that this method takes into consideration whether a vessel is sailing upstream or downstream. If a vessel is sailing downstream, it passes the location of ADV1 last. Subtracting 45, 60 or 75 seconds from this moment and the vessel is likely right next to the upstream groyne entering the groyne field and starting to have an effect on the water level. The interval 45 seconds before or after the closest point gives slightly low results after comparing it to the results in figure B.1. By increasing this delta to 60 seconds, the results become larger and looking at figure B.1, more realistic. Even further increasing the interval results in even larger results. To investigate which of these three intervals really covers the water level difference best, another filter is applied. The average water level difference of the vessels for whom in the ten minutes before arrival no other vessels have passed to groyne field and in the next five minutes after the vessel has passed the groyne field also no other vessel passes the groyne field have been shown in table B.3. The effect of these vessels on the water level difference has not been influenced by other vessels. This means that these values should reach a maximum when the interval is large enough. According to the table, the intervals do not reach a maximum for most locations. After inspecting the figures, a reason for this has been found. Looking at the first vessel arriving in figure B.2, which is part of the results of table B.3, it is visible that the water level before the vessel arrived was larger than when the vessel had actually arrived. This is visualised by the arrow in figure B.2. By increasing the interval, a value larger than actually created by the vessel is recorded. This means a too-large interval can also result in too-large values without the influence of other vessels. To keep this in balance the +/- 60 seconds delta is chosen to be the best fit for the closest point interval. Furthermore, at the location of ADV5, the value does not increase further when increasing the interval further than the +/- 60 seconds interval, indicating that the maximum is reached.

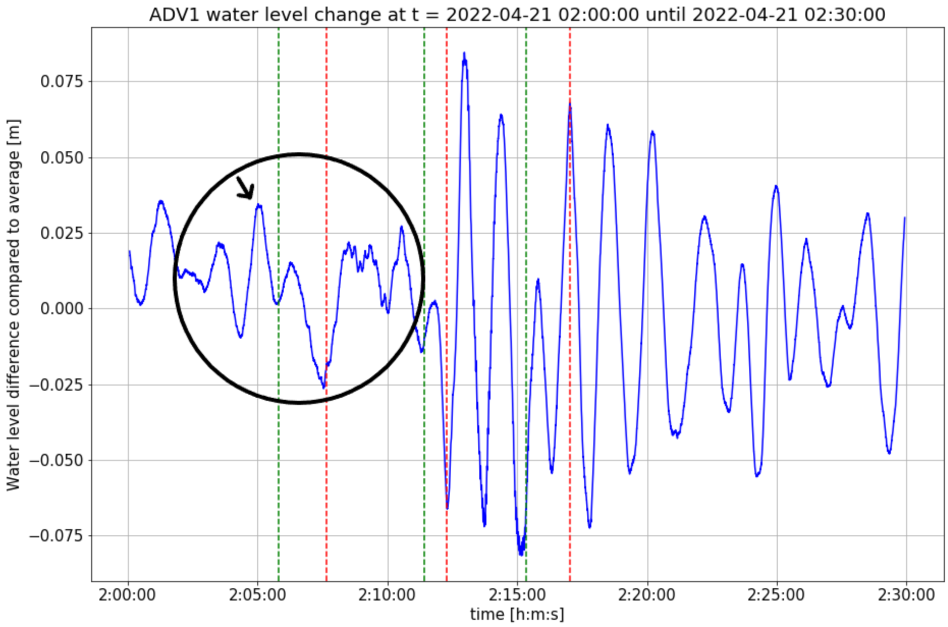

Figure B.2: Water level difference compared to the average water level at the location of ADV1 on the 21st of April from 02:00 until 02:30

	ADV1	ADV2	ADV4	ADV5
Closest point +/- 45 sec	0.093	0.083	0.094	0.103
Closest point +/- 60 sec	0.100	0.090	0.099	0.107
Closest point +/- 75 sec	0.105	0.095	0.101	0.107

Table B.3: Average water level difference for vessels where no vessel passes the groyne field in the ten minutes before and the five minutes after the measured vessel passes the measurement instrument in meters [m]

The interval where only the time between both groynes is taken into consideration does not take into account whether a vessel is sailing up- or downstream. When a vessel enters the groyne field, the interval starts. By investigating the results in table B.2, it is visible that the water level difference indeed increases when the interval is increased. The interval only selecting the period between the moment a vessel enters and leaves the groyne field gives unrealistic low results compared to the results in figure B.1. By increasing this interval, the results become increasingly realistic. By the moment the interval consists out of the moment a vessel enters and leaves the groyne field +/- 30 seconds the results give a good indication of the reality. When further increasing the interval duration, the problem described before, where multiple intervals overlay each other and the results become unrealistically large, appears. This can be seen by the results for vessel four which increases to a level of 0.180 meters while this large effect is likely created by vessel number three. The same can be said for the interval between in & out +/- 30 sec, since the water level difference of vessel four increases from 0.114 to 0.150 in that case. However, the effect of vessel three is not taken into account when the interval is smaller than in & out +/- 30 sec. To check whether the interval is large enough, the same filter applied in the previous section, where only the effect of a single vessel is taken into consideration, can also be applied to the in & out intervals. The results are visible in table B.4. It appears that the values again keep increasing the larger the interval. After investigating the figures, the same problem as described in figure B.2 occurs. It appears, therefore, that it is impossible to choose the perfect interval, but it is possible to choose the one which comes closest. Taking everything into consideration the in & out +/- 30 seconds interval is chosen to be the most accurate in & out interval for the water level difference.

	ADV1	ADV2	ADV4	ADV5
Between in & out	0.066	0.078	0.089	0.097
Between in & out +/- 10 sec	0.074	0.087	0.096	0.107
Between in & out +/- 20 sec	0.083	0.093	0.101	0.111
Between in & out +/- 30 sec	0.093	0.097	0.102	0.112
Between in & out +/- 40 sec	0.104	0.099	0.103	0.113
Between in & out +/- 60 sec	0.108	0.104	0.108	0.118

Table B.4: Average water level difference for vessels where no vessel passes the groyne field in the ten minutes before and the five minutes after the measured vessel passes the measurement instrument in meters [m]

To decide which interval will be used, both intervals have been used to calculate the water level difference for the entire dataset. The results are shown in table B.5. The results differ only several millimetres for each location. With the closest point +/- 60 seconds being larger at the locations of ADV1, ADV2 and ADV4, and being smaller for the location of ADV5. Since it is beneficial to keep the interval as small as possible and the interval 60 seconds before and after the closest point is 120 seconds long, while the other interval is on average 138 seconds, the first interval is preferred. As described before, this interval also takes into account whether a vessel is sailing up- or downstream. Therefore, this interval will be used for this research.

	ADV1	ADV2	ADV4	ADV5
Closest point +/- 60 sec	0.140	0.116	0.120	0.151
Between in & out +/- 30 sec	0.141	0.120	0.125	0.145

Table B.5: Measured average water level difference for the whole dataset period at all locations according to the different intervals in meters [m]

B.2 Flow velocity

The same approach to determine the best interval is used for the flow velocity. To investigate the influence of vessels on the flow velocity inside the groyne field, the maximum flow velocity caused by a vessel is of interest and not the difference between the lowest and highest velocity. This is because high flow velocities have a large effect on the sediment transport inside the groyne field and low velocities do not. In figure B.3 the flow velocity at the location of ADV1 from 00:00 until 00:30 on the 21st of April is visible. The green dotted lines indicate a vessel entering the area between the upstream and downstream groyne and the red dotted lines indicate a vessel leaving the area between the downstream and upstream groyne.

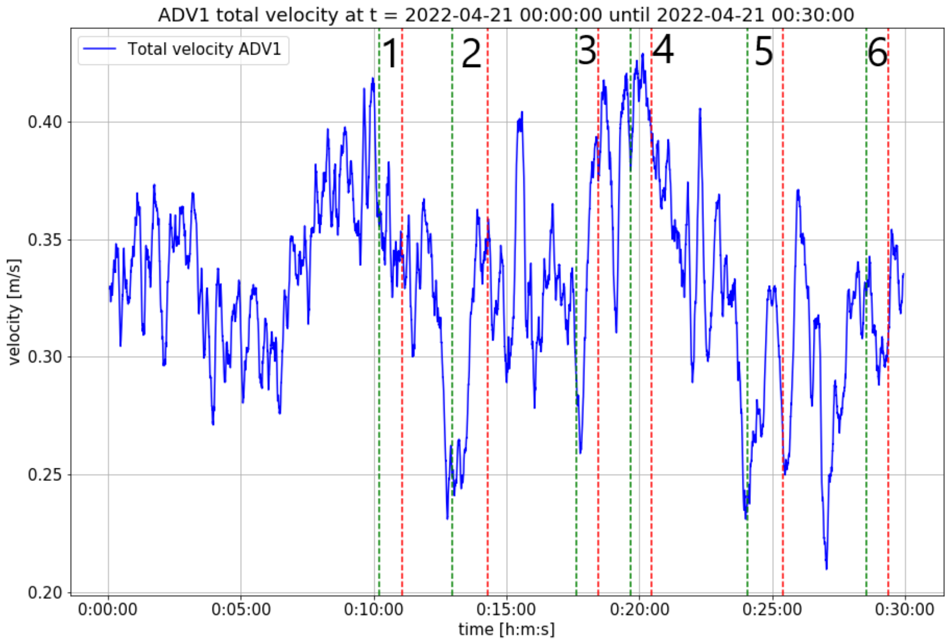

Figure B.3: Flow velocity at the location of ADV1 on the 21st of April from 00:00 until 00:30. The green dotted lines indicate the entrance of a vessel between the upstream and the downstream groyne, the red dotted lines a departure

In figure B.3 it is visible that the effect of a vessel on the flow velocity is less clear compared to the effect of a vessel on the water level difference. Besides an increase or decrease of the flow velocity inside the groyne field, vessels also create another effect, namely a change in the direction of the flow. This effect can be partly seen by the decrease in flow velocity when a vessel passes the groyne field. Nonetheless, the maximum flow velocity is the one which is more interesting. The average flow velocities at the 21st of April with the different intervals have been calculated and are visible in table B.6.

	ADV1	ADV2	ADV4	ADV5
Closest point +/- 45 sec	0.416	0.514	0.475	0.159
Closest point +/- 60 sec	0.424	0.525	0.483	0.164
Closest point +/- 75 sec	0.430	0.532	0.490	0.168
Between in & out	0.402	0.516	0.473	0.154
Between in & out +/- 10 sec	0.420	0.521	0.479	0.157
Between in & out +/- 20 sec	0.427	0.525	0.484	0.161
Between in & out +/- 30 sec	0.432	0.531	0.488	0.164
Between in & out +/- 40 sec	0.436	0.535	0.494	0.167
Between in & out +/- 60 sec	0.441	0.542	0.503	0.171

Table B.6: Average maximum flow velocity according to the different intervals at all locations on the 21st of April in meters per second [m/s]

The used intervals are the same as the intervals in the previous section for the water level difference. An increase in the interval range results in an increase of the maximum flow velocity as expected. In figure B.3 the six vessels passing the groyne field have again been numbered. In table B.7 the results for the maximum velocity for each vessel have been noted.

	Vessel 1	Vessel 2	Vessel 3	Vessel 4	Vessel 5	Vessel 6
Closest point +/- 45 sec	0.383	0.363	0.418	0.429	0.330	0.354
Closest point +/- 60 sec	0.418	0.363	0.418	0.429	0.333	0.354
Closest point +/- 75 sec	0.419	0.363	0.421	0.429	0.343	0.354
Between in & out	0.383	0.363	0.394	0.429	0.330	0.343
Between in & out +/- 10 sec	0.383	0.363	0.418	0.429	0.330	0.354
Between in & out +/- 20 sec	0.419	0.363	0.418	0.429	0.330	0.354
Between in & out +/- 30 sec	0.419	0.363	0.418	0.429	0.371	0.354
Between in & out +/- 40 sec	0.419	0.363	0.418	0.429	0.371	0.354
Between in & out +/- 60 sec	0.419	0.363	0.420	0.429	0.371	0.354

Table B.7: Measured water maximum flow velocity of the different vessels visible in figure B.3 according to all intervals in meters per second [m/s]

The closest point interval with the 45, 60 and 75 seconds delta before and after the closest point has again the advantage that it takes into account whether a vessel is sailing up- or downstream. It can be seen in table B.7 that the maximum velocity is reached relatively quickly. The closest point +/- 45 seconds interval gives the lowest results of the three looking at table B.7. The +/- 60 seconds delta gives only a larger value for vessel 1 while the +/- 75 seconds interval gives slightly higher results for vessels 1, 3 and 5. To determine whether the interval is large enough, the maximum velocity for the vessels where ten minutes before arrival no vessels are present and in the five minutes after arrival also no vessels are present can be measured. This is the same filter applied for the water level difference. In table B.8 the results are visible. It can be seen that the results between the different interval sizes differ very minor. It can be seen that at the location of ADV1 the maximum is reached with an interval delta of 60 seconds, at the location of ADV2 no maximum is reached, at the location of ADV4 the maximum is reached with a delta of 45 seconds and at the location of ADV5 the maximum is almost reached with a delta of 60 seconds. Taking all this into consideration, the closest point +/- 60 seconds interval has been chosen to be the best fit.

	ADV1	ADV2	ADV4	ADV5
Closest point +/- 45 sec	0.368	0.493	0.490	0.123
Closest point +/- 60 sec	0.371	0.498	0.490	0.128
Closest point +/- 75 sec	0.371	0.503	0.492	0.129

Table B.8: Average maximum flow velocities for vessels where no vessel passes the groyne field in the ten minutes before and the five minutes after the measured vessel passes the measurement instrument in meters per second [m/s]

The difference in & out intervals will be investigated next. By investigating the results in table B.7, the results are again comparable. By looking at the results in figure B.3 and comparing those with the results in the table, the results of the in & out +/- 20 seconds interval seem to be the most realistic. In table B.9 the results are shown again after applying the no vessel ten minutes before and five minutes after filter. The results do not seem to reach a maximum again. A reason for this can be that there are vessels taken into account which have a very minor influence on the flow velocity. Due to this, the flow velocity before or after the vessel has passed is larger than the actual effect of the vessel, resulting in unrealistic values. Taking into account that the interval should not be too large since the maximum velocity is reached more quickly compared to the water level difference and comparing the results of table B.7 to the results in figure B.3, the interval between in & out +/- 20 seconds has been to chosen to be the best fit.

	ADV1	ADV2	ADV4	ADV5
Between in & out	0.357	0.494	0.476	0.125
Between in & out +/- 10 sec	0.369	0.494	0.477	0.128
Between in & out +/- 20 sec	0.380	0.496	0.477	0.130
Between in & out +/- 30 sec	0.380	0.500	0.481	0.131
Between in & out +/- 40 sec	0.381	0.504	0.485	0.132
Between in & out +/- 60 sec	0.389	0.513	0.488	0.134

Table B.9: Average maximum flow velocities for vessels where no vessel passes the groyne field in the ten minutes before and the five minutes after the measured vessel passes the measurement instrument in meters per second [m/s]

To determine which interval will be used, both intervals have been used to compute the maximum flow velocity at all locations for the whole dataset. The results are visible in table B.10. The average measured maximum velocity differs only one or two millimetres between both intervals. The average interval time for both intervals is comparable. 120 seconds for the closest point +/- 60 seconds and 118 seconds for the in & out +/- 20 seconds. The deciding factor, therefore, is the ability of the closest point +/- 60 seconds interval to know whether the vessel is sailing upstream or downstream. Therefore, this interval will be used for this research.

	ADV1	ADV2	ADV4	ADV5
Closest point +/- 60 sec	0.427	0.537	0.508	0.169
Between in & out +/- 20 sec	0.428	0.539	0.510	0.168

Table B.10: Measured average maximum flow velocity for the whole dataset period at all locations according to the different intervals in meters per second [m/s]

C
Drawdown caused by vessels

In this section, the drawdown caused by vessels in a channel is investigated. When a vessel sails through a channel, the streamlines around the vessel change. The water is pushed up in front of the bow first. This causes a high-pressure zone in front of the vessel. At the back of the vessel, at the same time, a low-pressure zone is created since the vessel creates a void in the water's surface. Due to this low-pressure zone, the water flows towards this low-pressure zone from all directions filling the void. Besides these high- and low-pressure zones, also the propeller underneath the vessel guides the water in the opposite direction compared to the vessel's direction. All these factors accelerate the flow around the vessel causing an increase in kinetic energy and a decrease in potential energy inside the water. This decrease in potential energy is visible in the form of a decrease in the water level around the vessel, the drawdown(Das et al., 2012).

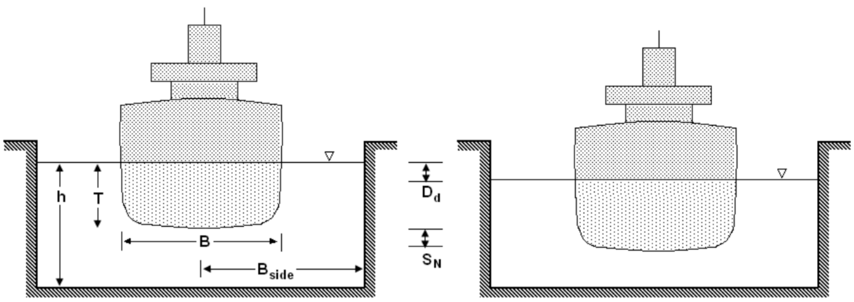

Figure C.1: Vessel in still water (left) and a moving vessel (right) with drawdown as Dd and squat as Sn (Das et al., 2012)

The drawdown is the largest closest to the vessel and decreases if the distance between the bank and the vessel increases. Currently, multiple drawdown formulas exist. Hochstein and Adams derived the following maximum drawdown formula from Bernoulli's equation.

$$\begin{aligned} D_d &= \gamma V_s^2 (a-1) \frac{W_c}{2g} \\ a &= \left(\frac{n}{n-1}\right)^{2.5} \\ n &= \frac{A_c}{A_s} \end{aligned} \tag{C.1}$$

With γ an empirical constant, n the blockage ratio, g the acceleration due to gravity, A_c the cross-sectional area of the channel, A_s the submerged area of the vessel, W_c the surface width of the channel and V_s the speed of the vessel with respect to the flow (Das et al., 2012).

Gelencser gave the following formula based on prototype and model results, with y the distance from the sailing line and L the length of the vessel:

$$D_d = 2 * 10^{-6} \left[\left(\frac{V_s^2 A_s L^2}{y\sqrt{A_c}} \right)^{1/3} \right]^{2.8} \tag{C.2}$$

The final formula presented is from Dand and White and is based on scaled ship model experiments:

$$D_d = 8.8 \left(\frac{A_c}{A_s} \right)^{-1.4} \left(\frac{V_s^2}{2g} \right) \tag{C.3}$$

Currently, there are even more formulas to calculate the drawdown caused by a vessel. In figure C.2 some other formulas and their input parameters are shown. It is visible that the vessel speed, the hydraulic mean depth, the ship cross-section, the waterway cross-section, the gravitational acceleration, the length of the vessel and the distance to the ship-shoreline are important parameters affecting the drawdown.

Author(s)	V	r	A_S	A_C	g	L	d	D	T	h	C_B
Schijf (1949)	•	•	•	•	•						
Gelencser (1977)	•		•	•		•	•				
Dand and White (1978)	•		•	•	•						
Bhowmik et al. (1981)	•		•	•	•	•	•				
Hochstein (1967)	•	•	•	•	•						
Maynord (1996)	•	•	•	•	•		•		•		
Kriebel and Seelig (2002)	•				•	•				•	•
CIRIA (2007)	•	•	•	•	•				•		

V: Ship speed
r: hydraulic mean-depth
A_S: Ship cross-section
A_C: Waterway cross-section
g: Gravitational acceleration
L: Ship length
d: Distance ship-shoreline
D: Ship draft
T: Waterway top
h: Water-depth
C_B: Ship-block coefficient

Figure C.2: Drawdown formulas and their input parameters (Dempwolff et al., 2022)

D

Relation between parameters

According to the drawdown analysis in Appendix C, the drawdown depends on multiple parameters. In this research, the influence of several parameters on the flow inside the groyne field is investigated. These parameters can be correlated to each other, meaning that changing the value of a single parameter result in the change of a different parameter. To be able to investigate the effect of a single parameter, it is important to know whether it is likely that this parameter will also influence another parameter. Therefore, in this section, the relation between all parameters is investigated. The parameters taken into consideration in this section are the length of the vessel, the width of the vessel, the draught of the vessel and the speed of the vessel.

D.1 Pearson's correlation coefficient

To investigate the relationship between two variables, Pearson's correlation coefficient is used. This correlation factor measures how strong the relationship is between two variables in the form of a number between -1 and 1. A correlation coefficient of -1 Indicates that there is a strong negative relationship, a correlation coefficient of 1 a strong positive relationship and a correlation coefficient of 0 no relationship at all. It is important to note that this method assumes a linear relationship between each other. This linear relation can be seen by plotting both variables and checking whether it is possible to draw a linear line through the data which represents the data accurately. After inspecting the results, the data does not seem to have a non-linear relation. The formula to calculate the correlation coefficient is visible in equation (D.1) with x and y representing both variables and n the number of data points taken into consideration.

$$r = \frac{n(\sum xy) - (\sum x)(\sum y)}{\sqrt{[n(\sum x^2) - (\sum x)^2][n(\sum y^2) - (\sum (y)^2]}} \tag{D.1}$$

To determine the relationship between both parameters, the correlation coefficient indicates how strong the relationship is. Therefore, the following relationship interpretations are used:

Value of correlation coefficient	relationship interpretation
0.000 - 0.199	very weak
0.200 - 0.399	weak
0.400 - 0.599	moderate
0.600 - 0.799	strong
0.800 - 1.000	very strong

Table D.1: Relationship classifications

Before really interpreting that there is a relationship between two variables, it should be investigated whether this relationship is realistic. It could be that two variables show a certain relationship with each other while in reality there is actually no sense that these variables have a correlation with each other.

D.2 Results

In this section, the results of the relationship between all variables are shown. Since there are four variables taken into consideration, six different combinations can be made. Each combination will be plotted and the correlation coefficient calculated.

Length vs width

First, the length vs width is plotted in figure D.1. The red line indicates the linear regression line which minimises the squared error. The correlation coefficient is 0.722 indicating a strong relationship between the two variables. This relationship is realistic since a larger vessel length also results in a larger vessel width in reality.

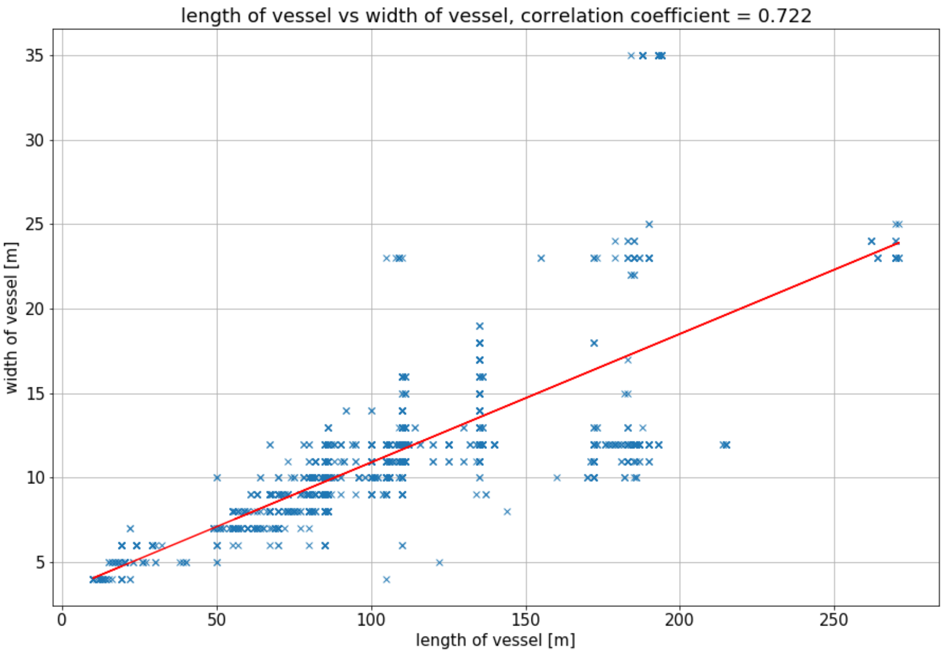

Figure D.1: Length of the vessel versus width of the vessel, correlation coefficient = 0.722

Length vs draught

Second, the length versus the draught of the vessel is plotted in figure D.2. In this figure, it is clear that it is harder to plot a straight line throughout the data which represents the data accurately. The correlation coefficient is calculated to be equal to 0.232, indicating a weak relation between the two variables.

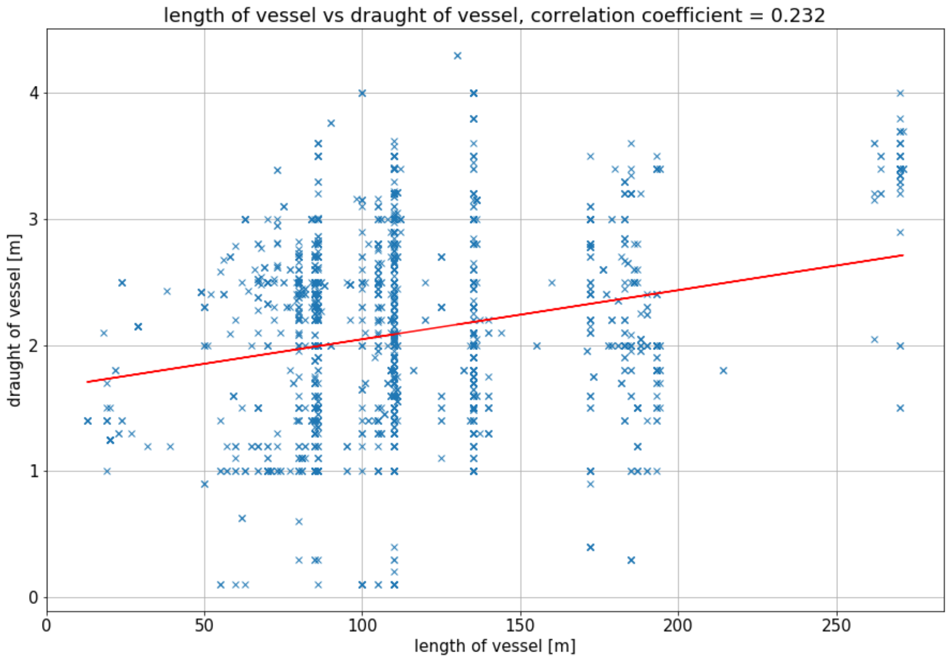

Figure D.2: Length of the vessel versus draught of the vessel, correlation coefficient = 0.232

Length vs speed

Third, the length versus the speed of the vessel is plotted in figure D.3. The red line shows a small decrease when the length of the vessel increases. The correlation coefficient is calculated to be equal to -0.227, indicating a weak relation between the two variables.

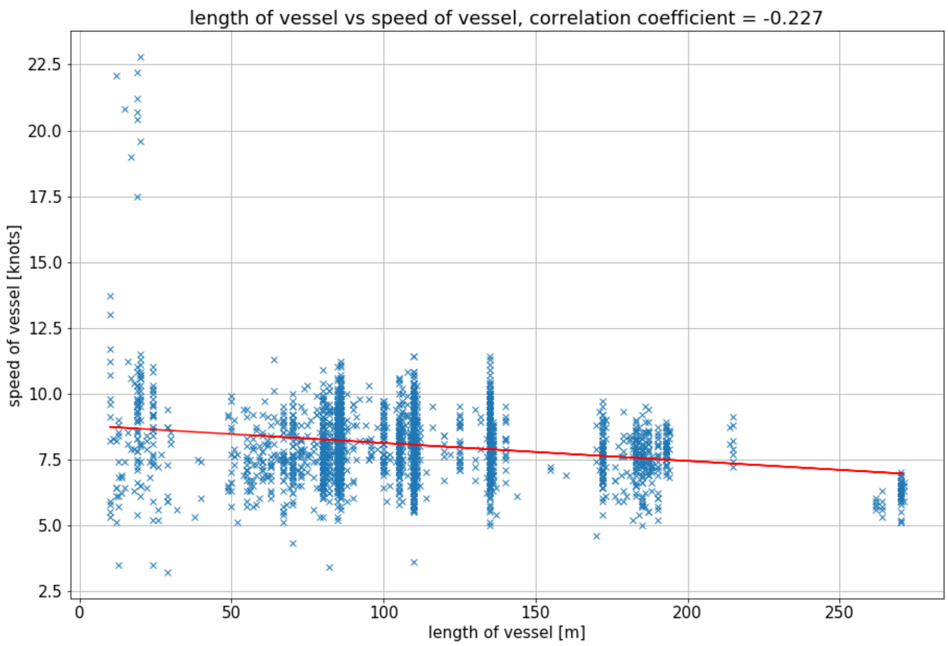

Figure D.3: Length of the vessel versus speed of the vessel, correlation coefficient = -0.227

Width vs draught

Fourth, the width versus the draught is plotted in figure D.4. The correlation coefficient is calculated to be equal to 0.167, indicating a very weak relationship between the two variables.

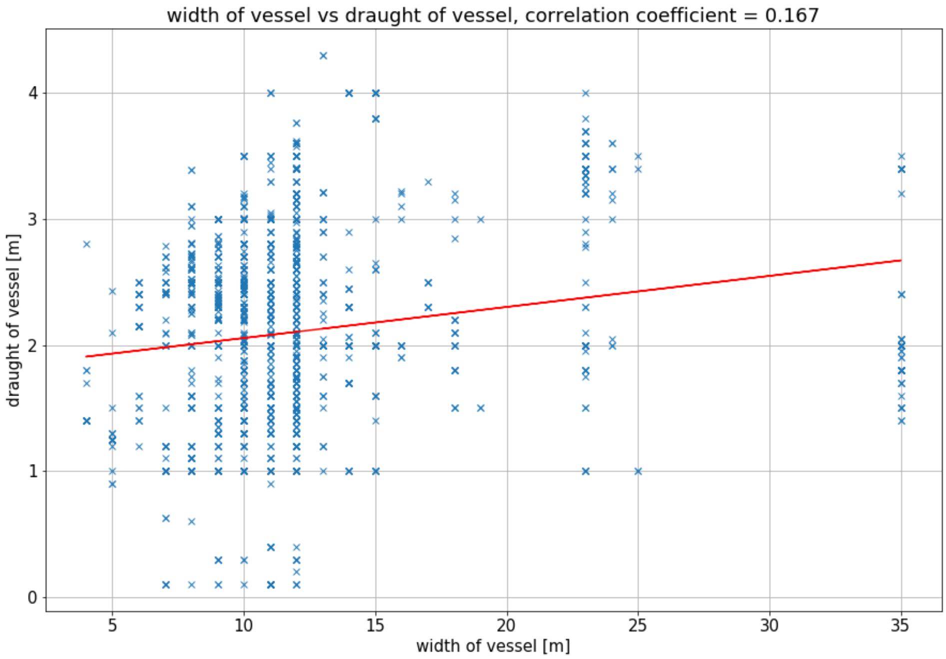

Figure D.4: Width of the vessel versus draught of the vessel, correlation coefficient = 0.167

Width vs speed

Fifth, the width versus the speed is plotted in figure D.5. The correlation coefficient is calculated to be equal to -0.160, indicating a very weak relationship between the two variables.

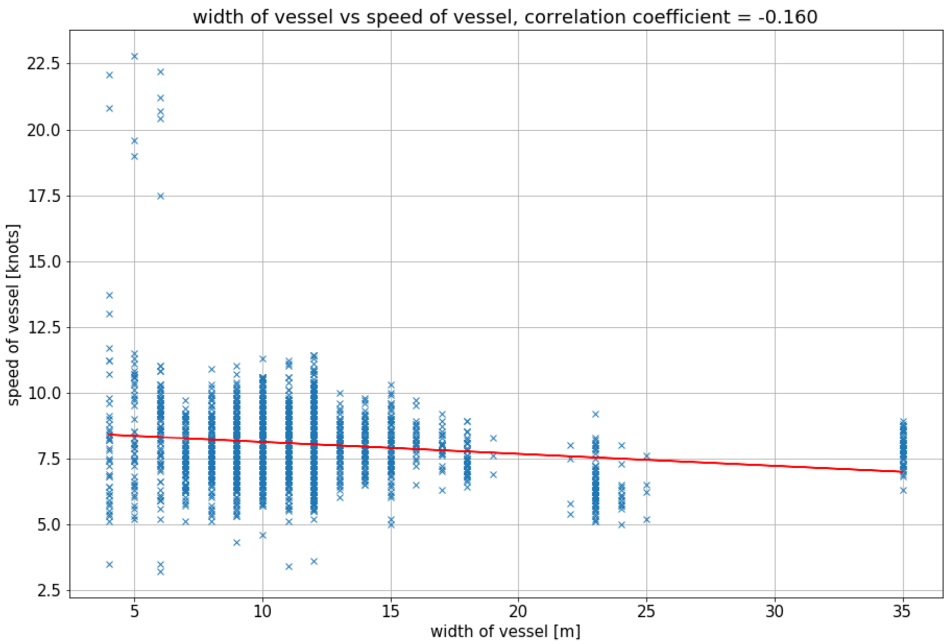

Figure D.5: Width of the vessel versus speed of the vessel, correlation coefficient = -0.160

Draught vs speed

Finally, the draught versus the speed of the vessel is plotted in figure D.6. The correlation coefficient is calculated to be equal to -0.123, indicating a very weak relationship.

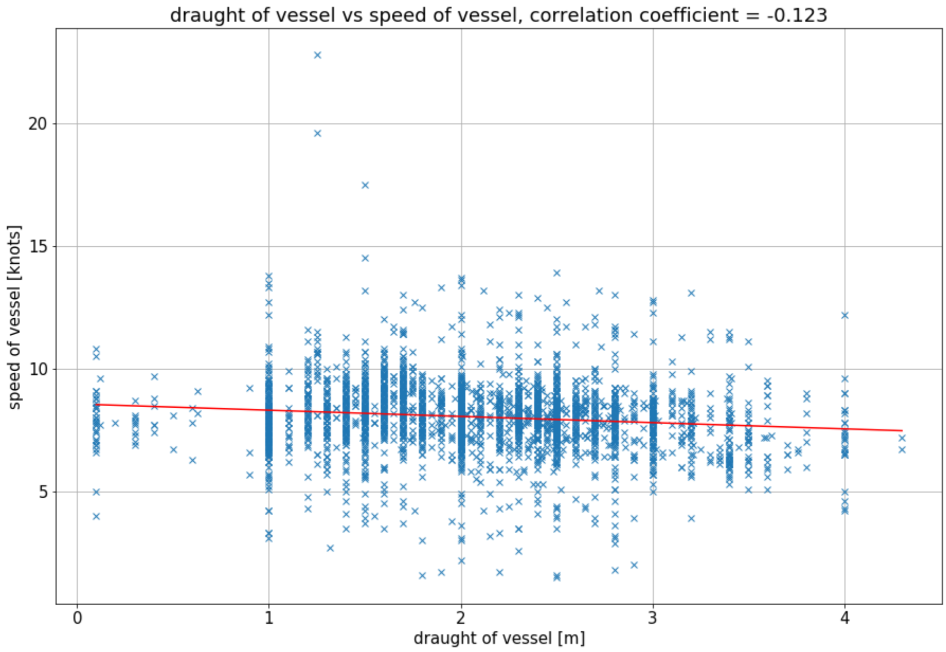

Figure D.6: Draught of the vessel versus speed of the vessel, correlation coefficient = -0.123

Overall results

The results are summarised in table D.2. The only two parameters showing a strong relationship are the length and the width. This is to be expected since the larger the length of a vessel, the larger the width has to be to remain stable. All the other parameters show a weak or very weak relationship with each other.

	length	width	draught	speed
length	1.0			
width	0.722	1.0		
draught	0.232	0.167	1.0	
speed	-0.227	-0.160	-0.123	1.0

Table D.2: Relationship coefficients

E

Vessel characteristics results

E.1 Water level change explanation

ADV2

In this section, the influence of the draught, sailing speed, distance to the measurement instrument, vessel length and vessel width on the water level at the location of ADV2 is investigated. The exact location of ADV2 is visible in figure 3.2. For this location, 425 vessel movements were registered taking into consideration a 10-minute interval after the previous vessel has passed the groyne field. In each figure, a black dashed line is present at a level of 0.03 meters. This dashed black line indicates the continuous water level difference present inside the groyne field when no vessel sails past the groyne field.

Draught

The draught versus the water level difference is plotted in figure E.3. The percentile lines are calculated by taking horizontal intervals of 0.5 meters from 0.75 to 3.75 meters.

According to the hypothesis, the water level difference should increase when the draught is increasing due to an increase in the underwater area of the vessel. The percentile lines, however, do not show an increasing pattern. The 50 % percentile line shows a horizontal pattern while the 90% percentile line even shows a decreasing pattern.

Sailing speed

The sailing speed versus the water level difference is plotted in figure E.4. The percentile lines are calculated by taking horizontal intervals of 0.5 knots from 6.0 to 10.5 knots.

According to the hypothesis, the water level difference should increase when the sailing speed is increasing. The percentile lines also show an increasing pattern. The 50% percentile line shows a slightly increasing pattern while the 90% percentile line shows a steeper slope, indicating that the more extreme values are more likely to occur when the sailing speed is high. At a sailing speed of 6.5 knots, a peak in the percentile lines is visible. This is probably due to the low amount of data points in that certain percentile interval.

Distance to measurement instrument

The distance to the measurement instrument versus the water level difference is plotted in figure E.5. The percentile lines are calculated by taking horizontal intervals of 25 meters from 100 to 250 meters. The vertical black dotted line indicates the minimum distance to the measurement instrument. If the distance would be smaller than 100 meters the vessel would be sailing inside the groyne field.

According to the hypothesis, the water level difference should increase when the distance towards the measurement instrument decreases. The percentile lines show an increasing pattern. The expected results show a comparable slope.

Length of the vessel

The length and the width of the vessel are strongly correlated to each other. To investigate the effect of the length of vessels on the water level difference, the width is kept constant. In figure E.6 the effect of the length on the water level difference for vessels with a width of twelve meters is plotted. As a result, the amount of data points has been reduced to 193. The percentile lines are calculated by taking horizontal intervals of 25 meters from 75 to 150 meters.

According to the hypothesis, an increase in the length of a vessel should result in an increase in the water level difference. The 50% percentile line shows a very minor increasing pattern. The 90% percentile line also shows a minor increasing pattern.

In figure E.7 the vessel length versus water level difference is plotted for the whole data set. The percentile lines are calculated by taking horizontal intervals of 25 meters from 50 to 150 meters. In this figure, the percentile lines show a more clear increasing pattern.

Width of the vessel

As stated before, the width and the length of a vessel are strongly related to each other. To investigate the effect of the width of a vessel on the water level difference, the length is kept between a certain interval. In this case between 110 and 135 meters. This is done to keep sufficient data points. The total amount of data points is now 216. The results are plotted in figure E.8. The percentile lines are calculated by taking horizontal intervals of 2.5 meters from 10 to 17.5 meters.

According to the hypothesis, an increase in width should result in an increase of the water level difference. The percentile lines show an increasing pattern similar to the expected result.

In figure E.9 the width versus the water level difference has been plotted for the whole data set. The percentile lines are calculated by taking horizontal intervals of 2.5 meters from 5.0 to 17.5 meters. The percentile lines show again an increasing pattern.

ADV4

In this section, the influence of the draught, sailing speed, distance to the measurement instrument, vessel length and vessel width on the water level at the location of ADV4 is investigated. The exact location of ADV4 is visible in figure 3.2. At this location, 449 vessel movements were registered taking into consideration a 10-minute interval after the previous vessel has passed the groyne field. In each figure, a black dashed line is present at a level of 0.04 meters. This dashed black line indicates the continuous water level difference present inside the groyne field when no vessel sails past the groyne field.

Draught

The draught versus the water level difference is plotted in figure E.10. The percentile lines are calculated by taking horizontal intervals of 0.5 meters from 0.75 to 3.75 meters.

According to the hypothesis, the water level difference should increase when the draught is increasing due to an increase in the underwater area of the vessel. The percentile lines, however, do not show an increasing pattern. The 50 % percentile line shows a horizontal pattern while the 90% percentile line even shows a decreasing pattern.

Sailing speed

The sailing speed versus the water level difference is plotted in figure E.11. The percentile lines are calculated by taking horizontal intervals of 0.5 knots from 6.0 to 10.5 knots.

According to the hypothesis the water level difference should increase when the sailing speed is increasing. The percentile lines agree with this hypothesis. The 50% percentile line shows an increasing pattern while the 90% percentile line shows an even steeper pattern. The 90% percentile line has almost the same slope as the expected results according to the existing formulas.

Distance to measurement instrument

The distance to the measurement instrument versus the water level difference is plotted in figure E.12. The percentile lines are calculated by taking horizontal intervals of 25 meters from 100 to 250 meters. The vertical black dotted line indicates the minimum distance towards the measurement instrument. If the distance would be smaller than 80 meters the vessel would be sailing inside the groyne field.

According to the hypothesis, the water level difference should increase when the distance towards the measurement instrument decreases. The percentile lines show a very minor increase in water level when the distance decreases. The measured effect is also less compared to the expected results according to the formula of Gelencser.

Length of the vessel

The length and the width of the vessel are strongly correlated with each other. To investigate the effect of the length of vessels on the water level difference, the width has to be kept constant. In figure E.13 the effect of the length on the water level difference for vessels with a width of twelve meters is plotted. By doing this, the amount of data points has been reduced to 200. The percentile lines are calculated by taking horizontal intervals of 25 meters from 75 to 150 meters.

According to the hypothesis, an increase in the length of a vessel should result in an increase in the water level difference. The 50% percentile line shows a small increasing pattern. The 90% percentile line shows a horizontal pattern. This is, however, probably due to a low amount of data points in the first percentile interval.

In figure E.14 the vessel length versus water level difference is plotted for the whole data set. The percentile lines are calculated by taking horizontal intervals of 25 meters from 50 to 150 meters. In this figure, the percentile lines do show a clear increasing pattern.

Width of the vessel

As stated before, the width and the length of a vessel are strongly related to each other. To investigate the effect of the width of a vessel on the water level difference, the length is kept between a certain interval. In this case between 110 and 135 meters. This is done to keep sufficient data points. The total amount of data points is now 222. The results are plotted in figure E.15. The percentile lines are calculated by taking horizontal intervals of 2.5 meters from 10 to 17.5 meters.

According to the hypothesis, an increase in the width should result in an increase in the water level difference. The percentile lines show an increasing pattern similar to that of the expected result.

In figure E.16 the width versus the water level difference has been plotted for the whole data set. The percentile lines are calculated by taking horizontal intervals of 2.5 meters from 5.0 to 17.5 meters. The percentile lines show again an increasing pattern.

ADV5

In this section, the influence of the draught, sailing speed, distance to the measurement instrument, vessel length and vessel width on the water level at the location of ADV5 is investigated. The exact location of ADV5 is visible in figure 3.2. At this location, 447 vessel movements were registered taking into consideration a 10-minute interval after the previous vessel has passed the groyne field. In each figure, a black dashed line is present at a level of 0.06 meters. This dashed black line indicates the continuous water level difference present inside the groyne field when no vessel sails past the groyne field.

Draught

The draught versus the water level difference is plotted in figure E.17. The percentile lines are calculated by taking horizontal intervals of 0.5 meters from 0.75 to 3.75 meters.

According to the hypothesis, the water level difference should increase when the draught is increasing due to an increase in the underwater area of the vessel. The percentile lines, however, do not show an increasing pattern. The 50 % percentile line and the 90% percentile line show a horizontal pattern, indicating no significant increase in the water level due to an increase in the draught.

Sailing speed

The sailing speed versus the water level difference is plotted in figure E.18. The percentile lines are calculated by taking horizontal intervals of 0.5 knots from 6.0 to 10.5 knots.

According to the hypothesis, the water level difference should increase when the sailing speed is increasing. The percentile lines agree with this hypothesis. The 50% percentile line shows an increasing pattern while the 90% percentile line shows an even steeper pattern. The 90% percentile line becomes very steep when the sailing speed increases. This is probably due to a reduction in the number of data points in that interval. The pattern of the 90% percentile line is comparable to that of the expected results according to the existing formulas.

Distance to measurement instrument

The distance to the measurement instrument versus the water level difference is plotted in figure E.19. The percentile lines are calculated by taking horizontal intervals of 25 meters from 100 to 250 meters. The vertical black dotted line indicates the minimum distance towards the measurement instrument. If the distance would be smaller than 100 meters the vessel would be sailing inside the groyne field.

According to the hypothesis the water level difference should increase when the distance towards the measurement instrument decreases. The 50% percentile line shows a horizontal pattern. The 90% percentile does however show an increasing pattern. It should be noted, however, that this is likely due to a low amount of data points in that certain interval.

Length of the vessel

The length and the width of the vessel are strongly correlated with each other. To investigate the effect of the length of vessels on the water level difference, the width has to be kept constant. In figure E.20 the effect of the length on the water level difference for vessels with a width of twelve meters is plotted. By doing this, the amount of data points has been reduced to 201. The percentile lines are calculated by taking horizontal intervals of 25 meters from 75 to 150 meters.

According to the hypothesis, an increase in the length of a vessel should result in an increase in the water level difference. The 50% percentile line shows a small increasing pattern. The 90% percentile line shows a decreasing pattern. This is, however, due to a low amount of data points in the first percentile interval.

In figure E.21 the vessel length versus water level difference is plotted for the whole data set. The percentile lines are calculated by taking horizontal intervals of 25 meters from 50 to 150 meters. In this figure, the percentile lines do show a clear increasing pattern.

Width of the vessel

As stated before, the width and the length of a vessel are strongly related to each other. To investigate the effect of the width of a vessel on the water level difference, the length is kept between a certain interval. In this case between 110 and 135 meters. This is done to keep sufficient data points. The total amount of data points is now 231. The results are plotted in figure E.22. The percentile lines are calculated by taking horizontal intervals of 2.5 meters from 10 to 17.5 meters.

According to the hypothesis, an increase in the width should result in an increase in the water level difference. The percentile lines show an increasing pattern similar to that of the expected result.

In figure E.23 the width versus the water level difference has been plotted for the whole data set. The percentile lines are calculated by taking horizontal intervals of 2.5 meters from 5.0 to 17.5 meters. The percentile lines show an increasing pattern.

E.2 Water level change figures

ADV1

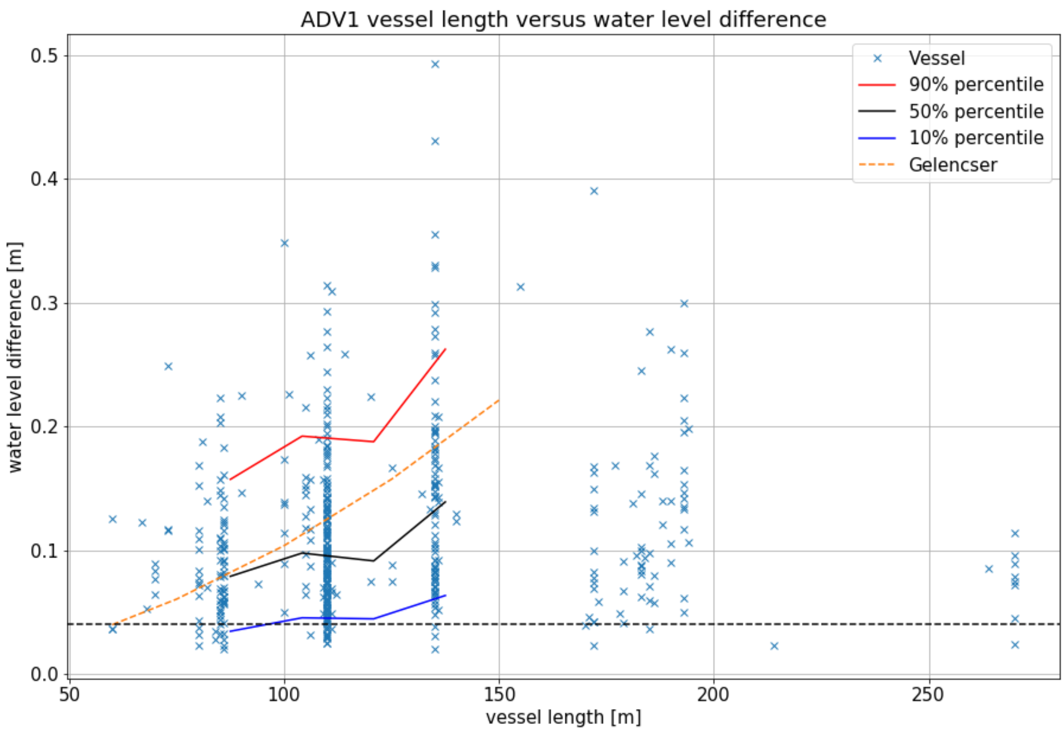

Figure E.1: ADV1 vessel length versus water level difference results with expected results according to formulas

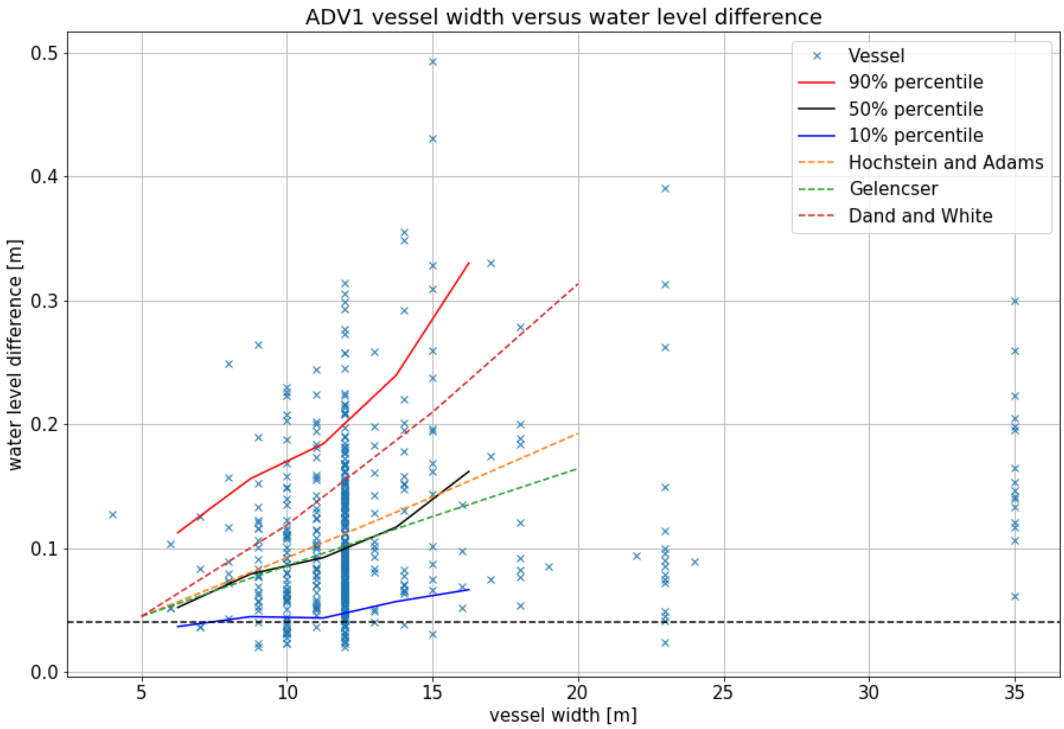

Figure E.2: ADV1 vessel width versus water level difference results with expected results according to formulas

ADV2

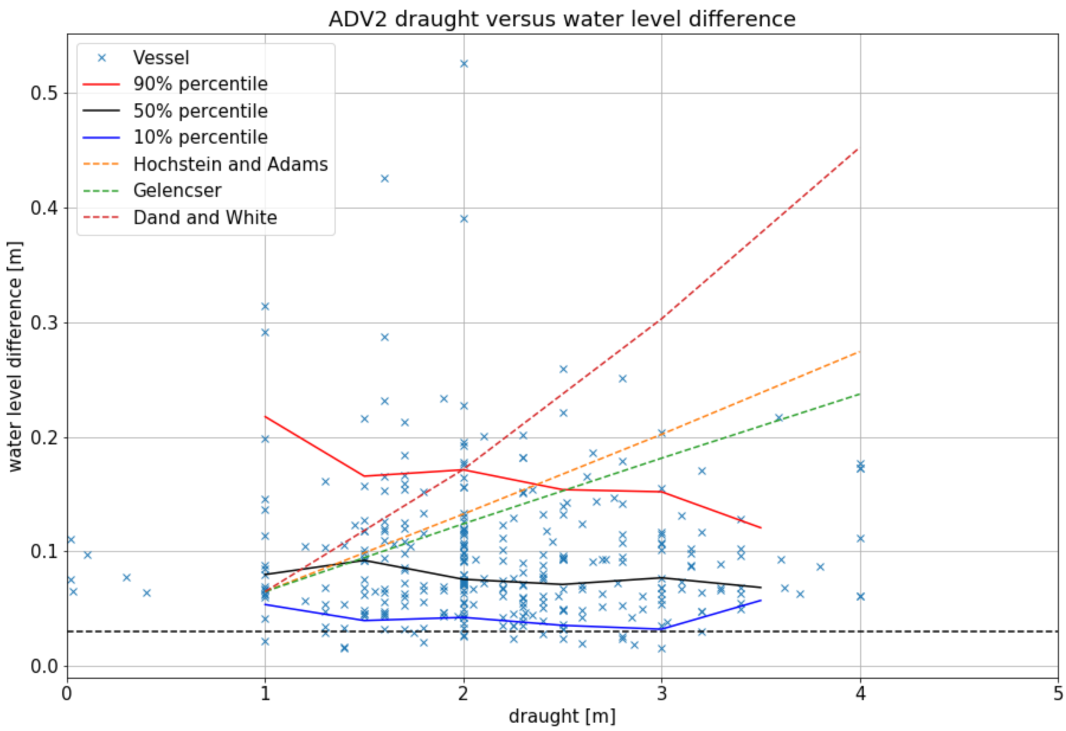

Figure E.3: ADV2 draught versus water level difference results with expected results according to formulas

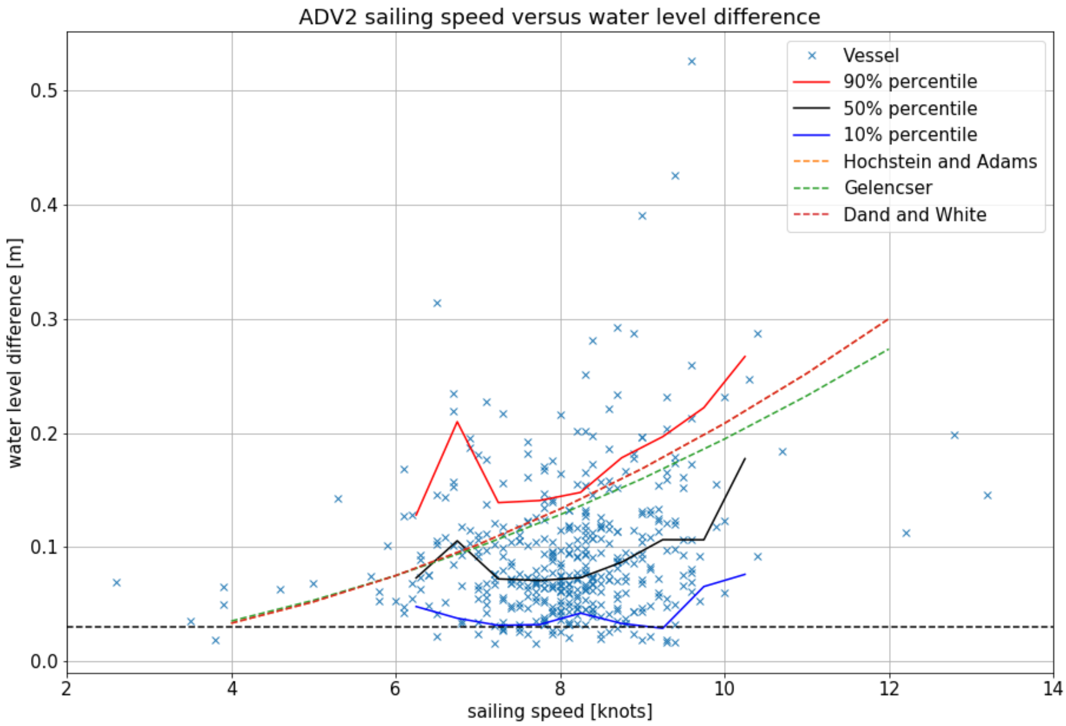

Figure E.4: ADV2 sailing speed versus water level difference results with expected results according to formulas

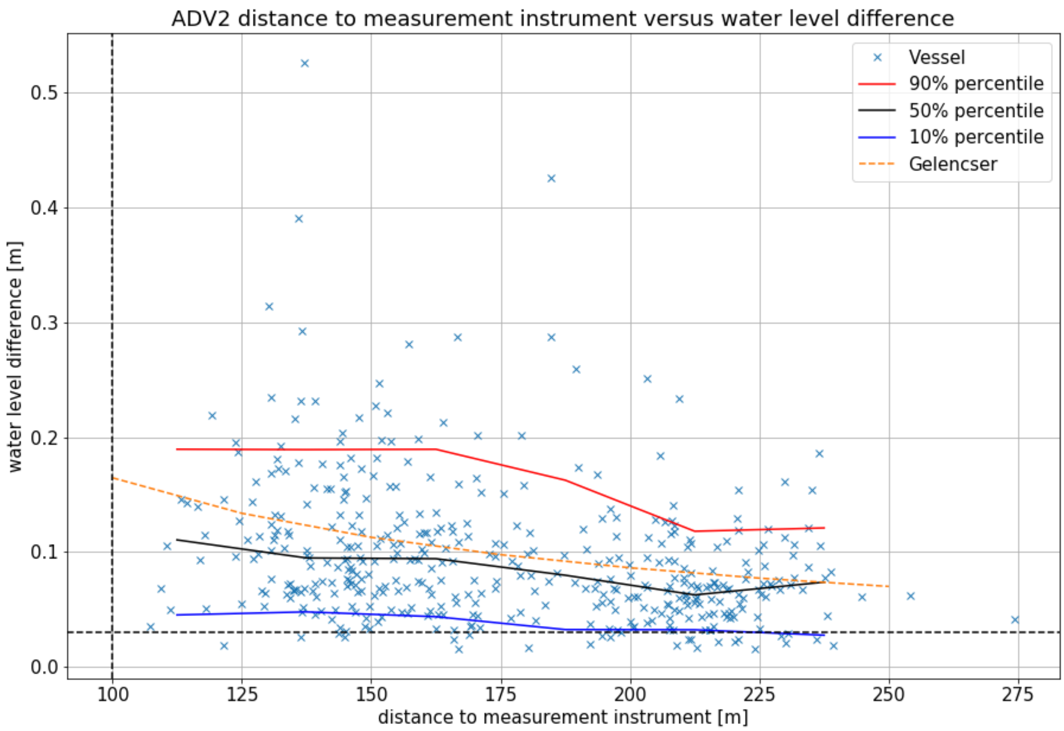

Figure E.5: ADV2 distance to measurement instrument versus water level difference results with expected results according to formulas

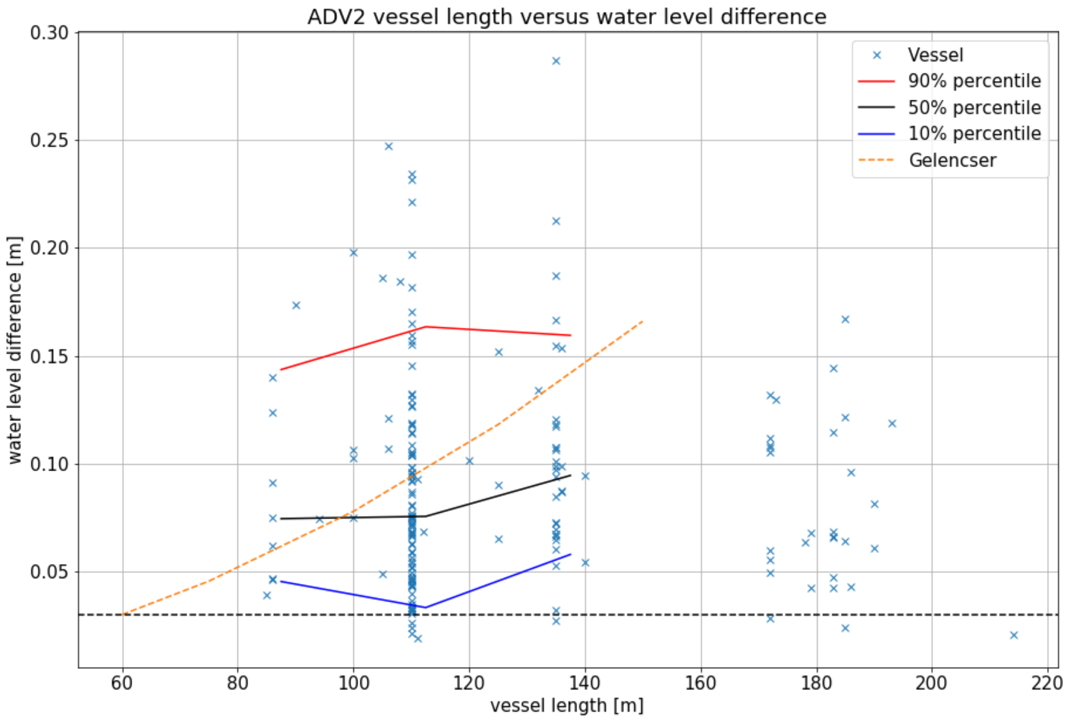

Figure E.6: ADV2 vessel length versus water level difference results for vessels with a width of 12 meters. Including expected results according to formulas

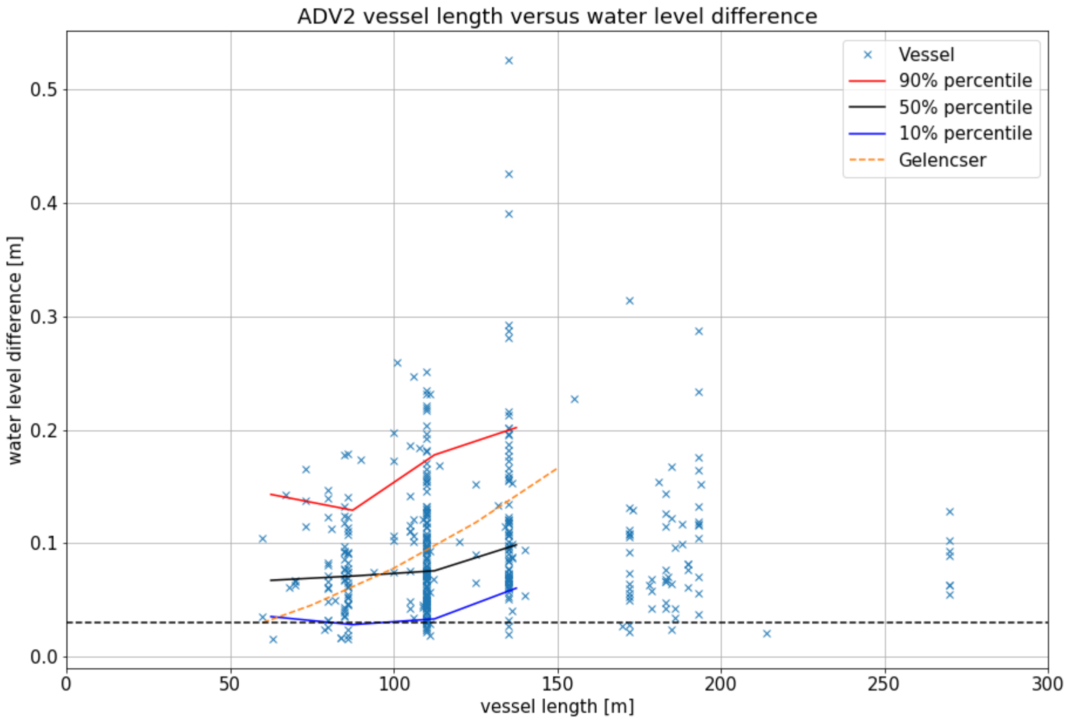

Figure E.7: ADV2 vessel length versus water level difference results with expected results according to formulas

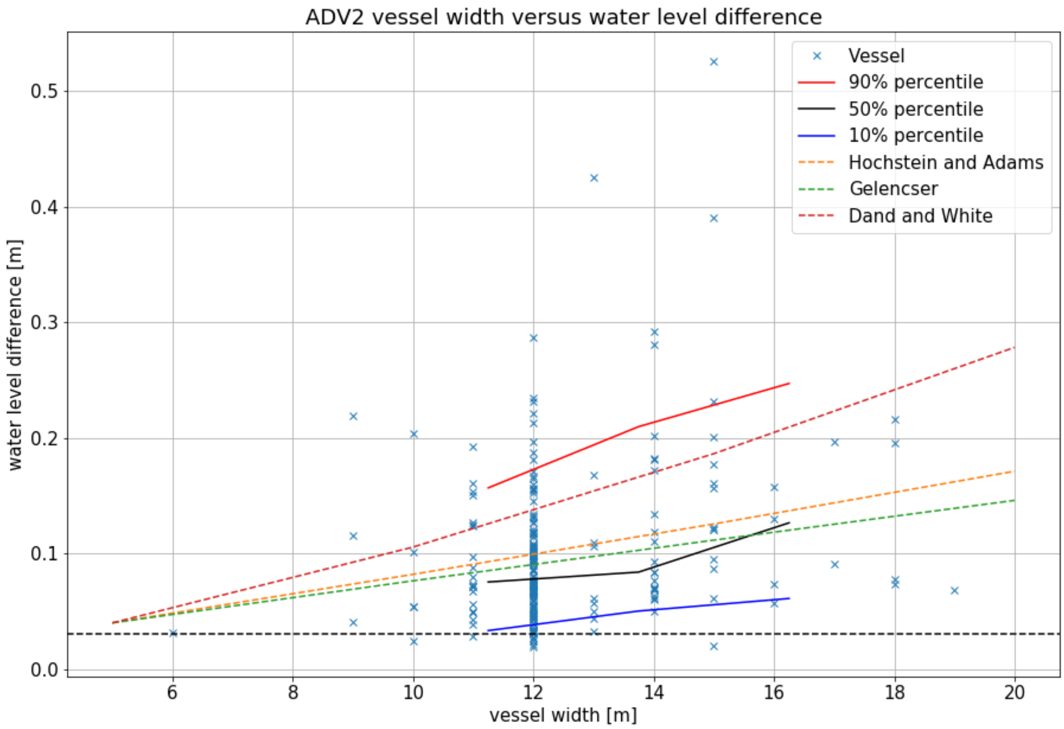

Figure E.8: ADV2 vessel width versus water level difference results for vessels with a length between 110 and 135 meters. Including expected results according to formulas

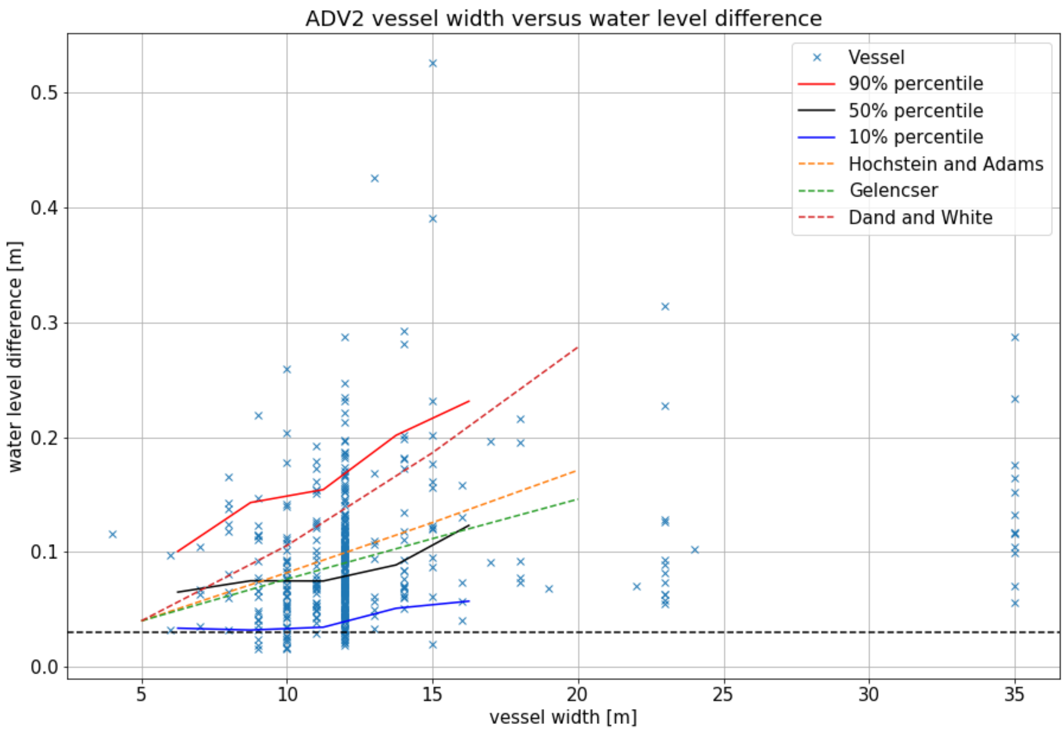

Figure E.9: ADV2 vessel width versus water level difference results with expected results according to formulas

ADV4

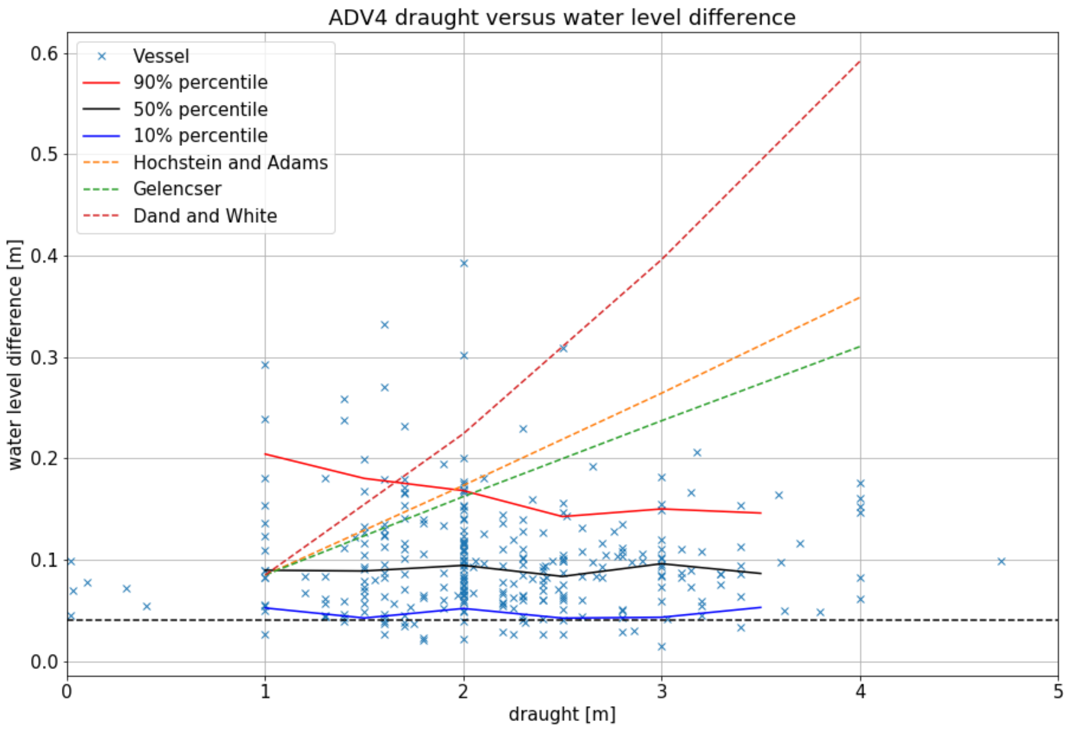

Figure E.10: ADV4 draught versus water level difference results with expected results according to formulas

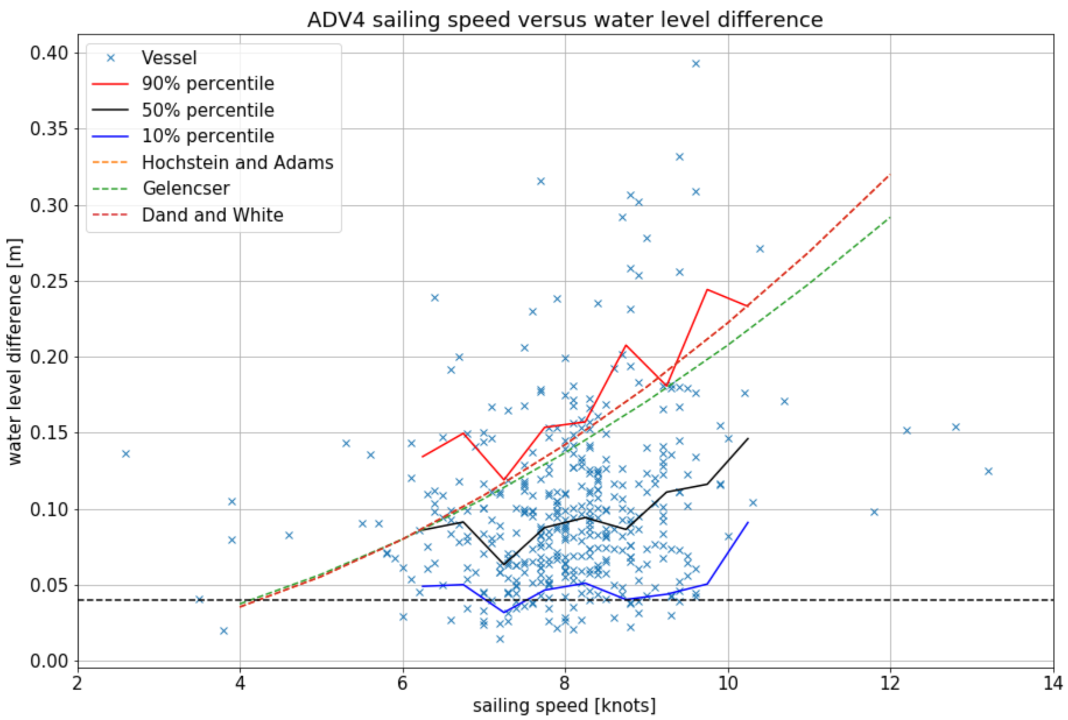

Figure E.11: ADV4 sailing speed versus water level difference results with expected results according to formulas

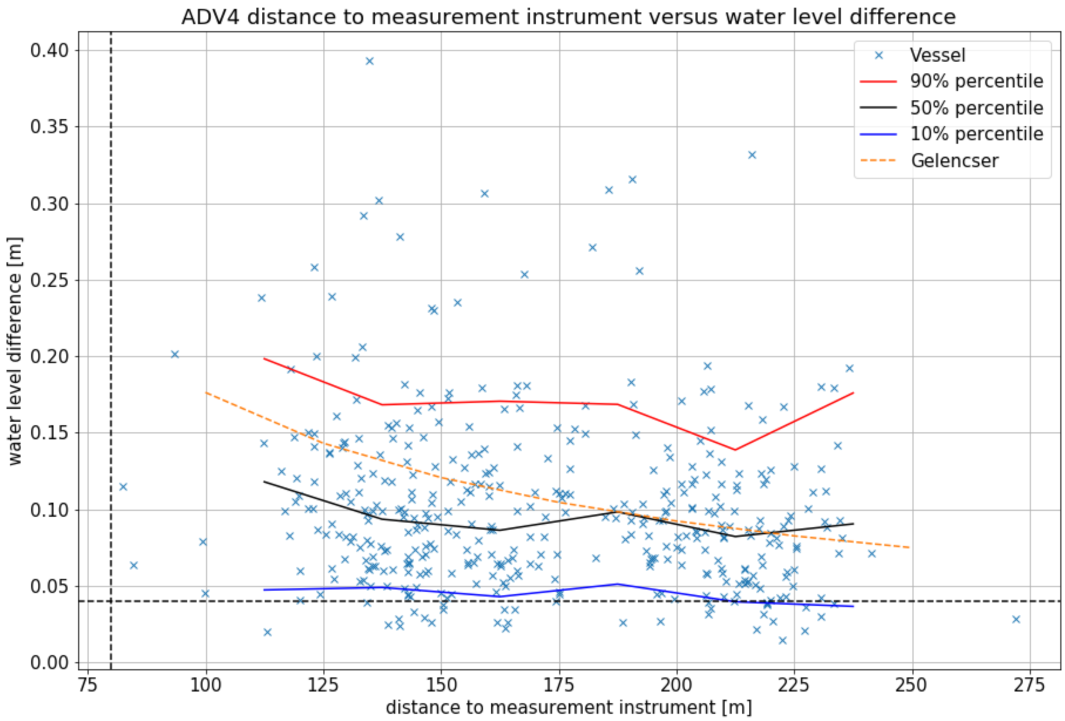

Figure E.12: ADV4 distance to measurement instrument versus water level difference results with expected results according to formulas

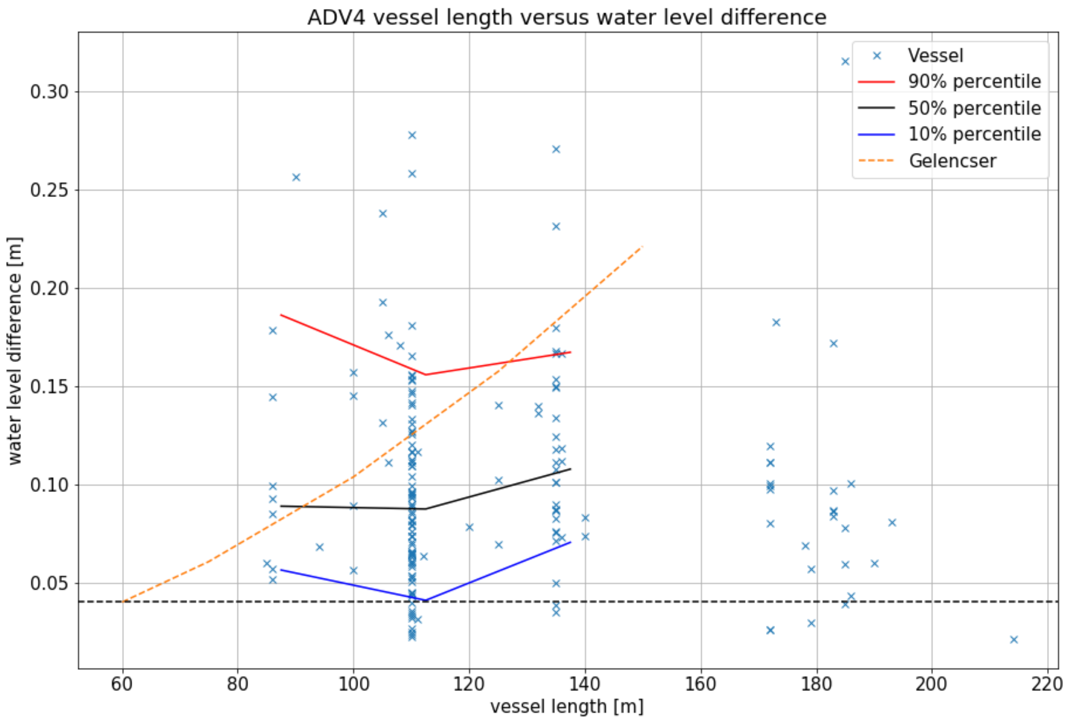

Figure E.13: ADV4 vessel length versus water level difference results for vessel with a width of 12 meters. Including expected results according to formulas

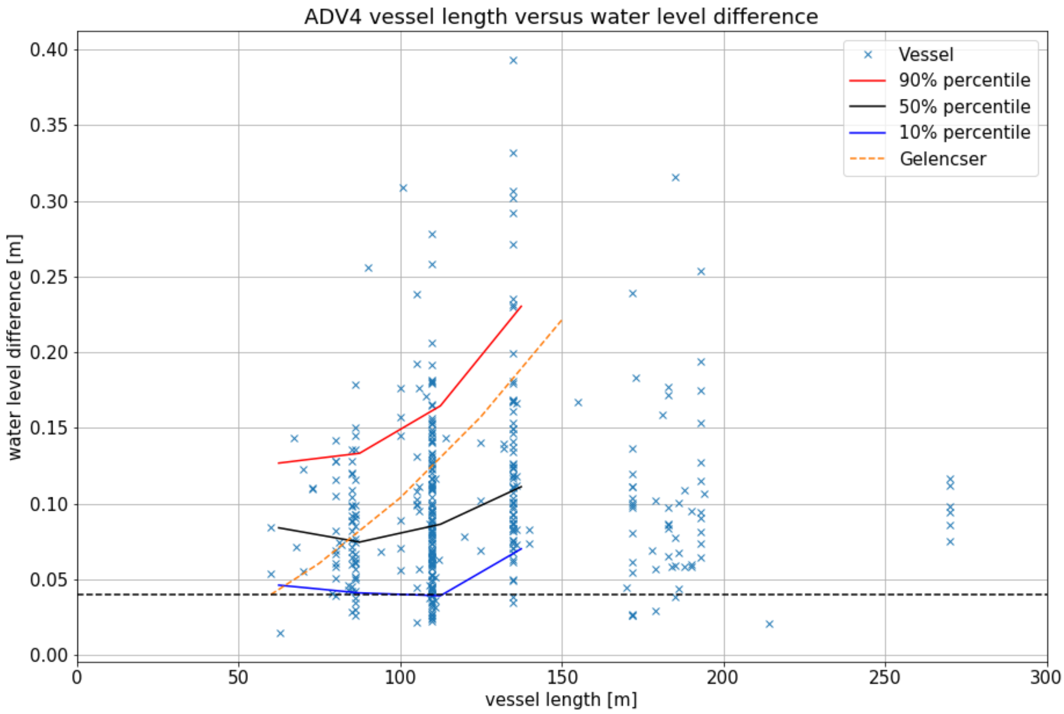

Figure E.14: ADV4 vessel length versus water level difference results with expected results according to formulas

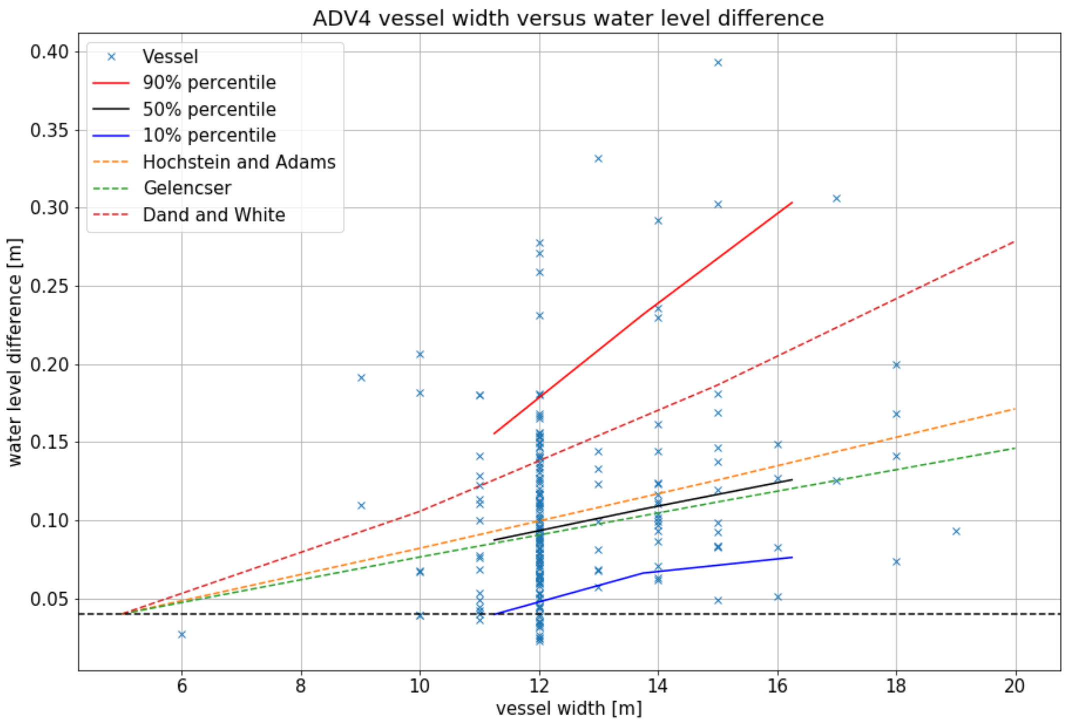

Figure E.15: ADV4 vessel width versus water level difference results for vessels with a length between 110 and 135 meters. Including expected results according to formulas

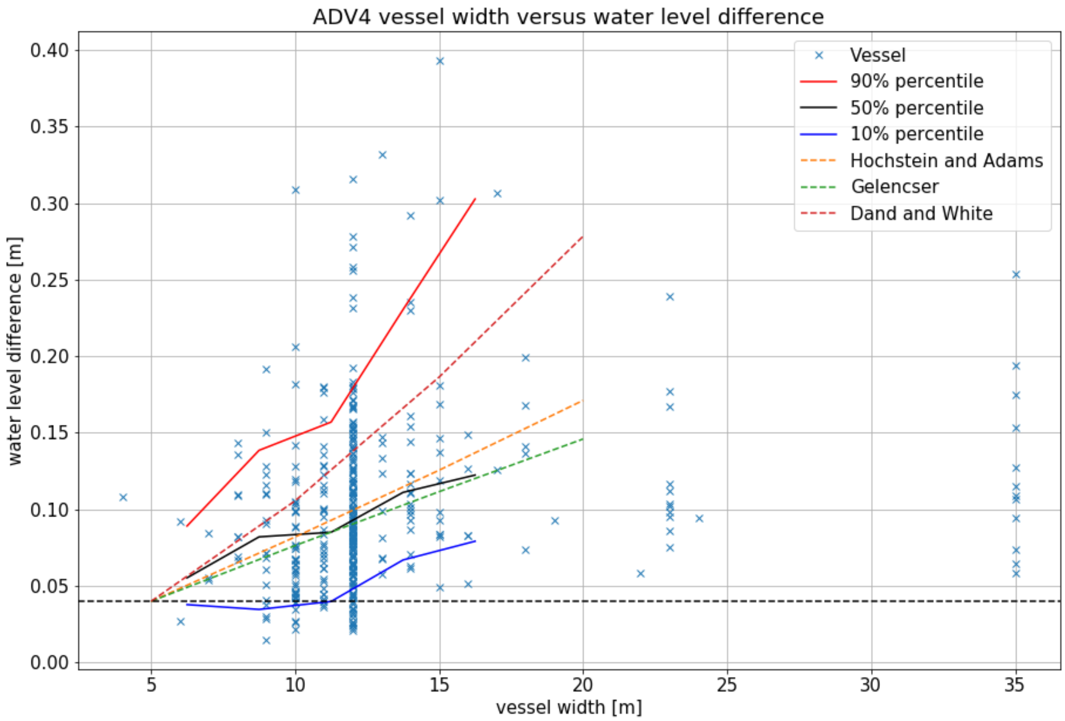

Figure E.16: ADV4 vessel width versus water level difference results with expected results according to formulas

ADV5

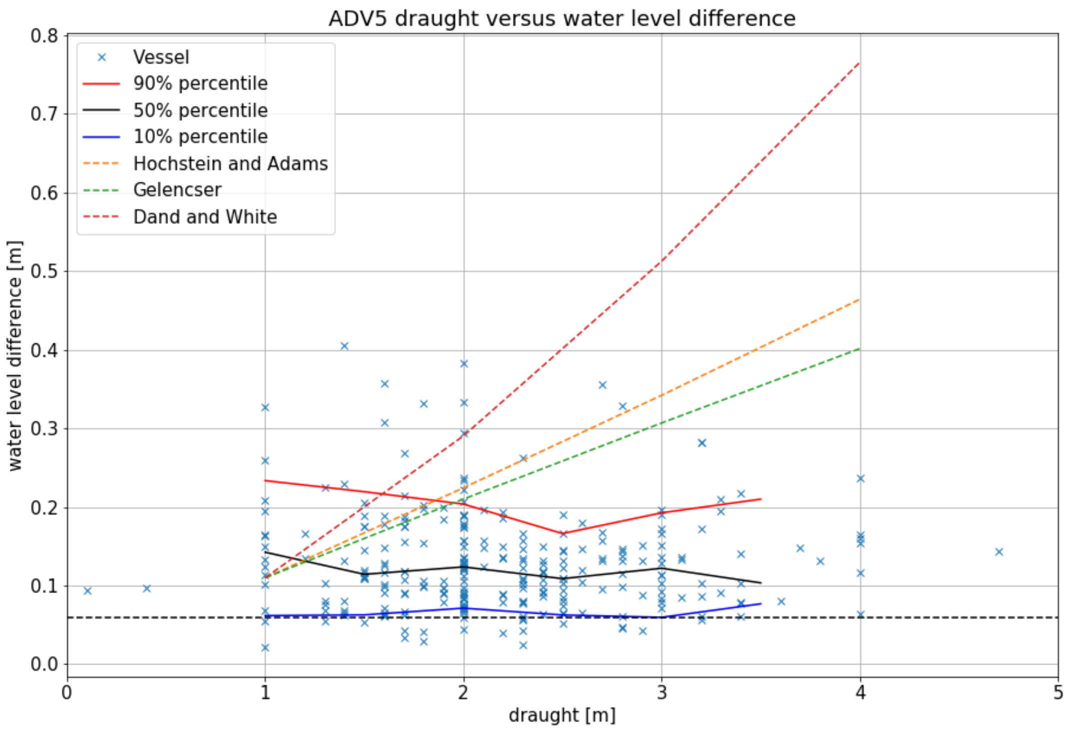

Figure E.17: ADV5 draught versus water level difference results with expected results according to formulas

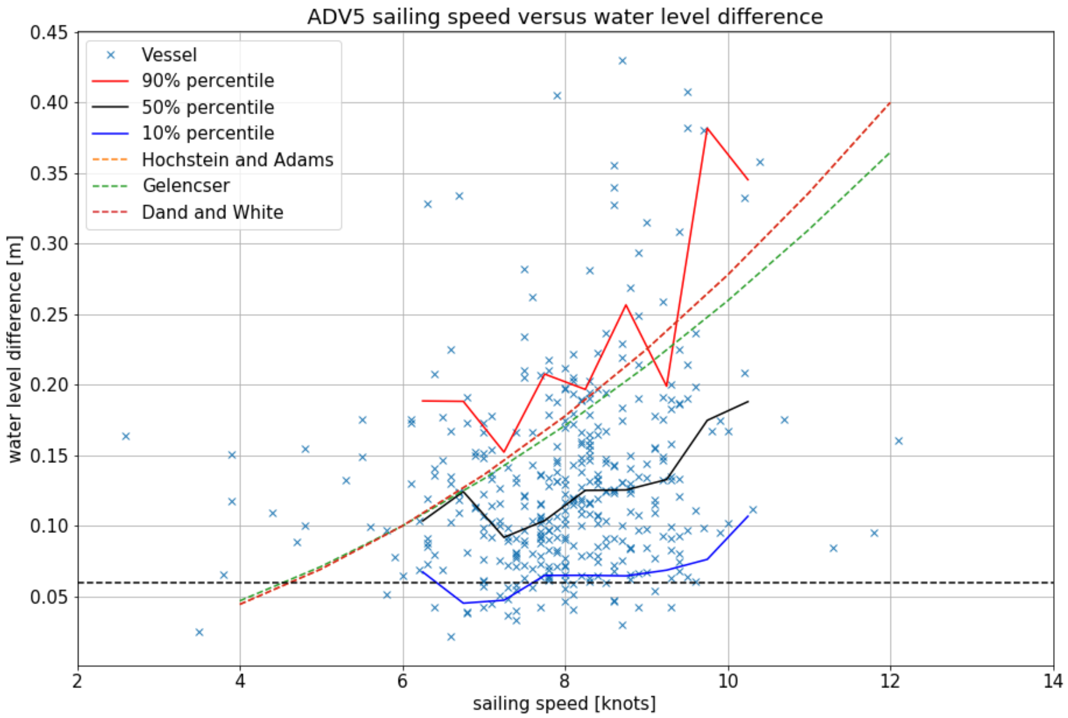

Figure E.18: ADV5 sailing speed versus water level difference results with expected results according to formulas

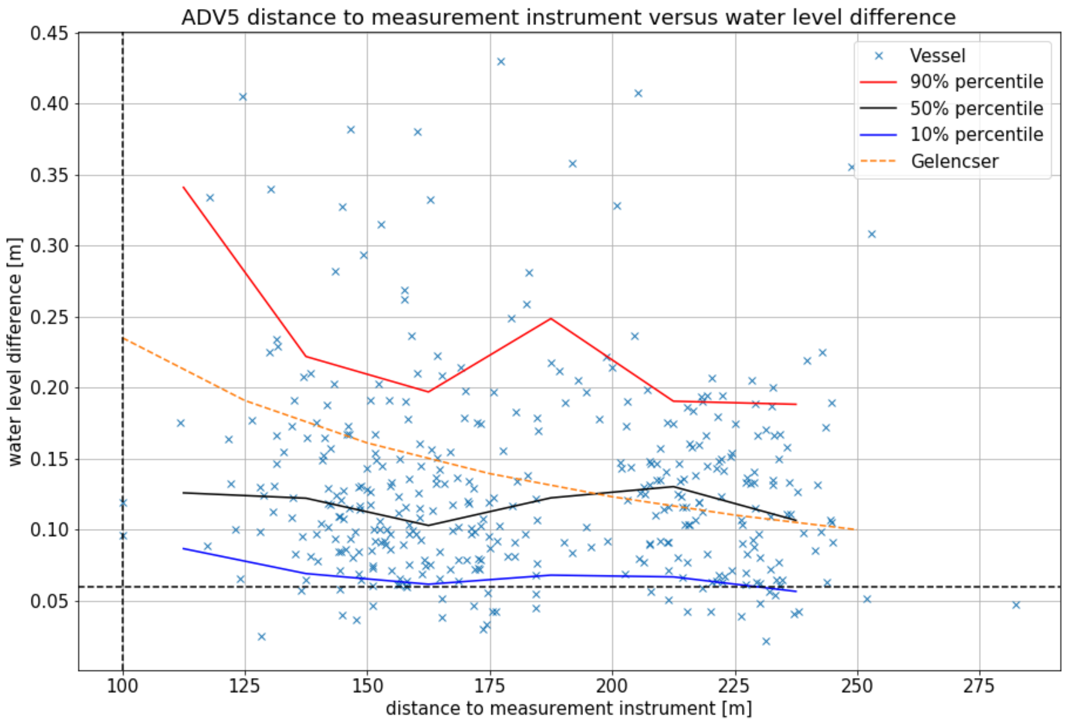

Figure E.19: ADV5 distance to measurement instrument versus water level difference results with expected results according to formulas

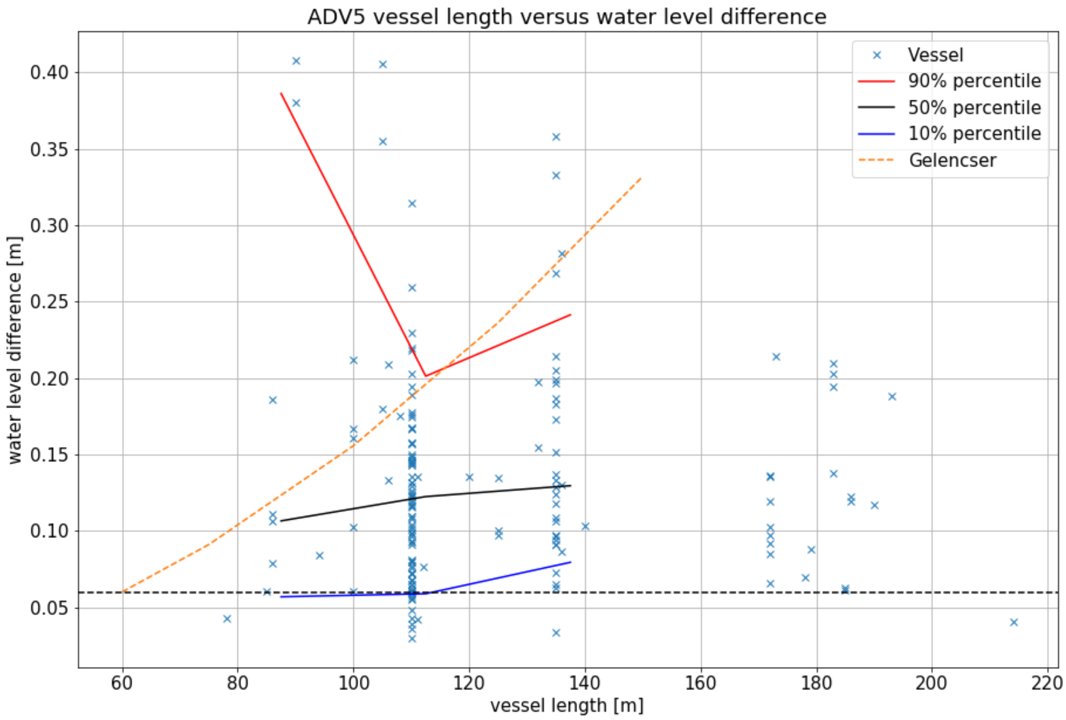

Figure E.20: ADV5 vessel length versus water level difference results for vessel with a width of 12 meters. Including expected results according to formulas

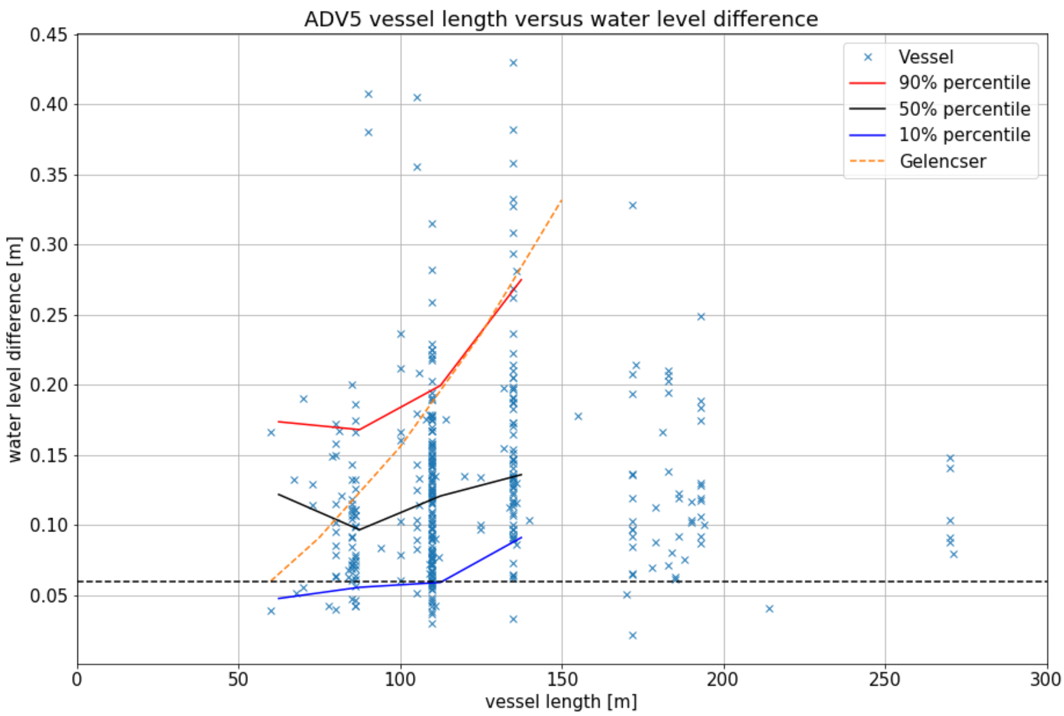

Figure E.21: ADV5 vessel length versus water level difference results with expected results according to formulas

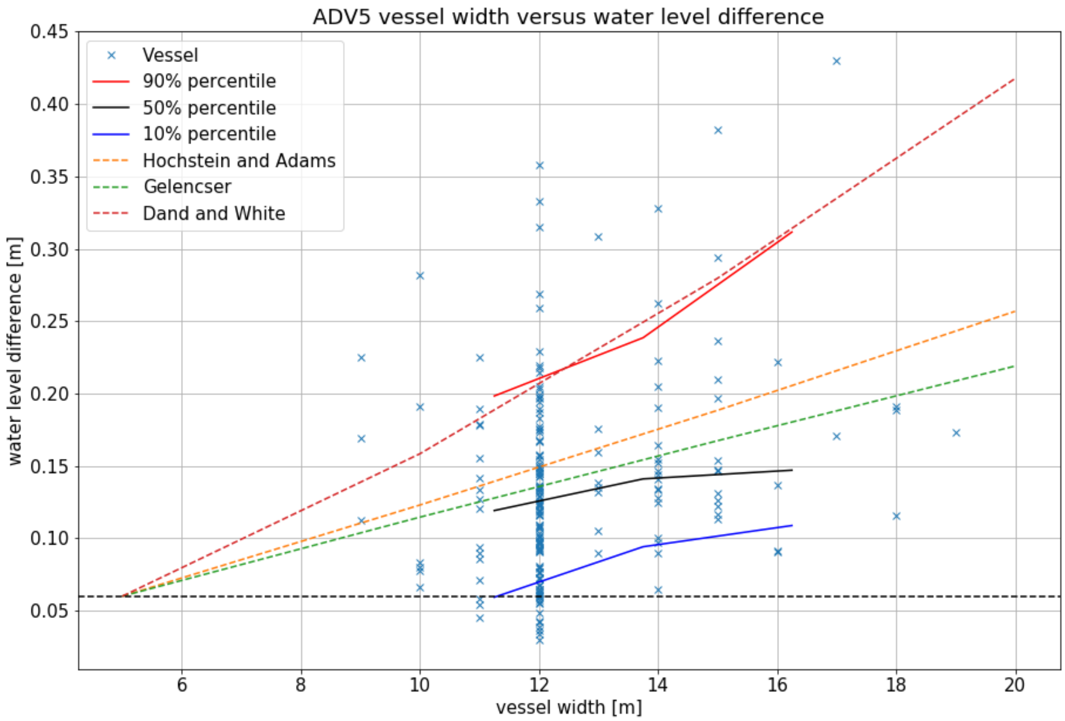

Figure E.22: ADV5 vessel width versus water level difference results for vessels with a length between 110 and 135 meters. Including expected results according to formulas

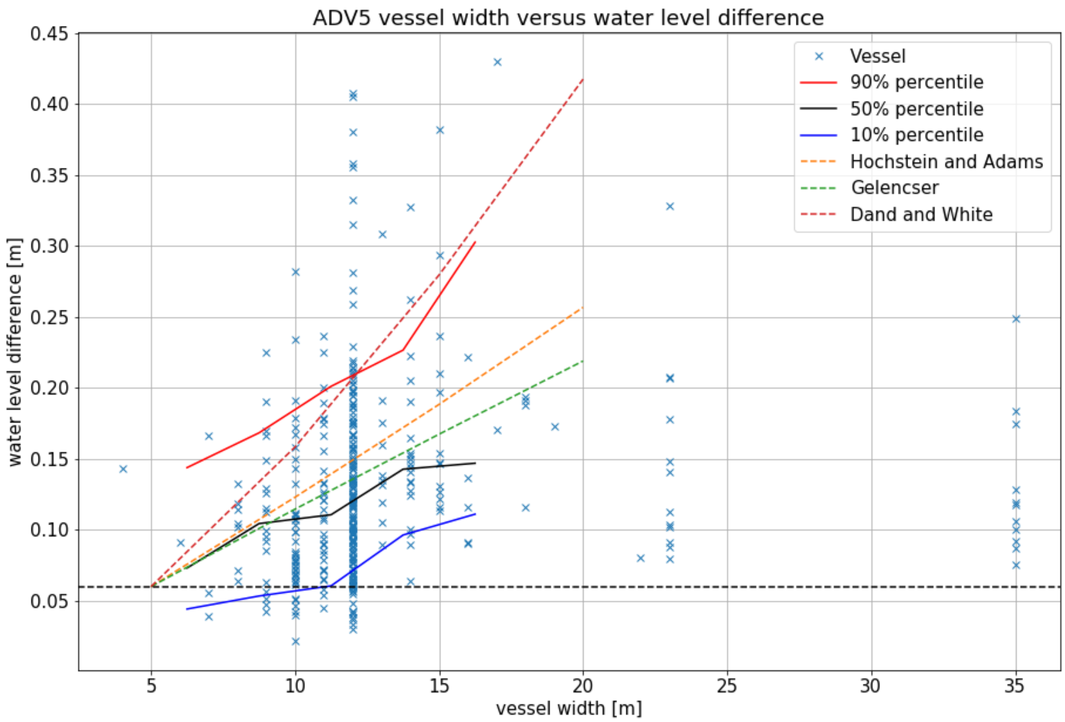

Figure E.23: ADV5 vessel width versus water level difference results with expected results according to formulas

E.3 Flow velocity explanation

ADV2

In this section, the influence of the draught, sailing speed, distance to the measurement instrument, vessel length and vessel width on the flow velocity at the location of ADV2 is investigated. The exact location of ADV2 is visible in figure 3.2. At this location 447 useful vessel movements were registered, taking into consideration the 10-minute interval. In each figure a black dashed line is present, indicating the flow velocity at the measurement location when no vessel is influencing the flow. At the location of ADV2, this flow velocity is equal to 0.41 m/s.

Draught

The draught versus the maximum flow velocity is plotted in figure E.26. The percentile lines are calculated by taking horizontal intervals of 0.5 meters from 0.75 to 3.75 meters.

According to the hypothesis, the flow velocity should increase when the draught is increasing due to an increase in the underwater area of the vessel and therefore an increase of the return current. The percentile lines, however, show a completely horizontal pattern. This indicates that an increase in the draught has no significant influence on the maximum flow velocity in this particular groyne field.

Sailing speed

The sailing speed versus the maximum flow velocity is plotted in figure E.27. The percentile lines are calculated by taking horizontal intervals of 0.5 knots from 6.0 to 10.5 knots.

According to the hypothesis, the water level difference should increase when the sailing speed is increasing. The percentile lines show a mixed pattern. Before 7.0 knots the effect of the sailing speed shows an increasing pattern but this is probably due to a low amount of data points in this percentile interval. When increasing the sailing speed, the percentile lines show a horizontal pattern until a sailing speed of 10 knots is reached. At this point, the percentile lines increase but this is, again, likely due to a low amount of data points in this interval section.

Distance to measurement instrument

The distance to the measurement instrument versus maximum flow velocity is plotted in figure E.28. The percentile lines are calculated by taking horizontal intervals of 25 meters from 100 to 250 meters. The vertical black dotted line indicates the minimum distance to the measurement instrument. If the distance would be smaller than 100 meters the vessel would be sailing inside the groyne field.

According to the hypothesis, the water level difference should increase when the distance towards the measurement instrument decreases. The percentile lines show an increasing pattern when the distance to the measurement instrument decreases, confirming the hypothesis.

Length of the vessel

The length and the width of the vessel are strongly correlated with each other. To investigate the effect of the length of vessels on the flow velocity inside the groyne field, the width has to be kept constant. In figure E.29 the effect of the length on the flow velocity for vessels with a width of twelve meters is plotted. By doing this, the amount of data points has been reduced to 201. The percentile lines are calculated by taking horizontal intervals of 25 meters from 75 to 150 meters.

According to the hypothesis, an increase in the length of a vessel should result in an increase of the flow velocity inside the groyne field. The percentile lines show a small increasing pattern, indicating an increase in the flow velocity when the vessel length increases.

In figure E.30, the vessel length versus the flow velocity for the entire data set is plotted. The percentile lines are calculated by taking horizontal intervals of 25 meters from 50 to 150 meters. In the figure, the percentile lines show a clear increasing pattern.

Width of the vessel

As stated before, the width and the length of a vessel are strongly related to each other. To investigate the effect of the width of a vessel on the flow velocity inside the groyne field, the length is kept between a certain interval. In this case between 110 and 135 meters. This is done to keep sufficient data points. The total amount of data points is now 216. The results are plotted in figure E.31. The percentile lines are calculated by taking horizontal intervals of 2.5 meters from 10 to 17.5 meters.

According to the hypothesis, an increase in the width should result in an increase in the flow velocity. The percentile lines show an increasing pattern when the vessel width increases.

In figure E.32 the width versus the water level difference is plotted for the entire data set. The percentile lines are calculated by taking horizontal intervals of 2.5 meters from 5.0 to 17.5 meters. The percentile lines show again an increasing pattern.

ADV4

In this section, the influence of the draught, sailing speed, distance to the measurement instrument, vessel length and vessel width and the flow velocity at the location of ADV4 is investigated. The exact location of ADV4 is visible in figure 3.2. At this location 447 useful vessel movements were registered, taking into consideration the 10-minute interval. In each figure a black dashed line is present, indicating the flow velocity at the measurement location when no vessel is influencing the flow. At the location of ADV4, this flow velocity is equal to 0.34 m/s.

Draught

The draught versus the maximum flow velocity is plotted in figure E.33. The percentile lines are calculated by taking horizontal intervals of 0.5 meters from 0.75 to 3.75 meters.

According to the hypothesis, the flow velocity should increase when the draught is increasing due to an increase in the underwater area of the vessel and therefore an increase of the flow velocity. The percentile lines, however, show a complete horizontal pattern. This indicates that an increase in the draught has no significant influence on the maximum flow velocity in this particular groyne field.

Sailing speed

The sailing speed versus the maximum flow velocity is plotted in figure E.34. The percentile lines are calculated by taking horizontal intervals of 0.5 knots from 6.0 to 10.5 knots.

According to the hypothesis the flow velocity should increase when the sailing speed is increasing. The percentile lines show an increasing pattern when the sailing speed increases. Mainly the 50% and 90% percentile lines show a steep increase when the speed increases.

Distance to measurement instrument

The distance to the measurement instrument versus maximum flow velocity is plotted in figure E.35. The percentile lines are calculated by taking horizontal intervals of 25 meters from 100 to 250 meters. The vertical black dotted line indicates the minimum distance to the measurement instrument. If the distance would be smaller than 80 meters the vessel would be sailing inside the groyne field.

According to the hypothesis the water level difference should increase when the distance towards the measurement instrument decreases. The percentile lines show an increasing pattern when the distance to the measurement instrument decreases, confirming the hypothesis.

Length of the vessel

The length and the width of the vessel are strongly correlated with each other. To investigate the effect of the length of vessels on the flow velocity inside the groyne field, the width has to be kept constant. In figure E.36 the effect of the length on the flow velocity for vessels with a width of twelve meters is plotted. By doing this, the amount of data points has been reduced to 201. The percentile lines are calculated by taking horizontal intervals of 25 meters from 75 to 150 meters.

According to the hypothesis, an increase in the length of a vessel should result in an increase of the flow velocity inside the groyne field. The 50% percentile line shows a small increasing pattern. The 90% percentile line shows a small decreasing pattern. However, this is probably related to the low amount of data points in the first percentile interval.

In figure E.37, the vessel length versus the flow velocity for the entire data set is plotted. The percentile lines are calculated by taking horizontal intervals of 25 meters from 50 to 150 meters. In the figure, the percentile lines show an increasing pattern.

Width of the vessel

As stated before, the width and the length of a vessel are strongly related to each other. To investigate the effect of the width of a vessel on the flow velocity inside the groyne field, the length is kept between a certain interval. In this case between 110 and 135 meters. This is done to keep sufficient data points. The total amount of data points is now 222. The results are plotted in figure E.38. The percentile lines are calculated by taking horizontal intervals of 2.5 meters from 10 to 17.5 meters.

According to the hypothesis, an increase in the width should result in an increase in the flow velocity. The percentile lines show an increasing pattern when the vessel width increases but this is mainly due to the low amount of data points.

In figure E.39 the width versus the water level difference is plotted for the whole data set. The percentile lines are calculated by taking horizontal intervals of 2.5 meters from 5.0 to 17.5 meters. The percentile lines show again an increasing pattern.

ADV5

In this section, the influence of the draught, sailing speed, distance to the measurement instrument, vessel length and vessel width and the flow velocity at the location of ADV5 is investigated. The exact location of ADV5 is visible in figure 3.2. At this location 447 useful vessel movements were registered, taking into consideration the 10-minute interval. In each figure a black dashed line is present, indicating the flow velocity at the measurement location when no vessel is influencing the flow. At the locations of ADV5, this flow velocity is equal to 0.04 m/s.

Draught

The draught versus the maximum flow velocity is plotted in figure E.40. The percentile lines are calculated by taking horizontal intervals of 0.5 meters from 0.75 to 3.75 meters.

According to the hypothesis, the flow velocity should increase when the draught is increasing due to an increase in the underwater area of the vessel and therefore an increase of the return current. The percentile lines, however, show a completely horizontal pattern. This indicates that an increase in the draught has no significant influence on the maximum flow velocity in this particular groyne field.

Sailing speed

The sailing speed versus the maximum flow velocity is plotted in figure E.41. The percentile lines are calculated by taking horizontal intervals of 0.5 knots from 6.0 to 10.5 knots.

According to the hypothesis, the water level difference should increase when the sailing speed is increasing. The percentile lines clearly show an increasing pattern when the sailing speed increases.

Distance to measurement instrument

The distance to the measurement instrument versus maximum flow velocity is plotted in figure E.42. The percentile lines are calculated by taking horizontal intervals of 25 meters from 100 to 250 meters. The vertical black dotted line indicates the minimum distance to the measurement instrument. If the distance would be smaller than 100 meters the vessel would be sailing inside the groyne field.

According to the hypothesis, the water level difference should increase when the distance towards the measurement instrument decreases. The 50% percentile line shows a horizontal pattern when the distance to the measurement instrument is decreasing. The 90% percentile line shows a small increasing pattern.

Length of the vessel

The length and the width of the vessel are strongly correlated with each other. To investigate the effect of the length of vessels on the flow velocity inside the groyne field, the width has to be kept constant. In figure E.43 the effect of the length on the flow velocity for vessels with a width of twelve meters is plotted. By doing this, the amount of data points has been reduced to 201. The percentile lines are calculated by taking horizontal intervals of 25 meters from 75 to 150 meters.

According to the hypothesis, an increase in the length of a vessel should result in an increase of the flow velocity inside the groyne field. The 50% percentile line shows a small increasing pattern. The 90% percentile, however, shows a very steep decreasing pattern. The reason for this is the low amount of data points in the first percentile interval.

In figure E.44, the vessel length versus the flow velocity for the entire data set is plotted. The percentile lines are calculated by taking horizontal intervals of 25 meters from 50 to 150 meters. In the figure, the percentile lines show an increasing pattern.

Width of the vessel

As stated before, the width and the length of a vessel are strongly related to each other. To investigate the effect of the width of a vessel on the flow velocity inside the groyne field, the length is kept between a certain interval. In this case between 110 and 135 meters. This is done to keep sufficient data points. The total amount of data points is now 231. The results are plotted in figure E.45. The percentile lines are calculated by taking horizontal intervals of 2.5 meters from 10 to 17.5 meters.

According to the hypothesis, an increase in the width should result in an increase in the flow velocity. The percentile lines show an increasing pattern when the vessel width increases.

In figure E.46 the width versus the water level difference is plotted for the whole data set. The percentile lines are calculated by taking horizontal intervals of 2.5 meters from 5.0 to 17.5 meters. The percentile lines show again an increasing pattern.

E.4 Flow velocity figures

ADV1

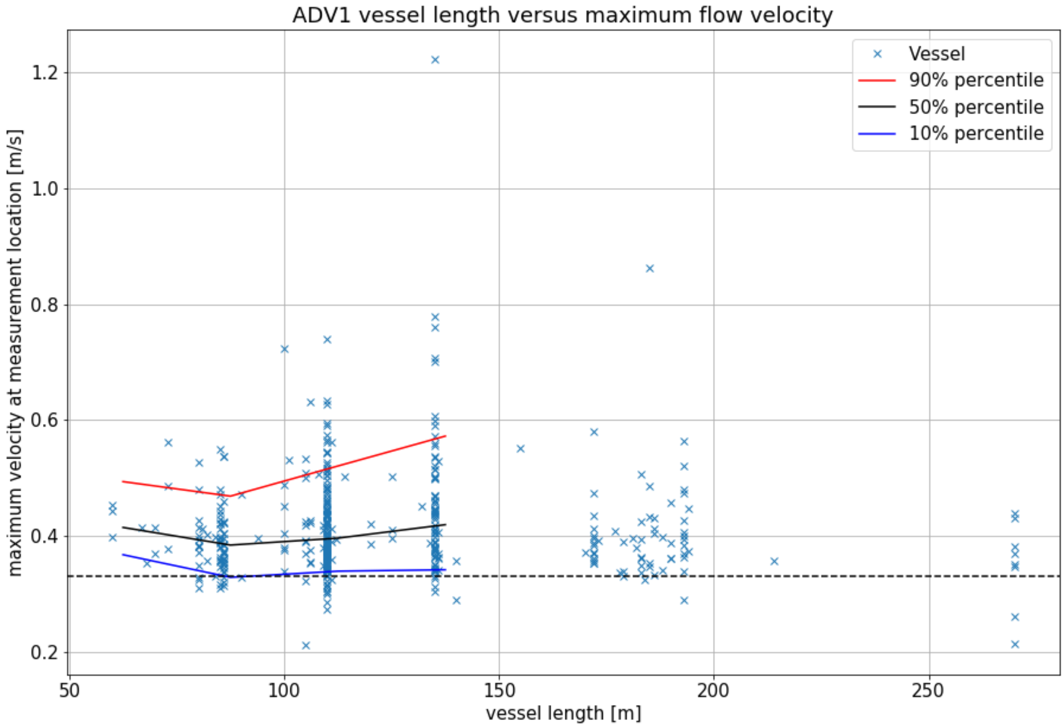

Figure E.24: ADV1 vessel length versus maximum flow velocity at measurement location

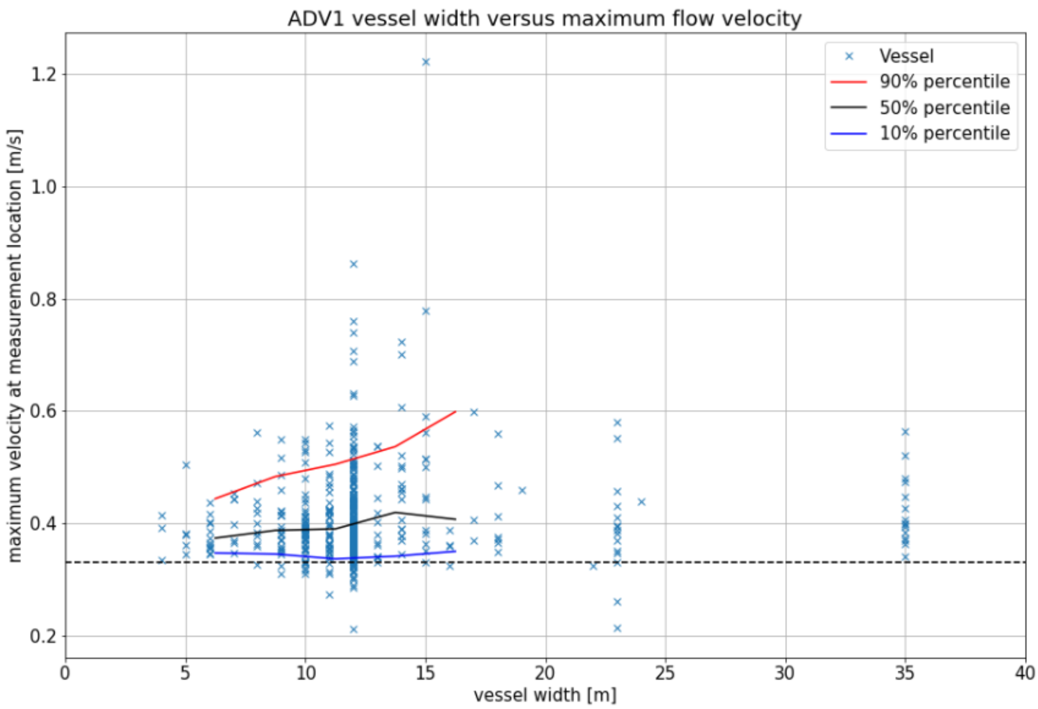

Figure E.25: ADV1 vessel width versus maximum flow velocity at measurement location

ADV2

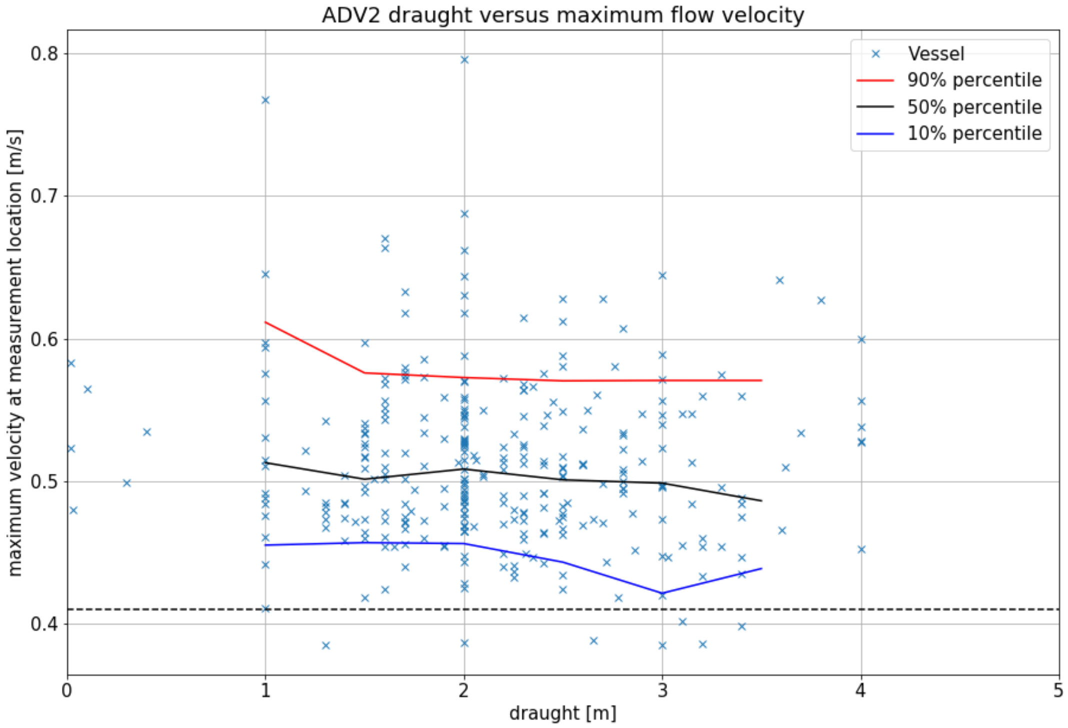

Figure E.26: ADV2 draught versus maximum flow velocity at measurement location

Figure E.27: ADV2 sailing speed versus maximum flow velocity at measurement location

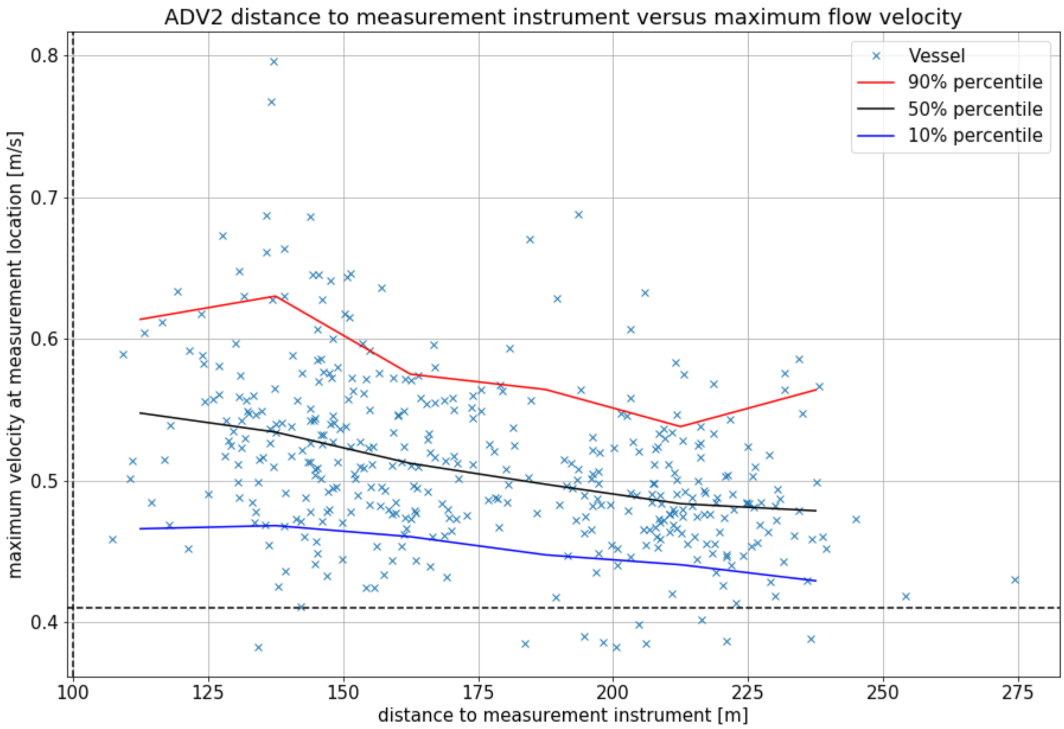

Figure E.28: ADV2 distance to measurement instrument versus maximum flow velocity at measurement location

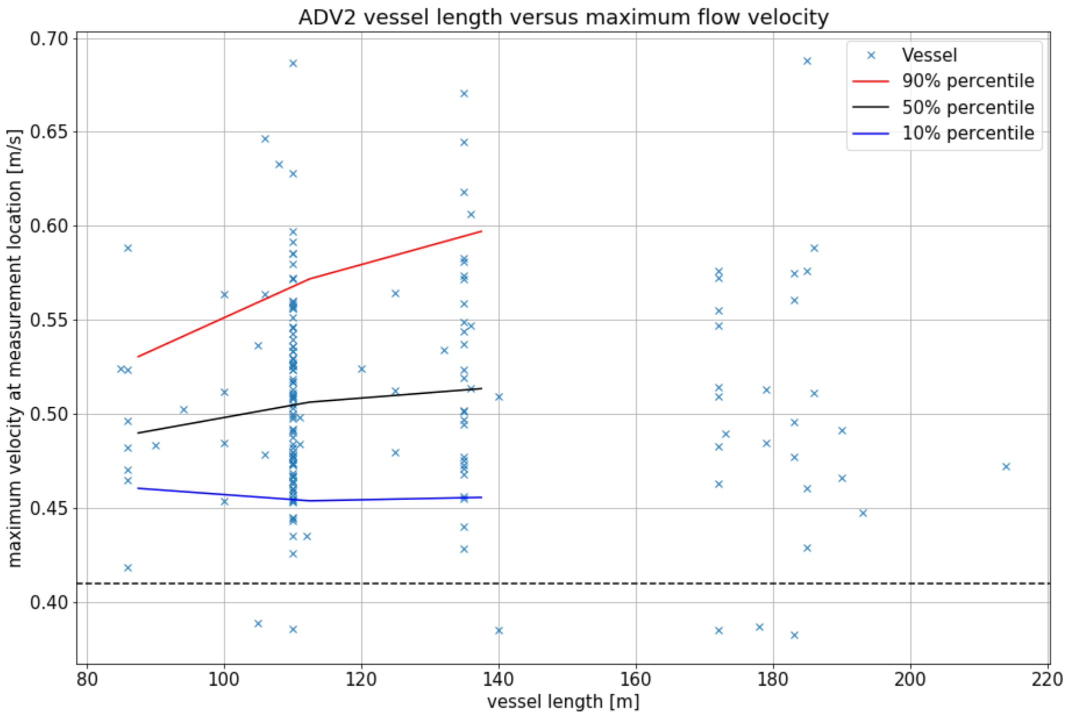

Figure E.29: ADV2 vessel length versus maximum flow velocity at measurement location for vessels with a width of 12 meters

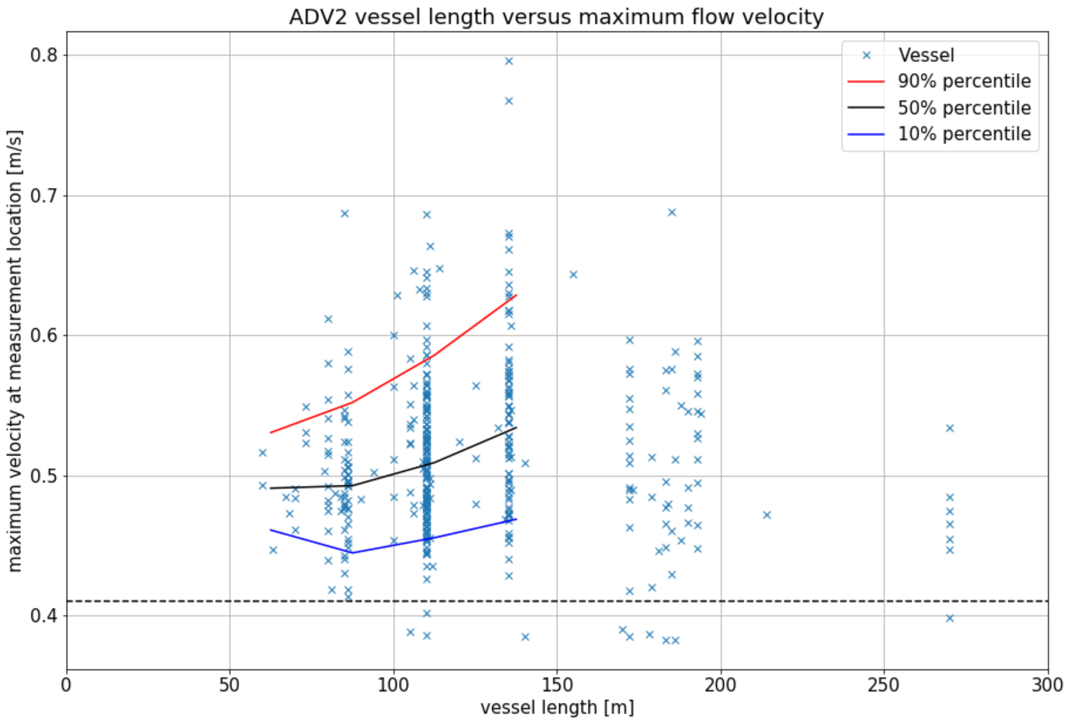

Figure E.30: ADV2 vessel length versus maximum flow velocity at measurement location

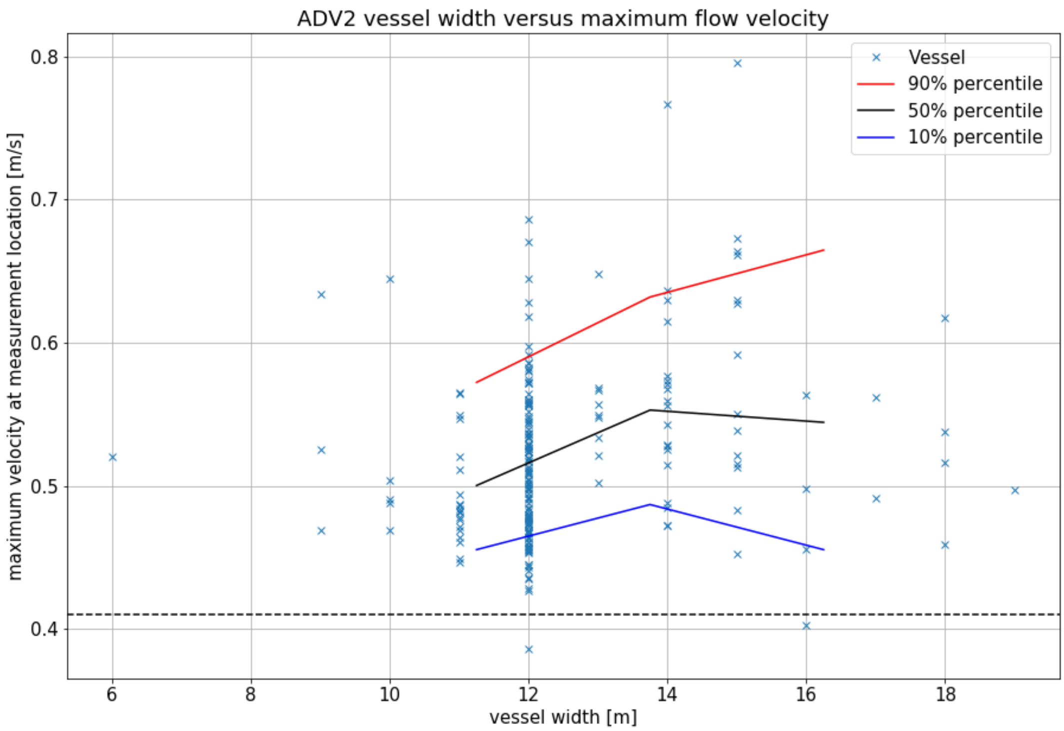

Figure E.31: ADV2 vessel width versus maximum flow velocity at measurement location for vessels with a length of 110 until 135 meters

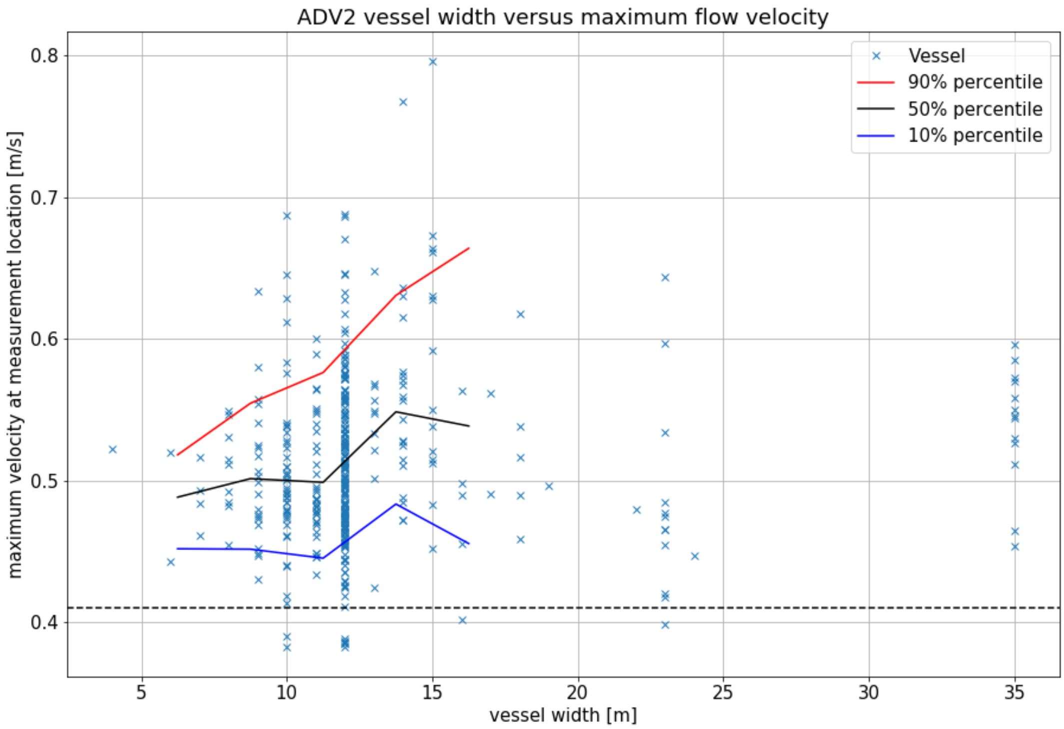

Figure E.32: ADV2 vessel width versus maximum flow velocity at measurement location

ADV4

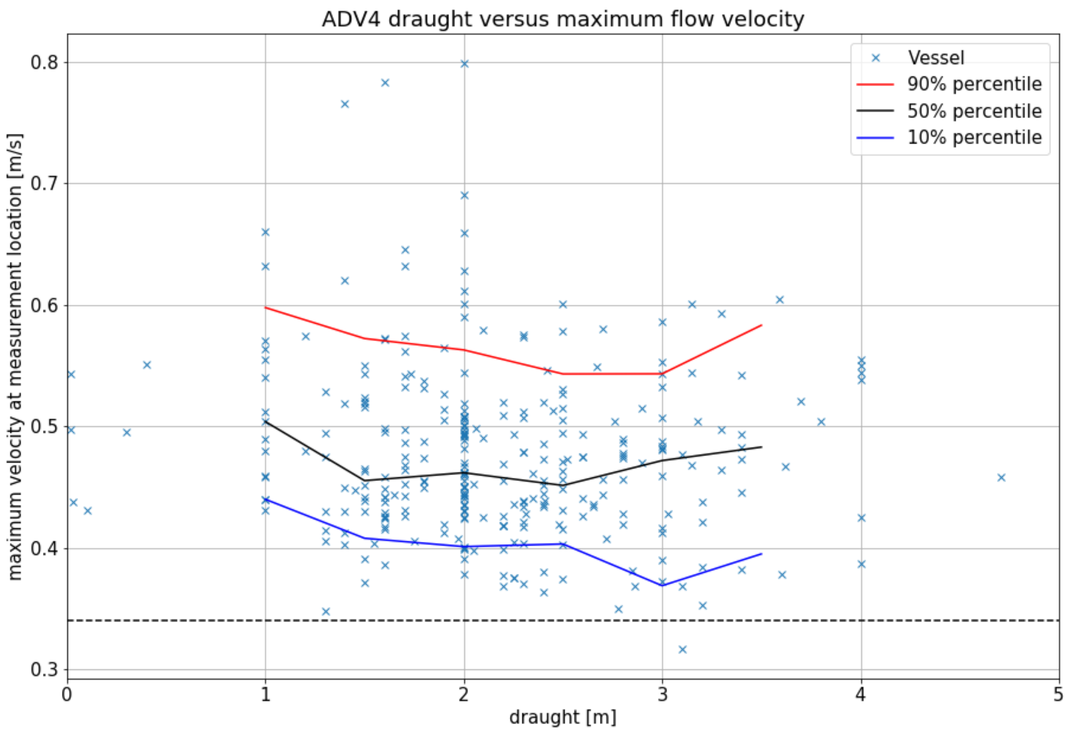

Figure E.33: ADV4 draught versus maximum flow velocity at measurement location

Figure E.34: ADV4 sailing speed versus maximum flow velocity at measurement location

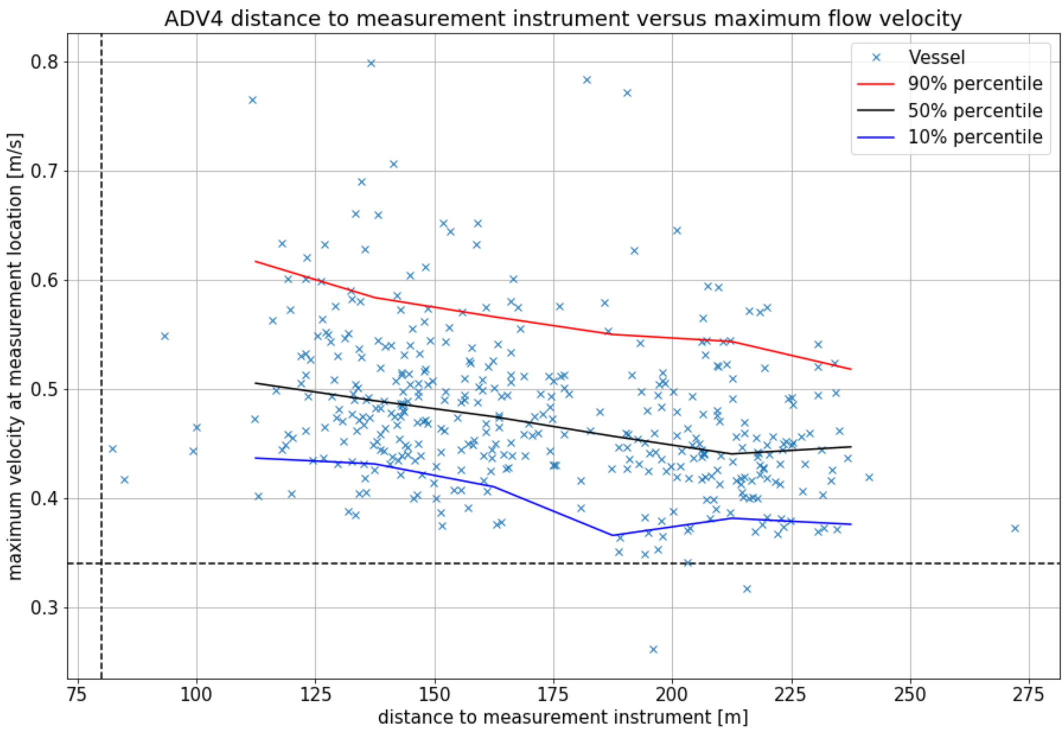

Figure E.35: ADV4 distance to measurement instrument versus maximum flow velocity at measurement location

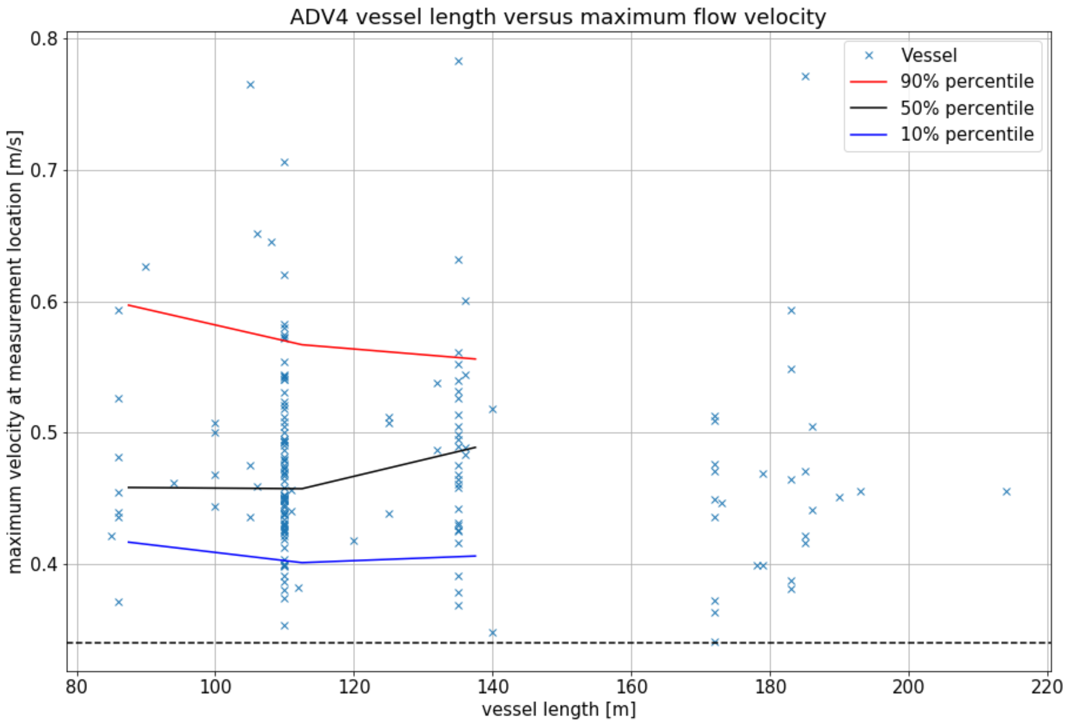

Figure E.36: ADV4 vessel length versus maximum flow velocity at measurement location for vessels with a width of 12 meters.

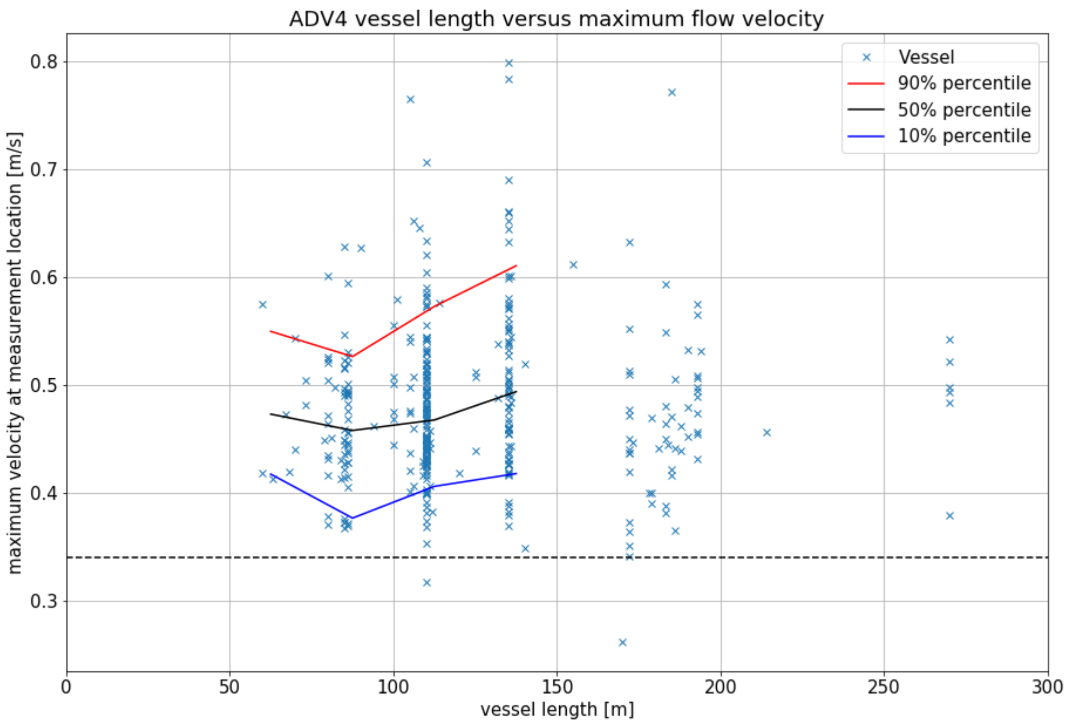

Figure E.37: ADV4 vessel length versus maximum flow velocity at measurement location

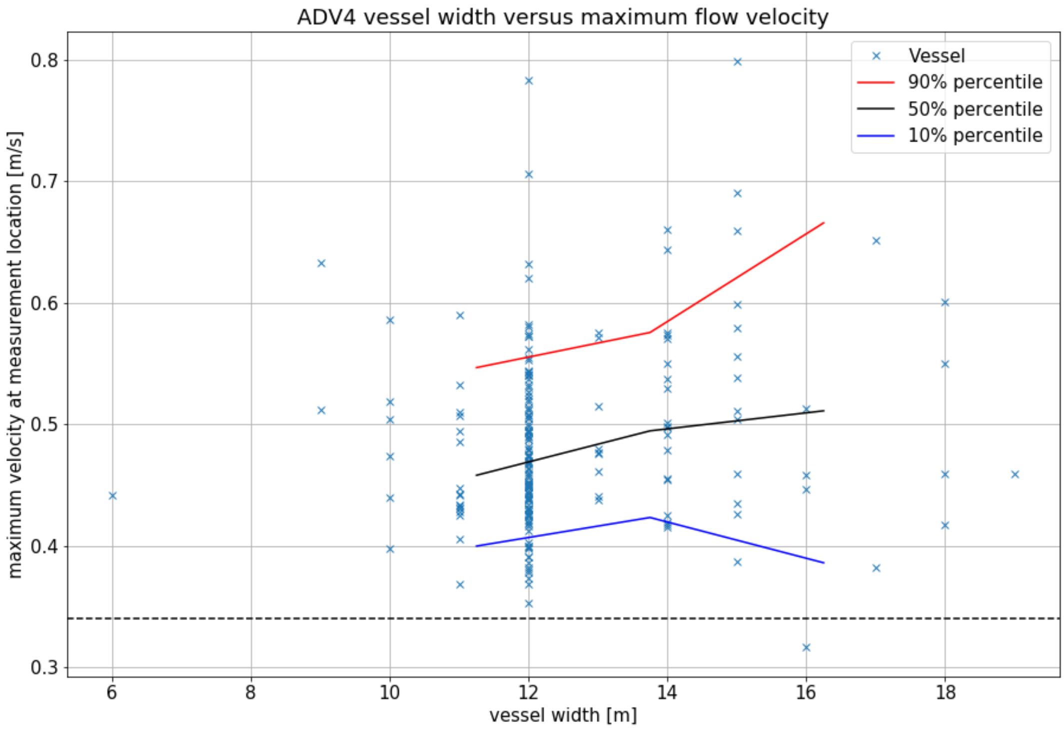

Figure E.38: ADV4 vessel width versus maximum flow velocity at measurement location for vessels with a length of 110 until 135 meters

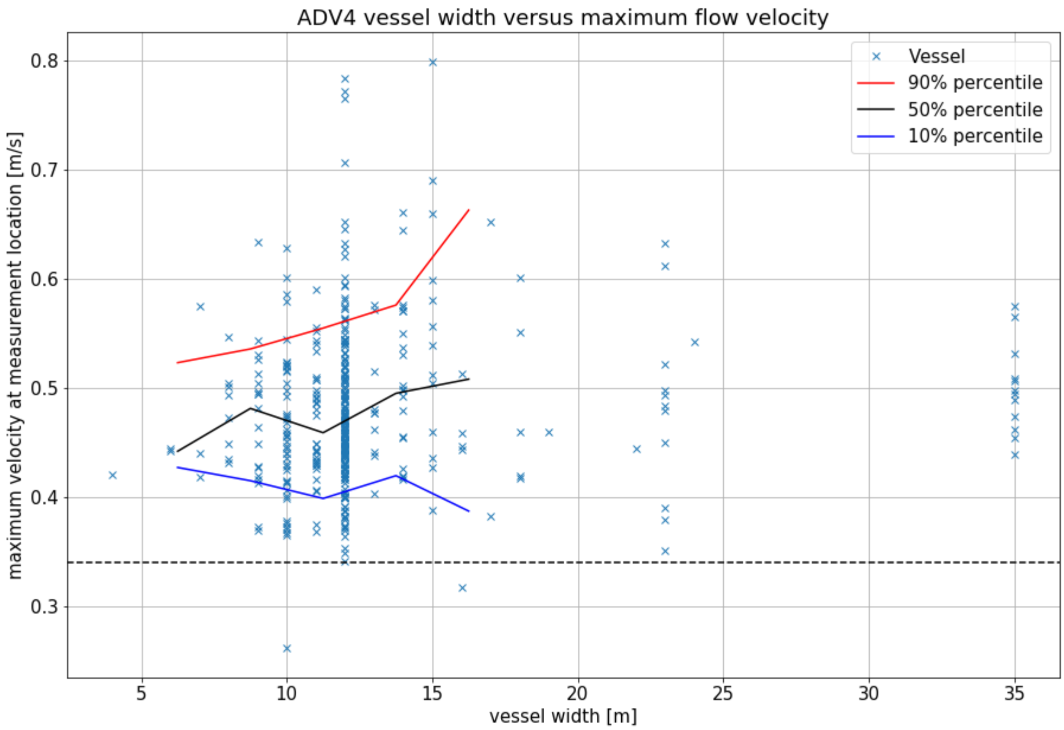

Figure E.39: ADV4 vessel width versus maximum flow velocity at measurement location

ADV5

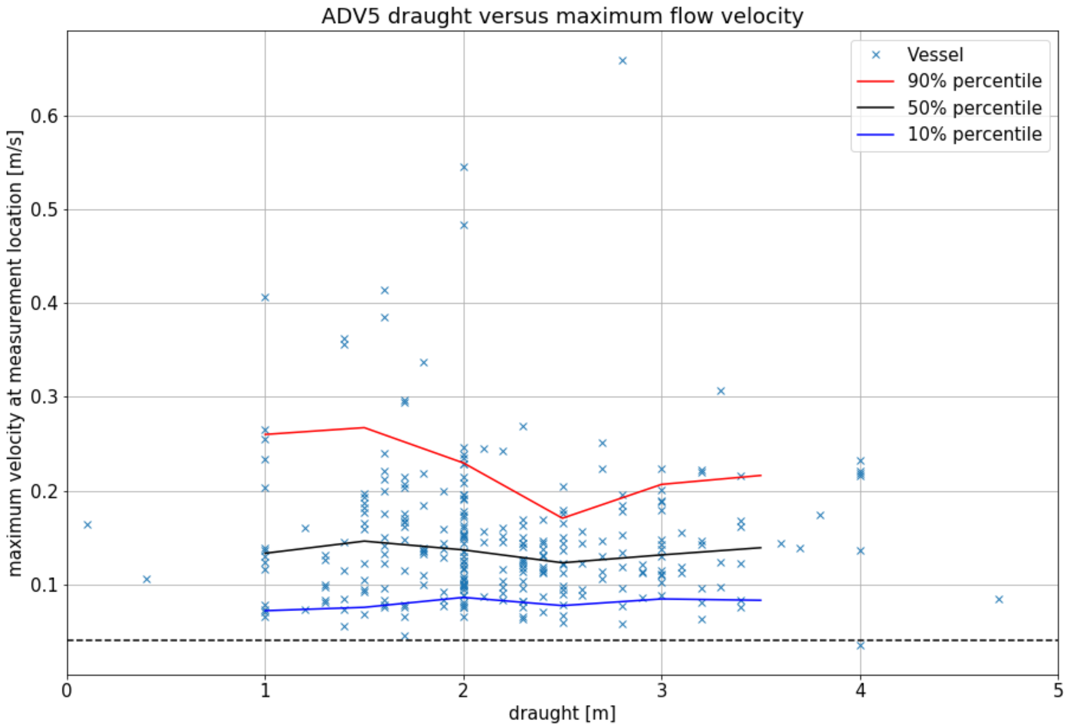

Figure E.40: ADV5 draught versus maximum flow velocity at measurement location

Figure E.41: ADV5 sailing speed versus maximum flow velocity at measurement location

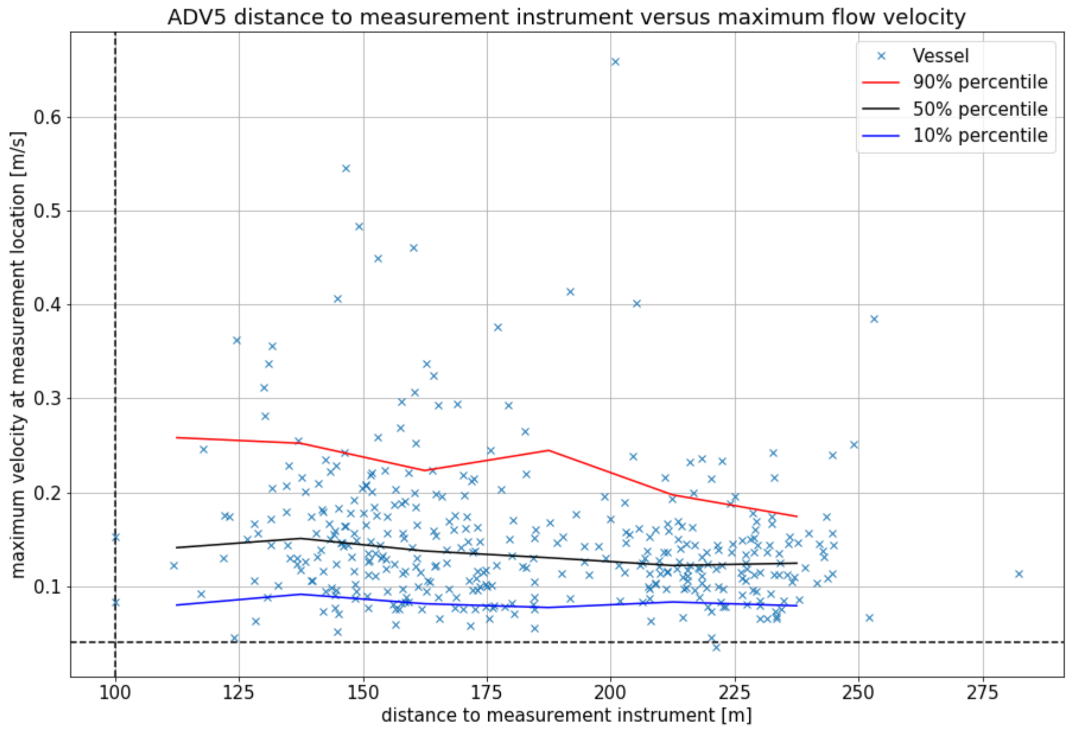

Figure E.42: ADV5 distance to measurement instrument versus maximum flow velocity at measurement location

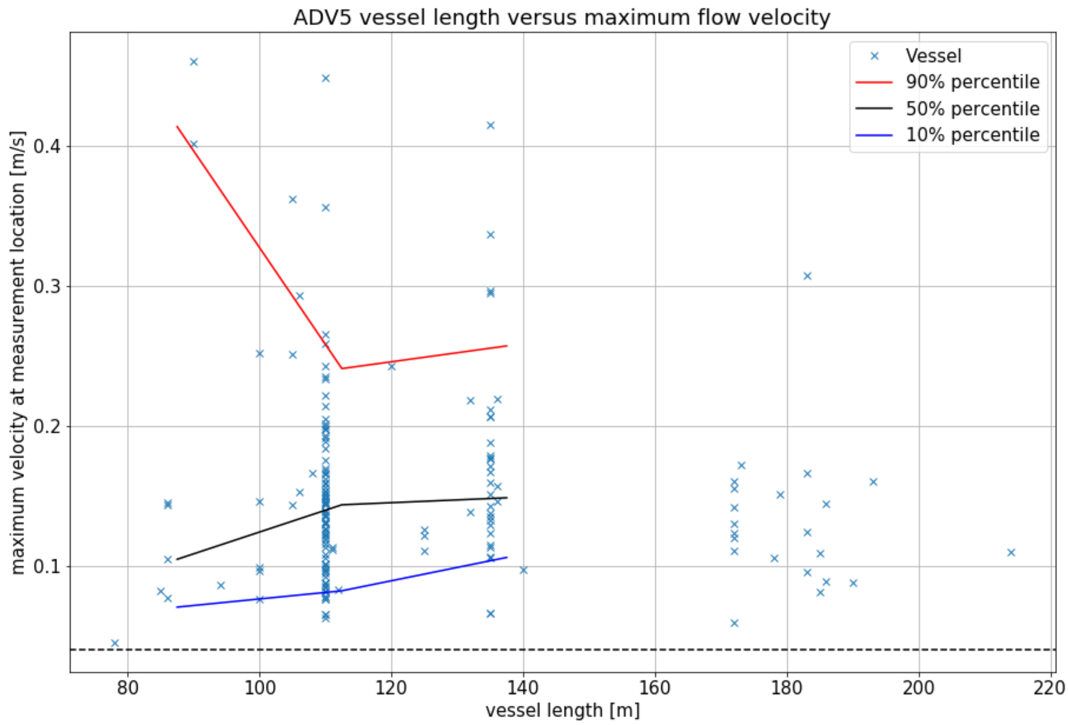

Figure E.43: ADV5 vessel length versus maximum flow velocity at measurement location for vessels with a width of 12 meters.

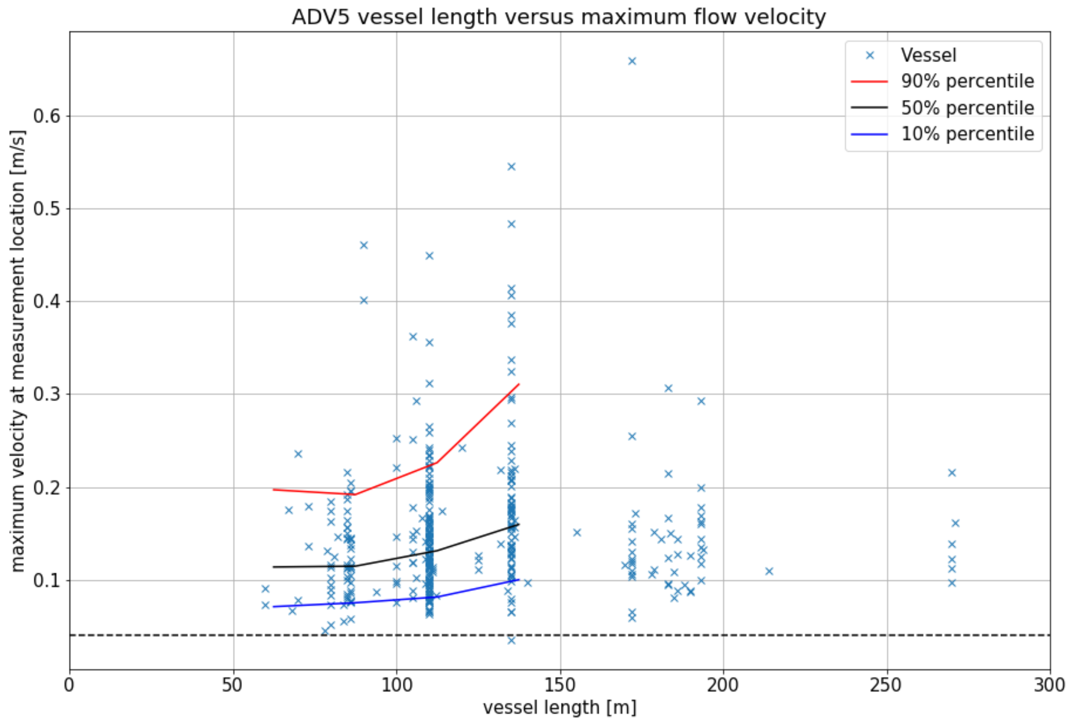

Figure E.44: ADV5 vessel length versus maximum flow velocity at measurement location

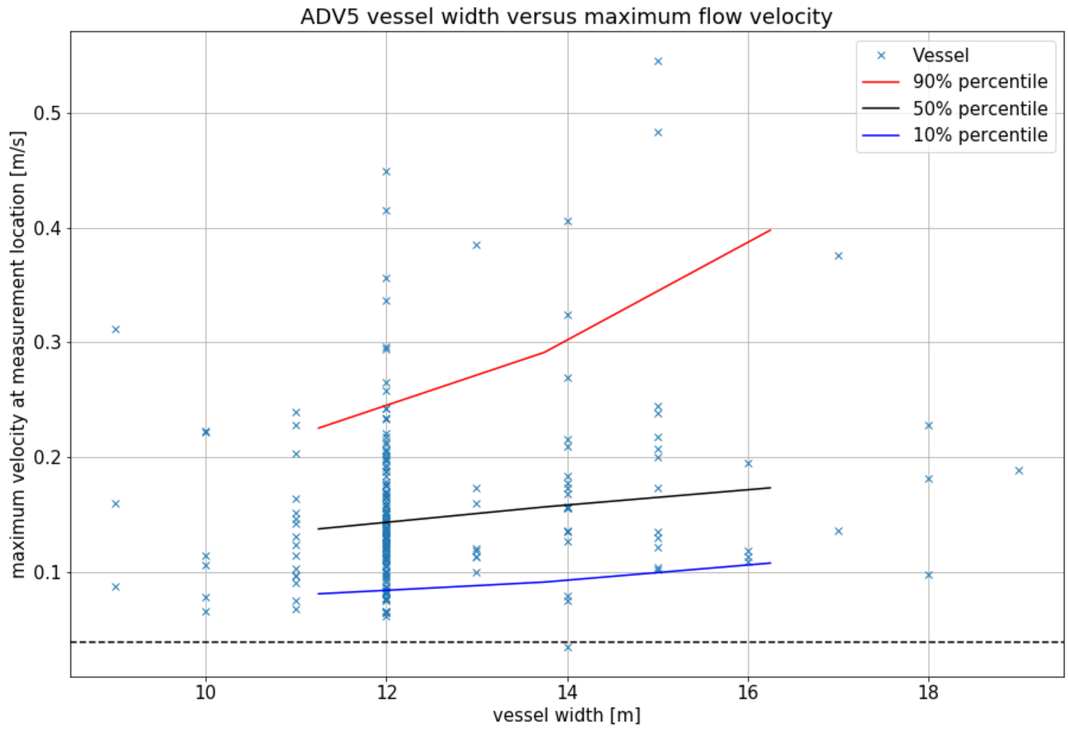

Figure E.45: ADV5 vessel width versus maximum flow velocity at measurement location for vessels with a length of 110 until 135 meters

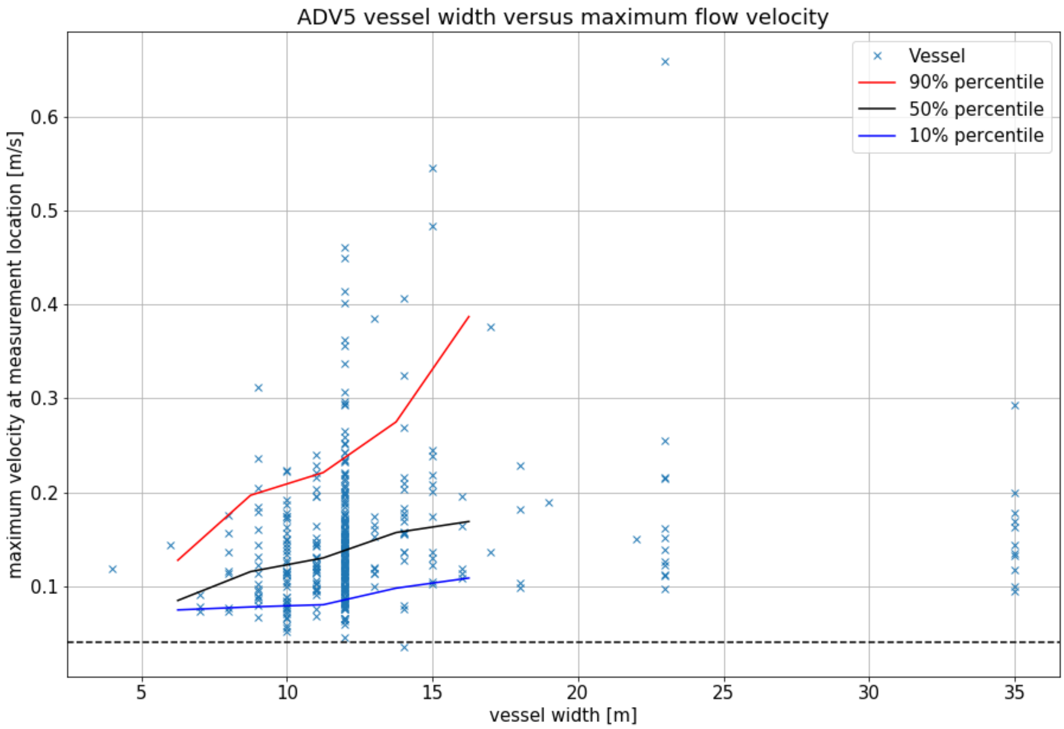

Figure E.46: ADV5 vessel width versus maximum flow velocity at measurement location

E.5 Velocity versus water level difference

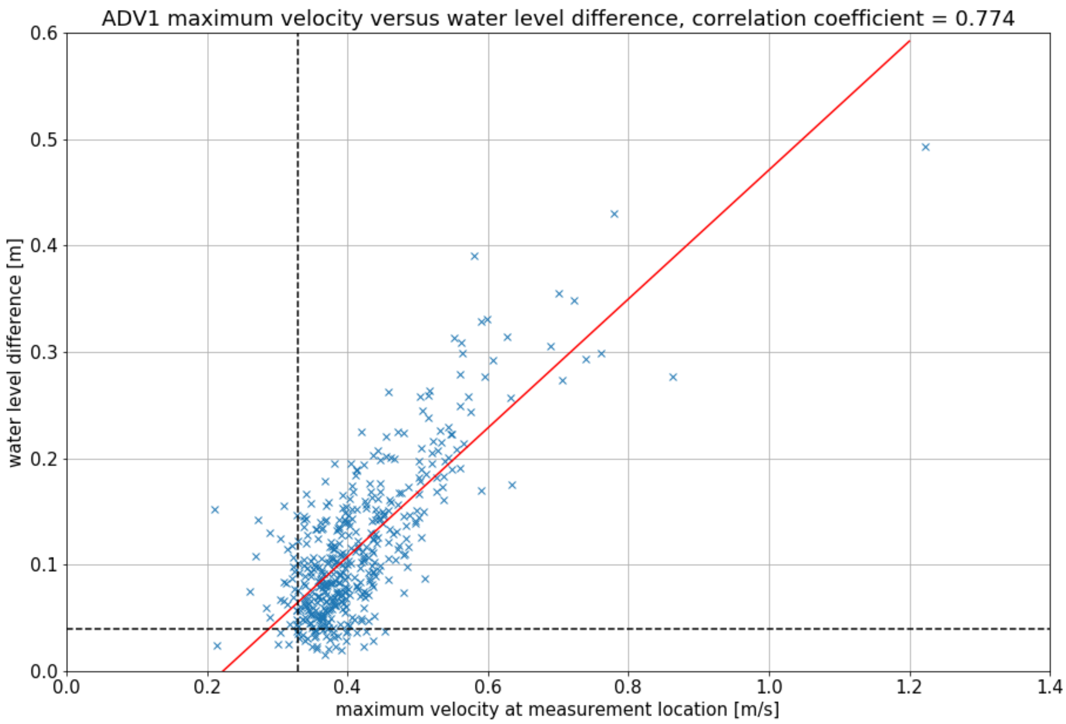

Figure E.47: Maximum flow velocity versus water level difference at the location of ADV1

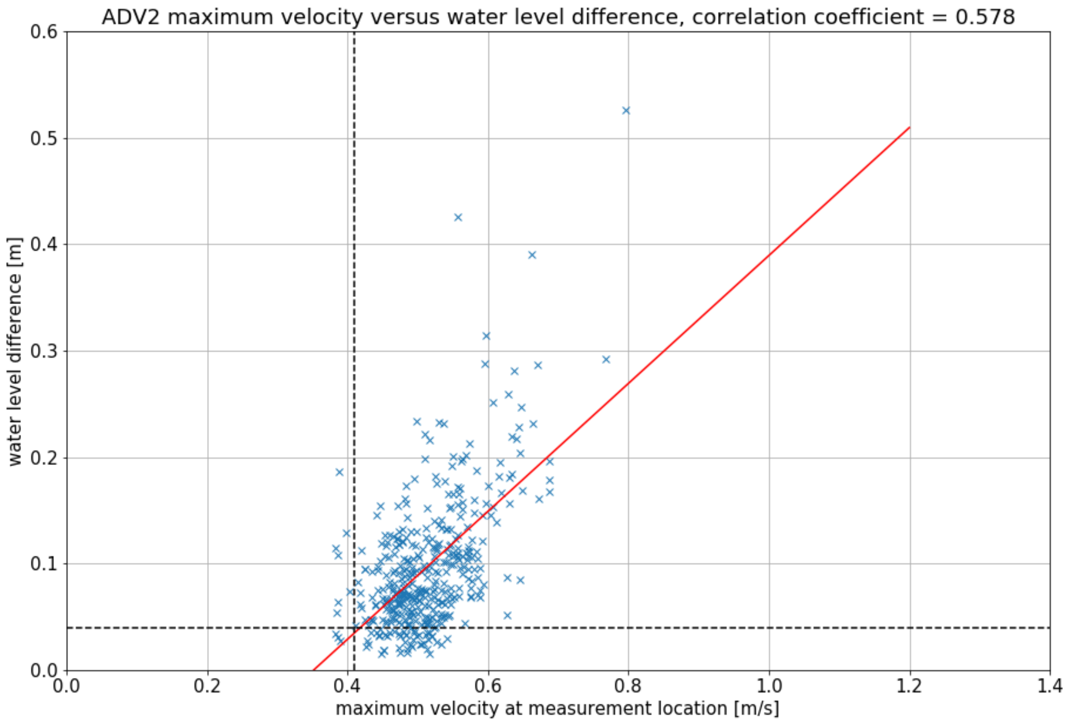

Figure E.48: Maximum flow velocity versus water level difference at the location of ADV2

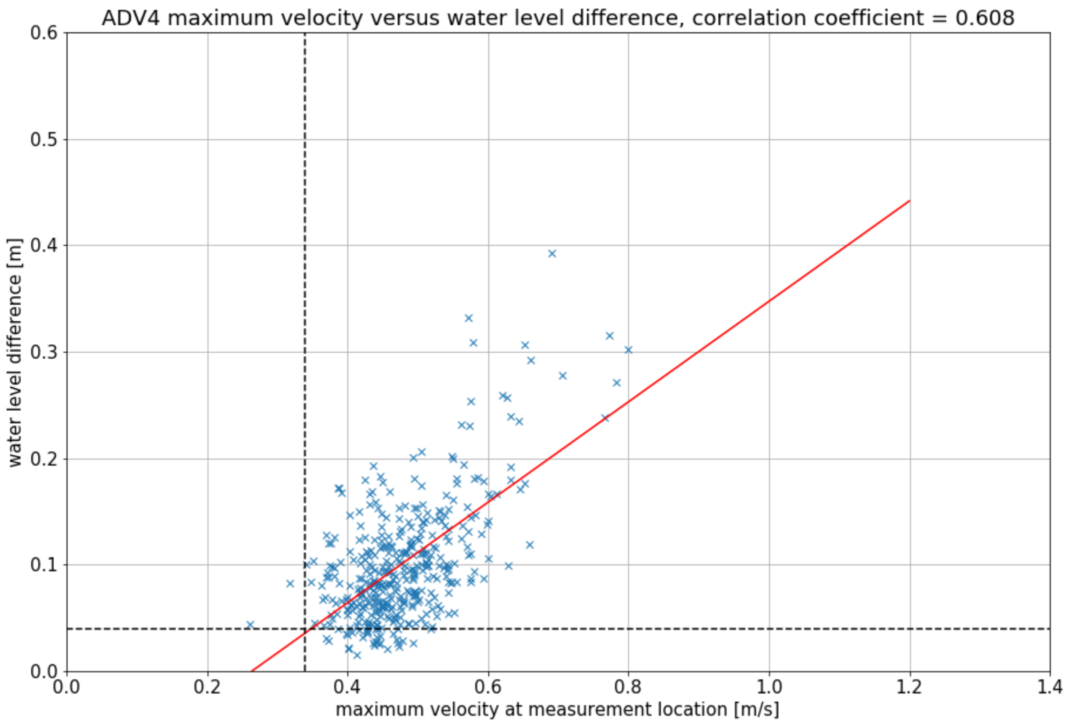

Figure E.49: Maximum flow velocity versus water level difference at the location of ADV4

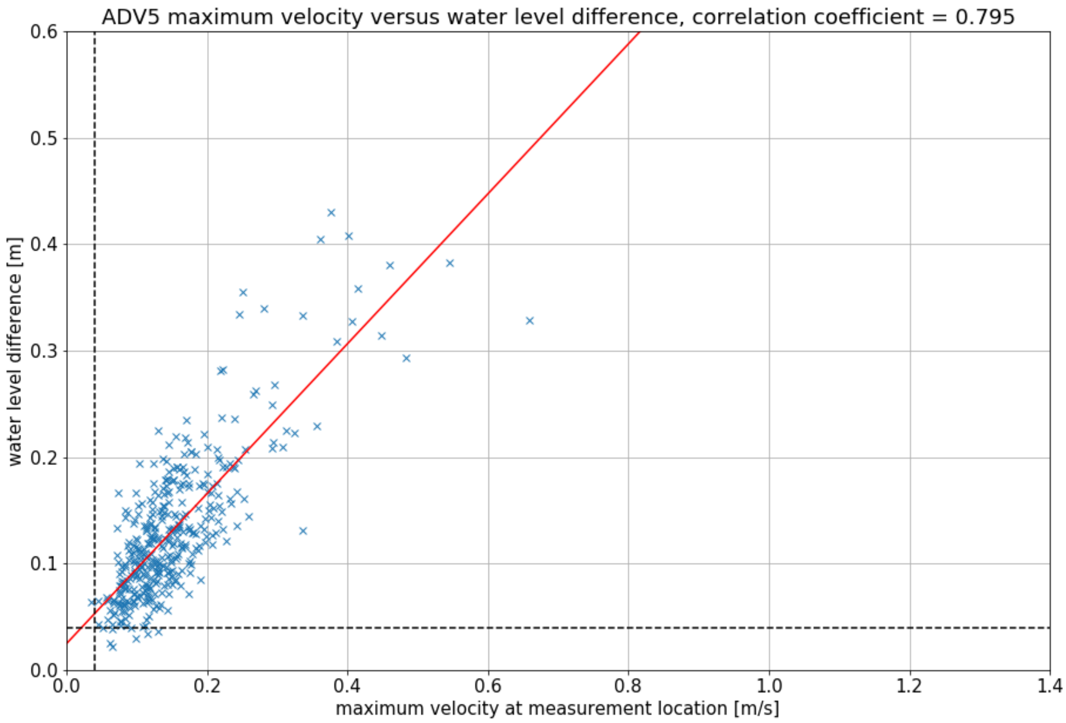

Figure E.50: Maximum flow velocity versus water level difference at the location of ADV5

F

Frequency analysis

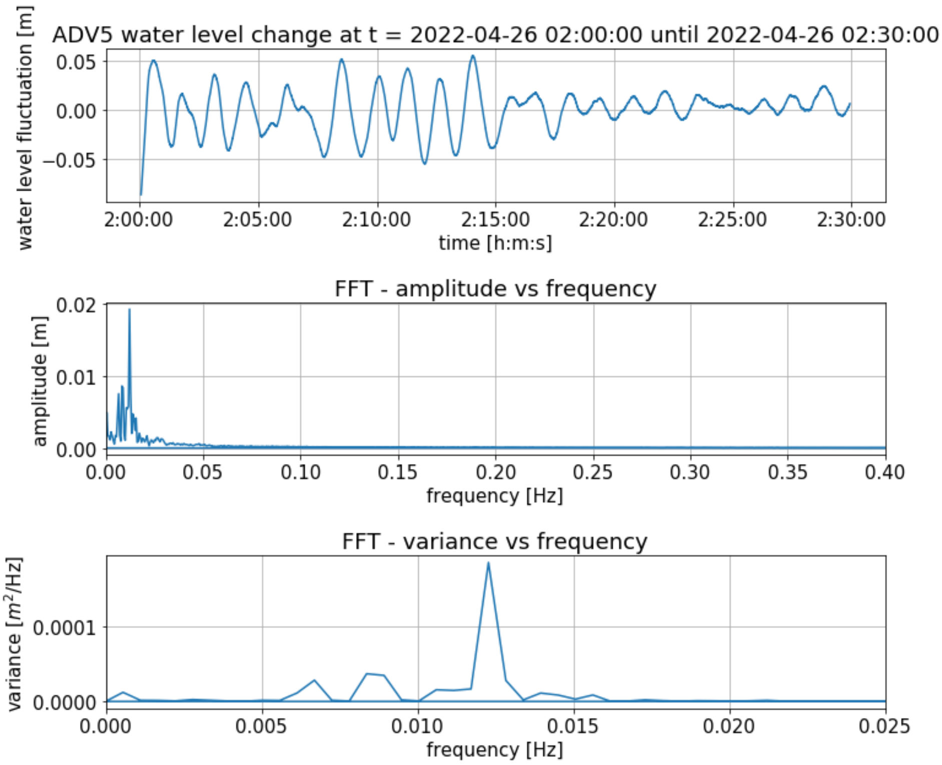

Figure F.1: Frequency analysis 26-04-2022 02:00:00 - 02:30:00. Top figure: water level fluctuation, middle figure: frequency vs amplitude, bottom figure: frequency versus variance

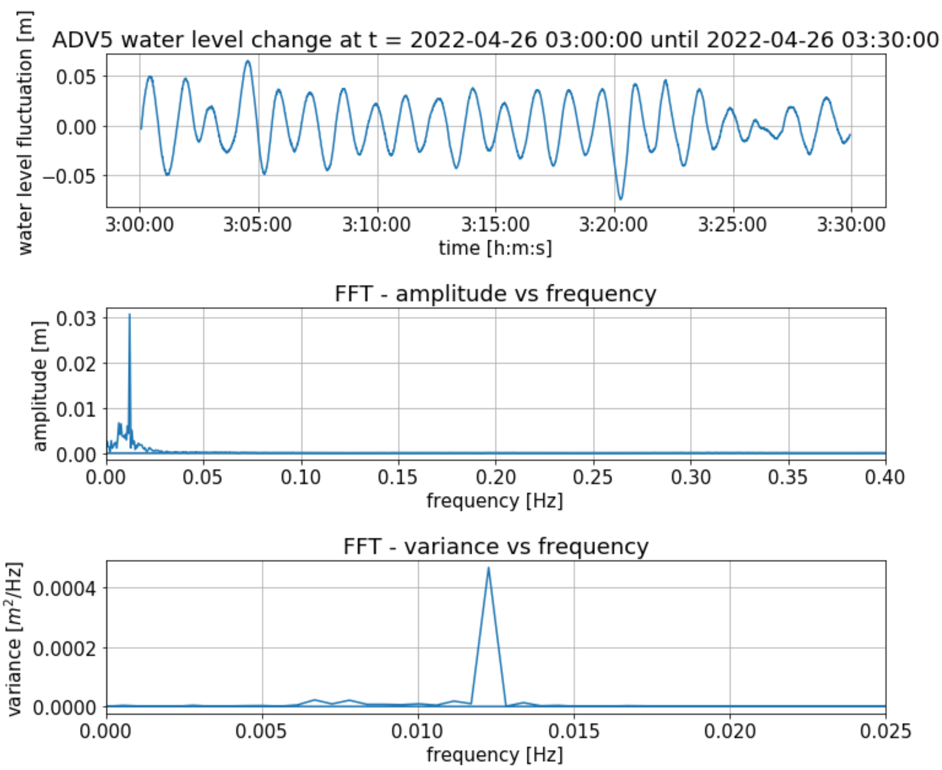

Figure F.2: Frequency analysis 26-04-2022 03:00:00 - 03:30:00. Top figure: water level fluctuation, middle figure: frequency vs amplitude, bottom figure: frequency versus variance

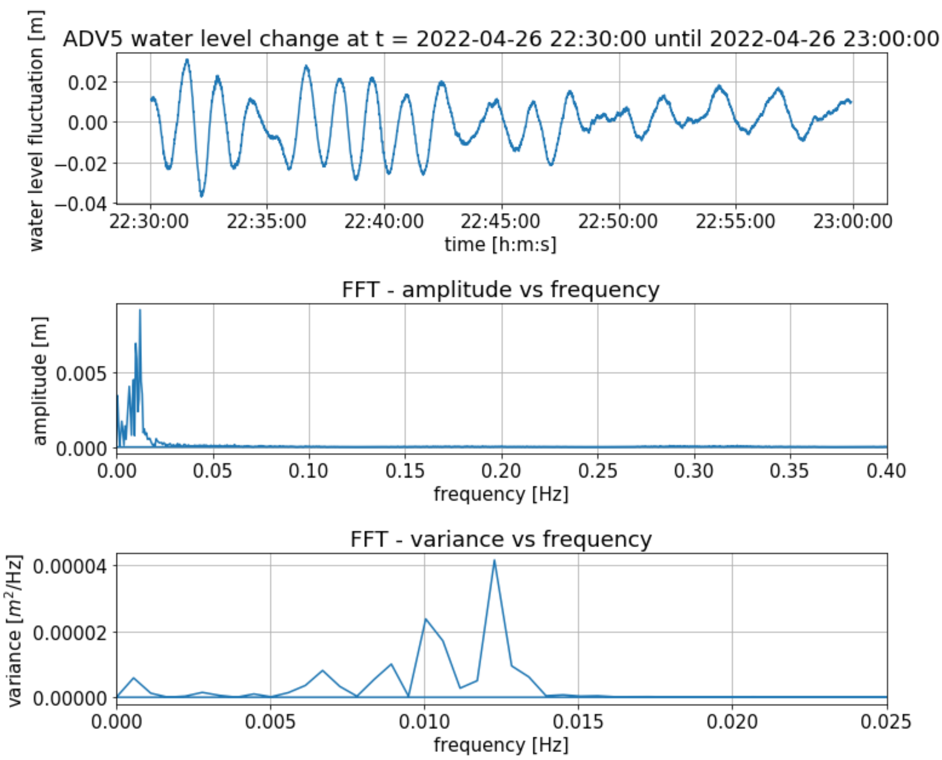

Figure F.3: Frequency analysis 26-04-2022 22:30:00 - 23:00:00. Top figure: water level fluctuation, middle figure: frequency vs amplitude, bottom figure: frequency versus variance

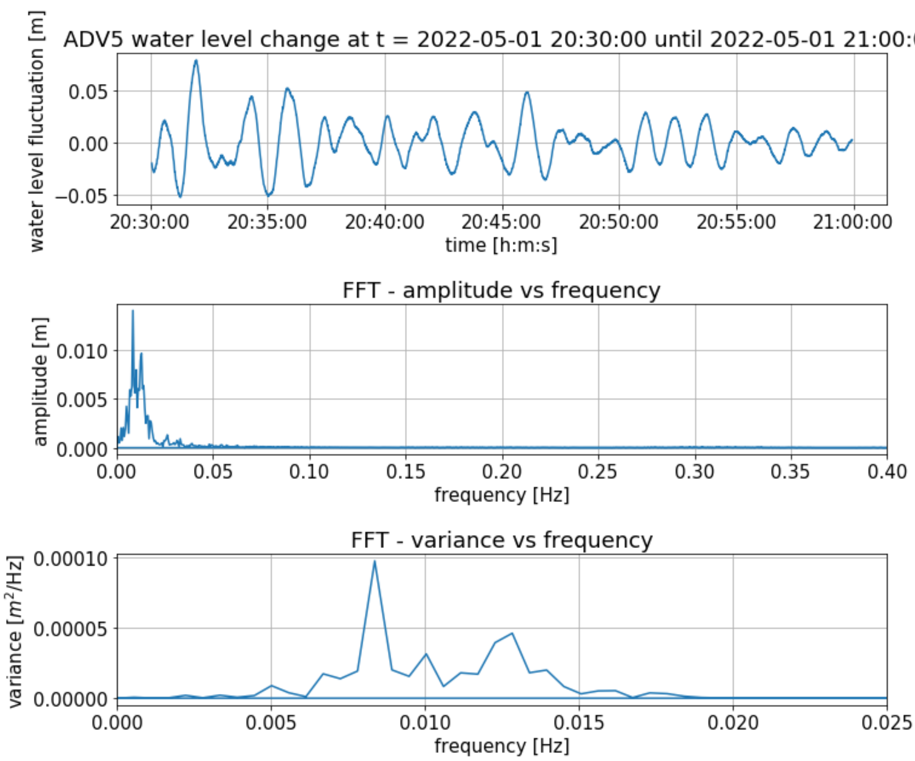

Figure F.4: Frequency analysis 01-05-2022 20:30:00 - 21:00:00. Top figure: water level fluctuation, middle figure: frequency vs amplitude, bottom figure: frequency versus variance

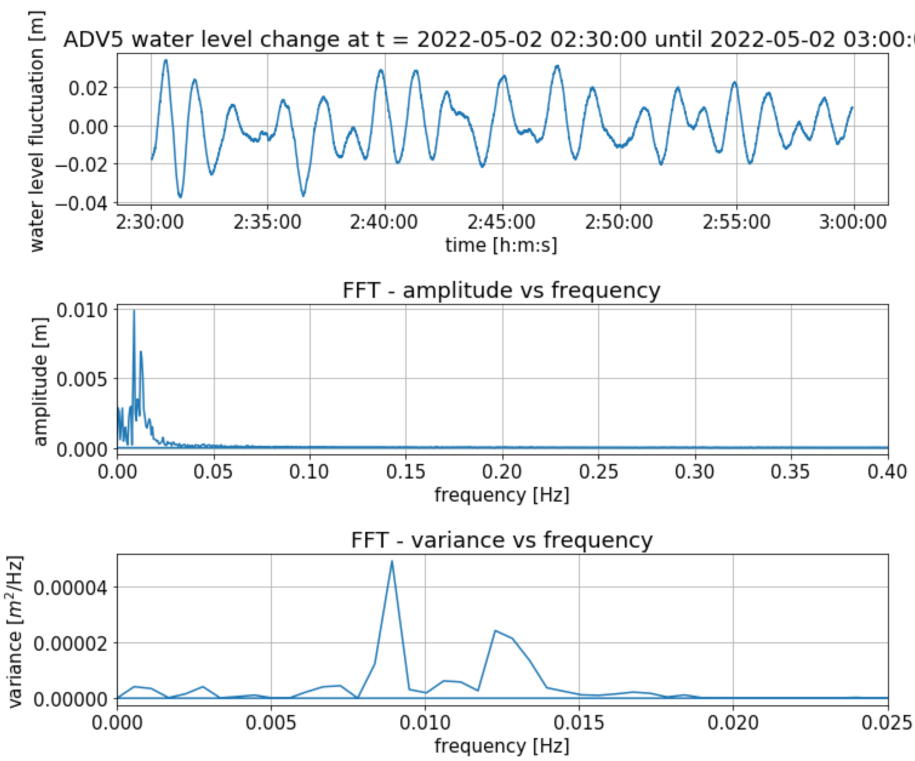

Figure F.5: Frequency analysis 02-05-2022 02:30:00 - 03:00:00. Top figure: water level fluctuation, middle figure: frequency vs amplitude, bottom figure: frequency versus variance