Eindevaluatie pilot Langsdammen in de Waal

Hydromorphological data and observations

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Front page: Longitudinal training wall at Dreumel (photo by Frank Collas)

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Executive summary

In the river Waal, longitudinal training walls (LTW) have been built in 2015 near Tiel as a pilot to replace the groynes. Combined with the realisation, also a measurement campaign of multiple years was started to study the effects of the LTW on water levels, flow velocities and bed level. In this report these measurements have been processed and analysed to answer the research questions posed by Rijkswaterstaat.

Measurements

Water levels have been obtained from longitudinal water level measurements (‘verhanglijnmetingen’), from the national LMW-network, and from measurements with divers. The longitudinal measurements have been executed biweekly from 2018 onwards, and several times per year for the period before. Small changes in water level can not be found as the measurements are strongly influenced by ship waves. Measurements with divers were installed at both river kilometre (rkm) 911.5 and 922 and at the head of all three LTW. The measurements by divers at rkm 911.5 and 922 were only available for the period between August 2013 and December 2016 and did not include periods of low discharge. Data of the divers at the head of the LTW was only available between October 2020 and December 2020. The data from the divers was thus considered insufficient for the analyses.

Flow velocity measurements were executed for many runs at the LTW with the use of ADCP. From 2018 onwards the frequency of the measurements was increased to biweekly campaigns. In each campaign, measurements were done at multiple location in the main channel and auxiliary channel, and each locations was measured in multiple runs. The ADCP measurements have been compared with four reference measurements of the situation before construction of the LTW. In addition, the flow field at the inlets is studied.

Bed level measurements are available from yearly soundings (‘JMP’) and from additional campaigns that were performed every eight weeks. Every campaign covers both the main channel and the auxiliary channel. The yearly sounding make it possible to compare with the situation before construction of the LTW. The soundings have been analysed using the ‘P-map’ method by Rijkswaterstaat, where statistics of the distribution in bed level soundings are derived for both short reaches (100 m) and long reaches.

It is found very valuable that the longitudinal training wall pilot was combined with an extended measurement campaign. However, data should not be merrily stored, but inspected and made available in a processed and uniformed format by an experienced party. This would allow all researches at universities over the past years to also include this extended dataset.

Effect on the water levels

Measurements at Tiel show a lowering of the water level for equal discharge as a result of bed erosion in the period before construction of the LTW. After construction of the LTW the water level at Lobith discharges below 2000 m^3/s remains stable or show a small increase in water level of several centimetres per year (figure 0.1). For average and high discharge, the water levels after construction have been lowered by approximately 20 cm as a result of removal of the groynes (figure 0.2). At high discharge the lowering of the water levels is also effected by the realisation of the side channel Passewaaij (right bank at Dreumel) and the lowering of the groynes downstream of the LTW.

The effect of changes in the inlets could unfortunately not be noticed in the measurements. Even though as a result of the closing of the inlet at Wamel (April 2018), it was found (in ADCP measurements) that the discharge in the auxiliary channel reduced which should have an effect of 10 to 20 cm on the water levels. Unfortunately, stationary (diver) measurements were not available at the inlet of Wamel and the effect is too small to be noticeable in the longitudinal measurements.

The effect of the withdrawal of river discharge through the Prins Bernhardsluizen is clearly visible in the water levels at Tiel. Days where a high discharge was measured through the Amsterdam-Rijnkanaal (up to 68 m^3/s) correspond with an approximately 15 cm lower water level.

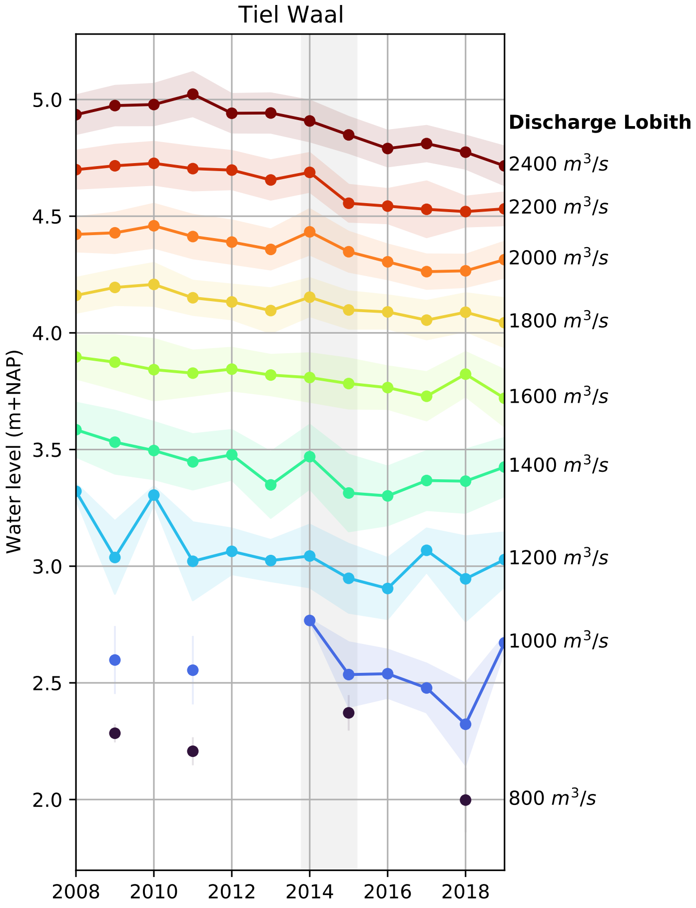

Figure 0.1 Trends in water level at Tiel, showing the mean and standard-deviation per discharge bin (+/- 100 m^3/s). The years influenced by construction are marked in grey.

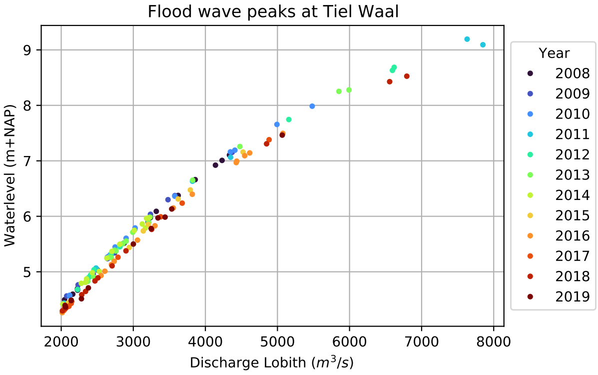

Figure 0.2 Trend in flood peaks per year at Tiel Waal.

Effect op flow velocity and sediment transport

From ADCP measurements a reduction in flow velocity of 2% to 15% is concluded for conditions where the dam is submerged (discharge Lobith above 3000 m^3/s (figure 0.3). It is expected that as a result the sediment transport capacity has decreased with approximately 40%. This is expected to result in sedimentation.

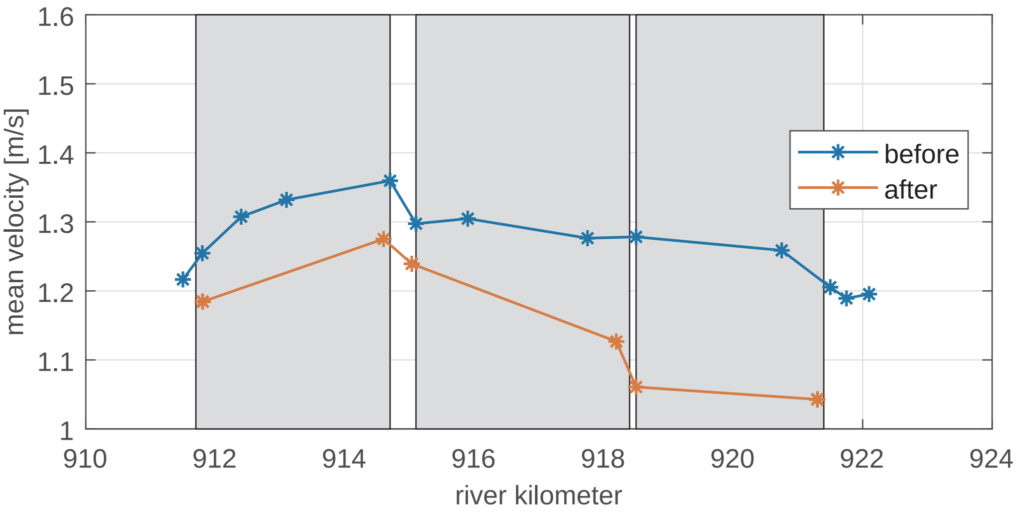

Figure 0.3 Cross-sectional and depth-averaged streamwise velocity at the central 100 m of main channel before intervention (1 Februari 2013) and after intervention (15 and 16 January 2019) for Condition 2 (2500 to 3500 m^3/s at Lobith).

Effect on bed level and water depth

From the P-map analyses (figure 0.4) it is concluded that prior to construction of the LTW the bed level had an small eroding trends at Dreumel, Wamel and upstream, and a small sedimentation trend at Ophemert and downstream of the LTW. During construction of the LTW, the bed level at Wamel and Ophemert shows a strong erosion. After construction at Ophemert the sedimentation is dominant, while at Wamel and Dreumel reaches of erosion and sedimentation are alternating. After the raising of the inlet of Wamel (April 2018), the discharge in the main channel increased and the bed level shows a stronger erosion trend. The smaller adjustments to the inlets of Dreumel and Ophemert, are not showing a change in trend in the measurements. On average the eroding trend (prior to construction) has been stopped and changed into a small sedimentation trend, which is in line with the ADCP measurements.

In combination with the stabilisation of the water levels, the higher bed results in a reduction of the average water depth. As the ADCP measurements show a reduction in flow velocities, this suggests an increase in the flow width. The effect on the local water depth is studied by comparing the bed level to the OLR reference level. This shows that especially at Ophemert the depth has decreased after construction, but that during periods of low discharge (OLA) this depth does not drop below 2.8 m, probably as result of maintenance.

The analyses using P-map can not conclude on the effect of the LTW on river dunes.

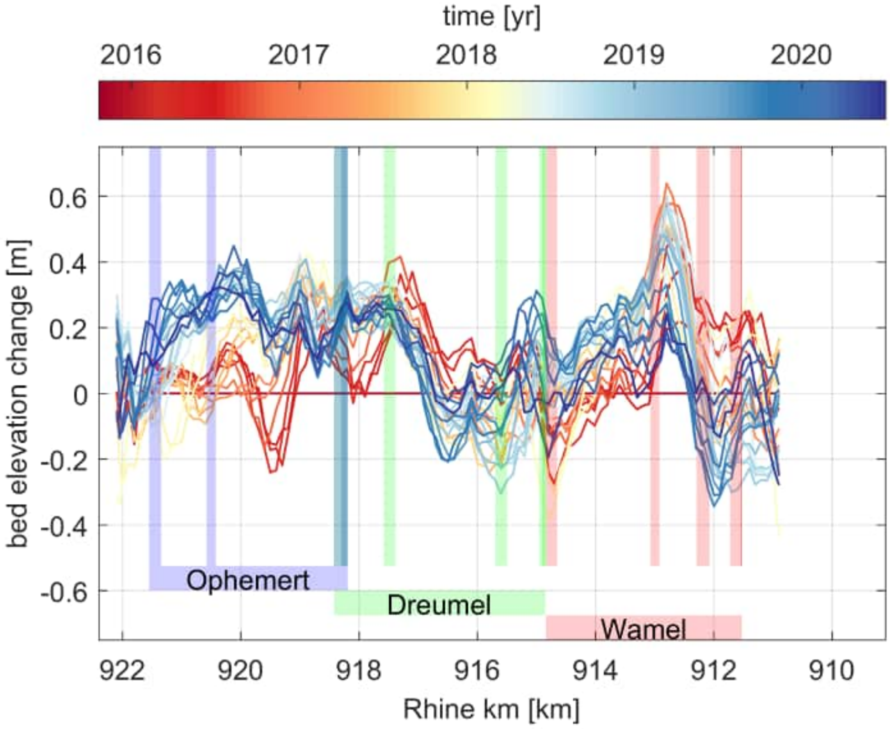

Figure 0.4 Average bed level development based on P-map analysis (averaged over 250 m upstream and downstream) relative to 2015 week 42

Contents

Preface

Het riviersysteem van de Rijn, met daarin alle Nederlandse Rijntakken, kent problemen met onder meer hoogwaterveiligheid, insnijding van de zomerbedbodem, daling van laagwaterstanden en grondwaterstanden, de kwaliteit van het rivierecosysteem, en het gebruik van de rivier als vaarweg. De laatste decennia wordt onderkend dat de sectorale aanpak niet efficiënt is. De beleidsdirecties van het ministerie van Infrastructuur en Waterstaat hebben de wens uitgesproken voor een meer innovatieve systeem- en gebiedsgerichte aanpak, met integrale aandacht voor alle probleemvelden tegelijk. Deze integrale aanpak beoogt de som van alle problemen te reduceren in plaats van slechts de problemen van een beperkt aantal sectoren.

Voor deze integrale aanpak heeft Rijkswaterstaat Oost-Nederland een idee gelanceerd onder de werknaam WaalSamen. Dit is een plan voor herinrichting van het zomerbed in de gehele Waal. De herinrichting wijzigt het principe van het bestaande normalisatiesysteem door het zomerbed te verdelen in twee parallelle stroomgeulen, gescheiden door een langsdam. Om de eigenschappen van deze systeemwijziging in de praktijk te beproeven is over een lengte van tien kilometer de pilot Langsdammen uitgevoerd. Het doel daarvan is een proof of concept, om meer zekerheid te verkrijgen over de integrale werking en de potenties van een dergelijke systeemwijziging.

Voor de pilot werd het Waaltraject Wamel-Ophemert (km 911.5-921.5) bij Tiel gekozen. Om redenen van efficiëntie werd de pilot tegelijk uitgevoerd met Fase III van het project Kribverlaging Waal van het programma Ruimte voor de Rivier. Hiervoor leverde Rijkswaterstaat Oost-Nederland op 30 juni 2011 de producten van een SNIP-3-besluit op aan de Programmadirectie Ruimte voor de Rivier van Rijkswaterstaat, inclusief een omwisselbesluit om geplande kribverlaging te vervangen door langsdammen. De Staatssecretaris van Verkeer en Waterstaat bekrachtigde dit eind 2011. De langsdammen tussen Wamel en Ophemert werden vervolgens in de periode van augustus 2014 tot maart 2016 gerealiseerd.

Voor, tijdens en na de aanleg van de langsdammen is een uitgebreid monitorings- en onderzoeksprogramma uitgevoerd door de partners van de samenwerkingsovereenkomst ‘WaalSamen’. Dit programma is afgesloten met een integrale eindevaluatie, onderverdeeld in 12 inhoudelijke deelprojecten die worden aangeduid met “WP” (werkpakket). Voor u ligt het deelrapport van WP0 over het onderdeel van de evaluatie van het tweegeulensysteem met langsdammen dat gericht is op hydromorphologische data en observaties. De deelrapporten vormen de ondergrond van het hoofdrapport, maar de inzichten en conclusies zijn bij het opstellen van dat hoofdrapport integraler beschouwd, verder geëvolueerd en verduidelijkt. Waar dat mogelijk tot verschillen heeft geleid, zijn de conclusies van het hoofdrapport leidend.

1 Introduction

In the river Waal, longitudinal training walls (LTW) have been built in 2015 near Tiel as a pilot to replace the groynes. Combined in construction plan, also a measurement campaign of multiple years was started. Each year, tens of measurement campaigns were executed, measuring velocities with ADCP, water levels as longitudinal tracks, and bed levels with multibeam soundings. In PhD- and MSc- research projects many of the measurements have been analysed, but a large part has never been processed before. In the evaluation of this pilot in 2020/2021 it became apparent that multiple research questions were still open which could possibly be answered by using this data. As a result, the evaluation was extended with a subproject for data analyses. This report gives the result of the data analyses.

The report has been divided into three chapter discussing the influence of the longitudinal training walls on the water level, on the velocity and discharge and on bed levels. For each of these data, the research questions are introduced, different analyses are performed, and results of the analysis are discussed related to the different research questions. Finally a combined chapter discusses all of the results combined. In addition, some recommendations are provided for some additional analyses based on available data.

The comparison to the numerical models has not been done in this report, as it is our impression that including those results will distract the message that the data is conveying on its own. The comparison of the model results to the data will be included in WP1 Paarlberg and Omer (2021).

In figure 1.5 an overview of the location of the longitudinal training walls is given with respect to the river kilometres. The map shows the inlet end outlet of all dams, as well as the (1 or 2) intermediate openings per dam.

A general description of the Asbuilt design, the dimensions of the inlets (and changes per year), the location of fixed layers are given in appendix A. This appendix also contains a timeline of measures in the region around the longitudinal training walls.

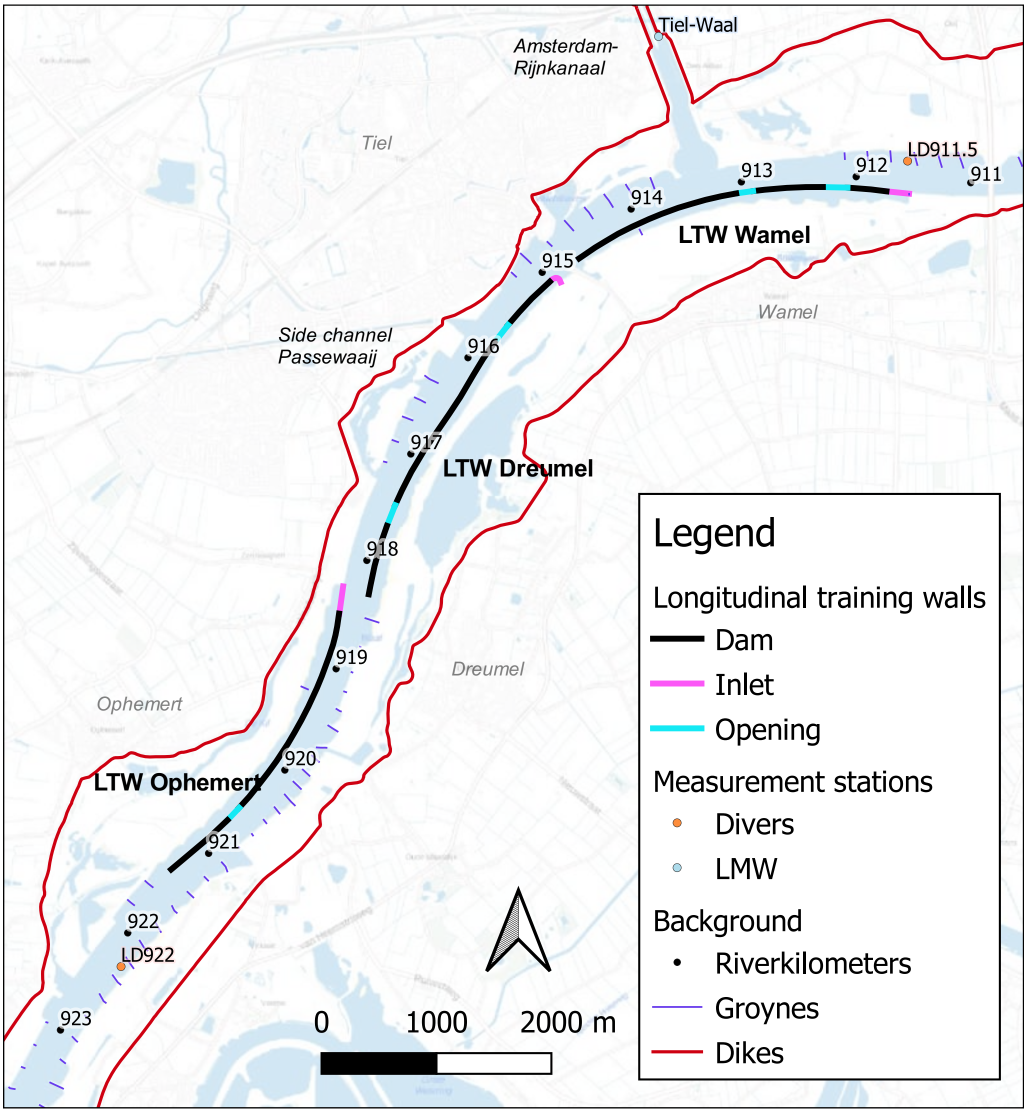

Figure 1.5 Overview map showing the location of the longitudinal training walls including the inlets, intermediate openings and outlets

2 Water level

2.1 Introduction

This chapter analyses several water level measurements that have been performed at the longitudinal training walls. By using these measurements we will be analysing the effect of the LTW on the water levels as well as the effect of the openings on hydraulics of the LTW.

The following research questions are posed:

1. What is the effect of LTW on the water level in the main channel?
2. What is the effect of openings on the discharge in the auxiliary channels and the effect on the main channel water level?

These questions are answered for both the conditions at low discharge and high discharge. Additional analysis is done to show the quality of using longitudinal measurements for local measures.

2.2 Available data

To answer these questions the following data were analysed:

- longitudinal measurements of water level and bed level. From 2008 to 2017 on average 3 measurements per year. From 2018 to 2020 this increased to 19 measurements per year (see B.2).
- time series from the Landelijk Meetnet Water (LMW) (also referred to as MWTL, Monitoring Waterstaatkundige Toestand des Lands) consisting of (amongst others) measured water levels at Zaltbommel, Tiel and Dodewaard and of discharges at Tiel and Lobith (derived from rating curves) from January 2008 up to July 2020.
- time series of water level measurements using a diver at the longitudinal training walls at rkm 911.5 and rkm 922. These measurements are only available from August 2013 to December 2016.
- time series of depth measurements using a diver at the head of all longitudinal training walls. These measurements are only available from October 2020 to December 2020.

In the sections below the processing of these measurements is described.

2.2.1 Processing of longitudinal measurements

In all recent years (from 2017) each set of longitudinal measurements of bed level and water level consists of multiple parallel tracks. Besides the track in the river axis (‘aslijn’) there are measurement at the left bank (‘L-oever’) and the right bank (‘R-oever’), and in the auxiliary channels Wamel, Dreumel and Ophemert. Details on each set of measurements are given in appendix B.3. An example is given in Figure 2.1. For each measurement the following subplots are given:

- Top left: Map of all measurements, showing the exact location and date of all tracks. The title of this plot is the label of the dataset at Rijkswaterstaat.
- Top right: Time of measurements (orange) with the discharge at Lobith. The discharge at the mean of the time span is used as the representative discharge for the post-processing.
- Centre figure: Longitudinal plot. Averaging is applied to make it more readable. Exact height and width of all openings is shown as dashed line (including the

changes in the dimensinos as given in appendix A.2).
- Lower figure: Difference in longitudinal measurements to the river axis. Vertical lines indicate the location of the inlet, outlets and openings.

Based on this sheet the following can be interpreted for this (randomly picked) single measurement. The measurement was taken during a falling discharge, this means that at the LTW the discharge might have been slightly higher, and also that later measurement will have been at a lower discharge. For this campaign they first measured the river axis, than the three auxiliary channels and than the right and left bank. These measurements took 6 hours.

From the longitudinal plot it shows that the inlets of Ophemert and Dreumel are fully flowing, while the inlet of Wamel, as well as all intermediate openings, are just about to be over-topped. From the longitudinal difference plot it shows that in tha auxiliary channel of Ophemert the water level is more or less equal to the river axis. This unlike the channels at Wamel and Dreumel which have a lower water level slope than the main channel, resulting in a head difference. This head difference only starts building upstream of the last (downstream) intermediate opening, showing that apparently this last opening has some role in the exchange of discharge, either by over-topping or due to the higher permeability of these sections.

On a more detailed level there are also some spikes in the difference plot. A spike in all lines indicate that the actual jump was in the reference (the river axis). These spikes are caused by passing ships (further mentioned below) and possibly other waves. Comparing the location of the spikes between measurement campaigns showed no correspondence.

The tracks have a high temporal resolution (approximately 1 second). With a vessel speed of 3 m/s (upstream direction) to 5 m/s (downstream direction) this results in a spatial resolution of several metres. In figure 2.2 and figure 2.3 unfiltered measurements of 20-08-2018 around rkm 920 are shown. Both figures clearly show a large scatter of approximately +/- 5 cm (macro turbulence). The measurements also show the effect of wind and ship waves on the local water level and thereby on the measurement vessel. Most apparent are the water level depressions of passing (i.e. encountering) vessels (at rkm 920.8) with a height of -15 cm and a length scale of 75 m (equal to 15 seconds). Assuming the measurement vessel is only small and that the relative velocity to the passing vessel is 8.5 m/s, this gives a water level depression with a length scale of 130 m. This is equal to the water level depression (induced by the return current) of a large Rhine vessel (ship type M9 or M12). Also note the increase in vessel velocity as a result of the return current.

For the analysis of the measurements we are mostly interested in the large scale impacts on the water levels. Therefore the results are filtered to remove the scatter and to remove the effect of waves. Several filters and filter parameters have been tested (see appendix B.1). As a result the longitudinal measurements have been processed into two products for different typical applications:
- a Savitsky-Golay filter[1] with a window of 81 m, which performs very well for only removing the scatter and keeping all local variation (Savitzky and Golay, 1964).
- a rolling average with a window of 1000 m, which removes both the large scatter as well as the local variation. However, this rolling average will have (slightly) lower water levels than the undistributed water levels due to water level depressions.

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[1] A Savitsky Golay filter can be interpreted like a rolling polynomial fit. In this study a second order fit is applied.

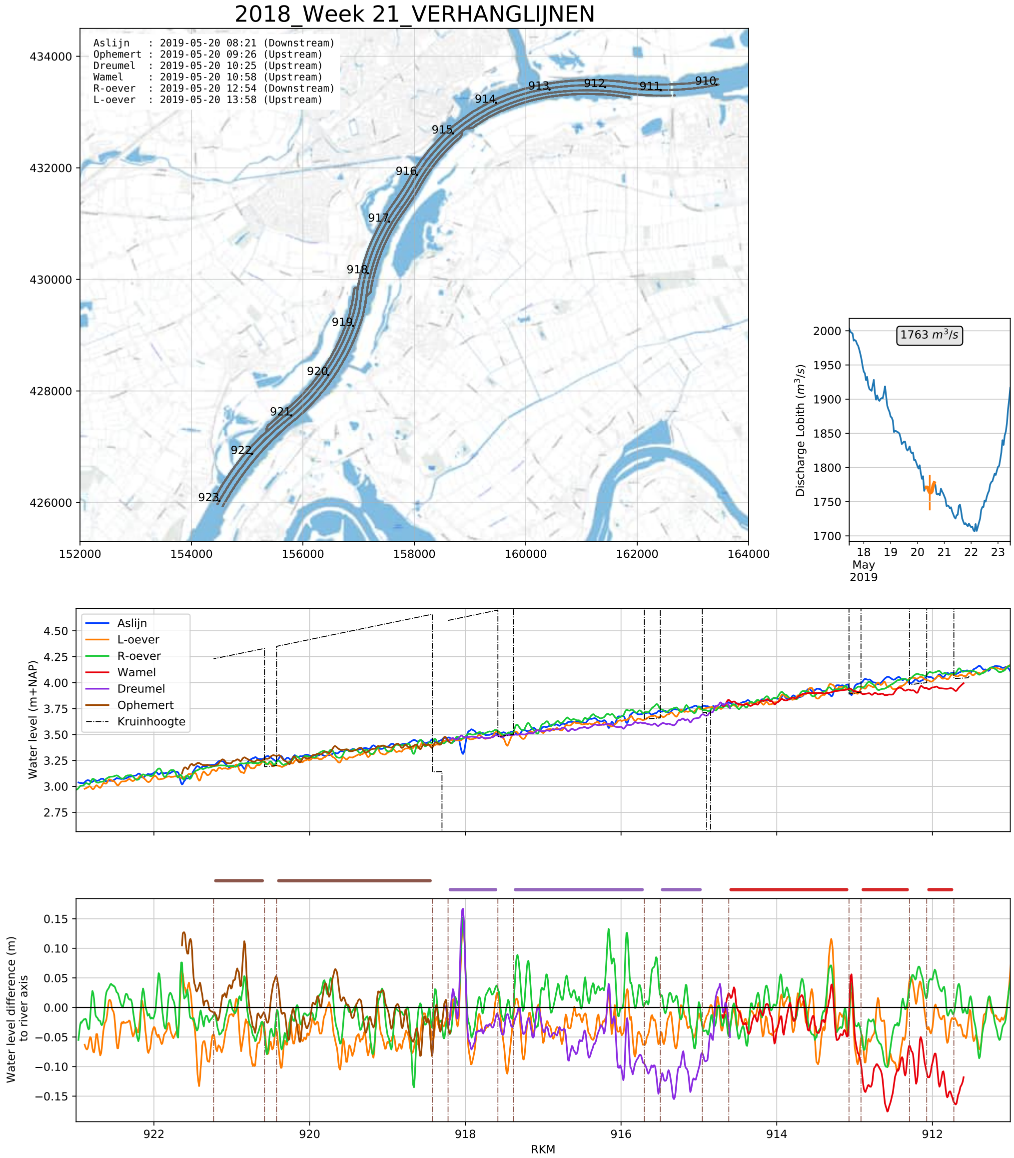

Figure 2.1 Example of the details given for each set of longitudinal water level measurements. A description of all lines in each subplot is given above

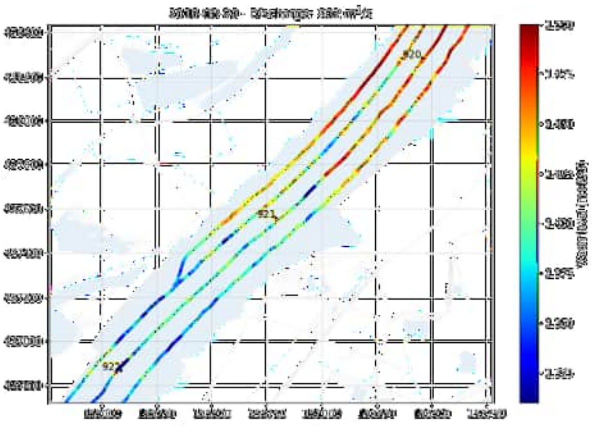

Figure 2.2 Map of longitudinal water level measurements between rkm 919.8 and 921.2 (date measurements: 20-08-2018)

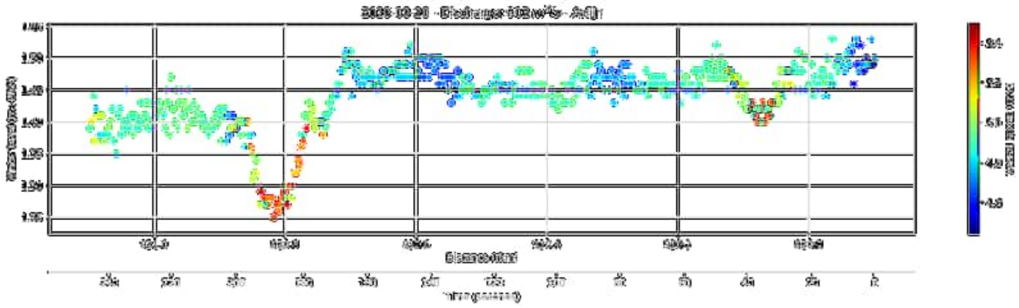

Figure 2.3 Longitudinal plot of water level measurements around rkm 920 (date measurements: 20-08-2018)

Each measurement campaign took multiple hours to several days. For (steeply) falling or rising discharges this can result in a bias in the different tracks up to several decimetres. In the analyses of the results, parameters are chosen such that are influenced by this bias as little as possible.

2.2.2 Processing of water level measurement stations

For the measurements from LMW and the diver stations no significant post-processing was required. An overview of the available measurements is given in figure C.1 for the LMW measurements and in figure C.37 and C.38 for the diver measurements. Both measurements are delivered with a temporal resolution of 1 hour.

For the measurements by divers at rkm 911.5 and rkm 922 only data up to November 2016 was made available. Although it is expected the divers are still in operation, more recent data could not been found by Rijkswaterstaat. For the divers at the head of all longitudinal training walls data was only available from October 2020 to December 2020. Although it is expected that the divers have been operationally for a longer period of time, data of the earlier period could not be found by Rijkswaterstaat.

2.3 Effect of the longitudinal training walls

In this section an analysis is given of the effectivity of the LTW in setting up the water levels. In this section we look at the entire section and the cumulative effect upstream of all LTW. In section 2.3.1 we try to get conclusions from the longitudinal measurements, but it is concluded that these effects are better analysed by using the water level timeseries at the LMW-stations which are given in section 2.3.2.

In the next section (section 2.4) the effect of each individual dam is analysed, taking into account the different configurations of the inlets.

2.3.1 Water level change in longitudinal water level measurements

A subset of all longitudinal measurements for discharges at Lobith between 1000 and 1500 m^3/s is included in figure 2.4. The difference in line style indicates if the measurement is done prior or after construction of the LTW. By using the rolling average local variation has been filtered. The effect of the LTW can be summarised by looking at the total head difference over the LTW between rkm 911.5 and rkm 922. This result is given in figure 2.5.

Results are split in a dataset before construction (all measurements until july 2014), during construction, and after construction (from november 2015). The water level difference has been plot against both the discharge at Lobith and the water level at rkm 922 on the x-axis. By plotting against the water level we correct for (short-term[2] and long-term[3]) changing discharge distribution on the Rhine branches (and upstream withdrawals, see section 2.5) and for the time offset between the Lobith and the LTW (the alternative to plot to the (rating curve) discharge at Tiel is discarded as the quality of this discharge has a negative bias[4]). However, also the water level at rkm 922 is influenced by measures (groyne lowering, effective at higher discharges) and by other external forcings like the wind set-up and tide (most significant at lower discharges[5]). Combined with the scatter from macro turbulence and ship waves in the measurements itself, this results in a plot with a large scatter.

From these measurements no conclusions can be drawn for the effect of the LTW on the water levels at rkm 911.5 at low discharges (lower than 1500 m^3/s). The point cloud in the measurements before and after construction seems very identical, i.e. the water levels of the in the new situation fall well within the point cloud band-width of the old situation. The large variation in the situations with low discharge (below 1200 m^3/s can also be the result of the withdrawal of discharge to the Amsterdam-Rijnkanaal, as the Prins Bernhardsluizen are opened in these conditions. This effect is further analysed in section 2.5.

For higher discharge (higher than 2000 m^3/s) the longitudinal water level measurements do show a reduction in water levels. However, the measurements

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[2] Short-term variation in discharge distribution is the result of the operation of the weir at Driel. By Rijkswaterstaat an analyses is performed of the difference between the measured water levels and discharge at Driel (and other weirs) with the expected water levels and discharge from the weir operations ('stuwprogramma'). From the analyses it can be concluded that the difference can be many decimetres (too high) and over 100 m^3/s (too low). However, these deviations were not during the lower and very high discharges and therefor do not influence the analyses.

[3] Long-term changes in dicharge distribution are the result of bed degradation around the bifurcations points. Over time the fraction of the discharge to the Waal is increasing.

[4] Sieben (2020) mentions that the current MWTL Waal discharge recordings currently underestimate the discharge compared to ADCP measurements

[5] From model simulations it is approximated that the tide at rkm 922 is approximately 7 cm at a discharge of 700 m^3/s and reduces to 4 cm at a discharge of 2000 m^3/s and below 1 cm for discharges above 9000 m^3/s. At Tiel the tidal amplitude is never larger than 1 cm.

before construction are only scarce and not sufficient for definitive conclusions on the effect of the LTW.

For higher discharge (between 1500 and 3000 m^3/s) the longitudinal water level measurements show that the water levels have become lower after construction of the LTW. The purple markers are clearly below the orange markers, even when considering the scatter bandwidth. At these discharges the intermediate openings are submerged, and the dam itself is just slightly over-topping at the high end of this spectrum (see also figure fig:dimensions). During these conditions the flow width (and area) has increased in the new situation. However, the higher 'before construction' measurements could also be the result of long term trends in the data set. It contains many measurements around 2000 to 3000 m^3/s between 2008 and 2011 with many more years of ongoing bed erosion (see also the analyses of LMW Tiel in section 2.3.3).

For higher discharges (larger than 3000 m^3/s only 1 valid measurement is available for the situation before construction.[6] No conclusions can be drawn from the longitudinal water level measurements for these conditions.

The longitudinal water levels are only a limited data set when it comes to long scale effects. In section 2.4 more analyses will be done on local effects from these measurements.

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[6] The two odd measurements at 7500 m^3/s seem to have been caused by a (overnight) break during the measurement campaign for a falling discharge (see also appendix B.13 and B.14).

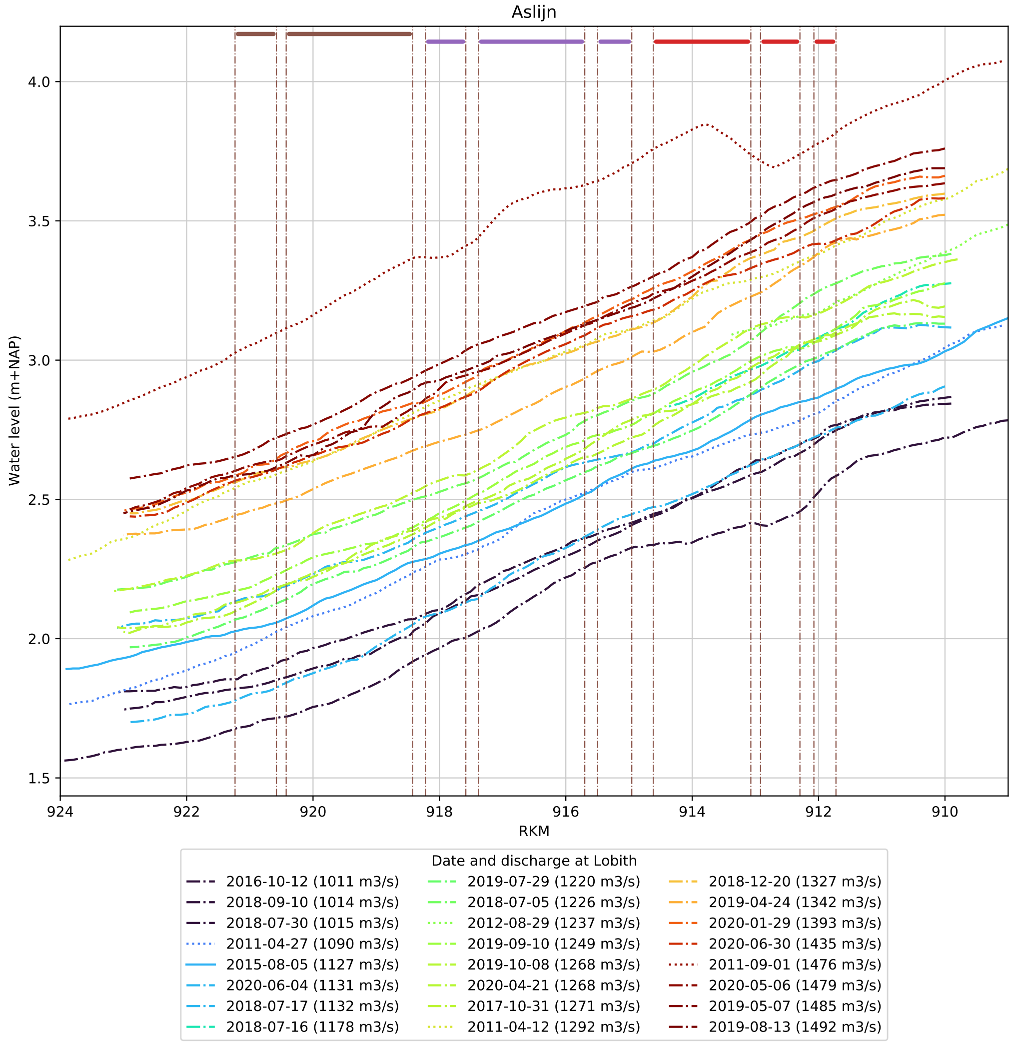
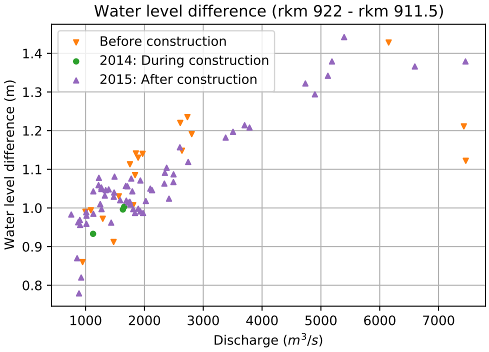
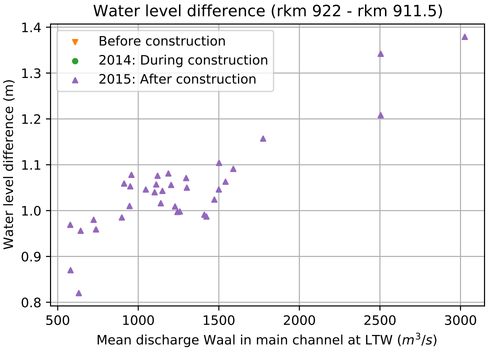


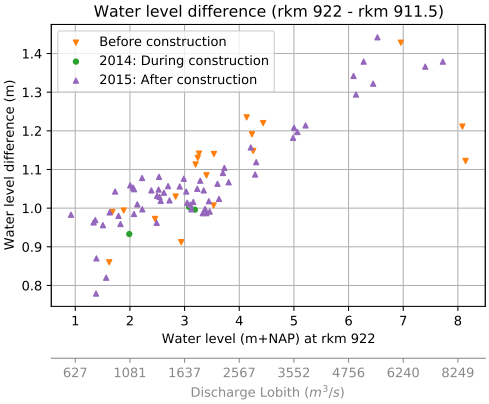
Figure 2.4 Longitudinal measurements at the river axis for a discharge at Lobith between 1000 and 1500 m^3/s. The data has been filtered using a rolling average over 1000 m. The line style indicated if the data is before construction (dotted), during construction (solid) or after construction (dash-dot).



(a) Plot against discharge at Lobith



(b) Plot against mean measured discharge on the Waal at the LTW. A tollerance of +/- 2 days is applied to increase the data set from 18 to 37 measurements.



(c) Plot against water level just downstream of the LTW. The discharge is based on the betrekkingslijnen

Figure 2.5 Water level difference (between rkm 922 minus rkm 911.5) from the longitudinal water level measurements based on all available longitudinal measurements, split in categories of before, during and after construction of the LTW.

2.3.2 Water level change at (LMW) measurement stations

In the remainder of this section the focus is on the water level measurements at the LMW measurement stations. The diver measurements did not add conclusive results, possibly due to the short time span of these measurements (less than one year after construction). Results are included in appendix C.2.

2.3.2.1 Mean water level per discharge Lobith

Similar to the analyses in WP10 of this evaluation (Chavarrías *et al.* (2021)) the water level measurements are analysed by discretising the discharge at Lobith in bins (of 200 m^3/s) and plotting the mean and standard deviations of each bin. This procedure and its limitations are further explained in appendix C.1.2, including results at various other stations along the Waal. Downsides of the usage of the discharge at Lobith as a reference parameter are given in section 2.3.1. As the period prior to construction contained a lowering trend in water levels, the grouping over long periods will include a (positive) bias. Therefore the analyse is split in groups of each individual years (2008 to 2019), this method is explained in appendix C.1.3 and shown for Tiel Waal in figure 2.6.

Although the variation per year includes some odd year to year variations, it is clear that the water levels showed a declining trend prior to constructing the LTW. After construction this has stabilised for lower discharges (smaller than 2400 m^3/s), while at higher discharges the declination in water levels continues.

The water level increase at lower discharges is not as significant as was expected from model studies. This is partly caused by the effect of downstream measures which have reduced the water levels (see section 2.3.3), but also show that the LTW are less effective than expected. Possible explanations, which may explain this water level reduction are (i) a reduction of the alluvial roughness, (ii) the lack of horizontal mixing (previously caused by groynes), (iii) the porosity of the longitudinal training wall structure, (iv) too much water entering the auxiliary channels, (v) changes in the bed level during and after construction, or (vi) the increase in flow velocity (due to an M2 backwater curve). Unfortunately, we have not been able to quantify which of these effects are most important.

The change in discharge distribution over the Rhine branches (as a result of bed degradation) probably results in an increasing discharge to the Waal for the same discharge at Lobith. This trend is expected to be present for both the period before as after construction. Without this additional discharge, the declination in water levels would have been larger. For very low discharges (below 1200 m^3/s) the withdrawal of discharges through the Amsterdam-Rijnkanaal (see section 2.5) might result in a reduction in discharge on the lower Waal, which could be the reason of the large dip in 2018 (also visible at Zaltbommel and St. Andries in figures C.5 and C.6).

The lowering of the water levels at the medium to high discharges in this plot (2500 to 5000 m^3/s at Lobith) show the expected water level lowering, but for an analysis at discharges waves (so most higher discharges) it is more effective to look at the peaks (see section 2.3.2.2).

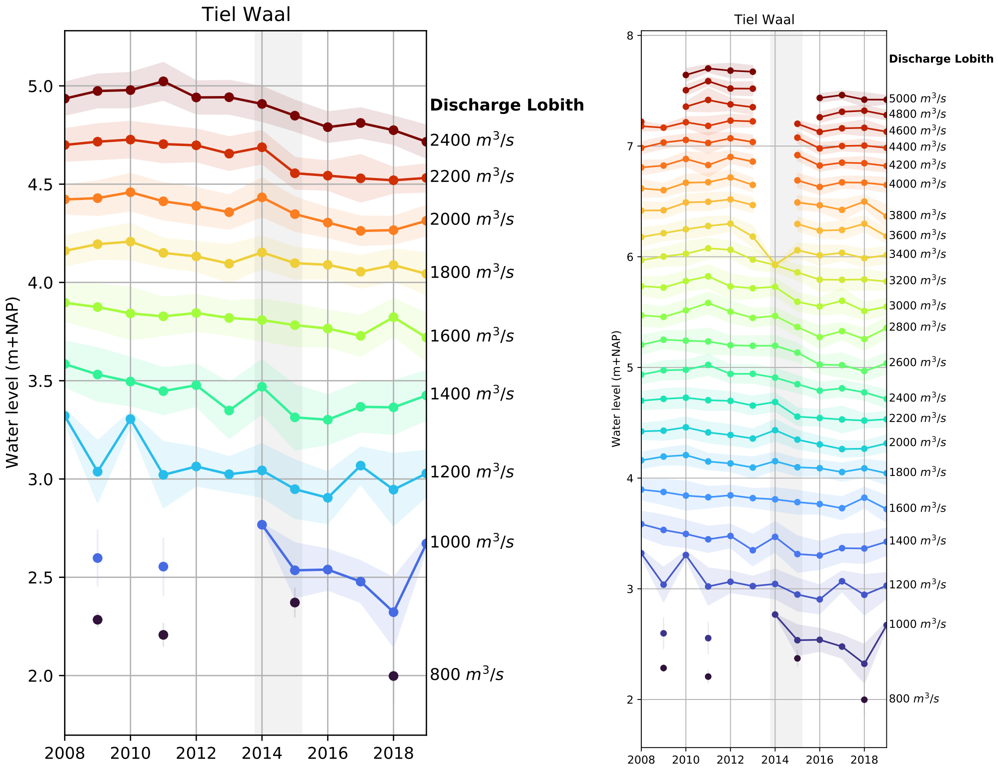


Figure 2.6 Trends in water level at Tiel, showing the mean and standard-deviation per discharge bin (+/- 100 m^3/s). The left plot shows the effect up to 2400 m^3/s, the right plot shows the effect up to 5000 m^3/s. The years influenced by construction are marked in grey.

2.3.2.2 Effect on peaks and troughs

As a final analyses of the water levels each peak and trough of the period 2008 to 2019 has been analysed (see appendix C.1.5). The results at Tiel are shown in figure 2.7. This further repeats the earlier conclusions or lower discharges, but additional shows the effect at the very high discharges (above 5000 m^3/s). At these higher discharge a similar water level reduction of 20 cm is concluded.

The construction of the LTW coincides with the lowering of the groynes (all groynes upstream of rkm 911.5 and downstream of rkm 922). And during the period also additional measures in the flood plains were constructed (e.g. side channel Passewaaij). It can therefore not be concluded that these effects are solely the effect of the LTW, but that they are the effect of these measures combined.

However, this trend might be biased due to other measures or due to a trend in the ‘Before’ period. To exclude these effects, the analyses is repeated for each seperate year in the data set, resulting in the point cloud of figure 2.8. Because all points are located on the diagonal, making it hard to spot the (relatively) small difference between the years, the right figure is added in which the water levels are corrected to a polynomial fit (more explanation in appendix C.1.6). This figure can also be interpreted as rotating the previous figure by 45 degree. In this plot the change over the years is more apparent: there is a clear reduction in water level for all measurements after 2015 to the measurements before 2014 for discharges of 2500 m^3/s and higher. This coincides with the construction of the LTW, but also with the lowering of the groynes and the side channel at Passewaaij (see appendix A.4). The reduction in peak water levels is approximately 20 cm.

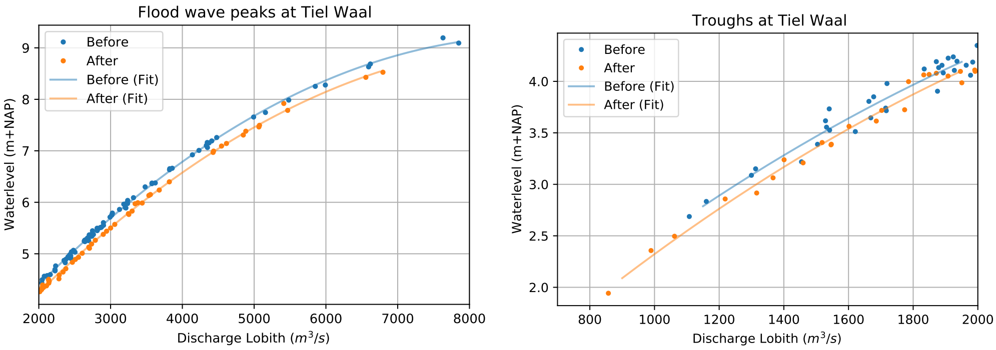


Figure 2.7 Peaks and troughs at Tiel Waal for the period January 2008 to March 2020. Including a least square second order polynomial fit.

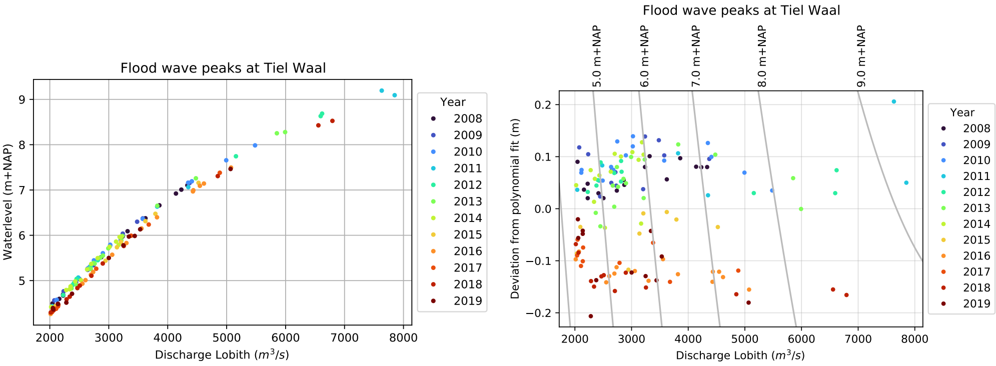


Figure 2.8 Trend in flood peaks per year at Tiel Waal. Left: Absolute water level; right: Water level after subtracting a polynomial fit for increased readability.

2.3.3 Change in head difference between measurement stations

In the earlier paragraph the absolute water levels were analysed. Those are also influenced by effects downstream of the LTW and might show deviation from the trend due to uncertainty in the discharge. To isolate the effect of the LTW this section analyses the difference in water level between the stations Tiel Waal and St. Andries. Most of this reach includes the longitudinal training walls. In figure 2.9 the trends are shown. The lower subplot includes the bed level over the entire ‘trajectvak’ (see also chapter 4) as an indicator for the reach scale bed level trends.

The figure show a gradual reduction in the head difference over the period 2008 to 2014. The reduction in head difference is more than the observed bed level trends in the lower plot. The reason for this is unsure, but possibly the average bed level is not representative for the flow area. From the start of the construction of the LTW, initially the water levels drop even further in 2015 to 2016, possibly as a result of the situation during construction. From 2017 onwards the head difference has recovered to the situation pre-construction and shows a slight increase in head difference over the years.

This trend in head difference shows a strong correlation with the trend in bed level as shown in the lower subplot. The drop in the average bed level in 2015, corresponds well with the reduction in head difference in 2015 and 2016. This suggests that (as expected) the head difference is very closely related to the bed level. There is a slight phase lag (the water level drop is later than the bed level drop), which might be the result of both the averaging over the reach, as the averaging over a full year: local and temporal information might be missed. The bed level change downstream of the LTW is not included, but might also influence the water levels up to Tiel.

For the evaluation of the LTW a clean comparison is necessary. To prevent side effects of the discharge withdrawal at the ARK (see section 2.5), we look at discharges above 1200 m^3/s. For these conditions the discharge in the auxiliary channels is larger than 12 % (apart from Wamel, see figure 3.18) resulting in the expectation of a reduced water level slope (as derived from theory in Sieben (2020)). To prevent the effect of bed level we look at years with approximately the same level: 2013 versus 2017. For these conditions, the lowering of the water levels is between 1 and 3 cm. This effect is most likely caused by the LTW.

Plots for other stations are included in appendix C.1.4. Although these plots show interesting trends, they are not further analysed as they are not in the scope of this project.

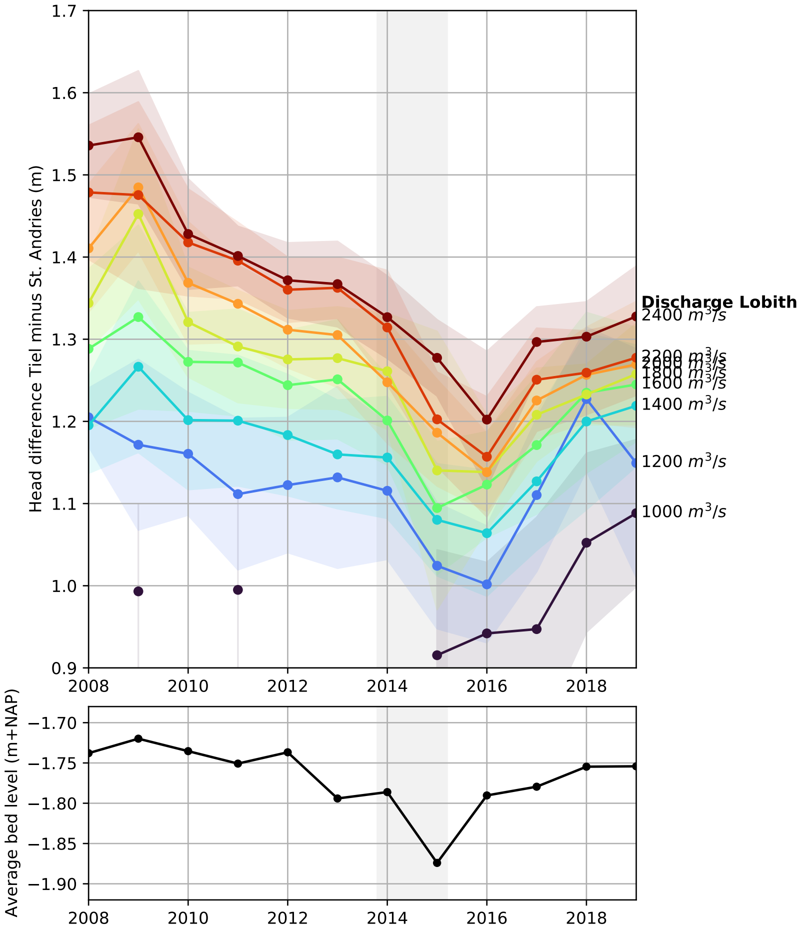


Figure 2.9 Trends in water level difference Tiel minus St. Andries, showing the mean and standard-deviation per discharge bin (+/- 100 m^3/s). The lower subplot includes the bed level over the entire 'trajectvak' (see also chapter 4)

2.4 Effect of changing in inlet openings

In this section we focus on the effect of the individual dams (section 2.4.1). An analysis is given of the effect of the openings on the water level just upstream of each dam, as well as the effect of the openings on the slope within each auxiliary channel (section 2.4.2).

2.4.1 Effect of openings on the water level in the river axis

Similar as the analysis in section 2.3, the water level difference at each LTW (upstream minus downstream) has been plotted against the water level downstream of Ophemert in figure 2.10. For each dam all phases of inlet design are show with different markers (see also appendix A.2 for dimensions and photos of the different inlet designs).

Similar to the analysis in section 2.3, also in these plots the scatter in results is very significant. As a result, no conclusions can be given with certainty because the (scarce) events can easily contain a bias as a result of the external forcing or geometry (assuming this is the cause of the scatter). More measurements, or different measurements are necessary gain more confidence in the results. Taking into account these possible pitfalls some crude interpretations can be made.

At Wamel the construction of the LTW seems to have caused (again) the lowering of water levels at median discharges (between 3 and 5 m+NAP at rkm 922). At low discharge insufficient measurements before construction are available to get any conclusion. There is also no significant effect of the lowering and rising of the inlet in 2018 and 2020. Unfortunately also the stationary measurements are not on the right location (Tiel is too far downstream of inlet Wamel) or have insufficient data (all diver measurements). The water level prior to the construction at the highest discharges, are outliers and should be ignored (these measurements contain an overnight break).

At Dreumel conclusions are very similar. After construction, the water level is reduced at median discharge (between 3 and 5 m+NAP at rkm 922), but also seems to have reduced at low discharge. The reducing of the width might have resulted in a slight increase in water levels, but only measurements are available for median to high discharges. The lowering of the inlet (2019; purple triangles) seems to have resulted in higher water levels (e.g. at 2 m+NAP at rkm 922), but as this is not the expected response, it is probably caused by other changes in forcing or geometry. At the highest discharges there is no visible difference between the situations before and after construction.

At Ophemert the measurements again show a clear lowering of the water levels at median discharge (between 3 m+NAP and 5 m+NAP at rkm 922). At low discharge little measurements were available before construction, but they indicate a significant reduction in water level. By reducing the width (in 2019) the water levels seem to have slightly increased.

2.4.2 Effect of openings on the water level slope in the auxiliary channel

Unlike the water level in main channel, the slope in longitudinal direction in the auxiliary channel is very significantly influenced by changes in the inlet and for changing discharge (for the times and dimensions of changes see appendix A.2). This can be seen in longitudinal plots of water level in Wamel in Figure 2.11. Both the Savitsky-Golay filtering and the rolling average are shown. The Savitsky-Golay shows so much information that it can be hard to comprehend, while the rolling average smoothens away many interesting details. Similar figures for all auxiliary channels and all discharges are given in appendix B.4 (only including the Savitsky-Golay filter). In appendix B.5 additional figures are included of the difference in water level to the main river axis (only including the rolling average).

From a discharge of 1700 m^3/s at Lobith the raised inlet (solid lines) is slightly over-topping and the intermediate openings start (more slightly) over-topping. Still the (right) figure shows that the slope has a knick-point between rkm 913.5 and 914 with the steepest downstream of this point, where there are no intermediate openings. This is most probabaly caused by the construction of a fixed layer in the auxiliary channel as bed protection for pipes (see also figure A.10).

For all lower discharges the slope in the entire channel is horizontal as there is no discharge in the channel (see figure B.95, except for the one measurement in 2017 before raising the inlet, which does contain a slope). The newest measurement of May 2020 shows a steep slope in the upstream part of the channel because of the lower of the inlet that was constructed. All other measurements since this alteration do not show any significant change.

The slope at the auxiliary channels of Dreumel and Ophemert is given in figure 2.12 for median discharges (1500 m^3/s to 2000 m^3/s at Lobith). Only the Savitsky-Golay filter is shown here, as these provide most information. Figures of other discharges are included in appendix B.4.

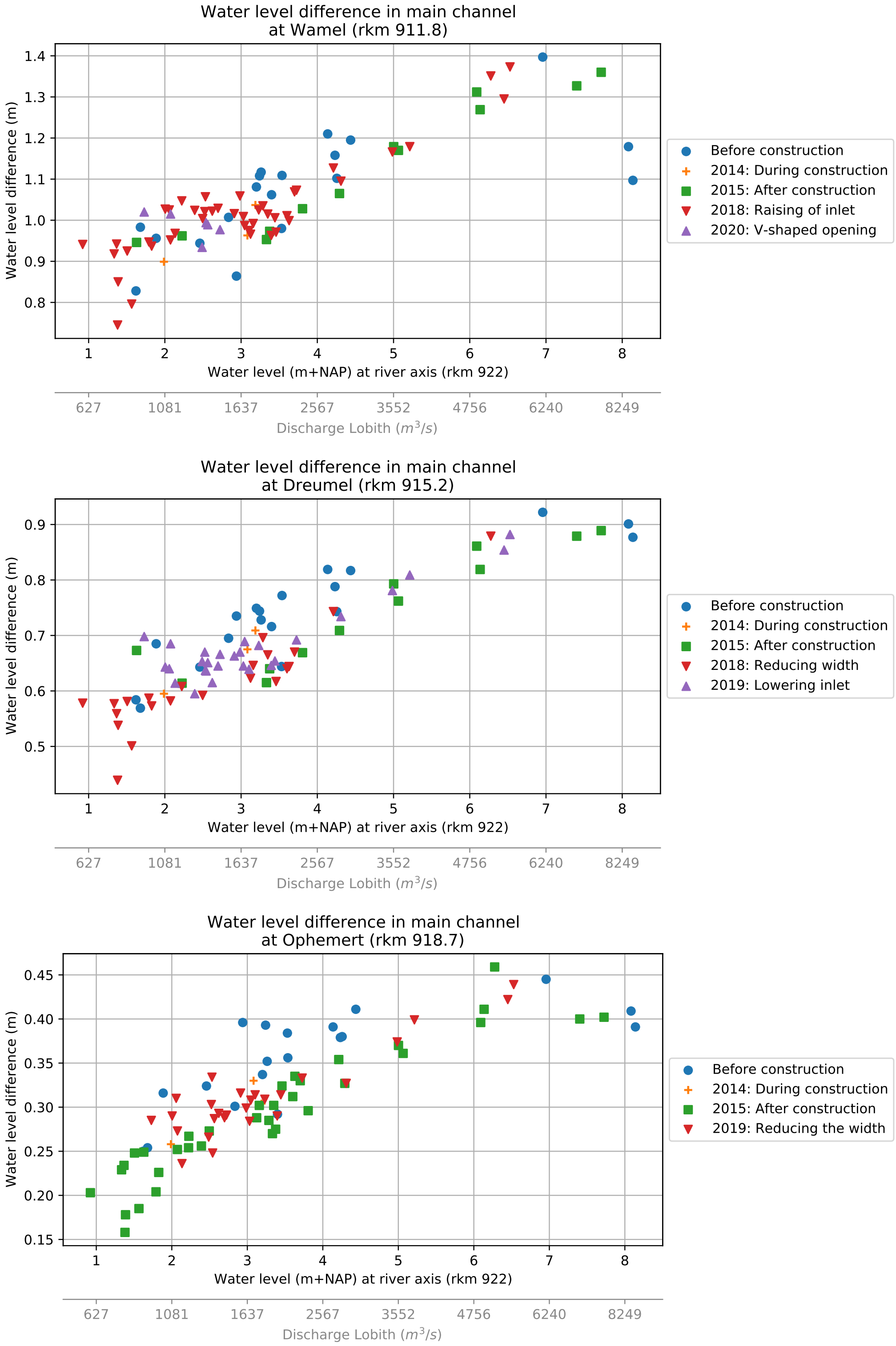
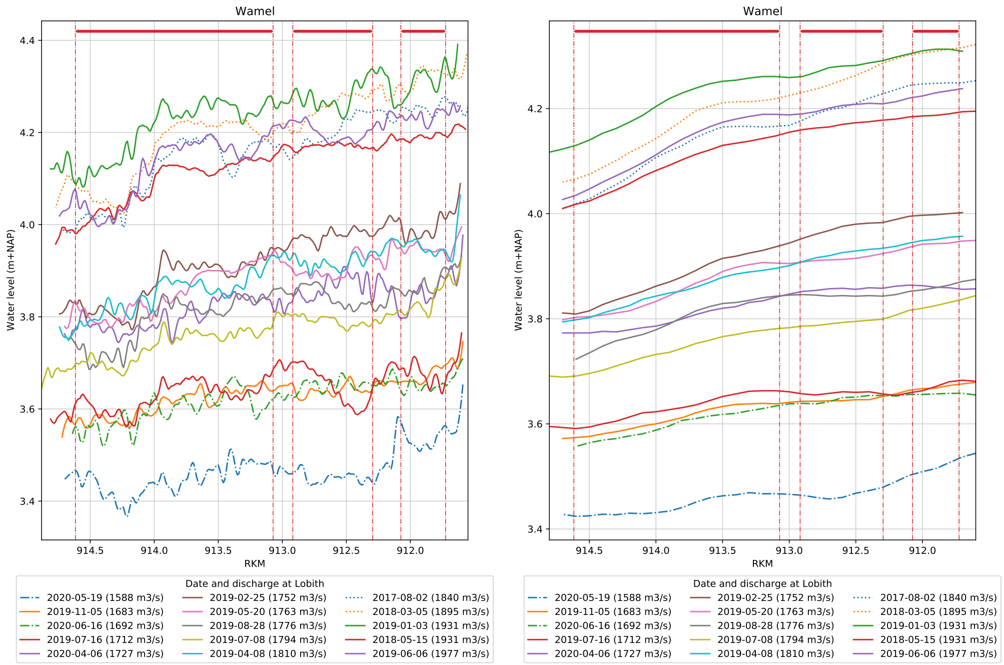


Figure 2.10 Effect of openings on the upstream water levels (minus water level at rkm 922) as a function of the downstream water level (rkm 922) (and the discharge estimated from betrekklingslijnen 2018).

The water level slope at Dreumel at low discharge is small but constant for the entire auxiliary channel (see appendix B.4). At median discharge (1500 m^3/s to 2000 m^3/s, see figure 2.12) the upstream end of the channel suddenly develops a much steeper slope. At these discharges the water level in the main channel (and at the inlet) has a



(a) Savitsky-Golay filtered **(b)** Rolling average

Figure 2.11 Longitudinal water level in the auxiliary channel at Wamel for all discharges between 1500 m^3/s and 2000 m^3/s. The linestyle indicates the situation just after construction (dotted), after raising the inlet (solid) and after construction of the V-shaped opening (dash-dot). The intermediate openings of Wamel are at rkm 912.3 and rkm 913.0.

higher slope than the water level in the auxiliary channel resulting in a head difference of over 10 cm at the inlet of Dreumel (see appendix B.5). This steep slope was far less significant in the measurements that were done before reducing the with of the inlet in April 2018 (dotted lines, measurements of 2017-08-02 and 2019-03-05). The slight widening of the inlet in April 2019 (the solid lines) does not show a significant effect.

Similarly, the auxiliary channel at Ophemert shows a very constant slope at all discharges and both opening configuration. There is no notable effect of the change in opening dimensions (see figure 2.12). Only at the downstream end the downward slope suddenly increases for these median discharges, which indicates that the water level in the auxiliary channel is higher than the main channel (mostly visible for discharges between 1200 and 2000 m^3/s). The outlet itself appears to be causing this local set-up. In contrast to the other auxiliary channels the discharge is relatievely high (see figure 3.17) and the design of the outlet also has a more sharp bend (see the map in figure 1.5). On photo A.8 it is also visible that a large part of the flow is not going through the opening, but flows in downstream direction over the (lowered) weir.

All of the measurements show fluctuations in the water level with a height up to 10 cm and length scales up to hundred metres. Most of those fluctuations do not show a consistent trend. Similar to section 2.2.1 these might be a temporal change as a result of passing ships. It is not clear how these waves arrive in the auxiliary channel. This could either be caused by the porosity of the dam, or as a result of a ship passing an opening (most probably the outlet) and introducing a translation wave in the channel, or a reflection of any of these waves.

At some locations (for example 2020-05-19 at Ophemert rkm 918.7) the effect appears to present in multiple measurements. Inspection of the bed level shows that this water

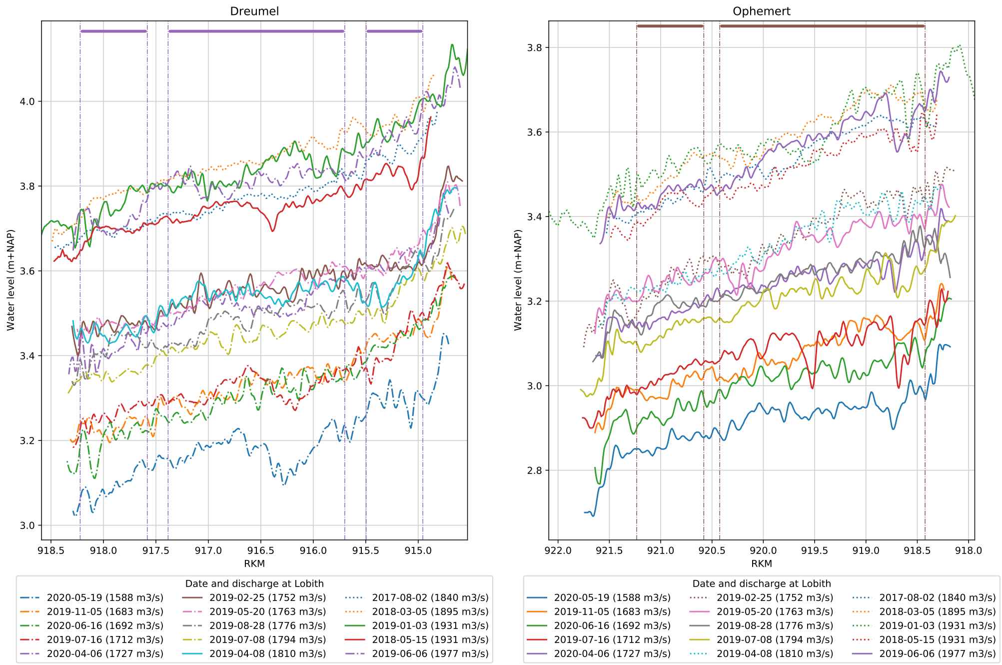


Figure 2.12 Longitudinal water level in Dreumel (left) and Ophemert right) for all measurements at discharges between 1500 m^3/s and 2000 m^3/s. For Dreumel the linestyles indicates the situation just after construction (dotted), after reducing the width of the inlet (solid) and after lower the inlet (dash-dot). For Ophemert the linestyles indicate just after construction (dotted), and after reducing the width (solid).

level depression is at the location of a shoal (see figure 2.13). The lowering of the water level is the result of Bernoulli's principle, which states that an increase in flow velocity results in a lowering of the water level. From theoretical approximations, it is expected that the local flow velocity at the shoal is over 1.5 ms, which gives a lowering of the water level of approximately 1 decimetre. As the measurement vessel is sailing against the flow, it has a relative sailing speed of over 4 m/s which should also result in an additional water level depression of approximately 1 decimetre. From the measurements it cannot be derived if the water level depression is caused by the undistrurbed flow, or by the return current.

To summarise all results in one figure per LTW, the mean slope of each measurement is computed. It is plotted in figure 2.14 (the standard deviation is on average 3.5 cm). The effect on the slope is only visible during lower discharge. The single measurement

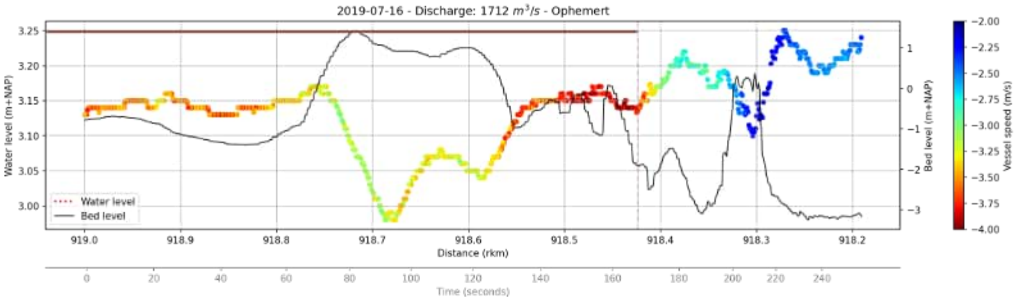


Figure 2.13 Water level (colored dots, left axis) and bed level (right axis) in the auxiliary channel Ophemert near the inlet. The color represents the sailing speed of the measurement vessel (negative means that it's sailing in upstream direction).

at Wamel before raising the inlet clearly shows a much larger slope.

A similar plot is also given in figure 2.15, but plotted to the measured discharge in each auxiliary channel. As not all longitudinal measurements have a discharge measurement in the same period (a tolerance of 2 days is applied), the number of measurements has been reduced to the previous plot. The figure show the relation between the discharge through the auxiliary channel and the slope. A strong correlation is expected, as slope should mainly be the result of this discharge. This correlation is most clear at Wamel, because very low discharges have been measured in this channel. At all auxiliary channels the slope has a variation in the point cloud of around 0.02 m/km. At Wamel a reducing trend seems visible in 2019 compared to 2018, which can be result of the change in inlet design: the same discharge occurs at a much higher water depth. The slight reduction in slope at Ophemert might be explained by the increase in flow area due to bank erosion (see section 4.4.3).

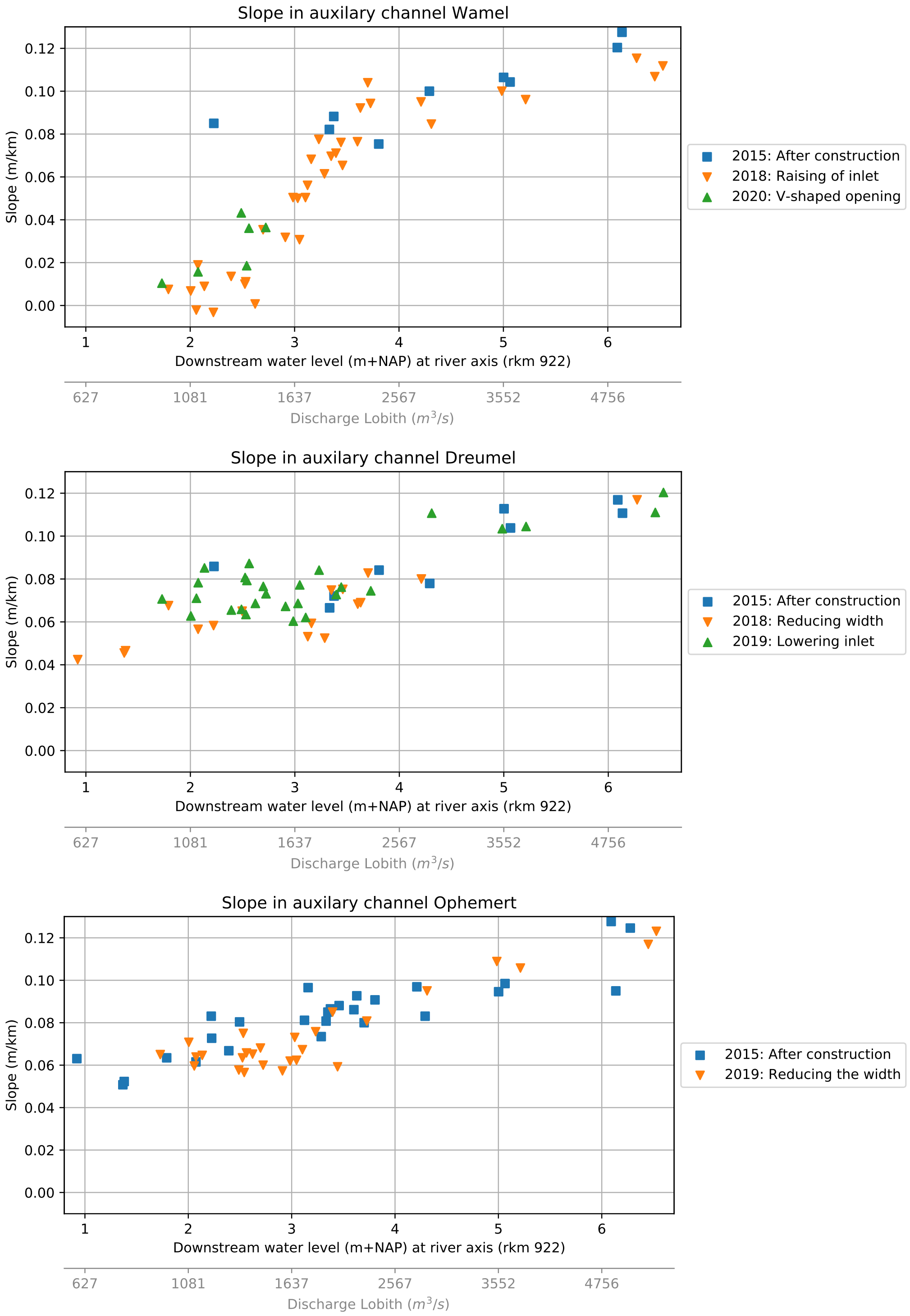


Figure 2.14 Average slope within de auxiliary channel plotted against the downstream water level (and the discharge at Lobith from betrekkingslijnen 2018). The measurements close to inlet and outlet are excluded. Each group of measurements visualises a different design of the inlet.

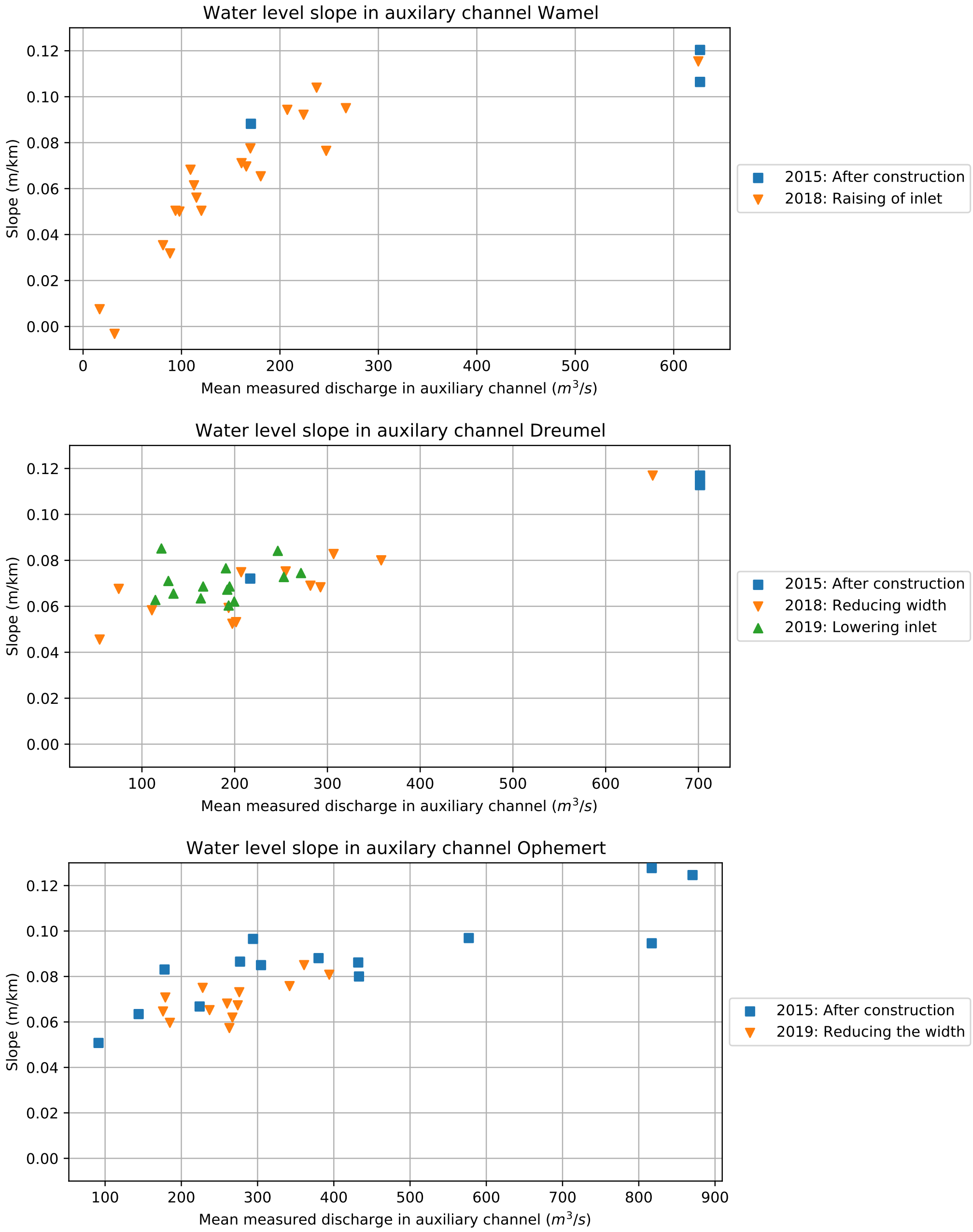


Figure 2.15 Average slope in de auxiliary channel plotted against the *measured discharge in the auxiliary channel*. For coupling to the ADCP measured discharge a tolerance of 2 days is applied to increase the data set from 10-12 measurements to 23-30 measurements.

2.5 Effect of opening the Prins Bernhardsluizen

During low discharge (water level Tiel below 3.0 m+NAP, approximately a discharge Lobith of 1200 m^3/s) the Prins Bernhardsluizen resulting in an open connection between the Waal and the Amsterdam-Rijnkanaal (and also the Nederrijn between Hagestein and Amerongen). During open conditions water from the Waal can also be used in northern parts of the Netherlands to prevent salinity intrusion (on the Lek and Noordzeekanaal) and as fresh water supply (through KWA+). This results in a high discharge that is being withdrawn from the Waal, which lowers the water level on the Waal. A basic rule of thumb is that every loss of 1 m^3/s, lowers the water level with approximately 3 mm at Tiel (and 2 mm at St. Andries).

The discharge through the Amsterdam-Rijnkanaal (ARK) has been measured with ADCP on several days, with a maximum measured discharge of 68 m^3/s. In figure 2.16 the water level at Tiel is plotted to the discharge at Lobith, with annotations of all ADCP-measurements. As expected, the higher measurements correlate to the lower water levels. An increase in ARK-discharge of 60 m^3/s lowers the water levels with approximately 15 cm. There are also some measurements that might have had an even higher discharge withdrawn for the Waal (for example around 900 m^3/s), but these conditions remain unmeasured.[7]

In appendix C.1.8 an analyse is also made of the head difference over the Prins Bernhardsluizen. A time series has been generated of all moments that the locks were presumably open (a head difference lower than 3 cm). The head difference is also correlated to the discharge, but the correlation is only very weak. Based on this conclusion it is not possible to differentiate within the measurements for timespans with high discharges in ARK and situations with lower discharges.

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[7] The discharge through the Betuwepand can be estimated from the volumebalance and the discharge stations at Hagestein and Wijk bij Duurstede (Van Putten (2021)). Although on first sight, the results show a deviation to the ADCP-measurements, the longer time series might provide a better and more continous respresentation of the daily average discharge.

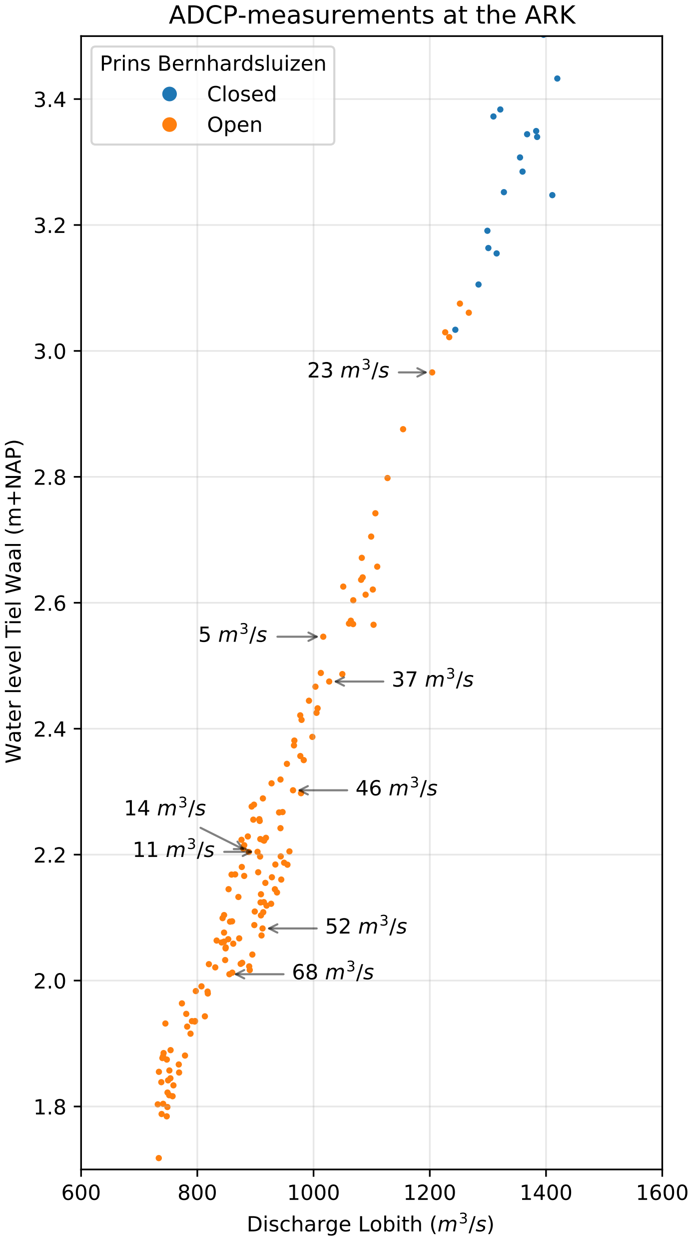

Figure 2.16 Relation between daily averaged discharge at Lobith and water level at Tiel Waal (including a correction of 17 hours) with annotation of the discharge from ADCP measurements at the ARK in 2018. The discharge is the average of multiple runs and has a large standarddeviation: between 10.6 and 37.5 m^3/s.

2.6 Waves in the auxiliary channel

As explained earlier, a large part of the small fluctuations in the longitudinal water level is probably caused by the heave of the ship as a result of various waves in the channel. It is expected that onboard technology on the survey vessel will correct for the ship movements (like the pitch), but is not able to correct for waves that move the entire vessel up and down. In this section these fluctuations are analysed for trends as a result of a changing flow regime (a higher or lower discharge). To isolate the variations, the difference between the Savitzky-Golay filtering and the Rolling average is taken. The root mean square (RMS) of this 'longitudinal difference' is used as an indicator for the height of the waves. In figure 2.17 this wave indicator is plotted to the discharge at Lobith. It should be noted that the length of a wave in a longitudinal profile is also dependent on the speed (as a result of sailing direction) of the measurement vessel. This inaccuracy is expected to be of only small effect.

From the figure it can be concluded that the wave indicator is highest at discharges around 2000 m^3/s. Although this might be partially caused by the larger dataset during these discharges, but can also explained by the design of the LTW. During these average discharges the channel is narrow and has one hard side. In these conditions waves entering the channel are well reflected and can propagate for some time. At these discharges waves can enter the channel both through the inlet and outlet, as well as over the intermediate openings (see the design in figure A.2).

At lower discharges (1000 m^3/s and lower) the wave indicator is lower at the auxiliary channels of Wamel and Dreumel. At these conditions the intermediate openings are no longer overtopping and also the inlets are significantly more closed (most measurements are after April 2018). As the core material of the intermediate openings consists of large rip rap (see as built design in appendix A), it is expected that the porosity of the intermediate openings is higher than the other parts of the dam (with a core of sand). The effects of a higher porosity can not be seen in the measurements.

At higher discharges (3000 m^3/s and above) the entire dam is overtopping. This means that more waves from a passing vessel can enter the channel, but also that the waves are less reflected and dampen out quicker. Also, at higher water depths the height of ship waves reduces, as a result of the reduction in water level depression of the return current.

This figure does not indicate local difference in wave climate within the channel. To study this local variation, all individual longitudinal measurements (see appendix B.4) have been inspected. These longitudinal profiles show variation of the auxiliary channel, but do not show a consistent trend the different measurements. The larger waves that appear might be caused by a ship passing closer by the dam or any of the openings. It can also be that the waves are partially caused the measurement vessel it self. Especially the translation wave caused by the vessel entering the auxiliary channel might reflect on the other end, and end up in the measurements.

For a more in depth analyses of how the waves propagate in the auxiliary channel it is advised to apply stationary measurements on multiple locations in the auxiliary channel at the same moment. Both the situation with and without overtopping intermediate openings should be measured. A simulation of the wave propagation can also help with understanding the waves in the auxiliary channel.

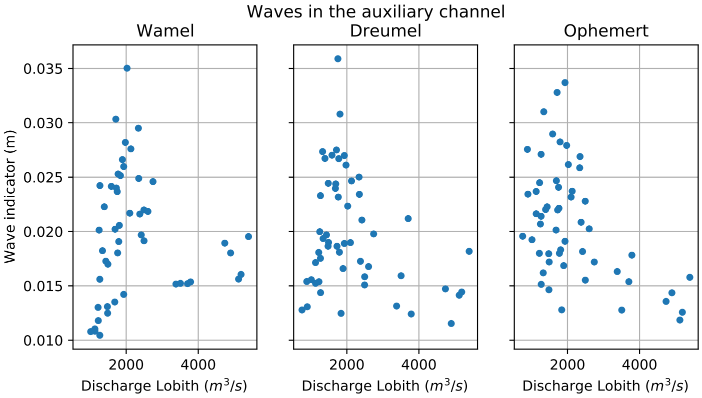

Figure 2.17 Wave indicator as a function of the discharge in the three auxiliary channels. The wave indicator is defined as the RMS of the difference between the Savitzky-Golay filter and the rolling average.

2.7 Discussion of the applicability of longitudinal measurements

In the analysis of the paragraph before, the longitudinal measurements did not proof valuable for detecting all the expected impacts. The effects on the water levels due to both the construction of the longitudinal training wall as well as the changes in inlet dimensions are too small to be measured, as they are marginal compared to the scatter. The effect of temporal variation by ship waves and possible spatial variation by small bed and bank features, is of a similar or higher order than those effects. Large smoothing or filtering is required, but this also reduces the value of the measurements.

The measurements provide a valuable insight in the highly variable slope in the auxiliary channel. But for these insights only few measurements would have been necessary. The large data set now available did not provide a necessary addition, because the scatter in the measurements do not allow further detailing.

Analysing the slope in cross direction of the different parallel runs is not included in this report as no valuable insights were gained from this. The bias between those parallel runs due to the different moment in time (a couple of hours up to a day later) are too large to make a useful comparison. A small study on the relation between curvature and cross slope is included in B.6, but neither gave any insights.

It is advised to reconsider the usage of longitudinal measurement for measurement campaigns of local measures with relatively small impacts compared to the expected fluctuations and scatter in water levels.

2.8 Conclusions and recommendations

From the measurements of the water level the following is concluded:

- From water level measurements it at the LMW-station at Tiel, it is concluded that at high discharge the water levels have been reduced by 10 to 20 cm as a result of the construction of the LTW and the other measures in this region.
- At low and median discharge, the water levels at Tiel have been stabilised since construction of the LTW: the downward trend in the period before construction is stopped. The water level at the station St. Andries (just downstream of the LTW) does show an continuous decline in the period after construction (expect for the lower discharges), which means that the head difference between the stations Tiel and St. Andries has actually increased. This effect can be contributed to the LTW.
- The effect of the change in the openings is not significant enough to conclude from the water level measurements. Only the raising of the inlet and Wamel was significant enough to show in the water level measurements of the auxiliary channel.
- An increased discharge through the Amsterdam-Rijnkanaal results in a reduction of the water levels on the Waal. The measured discharges at Tiel support the model simulation that every 1 m^3/s results in a water level reduction of 3 mm.
- From the experience in analysing the longitudinal measurements, it is advised to reconsider the application of this technique for measurement campaigns of local measures with relatively small impacts in relation to the large fluctuations in the longitudinal water levels. Although a single run can be used for analysing the bigger pictures, it can not be easily compared to other runs due to this macro turbulence. To increase the accuracy, it could be decided to measure on moments of lower ship intensity (less ship waves, e.g. at night), to sail at lower speed (not make waves with the vessel it self) and to do multiple runs of each measurement. However, larger time series at measurement stations (possibly at divers) is expected to provide better insights.
- In the pilot the costs to build many measurement stations was too high. Only a couple of divers could be placed to measure the water level. However, none of these stations have been retreived frequently nor checked for quality, resulting in a data set that was not usuable in this evaluation. It is adviced to have a clear ‘data owner’ in future evaluation projects that requests and validates the data during the project.

3 Flow velocity

3.1 Introduction

This chapter focuses on the data obtained by means of ADCP measurements. One important point of the longitudinal training walls is the morphodynamic changes they induce due to the change in sediment transport capacity. Another point of attention is the transverse velocities occurring at the inlets and outlets, which may hamper navigation. Hence, the following research questions are posed:

1. What is the influence of the longitudinal training walls regarding sediment transport capacity?
2. What is the influence of the longitudinal training walls regarding the transverse velocity near the inlets?

This chapter is organized as follows. In Section 3.2, the data used in this part of the project is described. Section 3.3 focuses on assessing the sediment transport capacity changes. Section 3.4 describes the transverse velocity profiles.

3.2 Available data

The data available to answer the research questions (Section 3.1) consists of ADCP measurements obtained between 2013 and 2020. The measurements were taken as:

- cross-sections in the main channel,
- cross-sections in the auxiliary channel,
- longitudinal sections in the main channel,
- longitudinal sections in the auxiliary channel,
- longitudinal sections in the surroundings of the inlet.

For obtaining one measurement several “rounds” (also referred to as “runs”) were taken. A round is a single sample, for instance, from the left bank to the right bank. The same cross-section is sampled several times (i.e., several rounds are taken) and the successful rounds comprise a single measurement.

In total there are 13,117 files. The data is in two different format types. Both formats are given as ASCII files and contain for each position (x, y) the velocity in north and east directions. Only one of the data types has information on the vertical velocity. Table D.12 summarizes all measurements. Only one round per measurement is shown by not showing measurements on the same day separated less than 10 m. The river kilometre is computed as the mean of all the points in the profile.

Coordinates are given in different reference systems and velocities in different units, amongst other differences. All files have been read, uniformed, and saved in Matlab® format.

Each of the 13,117 files have been plotted for inspection and are available for interested readers. In these figures, processing is minimal and it concerns only flipping of the measurement rounds such that the direction is the same in all cases, and projection of the velocity in the direction of the measurement plane based on the first and last positions. Figure 3.1 provides an example of a cross-sectional measurement. A positive crosswise velocity is defined in increasing distance along the section (see colorbar indicating distance along section). In all cases, the same and most recent satellite image in Google Earth® is used in the background. Hence, in the figures of the situation before construction of the longitudinal training walls, the walls are shown in the image although they were not present at that moment. It is remarkable that the vertical velocity shows an unrealistic profile. This will be discussed later in Section 3.3.3.2.

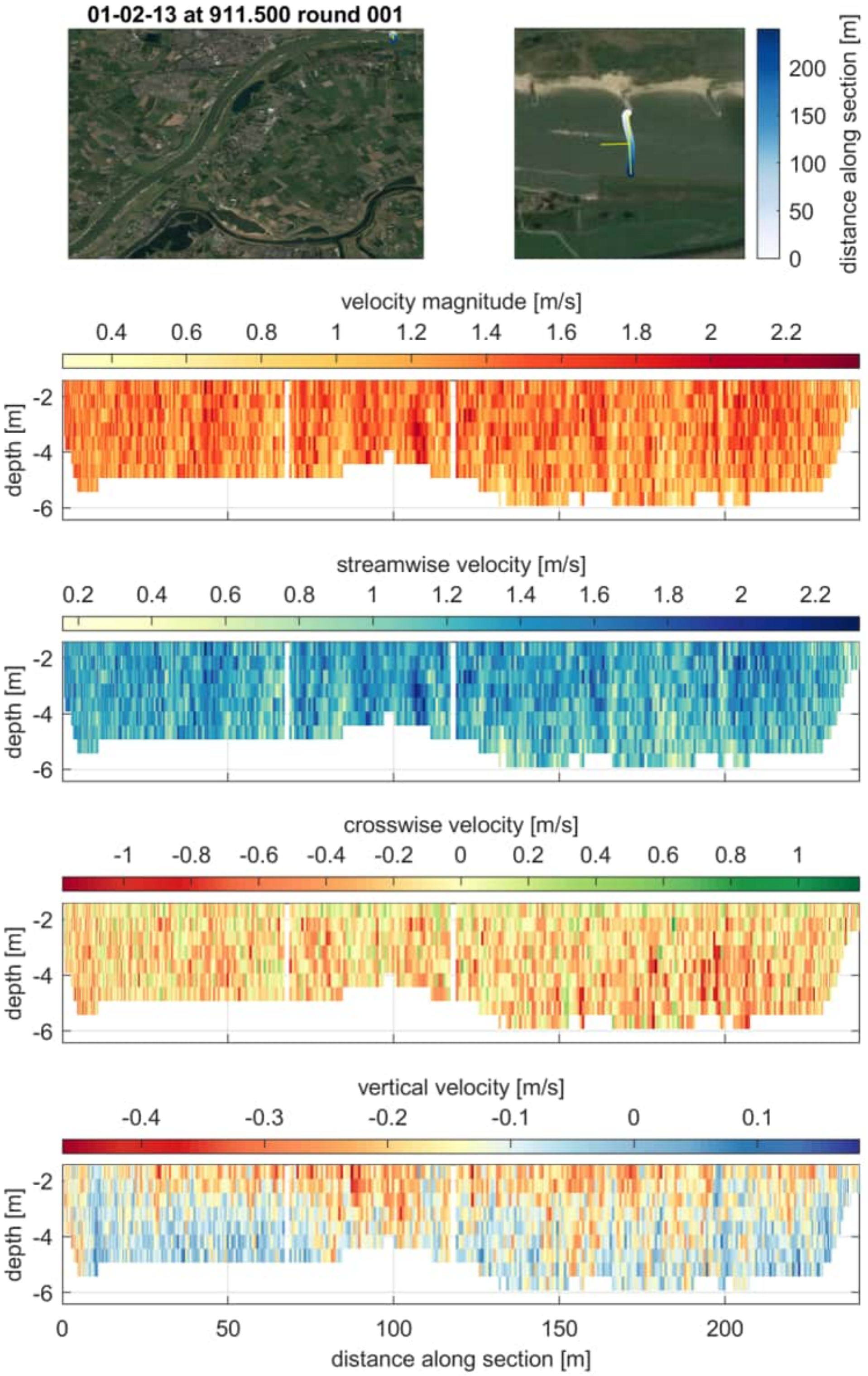

Figure 3.1 Example of a cross-sectional measurement.

Sieben (2020) conducted a preliminary analysis of the discharge measurements. His data-set is available to us as an Excel sheet in which the day, the river kilometre, whether the measurement was conducted along the main channel or the auxiliary channel, and the discharge is recorded.

3.3 Changes in flow due to the construction of the longitudinal training walls

This section focuses on analysing changes in sediment transport capacity due to the construction of the longitudinal training walls (i.e., answering Research Question 1). In analysing changes in sediment transport, flow patterns before construction of the longitudinal training walls are compared with flow patterns after intervention.

3.3.1 Methodology and results of the analysis of the flow changes

During a rising-flow event between the 1st and the 4th of February 2013 a measurement campaign was conducted. This serves as the basis of the situation prior to intervention. The discharge at Lobith and at Tiel during the measurement campaign are shown in Figure 3.2. It is not possible to speak about a single discharge for each measurement, as the time needed for sampling the whole river is substantial. Still, the data received labels the three measurements with the discharges 2380 m^3/s, 3870 m^3/s, and 4690 m^3/s, respectively. The labelling seems to be based on the discharges of the DVR model (Ottevanger *et al.*, 2015) but it does not seem to be consistent with the actual river discharge.

The lowest discharge in the 2013 campaign is already relatively high. For this reason, a measurement on the 17th of November of 2011 when the discharge at Lobith was approximately 922 m^3/s is also considered. This measurement forms part of a set of measurements conducted only at Tiel.

Overall, four conditions are considered which are labelled as Condition 1, 2, 3, and 4 in increasing discharge (Table 3.1).

label	date	discharge at Lobith at 12:00 [m^3/s]	locations
Condition 1	17-11-2011	922	1
Condition 2	01-02-2013	3436	13
Condition 3	02-02-2013	4170	13
Condition 4	04-02-2013	5087	13

Table 3.1 Conditions used to study the situation prior to intervention.

The water level at Tiel at 00:00 on the day of the measurement is obtained, which is then used to match with the measurement after construction of the longitudinal training walls in which the water level was closest to that which occurred during the measurement taken before construction (Figure 3.3). The absolute differences in water level between the situations before and after intervention for Conditions 1, 2, 3, and 4 are equal to 4 cm, 2 cm, 9 cm, and 14 cm, respectively. These relatively low values indicate that data can be compared, although attention needs to be paid when extracting quantitative conclusions.

Matching locations based on the water level at Tiel before and after intervention

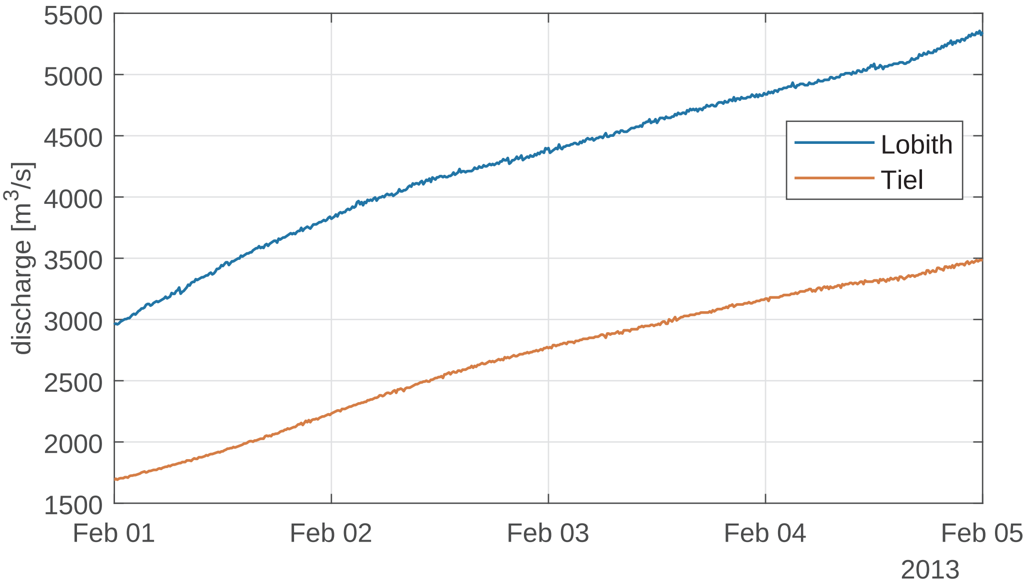

Figure 3.2 Water discharge at Lobith and Tiel during the measurement campaign before construction of the longitudinal training walls.

presents several limitations such as the fact that the intervention is expected to change the water level. One would prefer to match based on discharge, but this is also problematic due to the fact that a measurement at the auxiliary channel and the main channel at the same location needs to exists, conducted at the time in which the discharge was similar to the one prior to construction. Considering the variability it was found best to match on discharge. This and other limitations are further discussed in Section 3.3.3.

In each measurement campaign before intervention for Conditions 2, 3, and 4, 13 cross-sections were measured. For each of these locations, the closest measurement location inspected on the selected date is obtained. Hence, 13 locations after intervention for each of the three different discharges are selected to compare with the same locations before intervention (Figures 3.5, 3.6, and 3.7). Table D.13 summarizes the profiles that have been used.

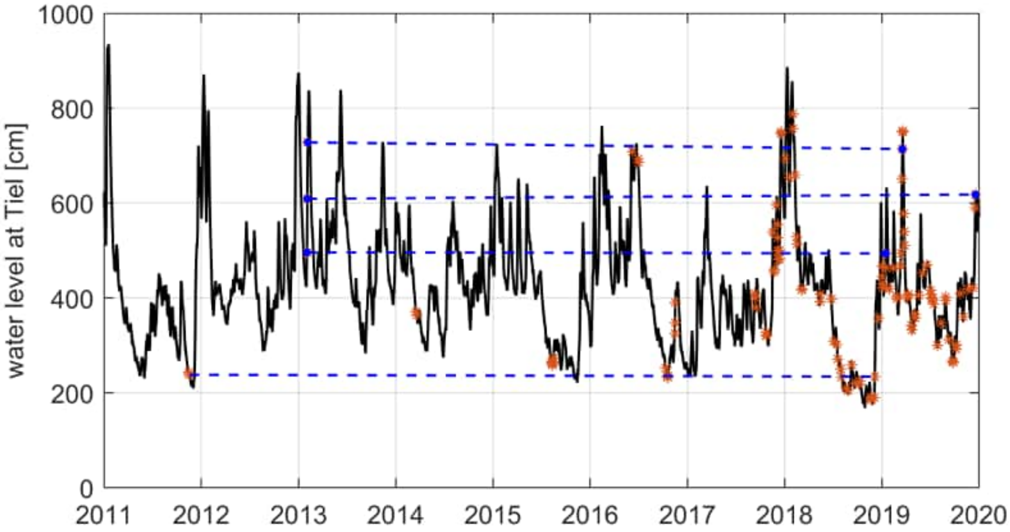

Figure 3.3 Water level at Tiel with time (black line) and times when each measurement campaign was done (red asterisks). The blue dashed line matches measurements taken before construction with measurements taken after construction which have a most similar water level.

Figure 3.4 Location of the cross-sectional measurements before and after intervention for condition 1. For this condition measurements were only conducted at one location. For each measurement before construction (square marker with number) the matched measurement after construction (circle marker) is given the same color.

Figure 3.5 Location of the cross-sectional measurements before and after intervention for condition 2. . For each measurement before construction (square marker with number) the matched measurement after construction (circle marker) is given the same color.

Figure 3.6 Location of the cross-sectional measurements before and after intervention for condtion 3. . For each measurement before construction (square marker with number) the matched measurement after construction (circle marker) is given the same color.

Figure 3.7 Location of the cross-sectional measurements before and after intervention for condition 4. . For each measurement before construction (square marker with number) the matched measurement after construction (circle marker) is given the same color.

At each location, all rounds are averaged for obtaining a representative cross-sectional measurement. Figure 3.8 shows an example of the averaging of all rounds at the same location as Figure 3.1. Note how the resulting averaging procedure filters the data.

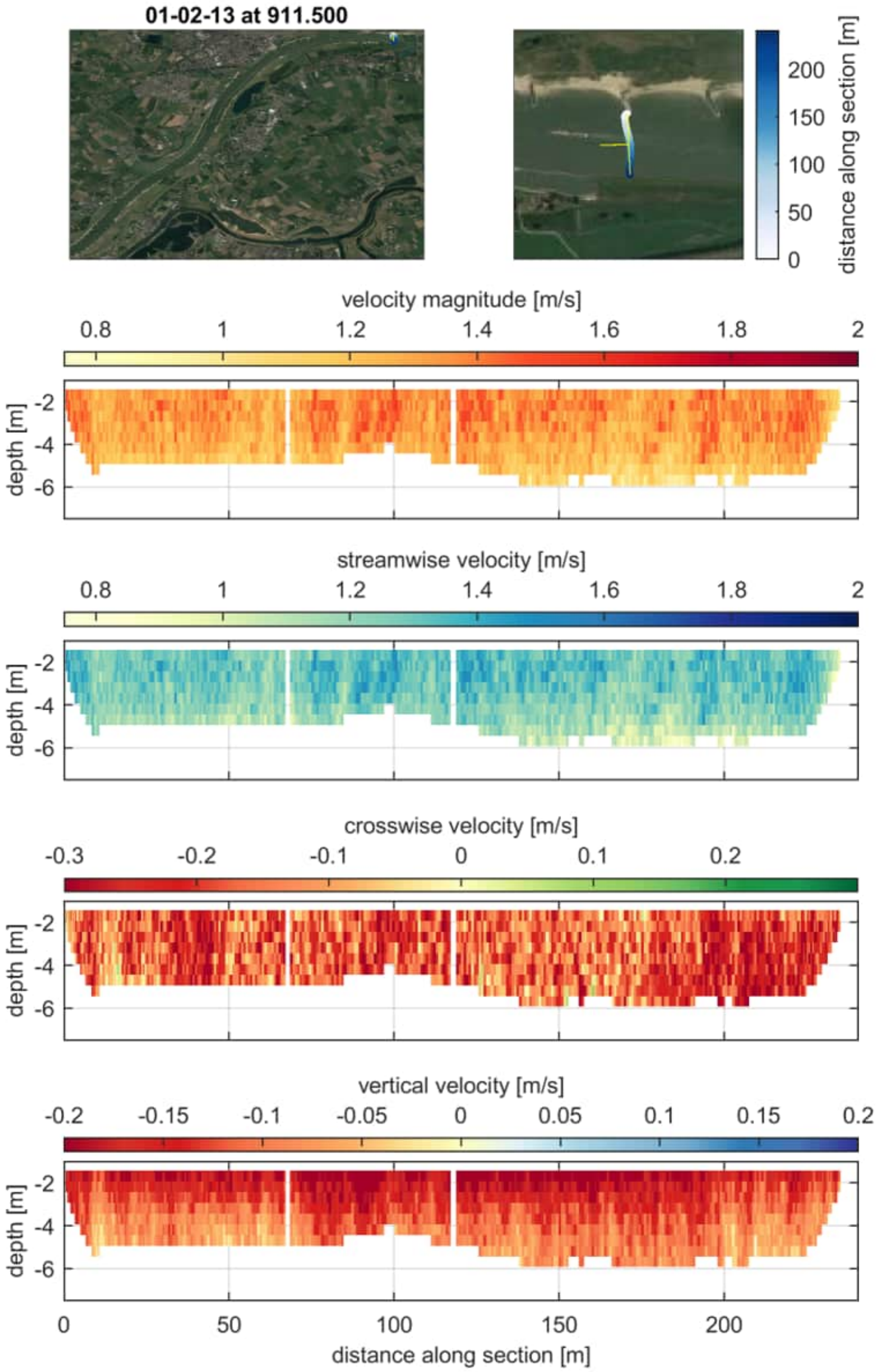

Figure 3.8 Cross-sectional measurements on 01-02-13 (discharge at Lobith at 12:00 equal to 3436 m^3/s) at rkm 911.500 projected on measurement plane.

The measurement plane does not exactly align with the transverse direction (i.e., it is not normal to the streamwise direction). For proper comparison of the situation before and after intervention it is desired that the measurement plane coincides with the transverse direction of the flow in all cases such that one can speak about velocity in the flow direction and in the transverse direction. This is necessary to be able to visualise the secondary flow circulation and for an accurate computation of the total discharge. It is especially necessary when comparing flow fields that were not on the exact same sailing track.

To this end, the streamwise direction is numerically found by minimization of the cross-sectional discharge (Figure 3.9). Worded differently, the cross-sectional discharge is computed for an arbitrary plane as the sum for all bins (in cross-wise and vertical direction) of the product of the velocity parallel to that plane and the flow depth of the bin. Then, the plane with smaller cross-sectional discharge is selected (this is a common method, e.g. Dietrich and Smith (1983)). In this way, measurements with zero cross-sectional discharge are found (Figure 3.10).

Figure 3.11 presents the measurements after intervention that is associated with the data before intervention as given in Figure 3.10.

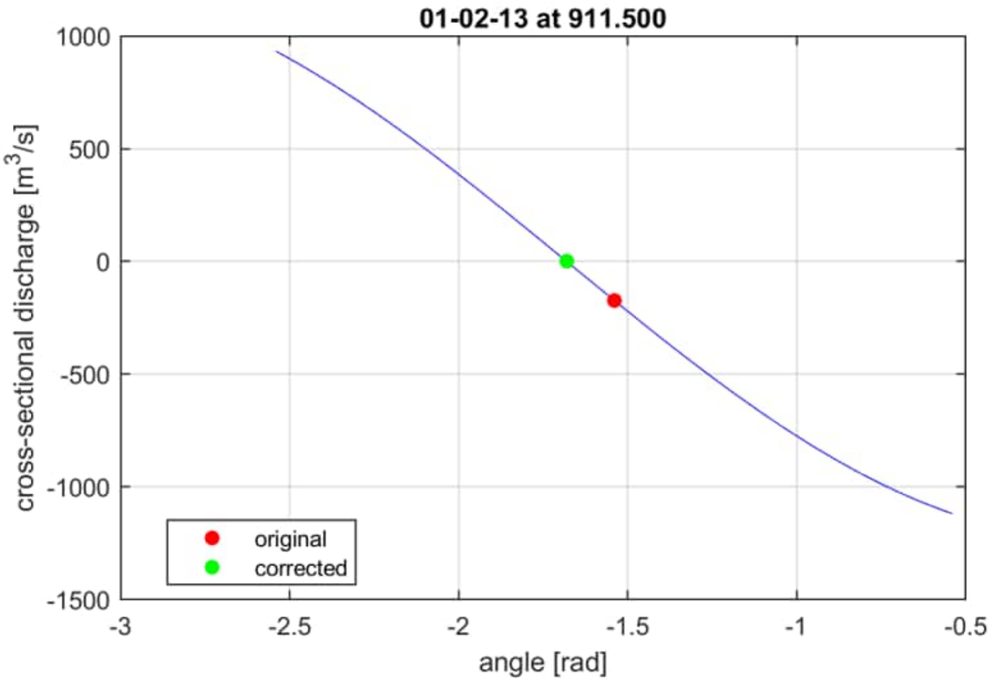

Figure 3.9 Cross-sectional discharge on 01-02-13 (discharge at Lobith at 12:00 equal to 3436 m^3/s) at rkm 911.500 as a function of the direction of the projection plane (blue line). The original measurement plane and the corrected plane are marked in red and green, respectively.

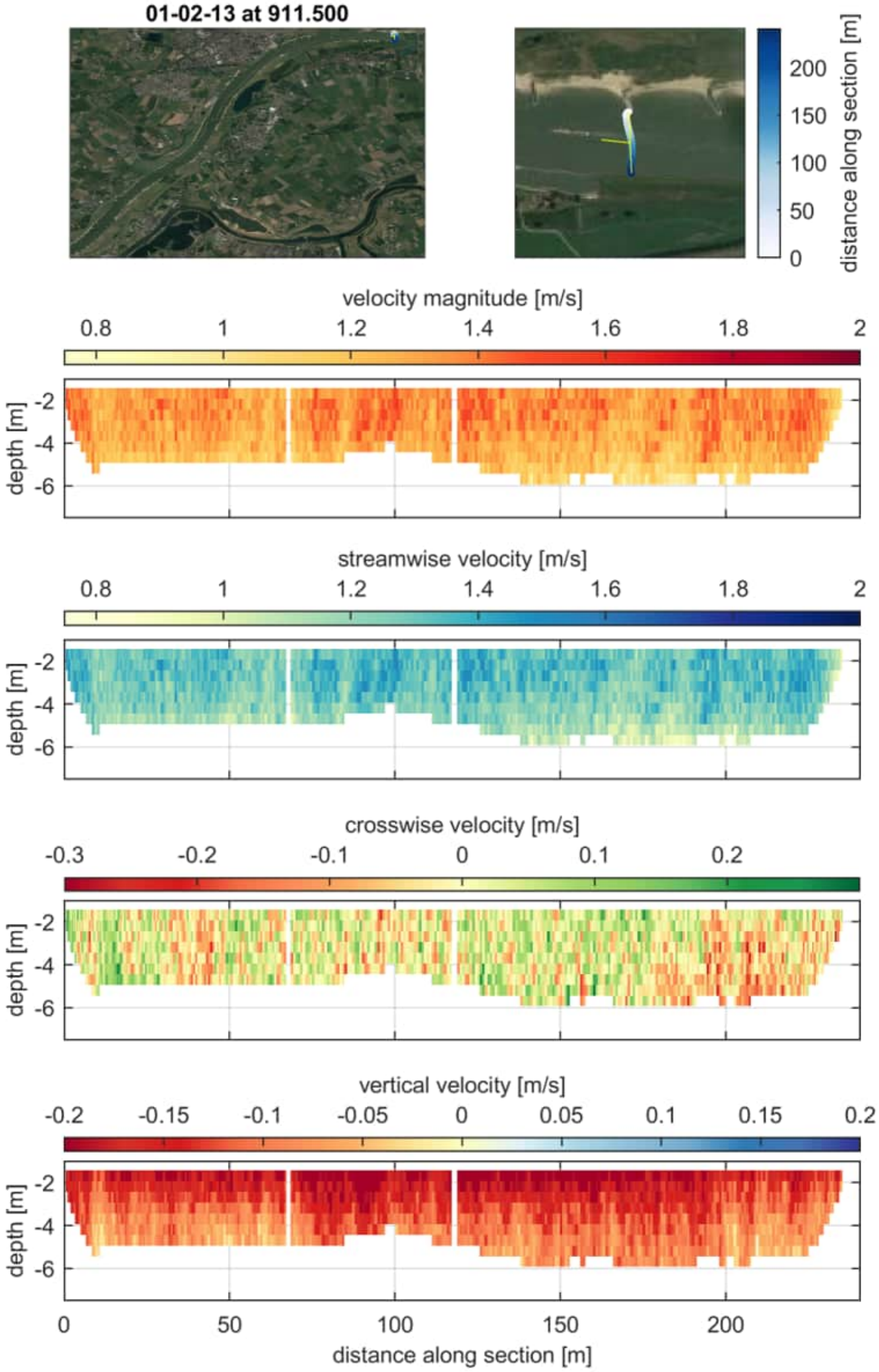

Figure 3.10 Cross-sectional measurements on 01-02-13 (discharge at Lobith at 12:00 equal to 3436 m^3/s) at rkm 911.500 projected on crosswise plane.

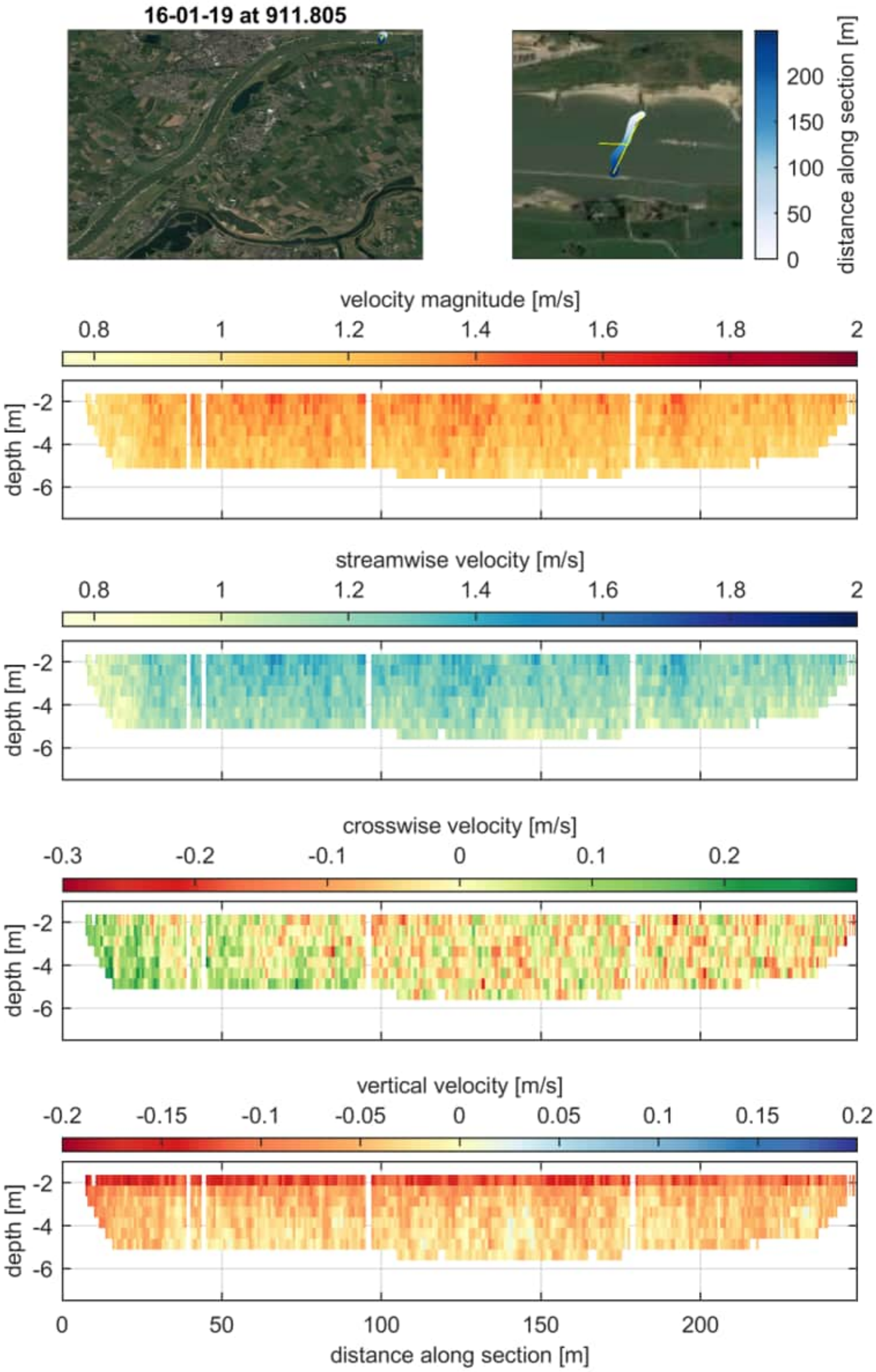

Figure 3.11 Cross-sectional measurements on 16-01-19 (discharge at Lobith at 12:00 equal to 3022 m^3/s) at rkm 911.805 projected on crosswise plane.

The last step consist of considering the data around the centre of the channel to study the effect of the intervention on the main channel velocity. To this end, the point of each measured profile closest to the river axis is found and the data 50 m to the left and right of the point is selected. The vertical profiles before and after intervention are averaged in transverse direction to obtain a representative velocity profile. Figure 3.12) shows one example. The thin lines in the background show all the velocity profiles in the central 100 m of the main channel. The thick lines are the average profiles. The error bars identify one standard deviation in each direction.

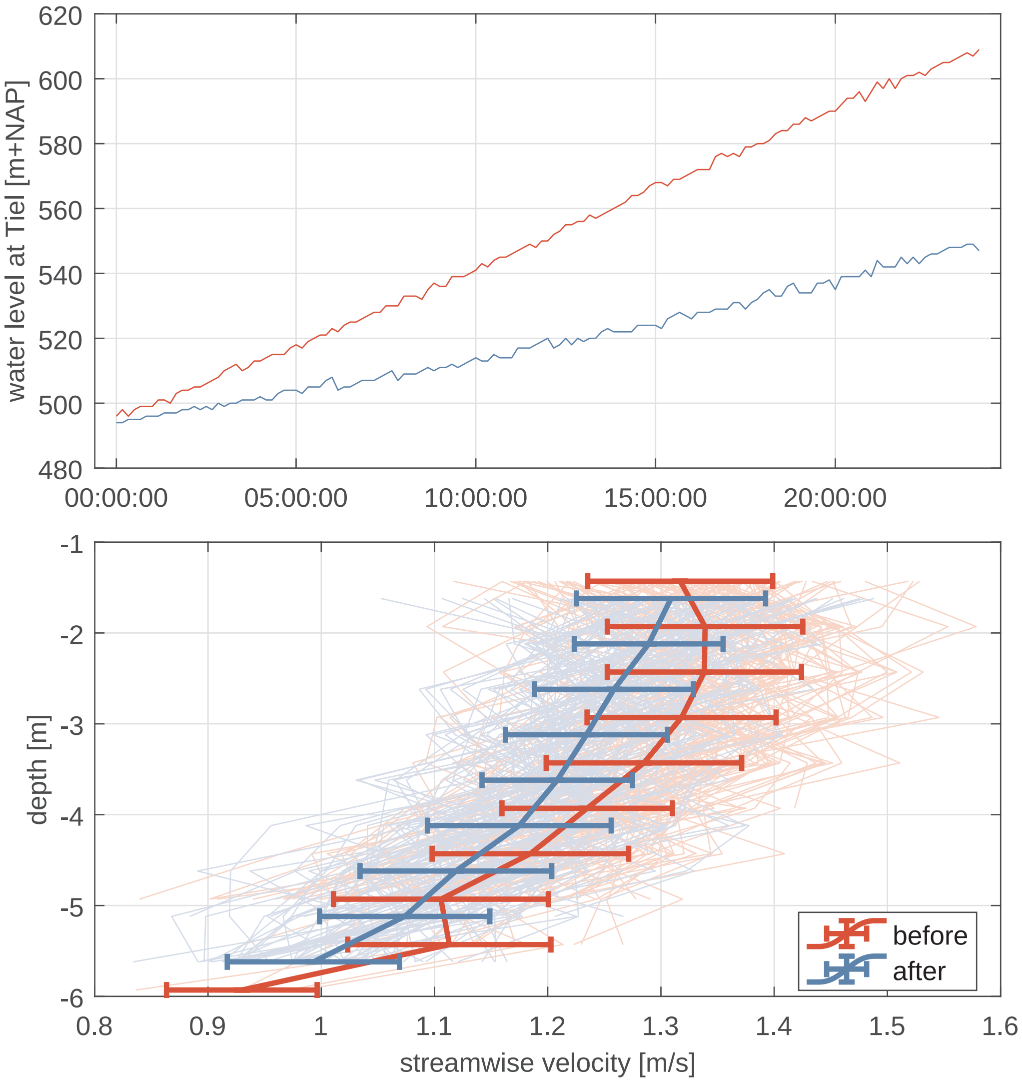

Figure 3.12 Streamwise velocity at the central 100 m of channel before (01-02-13, discharge at Lobith at 12:00 equal to 3436 m^3/s, rkm 911.500) and after (16-01-19, discharge at Lobith at 12:00 equal to 3022 m^3/s, rkm 911.805). Condition 2. (Note that the measurements are matched on the water level at Tiel. The time lag to Lobith in combination with the different water-rising speed causes a large difference in discharge.)

Appendix D.2 contains all the figures showing the flow pattern before and after intervention for all discharges. Tables 3.2, 3.3, 3.4, and 3.5 summarize the data for the four conditions. The velocity is shown in Figures 3.14, 3.15, and 3.16, respectively.

location [-]	rkm before	distance [km]	velocity before [m/s]	standard deviation before [m/s]	velocity after [m/s]	standard deviation after [m/s]	velocity change [%]
1	916	0.00	0.78	0.11	0.87	0.12	10.79

Table 3.2 Change in streamwise flow velocity for condition 1. “location” indicates the location number,“distance” indicates the distance between the two compared locations, “velocity” is the cross-sectional and depth-averaged flow velocity in the 50 m to the right and left of the river axis, and “standard deviation” is the mean of the standard deviation of the depth-averaged velocity. The water level Tiel is given in appendix D.2.

location [-]	rkm before	distance [km]	velocity before [m/s]	standard deviation before [m/s]	velocity after [m/s]	standard deviation after [m/s]	velocity change [%]
1	912	0.30	1.22	0.08	1.18	0.07	-2.64
2	912	0.00	1.25	0.08	1.18	0.07	-5.59
3	912	0.60	1.31	0.07	1.18	0.07	-9.41
4	913	1.30	1.33	0.09	1.18	0.07	-11.07
5	915	0.10	1.36	0.09	1.28	0.09	-6.21
6	915	0.07	1.30	0.08	1.24	0.08	-4.48
7	916	0.87	1.30	0.08	1.24	0.08	-5.02
8	918	0.45	1.28	0.07	1.13	0.09	-11.72
9	919	0.00	1.28	0.11	1.06	0.07	-17.01
10	921	0.55	1.26	0.08	1.04	0.07	-17.15
11	922	0.20	1.21	0.08	1.04	0.07	-13.48
12	922	0.45	1.19	0.08	1.04	0.07	-12.31
13	922	0.80	1.20	0.08	1.04	0.07	-12.76

Table 3.3 Change in streamwise flow velocity for condition 2. “location” indicates the location number,“distance” indicates the distance between the two compared locations, “velocity” is the cross-sectional and depth-averaged flow velocity in the 50 m to the right and left of the river axis, and “standard deviation” is the mean of the standard deviation of the depth-averaged velocity. The water level Tiel is given in appendix D.2.

location [-]	rkm before	distance [km]	velocity before [m/s]	standard deviation before [m/s]	velocity after [m/s]	standard deviation after [m/s]	velocity change [%]
1	912	0.30	1.34	0.08	1.33	0.10	-0.12
2	912	0.00	1.39	0.07	1.33	0.10	-4.02
3	912	0.60	1.42	0.08	1.33	0.10	-6.23
4	913	1.30	1.43	0.09	1.33	0.10	-6.78
5	915	0.10	1.36	0.09	1.41	0.10	3.48
6	915	0.07	1.50	0.09	1.33	0.11	-11.72
7	916	0.87	1.45	0.09	1.33	0.11	-8.33
8	918	0.45	1.37	0.09	1.37	0.10	-0.05
9	919	0.03	1.33	0.10	1.21	0.11	-8.88
10	921	0.55	1.41	0.08	1.30	0.12	-7.62
11	922	0.20	1.31	0.08	1.30	0.12	-0.56
12	922	0.45	1.41	0.08	1.30	0.12	-7.93
13	922	0.80	1.40	0.08	1.30	0.12	-6.83

Table 3.4 Change in streamwise flow velocity for condition 3. “location” indicates the location number,“distance” indicates the distance between the two compared locations, “velocity” is the cross-sectional and depth-averaged flow velocity in the 50 m to the right and left of the river axis, and “standard deviation” is the mean of the standard deviation of the depth-averaged velocity. The water level Tiel is given in appendix D.2.

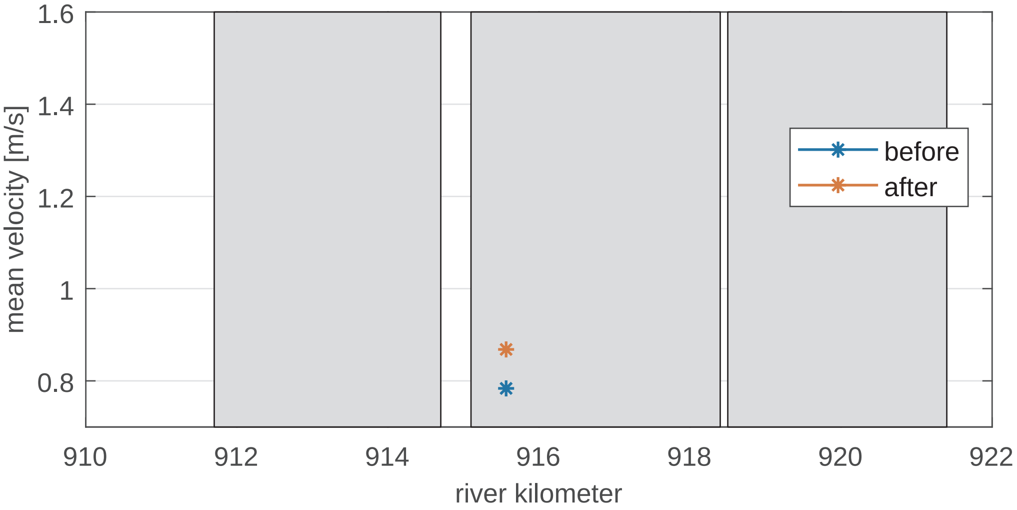

Figure 3.13 Cross-sectional and depth-averaged streamwise velocity at the central 100 m of main channel before and after intervention for Condition 1.

location [-]	rkm before	distance [km]	velocity before [m/s]	standard deviation before [m/s]	velocity after [m/s]	standard deviation after [m/s]	velocity change [%]
1	912	0.30	1.44	0.08	1.39	0.06	-3.42
2	912	0.00	1.43	0.08	1.39	0.06	-2.78
3	912	0.05	1.50	0.09	1.42	0.04	-5.44
4	913	0.01	1.57	0.09	1.50	0.06	-4.50
5	915	0.10	1.49	0.08	1.50	0.05	0.54
6	915	0.07	1.52	0.08	1.55	0.07	2.11
7	916	0.08	1.48	0.09	1.45	0.05	-2.23
8	918	0.01	1.48	0.08	1.41	0.05	-4.92
9	919	0.03	1.38	0.09	1.31	0.05	-5.32
10	921	0.03	1.48	0.08	1.45	0.04	-2.40
11	922	0.20	1.42	0.08	1.42	0.05	0.50
12	922	0.25	1.50	0.08	1.50	0.04	-0.03
13	922	0.10	1.49	0.07	1.50	0.04	0.78

Table 3.5 Change in streamwise flow velocity for condition 4. “location” indicates the location number,“distance” indicates the distance between the two compared locations, “velocity” is the cross-sectional and depth-averaged flow velocity in the 50 m to the right and left of the river axis, and “standard deviation” is the mean of the standard deviation of the depth-averaged velocity. The water level Tiel is given in appendix D.2.

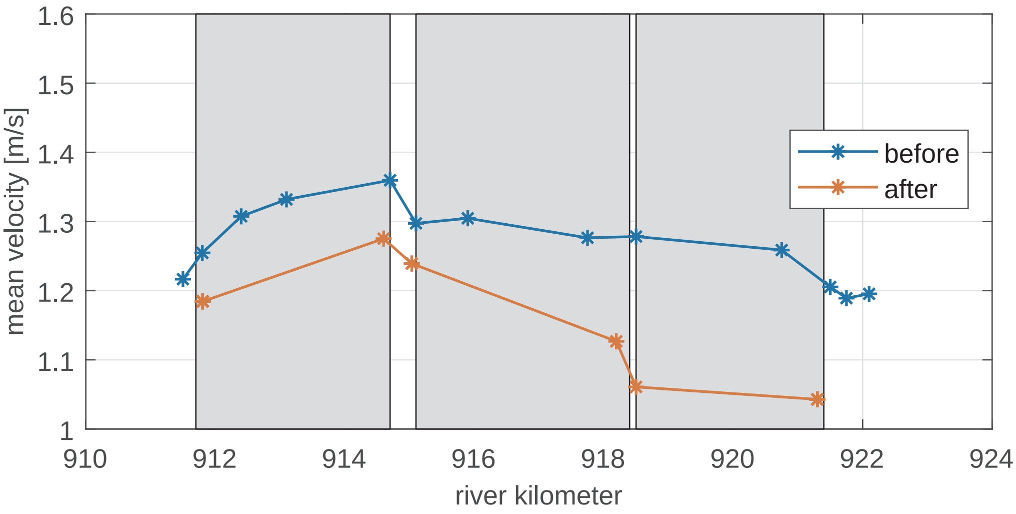

Figure 3.14 Cross-sectional and depth-averaged streamwise velocity at the central 100 m of main channel before and after intervention for Condition 2.

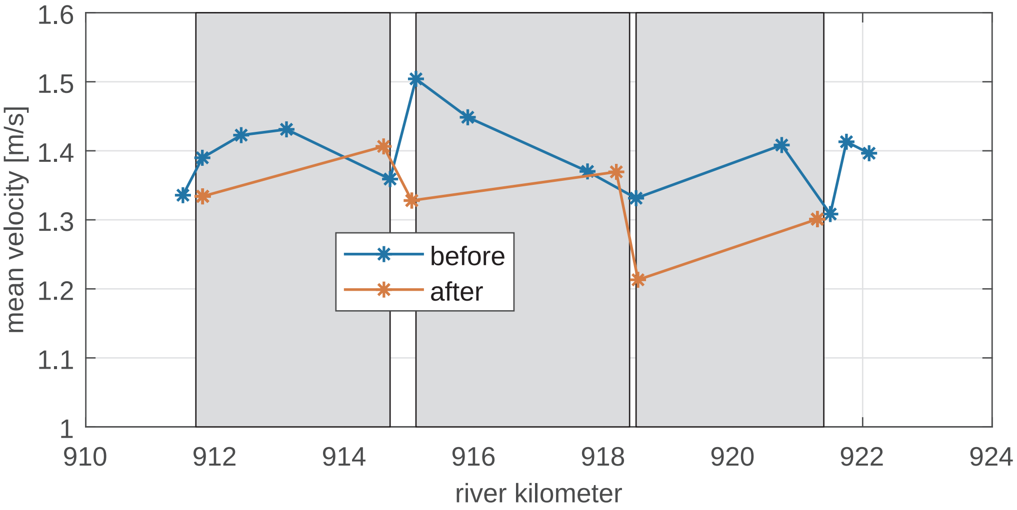

Figure 3.15 Cross-sectional and depth-averaged streamwise velocity at the central 100 m of main channel before and after intervention for Condition 3.

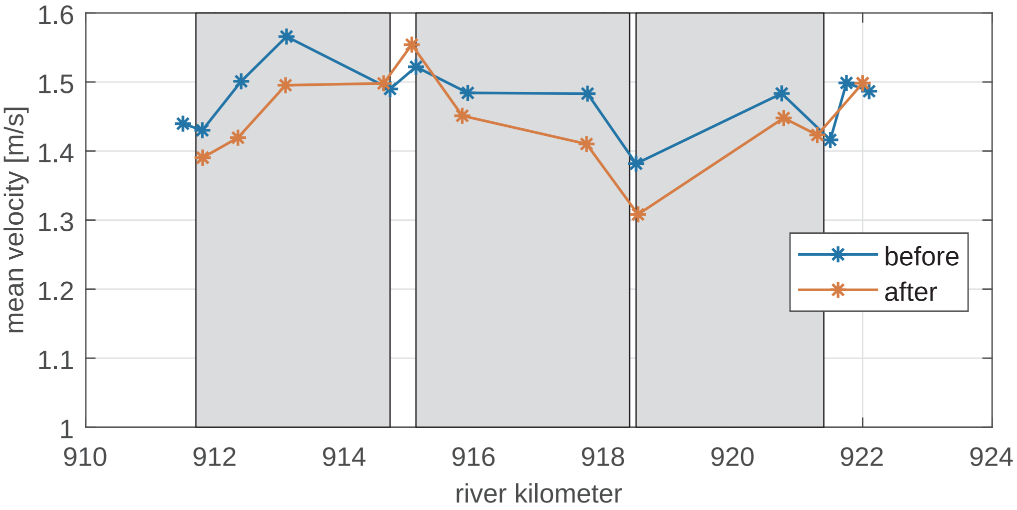

Figure 3.16 Cross-sectional and depth-averaged streamwise velocity at the central 100 m of main channel before and after intervention for Condition 4.

The velocity for the lowest discharge increases significantly (10%) after intervention. Unfortunately, there is only one measurement for this condition, which hinders generalization. For Conditions 2, 3, and 4, the velocity after intervention is smaller than before the construction of the longitudinal training walls. The change in flow velocity between the situation before and after intervention increases as the discharge decreases. Worded differently, for a low discharge, the effect of the longitudinal training walls on the main channel flow velocity is larger than for a high discharge.

The largest change in velocity occurs at Ophemert (Locations 9-13) for Condition 2. In this case, it is larger than 10%, even reaching 17% at the upstream end. At Wamel and Dreumel it is in the order of 5%. It is relevant to remind the reader that the discharge in the measurement before interventions is certainly different than in the measurement after intervention given the limitations in the analysis (see Section 3.3.3). Yet, the reduction flow velocities appears to be consistent among most measurements, although varying in magnitude. This suggest that the change is indeed due to the longitudinal training walls and not to limitations in the methodology.

3.3.2 Methodology and results of the analysis of the discharge partitioning

The data compiled by Sieben (2020) is used for studying the effect of the inlet openings on the discharge distribution. From all the measurements, those for which there is a measurements in the auxiliary channel and in the main channel on the same day and river kilometre are selected and matched.[1] These selected measurements are discretized according to the date at which they where taken as (see appendix A.2):

- from construction until May 2018,
- from May 2018 until May 2019,
- from May 2019 until present.

In summary, in April 2018 the inlets at Wamel and Dreumel were raised and in April 2019 the inlet at Dreumel was lowered and the one at Ophemert was narrowed.

Figures 3.17 and 3.18 present the fraction of the discharge along the auxiliary channel as a function of the river kilometre and the total discharge in the cross section, respectively. The total discharge is computed by adding the ADCP measurement of the main channel to the measurement in the auxiliary channel. As a result, measurement campaigns without measurements on both location are excluded. In Appendix D.6 the figures for each river kilometre are shown.

The amount of discharge along the auxiliary channel varies between less than 5% and more than 25% of the total discharge. For a larger total discharge, a larger fraction is transported along the auxiliary channel. This is the expected behaviour: for low discharges flow is concentrated in the main channel and as the discharge increases a larger proportion is transported along the auxiliary channel.

In general, the effect of varying the inlets is not visible in the data. For instance, Figure 3.19 shows the inlet of Dreumel. The measurements before and after intervention do not cluster at different locations. For a discharge equal to 1000 m^3/s one may conclude that after May 2019 the auxiliary channel transports a larger proportion of water than before. This may be in line with the fact that the inlet was lowered. At discharges of approximately 1400 m^3/s the figure does not show differences between the situation before and after intervention.

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[1] In Sieben (2020) also measurements are presented that had could not be matched between main and auxiliary channel. The discharge fraction through the channel is computed based on an assumed discharge (through regression with Lobith). This also results in discharge fractions higher than 100%. The discharge analysis by Sieben also includes discharge extractions towards the Tiel-Kanaal.

At Wamel, the figures cannot be used to show the effect of the change in inlet (May 2018), because no measurements prior to May 2018 are available with a matching to main channel measurements. The available measurements show with the closed inlet show very low discharges through the channel: 1 to 2 % at a Waal discharge between 600 and 1000 m^3/s. This shows that the closing of the inlet resulted in a low (but not 0) discharge. Estimates by Sieben (2020) show that before construction the discharge through the channel was approximately higher than 12 %.

Further downstream in the auxiliary channel of Wamel, the discharge increases. Probably as a result of the porosity of the dams. The porosity of the dams is probably the highest at the inlet and intermediate openings as these are only constructed of coarse material (40 - 100 kg), see figure A.1.

Sieben (2020) shows that, from theory, when the discharge in the main channel is 88 % or more of the total Waal discharge, this will result in an increase in water levels compared to the situation prior to construction. This is the same as a discharge through the auxiliary channel of less than 12 %, which can be concluded from either figure 3.18 or from Sieben (2020). At Wamel, for a discharge at Lobith lower than 2500 m^3/s is lower than 12 % of total Waal discharge, which should in theory result in an increase in water levels compared to prior to construction. At Dreumel, the only at Boven-Rijn discharges of roughly 1250 m^3/s and lower the auxiliary channel discharge is lower than 12 % of the total Waal discharge. At Ophemert the auxiliary channel discharge is never below 12 %.

The main limitation is that, while there are 650 measurements, only 160 pairs of points are useful for the analysis considering that they need to be taken on the same day and location. Moreover, measuring the discharge accurately is challenging and even more in the shallow auxiliary channel.

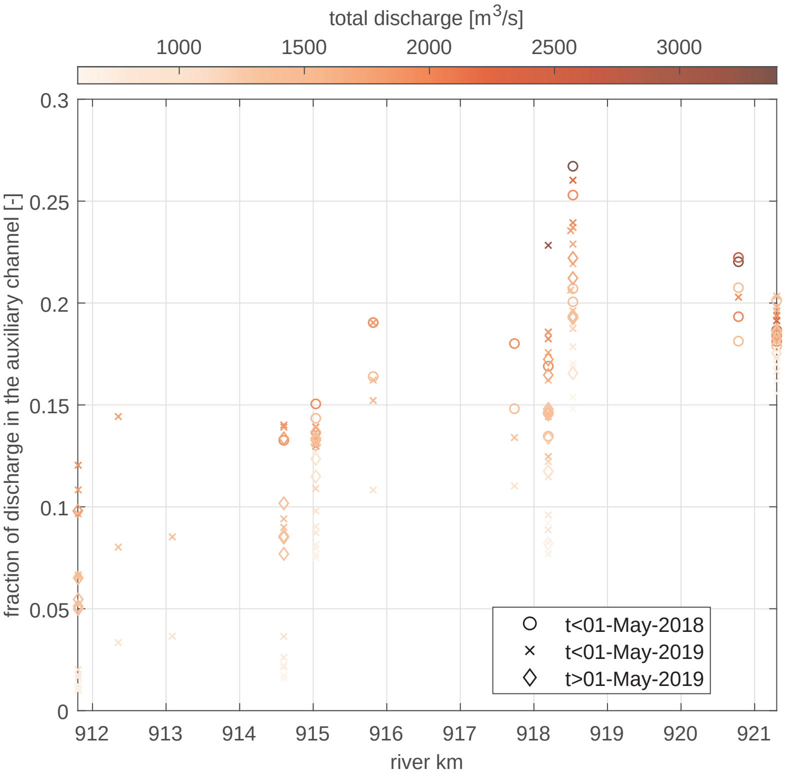

Figure 3.17 Fraction of discharge along the auxiliary channel for a varying river kilometre.

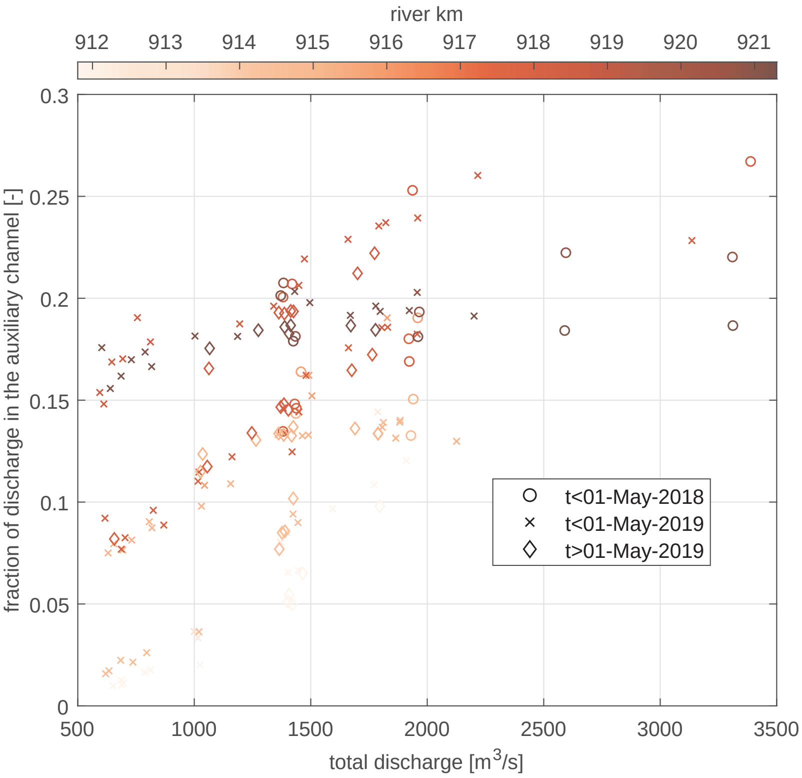

Figure 3.18 Fraction of discharge along the auxiliary channel for a varying total discharge.

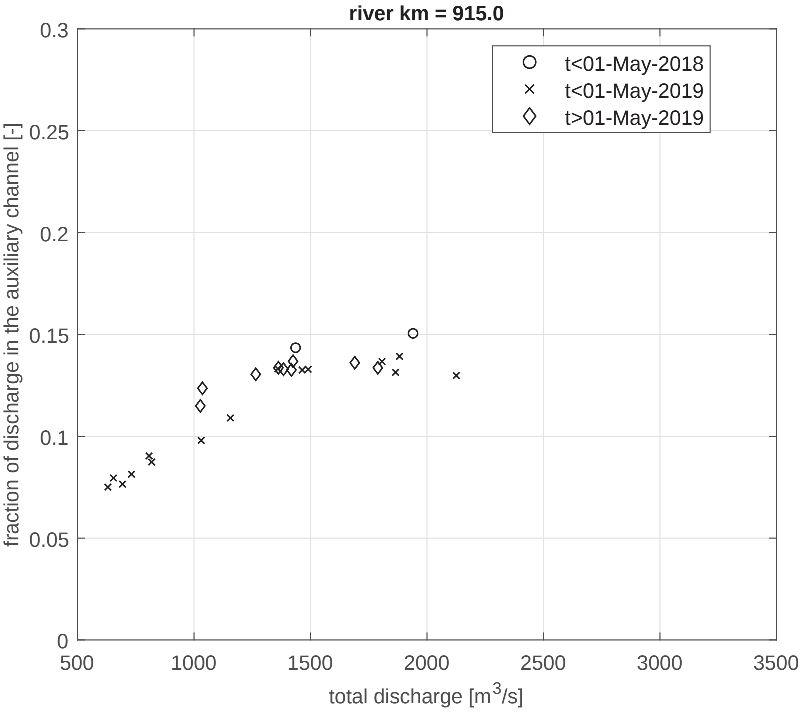

Figure 3.19 Fraction of discharge in the auxiliary channel as a function of the total discharge for the measurements at river km 915.0

3.3.3 Discussion of the results of the analysis of the changes in flow and recommendations

3.3.3.1 Consequences for sediment transport

For Condition 1 with low-flow (922 m^3/s), a velocity increase after intervention is observed. This is reasonable given that the width of the main channel has been reduced. This results in an increase in sediment transport. However, these low discharges only occur a couple of days per year and are measured along the LTWWamel, while the inlet was fully raised. At other LTW this increase in velocity might not be present, due to a higher discharge in the auxiliary channel. Also at higher discharges, when the auxiliary channels become more active, the velocity increase might not be present.

For a discharge at Lobith equal to 3436 m^3/s and higher (i.e., Conditions 2, 3, and 4), the mean flow velocity in the main channel appears to have decreased due to the construction of the longitudinal training walls. At this discharge overtopping of the longitudinal training wallsoccurs (Section A.5) and the expected outcome of the river intervention is, as measured, a decrease of the flow velocity in the main channel, as more flow is transported through the auxiliary channel (which before intervention was a high-friction groyne field).

The implications for sediment transport capacity can be derived by assuming a power 5 relation between mean flow velocity and sediment transport capacity (Engelund and Hansen, 1967). In this case, a 10% reduction in flow velocity (representative of low-flow conditions) causes a 40% reduction in sediment transport capacity and a 1% reduction in flow velocity (representative of high-flow conditions) causes a 5% reduction in sediment transport capacity. The sediment transport rate is higher during high-flow than during low-flow condition, but low-flow conditions occur over a longer period. For the sake of exemplifying what the yearly implications of the reductions are, we assume that low flow occurs during 11 months a year with a velocity equal to 1.3 m/s (approximated value from Table 3.3) and high flow during 1 month a year with a velocity equal to 1.45 m/s (approximated value from Table 3.5). In this case, the reduction in yearly sediment transport rate would be 36%.

A reduction in the sediment transport capacity is coherent with the aggradation (or reduction in degradation) observed in the bed level measurements and in the simulation results. It is relevant to have in mind that it seems from the velocity measurements that this is mainly due to the effect under low-flow conditions, rather than high-flow conditions, as the change in velocity is largest for the conditions with a lower flow.

3.3.3.2 Limitations and recommendations

Data has been delivered in two different formats, one of them without vertical velocity. The coordinates system varies between profiles. This lack of uniformity may have its origin in different contractors and organizations obtaining the measurements. Importantly, it unnecessary complicates data processing. Moreover, data is structured in a non-uniform and non-intuitive format. The names of the files and folders do not follow a convention. Furthermore, the folder names are used to provide information, rather than “readme” files and tables, which causes names so long that cannot processed with some software. We strongly recommend to structure data in a uniform machine-readable manner with proper meta-data.

Several observations follow from the raw ADCP measurements (e.g., Figure 3.8). In all profiles, the vertical velocity is unrealistically large and shows an unrealistic pattern in which the top part of the flow is directed downwards and the bottom part upwards. The expected magnitude of the vertical velocity may be too small to be captured by the ADCP using the configuration that was set, which seems to have been set to capture the streamwise velocity. The precise ADCP configuration is unknown to us which prevents us from assessing the device accuracy. Most probably, the ADCP was not configured to measure vertical velocities.

Similarly, the crosswise-velocity pattern does not show the details of secondary flow one would expect. Being two orders of magnitude smaller than the streamwise velocity, most probably the instruments and measurement campaign were not set and designed to capture these subtle characteristic of the flow.

A larger number of rounds for each measurement would help in filtering noise related to turbulence. If the main question to be answered is the flow velocity, a measurement at a fixed location in the main channel for a long time would be more helpful and cheaper than several rounds measuring the entire cross-section. Certainly, this would not provide information on discharge. Measurement at a fixed location is not trivial, as instruments cannot be placed in the navigational channel, but a ship could maintain a fixed location for a certain time. This is again not trivial given how busy is the Waal River. Still, such a measurement would allow filtering in time and obtaining a precise view of the vertical profile.

In comparing the situation before and after intervention, we are severely limited by the scarce number of measurements conducted before intervention. The extensive dataset available may serve other purposes than then ones treated here. Nevertheless, for assessing the impact of the construction, once the exact same locations measured before intervention have been measured for the exact same discharge occurring at that time, extra measurements do not add further information.

A second important limitation is the fact that measurements have not been conducted at always the same location. For instance, the closest location after intervention to Location 4 in 2013 for a low discharge (rkm 913.100,upstream of Amsterdam-Rijn Kanaal inlet) is 1300 m upstream. Comparison of these two locations is far from ideal. Some other locations are ideal for comparison. For instance, Locations 2 and 5 for all discharges are right at the same point before and after intervention.

Regarding the analysis, the water level at Tiel has been used to match measurements before and after intervention. A problem with this approach is that the construction of the longitudinal training walls affects the water level at Tiel. As it is expected that the water level is lowered thanks to the construction of the longitudinal training walls, by matching the water level the discharge (and flow velocity) after construction are underestimated. Hence, the change in flow velocity may be larger than estimated.

The construction of the longitudinal training walls is not the only source of change in water level at Tiel. Groynes downstream and upstream from the longitudinal training walls have been lowered and other interventions even affect the water partitioning at the Pannerdensche Kop. The flow conditions are also important. Following a flood wave a larger friction is expected due to bed forms.

It is relevant to mention that the lowering of the water level is not clearly visible in the data due to large scatter (see report of WP10). Moreover, its effect would be negligible compared to the standard deviation of the measurements and averaging procedure in depth and cross directions.

One could think about computing the discharge in all measurements and match data based on discharge. This approach presents several issues. The first is that the uncertainty in velocity and in discharge computed by integration in vertical and cross directions is large. Note the noise visible in the raw plots of the profiles and the standard deviation in velocity measurements. Hence, most probably this uncertainty is larger than the effect of a change in water level. Second, it would be necessary to add the discharge measured in the main channel to that in the auxiliary channel. This adds further uncertainty as sections in the main channel and auxiliary channel where not taken at the same time and at the same river kilometre. Measurements which are not taken at the same river kilometre are difficult to add, considering that it is known that there is flow through the walls. Moreover, seeing that the closest measured data already have a difference in water level between 2 and 14 cm, it is foreseeable that also if using discharge, a condition exactly equal (in terms of discharge) to the original one cannot be found. Overall, the best way to match conditions before and after is the water level at a station.

One clear effect of the construction of the longitudinal training walls on the main channel under low-flow conditions has been a reduction of the width. A secondary effect is the fact that while before there was an exchange of mass and momentum between groyne fields and main channel, now there is not. The consequences of such decrease in mixing have not been considered. A first assessment could be done by comparing results of three-dimensional schematized simulations of a river section with groynes and with a longitudinal training wall.

3.4 Transverse velocity near the inlets

3.4.1 Methodology and results of the analysis of the transverse velocity

This section focuses on analysing the flow pattern in the inlets and outlets with focus on navigation (i.e., answering Research Question 2).

An indicator of nautical safety is the transverse velocity. As an order of magnitude of the transverse velocity that is relevant for safety purposes, for small channels in which the streamwise velocity is smaller than 0.5 m/s, the transverse velocity should be smaller than 0.3 m/s (Koedijk, 2020). In rivers the conditions usually requires specific research. Here, we will use the value of 0.3 m/s in plots simply as an order of magnitude as this is not an actual threshold for navigation under the conditions in the longitudinal training walls.

In order to study the transverse velocity at the inlets, the focus is on analysing the profiles taken in streamwise direction at the inlets. The velocity is depth-averaged for:

- the entire flow depth, and
- the top 2 m of the water column.

The second averaging is done for the reason that the velocity affecting navigation is the one occurring on the top part of the flow, although the criterion is set for the depth-averaged velocity.

A grid is generated oriented following the flow and the values from the profiles are averaged on the grid to get a spatial view of the flow pattern (e.g., Figure 3.20). All the figures analysed are shown in Appendix D.5 grouped per inlet.

The maximum transverse velocity is in general observed along the inlet itself. As one moves towards the auxiliary channel, large transverse velocities are still observed, while the transverse velocity rapidly decreases towards the main channel. See, for instance, Figures D.137, D.145, D.181.

Figure 3.21 shows the maximum transverse velocity (averaged in the grid) for each of the conditions that have been analysed. Table D.14 describes the locations. In general, the maximum is below 1 m/s, although above 0.3 m/s. Nevertheless, the area in which the velocity is larger than 0.3 m/s is relatively small and it is concentrated in the inlet and towards the auxiliary channel. For comparison, in Figure D.167 there are 1948 m^2 in which the velocity is above threshold, which is representative of a location with a small area.

Another data-set for studying the transverse velocity is available. A limited number of longitudinal profiles have been taken along the main channel (e.g., Figure 3.22). In this figure we see how, at the inlet of Ophemert, a larger-than-average cross-wise velocity is observed. The main limitation of using this data-set is that only one profile was measured (i.e., there are no several rounds that can be averaged). Hence, it is not possible to filter several profiles in order to derive the mean-flow velocity from the instantaneous one. It is relevant to mention that we see in this profile the aggradation at the inlet at the same location where the increase in transverse velocity is observed. This is a sign to where influence of the inlet is noticeable on the flow field and indirectly on the bed level.

We attempt to study differences in flow pattern due to changes in the inlet shape. To this end, we focus on the upstream inlet at Wamel. Here, the crest-level change is largest, as it increased from 1 m+NAP to 4 m+NAP in April 2018 (Figure A.3).

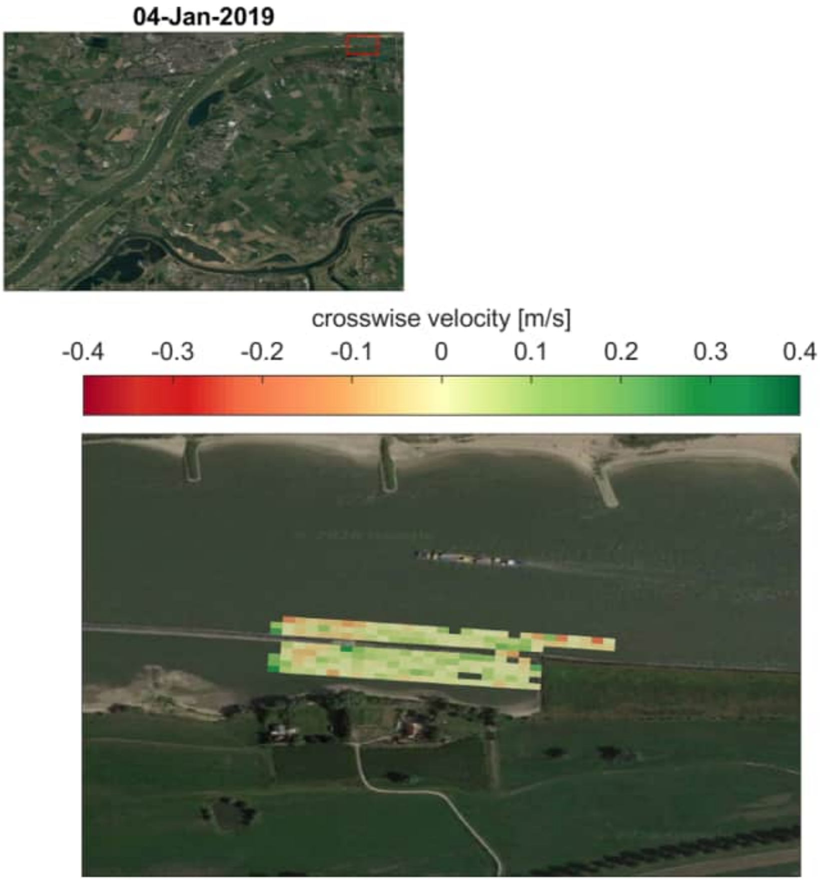

Figure 3.20 Depth-averaged velocity field considering the full water column on 04-01-19 (discharge Lobith: 1800 m^3/s).

We consider a situation before and after the change in crest level with flow conditions being as close as possible. On February 2, 2018, the water level at Tiel was 7.57 m+NAP. The closest water level in which measurements are available after changing the inlet were conducted on March 20, 2019, and the water level was equal to 7.50 m+NAP. The two figures showing the flow field in these cases are Figure 3.23 and Figure 3.24, respectively. No substantial changes in flow pattern can be observed.

Another comparison can be drawn between that situation on December 1 2017, when the water level at Tiel was 5.96 m+NAP. The closest water level in which measurements are available after changing the inlet were conducted on December 19, 2019, and the water level was equal to 6.18 m+NAP. The two figures showing the flow field in these cases are Figure D.177 and Figure D.167, respectively. The same conclusion can be extracted: no significant changes are observed and the changes can be associated the fact that the water discharge in the two situations we are comparing is not exactly the same.

Given that these are the largest changes expected to occur, we conclude that with the current approach the changes in depth-averaged flow pattern at the inlet due to a change in crest level are not appreciable.

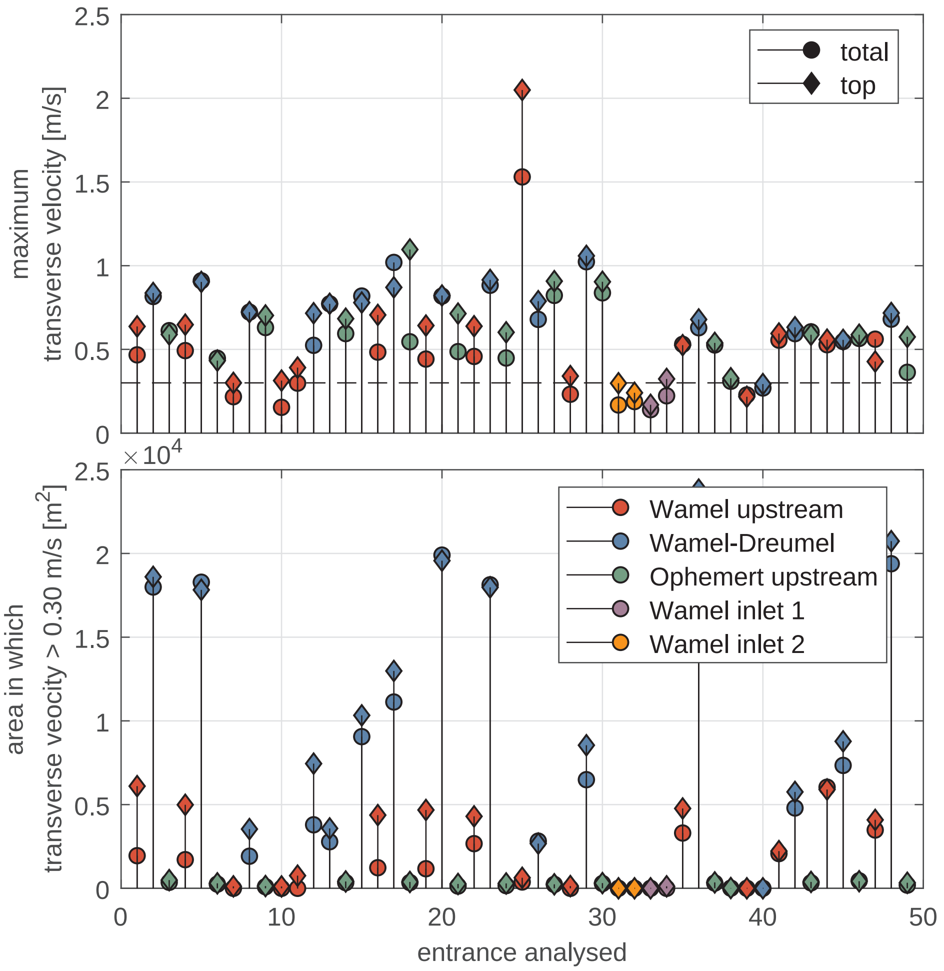

Figure 3.21 Maximum transverse velocity at each of the situations analysed (top figure) and area in which the transverse velocity is larger than 0.3 m/s (bottom figure). The analysis is conducted on the full depth-averaged velocity (total) as well as in the top 2 m of flow (top). 49 situations have been analysed at different times and locations (horizontal axis).

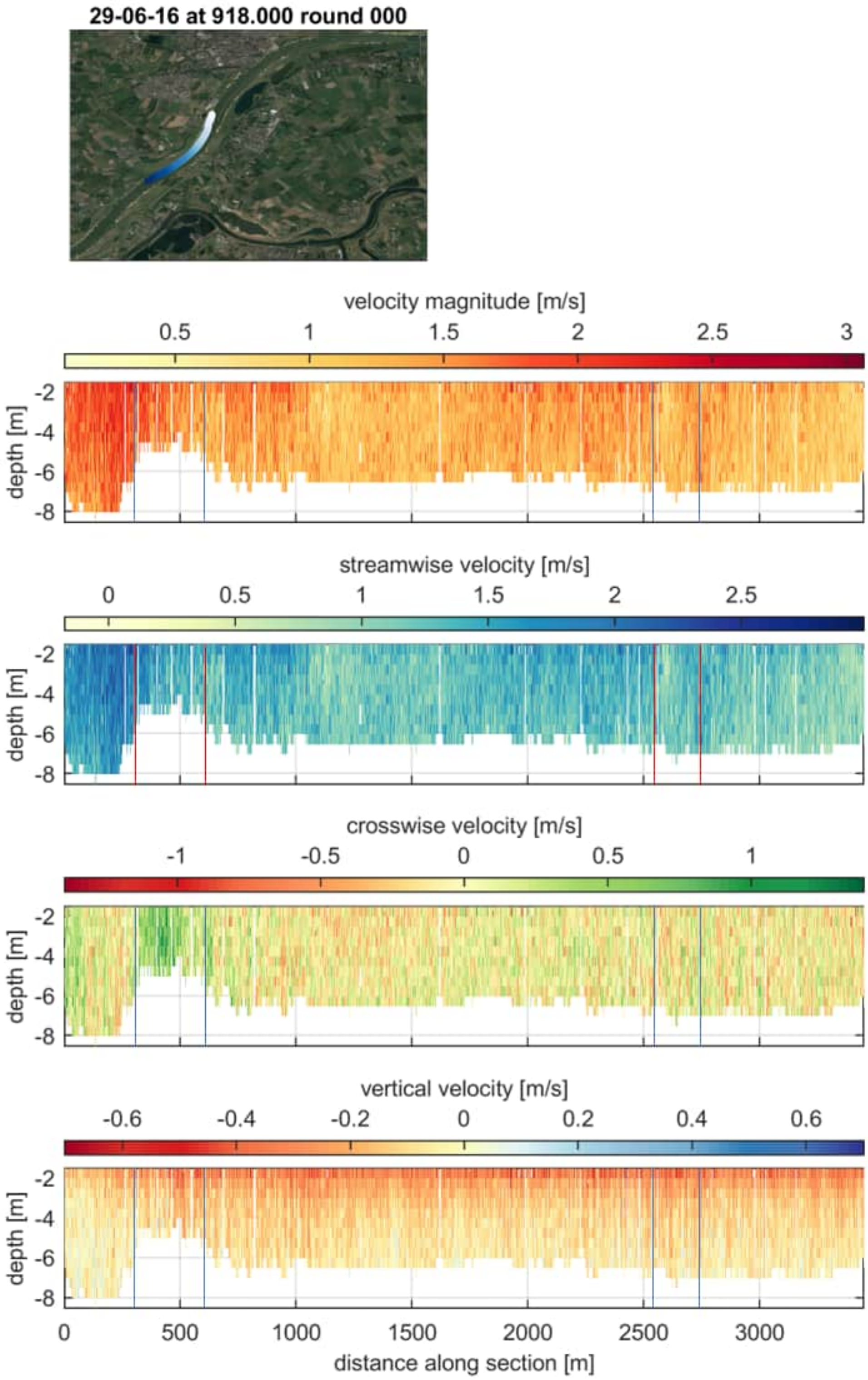

Figure 3.22 Velocity along a longitudinal profile. Positive cross-wise direction directed to the right bank. Vertical lines mark the inlet (at 500 m) and intermediate opening (at 2600 m) of the longitudinal training wall.

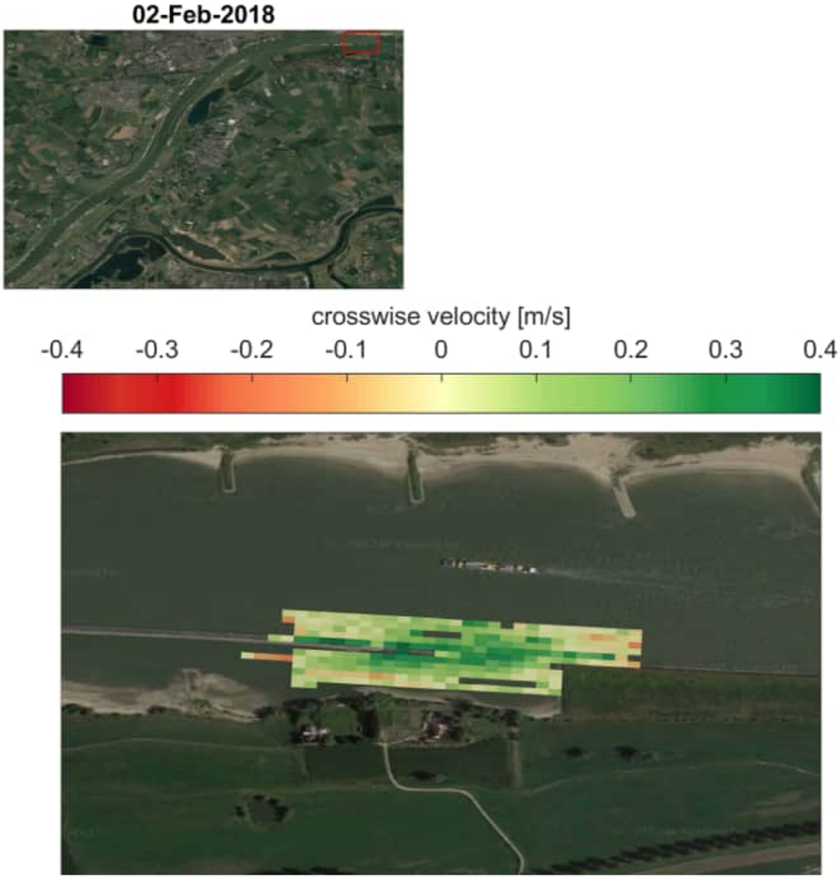

Figure 3.23 Depth-averaged velocity field considering the full water column on 02-02-18.

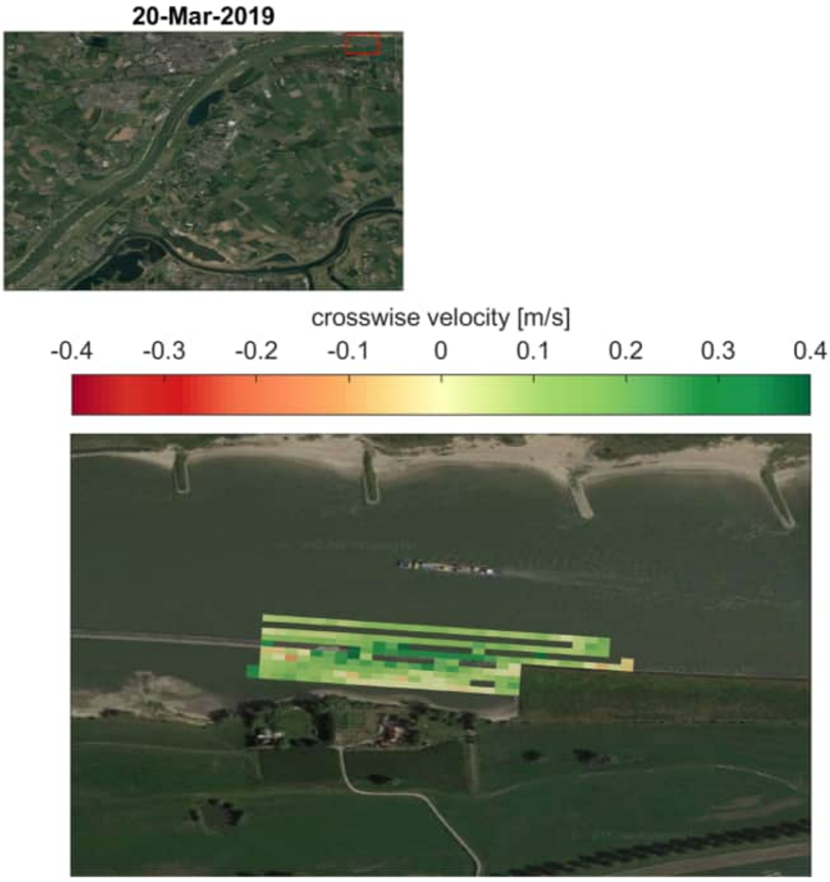

Figure 3.24 Depth-averaged velocity field considering the full water column on 20-03-19.

3.4.2 Discussion of the results of the analysis of the transverse velocity near inlets and recommendations

The depth-averaged flow fields reproduced in the results show the expected general patterns. They capture the flow in the main and auxiliary channel as well as the change in direction at the inlet and even eddies. The results show that inlets have no significant effect in the transverse velocity in the navigational fairway. At the inlet, the maximum transverse velocity is around 0.5 m/s.

Nevertheless, it relevant to mention that the same limitations discussed in Section 3.3.3.2 apply to this case. Namely, data seems to well capture the velocity in the main flow direction but not the flow subtleties in the vertical direction. Similarly, less data in time but under the same flow condition is more useful than more data in time under different flow conditions.

We recommend to *a priori* set certain water levels at Tiel spanning the whole range of relevant water discharges at which measurements will be taken. In this way, a detail study of the effect of modifying the inlet shape is possible. Furthermore, if the question to be answered is the main channel transverse velocity, the most useful measurement is obtained by fixing the ADCP (i.e., the boat) in the main channel at a fixed position for a long enough time (order of minutes). This allows filtering of turbulence, ship waves, and all other disturbances affecting the results.

3.4.3 Conclusions and recommendations

From the ADCP measurements the following is concluded:

- From ADCP measurements the change in velocity is analysed. For a discharge at Lobith of 922 m^3/s, an increase in flow velocity in the order of 10% is observed. An increase in flow velocity was expected as flow is concentrated in the main channel thanks to the longitudinal training walls. For a discharge at Lobith equal to 3436 m^3/s, 4170 m^3/s, and 5087 m^3/s, a decrease in flow velocity was observed of approximately 15%, 5% and 2%, respectively. For these discharges the longitudinal training walls are fully submerged making the flow width wider than the situation prior to construction of the LTW.
- Based on a simple estimate based on Engelund and Hansen (1967) related to the average velocity before and after the construction of the longitudinal training walls, it is estimated that a low discharges the sediment transport is reduced by 40 % and at high discharges the sediment transport is reduced by roughly 5 %.
- A discharge through the auxiliary channel of less than 12 % is expected to be succesful in raising the water levels in the main channel. At Wamel, only the situation after raising the inlet is evaluated, after which the discharge is smaller than 12 % for all discharges smaller than 2500 m^3/s. At Dreumel, this only goes for discharges below 1250 m^3/s. At Ophemert, this never occurs. For more set-up in the main channel the discharge through the auxiliary channel should be reduced.
- Near the inlets, the transverse velocity is in general above 0.3 m/s, but below 1 m/s. Nevertheless, the area in which the velocity is larger than 0.3 m/s is relatively small.

4 Bed level

4.1 Introduction

This chapter discusses the data analysis based on multibeam measurements of the bed level. In this chapter the following research questions are considered.

1 How is the bed level and the bed level trend related to the overall degradation, influenced by the construction of the longitudinal training walls?
2 What is the effect of changes to the inlets?
3 How does the bed level develop in the auxiliary channels?
4 What is the influence of the longitudinal training walls on the navigation depth and width?

4.2 Available data

Before starting on the data analysis, first an overview is given of the available data, which will be described in further detail in the subsequent sections.

- Yearly multibeam measurements for the bed level
- Eight-weekly measurement campaigns from 2015 week 42 until 2020 week 26 covering the full with of the main channel
- Reference plane OLR of 2012
- Polygons for reach and hectometres, delineating different sections of river.
- P-map scripts for post-processing the bed levels from the multibeam and the eight-weekly measurement campaigns
- Auxiliary channel zones

4.2.1 Yearly multibeam measurements 2000-2017

Rijkswaterstaat kindly provided us with multbeam measurements.

The data is processed using the P-map method. The averaging polygons used are shown in Figure 4.4 in purple. These are the polygons before construction of the longitudinal training walls. The data was provided per year, the month of the measurement was estimated from the date of the last measurement done for that year (cf. Figure 4.1).

4.2.2 8 weekly multibeam measurements

In addition *Rijkswaterstaat* provided multibeam measurements from the period after 2015 week 42 until 2020 week 26 for the region at the longitudinal training walls both inside the navigation channel and in the auxiliary channels (see Figure 4.2). This data was provided in many different formats, with the vertical reference in either centimetres, decimetres or metres, the reference direction as positive up or down depending on the date of the measurement, and the data was stored in integer or float. Fortunately, all the data appeared to be consistent with the reference level NAP (Normaal Amsterdams peil). The horizontal resolution is 1 m.

4.2.3 P-map procedure

The procedure (Kater, 2014) to compute the bed level trends was also shared with us. The procedure consists of Arcgis python® scripts which combine subsequent multibeam data and obtain the average, minimum and maximum for each of the polygons as described in Section 4.2.5.

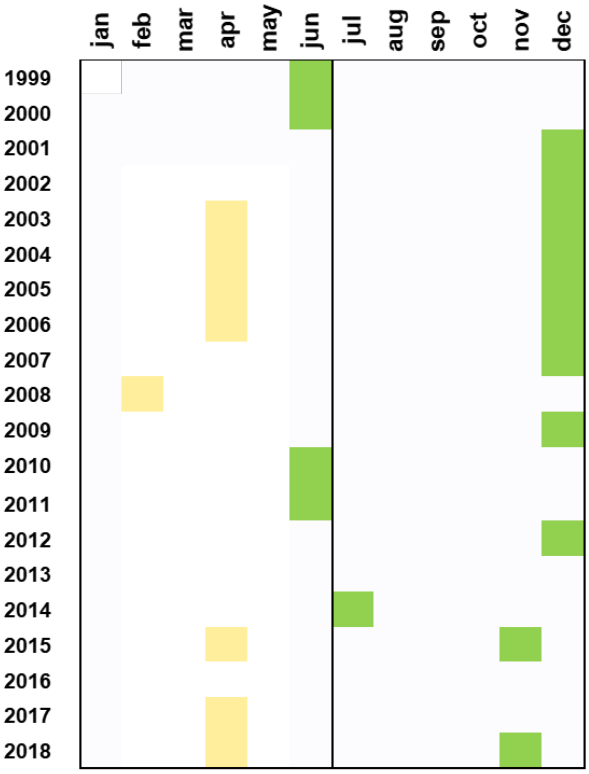

Figure 4.1 Overview of the provided yearly multibeam measurements. Sometimes multiple measurements are done in a year, but the month of the measurement is said to be the last measurement of the year (green, not the yellow).

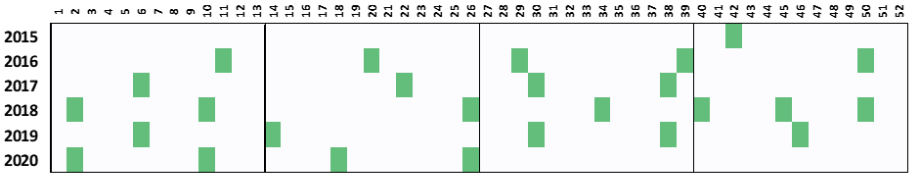

Figure 4.2 Overview of the provided 8 weekly measurements. The horizontal axis shows week numbers.

4.2.4 Reference plane OLR

OLR is the agreed upon low river reference level (in Dutch: Overeengekomen lage rivierstand) and this was provided to us by *Rijkswaterstaat* . For the Rhine branches the associated discharge is referred to as OLA (In Dutch: Overeengekomen lage afvoer), and its magnitude is 1020 m^3/s.

4.2.5 Channel widths and analysis polygons

Many definitions exist for the defining the width of the river or fairway on the river. In WP7 (Van der Wijk and Van der Mark, 2021) these definition have been written down carefully and sketched. As these widths are used for the analyses of the bed level, the sketch is included in Figure 4.3 and the definitions as used in this report are given below in Table 4.6. The location of the navigation channel has been adjusted since the construction of the longitudinal training walls, and only this new definition has been used throughout this research.

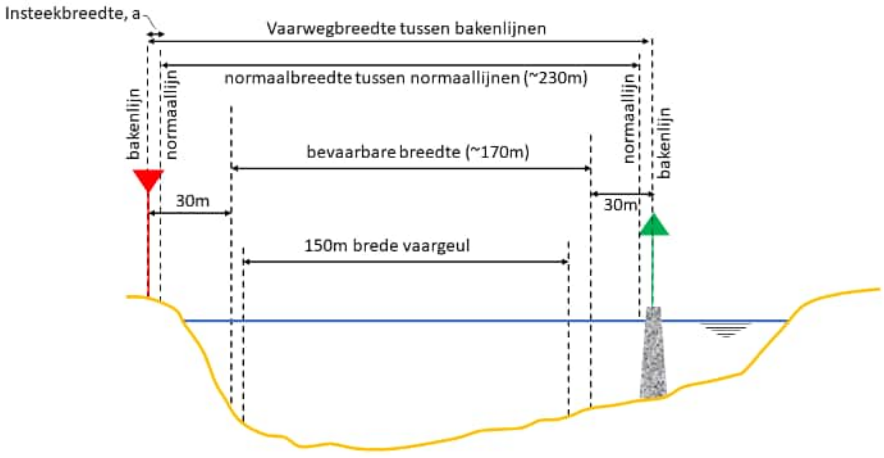

Figure 4.3 Definitions of widths of river and fairway. For more information see (Van der Wijk and Van der Mark, 2021).

Table 4.6 Definitions of widths of river and fairway For more information see (Van der Wijk and Van der Mark, 2021).

Definition (NL)	Definition (EN)	Description
'vaargeul'	navigation channel	Formal width of the fairway that is being maintained at a depth of 2.8 m (at OLA-discharge). It is following the deeper sections of the river. This width is 150 m for the middle and upper Waal.
'bevaarbare breedte'	navigable width	The part of the river that is located between 30 m from fixed beacons and 5 m from floating beacons. For this part of the river the MGD is registered. At the LTW this width is 170 m. In this bed level analyses it is agreed with RWS to design this polygon by applying a 10 m buffer to both sides of the navigation channel.
'zomerbed secties'	main channel section	Polygons defined by *Rijkswaterstaat* for the analyses of bed level effects. These are defined as the Normal Width minus 15 m on both sides. At the LTW this has a width of 200 m
Normaalbreedte	Normal width	Width between the 'normaallijnen', which on the Waal approximately follow the beacons. Upstream of the LTW this has a width of 260 m, which reduces to 230 m just after the inlet at Wamel and remains this width for the remainder of the LTW.

The auxiliary channel zones indicate the locations in the auxiliary channel near the main channel and near the river bank. These polygons are also split into 100 m sections. An example of these zones can be seen in Figure 4.4. They correspond to the sections Br, Bl, Cr and Cl in the figure in the same section. B refers to the near channel zone, while C refers to the near bank zone. The small letters l and r refers to left and right bank, respectively.

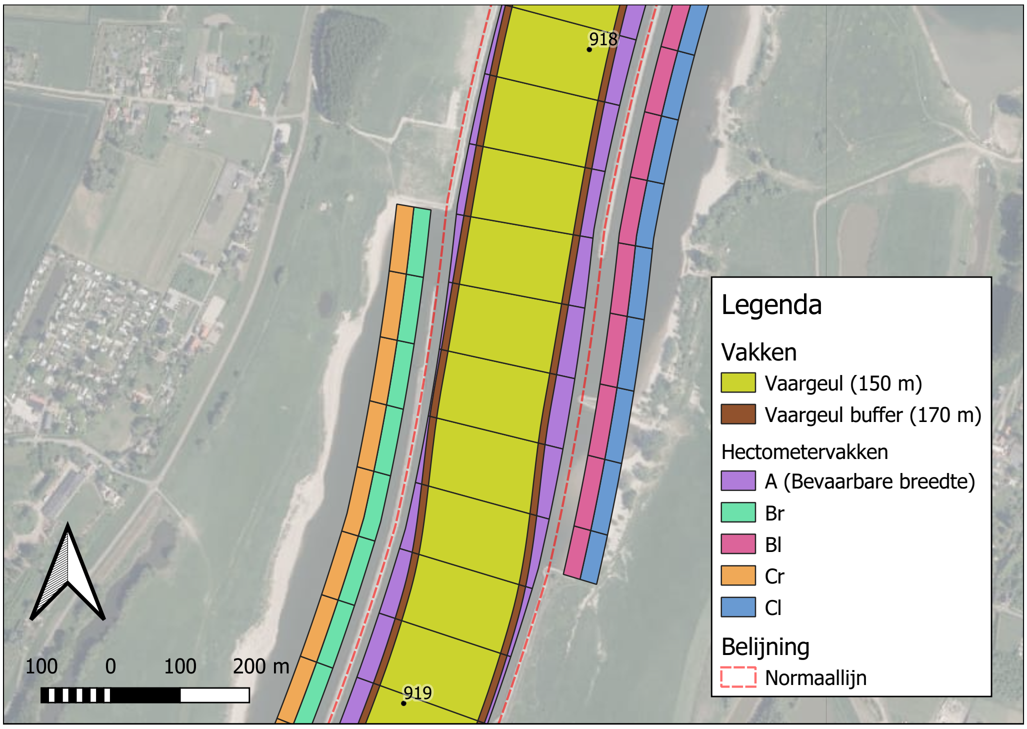

Figure 4.4 Averaging areas for the bed level 'zomerbed secties'. Note: the definition 'Bevaarbare breedte' was later in this study changed to 'zomerbed secties' (main channel section)

4.3 Methodology

The following steps are followed in this analysis of the bed levels:

- Data clean-up
- P-map analysis
- Processing and plotting based on available scripts (Chavarrías and Ottevanger, 2019)
- Additional scripts for computation of percentile of OLR - 2.8 m
- Sharing of cleaned data and scripts

For the provided multibeam data, each of these files had to be inspected manually to confirm the correctness, and be transformed to the form which could be used in combination with the P-map procedure. There was no meta-data available to describe how the data was stored. All the data was transformed to centimetres w.r.t. NAP, vertical positive up, and stored as an integer with a horizontal resolution of 1 m. The data was stored as an ESRI grid file.

The OLR data was also transformed into centimetres, positive up w.r.t. NAP. After this, rasters were computed of the difference OLR minus multibeam bed level. An example of this is shown in Figure 4.5.

Next the P-map approach was applied to the bed level measurements and the depths w.r.t. OLR for the navigation channel, navigable width and main channel section and different reach polygons shown in in Section E.1. For all analyses the location of the channels after construction of the LTW was used.

In addition, extra analysis was developed for determining the standard deviation and the percentile at which the depth is equal to 2.8 m w.r.t. OLR.

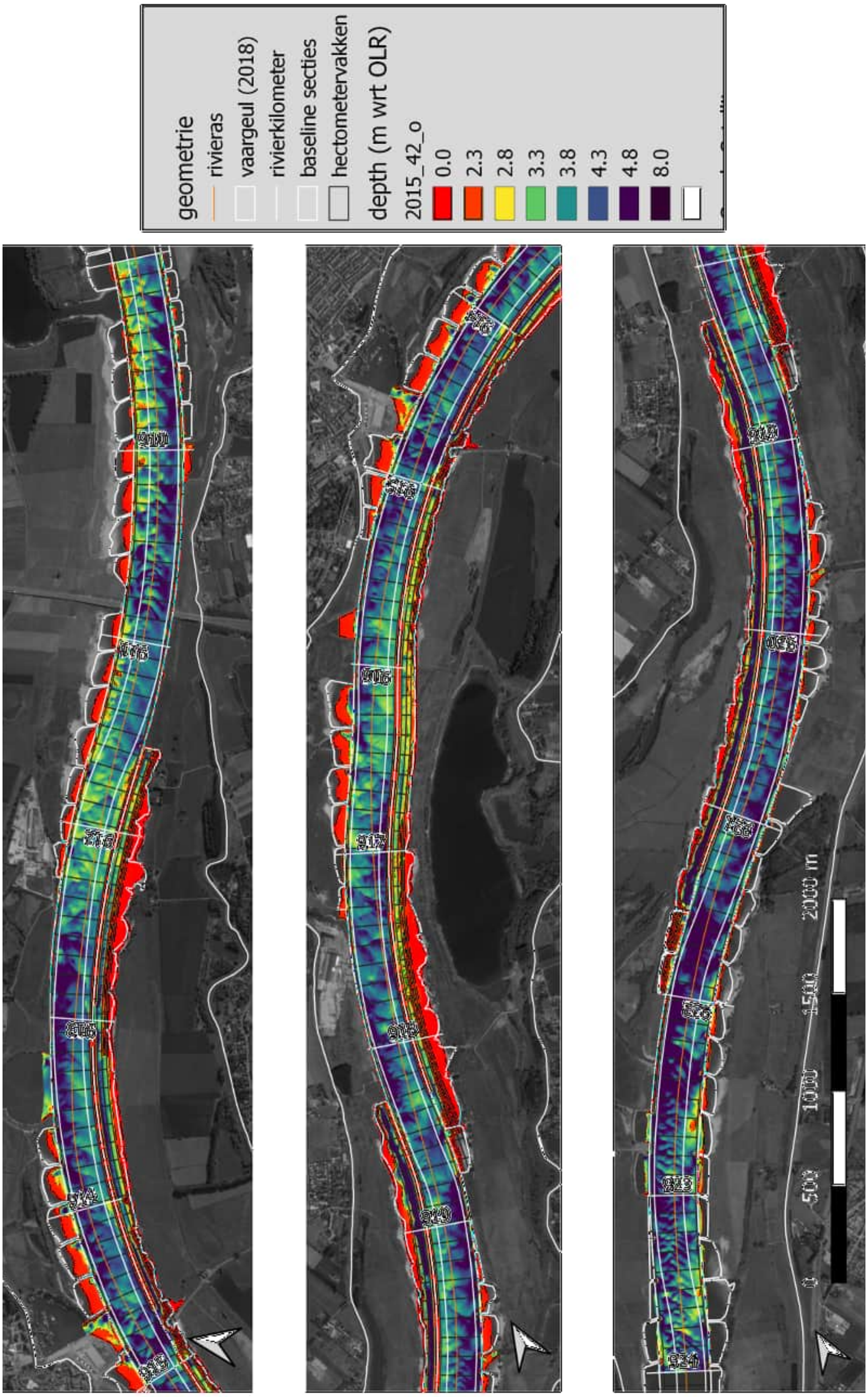

Figure 4.5 Depth w.r.t. OLR in 2015 week 42.

4.4 Results

4.4.1 Main channel development

Firstly, the P-map approach was applied to larger sections. The large scale polygons for which the analysis was done are shown in Appendix E.1. These data have been simplified to reaches upstream, downstream and at the three different auxiliary channels of Wamel, Dreumel and Ophemert (cf. Table 4.7).

location	river kilometre	
	start	end
Langsdam hoofdgeul Upstream	909.000	911.755
Langsdam hoofdgeul Wamel	911.755	914.750
Langsdam hoofdgeul Dreumel	914.750	918.450
Langsdam hoofdgeul Ophemert	918.480	921.550
Langsdam hoofdgeul Downstream	921.550	922.500

Table 4.7 Locations for averaging of the P-map results.

Figure 4.6 shows the P-map data for the sections as presented in Table 4.7.

Based on the yearly multibeam measurements, the Upstream, Wamel, Dreumel seem to have average bed levels which are stable over time until 2010. Wamel shows a slight degrading trend.

From 2015 to 2017 (or 2018) the bed levels, at Wamel, Ophemert and downstream the bed seems to be eroding. The construction of the longitudinal training walls took place from August 2014 until November 2015 (see appendix A.2), which implies that some of these changes happened during the construction phase. Based on the situation after construction, it appears that at the upstream and at Dreumel the bed level remains stable, while Wamel shows a bit of sedimentation until 2018. At Ophemert there appears to be sedimentation after 2018 and downstream the bed initially shows erosion and some sedimentation in the last two years (2019, 2020), but is still developing. This is apparent from the main channel average developments at Wamel, Ophemert and Downstream. A similar analysis for alternative reaches (for example the entire reach) is included in appendix E.3. In appendix E.2 a discussion to the findings of Czapiga *et al.* (2021) is included.

	1999-2015	**2015 – 2017**	**2017 -2019**	**2019-2020**
Upstream (909.0-911.8)	Minor degradation 7 mm/yr	Stable	Small degradation	Stable
Wamel (911.8-914.8)	Minor degradation 7 mm/yr	Degradation	Stable	Degradation
Dreumel (914.8-918.5)	Minor degradation 2 mm/yr	Stable	Stable	Stable
Ophemert (918.5-921.5)	Aggradation 5 mm/yr	Degradation/Stable	Aggradation	Stable
Downstream (921.5-922.5)	Aggradation 9 mm/yr	Lowering	Degradation	Aggradation

Table 4.8 Observed bed-level trends per section.

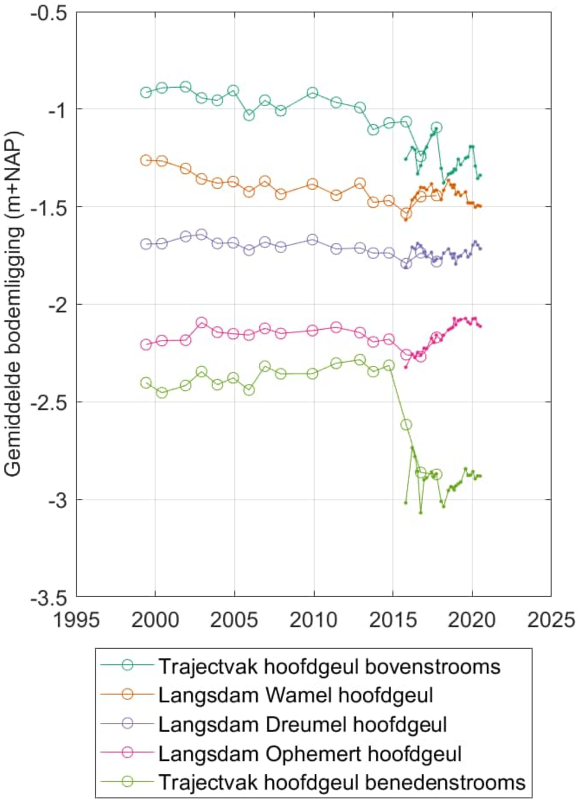

Figure 4.6 The average over different reaches of the P-map *average* bed level.

The minimum bed levels per for the sections in Table 4.7 as computed through the P-map analysis is shown in Figure 4.7. At the auxiliary channel locations the minimum bed level seems to increase slightly since the construction of the longitudinal training walls.

The maximum bed levels per section as computed through the P-map analysis is shown in Figure 4.8. It appears that the maximum bed level remains rather constant over time.

The standard deviations of the bed levels per section as computed through the updated P-map analysis is shown in Figure 4.9. It appears that the standard deviation is larger after construction than in the period 2005-2015. It is not clear if the yearly multibeam measurements are based on the situation after maintenance dredging, and whether the same holds for the 8 weekly measurements. This can possibly be refined by comparing with maintenance records (as visualised by Chavarrías *et al.* (2021)).

The standard deviation of the P-map approach is used to act as a proxy for the height of the bed forms, or at least indicative of it. From the analyses in figure 4.9 it shows that for the new data set the standard deviation follows the river discharge (cf. Figure 3.3). This is confirming the knowledge that at (and after) higher discharges higher bed forms appear (as expected). For the old data set the temporal resolution is lower, thence not showing the effects of individual discharge wave. The data since 2015 appear to show a larger standard deviation. It is not clear if this larger value is solely the effect of the moment in time at which was measured.

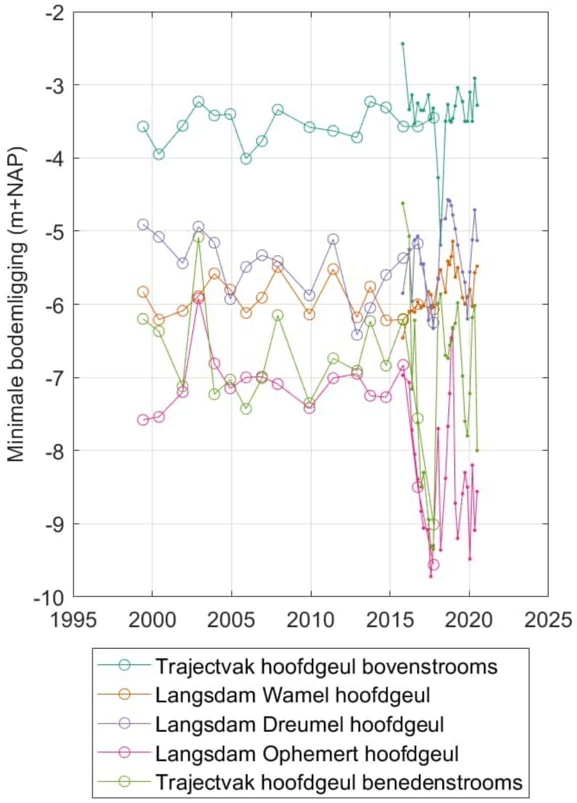

Figure 4.7 The average over different reaches of the P-map *minimum* bed level.

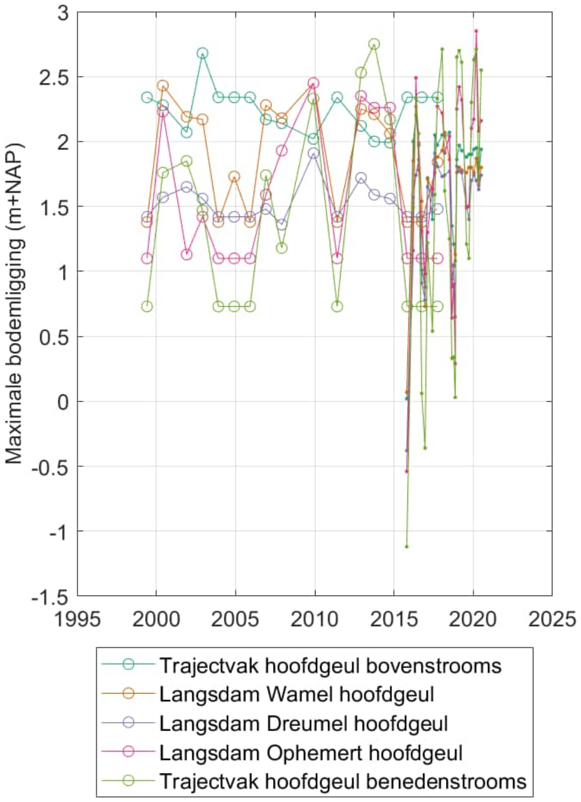

Figure 4.8 The average over different reaches of the P-map *maximum* bed level.

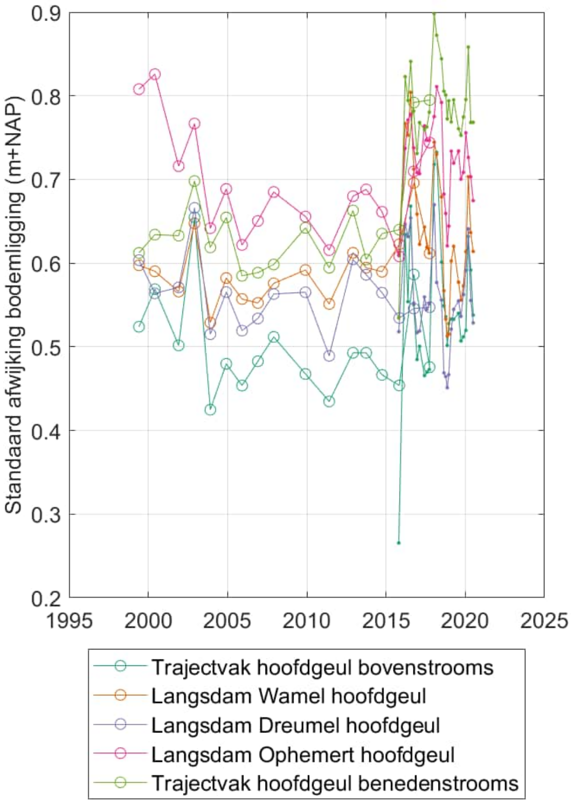

Figure 4.9 The average over different reaches of the P-map standard deviation of the bed level.

Finally, the trend is plotted per rkm for the eight-weekly measurements (cf. Figure 4.10). This figure contains a lot of variation probably caused for the most part by the seasonality. To remove this effect the bed level measurements have been spatially averaged over a length of 500 m, and plotted for the 8 weekly measurements only. The result of this action can be found in Figure 4.11. The relative bed level development is given in figure 4.12.

The figures shows a degrading trend upstream of Wamel. At the reach of Wamel, degradation in the upstream reach and sedimentation in the lower reach is visible. A similar trend can be seen at Dreumel with strong sedimentation up till the first opening along the LTW, from which point erosion is shown. The sedimentation in the Dreumel section coincides with the side channel Passewaaij on the right bank (see also figure 1.5). This side channel has been opened for permanent flow in 2015, so it adds to the sedimentation you see between 916.3 (entrance of the side channel) and 917.3 (exit).

At Ophemert the overall stretch seems to be agrading to about 0.3m on average higher than at the start of the 8 weekly measurements. Downstream of the last dam (Ophemert), an erosion wave appears to be progressing. It is interesting to see that exactly at the outflow of the Ophemert auxiliary channel (rkm 921.3) the bed level is showing some recovery by local sedimentation until 2018.

Upstream of the first intermediate opening of Ophemert a strong degradation is seen initially, similar but stronger than the other LTW, possibly caused by the larger discharge in Ophemert's auxiliary channel (see also Sieben (2020)).

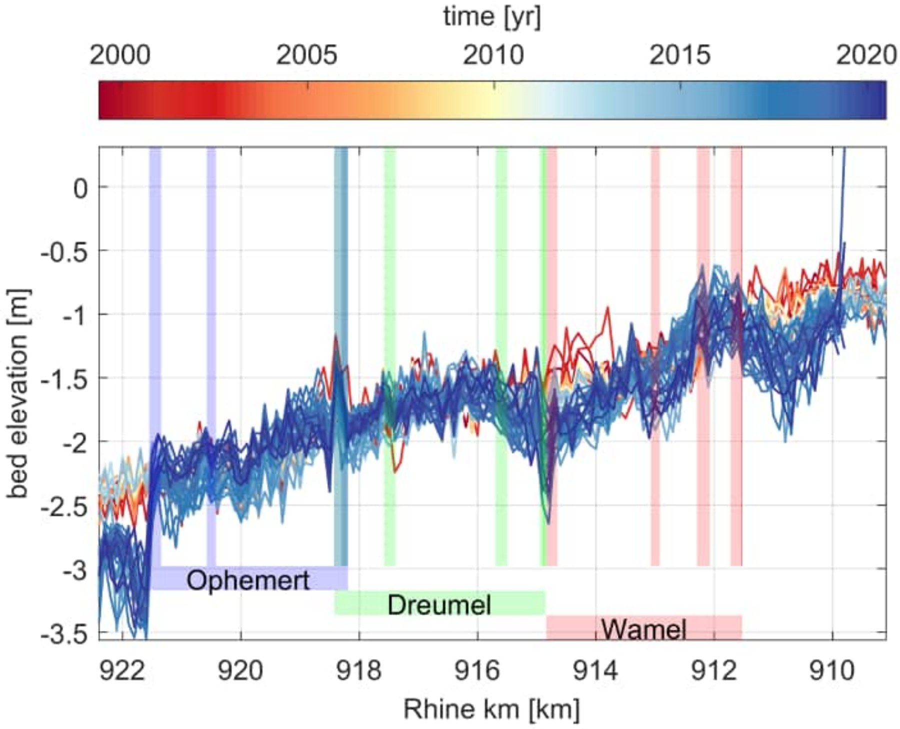

Figure 4.10 Average bed level development based on P-map analysis.

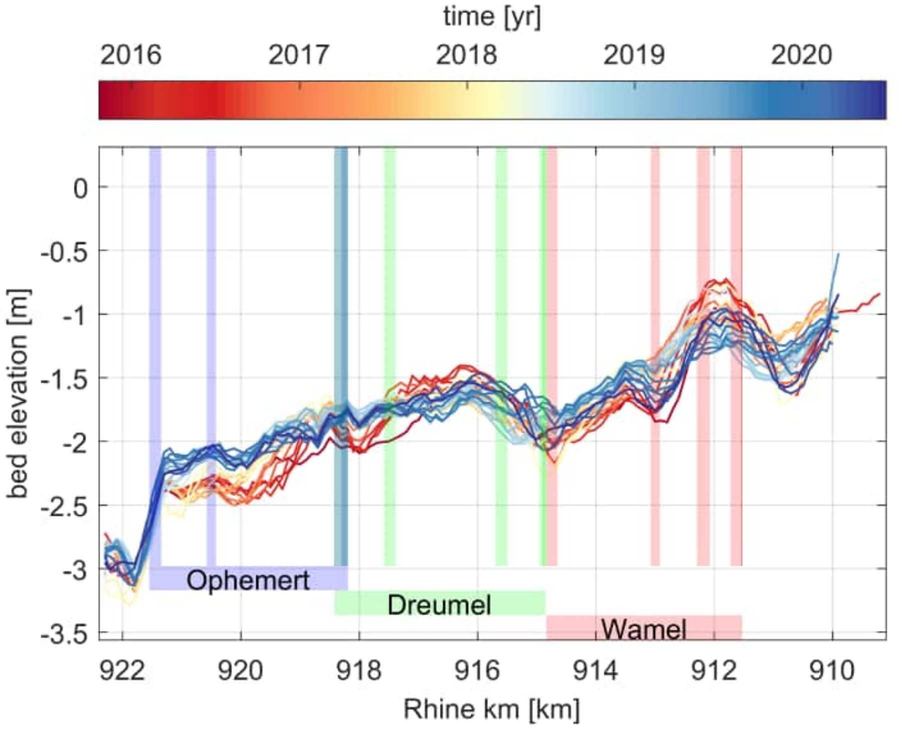

Figure 4.11 Average bed level development based on P-map analysis (averaged over 250 m upstream and downstream) from 2015 week 42

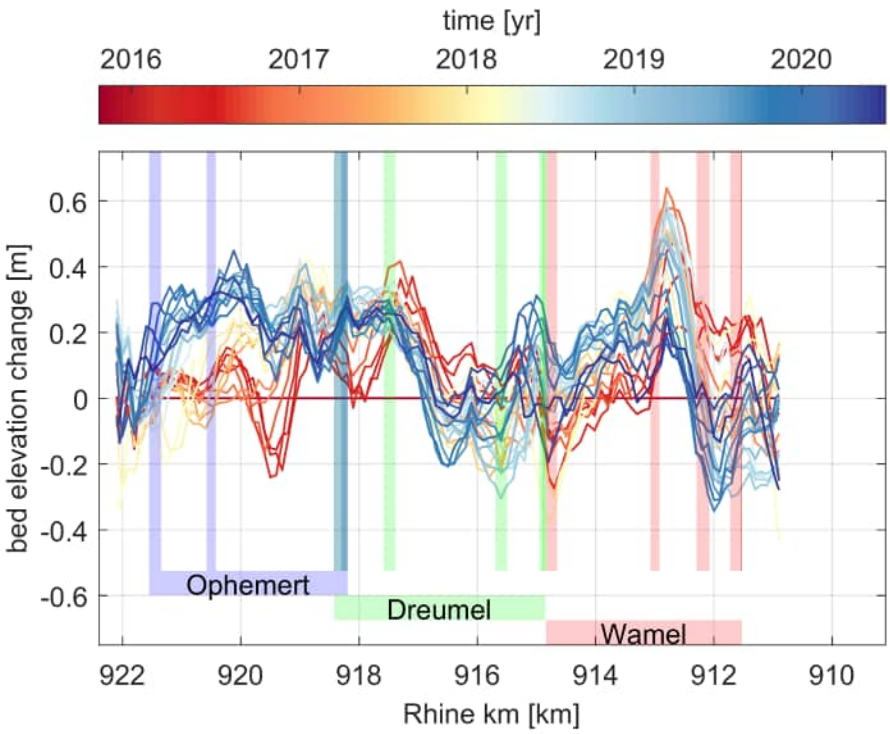

Figure 4.12 Average bed level development based on P-map analysis (averaged over 250 m upstream and downstream) relative to 2015 week 42

4.4.2 Effect of the change in inlets on the bed level trends in the main channel

We have tried to see the impact of the level of the inlets of the auxiliary channels to the bed level trends. The inlets of Wamel and Dreumel had a large adaptation in April 2018. At Ophemert the change was only done after April 2019, and at Dreumel a slight adaptation occurred in April 2019. Dimensions of the adaptations are given in appendix A.2.

To be able to use the data we look at trends between 2015 and April 2018, and after after April 2018 until 2020 week 26. The results of this analysis are shown in Figure 4.13 up till 2018, and in Figure 4.14 after 2018. As we do not have measurements of the sediment transport or its distribution between main and auxiliary channel, we look at the development of the average main channel bed level instead. As a word of caution, bed level changes in the main channel do not necessarily equate to differences in sediment entering the auxiliary channel.

At Wamel, a sedimentation wave develops after construction of the longitudinal training walls. In addition, erosion develops at the upstream region of Dreumel. From river kilometre 916 sedimentation occurs, reaching a maximum at the outflow of Dreumel and the inflow of Ophemert, which are located on opposite sides of the river. Further downstream towards the outflow of Ophemert, erosion is visible. As mentioned earlier, this might be related to the opening of the side channel at Passewaaij at the right bank.

After the update of the sill in April 2018, the behaviour in the main channel changes. At Wamel, the sediment transport is directed in the direction of the main channel, thereby reducing the sedimentation which took place up till April 2018. Interesting to mention is that it is possible that the observed change in trend after modification of the inlet is a coincidence. The bed level data shows degradation upstream of Wamel in week 2 of 2018 at rkm 910-911 which is possibly due to dredging. This trench propagates in downstream direction, and its location coincides with the location of the inlet. The erosion at the downstream end of Wamel gets filled up again after April 2018.

The bed level in the reach of Dreumel does not change much over time. Just downstream of the last intermediate opening of Dreumel (rkm 917.5), erosion occurs. Possibly, some maintenance dredging has taken place here. For the Ophemert reach, the upstream part does not change, and sedimentation occurs at the intermediate opening and the outlet (rkm 920.5 and rkm 922).

Although the trends appear to point in the direction that the raising of the sills indeed have an effect on the main channel bed levels, we remind the reader that only two years have passed since the construction. This implies that, the inherent variability of the river may also explain the changes which are observed. Furthermore, we have not considered effects of possible maintenance dredging in the evolution of the bed.

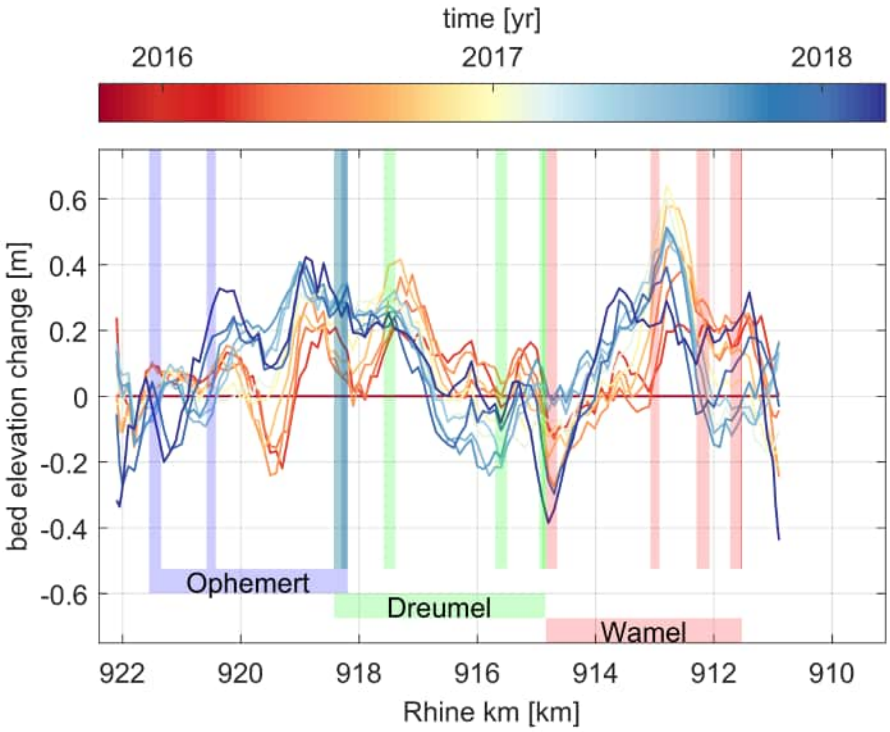

Figure 4.13 Bed level development (averaged over 250 m upstream and downstream) *before* adjustment of sill in April 2018. Bed level change relative to 2015 week 42.

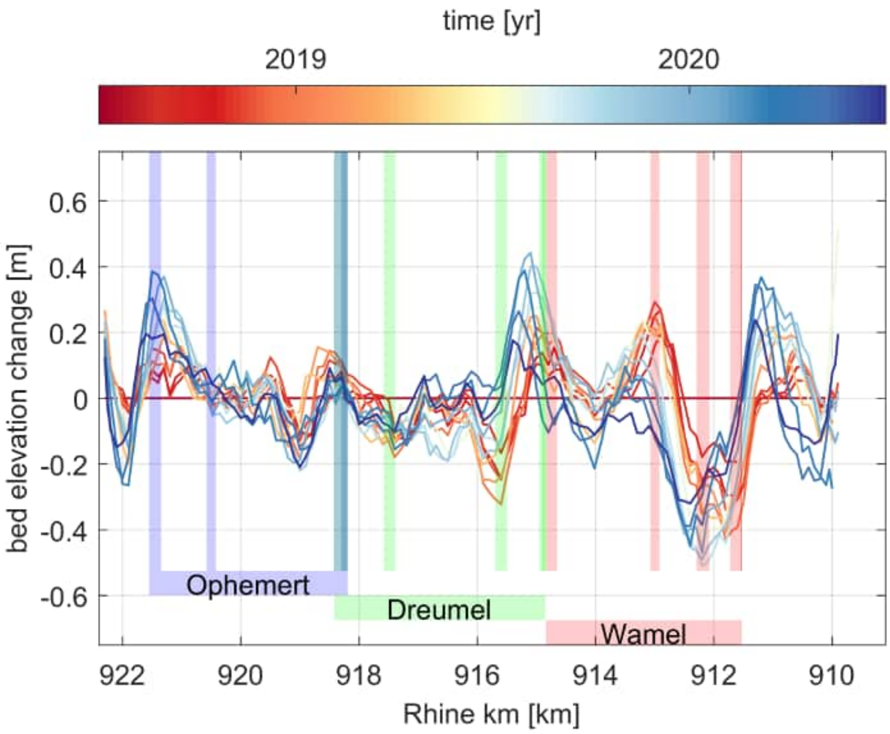

Figure 4.14 Bed level development (averaged over 250 m upstream and downstream) *after* adjustment of sill in April 2018. Bed level change relative to April2018.

4.4.3 Auxiliary channel development

De Ruijsscher *et al.* (2019, 2020) studied the effect of the inlet sill on the bed morphodynamics. Based on his flume experiments he developed a schematic overview of the sedimentation and erosion patterns in the auxiliary channel shown in Figure 4.15. Interestingly, he also mentions that remains of the former groynes in the region may limit erosive processes in the auxiliary channel and stabilize the bank. It is not clear if the wake causing the sedimentation at I really occured in the field, as the off-take is at a very small angle and will cause only little flow separation.

The development of the auxiliary channels Wamel and Dreumel is shown in Figure 4.16. This shows that although the main channel shows changes in the order of 0.5 m, the changes in the auxiliary channel can be much larger.

At the Wamel inlet the divergence bar (II in figure 4.15) is not visible, but the sedimentation pattern just downstream of the inlet is. From figure 4.16 it shows that the sedimentation (line BI) has a length scale of approximately 1 km and is thereby considerably larger than a possible wake (mentioned as I in figure 4.15). The erosion pit does not show (line CI; III in figure 4.15), but caution is advised using the C line as there is very little measured data initially 2015 week 42 (cf. Appendix E.4).

The raising of the inlet in April 2018, does seemingly not lead to large changes in the auxiliary channel. A slight increase in the erosion and sedimentation can be seen. Further details of the Wamel inlet can be found in Section E.6. Further downstream in the Wamel auxiliary channel, there is a large sedimentation, which seems to increase after the raising of the Wamel inlet sill in April 2018. This is probably caused by the decrease in sediment-transport capacity and the ongoing bank erosion.

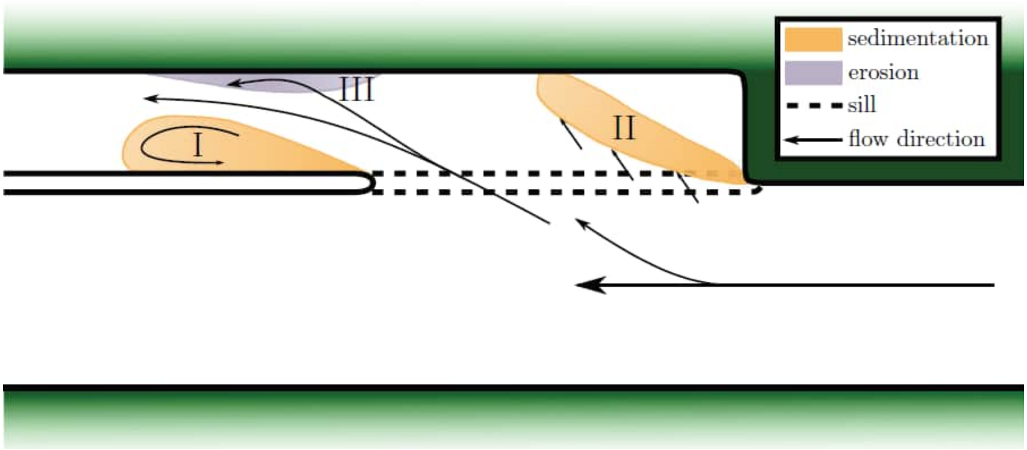

Figure 4.15 Schematic overview of the bed morphology at the bifurcation, highlighting (I) the inner-bend depositional bar caused by flow separation, (II) the divergence bar, induced by widening of the river at the auxiliary channel entrance and an increasing flow depth just behind the inlet, and (III) an erosion pit along the auxiliary channel bank, which might result from the solid flume wall. (From De Ruijsscher *et al.* (2019))

At Dreumel, the patterns at the inlet, are less pronounced than at Wamel. This is probably caused in part by the inlet location at the inner bend of the river, the fact that is more gradually departing from the main channel than the Wamel inlet, and it is close to the outlet of the Wamel auxiliary channel (see also Section E.7). According to Sieben (2020) the discharge into the auxiliary channel at Dreumel is similar to that at Wamel prior to the adaptation in April 2018 (after the adaptations the discharge in the auxiliary channel Wamel is greatly reduced). The Dreumel auxiliary channel can be considered as more or less a continuation of the Wamel channel, only partially separated by the 'veerstoep' (ferry landing) of Wamel. The feed into Dreumel is for a large part directly the outflow from Wamel channel with relative low sediment loads, although there is some limited exchange and attraction of the water from the main channel with sediment. That water is running around the Veerstoep is also causing a deep scour hole in front of the Veerstoep as seen in the figure E.38. It has not been measured how these processes work out at the entrance.

The development of the auxiliary channel at Ophemert is shown in Figure 4.17. Here strong sedimentation is found just downstream of the inlet. This side channel has the lowest sill level which was not adapted until the narrowing in April 2019. The bed in the side channel appears to be stable. The erosion and the sedimentation compared to the measurement of 2015, week 42 shows strong adjustment midway and at the end of the auxiliary channel.

The figures for the detailed development in the auxiliary channels can be found in the appendix from figure E.24 to E.27.

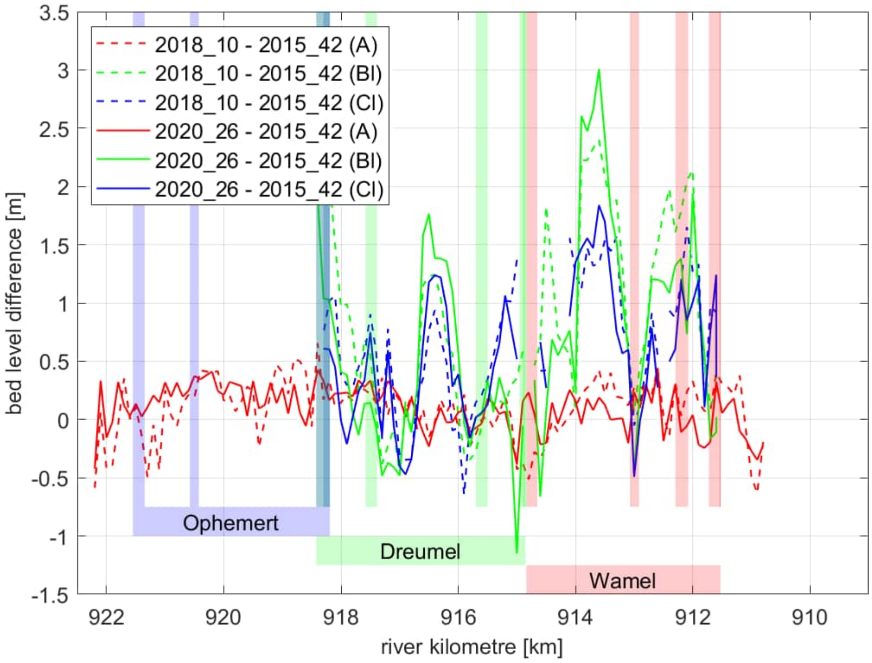

Figure 4.16 Development of the bed level in the auxiliary channels at Wamel and Dreumel. The lines indicate: A the main channel, Bl the left auxiliary channel zone, and Cl the left auxiliary channel bank zone (see 4.2.5).

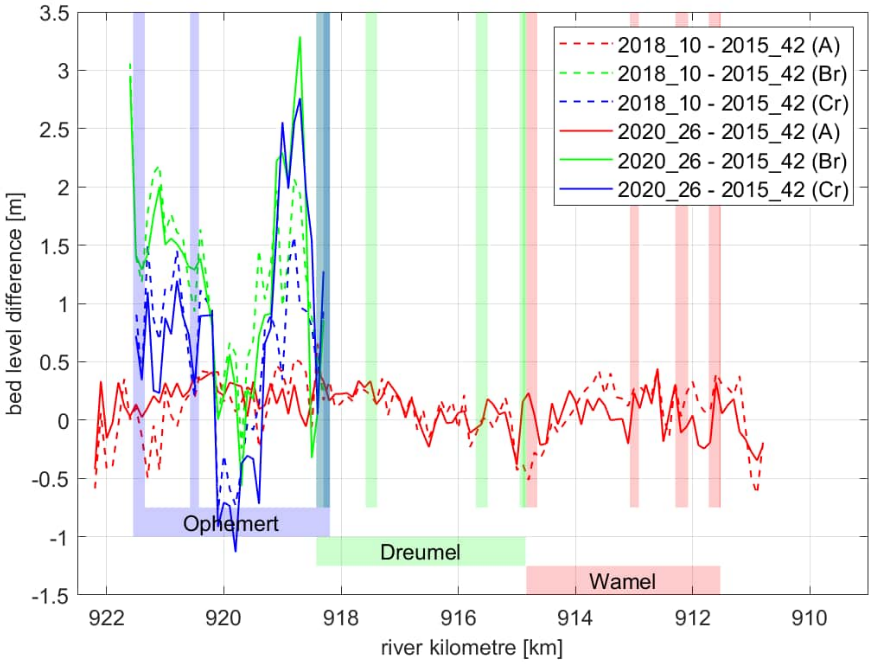

Figure 4.17 Development of the bed level in the auxiliary channel at Ophemert. The lines indicate: A the main channel, Bl the right auxiliary channel zone, and Cl the right auxiliary channel bank zone (see 4.2.5).

4.4.4 Bank erosion in the auxiliary channels

LiDAR measurements of the bank area have been taken on a yearly basis. These data have been combined by Flores *et al.* (2021) with multibeam echosounder data of the auxiliary channels to obtain a complete picture of the dynamics of shore with the objective of calculating net aggradation and degradation in the side channel.

It is observed that at the banks there is net degradation while close to the longitudinal training walls there is net aggradation. This seems to indicate bank erosion on one side and aggradation of the recreational navigational channel of the auxiliary channel on the other side. The bank lines in the bank area's that showed erosion were manually digitized. For Wamel this section has a length of 547 m and for Dreumel a length of 792 m. The yearly retreat of the bank line between 2014 and 2019 at Wamel and Dreumel oscillates between 0.1 m/year and 3.2 m/year with an average of 1.2 m/year at Wamel and 2.0 m/year at Dreumel (see also 4.18). No number for Ophemert is given. The rate of erosion decreases with time, which indicates stabilization.

Flores finds that the net reduction of volume in Dreumel bank zones is in the order of 156 000 m^3, or 4400 m^3 per 100 m. A rough estimate considering an average bank retreat of 1.2 m/year during 5 years and 4 m high bank equals 2400 m^3 per 100 m. Considering a width of the auxiliary channel of 90 m, the measured loss of sediment from the bank would equal 48 cm of homogeneous aggradation in the auxiliary channel, while it appears the recreational channels within the auxiliary channel have aggraded. These rough estimates provide evidence that the net loss of sediment in the side channels comes from bank erosion and not the recreational channels itself, which seem to aggrade.

It is relevant to take into consideration that the multibeam measurement that was taken as close as possible in time to the yearly LiDAR measurement is considered as representative for the whole year. This is a caveat given the dependence of the bed elevation in the underwater are from changes in the discharge. This effect should be filtered out when several measurements are taken or if the LiDAR measurements were obtained under similar flow conditions.

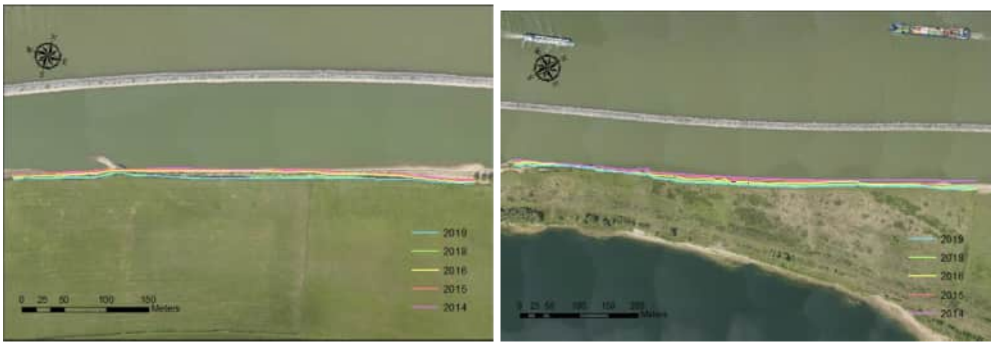

Figure 4.18 Digitized bank lines for the erosion areas in shore channels at Wamel (left) and Dreumel (right) in the river Waal. (Figure from Flores *et al.* (2021)).

4.4.5 Effect on navigation

For navigation, the question is if there is an increase in navigation depth due to a change in bed form heights and increase in water levels. In an earlier analyses (Figure 4.9) no conclusion could be made on the change in bed form dimensions. In this section the bed level is analysed with respect to OLR/OLW (later abbreviated to OLR). This 'depth' w.r.t. OLR is compared to the required navigational depth. This required depth is 2.8 m for most of the Rhine river, but increase towards the river mouth. According to Doornekamp (2019) within the area of interest, it increases slightly towards St. Andries w.r.t. OLR (from 2.8 m w.r.t OLR at river kilometre 917 to 2.92 m at river kilometre 922).

For the analyses of the bed level, the minimum bed level in the P-map results are subtracted from the bed level. Similar to the earlier analyses this is performed for different section widths (‘vaargeul’of 150 m, ‘bevaarbare breedte’of 170 m, ‘zomerbed secties’of 200 m). In this section only figures of ‘vaargeul’are included. Figures for the other widths are included in Appendix E.4.

Figure 4.19 show the minimum depth (most shallow location) for the ‘vaargeul’(150 m) per hectometre. It shows that there are many locations along the reach of the longitudinal training walls where the requirement of 2.8 m is not satisfied. This is exceeded more for wider widths (Figure E.29 and E.30), as the bed outside the ‘vaargeul’is not maintained by dredging. This figures gives an indication of the spatial variability, with the lowest depths around the inlets of Ophemert and Wamel. However, it does not clearly show the temporal variability nor its relation to the discharge.

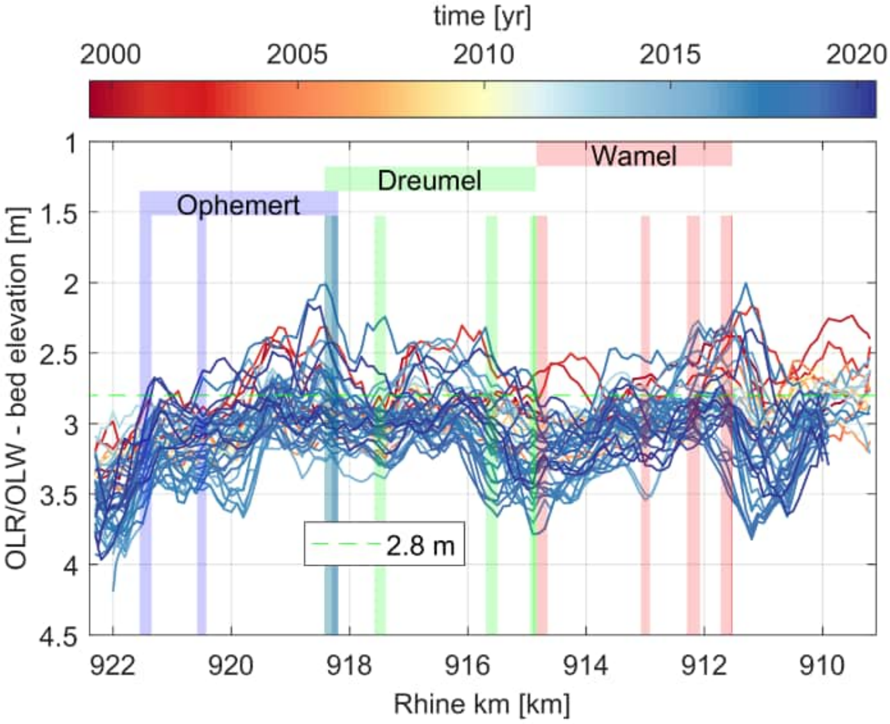

Figure 4.19 Minimum depth w.r.t. OLR/OLW in the hectometre area for the *‘vaargeul’ (150 m)* (averaged over 250 m upstream and downstream)

The minimum depth with respect to OLR/OLW in the ‘vaargeul’ (150 m) is shown in Figure 4.20 in the form of an heatmap. The discharge at Lobith is included in the plot as well. During higher discharges the height of the dunes increases, and the height decreases again during the lower discharges. During the high discharges the dredging activities are stopped as the depth is already sufficient for inland navigation. In the figure this is visible in the start of 2016, January 2018 and the first months of 2020, where the depth is lower than 2.8 m with respect to OLR (but the total depth is much larger). From the figure it can be concluded that in general the depth (w.r.t. OLR) is highest in the months with the low discharge (end of 2016, end of 2018). Partially because of the lower dune heights, but probably mostly due to dredging.

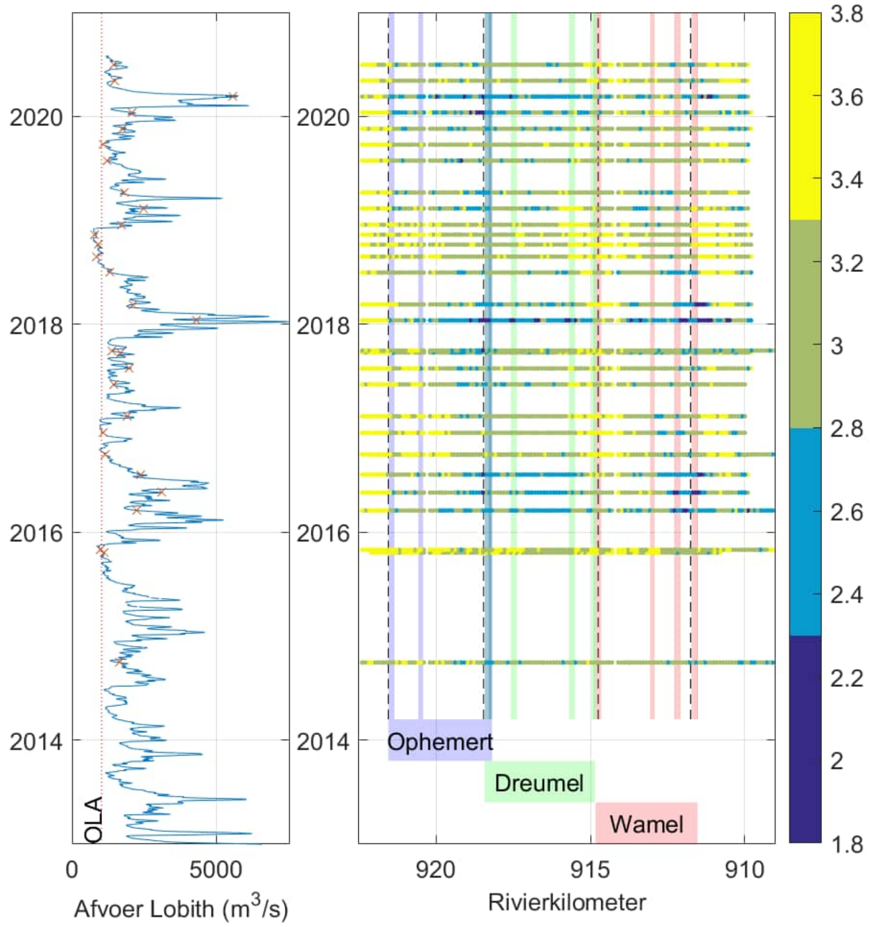

Figure 4.20 Minimum depth w.r.t. OLR/OLW in the hectometre area for the *'vaargeul' (150 m)* with comparison to discharge at Lobith

As an alternative analyses also a comparison is made of the percentile of the water depth within each channel definition is lower than 2.8 m at OLA, which can be found from Figure 4.21 for a channel width of 150 m (170 m is given in E.35 and 200 m in E.36). This analysis is less influenced by outliers and shows what fraction of the channel exceeds the required depth. For the period after the construction of the longitudinal training walls the largest percentiles are found near the inlet of Ophemert and the upstream end of Wamel (blue lines). However, both locations are also already limiting in the period before (red lines).

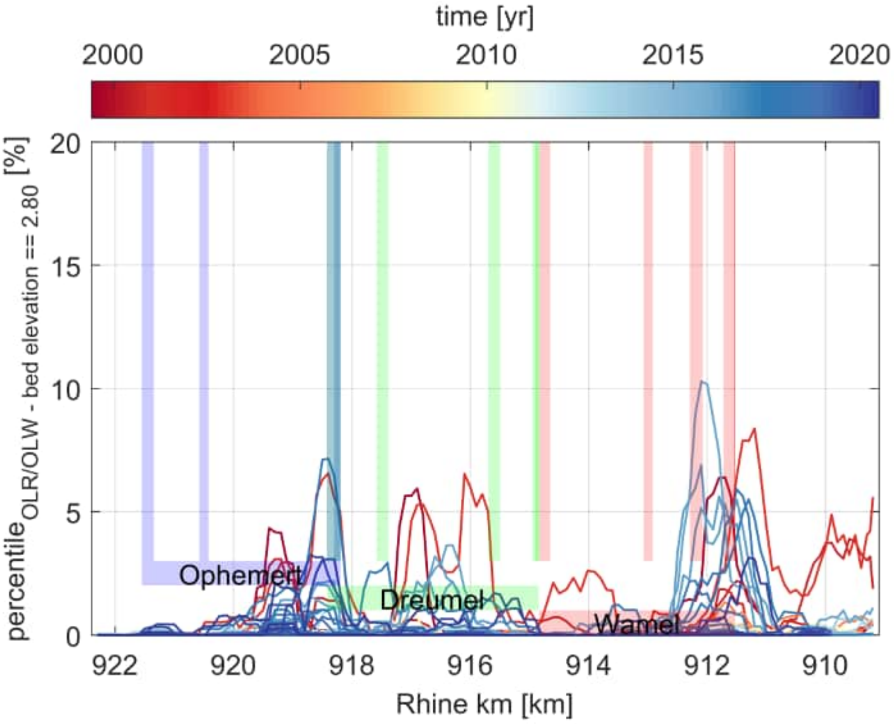

Figure 4.21 Percentage of the hectometre area for the *navigation channel (150m)* at which the depth is less than 2.80 w.r.t. OLR/OLW (averaged over 250 m upstream and downstream)

As an additional question it was asked if locations with an MGD are registered in the reach of the longitudinal training walls. Figure 4.22 shows that until 2013 most MGD's in this reach were found next to the Passewaaij flood plain with its large wetland and channel. From 2015, after construction of the longitudinal training walls, the depth around 919 next apparently reduced to such an extent that it caused the MGD to occur there rather than at Passewaaij. Even the opening of the side channel at Passewaaij and consequent sedimentation were less restrictive to the depth than the sedimentation next to the Ophemert longitudinal training wall.

For the period 2015 to 2018 MGD registrations are shown in appendix F. The MGD at Ophemert starts appearing in 2017, just downstream rkm 919. Starting in 2017 the MGD is registered for multiple reaches of the Waal. This has no effect on the lowest MGD (at rkm 876), but other MGD locations (like Ophemert) will show significantly more registrations. If the policy of only MGD for the Waal was followed, the number of registrations at MGD would have been reduced by half. In 2018 an MGD was hardly ever registered at Ophemert. Probably also as a result of dredging activities.

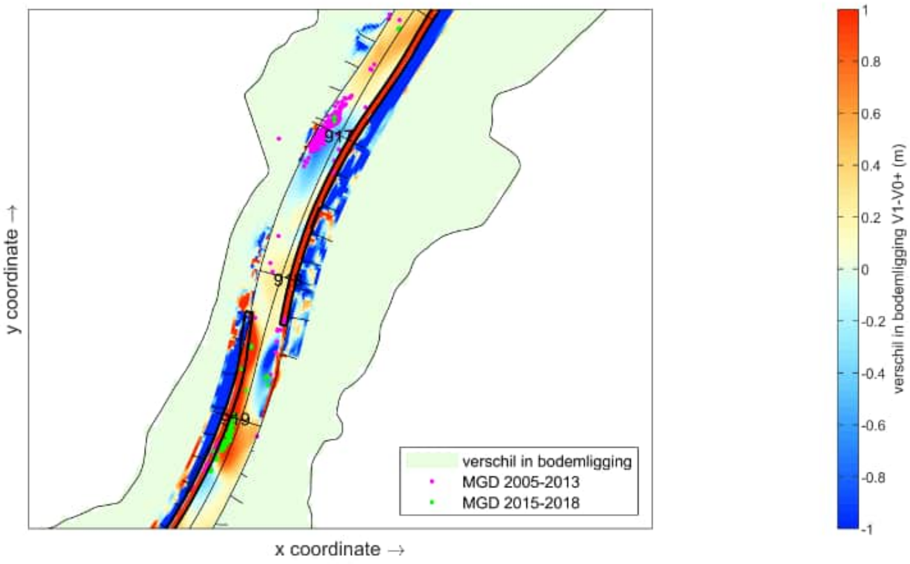

Figure 4.22 Locations of the MGD between 2005 and 2013 near rkm 917, and downstream of rkm 919 between 2015 and 2018 (Least measured depth, from Dutch: Minst gepeilde diepte) From: (Van der Wijk and Van der Mark, 2021).

4.5 Conclusions and recommendations

This chapter addresses the observed changes in bed level and water depth that have occurred after the construction of the longitudinal training walls.

How is the bed level and the bed level trend related to the overall degradation, influenced by the construction of the longitudinal training walls

Upstream of Wamel, prior to 2015 degradation is visible, and this continues after the construction of the longitudinal training walls. At the section of Wamel, prior to 2015 shows degradation and after construction shows sedimentation and slight degrdation in the last few years. At Dreumel, slight degradation is visible prior to 2015, and the appears stable, possibly showing slight sedimentation. At Ophemert the bed was stable prior to 2015, and shows overall sedimentation after construction. Downstream of Ophemert, the overall area was aggrading prior to constuction, and a strong lowering of the overall bed level is found after construction. These finding are found for the reach averaged behaviour. Locally in the Wamel and Dreumel sections, both erosion and sedimentation is found locally. Furthermore, the morphological response to the dams, as well as groyne lowering and opening of the side channel at Passewaaij, is still in a developing state. Also this transition makes it difficult to predict the long-term cumulative impacts of the measures.

For the average main channel bed level, the largest change which can be seen is the lowering of the average main channel bed level at Wamel, Ophemert and downstream of the longitudinal training walls, during construction (April 2014 - October 2015). It is hard to say if there is a change in the trend, as the river appears to still be adapting to the new conditions.

The minimum bed level appears to be increasing slighty at the locations of the auxiliary channels.

The maximum bed level cannot be compared one to one, but the maximum bed level appears to be constant over time, except during the construction phase.

The standard deviation of the bed level can also not be compared one-to-one, due to the different temporal frequency of the measurement sets. The impression is however that the standard deviation has increased compared to the period 2005-2015.

What is the effect of changes to the inlets?

The question about whether the sill levels have an influence on the sediment distribution and on the bed level development has been researched in the current study. The findings are that at Wamel, the bed level development is influenced by the raising of the sill in April 2018. This led to an reduction of the sedimentation which occurred until April 2018. Just prior to this a trench appears to be passing the location too. At the entrance to Dreumel, the effect of the sill adaptation is less pronounced, which is probably due to the location (inner bend and continuation of Wamel channel) and the fact that the adaptation was less extreme. At Ophemert the sill is not adjusted. What is apparent is that the MGD has been occurring just downstream over river kilometre 919, so there is apparently more sedimentation or larger bed forms in this reach. This point brings us to the final question on the navigation width. Although the trends appear to be clear, the time since the adaptation is short (two years) and the visible effects may also be due to river variability.

How does the bed level develop in the auxiliary channels? The bed level changes in the auxiliary channel are much larger than in the main channel.

At Wamel, aggradation occurs over the full length of the channel, but most significantly near the inlet (over +1 m aggradation) and after the last intermediate opening (over +2 m aggradation). The effects of raising the inlet of Wamel does seemingly not lead to large changes.

At Dreumel, the patterns are less pronounced than at Wamel, with alternating reaches of sedimentation (over +1 m) and erosion (-0.5 m). This is probably caused be the position of the channel in the wake of the ferry and the channel of Wamel.

At Ophemert, there is large sedimentation just downstream of the inlet (over 2 m). This reduces in downstream direction (around 0 m). Between the intermediate opening and the outlet the erosion is again higher (over 1 m).

What is the influence of the longitudinal training walls on the navigation depth and width?

For all P-map polygons (per hectometre) it is analysed what fraction of the polygon had a depth less than 2.8 m for each multibeam. Within the fairway (width of 150 m), this resulted in shallow locations at the Wamel inlet at 912, locally along the Dreumel (and Passewaaij) section at 917 and just downstream of the inlet at at Ophemert. For the opening at Wamel the size of the shallow area reduced in later years (most likely due to the raising of the sill). For the locations along Dreumel and just downstream of the Ophemert inlet at rkm 919, the shallow areas are more apparent in recent years. These conclusions also apply to the analyses with a width of 170 and 200 m.

Recommendations

Related to data there are some recommendations which are standardise the way that multibeam data are stored, and provide details of how the data was stored in the metadata document (vertical orientation, reference plane, units, horizontal resolution, etc. Furthermore, it is recommended to repeat some the bed level analyses based on the new polygons using the biweekly measurements prior to 2015.

5 Conclusions and recommendations

In this research a vast range of measurements of water levels, velocities and bed levels were used to analyse the effect of the longitudinal training walls on the river, compared to the situation prior to their construction. In this chapter we try to answer or discuss all research questions posed by Rijkswaterstaat. The questions have been translated, combined and rephrased to structure this section as much as possible. This chapter finishes with a list of recommendations for further research .

5.1 Water levels

What is the effect of the longitudinal training walls on the water levels at high discharge?

Based on the current analyses at high discharge, we conclude that the water levels are lowered, with respect to the situation prior to the construction of the longitudinal training walls. Analyses of the peak water levels show a lowering of 10 to 20 cm at station Tiel Waal for discharges higher than 2500 m^3/s (figure 2.8). The effect cannot be quantified as being solely dependent on the longitudinal training walls, as in the same period downstream of the longitudinal training walls the groynes were lowered and the side channel at Passewaaij was realised.

What is the effect of the longitudinal training walls on the water levels at low discharge?

By reducing the cross-sectional area at low river discharge, it is expected that the water depth increases during these conditions (discharges lower than 1500 m^3/s). The analyses of the water levels at station Tiel Waal shows that the lowering trend in water levels in the period before construction has been stopped for discharges below 2400 m^3/s (figure 2.6). This appears to be strongly linked to the bed level trends. The effect at very low discharge can not be accurately analysed due to the varying and unknown withdrawal through the ARK. From measurements a set-up of the water levels can not be concluded.

At the station Sint Andries Waal, downstream of the longitudinal training walls, the water levels show a lowering trend from 2017 onwards. This means that the head difference between Sint Andries and Tiel has actually increased in the period after construction of the LTW (see figure 2.9). It is expected that this increase is the result of the LTW.

5.2 Velocity and Discharge

What is the effects of the longitudinal training walls on the flow velocity

From ADCP measurements the change in velocity is analysed. For a discharge at Lobith of 922 m^3/s, an increase in flow velocity in the order of 10% is observed. An increase in flow velocity was expected as flow is concentrated in the main channel thanks to the longitudinal training walls. For a discharge at Lobith equal to 3436 m^3/s, 4170 m^3/s, and 5087 m^3/s, a decrease in flow velocity was observed of approximately 15%, 5% and 2%, respectively. For these discharges the longitudinal training walls are fully submerged making the flow width wider than the situation prior to construction of the LTW.

How is the the discharge distribution between main and auxiliary channel?

At Wamel, for a discharge at Lobith lower than 2500 m^3/s is lower than 12 % of total Waal discharge, which should in theory result in an increase in water levels compared to prior to construction.

At Dreumel, the only at Boven-Rijn discharges of roughly 1250 m^3/s and lower the auxiliary channel discharge is lower than 12 % of the total Waal discharge.

At Ophemert the auxiliary channel discharge is never below 12 %.

What is the effect of alterations to the inlets, and is there a view on the range to which the velocity can be influenced?

This was not clearly visible from the analysis of the velocity measurements. The patterns in the sedimentation and erosion after adjustment of the sill heights and the discharge analysis by Sieben (2020) show that there is an opportunity to influence the velocity in the main channel and thus indirectly also in the auxiliary channel. At this moment we are not able to quantify to what range the velocity can be influenced.

5.3 Sediment transport

What is the effect of the LTW on the sediment transport capacity in the main channel?

Based on a simple estimate based on Engelund and Hansen (1967) related to the average velocity before and after the construction of the longitudinal training walls, it is estimated that a low discharges the sediment transport is reduced by 40 % and at high discharges the sediment transport is reduced by roughly 5 %. The sediment transport is more significant at higher discharges (i.e., it relates non-linearly with velocity), but on the other hand the lower discharges occur more frequent. Therefore a weighing of both conditions is complex and requires numerical modelling. If the numerical simulations prove to correctly capture the flow velocity, these are the ideal tool for answering questions related to sediment transport. However, it is clear that the sediment transport capacity has reduced on average.

The raising of the sill height at Wamel showed that it was possible to influence the sediment transport in the main channel, and as such this may offer some possibilities for further refinement of the layout, particularly to optimise the water levels at low discharge.

These measurement are showing the initial morphological impact. The long term effects can show a very different response if due to the sedimentation the flow velocities increase again, resulting in the restoring of the transport capacity.

5.4 Bed levels

Has the trend in bed level evolution changed after construction of the longitudinal training walls?

An important objective of the longitudinal training walls, with regards to the bed level in the main channel is to stop the long term bed degradation. The long-term development before 2015 shows that upstream and along Wamel and Dreumel the bed has been degrading mildly, while at Ophemert and downstream a small aggrading trend has been observed. During the construction period between 2014 and 2015 some parts of the average main-channel bed level at Wamel and Ophemert show a strong lowering. After the construction of the dam was completed (and Phase 3 groyne lowering downstream), the analyses at Wamel, Dreumel and Ophemert appears to show that the eroding trend has stopped. The reach at Ophemert shows clear sedimentation, while at Wamel and Dreumel reaches of erosion and sedimentation are alternating.

The effect on the long term and large scale bed level changes cannot be determined on the basis of the current data, as the bed level is still adapting to the measure. In addition, for longer reaches and time scales, other Room for the River measures such as groyne lowering along the Waal, and others are also influencing the overall evolution of the bed which make it impossible to isolate the effect of the longitudinal training walls on the large scale behaviour from the data.

For both low and high discharge, the velocity is lower than prior to the construction of the longitudinal training walls. As indicated, this will lead to a lowering of the sediment transport in the reach, ultimately leading to a shallower section, which may hamper navigation and counteracts the reduce the water level reduction at high discharges as intended with this measure.

Do the sill levels have an influence on the sediment distribution between main and auxiliary channel?

The sill levels can be used to influence the sediment transport capacity in the main channel. This was illustrated by the different response to the change in inlet at Wamel, and also, but less pronounced at the Dreumel inlet. This change in functioning of both inlets is possibly caused by position of the inlet in relation to the curvature: offtakes in inner bends get more sediment and are therefore prone to close off. This was clearly apparent from the sedimentation prior to April 2018 and erosion after 2018 at the Wamel inlet shown in Figure 4.13 and Figure 4.14.

The bed levels in the side channel show sedimentation and erosion of larger magnitudes than in the main channel. At Wamel, the divergence bar is not visible, but the erosion and sedimentation patterns just downstream of the inlet are visible. After raising the sill at Wamel increased sedimentation is found after April 2018. It is however not directly clear what causes the sedimentation. At Dreumel the effects are less pronounced, and at Ophemert, where the sill level was never raised (but it was narrowed in April 2019), significant sedimentation occurs just downstream of the inlet.

Although the bank erosion might have a large contribution to the sediment and the bed level in the auxiliary channels, these have not been investigated in this report, but is being researched at the Radboud University.

5.5 Dune height

Do the bed level measurements show that the bed forms have lower amplitude in the reach of the longitudinal training walls?

Based on the P-map analysis of the bed levels, the standard deviation of the bed levels within certain polygons was defined as well. This value indicates what the variability of the bed level is and could refer to groyne flames, dunes, or any other variation in the bed level measurements (including the initial morphological response of the longitudinal training walls). According to the section averaged analysis the standard deviation of the bed level in the period 2015-2020, as derived from two-weekly multibeam soundings of the navigation channel, is larger than in the period 2005-2015 as derived from the yearly multibeam measurements.

As the temporal resolution of the 8 weekly measurements is higher than the yearly multibeam measurements, it may be that the effect is not as it appears. A possible explanation is that, although the amplitude of the local groyne flames are larger, overall there is more variation in the bed after construction of the longitudinal training walls. This analysis does not separate steady and migrating features, does not consider their distribution in space, and does not account for the propagation of dunes from upstream. This means that based on the current analysis, it is not possible to conclude that the dune heights are increasing along the longitudinal training wall reach. A recommendation is to redo the P-map analysis for the biweekly multibeam measurements prior to 2015. Furthermore alternative data-analysis methods should be applied for further detailing, e.g. wavelet, zero-crossing or similar for smaller frequencies.

Is it true that the lower bed forms are not a matter of smaller dune heights, but due to the suppression of groyne flames?

Unfortunately, this cannot be answered based on the current analysis.

5.6 Navigation

What is the effect of the longitudinal training walls on transverse currents, and how large are these currents and how do these extend over the transverse cross-section?

None of the flow velocity measurements showed strong cross-flow components larger than 0.3 m/s in the main channel. However, the data-set for answering this question is not ideal. Longitudinal ADCP measurements were taken, but not repeated. Hence, it is not possible to filter turbulence from mean-flow properties. The detailed measurements at the inlets have been used, but these do not extend enough towards the main channel.

Is there potential for reducing the requirements for the navigation depth due to a change in bedform height?

It is an interesting point that dunes could play a role in increasing the water level due to increased roughness, but at the same time form shallow locations limiting the navigable depth in the river. Based on the current data analysis we are unable to answer, how this works out in the field. A more detailed bed-form analysis on the multibeam data is required to judge whether the conditions have changed.

Are the locations where a MGD least measured depth is measured in the reach of the longitudinal training walls and where are the located?

Just downstream of rkm 919 at Ophemert, there is a location where the MGD often occurs (Figure 4.22), mainly in 2017. This location appears to become more restrictive to the depth than the location around river kilometre 917 at the side channel to Passewaaij which used to generate the MGD's in this section prior to the construction of the longitudinal training walls.

Are there locations in the reach of the longitudinal training walls, where the bed level exceeds OLW/OLR - 2.8 m for the 150 m navigation channel, the 170 m navigable width, or the 200 m main channel section, and if so when were these observed?

At various locations along the reach of the longitudinal training walls the requirement of 2.8 m is not satisfied (cf. Figures 4.19 and appendix E.5). This depth is exceeded more often for wider widths. Looking at the percentile of the bed level at -2.8 m w.r.t. OLR where this occurs, it can be seen that initially at the inlet of Wamel and midway the Dreumel structure. In more recent years the shallow section downstream near the Ophemert inlet appears (cf. Figure 4.22). These locations appear only at OLA discharges or smaller, indicating that the bed level could be maintained. The strict requirement of OLR/OLW - 2.8 m was not satisfied, but probably the water depth was sufficient at all times. It is recommended to formalise the unwritten maintenance rules for the situation with discharges above OLA and to analyse the temporal evolution of the water depth along the river.

5.7 Recommendations

5.7.1 Further research on different effects at low discharge

The increase in water levels at low discharges is less than expected from theory. We have put forward a number of different possibilities which could explain this, but we are currently not in a position to conclude based on the current data (analysis). Based on these points, recommendations for further analysis and measurements are provided:

5.7.1.1 Reduction of the alluvial roughness

Based on the current analysis, it was not possible to determine whether or not the bed form dimensions have reduced after construction of the longitudinal training walls. For this, we recommend to extend the P-map analysis in to the past using the biweekly bed level measurements, thereby removing the temporal uncertainty. Other techniques could also prove useful such as the wavelet analysis, or a zero crossing method, both to confirm the conclusions, but also as a check if the different methods provide similar insight. This analysis would also benefit the general change in the bed level trends for the area.

5.7.1.2 Reduction of horizontal mixing

A possible suggestion is that due to the removal of the groynes, large scale horizontal eddies are not generated as much as after the construction of the longitudinal training walls. On the other hand the roughness generated by the rockfill surface of the dams generates reasonable amount of friction. To check this we recommend to do measurements in which the horizontal stresses can be derived, and their impact on overall flow can be assessed. The most logical location for this would be just upstream of Wamel (in the groyne section) and further downstream, just upstream of the bend. A first assessment of this hypothesis could be done by comparing results of three-dimensional schematized simulations of a river section with groynes and with a longitudinal training wall.

5.7.1.3 Porosity of the longitudinal training wall

It is known that the dams are porous, and that water is flowing through the dam especially at low discharge when there is a head difference over the dam and especially at the openings which are constructed differently. The available ADCP and longitudinal measurements are not accurate enough to derive this quantity, therefore it is recommended to directly measure the flow through the longitudinal training wall. This could be achieved by more accurate ADCP surveys or the application of tracer measurements to track the flow through the porous medium.

5.7.1.4 Distribution of the water at the inlets

It would be good to have water level and velocity measurements just prior and just after adjustment of an inlet. Ophemert could possibly be a location for this, as it has not undergone any adjustment until now, and locally causes a water level lowering of 5 cm according to (Sieben, 2020) (although how this value is found is not immediately apparent, cf. Section 5.1), and appears to cause large sedimentation and is a location of where the MGD is measured.

In the past ships have been used to narrow the channel (an example is the IJsselkogge from the fifteenth century. Possibly, one of the inlets could be blocked by a barge, such that the effect of inlet closure on the water levels can be seen, but we realise, this may not be feasible.

5.7.2 Distribution of the water in the Rhine at low discharge

The trends in discharge distribution should be analysed further, and it would be good to have more insight into the discharge distribution at low discharges, preferably from measurements. The discharge currently given by MWTL is apparently lower than what can be concluded from available measurements. The MWTL product can be improved with for example more frequent measurements of the discharge for all river branches at all bifurcation points. It would be very valuable to include new insights in the discharge distributions in the officially distributed (MWTL) discharges.

5.7.3 Change in sediment transport capacity

We recommend to incorporate the insight from numerical models on this point, or to sediment transport measurements prior and just after the adjustment of a sill. Not only the sediment capacity, but also the grain-size fractions before and after the inlets would be of interest to better understand the seperation of the mixture and the type of sediment being transported in the auxiliary channels. Furthermore, other analysis based on the current adjustment at Wamel, may form interesting validation material for such numerical models.

5.7.4 Improvements to systematic storing of the data

For at least the velocity measurements and the multibeam data, the data was not stored in a clear and systematic method. It involved many iterations to obtain the correct orientation and magnitude of the provided data.

For the ADCP data the lack of a consistent naming convention may be the most limiting factor. Detailed recommendations are given in Section 3.3.3.2.

For the multibeam bed level data, the measurements were sometimes in centimetres, decimetres or metres, without any metadata explaining how it was organised. Similarly, sometimes the data was positive down, rather than positive up.

It is recommended to create guidelines/requirements for how different data should be stored, such that the next person working with it does not have to reprocess all the manual steps again.

Of a different nature is the registration of the water level measurements with divers. As these measurements were considered to be expensive, only 5 divers were placed. However, none of these measurements have been regularly loaded and saved. These potentially valuable measurements could therefore not be used.

During this pilot of the longitudinal training walls a data management system was set-up. It was hosted by Deltares, but the responsibilities for its content remained at Rijkswaterstaat. The data was hosted only passively without any active users. However, a similar system with active users could help in the ownership and quality assurance of the measurements. In other projects these collaborations have resulted in the set-up of a data house (‘datahuis’), which might also be a recommendation for riverine pilots.

5.7.5 Reconsider of longitudinal water level measurements

From the experience in analysing the longitudinal measurements, it is advised to reconsider the application of this technique for measurement campaigns of local measures with relatively small impacts compared to the expected fluctuations and scatter in water levels. Although a single run shows many interesting details, it can not be easily compared to other runs due to this macro turbulence.

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