The influence of the hydrograph and the river geometry on sediment management in the Waal

A research into dredging data

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Thesis

TU Delft

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by

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Preface

The report in front of you is my thesis on sediment management in the Waal. This thesis is the concluding work of my MSc in Hydraulic Engineering. Although much time and effort went into writing this thesis, it was fun and I learned a lot about dredging and river engineering. Firstly, I would like to thank TU Delft and Rijkswaterstaat for providing and entrusting me with this interesting research topic. I would like to express my gratitude towards everyone in my graduating committee: A. Blom, D. van Putten, R. Schielen, A. de Swaaf and P. Taneja, for accompanying and aiding me through the process of writing this thesis. In particular I would like to thank my supervisor R. Schielen for investing a lot of time in advising and supporting me. I would also like to thank P. van Denderen at the University of Twente, N. Nibbeling at Rijkswaterstaat and T. Klop at Van den Herik for always being available for questions.

B.A. Deuss
Delft, May 12 2021

Summary

In this research, we investigate the influence of the hydrograph and the river geometry on sediment management in the Waal. The hydrograph is the graph of the river discharge over time. The river geometry means the geometrical characteristics along the river, like sharp bends, gentle bends, crossings between bends and fixed layers. With sediment management the maintenance dredging and plowing of the river bed is meant. The Waal is a main branch of the Dutch Rhine delta system.

More insight in the way sediment management responds to the variability of both the hydrograph and the river geometry can help in making substantiated predictions about the influence of changes in the river geometry on sediment management. Also, more insight in sediment management can help in optimizing the currently used and future dredging strategy of the contractor, which can help Rijkswaterstaat in drawing up realistic dredging contracts.

The main research question that we answer in this report is:

- How are dredging volumes and plowing activity in the Waal influenced by the hydrograph and the river geometry?

The sub-questions are:

1. How can dredging volumes and plowing activity be quantified and what are the associated uncertainties?
2. What are hotspots for sediment management and what is their relation with Least Available Dephts and the river geometry?

We answer these research questions by analysing historical data. The following historical data sets are available:

- The hydrograph. The river discharge is measured at Lobith where the Rhine enters the Netherlands.
- The sail tracks. These are logs of both dredging vessels and plowing vessels per minute. These sail tracks are supplied to Rijkwaterstaat by the contractor. They contain information like the coordinates, time, date, activity (like dredging, dumping, plowing, sailing full, sailing empty) and the sediment volume in the hopper of the vessel.
- The BRW data. These are a record of dredging volumes, locations and dates that the contractor kept independently from the sail tracks to keep track of the dredging work. 'BRW' is an abbreviation for 'Bovenrijn en Waal'.
- The multibeam measurements of the bed level from control surveys. These measurements are taken every 2 weeks. The measurements consist of a data point for the bed level of the main channel per cell of 1 × 1 m. This data set is however not used for any in-depth analysis and is used mostly to show examples of the river bed.
- The Least available depths (LADs). These data contain the location with the smallest depth in the Waal per day.

The sail tracks contain much erroneous data which are mainly incorrect coordinates and can not be used to analyse dredging locations. Therefore the sail tracks have been reduced by Van der Werff ten Bosch and Tuijnder (2016) and Nibbeling (2020), which means that sail tracks with erroneous data mostly have been deleted. As a result the dredging volumes are largely underestimated and thus unsuitable for determining dredging volumes. We use the reduced sail tracks however for determining plowing activity since the sail tracks of the plowing vessel are relatively reliable (although for long periods data is missing) but are also the only data set that contains information about plowing. The BRW data set is more suited for determining the dredging volumes, since it contains more reliable dredging volumes than the reduced sail tracks and contains

dredging locations. The BRW data still contains some periods for which no data is available however. For analyses in which no information about the dredging location is required we complete these periods with data from the original (unreduced) sail tracks. This is not possible however for analyses in which information about the dredging locations is required. For plowing activity sail tracks are the only option and thus we can not complete missing periods with another data set.

We indicate dredging activity in graphs per month and per Rhine-kilometer as a dredged sediment volume according to the BRW data. We indicate plowing activity in graphs per month and per Rhine-kilometer as the amount of reduced sail tracks with a dredging activity. The Rhine-kilometer (abbreviated as rkm) gives information about the location on the Waal. The upstream en of the Waal is located at rkm 867.4 and the downstream en of the Waal is located at rkm 952.6.

It follows from the created graphs that there are certain locations along the Waal with a continuous large dredging volume or plowing activity, which are indicated as hotspots. The most apparent dredging hotspots are at rkm 876, 885 and 928. The most apparent plowing hotspot is at rkm 928. These hotspots are situated at the end of the submerged bendway weirs near Erlecom (rkm 876), at the end of the fixed layer near Nijmegen (rkm 885) and at the end of the fixed layer near St. Andries (rkm 928). At the end of these fixed layers a large erosion pit occurs at the outside of the bend and a large bar occurs at the inside of the bend (White and Blom, 2020). The accretion at the inner bend is the reason for large dredging volumes and plowing activity and probably occurs with the following reason. In river bends sediment is transported from the outer bend to the inner bend due to the helical flow pattern that occurs in bends. The fixed layers and submerged bendway weirs have been constructed with the goal of reducing the amount of sediment being eroded at the outer bend and thus the amount of sediment being transported from the outside to the inside of the bend. This results in less accretion at the inner bend and thus a wider navigation channel. Sediment transport in downstream direction mainly occurs at the inside of the fixed layer, where the bed is not fixed (White and Blom, 2020). This has as a result that there is no sediment supply in the outer bend at the downstream end of the fixed layer, which means that the sediment load is below the transport capacity. Thus a large erosion pit occurs. The sediment transported from this erosion pit towards the inner bend due to the helical flow pattern is likely the main reason for the accretion at the inner bend. The sediment being suppied at the inner bend probably contributes to the accretion.

We hypothesise that locations with regular little depth need more dredging than locations with regularly large depth. Therefore, we investigate the relation between locations with measured LADs and dredged locations is investigated. It follows that most LADs are measured at the hotspots, which agrees with the expectation. It however also follows that there is no relation between LADs measured at a certain rkm and month on one side and the dredging volume at that same rkm and month on the other side. This might have the following reasons.

- The fact that LADs are measured at a certain location does not necessarily mean that at that location dredging is necessary, since the contractor is contractually obliged to maintain a certain bed level and not a certain water depth.
- Dredging does not always take place on the right location. The contractor uses only one dredging vessel which makes it impossible to dredge at several locations at once.
- There are no-dredging zones present at some locations in the Waal.
- In reality a lot more rkms are dredged preventively than the three hotspots defined in this research.
- Since this analysis takes all months into account, months with missing data about dredging volumes are also taken into account.

We distinguish two types of morphological phenomena in the context of this research (Klaassen and Sloff, 2000):

- Stationary phenomena which are non-migrating bars that are mainly the result of the geometry of the main channel, like bends and crossing between bends.
- Non-stationary phenomena which propagate through the river, like dunes moving in downstream direction over the river bed.

Dredging is mostly used for lowering stationary phenomena and plowing for both non-stationary phenomena and assisting the dredging vessel at stationary phenomena. From analysing the characteristics of the river geometry at the dredging and plowing locations we conclude the following:

- Dredging takes place quite uniformly over the Upper, Middle and Lower Waal. Compared to plowing, dredging takes place more toward to Upper Waal, where the morphology is governed by sharp bends and thus stationary phenomena are prevalent.
- Most plowing takes place in the Lower Waal, where both stationary phenomena and and non-stationary phenomena occur.
- After most peaks a significant part of dredging and plowing takes place at the hotspots. However, when the peak discharge becomes very large, relatively more dredging and plowing starts to take place at other locations along the waal compared to the hotspots.

We hypothesise that dredging volumes and plowing activity increase after peaks in the hydrograph. Therefore, we investigate the relation between peaks in the hydrograph and the subsequent dredging volume and plowing activity. We plot the characteristics of the all peaks in the hydrograph (namely the peak height, peak length and decrease rate of the peak) against the total dredging volume and the total plowing activity in the calendar month subsequent to the month of the discharge peak. From the resulting scatter plots we conclude the following.

- There is no relation between the peak height and the subsequent dredging volume or plowing activity.
- There is no relation between the peak length and the subsequent dredging volume or plowing activity.
- There is no relation between decrease rate of the peak and the subsequent dredging volume or plowing activity.

An explanation could be that dredging volumes are determined in the first full calendar month subsequent to the discharge peak. when a discharge peak occurs late in a month, the dredging volumes and plowing activity are regarded earlier after the peak than when a discharge peak occurs early in a month. A second explanation could be that the data is not complete enough. Since some month are missing in the data, it might be the case that the months with available data are not complete either. This could lead to an underestimation of the dredging volumes and plowing activity after certain discharge peaks. A third and likely explanation is the preventive dredging and plowing at hotspots. However, when the hotspots are disregarded in the total dredging volume and plowing activity, there is still no relation between peak characteristics and subsequent dredging volume or plowing activity. This could be due to the fact that in reality a lot more rkms are dredged and plowed preventively than the three hotspots defined in this research.

There is also no relation between increasing discharge peaks and the interval between dredging activities, which is amost always between 1 and 2 days. Since no dredging activities are carried out in weekends an interval of approximately 1.4 days makes sense and proves that continuous preventive dredging takes place.

When we regard all months for which data is available (instead of only looking at discharge peaks), there is also no relation between the monthly maximum discharge and the dredging volume or plowing activity in the subsequent month. The most likely reason is again the continuous preventive sediment management carried out by the contractor.

Contents

1

Introduction

1.1. Background and motivation

Inland water transport is an important economic factor for the Netherlands. 50% of international and 25% of national transport is carried out by ship. In addition to that, inland water transport is one of the most energy efficient ways of freight transport at long distances (>150 km) (Gille et al., 2011). Inland water transport is even more efficient than rail transport (lower CO_2 emission) for vessels with a large tonnage (Gille et al., 2011). The Rhine river in particular is the major transport route between the North-Sea and Germany (Sloff, 2011) and the Waal river, being a main branch of the Dutch Rhine delta system, is a vital part of the transport route (Kisoensingh, 2015). As the demand for transport efficiency and vessel sizes increases (et al., 2015), it is important that the navigation channel of the Rhine river and thus also the Waal are well maintained to accomodate intensive, fast and safe inland navigation (Sloff, 2011). Maintenance of the navigation channel can be done by river training (structural solutions) or sediment management. Sediment management can be both dredging and plowing. Dredging is used for relocating sediment from one site to another site and plowing is used for flattening the river bed. Dredging and plowing are discussed in more detail in Section 2.3. In this report we use the term 'sediment management'to indicate the total picture of dredging volumes, plowing activity, dredging locations and plowing locations. The maintenance for the main waterway of the Dutch Rhine, so also river training and sediment management are the responsibility of Rijkswaterstaat (the executive agency of the Dutch Ministry of Transport, Public Works and Water Management).

The Rhine is a large river in Western Europe, which originates in Switzerland as a snowmelt-fed river and eventually debouches as a rain and snowmelt-fed river in the North Sea in the Netherlands. The main Rhine branches in the Netherlands are the Bovenrijn, Waal, Pannerdensch Kanaal, IJssel, Nederrijn and Lek. This research focuses on the Waal, which bifurcates at Pannerdensche Kop and ends at Woudrichem where its name changes into the Merwede. An overview of the Dutch Rhine system can be seen in Figure 1.1.

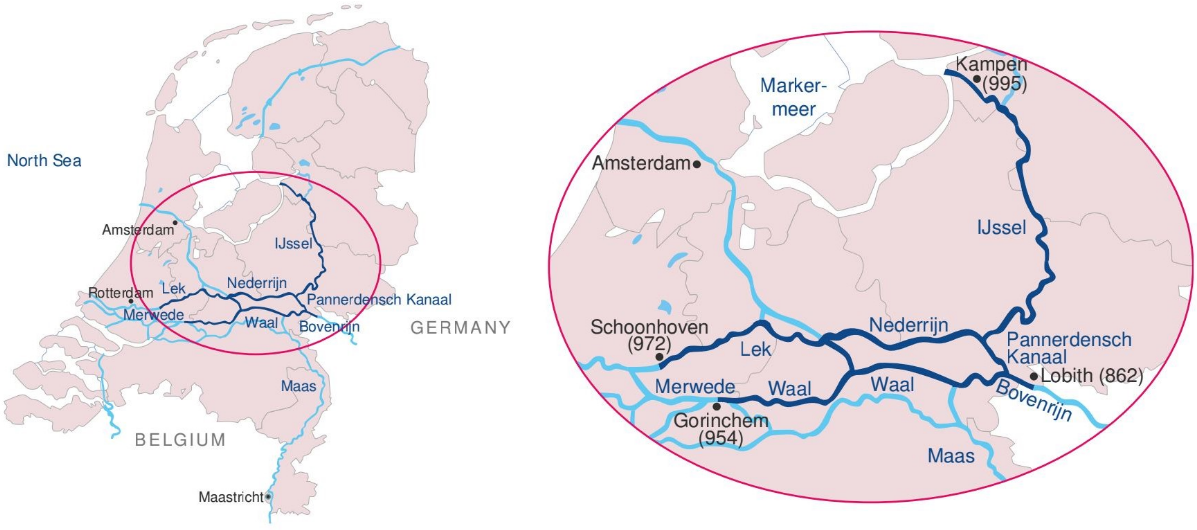


Figure 1.1: Overview of the Dutch Rhine system (Ylla Arbós et al., 2019)

To make intensive navigation on the Waal possible Rijkswaterstaat has established requirements for minimum dimensions of the navigation channel. These required dimensions for the navigation channel of the Waal are 150 m width and 2.8 m depth at Agreed Low Water Level (ALW). ALW is an important reference water level for the Waal. In Dutch it is called 'Overeengekomen Lage Rivierstand' (OLR) and it is the water level that corresponds with Agreed Low Discharge (ALD). ALD is a discharge that is 5% of the time not exceeded. This means that 95% of the time the channel dimensions are larger than required at ALW. ALD is generally deduced every decade, since water levels are not constant over time. The current discharge for ALD is 1020 m^3/s. It was deduced in 2012 and is agreed upon until 2022 (Jans et al., 2018).

A second requirement is that the width-averaged depth in the navigation channel should be at least 4 m at ALW. This second requirement is generally not met since it would lead to enormous dredging volumes (Havinga and van Adrichem, 2013). According to Van Vuren, Paarlberg, and Havinga (2015) the requirement of at least 4 m of width-averaged depth in the navigation channel is only taken into account in the design phase of projects. For sediment management this requirement is usually not taken into account. The minimum required dimensions of the navigation channel are shown in Figure 1.2.

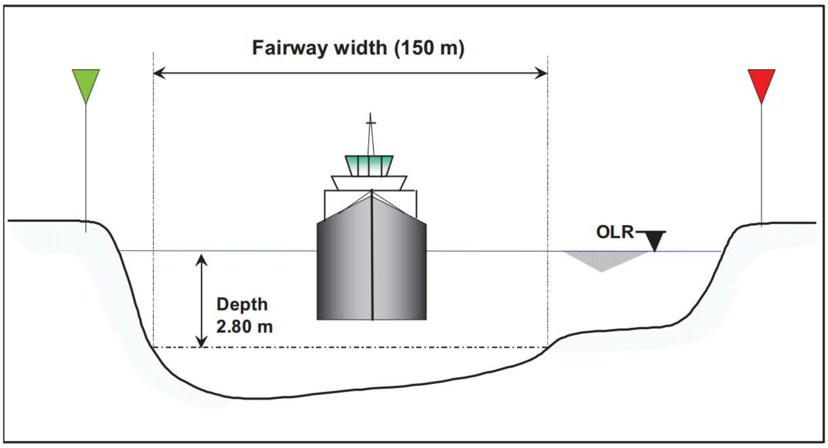


Figure 1.2: Agreed navigation channel dimensions relative to ALW (indicated as OLR) in the Bovenrijn and Waal (Sloff, 2011)

Besides navigation, other important functions of a river are the transport of water, sediment and ice. This means that it is important to keep the conveyance of the river large enough such that flood safety is ensured. The Rhine was trained in the 19th and 20th century with the purpose of improving navigability and a safe discharge of water, sediment and ice. The river training involved canalization, construction of levees and bend cut-offs. However, river training can result in a decline of the ecological value of the river. According to Wang et al. (2007) the canalization of a river can adversely affect the morphological and biological characteristics of the river channels and the artificial cut-off of meanders results in a less ecologically sound river. In the last decades, there has been a lot of attention for restoring the ecology of the Dutch river system. Due to large discharge peaks in 1993 and 1995 in the Rhine river, there has been a focus on further increasing flood safety along the Dutch river system as well (Kisoensingh, 2015). This has initiated programs like Room for the River (RfR) and the European Water Framework Directive (WFD).

The RfR program is developed to increase the discharge capacity of the Dutch rivers to allow for higher discharges avoiding the need to raise the levees (Bardoel, 2010). Also projects have been started to restore nature in the floodplains and to secure the quality of water bodies. These projects are usually WFD initiatives. Overall the RfR program focuses on increasing flood conveyance capacity while WFD measures focus on increasing the ecological value of river systems by increasing river dynamics. As part of these initiatives at various locations in the Dutch river system spatial measures have been implemented. Between 2006 and 2019 34 measures have been implemented and with that the RfR program is completed (Rijkswaterstaat, 2019a). We refer to the river interventions due to RfR, WFD or even other initiatives, as 'RfR measures' in this report.

Research into sediment management on the Waal has been carried out before by for instance Bardoel (2010), Van Adrichem (2013) and Kisoensingh (2015). These researches focus mostly on the influence of RfR measures on sediment management. In previous reasearch there is less focus on the influence of the river geometry overall and the influence of the hydrograph on sediment management. The hydrograph is a graph of the varying river discharge versus time.

1.2. Problem definition and research questions

The discharge of a river is highly variable and can change drastically in a short period of time. The river geometry is also variable, for instance due to the implementation of RfR measures. These RfR measures have changed the river geometry which in term influences the needed amount of sediment management to maintain the required dimensions of the navigation channel. Also due to changes in the river discharge the geometry of the river changes slightly as flood plains and side channels start to convey water at high discharges. This makes the hydrograph and the river geometry coupled to each other. It is therefore important that enough knowledge is available about the way in which the morphology, and thus the sediment management responds to the variability of both the hydrograph and the river geometry. This can for instance help in determining the influence of RfR measures on sediment management or help in making substantiated predictions about the influence of new changes in the river geometry on sediment management.

There is another reason for the need for more insight in the dependency of sediment management on the variability in the river geometry and the hydrograph. In the past dredging strategies were based on the expert knowledge of employees at Rijkwaterstaat but in 2005 the sediment management of the Waal was outsourced to contractors through a performance-based contract (Bardoel, 2010). A performance-based contract means that the contractor is allowed to act freely as long as the required dimensions for the navigation channel are maintained. To be able to draw up realistic contracts, insight in sediment management is required at Rijkswaterstaat. Also more insight in sediment management can help in optimizing the currently used and future dredging strategy of the contractor.

This leads to the objective of this research, which is to gain more insight in how sediment management in the Waal is influenced by the hydrograph and river geometry.

We have several expectiations about the results of this research. These expectations are largely based on input provided by the contractor (see Section 3.3). Firstly, we hypothesise that the largest dredging volumes are required at sharp bends and at crossings between sharp bends in the Waal. Plowing activity is expected to be less concentrated at sharp bends and to be more spread across the Waal (see Section 4.2). Secondly, at locations where often Least Available Depths (a daily determined location with the least water depth along the Waal) are measured, the dredging volumes are expected to be large (see Section 3.5). Finally, we hypothesise that dredging volumes and plowing activity along the Waal increase after peaks in the hydrograph. As the peak discharge, peak duration or the decrease rate of the peak increase, the dredging volumes and plowing activity are expected to increase as well (see Section 4.3). By finding answers to the research questions, we test these hypotheses.

The main research question that we answer in this report is:

- How are dredging volumes and plowing activity in the Waal influenced by the hydrograph and the river geometry?

The sub-questions are:

1. How can dredging volumes and plowing activity be quantified and what are the associated uncertainties?
2. What are hotspots for sediment management and what is their relation with Least Available Dephts and the river geometry?

1.3. Method

We answer the above mentioned research questions by analysing historic data. The following data available at Rijkswaterstaat about the hydrograph, river geometry, bed levels, dredging activities and plowing activities in recent years, are used:

- The hydrograph for the period 2005-2020. The river discharge is measured at Lobith where the Rhine enters the Netherlands.
- The 'vaartracks' for the period 2005-2020. These are logs kept by both dredging vessels and plowing vessels per minute (Nibbeling, 2020). The 'vaartracks' are supplied to Rijkwaterstaat by the contractor. Amongst others, they contain information about the x-coordinate, y-coordinate, time, date, activity (for instance dredging, dumping, sailing full, sailing empty or plowing) and the sediment volume in the hopper of the vessel. The Dutch name 'vaartrack' originates from the eponymous program that registers this information. The English translation would be 'sail track'. Thus in this report the 'vaartracks' are referred to as 'sail tracks'.
- The BRW data for the period 2014-2020. These are a record of dredging volumes, locations and dates that the contractor kept independently from the sail tracks to keep track of the dredging work. 'BRW' is an abbreviation for 'Bovenrijn en Waal'.
- The multibeam measurements of the bed level from control surveys. These measurements are taken every 2 weeks (Van Denderen, 2020) and are available for the period 2005-2020. Control surveys are multibeam measurements that the contractor has to carry out, such that Rijkswaterstaat can verify that the dredging has been implemented according to the contract (Bardoel, 2010). The measurements consist of a data point for the bed level of the main channel per cell of 1 × 1 m. This data set is however not used for any in-depth analysis and is used mostly to show examples of the river bed.
- The Least available depths (LADs) for the period 2005-2019. These data contain the location with the smallest depth in the Waal per day (for the year 2019 multiple locations per day).

Overall the research can be subdivided into three research activities, namely A, B and C.

A: Determining dredging volumes and plowing activity

With the information obtained in research activity A we can answer the first sub-question. By analysing data the dredging volumes and plowing activity are determined. We use the sail tracks from dredging vessels as well as the BRW dredging volumes to determine the dredged volumes of sediment per month. We use the sail tracks from plowing vessels to determine the amount of plowing activity per month. The exact difference between dredging and plowing is explained in Section 2.3.

The reliability of the data can be a problem however. The uncertainties due to these reliability issues are taken into account during the analysis of the data.

B: Analysis of hotspots and Least Available Depths

With the information obtained in research activity B we can answer the the second sub-question. We obtain the monthly dredging and plowing locations along the Waal. To determine dredging and plowing locations from sail tracks, we use the GIS program QGIS. We also determine dredging locations from the BRW data, for which no GIS program is required. We then use the resulting information about dredging and plowing locations to determine hotspots for sediment management. Subsequently, we obtain the monthly locations of measured LADs along the Waal. This makes it possible to analyse the relation between dredging locations and LADs. Finally, we analyse the relation of hotspots with LADs and the river geometry. We do this by indicating the geometrical characteristics along the Waal, together with the locations of measured LADs and of the hotspots.

C: Analysis of the influence of the river geometry and the hydrograph on sediment management

The main research question can be answered with the information obtained in research activity C. We analyse the relation that all dredged and plowed locations along the Waal have with the river geometry.

We also make graphs in which certain characteristics of the discharge peaks are plotted against the subsequent total dredging volume or plowing activiy along the Waal. In this way we investigate the response of the dredging volumes and plowing activities to discharge peaks. We do this by looking at the response of the dredging volume and plowing activity on the following characteristics of discharge peaks:

- The height of the peaks in the hydrograph;
- The duration of the discharge peaks;
- The decrease rate at the falling side of the dischscharge peaks.

We then make graphs in which the response of the interval between dredging activities to discharge peaks is investigated. Here, the same characteristics of discharge peaks as enumerated above are used. Finally, we make graphs in which the response of dredging volumes and plowing activitiy to the river discharge in general is investigated (instead of only looking at the response to discharge peaks).

The dredging volumes in these graphs originate from BRW data. Months for which no BRW data is available, are filled in with volumes originating from sail tracks. The plowing activity in these graphs originates from sail tracks. Months for which no sail track data is available cannot be filled in.

2

Historic data

2.1. Chapter introduction

First in this chapter, Section 2.2 until 2.6 each explore the data sets as enumerated in Chapter 1 and elaborate upon the associated uncertainties. Then, in Section 2.7 we use the sail tracks and the BRW data to quantify monthly dredging volumes and in Section 2.8 we use the sail tracks to quantify the monthly plowing activity.

2.2. Hydrograph

In this report we indicate the river discharge in the Waal by the measured discharge at Lobith, where the Rhine enters the Netherlands. Approximately 66% of the Rhine discharge as measured at Lobith goes through the Waal and 33% of the discharge goes through the Pannerdensch kanaal (Brinke, 2004). The used data consists of an hourly discharge measurement at Lobith for the period 2005-2012 and consists of a 10-minutes discharge measurement for the period 2013-2020.

The data contain some measurement errors, which are ususally unrealistically large values. To make the data usable we replace the values above a threshold by the mean of the previous and subsequent values. When several erroneously large values succeed each other we replace these values by the previous value. Finally, we take the mean value of the cumulative measurements of each day which results in a more manageable amount of values for the data analysis. For determining maximum values we still use all measurements instead of daily averaged values.

The data can be shown as a hydrograph, which is a graph in which the river discharge is plotted against time. The hydrograph for the period 2005-2020 is shown in Figure 2.1. In Appendix A.1 the hydrograph is shown for each separate year.

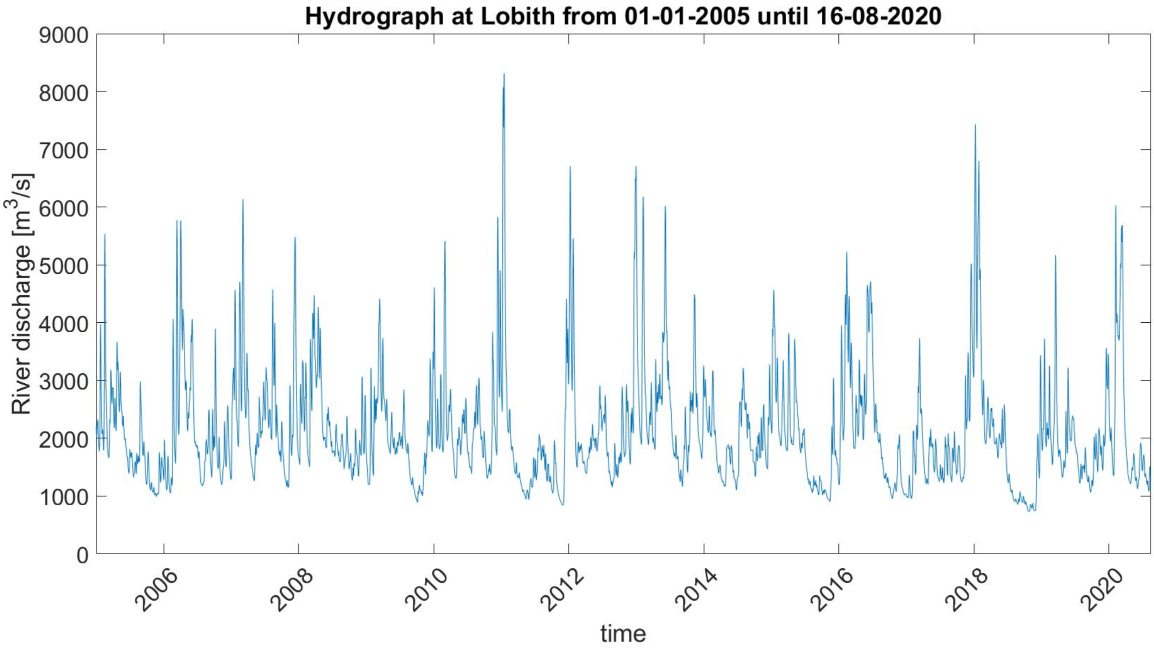


Figure 2.1: The hydrograph at Lobith for the period 2005-2020

Some hydrograph statistics for the period 2005-2020 are shown in Appendix A.2. The same statistics are also shown per year in Appendix A.3.

When examining the hydrograph in Figure 2.1 or in Appendix A.1, it appears that most high discharge events occur in the period approximately from November to May (the high water season). Table 2.1 shows the highest discharge for each high water season and at what date they occured.

Table 2.1: Highest discharges in each high water season

Winter	Date of discharge peak	Peak discharge
2004-2005	17-02-2005	5622 m^3/s
2005-2006	14-03-2006	5828 m^3/s
2006-2007	06-03-2007	6174 m^3/s
2007-2008	13-12-2007	5526 m^3/s
2008-2009	14-03-2009	4452 m^3/s
2009-2010	03-03-2010	5518 m^3/s
2010-2011	17-01-2011	8388 m^3/s
2011-2012	09-01-2012	6750 m^3/s
2012-2013	30-12-2012	6746 m^3/s
2013-2014	11-11-2013	4547 m^3/s
2014-2015	14-01-2015	4625 m^3/s
2015-2016	13-02-2016	5268 m^3/s
2016-2017	13-03-2017	3779 m^3/s
2017-2018	10-01-2018	7553 m^3/s
2018-2019	19-03-2019	5226 m^3/s
2019-2020	07-02-2020	6142 m^3/s

To put these values in perspective: The highest ever recorded discharge is 12.600 m^3/s, which occured in 1926. The peak discharges of the flood events of 1993 and 1995 were 11.100 m^3/s and 12.000 m^3/s respectively (Jorissen, 1995). At a discharge below 1350 m^3/s, all discharge is in the low water bed that is confined by groynes. The flow is below bankfull along the whole Waal at discharges smaller than approximately 3000 m^3/s. At higher discharges floodplains thus start to convey water. Until 2017 the Waal had a design discharge of 16.000 m^3/s, which has a probability of occurence of 1 × 1250 years. Since 2017 however the standardization of water safety is not expressed through a design discharge anymore but through the flood risk per dike ring section (Slootjes and van der Most, 2016).

2.3. Sail tracks

Maintenance of the navigation channel of the Waal is done by both dredging and plowing. The type of dredging vessel used on the Waal is a trailing suction hopper dredger. This vessel uses a suction pipe with a draghead attached at the end that can be lowered to the river bed to pump sediment into its own hopper wich has a capacity of approximately 500 m^3. Later the sediment can be dumped at a convenient location on the river by using bottom doors. An example of a dredger as used on the Waal is shown in Figure 2.2.

Figure 2.2: Example of a dredging vessel as used on the Waal (Roeland, 2017)

A plowing vessel has a plow suspended at the stern. The plow can be lowered to the river bed and dragged after the ship to level out the river bed. An example of a plowing vessel as used on the Waal is shown in Figure 2.3.

Figure 2.3: Example of a plowing vessel as used on the Waal (Roeland, 2013)

The dredging and plowing vessels that are used for maintaining the navigability of the Waal each keep a log. This log consists of sail tracks. A new sail track is created every minute the vessel is active. Each sail track contains information about for instance the coordinates, date, time, the activity of the vessel or the volume inside the hopper. This information can be used to determine dredging volumes, dredging locations, plowing activity and plowing locations. More in depth information about the sail tracks can be found in Appendix B.

The reliability of the sail tracks can be a problem however. Some sail tracks contain unrealistic information and thus are not usable. They need to be removed or corrected. The following reliability issues in the sail tracks are the most common (Van der Werff ten Bosch and Tuijnder, 2016):

- An activity cycle of a dredger has to go through the activities in the order 'sailing empty - dredging - sailing loaded - dumping' before a new cycle starts. The activity needs to be selected manually on the dredging or plowing vessel but the selection of a new activity seems to be forgotten sometimes. The activity cycles are therefore occasionally faulty, which results in unrealistic hopper volumes, dredging locations or dumping locations.
- Sometimes sail tracks are exact copies of eachother.
- Sometimes sail tracks are copies of earlier sail tracks but the the date and the volume differ. The time, x-coordinates and y-coordinates are exactly the same, which is very unlikely. They are probably copied by the contractor which makes the information given in these sail tracks unreliable. Why the contractor has done this is unknown.
- Many sail tracks contain incorrect dates (showing for instance a 13th month or a future year).
- Most incorrect information is due to unrealistic coordinates (indicating for instance a location in Africa).

In an attempt to increase the reliability of the sail tracks, they have been 'edited'. The process of 'editing' the data mostly involved deleting sail tracks. Since large amounts of data have been deleted, we refer in this report to the 'edited' data sets as 'the reduced sail tracks'. The sail tracks in the period from 01-03-2005 up until 01-04-2016 have been reduced by Arcadis (Van der Werff ten Bosch and Tuijnder, 2016). The sail tracks in the period from 15-12-2014 up until 14-02-2020 have been reduced by Nibbeling (2020).

Not all erroneous sail tracks have been deleted however. For data reduced by Van der Werff ten Bosch and Tuijnder (2016), sail tracks with an incorrect cycle are corrected by changing the activity of the last sail track before the missing activity into the missing activity. For data reduced by Nibbeling (2020), sail tracks with an incorrect cycle are corrected by copying the last sail track before the missing acivity and change its activity into the missing one. Both methods complete the cycle again and the missing activity is represented in one sail track.

The percentage of the sail tracks that remained after being reduced by Nibbeling (2020) is shown in Table 2.2. It follows from this Table that the percentage of remaining data is quite large for the plowing vessel but is small for the dredger. For instance in the year 2019 only 3% of the data remains and in the year 2020 all data has been deleted. The large amounts of unusable data in case of the dredger are mostly due to unrealistic coordinates (Nibbeling, 2020).

Table 2.2: Data usability for the dredger and the plowing vessel (Nibbeling, 2020)

Year	Usability dredger (the Wilma)	Usability plowing vessel (the Dintel)
2014	-	100%
2015	62.9%	100%
2016	15.0%	100%
2017	88.6%	93.7%
2018	84.5%	96.9%
2019	3.0%	86.8%
2020	0.0%	90.3%

To conclude, several data sets of sail tracks are available, namely:

- Reduced dredging sail tracks from Van der Werff ten Bosch and Tuijnder (2016) (March 2005 until Augustus 2015);
- Reduced plowing sail tracks from Van der Werff ten Bosch and Tuijnder (2016) (October 2007 until Augustus 2015);
- Reduced dredging sail tracks from Nibbeling (2020) (February 2015 until february 2020);
- Reduced plowing sail tracks from Nibbeling (2020) (December 2014 until february 2020);
- Original dredging sail tracks (January 2015 until February 2020);
- Original plowing sail tracks (January 2015 until February 2020).

2.4. BRW data

The BRW data is a record kept by the contractor containing dredging volumes together with the date and location (expressed in Rhine-kilometers) on which these volumes have been dredged. This data is stored in a spreadsheet for each year in the period 2014-2020. For 10 months throughout these years dredging volumes are missing however. These months are:

- November 2015;
- January 2018;
- February 2018;
- March 2018;
- April 2018;
- May 2018;
- October 2019;
- November 2019;
- December 2019;
- January 2020.

Appendix C shows a part of a spreadsheet with BRW data to give an impression of how the data is stored.

2.5. Multibeam measurements

Multibeam measurements are the result of control surveys that the contractor has to carry out such that Rijkswaterstaat can varify if the contractor has acted in accordance with the contract (Bardoel, 2010). The control surveys are carried out approximately every 2 weeks. Each bi-weekly multibeam measurement is an image file that consist of data points for the bed level of the main channel of the Waal for each 1 × 1 m. They provide regular measurements of the bed level which can be used to analyse the topography of the river bed. The multibeam measurements are not used for data analysis in this research, but only for providing insights about what the river bed looks like at certain locations. See Figure 2.4 for a visualization of a multibeam measurement. A shadow effect has been used to emphasize the shapes of the bed so no useful colorbar about bed levels can be added.

Figure 2.4: Visualization of a multibeam measurement at the end of fixed layer near St. Andries (Multibeam measurement taken at 13 March 2013)

2.6. Least Available Depths

The Least Available Depths (LADs) are stored in three spreadsheets. One for the period 2004-2017, one for the period 2015-2018 and one for the year 2019. There is some overlap between the first two spreadsheet so it has been ensured in this research that only unique LADs are used in the data analysis. Since most data sets are available from 2005, the year 2004 is disregarded in the first BRW spreadsheet. The LAD spreadsheets contain the location (expressed in both Rhine-kilometers and coordinates) along the Waal where the smallest available water depth is recorded for each day. In the LAD spreadsheet for the year 2019 however multiple locations are recorded per day. Appendix D shows a part of a spreadsheet with LAD data to give an impression of how the data is stored.

2.7. Total dredging volumes

We sort the total dredging and dumping volumes according to the reduced sail tracks (summed over the whole Waal) by month. We do this, like all data processing in this research, by using a MATLAB script. Appendix E elaborates further on the used scripts in this research.

The results are shown in Figure 2.5 for the year 2016. The results for each year (from 2005 until 2020) can be found in Appendix F.1.

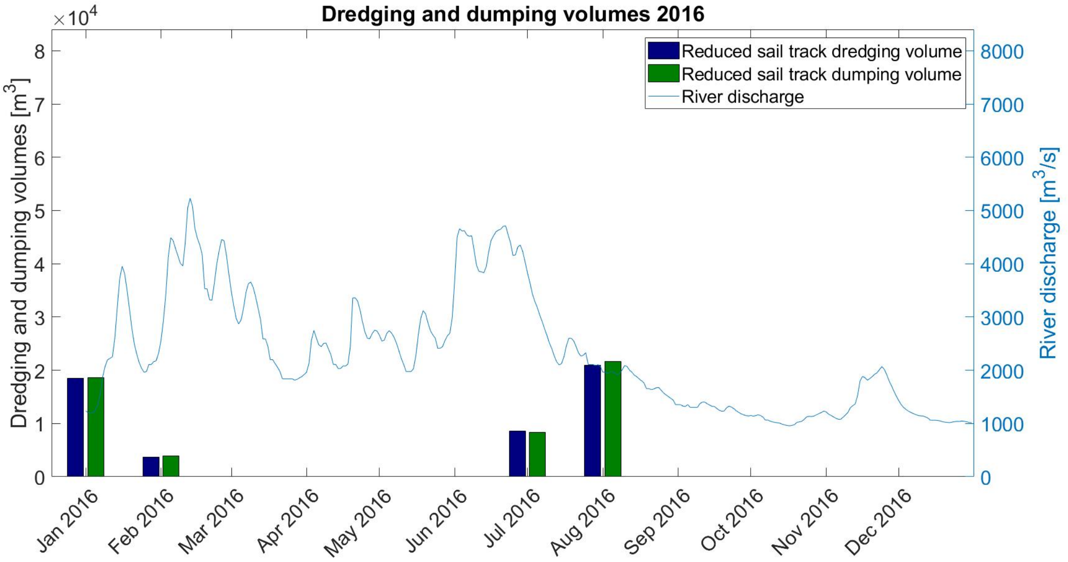


Figure 2.5: Dredging and dumping volumes according to reduced sail tracks 2016

It can be seen in Figure 2.5 that the dredging and dumping volumes are quite similar, which indicates that in the reduced sail tracks the dredging cycles have been succesfully retained or corrected. It can also be seen that a lot of months show no dredging and dumping volume. In the reduced sail tracks a significant amount of sail tracks was deleted from the data set. Large amounts of information on dredging volumes are missing and thus monthly dredging and dumping volumes are underestimated.

To get an indication of how complete the dredging volumes from the reduced sail tracks are, we compare them to another data set of dredging volumes. For this the BRW data is used. In the BRW data the volumes are accounted for per date and per rkm on the Rhine-kilometer scale. We take the total BRW dredging volumes (summed over the whole Waal) per month and compare them to the results from the reduced sail tracks.

The results are shown in Figure 2.6 for the year 2016. The results for each year (from 2014 until 2020) can be found in Appendix F.1.

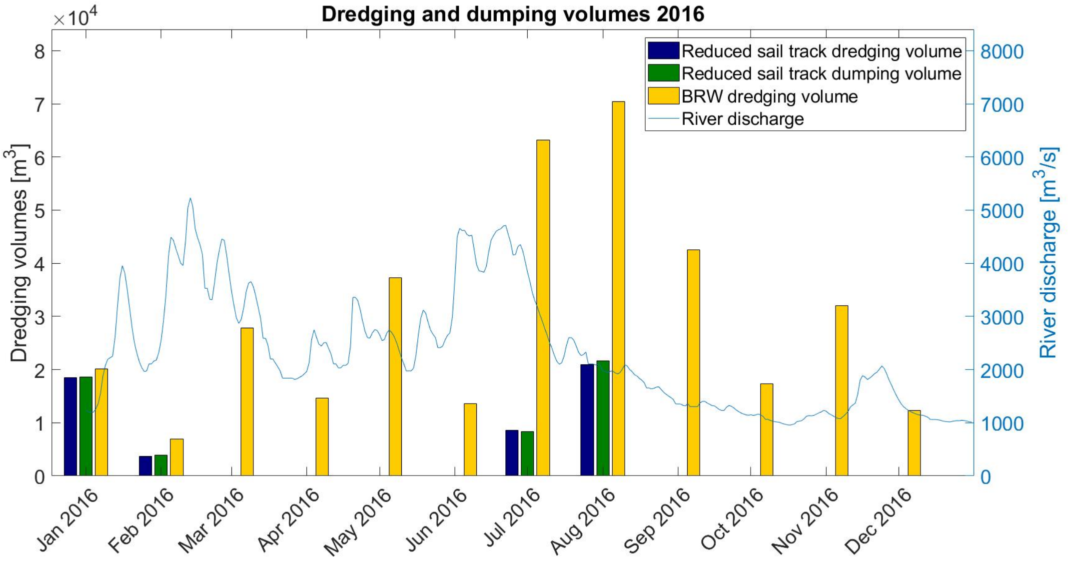


Figure 2.6: Dredging and dumping volumes according to reduced sail tracks and the BRW dredging volumes 2016

From Figure 2.6 can be concluded that the dredging volumes from the reduced sail tracks are in general smaller than the BRW dredging volumes. The BRW dredging volumes also show dredged volumes during the months that according to the reduced sail tracks no dredging has taken place. This implies that indeed large dredging volumes were lost in the process of editing the original sail tracks and creating the reduced sail tracks.

An option to obtain a more realistic picture of the dredged volumes from the sail tracks is to use the original unreduced sail tracks instead of the reduced sail tracks. It sounds counterintuitive but since many sail tracks have been deleted in the reduced data, the original sail tracks give a more complete picture of the total dredging volumes. The drawback is that the original sail tracks contain a lot of erroneous information as explained in Section 2.3. Most errors regard coordinates and therefore it is not possible to use information about the dredging or dumping locations. However, since in this section we only consider the total dredging volumes (summed over the whole Waal) this poses no problem. Because the amount of errors regarding dates is relatively small we can sort the total dredging volumes per month.

The results are shown in Figure 2.7 for the year 2016. The results for each year (from 2015 until 2020) can be found in Appendix F.1.

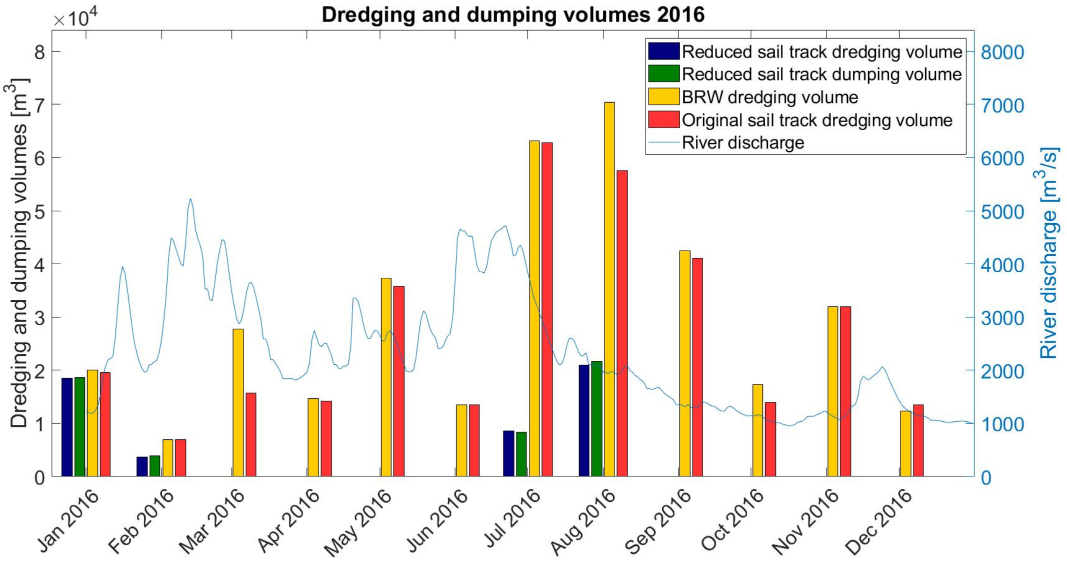


Figure 2.7: Dredging and dumping volumes according to reduced and original sail tracks and the BRW dredging volumes 2016

It can be concluded from Figure 2.7 that the dredging volumes from the original sail track match the BRW dredging volumes quite well. This indicates that the dredging volumes from the reduced sail tracks are less complete than the other data sets. For the year 2017, the reduced sail tracks are still quite reliable however. Since the reduced sail tracks underestimate the dredging volumes and the original sail tracks cannot be used to determine dredging locations, we use the BRW data for most analyses of dredging volumes in this research. It is important to keep in mind that although the BRW data are more reliable than the reduced sail tracks, they are still not completely reliable. Namely, the BRW data still contains some months in which no dredging volumes are available.

The reduced sail tracks might not produce the most reliable total dredging volumes over the whole Waal, but they do contain reliable coordinates. Because the reduced sail tracks contain coordinates, they provide a more detailed impression of the dredging and dumping locations than the BRW data (in which locations are only indicated by the Rhine-kilometer scale). Also the reduced sail tracks can be used to investigate both the dredging and dumping locations where the BRW data can only be used to investigate dredging locations. Dredging locations are treated in Section 3.4.

2.8. Plowing activity

Just as for the dredging and dumping volumes, we can show the plowing activity over the whole Waal per month. Because no volumes are attributed to plowing, we define the activity as the amount of sail tracks with a plowing activity. We do this for both the reduced and original sail tracks. The results are shown in Figure 2.8 for the year 2017. The results for each year (from 2007 until 2020) can be found in Appendix F.2.

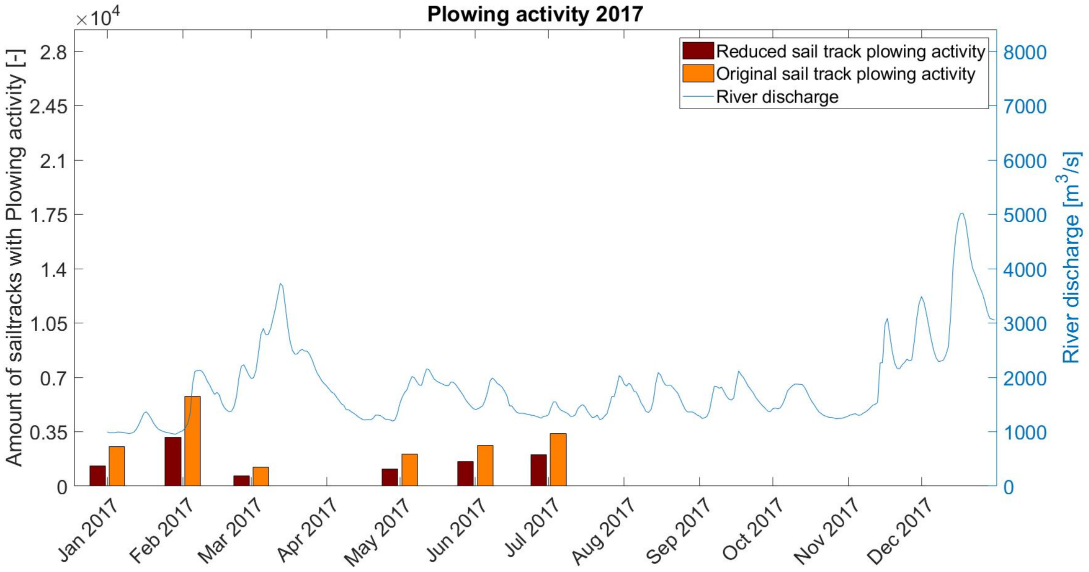


Figure 2.8: Plowing activity according to reduced and original sail tracks 2017

It follows from these graphs that no plowing activity is shown for quite some months. This is however likely not due to the process of reducing the data, since the original data also shows no plowing activity for those months. It can be concluded that although there is a difference in plowing activity between the reduced and original sail tracks, always approximately 1/2 to 2/3 of the monthly plowing activity remains. Thus the proportions between the bars stay largely the same. This means that the reduced sail tracks are more useful since they are available for a larger amount of years (2005-2020 instead of 2015-2020) and they still contain usable information about the plowing locations. Also the exact numbers in which the plowing activity is expressed is meaningless anyway since it is expressed in the amount of sail tracks. However, quite some months of data are missing which we have to take into account when analysing the data.

3

The relation between Hotspots, Least Available Depths and the river geometry

3.1. Chapter introduction

In this chapter we first give some information about the layout of the Waal in Section 3.2, because later in this chaper we will refer to certain locations along the Waal. Subsequently, in Section 3.3 we elaborate an interview with the contractor about sediment management and the influence of the hydrograph on sediment management. This helps in creating a frame of reference for the research discussed in both Chapter 3 (this chapter) and in Chapter 4. Then, in Section 3.4 we determine the dredging and plowing locations and the associated hotspots. In Section 3.5 we investigate the relation of dredging locations with Least Available Depths. Finally, we investsigate the relation of hotspots and Least Available Depths with the river geometry in Section 3.6. With this purpose a river geometry analysis is introduced. This same geometry analysis is also used in Chapter 4.

3.2. The Waal

Distances and locations on the Waal are expressed in Rhine-kilometers (usually referred to as rkm) which are measured over the river axis (Bardoel, 2010). The river Waal starts at Pannerdesche Kop, where the Rhine-kilometer scale equals rkm 867.4 and the Waal ends at Woudrichem, where the Rhine-kilometer scale equals rkm 952.6. Thus the Waal is approximately 85 km long (Rijkswaterstaat, 2019b). Figure 3.1 shows an overview of the Waal. Indicated in this overview are the locations to which we refer in this report.

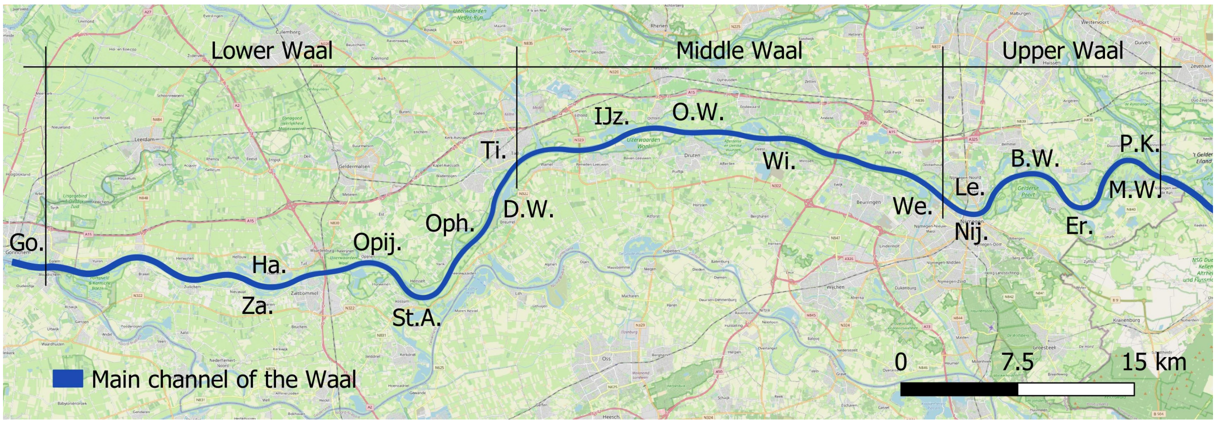


Figure 3.1: Overview of the Waal river. The abbreviations indicate the following locations along the Waal: B.W. Bemmelse Waard, Er. Erlecom, Go. Gorichem, Ha. Haaften, IJz. IJzendoorn, Le. Lent, M.W. Millingerwaard, Nij. Nijmegen, Oph. Ophemert, Opij. Opijnen, O.W. Ochtensche waarden, P.K. Pannerdense kop, St.A. St. Andries, Ti. Tiel, We. Weurt, Wi. Winssen, Za. Zaltbommel.

The Waal is usually subdivided into three reaches. According to Bardoel (2010) the following reaches are defined:

- The ’Boven-Waal’ or Upper Waal. This reach starts at Pannerdensche Kop and ends at Nijmegen.
- The ’Midden-Waal’ or Middle Waal. This reach starts at Nijmegen and ends at Tiel.
- The ’Beneden-Waal’ or Lower Waal. This reach starts at Tiel and ends at Woudrichem.

3.3. Explanations of the contractor

We have interviewed an employee at the contractor with the purpose of gaining information about the dredging and plowing strategy of the contractor. Another purpose of the interview was to gain information about the influence of the hydrograph and the river geometry on sediment management, which can be used as a frame of reference for the research discussed later in this chapter and in Chapter 4. The statements made by the employee are summarized here.

3.3.1. Statements about dredging volumes and plowing activity after discharge peaks

The contractor reckons that accretion occurs along the Waal after discharge peaks and that thus the dredging volumes and plowing activity increase after the discharge peak has passed. How much sediment management is required after a discharge peak depends on the amount of accretion that occurs. Based on experience, the contractor suspects that the amount of accretion after a peak depends more on the length of the discharge peak and the decrease rate of the discharge peak than on the actual peak discharge. In the most extreme case it would take about a month to seven weeks after a discharge peak to completely restore the the bed level along the whole Waal. Sediment management can be stopped during very high discharge peaks since it can become difficult when water depths are large. Also usually no dredging takes place in weekends.

3.3.2. Statements about measuring the bed level and determining dredging locations

The contractor takes multibeam measurements on a daily basis such that a complete picture of the bed of the Waal is obtained approximately every week. This means that the contractor has more multibeam measurements available than the bi-weekly multibeam measurements that Rijkswaterstaat receives. Also some hotspot measurements are taken at seven locations along the Waal. These seven locations are known to be subject to accretion after high discharge events (and continuous accretion). These locations are therefore being dredged preventively and are referred to as hotspots. They are located at:

- Bend at Millingerwaard (rkm 869, 870 and 871);
- Crossing between bends at Erlecom and Bemmelse Waard (rkm 876 and a small part of 877);
- Bend at Bemmelse Waard/Lent (rkm 880, 881 and a small part of 882);
- Winssen (rkm 894, 895 and a small part of 986);
- Bend at Tiel/Dreumelse Waard (rkm 914, 915, 916, 917 and 918);
- Dreumelse Waard/Ophemert (rkm 918, 919 and 920);
- Crossing between the bends at St. Andries and Opijnen (rkm 928 and a small part of 929). This is the hotspot with the largest required dredging and plowing effort.

An overview of the Waal including these hotspots is shown in Appendix G. The contractor admitted that preventive dredging can also regularly take place at other locations (not indicated as hotspots).

Dredging vessels and plowing vessels have certain home ports at:

- Nijmegen/Weurt (rkm 886);
- IJzendoorn (rkm 907);
- Tiel (rkm 913);
- Haaften (rkm 936).

These home ports have been located such that the hotspots are easily accesible. Naturally, because of the sailing from and towards the home ports the dredging and plowing vessel sail with an increased regularity in the vicinity of these ports. The contractor indicated that this should have no influence on the dredging or plowing activity close to the home ports.

The contractor needs to keep the bed level below a certain reference plane, according to a performance-based contract. In recent years only one dredging vessel and one plowing vessel have been used so it is impossible to dredge or plow at several locations at the same time. Therefore, the hotspots are dredged and plowed preventively to keep the bed level there beneath the reference plane after a high discharge event. This usually also means that when a high discharge event has occured, the bed level starts to exceed the reference plane at other locations. The type of morphological phenomena at these locations of accretion is then determinded to choose if either dredging or plowing is required. More information about morphological phenomena is given in Chapter 4. Determining the morphological phenomena can be done by using multibeam measurements but based on experience often the location of the accretion gives enough information about the morphology. The dredging vessel is used if the accretion is a non-migrating bar. In case of migrating dunes with a volume of approximately 10-100 m^3 the plowing vessel is used.

Plowing is also used to assist the dredging vessel. Dredging is usually done by sailing in longitudinal direction, creating a 1 to 2 m wide trench (the width of the draghead). When at a certain location intensive dredging needs to be done, the dredging vessel turns regularly and creates a new trench next to the old trench. To prevent the draghead from sliding into the old trench, the plowing vessel sails behind the dredging vessel and evens out the trench with its plow. This is possible because the plow of the plowing vessel is significantly wider than the draghead of the dredging vessel (approximately 8 m wide). This use of the plowing vessel means that it is also often used at the hotspots.

3.4. Dredging and plowing locations

Because the sail tracks are delimited text files (see Figure B.1 in Appendix B), we can open them in a GIS program. We can use the coordinates to visualize each sail track as a point. In this research we use the GIS program QGIS. We use QGIS to add information to each point (sail track) about all information that is stored in the sail tracks. We add information about its location on the Waal to each point by overlaying the points with a grid. See Figure 3.4 for a visualization of the points and the grid in QGIS. The transversal lines of the grid represent each hectometer line of the Rhine-kilometer scale. The longitudinal lines of the grid subdivide the grid cells into six parts. Each grid cell contains information about its longitudinal location (expressed in the Rhine-kilometer scale) and its transversal location (expressed as ’left bank’, ’middle left’, ’axis left’, ’axis right’, ’middle right’ and ’right bank’). The grid cells have a size of roughly 100 × 45 m.

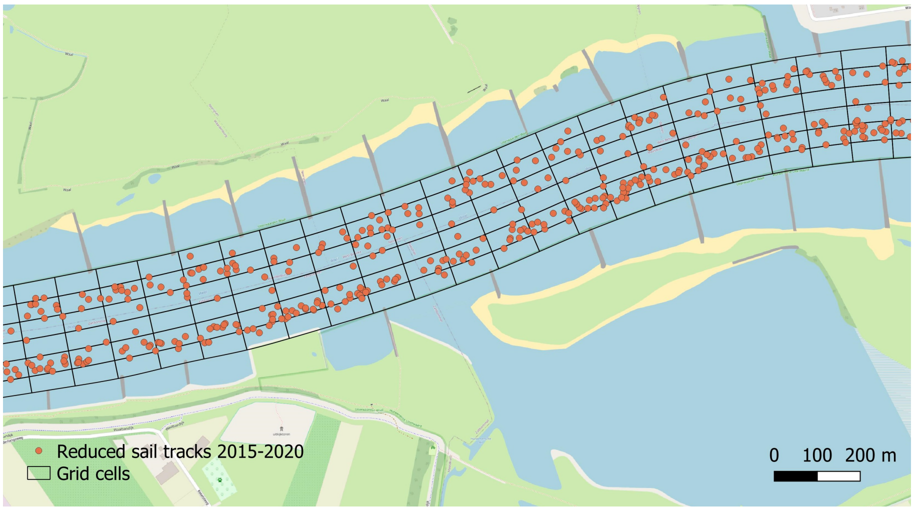


Figure 3.2: The points that represent sail tracks from the period 2015-2020 and the grid near Opijnen

Every sail track is subdivided according to the river kilometer and the side of the river (the six longitudinal grid cells are used to locate sail tracks on the left and right side of the river).

The results are shown in Figure 3.3 and 3.4 for the year 2017, since this is a year with few deleted sail tracks. Figure 3.3 shows the monthly dredging locations and Figure 3.4 shows monthly dumping locations. The same graphs can be found in Appendix H.1 for the period 2005-2020. These graphs show the hydrograph, the dredging locations and dredging volumes. Time is shown on the lower x-axis (in months) and the river discharge is shown on the right y-axis (in m^3/s). The location on the waal is shown on the left y-axis (in rkms) where the origin is the upstream end of the Waal. The upper x-axis divides each month in a left side and a right side. In this way we can show twelve representations of the waal next to each other; one for each month of the year. By using color intensity we can indicate the dredging volumes for each location along the waal (rkm, left side, right side) and how these change over the months.

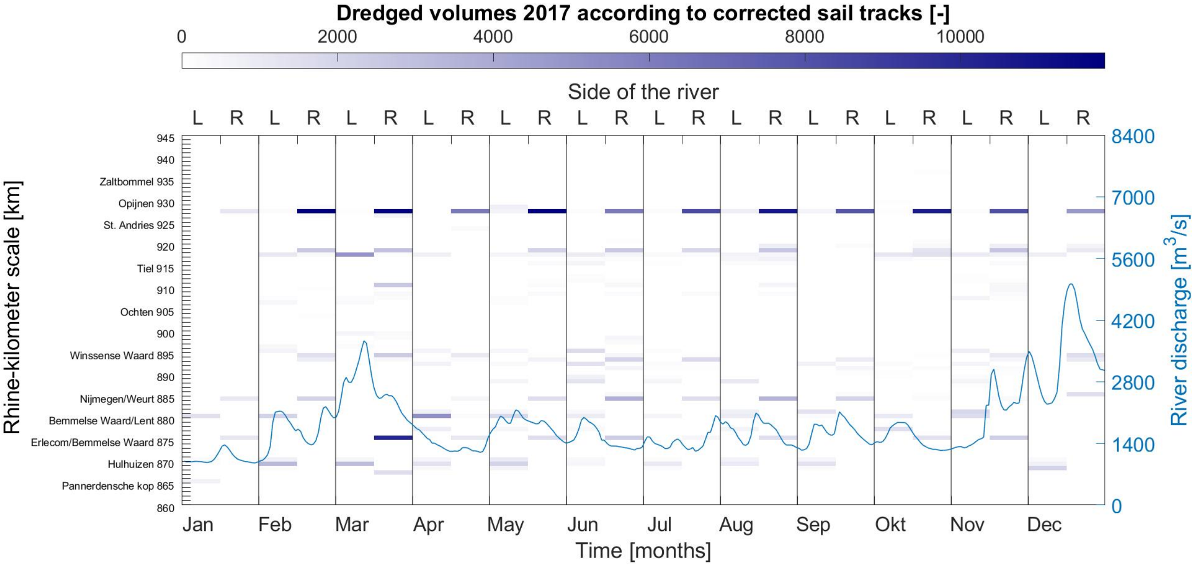


Figure 3.3: Dredging volumes and locations reduced sail tracks 2017

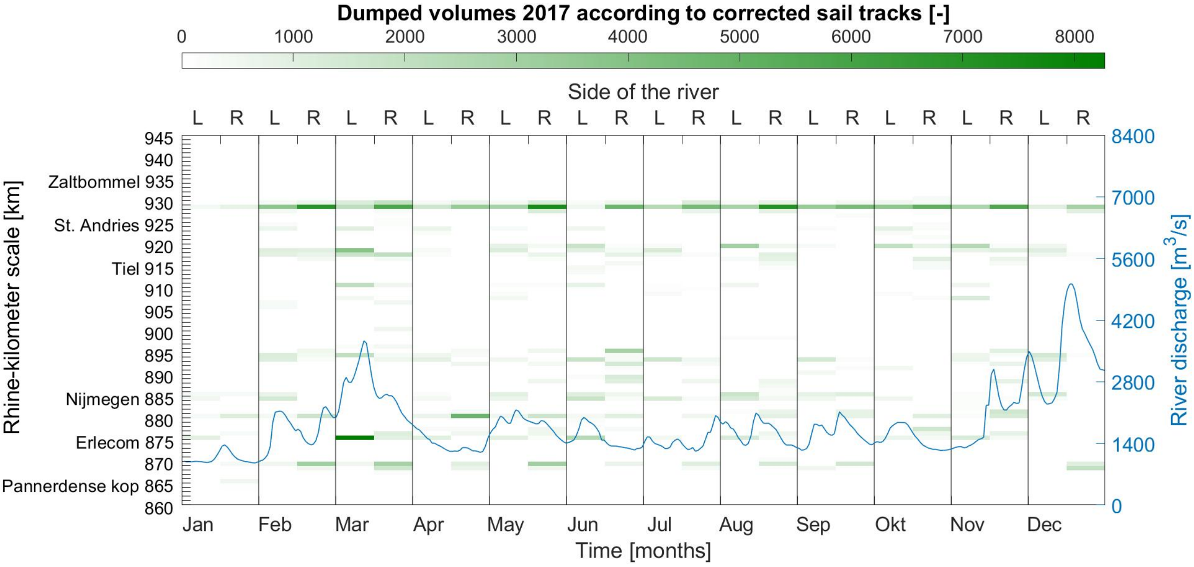


Figure 3.4: Dumping volumes and locations reduced sail tracks 2017

Three things appear from these graphs. Firstly, the dredging vessel only operates upstream of Zaltbommel (rkm 935). Downstream of Zaltbommel dredging in the Waal is done by different vessels with the purpose of sediment extraction. Secondly, it also appears from the graphs that there are several locations that have countinuously large dredging volumes, of which rkm 928 is the most obvious. Other obvious locations of continuous dredging are at rkm 876 and 885 and slightly less obvious locations of continuous dredging are around rkm 869 and 919. The reasons why large dredging volumes continuously occur at these locations are treated in Section 3.6. Thirdly, dumping happens broadly on the same locations as dredging but the locations differs very slightly. Appendix I shows a brief analysis of the reloction of sediment, based on these dredging and dumping graphs.

As explained, in several years large volumes are missing. Therefore, we make the same graphs with the BRW data set which is more complete. The BRW data however still has some shortcomings. Firstly, with the BRW data it is not possible to indicate dumping volumes since only dredging volumes are stored in the data set. Secondly, no coordinates or information about the side of the river are stored which makes it not possible to subdivide BRW volumes into left and right. Thirdly, the BRW data is only available for the period 2014-2020 which restricts the period over which the BRW volumes can be analysed. Lastly, the BRW data still contains some months without data (this is treated earlier and can be derived from Appendix F.1), which has to be taken into account when analysing the data. The results are shown in Figure 3.5 for the year 2017. The results can be found in Appendix H.2 for the period 2014-2020.

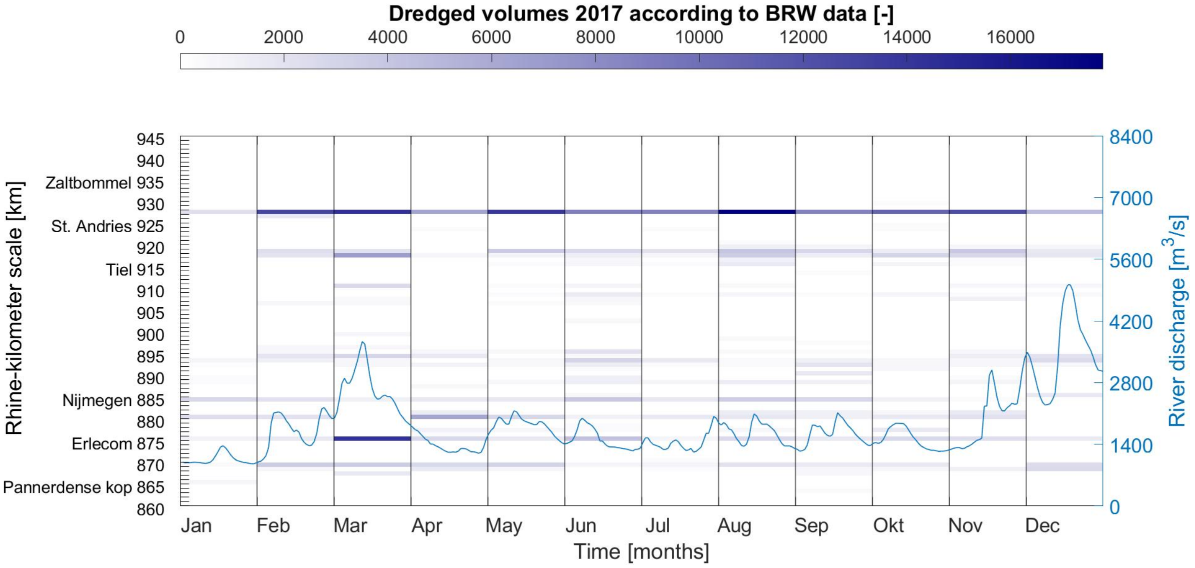


Figure 3.5: Dredging volumes and locations BRW data 2017

Overall, the same conclusions can be drawn as earlier from analysing Figure 3.3 and 3.4. The dredging vessel only operates upstream of Zaltbommel and the most notible locations of continuous dredging are rkm 876, 885 and 928.

The BRW data being more complete than the reduced sail tracks makes them more suited for analysing dredging volumes and dredging locations. Therefore, we do all analysis of dredging volumes in this research by using the BRW data. Although the dredging volumes from the BRW data are more reliable, the reduced sail tracks contain some information that the BRW data set is missing. The reduced sail tracks subdivide dredging and dumping into the left and right side of the river and contain information about dumping locations. This helps in analysing the relocation of sediment. In this research we do not focus on the relocation of sediment but as mentioned earlier Appendix I shows a brief analysis of it.

We use the same approach as used for creating Figure 3.3 and 3.4 to show the monthly plowing activity per location. The results are shown in Figure 3.6 for the year 2017. The results can be found in Appendix F.2 for the period 2007-2020.

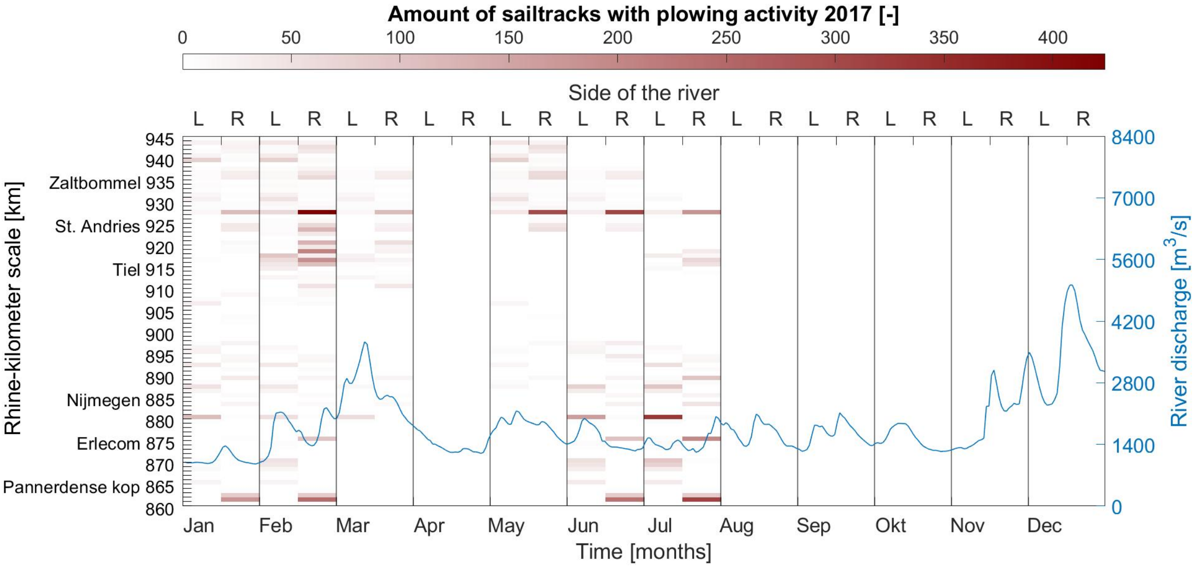


Figure 3.6: Plowing locations 2017

It appears from these graphs that the plowing locations differ significantly from the dredging locations. Plowing continues for instance downstream of Zaltbommel, in contrast to dredging. However, the plowing locations with continuous plowing seem to correspond relatively well with locations of continuous dredging; rkm 928 being the most notible. Differences between dredging and plowing locations are further analysed in Chapter 4.

Concluding, most obvious from these graphs are certain locations with continuous very large dredging volumes and plowing activity. For dredging the most apparent locations with continuous dredging are at rkms 876, 885 and 928. Other locations with continuous dredging are around rkm 869 and 919. For plowing the most apparent location is at rkm 928.

The locations of continuous dredging at rkm 876 and 928 agree with the hotspots indicated by the contractor. The same goes for locations around rkm 869 and 919. The contractor indicated that hotspot at rkm 928 requires the largest dredging and plowing effort, which coincides with the data. However, rkm 885 is not indicated as a hotspot by the contractor but is apparent in the data. From this point on, when we use the term 'hotspots', we refer to rkm 876, 885 and 928 for dredging and rkm 928 for plowing. Continuous large mounts of dredging and plowing occur at these hotspots because the contractor chooses to preventively dredge and plow at these locations. The reasons for the continous preventive dredging and plowing at these hotspots are treated in Section 3.6.

3.5. Relation between Least Available Depths and dredging locations

In an attempt to gain insight in why dredging and plowing happens continuously at certain locations, we use LADs. We compare the dredging locations as indicated in Section 3.4 to locations of measured LADs. In this way a relation between measured LADs and subsequent dredging might be obtained. The Least Available Depths is a data set that contains the location with the smallest depth in the Waal per day and for the year 2019 multiple locations per day. We can show the LADs in graphs to indicate locations where LADs have been measured over time. Figure J.13 shows such a graph for the year 2017. The results can be found in Appendix J for the period 2005-2019. The color intensity in these graphs shows the amount of times an LAD has been measured in each month and rkm (divided into left and right side of the river).

It follows from the Figures in Appendix J that over the years most LADs are measured at rkm 876, 885 and 928. In the year 2019, where more LADs per day are stored, other locations with frequent measured LADs around rkm 869 and 919 become clear. Rkm 876, 885 and 928 are continuously the most apperent locations when just one LAD is stored per day, which indicates that those locations overall have the least depth. These locations match with the hotspots and the increased dredging volume at these locations thus makes sense.

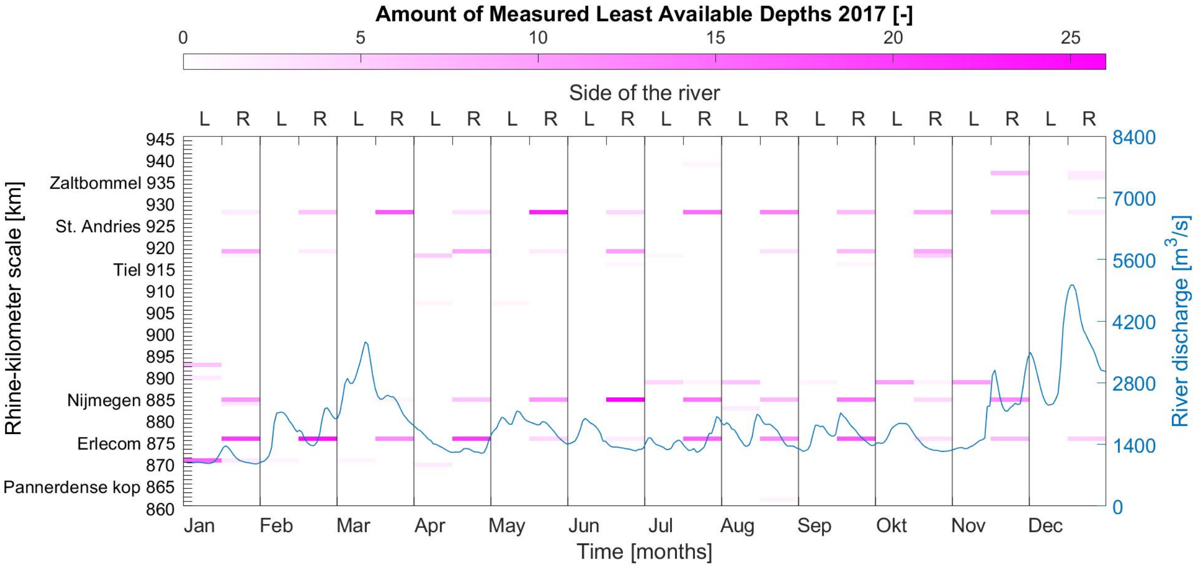


Figure 3.7: Least Available Depths 2017

As mentioned in Chapter 1, we expect that at locations where often LADs are measured the dredging volumes are large as well. We thus investigate if there is a positive relation between the amount of LADs measured on a certain location in a certain month and the dredging volume on that same location and in that same month. This relation between LADs and the dredging volume is shown as a scatter plot in Figure 3.8. The y-axis shows the amount of measured LADs per month on a specific rkm. We only take monthly locations with a nonzero amount of measured LADs into account here. The x-axis shows the dredging volume on that same location and in the same month. Each dot thus indicates both a month and an rkm. We plot a least squares regression line through the dots. Since we expect a positive relation between the amount of measured LADs and the dredging volume in a specific month and rkm, we expect an upward regression of the dots in Figure 3.8.

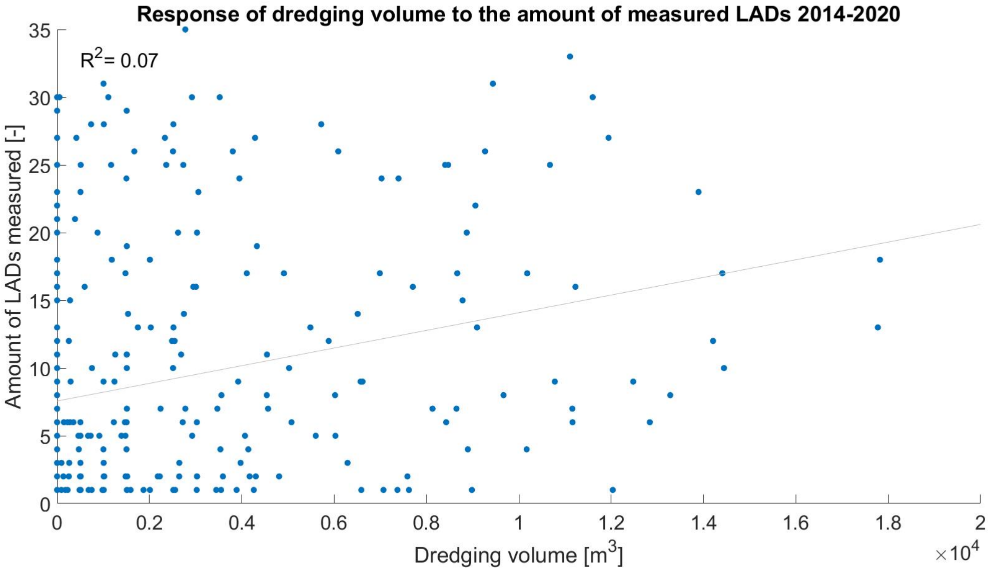


Figure 3.8: Scatter plot of the amount of measured LADs against the dredging volume on that same location and in the same month

Figure 3.8 shows the coefficient of determination (R^2), which is 0.07. R^2 is very close to 0, which means that the overall distance of the dots to the regression line is very large. We can observe this in Figure 3.8 when looking at the distances between the dots and the regression line. We conclude that the dots show no trend, even though the regression line is positive.

A reason for this might be that at the hotspots located at rkm 876, 885 and 928 dredging volumes are almost always large independent of the amount of measured LADs there. According to the contractor the hotspots are continuously dredged and other locations are usually only dredged after a discharge peak.

If we disregard the most important hotspots the dredged locations after discharge peaks become more prominent in the data. We thus expect that when the hotspots are disregarded the dots will show a clearer trend. We make the same scatter plot for the amount of measured LADs against the dredging volume without taking the dredging hotspots at rkms 876, 885 and 928 into account. See Figure 3.9.

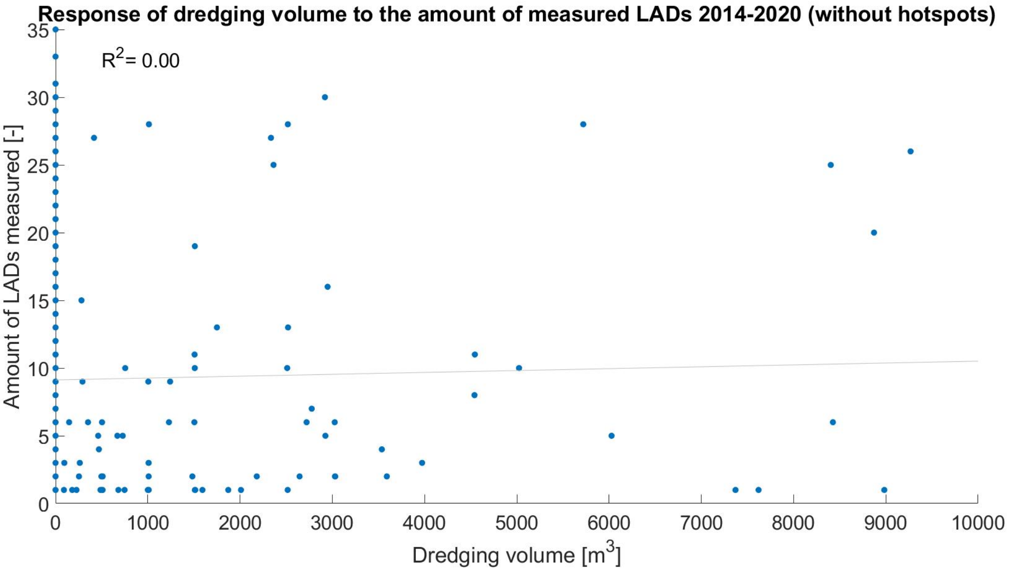


Figure 3.9: Scatterplot of the amount of measured LADs against the dredging volume on that same location and in the same month

It needs to be noted that the dots representing hotspots are not completely removed from the plot. They are horizontally shifted towards a dredging volume of 0 m^3 (they are placed on the y-axis). This means that the regression line is more horizontal and the coefficient of determination is probably lower than when these values would be completely deleted from the plot.

We can still draw three conclusions. Firstly, a significant amount of dots can be attributed to the hotspots at rkm 876, 885 and 928, since in Figure 3.9 a lot less dots are visible as in Figure 3.8. Secondly, the dots with the largest dredging volumes in Figure 3.9 are much smaller than the dots with the largest dredging volumes in Figure 3.8, which indicates that dredging volumes at the hotspots can become much larger than at other rkms. Lastly, in both scatter plots there is a large scatter and it appears that many dots with a large amount of measured LADs have no or a very low dredging volume, which is contrary to the expectation. This last conclusion might have four reasons, which are elaborated below.

Firstly, The fact that LADs are measured at a certain location does not necessarily mean that at that location dredging is necessary. The contractor has often no reason to dredge at the locations with the least depth, since the contractor is contractually obliged to keep the bed level lower than the reference plane. The available water depth does not necessarily say anything about the bed level and the reference plane.

Secondly, dredging does not always take place on the right location. The contractor uses only one dredging vessel which makes it impossible to dredge at several locations at once. If at several places at once dredging is required (which could be represented in measured LADs), some of these might not be dredged in short notice since there is not enough dredging capacity available.

Thirdly, there are no-dredging zones present at some locations in the Waal. These no-dredging zones are located where for instance cables cross the Waal underneath the bed. The no-dredging zones prevent the bed from being dredged even though LADs might have been measured there. The fact that dredging is not allowed at a no-dredging zone might even increase the probability that LADs are measured there. Appendix K shows what rkms of the Waal contain no-dredging zones.

When considering the rkms 868 up and including 945 (the length of the Waal), 27 of the 77 rkms contain at least one no-dredging zone. This is 35% of the rkms. 68% of all LADs have been measured within the rkms containing no-dredging zones so more LADs are measured in rkms with no-dredging zones than in rkms without no-dredging zones.

The no-dredging zones each have a length of approximately 100 m. Sometimes a no-dredging zone is a little larger or multiple no-dredging zones are present within a rkm. However, in each rkm always more than enough room remains where dredging is allowed. It is even the case that rkm 876 and 885 contain no-dredging zones although they are two of the rkms with the largest dredging volumes. It is clear that more LADs are measured in rkms with no-dredging zones than in other rkms but the no-dredging zones do not seem to decrease the dredging volumes in those rkms much. It is difficult to analyse the exact influence of no-dredging zones on LAD locations and dredging volumes since the dredging volumes are regarded per kilometer and the no-dredging zones are only about 100 m long.

Fourthly, the dredging volumes are obtained from the BRW data and several months are missing in this data set (see Section 2.4). Figure 3.8 and 3.9 take all months into account. This means that they also show months in which no data about dredging volumes is available. Missing data about dredging volumes in a certain month can result in no or a very low dredging volume, even though (many) LADs have been measured.

3.6. The relation of hotspots and Least Available Depth with the river geometry

In Section3.5 it became clear that the water depth at the hotspots is usually the smallest along the Waal. To further substantiate the reasons of the small water depth at the hotspots and the resulting dredging and plowing there, we determine the geometrical characteristics of the Waal for each rkm of the Waal. How we defined the geometrical characteristics along the Waal is shown for each rkm in Appendix N.1. The impact that each geometrical characteristic has on the morphology is treated in detail in Chapter 4.

We deterimine the dredged and plowed rkms for each separate discharge peak. Then we analyse the geometrical characteristics at these dredged and plowed rkms. This makes it possible to find possible reasons for sediment management at those locations. How sediment management overall appears to be influenced by the river geometry from this analysis is treated in Chapter 4. In this section we use the analysis to investigate the influence of the river geometry at the locations of hotspots and measured LADs only.

We define the discharge peaks as peaks with a discharge larger than 3000 m^3/s that are significantly higher than the preceding and subsequent discharge (at least 1500-2000 m^3/s larger) and which are not clearly part of a larger peak. We only take peaks into account that are followed by a month for which data about dredging volumes and plowing activity is available. A list of discharge peaks can be found in Appendix L.

We use an inundation atlas that shows what floodplains convey water at certain water levels (Rijkswaterstaat, 2019c). We note the locations where the conveying bed widens, because downstream of these locations accretion is expected to occur in the main channel due to the deceleration of the flow. Accretion in the main channel due to high river discharges is explained in more detail in Appendix M. By using a wavelet method Van Denderen (2020) has indicated locations of erosion and accretion along the Waal. We define the locations with a widening winter bed as the locations of accretion as indicated by Van Denderen (2020) just downstream of locations where the winter bed widens. These locations change as the river discharge changes so they differ per discharge peak.

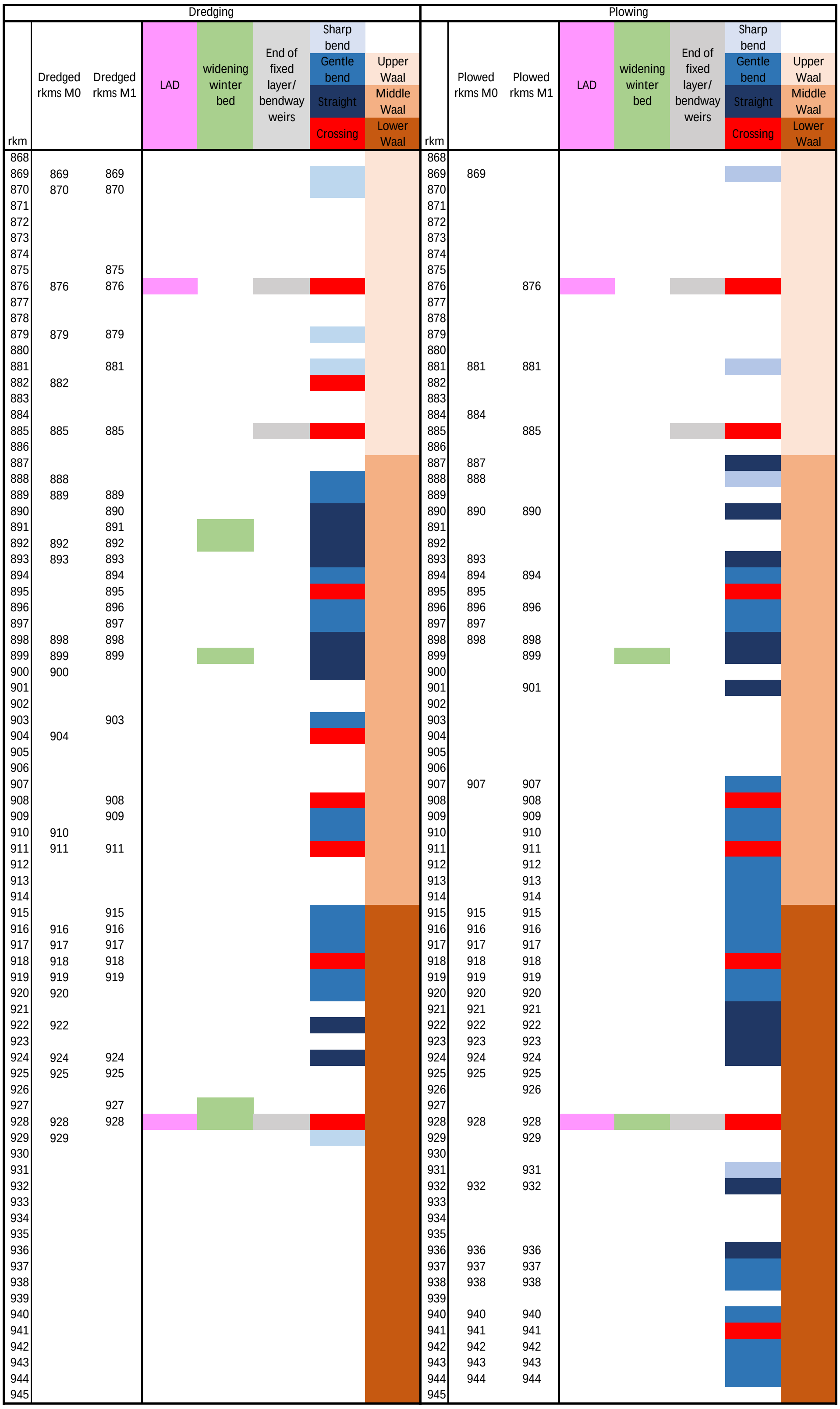
We determine the dredging and plowing locations for two calendar months after each peak in the hydrograph. Firstly, we determine the dredging and plowing locations in the remainder of the calendar month of the discharge peak and secondly, we determine the dredging and plowing locations in the first full calendar month after the discharge peak. We look only at dredging and plowing locations in the remainder of the calendar month of the discharge peak and in the subsequent full calendar month because the contractor indicated that in the most extreme case it would take about a month after a discharge peak to completely restore the the bed level along the whole Waal (see Section 3.3). We do the same for the locations of measured LADs.

The hydrograph is measured at Lobith. It thus takes some time before these changes are actually perceived over the whole Waal. There is also a measuring station at Tiel. From comparing several time intervals between a measured discharge peak at Lobith and at Tiel, it follows that it takes approximately 12 hours for a discharge peak to travel from Lobith to Tiel. We thus assume that it takes 24 hours before the peak has passed the whole Waal. Therefore, when determining the dredging volume, plowing activity or amount of measured LADs in the remainder of the month of the discharge peak, we do not take into account the day of the discharge peak and the day after the discharge peak.

As an example the analysis of the dredging locations, plowing locations and the geometric characteristics is shown in Figure 3.10 for the peak discharge in August 2014. The analysis shown in Figure 3.10 is constructed as indicated below.

- The first column shows all rkms of the Waal.
- The second column shows what rkms are dredged in the remainder of the calendar month in which the discharge peak occured (denoted as M0).
- The third column shows what rkms are dredged in the complete calendar month subsequent to the month of the discharge peak (denoted as M1).
- The fourth column shows in what dredged rkms (in both the M0 and M1 month) LADs have been measured.
- The fifth column shows in what dredged rkms the conveying bed widens (depending on the peak discharge).
- The sixth column shows in what dredged rkms a fixed layer ends.
- The seventh column shows the geometrical characteristics of the dredged rkms (a sharp bend, gentle bend, a relatively straight part or a crossing between bends).
- The eighth column shows the different reaches of the Waal (the Upper Waal, Middle Waal and Lower Waal).

The same is shown in column 9 until 16 for the plowing activity. In this report we refer to this kind of analysis as a geometry analyis. The geometry analyses are shown for all peaks in the period 2014-2020 in Appendix N.2.



Dredging								Plowing							
rkm	Dredged rkms M0	Dredged rkms M1	LAD	widening winter bed	End of fixed layer/ bendway weirs	Sharp bend ░ Gentle bend ▒ Straight ▓ Crossing 🟥	Upper Waal ░ Middle Waal ▒ Lower Waal ▓	rkm	Plowed rkms M0	Plowed rkms M1	LAD	widening winter bed	End of fixed layer/ bendway weirs	Sharp bend ░ Gentle bend ▒ Straight ▓ Crossing 🟥	Upper Waal ░ Middle Waal ▒ Lower Waal ▓
868							░	868							░
869	869	869				░	░	869	869					░	░
870	870	870				░	░	870							░
871							░	871							░
872							░	872							░
873							░	873							░
874							░	874							░
875		875					░	875							░
876	876	876	■		■	🟥	░	876		876	■		■	🟥	░
877							░	877							░
878							░	878							░
879	879	879				░	░	879							░
880							░	880							░
881		881				░	░	881	881	881				░	░
882	882					🟥	░	882							░
883							░	883							░
884							░	884	884						░
885	885	885			■	🟥	░	885		885			■	🟥	░
886							░	886							░
887							▒	887	887					▓	▒
888	888					▒	▒	888	888					░	▒
889	889	889				▒	▒	889							▒
890		890				▓	▒	890	890	890				▓	▒
891		891		■		▓	▒	891							▒
892	892	892		■		▓	▒	892							▒
893	893	893				▓	▒	893	893					▓	▒
894		894				▒	▒	894	894	894				▒	▒
895		895				🟥	▒	895	895					🟥	▒
896		896				▒	▒	896	896	896				▒	▒
897		897				▒	▒	897	897					▒	▒
898	898	898				▓	▒	898	898	898				▓	▒
899	899	899		■		▓	▒	899		899		■		▓	▒
900	900					▓	▒	900							▒
901							▒	901		901				▓	▒
902							▒	902							▒
903		903				▒	▒	903							▒
904	904					🟥	▒	904							▒
905							▒	905							▒
906							▒	906							▒
907							▒	907	907	907				▒	▒
908		908				🟥	▒	908		908				🟥	▒
909		909				▒	▒	909		909				▒	▒
910	910					▒	▒	910		910				▒	▒
911	911	911				🟥	▒	911		911				🟥	▒
912							▒	912		912				▒	▒
913							▒	913		913				▒	▒
914							▒	914		914				▒	▒
915		915				▒	▓	915	915	915				▒	▓
916	916	916				▒	▓	916	916	916				▒	▓
917	917	917				▒	▓	917	917	917				▒	▓
918	918	918				🟥	▓	918	918	918				🟥	▓
919	919	919				▒	▓	919	919	919				▒	▓
920	920					▒	▓	920	920	920				▒	▓
921							▓	921	921	921				▓	▓
922	922					▓	▓	922	922	922				▓	▓
923							▓	923	923	923				▓	▓
924	924	924				▓	▓	924	924	924				▓	▓
925	925	925					▓	925	925	925					▓
926							▓	926		926					▓
927		927		■			▓	927							▓
928	928	928	■	■	■	🟥	▓	928	928	928	■	■	■	🟥	▓
929	929					░	▓	929		929					▓
930							▓	930							▓
931							▓	931		931				░	▓
932							▓	932	932	932				▓	▓
933							▓	933							▓
934							▓	934							▓
935							▓	935							▓
936							▓	936	936	936				▓	▓
937							▓	937	937	937				▒	▓
938							▓	938	938	938				▒	▓
939							▓	939							▓
940							▓	940	940	940				▒	▓
941							▓	941	941	941				🟥	▓
942							▓	942	942	942				▒	▓
943							▓	943	943	943				▒	▓
944							▓	944	944	944				▒	▓
945							▓	945							▓

Figure 3.10: Geometry analysis of dredging and plowing locations after the peak in Augusts 2014 (peak discharge: 3270 m^3/s)

Note that the analysis is based on rkms with dredging activity and plowing activity. We do not take the dredging volume or amount of plowing activity per rkm into account.

We can use the geometry analyses in Appendix N.2 for investigating the relation between sediment management and measured LADs. Dredged rkms after discharge peaks at which LADs have been measured in the same month are shown in Table 3.1. The same is shown in Table 3.2 for plowed rkms. These graphs also show the amount of discharge peaks after which LADs have been measured at the dredged or plowed rkm and the geometrical characteristics of the rkm.

For determining these dredging and plowing locations we only take rkms into account where LADs were measured more than once to disregard coincidences. These dredging and plowing locations are from the period 2014-2018. In this period only one LAD per day is measured. We do not take the year 2019 into account, since more than one LAD location is stored per day in that year. This means that more dredged and plowed locations with measured LADs would be shown in 2019 even though the depth is not smaller at those extra locations. It would detract from the significance of the LAD locations if the year 2019 was included.

Table 3.1: Dredged rkms after discharge peaks with measured LADs in same month

rkm	times occurring	geometrical characteristic
870	3 ×	at a sharp bend
876	11 ×	at the end of a fixed layer and at a crossing
885	6 ×	at the end of a fixed layer and at a crossing
888	3 ×	at a gentle bend
889	2 ×	at a gentle bend
918	2 ×	at a crossing
919	2 ×	at a gentle bend
925	2 ×	on a fixed layer (and in 1 case a widening winter bed)
928	12 ×	at the end of a fixed layer and at a crossing (and in 3 cases a widening winter bed)

Table 3.2: Plowed rkms after discharge peaks with measured LADs in same month

rkm	times occurring	geometrical characteristic
876	7 ×	at the end of a fixed layer and at a crossing
885	2 ×	at the end of a fixed layer and at a crossing
888	3 ×	at a gentle bend
925	2 ×	on a fixed layer (and in 1 case a widening winter bed)
928	11 ×	at the end of a fixed layer and at a crossing (and in 3 cases a widening winter bed)
937	2 ×	at a gentle bend

It follows from Table 3.1 that the rkms 876, 885 and 928 have the most overlap between measured LADs and dredging. It follows from Table 3.2 that the rkms rkms 876 and 928 have the most overlap between measured LADs and plowing. These results are for a large part in agreement with the hotspots as indicated in Section 3.4, namely rkm 876, 885 and 928 for dredging and rkm 928 for plowing.

These results show that at rkms with a large dredging volume or large plowing activity more often LADs are measured, although it followed from the analysis in Section 3.5 that there is no relation between the amount of measured LADs and the subsequent dredging volume. An explanation for these contradicting results could be that only the dredging and plowing directly after discharge peaks are regarded in this geometry analysis. The analysis in Section 3.5 takes all months into account.

Table 3.3 and 3.4 show statistical results about the dredged and plowed hotspots that follow from the geometry analysis. By using these statistical results, we obtain more insight in the relation between the locations of the hotspots and the geometrical characteristics of the river. These tables are constructed as indicated below.

- The first column shows the geometrical characteristics along the Waal.
- The second column shows what percentage of the dredged or plowed rkms have the geometrical characteristics as shown in the first column averaged over all discharge peaks.
- The third column shows what percentage of the dredged or plowed rkms have the geometrical characteristics as shown in the first column averaged over the peak discharges of 3000-4000 m^3/s.
- The fourth column shows what percentage of the dredged or plowed rkms have the geometrical characteristics as shown in the first column averaged over the peak discharges of 4000-5000 m^3/s.
- The fifth column shows what percentage of the dredged or plowed rkms have the geometrical characteristics as shown in the first column averaged over the peak discharges of 5000 m^3/s and up.

Note that in the last row of Table 3.3 and 3.4 we only take the dredged or plowed hotspots with measured LADs into account for the period 2014-2018. Since in 2019 more than one LAD location is stored per day, including this year would detract from the significance of the LAD locations. Another important thing to note is that data is missing for some months, as explained in Section 2.7. Also in some cases no data is left in the remainder of the month of the discharge peak (the M0 month). This can for instance happen if the discharge peak occured late in that month. As a result no (or too little) information is available for several months, as can be seen in Appendix N.2. Months that contain no information are not taken into account in Table 3.3 and 3.4. Partly because of this only two peaks with a discharge of 4000-5000 m^3/s have useful information. Also only three peaks larger than 5000 m^3/s have useful information for dredging and only one peak larger than 5000 m^3/s has useful information for plowing. This makes the results in the fourth and fifth column not very reliable.

Table 3.3: Dredging statistics for hotspots (rkm 876, 885 and 928) from geometry analysis

Geometrical characteristic	Percentage of dredged rkms (average of all peaks)	Percentage of dredged rkms (average of peaks 3000-4000 m^3/s)	Percentage of dredged rkms (average of peaks 4000-5000 m^3/s)	Percentage of dredged rkms (average of peaks 5000- m^3/s)
Sharp bend	0%	0%	0%	0%
Gentle bend	0%	0%	0%	0%
Crossing	100%	100%	100%	100%
Straight	0%	0%	0%	0%
End of fixed layer	100% (88% of all rkms with fixed layer is dredged)	100% (95% of all rkms with fixed layer is dredged)	100% (84% of all rkms with fixed layer is dredged)	100% (67% of all rkms with fixed layer is dredged)
Widening winter bed	11% (5% of all rkms with widening winter bed is dredged)	0% (7% of all rkms with widening winter bed is dredged)	0% (0% of all rkms with widening winter bed is dredged)	0% (0% of all rkms with widening winter bed is dredged)
Rkms with measured LADs	77% (57% of all rkms with measured LADs is dredged)	86% (61% of all rkms with measured LADs is dredged)	34% (50% of all rkms with measured LADs is dredged)	67% (33% of all rkms with measured LADs is dredged)

Table 3.4: Plowing statistics for hotspots (rkm 928) from geometry analysis

Geometrical characteristic	Percentage of plowed rkms (average of all peaks)	Percentage of plowed rkms (average of peaks 3000-4000 m^3/s)	Percentage of plowed rkms (average of peaks 4000-5000 m^3/s)	Percentage of plowed rkms (average of peaks 5000- m^3/s)
Sharp bend	0%	0%	0%	0%
Gentle bend	0%	0%	0%	0%
Crossing	100%	100%	100%	100%
Straight	0%	0%	0%	0%
End of fixed layer	100% (33% of all rkms with fixed layer is plowed)	100% (33% of all rkms with fixed layer is plowed)	100% (33% of all rkms with fixed layer is plowed)	100% (33% of all rkms with fixed layer is plowed)
Widening winter bed	27% (5% of all rkms with widening winter bed is plowed)	33% (7% of all rkms with widening winter bed is plowed)	0% (0% of all rkms with widening winter bed is plowed)	0% (0% of all rkms with widening winter bed is plowed)
Rkms with measured LADs	93% (26% of all rkms with measured LADs is plowed)	100% (27% of all rkms with measured LADs is plowed)	50% (25% of all rkms with measured LADs is plowed)	100% (17% of all rkms with measured LADs is plowed)

We draw four conclusions from Table 3.3 and 3.4, which are elaborated below.

Firstly, the hotspots at rkms 876, 885 and 928 are all situated at the end of one of the fixed layers along the Waal. These are structures on the bed in outer bends meant to increase the navigation width. Three of these structures are present in the Waal, namely submerged bendway weirs at the bend of Erlecom, a fixed bed at the bend near Nijmegen and a fixed bed at the bend near St. Andries. The submerged bendway weirs in the bend near Erlecom ends in rkm 876, the fixed bed near Nijmegen ends in rkm 885 and the fixed bed near St. Andries ends in rkm 928.

We expect that the reason for the large dredging volumes and plowing activity at the end of these fixed layers is the following. In river bends sediment is transported from the outer bend to the inner bend due to the helical flow pattern that occurs in bends (this principle is further explained in Section 4.2). The fixed layers and submerged bendway weirs have been constructed with the goal of reducing the amount of sediment being eroded at the outer bend and thus the amount of sediment being transported from the outside to the inside of the bend. This results in less accretion at the inner bend and thus a wider navigation channel. However, at the end of these fixed layers a large erosion pit occurs at the outside of the bend and a large bar occurs at the inside of the bend (White and Blom, 2020). Sediment transport in downstream direction mainly occurs at the inside of the fixed layer, where the bed is not fixed. The sediment transported over the fixed layer is forced toward the inner bend due to the helical flow pattern where it is further transported in downstream direction (White and Blom, 2020). This has as a result that there is no sediment supply in the outer bend at the downstream end of the fixed layer, which means that the sediment load is below the transport capacity. Thus a large erosion pit occurs. We expect that the sediment transported from this erosion pit towards the inner bend due to the helical flow pattern is the main reason for the accretion at the inner bend. Also the sediment being suppied at the inner bend probably contributes to the accretion. The accretion at the inner bend is the reason for large dredging volumes and plowing activity (Figure I.1 in Appendix I shows that dredging at St. Andries mainly takes place at the inner bend downstream of the fixed layer).

We concluded in Section 3.4 that dredging volumes and plowing activity are larger at rkm 928 than at rkm 876 and 885. This is probably due to the downstream effects being larger at the end of the fixed layer at St. Andries. This in turn is probably due to the fixed layer at St. Andries being longer and more stable (White and Blom, 2020).

Secondly, we conclude from Table 3.3 and 3.4 that according to the analysis all hotspots are situated at a crossing between bends as well. The reason for the hotspots being located at crossings is probably that the submerged bendway weirs and fixed layers are located in sharp bends and logically end where the bend ends as well, which is often a crossing. The morphology at the hotspots is probably not as much influenced by the fact that they are situated at crossing between bends than the fact that the hotspots are all situated at the end of a fixed layer but it probably contributes to accretion at these rkms, since the bar at the inside of the bend crosses the river at a crossing.

Thirdly, at some discharge regimes the hotspot at rkm 928 is situated at a widening winter bed. At other discharge regimes this is not the case. Rkm 928 is being dredged and plowed after almost all discharge peaks, regardless of the peak discharge. It thus seems that the shape of the winter bed has not as much influence on dredging and plowing at this location as the fixed layer has.

Fourthly, a large percentange of the dredged or plowed hotspots show measured LADs in that same rkm and month (especially for plowing). This is in accordance with the earlier conclusion that more often LADs are measured at locations with large dredging volumes or a large plowing activity.

4

The influence of the geometry and the hydrograph on sediment management

4.1. Chapter introduction

In this chapter we first place the earlier obtained results about sediment management in context of the river geometry in Section 4.2. Subsequently, we treat the influence of the variability of the hydrograph on dredging volumes and plowing activity in Section 4.3. This section is divided into subsections. Firstly, in Subsection 4.3.1 we investigate the relation of dredging volumes and plowing activity with discharge peaks. Subsequently, we investigate the relation of sediment management at hotspots with sediment management at the other locations along the Waal in Subsection 4.3.2. Then, in Subsection 4.3.3 we investigate the relation of the interval between dredging activities with discharge peaks. Until here only the influence of discharge peaks on sediment management are regarded. Therefore, we investigate the relation of dredging volumes and plowing activity with the monthly river discharge (over all months with available data, instead of only regarding the discharge peaks) in Subsection 4.3.4.

4.2. The geometry of the river

Conditions like the river discharge and the river geometry are continuously changing. This also means that the morphological response of the river is very dynamic, because it tries to find an equilibrium between these changing influences (Reneerkens, 2020). Two types of morphological phenomena are distinguised in the context of this research (Klaassen and Sloff, 2000):

- Stationary phenomena that are mainly determined by the geometry of the main channel, like bends and crossing between bends.
- Non-stationary phenomena which propagate through the river, like dunes moving in downstream direction over the river bed.

Stationary phenomena are non-migrating bars that usually occur at river bends. In river bends, the difference in centripedal acceleration between the inner and outer bend results in a larger water level in the outer bend than in the inner bend. The difference in hydrostatic pressure between the outer and inner bend results in a helical flow pattern where water moves toward the outer bend near the surface and water moves toward the inner bend near the bed. The flow near the bed couses sediment transport from the outer bend towards the inner bend, which has a bar at the inner bend as a result. See Figure 4.1 for a visualisation of this principle. When two bends (which go in a different direction) follow each other up, the bars at both inner bends are located on different sides of the river and can 'connect' to each other by crossing the river. This results in a bar in the middle of the river at the crossing between the two bends.

Non-stationary phenomena are bed forms that propagate downstream. Dunes propagate because of erosion at the stoss side of the dune and the accretion at the lee side of the dune. Sediment erodes at the stoss side, is then transported over the crest of the dune and then settles at the lee side due to the relative slow flow

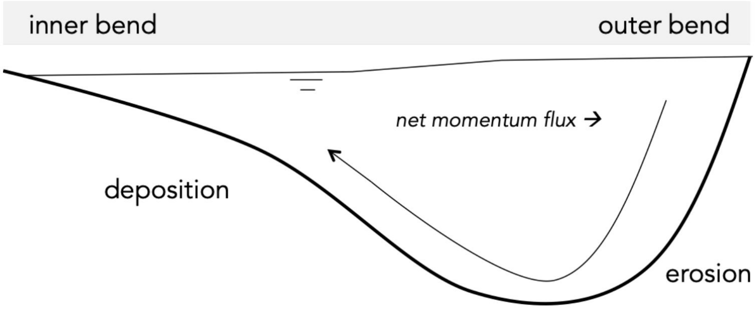


Figure 4.1: Visualisation of the flow around a river bend (White and Blom, 2020)

of the eddy behind the dune. See Figure 4.2 for a visualisation of this principle. How dunes are initiated is treated in Appendix M. The adaptation period of non-stationary phenomena to new river conditions is much shorter than for the stationary phenomena.

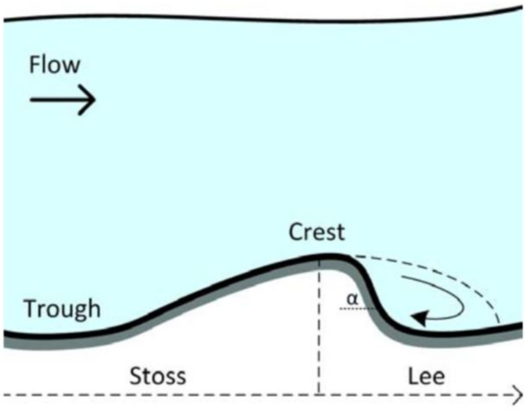


Figure 4.2: Visualisation of the flow over a dune (Naqshband, 2014)

Based on the morphological phenomena treated earlier in this section, we can subdivide the Waal into three reaches (see Figure 3.1). The defined reaches are elaborated below.

- The ’Boven-Waal’ or Upper Waal. This reach starts at Pannerdensche Kop and ends just after the fixed bed at Nijmegen. The Upper Waal is characterized by relatively sharp bends. Therefore the morphology is mostly governed by stationary phenomena. The Upper Waal is subject to structural erosion of the bed.
- The ’Midden-Waal’ or Middle Waal. This reach starts at Nijmegen and ends at Tiel. The Middle Waal is relatively straight and the morphology is mostly governed by non-stationary phenomena. Because the river is relatively straight and contains less sharp bends here, less sedimentation occurs on the inside of bends and at crossings. Dunes are therefore free to propagate here. Just as the Upper Waal, the Middle Waal is subject to structural erosion of the bed.
- The ’Beneden-Waal’ or Lower Waal. This reach starts at Tiel and ends at Woudrichem. The Lower Waal contains two sharp bends at St. Andries and Opijnen and it contains some smaller gentle bends. The morphology is therefore governed by both stationary and non-stationary phenomena. This reach of the Waal is subjected more to back water effects from the sea than the other two reaches which gives it a larger water depth. Unlike the Upper Waal and the Middle Waal, the Lower Waal is not subject to structural erosion of the bed.

Figure 4.3 shows a part of the Upper Waal near Bemmelse Waard. It can be seen that there are no large dunes here. The bed is governed by stationary phenomena. Because of the helical flow patern in the bend, the outer bend is relatively deep and the inner bend relatively shallow. A shadow effect has been used to emphasize the shapes of the bed so no useful colorbar about bed levels can be added.

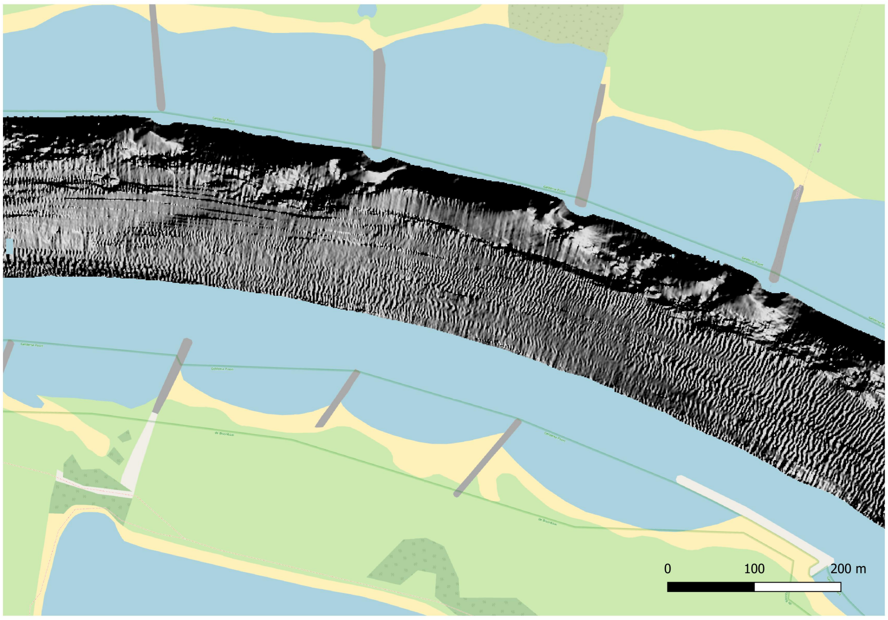


Figure 4.3: The bed level in the bend near Bemmelse Waard in the Upper Waal (Multibeam measurement taken at 10 March 2018)

Figure 4.4 shows a part of the Middle Waal near Ochtensche Waard. There are large dunes visible here and no stationary phenomena due to bends.

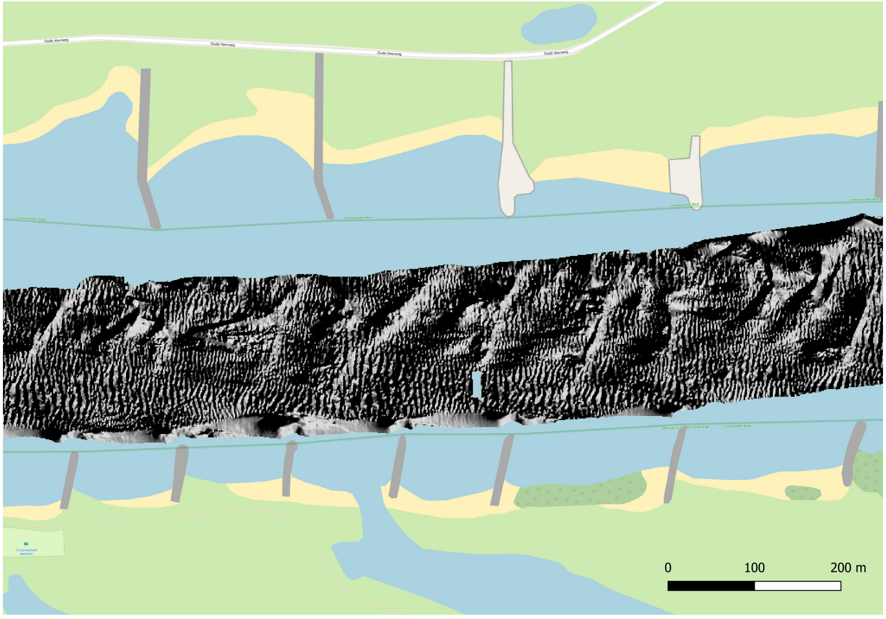


Figure 4.4: The bed level near Ochtensche Waard Waard in the Middle Waal (multibeam measurement taken at 14 March 2018)

Figure 4.5 shows a part of the Lower Waal (in the bend near Opijnen). There are large dunes visible here but these have a smaller wavelength than in the Middle Waal. Due to stationary phenomena the deepest parts occur in the outer bend and the most shallow parts occur in the inner bend.

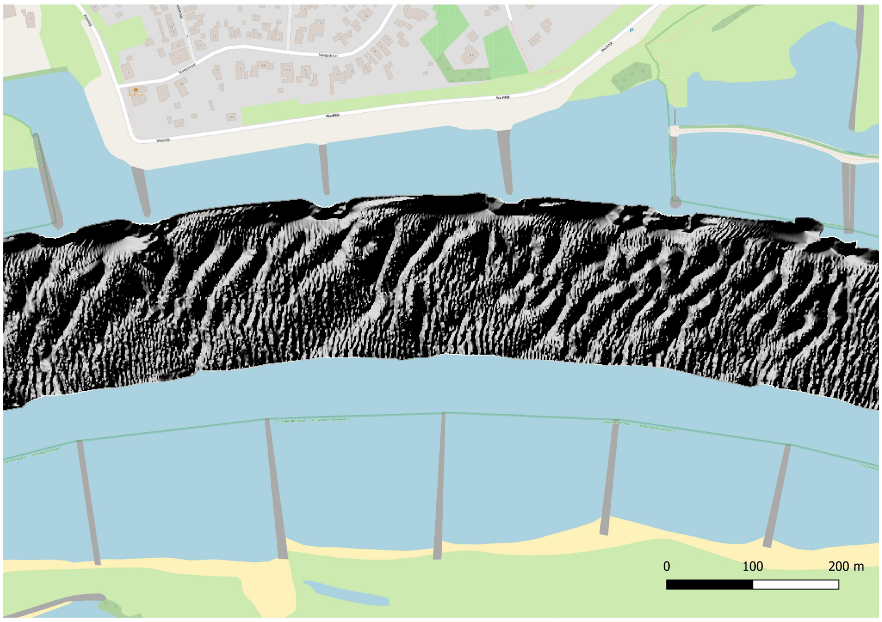


Figure 4.5: The bed level in the bend near Opijnen in the Lower Waal (multibeam measurement taken at 13 March 2018)

Based on the above treated theory, we hypothesise (as already mentioned in Chapter 1) that the largest dredging volumes are required at sharp bends and at crossings between sharp bends, which are mainly situated in the Upper Waal. We expect this because dredging is used for stationary phenomena. Plowing activity is expected to be less concentrated at sharp bends and to be more spread across the three reaches of the Waal. We expect this because plowing is used for non-stationary phenomena but also can be used to support the dredging vessel.

We try to substantiate the dredging and plowing locations along the Waal to test the above mentioned hypothesis. For this we use the geometry analysis as described in Section 3.6. Now we do not only show the statistics of dredged and plowed hotspots but the statistics of all dredged and plowed rkms. The statistical results about the dredging and plowing locations and the geometrical characteristics of those locations resulting from the geometry analysis are shown in Table 4.1 and 4.2.

Just as in Section 3.6 it needs to be noted that in the last row of Table 4.1 and 4.2 we only take the dredged or plowed hotspots with measured LADs into account for the period 2014-2018, since in 2019 more than one LAD location is stored per day. Again it is also important to note that not much data is available in the months after very high discharge peaks, which makes the results in the fourth and fifth column not very reliable.

Table 4.1: Dredging statistics from geometry analysis

Location on the Waal	Percentage of dredged rkms (average of all peaks)	Percentage of dredged rkms (average of peaks 3000-4000 m^3/s)	Percentage of dredged rkms (average of peaks 4000-5000 m^3/s)	Percentage of dredged rkms (average of peaks 5000- m^3/s)
Upper Waal	29%	30%	28%	22%
Middle Waal	39%	38%	47%	38%
Lower Waal	32%	31%	26%	40%
Sharp bend	16%	15%	22%	17%
Gentle bend	28%	28%	26%	33%
Crossing	37%	42%	28%	23%
Straight	20%	19%	24%	22%
End of fixed layer	17% (88% of all rkms with fixed layer is dredged)	21% (95% of all rkms with fixed layer is dredged)	9% (84% of all rkms with fixed layer is dredged)	8% (67% of all rkms with fixed layer is dredged)
Widening winter bed	20% (39% of all rkms with widening winter bed is dredged)	13% (38% of all rkms with widening winter bed is dredged)	37% (44% of all rkms with widening winter bed is dredged)	39% (41% of all rkms with widening winter bed is dredged)
Rkms with measured LADs	26% (80% of all rkms with measured LADs is dredged)	29% (83% of all rkms with measured LADs is dredged)	6% (67% of all rkms with measured LADs is dredged)	35% (79% of all rkms with measured LADs is dredged)

Table 4.2: Plowing statistics from geometry analysis

Location on the Waal	Percentage of plowed rkms (average of all peaks)	Percentage of plowed rkms (average of peaks 3000-4000 m^3/s)	Percentage of plowed rkms (average of peaks 4000-5000 m^3/s)	Percentage of plowed rkms (average of peaks 5000- m^3/s)
Upper Waal	11%	12%	10%	13%
Middle Waal	29%	27%	36%	33%
Lower Waal	60%	62%	55%	54%
Sharp bend	12%	12%	13%	13%
Gentle bend	40%	39%	45%	40%
Crossing	19%	19%	19%	17%
Straight	22%	23%	18%	21%
End of fixed layer	7% (64% of all rkms with fixed layer is plowed)	7% (64% of all rkms with fixed layer is plowed)	5% (67% of all rkms with fixed layer is plowed)	4% (67% of all rkms with fixed layer is plowed)
Widening winter bed	19% (46% of all rkms with widening winter bed is plowed)	16% (41% of all rkms with widening winter bed is plowed)	34% (63% of all rkms with widening winter bed is plowed)	33% (74% of all rkms with widening winter bed is plowed)
Rkms with measured LADs	9% (65% of all rkms with measured LADs is plowed)	9% (60% of all rkms with measured LADs is plowed)	5% (84% of all rkms with measured LADs is plowed)	10% (83% of all rkms with measured LADs is plowed)

From Table 4.1 and 4.2 we can conclude seven things, which are elaborated below.

Firstly, approximately the same amount of dredging takes place in the Upper Waal, Middle Waal and Lower Waal. Since the Upper Waal is quite a bit shorter than the Middle Waal and the Lower Waal (see Figure 3.1), dredging is more prominent in the Upper Waal relative to the other reaches. This is probably due to the morphology being mostly governed by stationary phenomena in the Upper Waal and two of the three dredging hotspots being located in the Upper Waal. When the discharge peak becomes large, less dredging takes place in the Upper Waal and dredging shifts more toward the Middle and Lower Waal. According to the contractor dredging shifts relatively more from hotspots towards other locations along the Waal after large discharge peaks (see Section 3.3). Since two of the three dredging hotspots are located in the Upper Waal it makes sense that when relatively less is dredged at these two hotspots, relatively more dredging takes place at the other reaches.

Secondly, the largest amount of plowing takes place on the Lower Waal. This is probably due to the plowing hotspot being located in the Lower Waal. When the discharge peak becomes large, slightly less plowing takes place on the Lower Waal and plowing shifts more toward the Middle Waal. Since the plowing hotspot is located in the Lower Waal it makes sense that when relatively less is plowed at this hotspot, relatively more plowing takes place at the other reaches. In the Upper Waal plowing activity never becomes very large, since the morphology there is not goverened by non-stationary phenomena contrary to the Middle and Lower Waal.

Thirdly, most dredging takes place on crossings between bends. A likely explanation for this is that dredging is mainly used for stationary-phenomena, which occur at bends and at the crossings between bends. Also the fact that all three dredging hotspots are located at a crossing will contribute to this result. When the discharge peak becomes large, less dredging takes place on these crossings, which seems to confirm that most dredging at crossings is due to the hotspots.

Fourthly, most plowing takes place in gentle bends. A likely explanation for this is that plowing is mostly used at non-stationary phenomena which occur on the Middle and Lower Waal, where a lot of gentle bends are present.

Then, an important thing that follows from this analyis is that when the discharge peak increases (from 4000 m^3/s and up), relatively less dredging takes place at the locations at the end of fixed layers, which are the locations of the hotspots. The same applies to lesser extend for plowing. This agrees with the statement of the contractor that dredging after discharge peaks temporarily deviates from the hotspots. The reason for sediment management shifting away from hotspots after large peaks is that hotspots are dredged (and plowed) preventively with the goal of keeping the bed level from exceeding the reference plane after discharge peaks. This is usually not done at other locations so the bed level at these other locations can exceed the reference plane after large peaks. Lowering of the bed at these locations becomes necessary so the hotspots are temporarily not dredged (and plowed). The fact that only one dredging vessel and one plowing vessel are used contributes to this.

Next, it follows from the analysis that the amount of dredged and plowed rkms at locations with a widening winter bed increases when the discharge peak becomes large. This probably happens because the shape of the conveying bed starts to show more widening and narrowing locations as more flood plains start to convey water. When the river is below bankfull there are almost no widening and narrowing locations along the Waal. As discussed in Section 3.6 the effect of a widening bed is usually sedimentation just downstream of the location where the bed widens due to the deceleration of the flow.

Lastly, Relitevely more LADs are measured per dredged rkm than per plowed rkm. This is probably due to the fact that because overall more rkms are being plowed than dredged (see the geometry analyses in Appendix N.2), the percentage of rkms with measured LADs is lower for the plowed rkms.

4.3. The influence of the hydrograph on dredging volumes

4.3.1. The relation of dredging volumes and plowing activity with discharge peaks

The statements by the contractor (see Section 3.3) suggest that dredging volumes and plowing activity increase after river discharge peaks. This leads to the following three hypotheses (as already mentioned in Chapter 1):

- When the peak discharge increases, the dredging and plowing effort after the peak is expected to increase as well. This is expected because the difference in equilibrium depth between the peak discharge situation and the regular discharge situation increases as the peak discharge increases.
- When the length of the discharge peak increases, the dredging and plowing effort after the peak is expected to increase as well. This is expected because the time for the bed to adapt to the equilibrium depth of the peak discharge situation increases.
- When the rate at which the discharge falls after the peak increases, the dredging and plowing effort after the peak is expected to increase. This is expected because the time for the bed to slowly adapt again to the original equilibrium depth during falling discharge decreases.

We test these hypotheses by plotting the characteristics of discharge peaks (the peak discharge, the length of the discharge peak and the decrease rate) against the dredging volumes in the subsequent period of time. We do this also for the plowing activity following the discharge peaks. Just as for the geometry analysis, we define the discharge peaks as peaks with a discharge larger than 3000 m^3/s that are significantly higher than the preceding and subsequent discharge (at least 1500-2000 m^3/s larger) and which are not clearly part of a larger peak. See Appendix L for a list of the discharge peaks.

We define the dredging volume as the total dredging volume (taken over the whole Waal) in the month subsequent to the one in which the discharge peak occurred. We define the plowing activity as the total amount of sail tracks with a plowing activity (taken over the whole Waal) in the month subsequent to the one in which the discharge peak occured. This has as a negative consequence that when a discharge peak occurs late in a month, the dredging volumes and plowing activity are regarded earlier after the peak than when a discharge peak occurs early in a month.

We use the dredging volumes from the BRW data since these produce the most reliable and complete total dredging volumes. There are however some months for which the BRW data is missing. Since we consider the total dredging volumes over the Waal, these months can be filled in with dredging volumes from uncorrected sail tracks if these are available for that month. For the plowing activity no such thing is possible since only one data set is available. We only take peaks into account that are followed by a month for which dredging volumes and plowing activity are available. The amount of peaks considered for dredging volumes and plowing activity differs for this reason.

The results are depicted in scatter plots. In these plots we show the influence of an increasing discharge peak (being an increasing height of the peak, an increasing length or and an increasing decrease rate) on the subsequent dredging volumes and plowing activity. The response to the maximum discharge of each peak is shown in Figure 4.6 for the dredging volumes and in Figure 4.7 for the plowing activity. The response of dredging and plowing to the duration of each peak and to the decrease rate of each peak can be found in Appendix O.1. In Appendix O.1 also the response of dredging and plowing to two different definitions of peak discharges are shown. These definitions are discharge peaks with a peak larger than 4000 m^3/s and the relative peak height (which is the peak discharge compared to the low discharge that follows the peak). We plot a least squares regression line through the points. Since we expect a positive relation between an increasing discharge peak and the dredging volume or plowing activity in the subsequent calendar month, we expect an upward regression of the dots in the scatter plots.

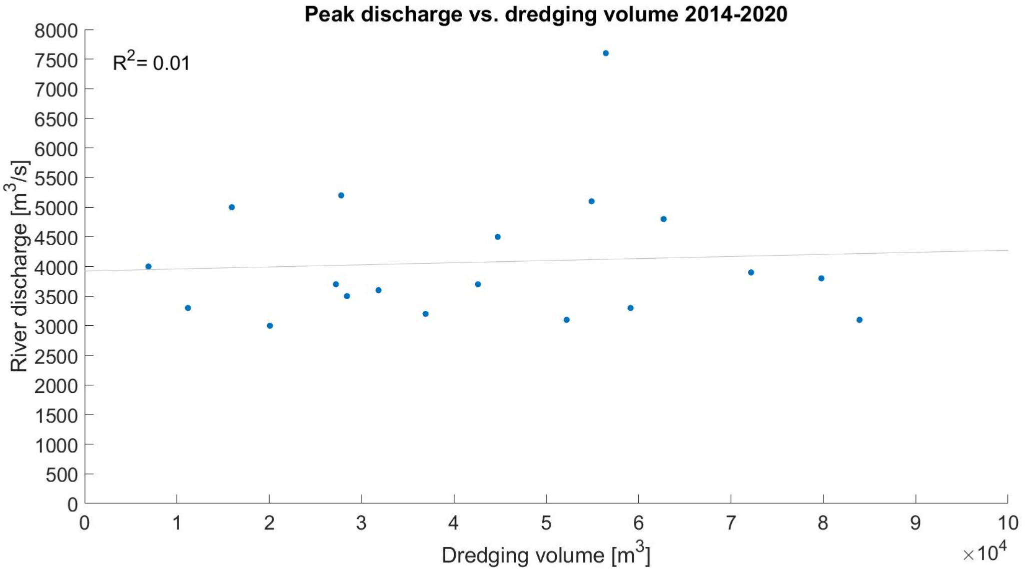


Figure 4.6: Scatter plot of peak discharge against dredging volume in the subsequent month

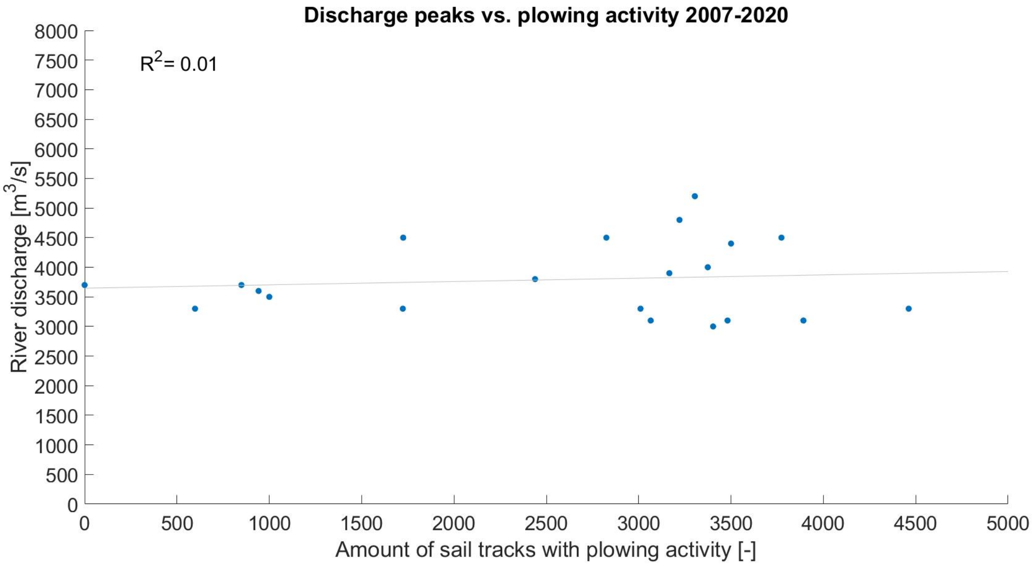


Figure 4.7: Scatter plot of peak discharge against plowing activity in the subsequent month

We conclude is that there is a large scatter. This means that a large variation of dredging volumes and plowing activity are identified for the same order of peak discharge, peak length or decrease rate. This is reflected by the coefficient of determination (R^2) which is in all plots close to 0. The discharge peaks larger than 4000 m^3/s plotted against the dredging volume (Figure O.13 in Appendix O.1) shows a significantly larger coefficient of determination (R^2 = 0.22) but it is still small. We can also conclude that the regression line is almost horizontal and no clear clusters can be distinguished.

The results show hardly any relation between the dredging volumes or plowing activity and the size of the discharge peaks, which contradicts the hypothesis. This could be due to the method of using dredging volumes and plowing activity per calendar month. As already mentioned, when a discharge peak occurs late in a month, the dredging volumes and plowing activity are regarded earlier after the peak than when a discharge peak occurs early in a month.

A second reason for this could be that the data is not reliable enough. We earlier assumed that the months with available data are complete but this might not be the case. This could lead to an underestimation of the dredging volumes and plowing activity after certain discharge peaks.

A third reason could be that due to continuous preventing dredging and plowing the relation between discharge peaks and sediment management is distorted. As concluded in Section 4.2, certain hotspots are dredged or plowed preventively and thus rather independently from the hydrograph.

Preventive dredging happens mainly at rkm 876, 885 and 928 and preventive plowing happens mainly at rkm 928. Therefore, we investigate if a more accurate picture of the influence of the hydrograph on sediment management is obtained when we disregard dredging volumes and plowing activity at these hotspots. The results are shown in Figure 4.8 and 4.9 for the peak height. In Appendix O.2, the results are shown for the peak length and the decrease rate of the peak. Appendix O.1 also shows the same scatter plots for peaks larger than 4000 m^3/s and the relative peak height.

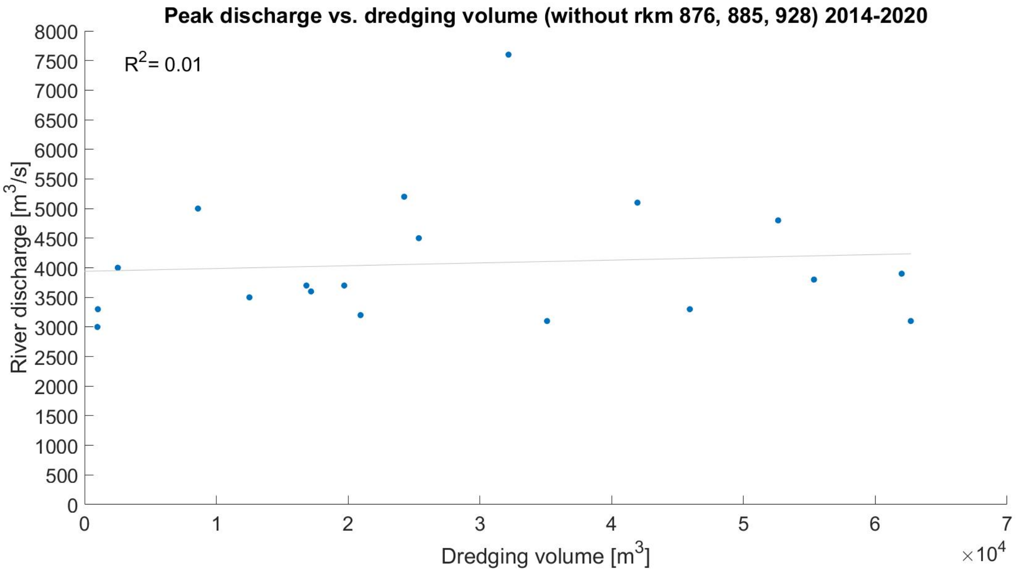


Figure 4.8: Scatter plot of peak discharge against dredging volume in the subsequent month (without rkm 876, 885 and 928 taken into account)

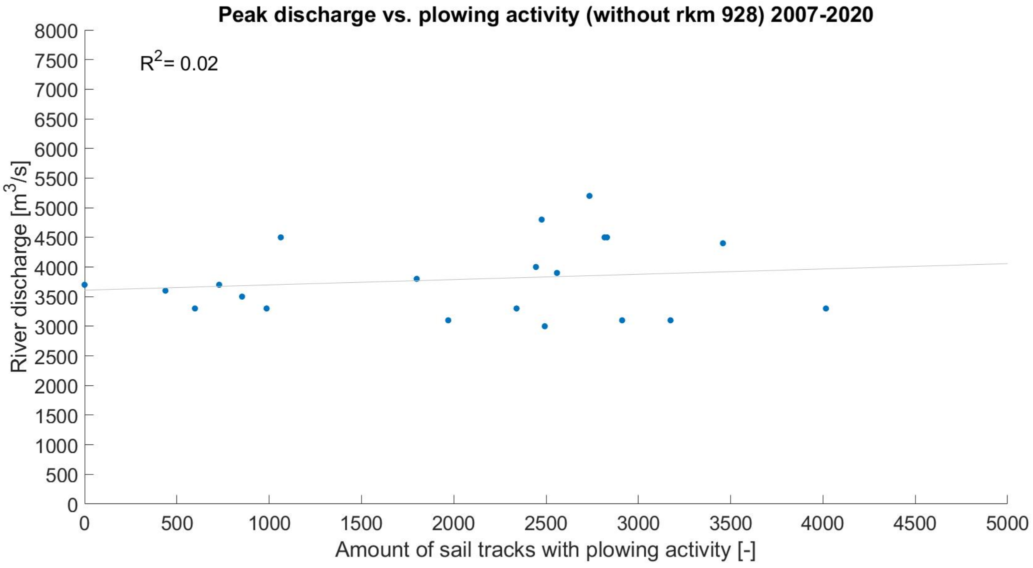


Figure 4.9: Scatter plot of peak discharge against plowing activity in the subsequent month (without rkm 928 taken into account)

We observe that the dredging volumes and plowing activity have become smaller. However, there again is a large scatter which is reflected in the coefficient of determination (R^2 is close to 0). We can also distinguish no clear clusters. The conclusion is that, although locations with continuous dredging or plowing are disregarded, the results still show hardly any relation between the dredging volumes or plowing activity and the size of the discharge peaks. This contradicts the hypothesis.

Just as before, this could be due to the method of using dredging volumes and plowing activity per calendar month and again, this could also be due to the data being not complete enough. Another reason for the scatter plots still not showing any relation could be that we only define rkm 876, 885 and 928 as hotspots. These rkms are defined as hotspots because they are most aparent in the data. The contractor however defines more hotspots which are still distinguisable in the data. The results could therefore still be distorted by continuous dredging and plowing at certain locations.

4.3.2. The relation of sediment management at hotspots with sediment management at the other locations along the Waal

We further investigate the influence of disregarding the locations with a continuous dredging or plowing effort. We do this by plotting the remaining percentage of the dredging volume after rkm 876, 885 and 928 are disregarded and the plowing activity after rkm 928 is disregarded for each discharge peak. Figure 4.10 and 4.11 show the results for the dredging volumes and plowing activity in the first month after the discharge peak.

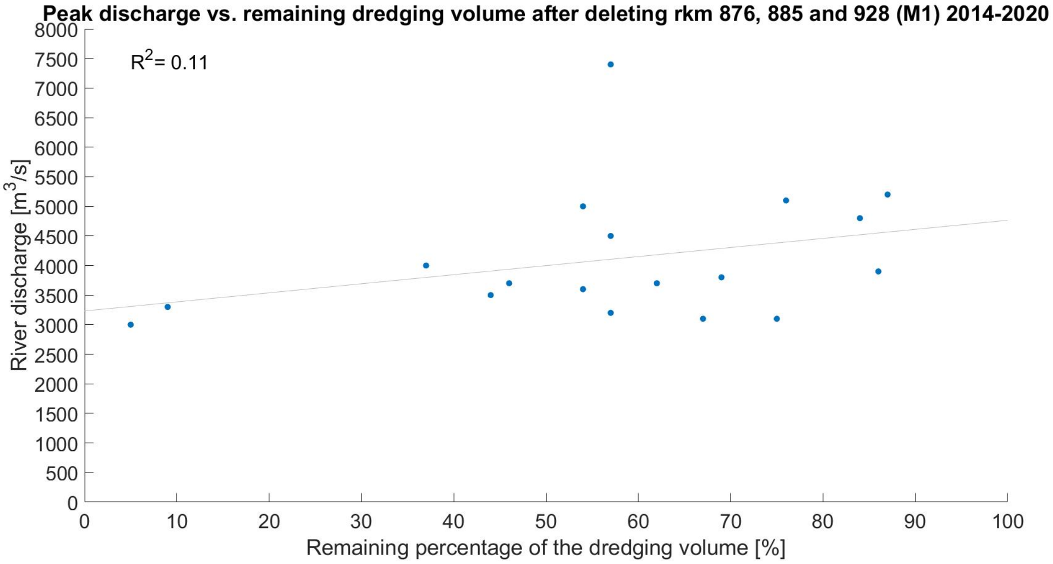


Figure 4.10: Scatter plot of peak discharge against dredging volume in the subsequent month (without rkm 876, 885 and 928 taken into account)

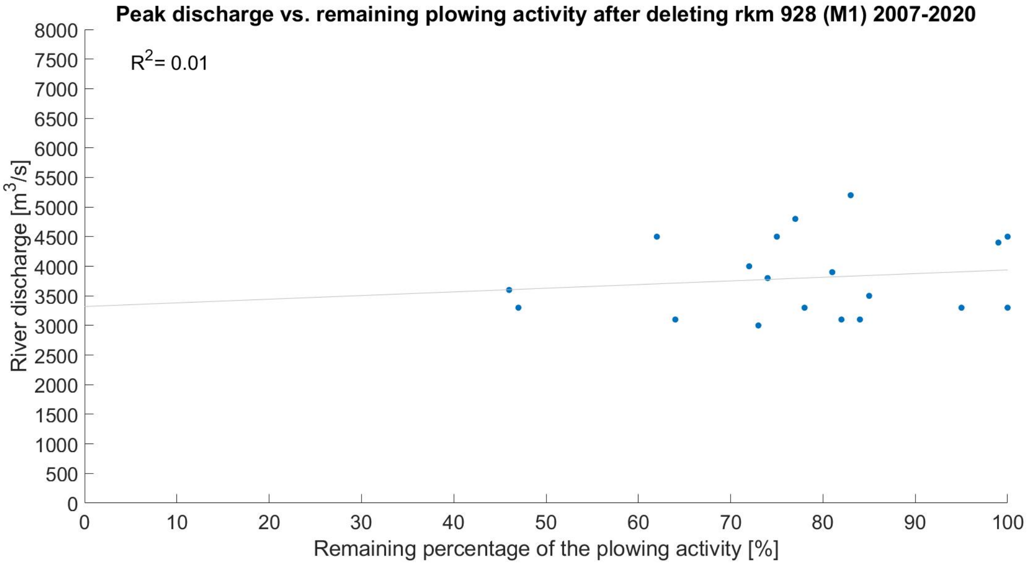


Figure 4.11: Scatter plot of peak discharge against plowing activity in the subsequent month (without rkm 928 taken into account)

It follows from these plots that for dredging the majority of the dots are situated above approximately 40% and for plowing the majority of the dots are situated above approximately 60%. This means that in the first month after discharge peaks up to approximately 60% of the dredging is done at the rkms 876, 885 and 928 and up to approximately 40% of the plowing is done at the rkm 928. We can conclude that after peaks a large part of the dredging volumes and plowing activity can be attributed to the hotspots. However, after most peaks this is less than half of the total dredging volume or plowing activity along the Waal.

To check if this remaining percentage after discharge peaks is overall larger or lower than usual, we compare the results with a situation in which there is probably no relation between the discharge peaks and the dredging volumes or plowing activity. We do this by regarding the dredging volumes and plowing activiy in the second month after the peak (referred to as M2) instead of the first month after the peak (referred to as M1). See Figure 4.12 and 4.13 for the results.

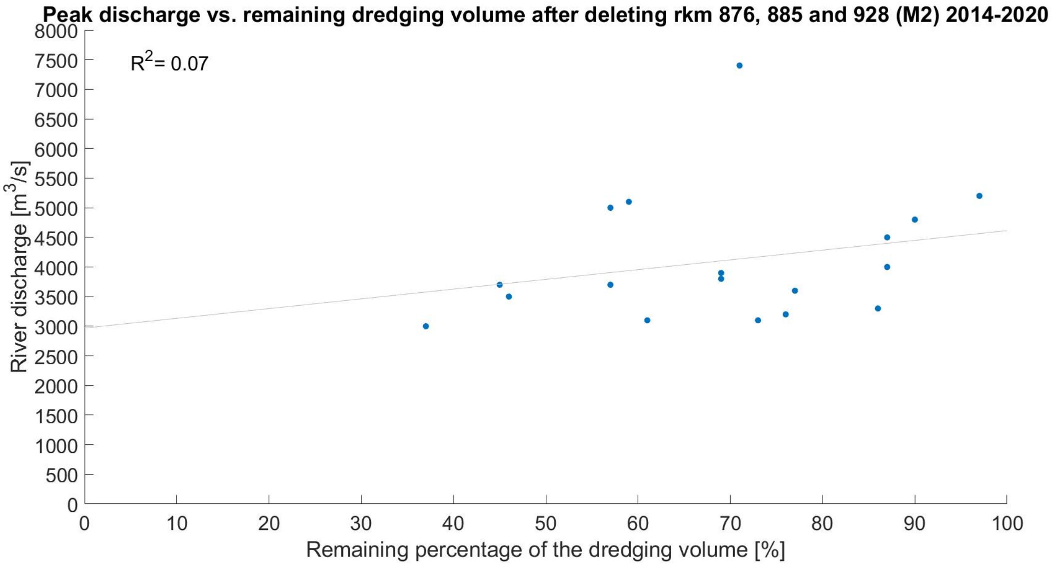


Figure 4.12: Scatter plot of peak discharge against the remaining dredging volume in the second month after the peak (after disregarding rkm 876, 885, 928)

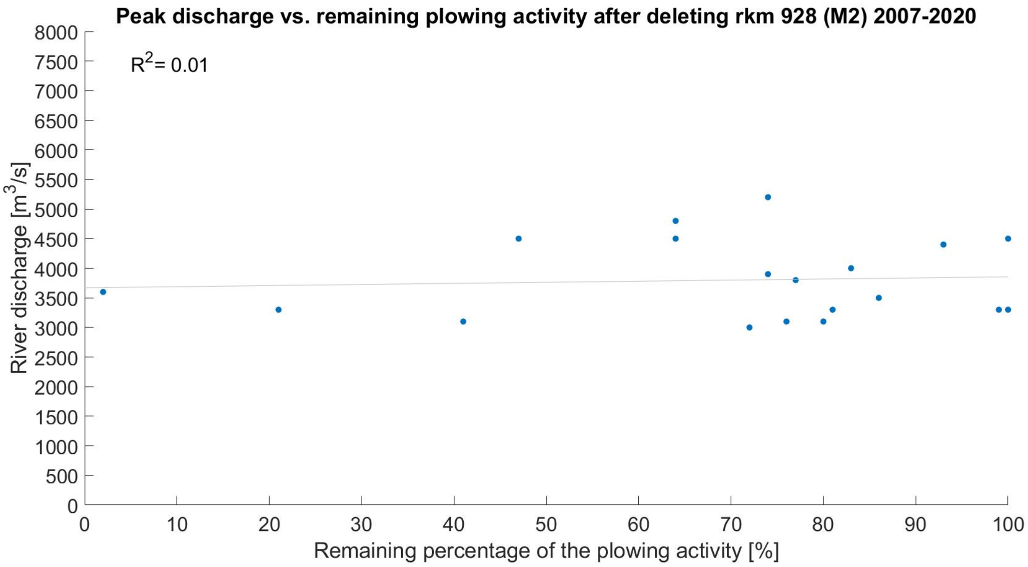


Figure 4.13: Scatter plot of peak discharge against the remaining plowing activity in the second month after the peak (after disregarding rkm 928)

Although there is not much difference between the scatter plots regarding the first month (M1) and the scatter plots regarding the second month (M2) after the peak, we observe some slight differences between the M1 and M2 situation. The dots in the scatter plot of the dredging volumes in the M2 situation are shifted towards higher percentages when compared to the dredging volumes in the M1 situation. This means that relatively more dredging occurs outside of the hotspots after discharge peaks than usual, which agrees with the expectations. The dots in the scatter plot of the plowing activity in the M2 situation are shifted slightly towards lower percentages when compared to the plowing activity in the M1 situation. This means that relatively less plowing occurs outside of the hotspots after discharge peaks than usual, which contradicts the expectations.

A likely reason for the vague results that differ slightly from the expectations is probably that we take all peaks into account in the scatter plots. From Table 4.1 and 4.2 in Section 4.2 it followed that the shifts from the hotspots toward other dredging and plowing locations become more obvious at large peak discharges (4000 m^3/s and up) and are less clear at peaks of average height.

Another reason could be that we only define rkm 876, 885 and 928 as hotspots. The contractor however defines more hotspots which are still distinguisable in the data. The results might be clearer if the remaining percentages of the dredging volume and plowing activity were determined after disregarding all hotspots according to the contractor.

4.3.3. The relation of the interval between dredging activities with discharge peaks

The initial hypothesis that dredging effort increases after river discharge peaks might suggest that the time between dredging activities decreases after discharge peaks as well. However, because of preventive dredging at hotspots we expect that no significant change in the interval between dredging activities will occur after discharge peaks. We investigate this here.

We determine the average interval between dredging activities according to the BRW data per month. The results are shown in Figure 4.14 for the year 2017. The results for each year (from 2014 until 2020) can be found in Appendix P.1.

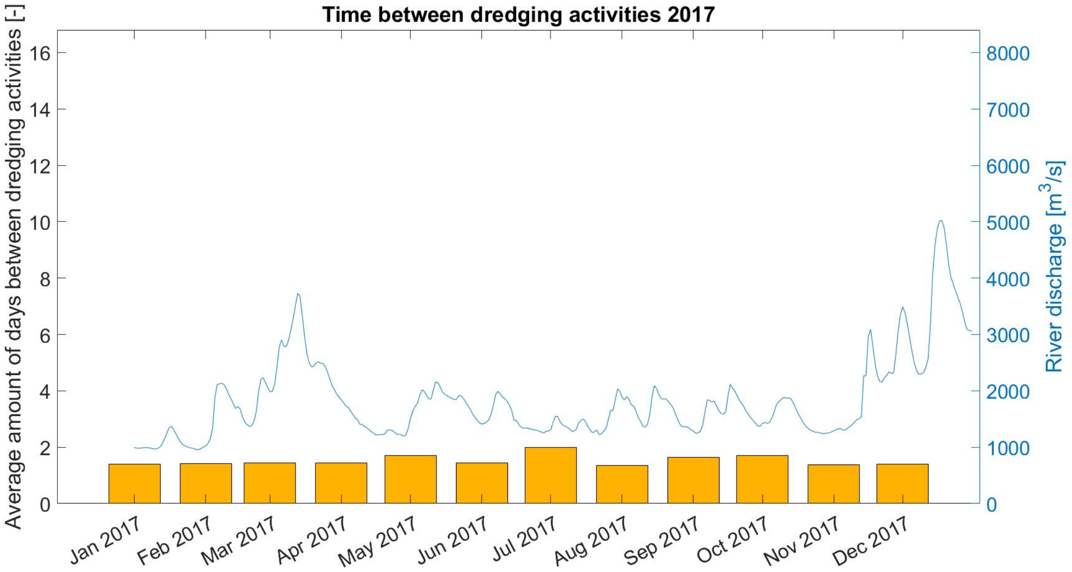


Figure 4.14: Average amount of days between dredging activities 2017

We conclude that the interval between dredging activities is quite stable and is usually 1 to 2 days. The results indicate that there is almost no influence of the hydrograph on the interval between dredging activities.

We plot the characteristics of the discharge peak (height, length and decrease rate) against the average interval between dredging activities in the first calendar month after the peak. The results for the peak discharge are shown in Figure 4.15. The results for the peak length, decrease rate and other definitions of the peak height (peaks larger than 4000 m^3/s and the relative peak height) are shown in Appendix P.2.

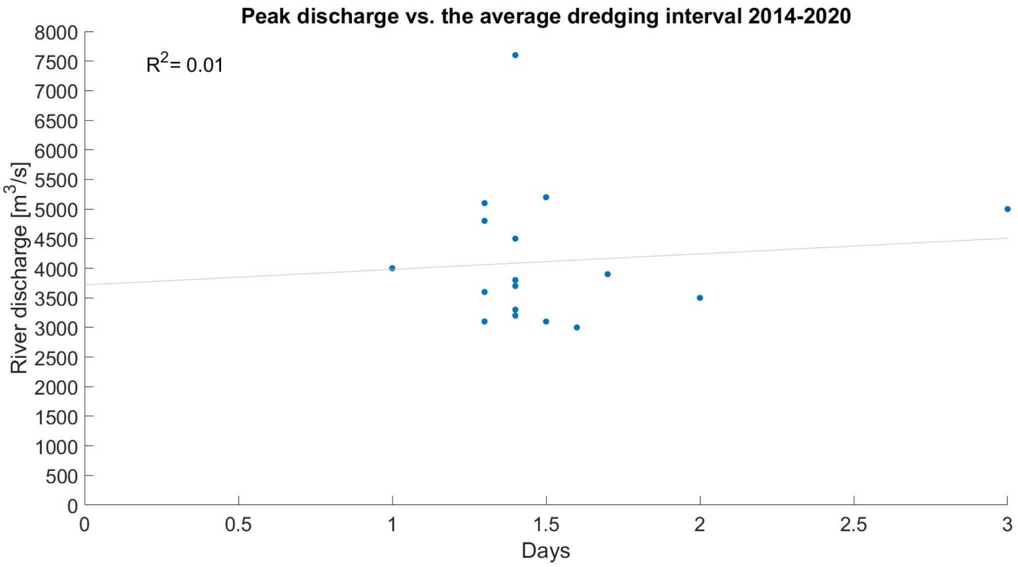


Figure 4.15: Scatter plot of the discharge peak against the dredging interval

It follows that there is no obvious relation between discharge peaks and the subsequent dredging interval. The scatter is large (R^2 is 0) but there is a cluster at approximately 1.5 days for discharge peaks of all ranges. Since according to the contractor usually no dredging activities are carried out in weekends a cluster around an interval of 1.4 days would be expected if continuous preventive dredging is carried out. The results thus support the expectation that continuous preventive dredging is carried out. This is also in line with the earlier results that the dredging volume does not increase much after discharge peaks, since due to continuous preventive dredging only the dredging locations change but not the volume.

We check if the average interval between dredging activities changes, when the dredging hotspots are disregarded. The result is shown in Figure 4.16 for the peak discharge. The results for the peak length, decrease rate and other definitions of the peak height are shown in Appendix P.3.

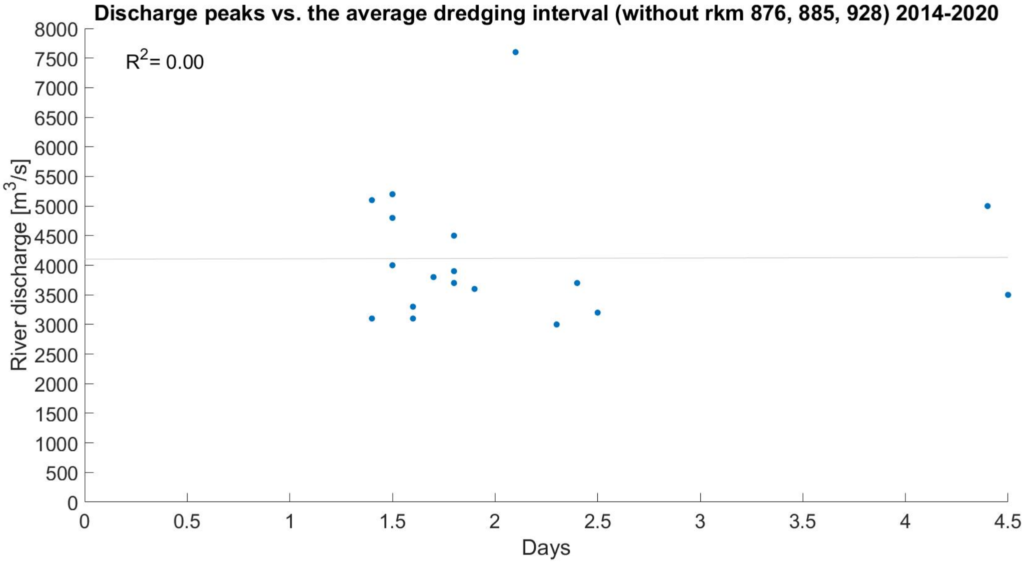


Figure 4.16: Scatter plot of the discharge peak against the dredging interval (without rkm 876, 885, 928 taken into account)

We conclude that there is still a very large scatter (R^2 is close to 0) and that discharge peaks still have no clear influence on the interval between dredging activities outside of the hotspots. However, it is obvious that when the hotspots are disregarded the dots are shifted towards the right. Clusters are less distinguishable and are shifted slightly toward 2 days. This indicates that the average interval between dredging activities is smaller at the hotspots than outside the hotspots. Thus after discharge peaks the hotspots are still dredged more often than other locations along the Waal.

4.3.4. The relation of dredging volumes and plowing activity with the monthly river discharge

All previous plots in this section show the influence of an increasing discharge peak (being an increasing peak height, an increasing length or and an increasing decrease rate) on the subsequent dredging volumes and plowing activity. In these previous plots only discharge peaks are included. Therefore, the plots do not show the influence of high discharges on sediment management in general compared to the influence of regular or low discharge regimes on sediment management. We investigate this here. Figure 4.17 shows the monthly maximum discharge measured at Lobith for every month in the period 2014-2020, plotted against the total dredging volume in the subsequent calendar month. Figure 4.18 shows the monthly maximum discharge measured at Lobith for every month in the period 2007-2020, plotted against the total plowing activity in the subsequent calendar month. We only take months with available into account.

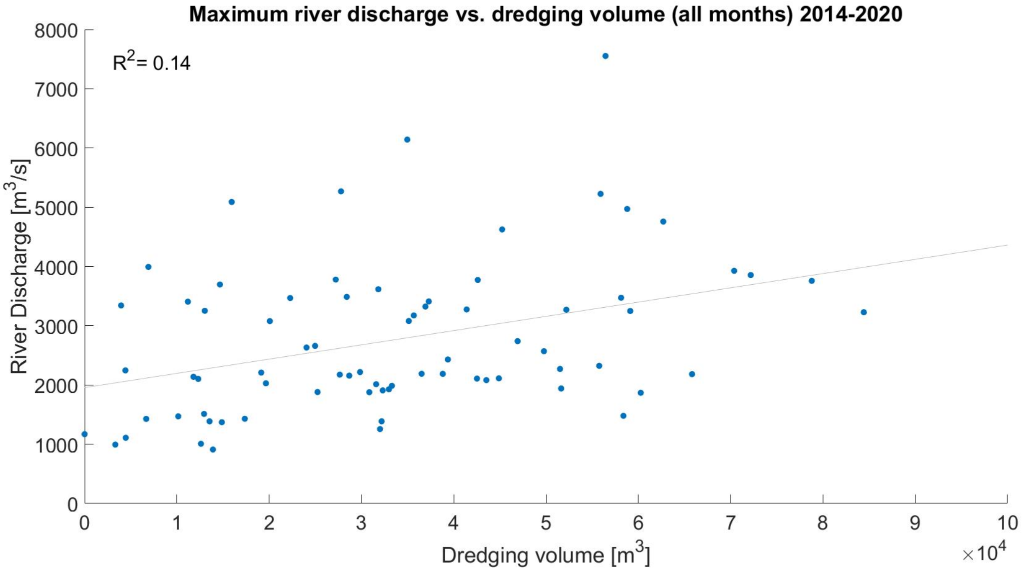


Figure 4.17: Scatter plot of the monthly maximum discharge against the total dredging volume in the subsequent calendar month

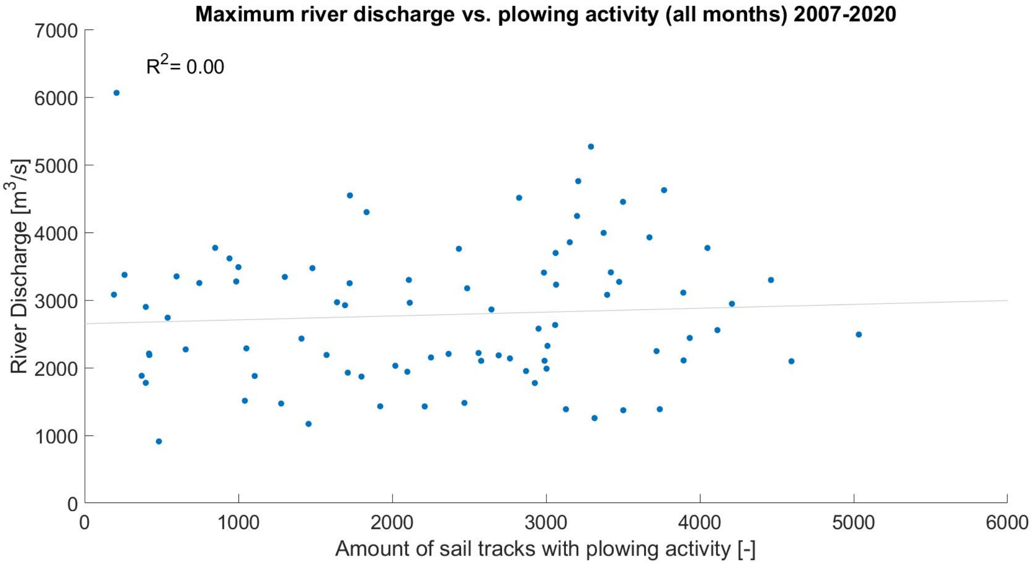


Figure 4.18: Scatter plot of the monthly maximum discharge against the total plowing activity in the subsequent calendar month

We conclude that the relation between the river discharge and the subsequent dredging volume shows a slightly upward trend. However, the scatter is still large (R^2 is 0.14). The relation between the river discharge and the subsequent plowing shows an even larger scatter (R^2 is 0). There thus seems to be no significant relation between the river discharge and the subsequent dredging volume or plowing activity. Again, the likely reason for this is the continuous preventive dredging and the fact that only one dredging vessel and one plowing vessel are used.

The overall conclusion of this section is that the analysed data shows that the variability of the hydrograph has no influence on dredging volumes or plowing activity. Because of preventive sediment management at hotspots the dredging volumes and plowing activity cannot increase much after discharge peaks. The fact that the contractor uses only one dredging vessel and one plowing vessel contributes to this.

5

Discussion

The availability and reliability of the data was an issue in this research. If data would have been available for a longer period, more discharge peaks could be used for the analysis of the relation between discharge peaks and the subsequent sediment management. Also if the data would have been more reliable, the analysis of the relation between discharge peaks and the subsequent sediment management would become more reliable as well. The issues about the availability and reliability of the data are explained here.

The sail tracks contain much erroneous information. Therefore the data set had to be reduced and in the process of reducing the data set much information has been lost. Using BRW data was a reasonable alternative, however this data set is available for a much shorter period. The BRW data is available for the period 2014-2020 instead of the period 2005-2020 of the sail tracks. This results in few discharge peaks being available for analysis of the relation between discharge peaks and the dredging volume. Apart from that, the BRW data still contains periods for which no data is available. In analyses for which no information about the dredging location is needed, the months with missing BRW data could be completed with the total dredging volumes from the original (unreduced) sail tracks. However, due the BRW data containing periods for which no data is available, it is not completely certain that the periods for which data is available are complete as well. This has as a result that the few discharge peaks that are available for anaysis, are not completely reliable.

The reduced sail tracks are the only usable data set containing information about plowing activity. Although they are available for a long period (namely 2007-2020), they contain large periods for which no data is available. This results in few discharge peaks being available for analysis of the relation between discharge peaks and the plowing activity. Due the reduced sail tracks containing large periods for which no data is available, it is not completely certain that the periods for which data is available are complete as well. This has as a result that the few discharge peaks that are available for anaysis, are not completely reliable.

In chapter 3 it seemed that there is not much overlap between hotspots as indicated by the contractor and the hotspots that are apparent from the data. We investigated cases in which the hotspots are not taken into account for both the relation between the amount of measured LADs and dredging volumes and for the relation between the characteristics of discharge peaks and the subsequent dredging or plowing. In this research rkm 876, 885 and 928 for dredging and rkm 928 for plowing have been disregarded in this research, since those are most apperent from the data. In mosts cases no significant difference could be seen between the results that regard all locations along the Waal and the result that disregard the hotspots. It might have produced clearer results if we not only disregarded the most apparent hotspots but also less apparent hotspots. For instance disregarding all rkms indicated by the contractor as hotspots would be an option.

The analysis of the relation between the amount of measured LADs and the dredging volume is probably not optimal. We used the measured LADs and the dredging volume from the same month in this research. If late in a month many LADs are measured and the dredging volume increases, the increased dredging takes probably place in the next month and is not taken into account. It might give more reliable results if the dredging volume is used from the month subsequent to the month in which the LADs are measured.

We only investigated the relation between the amount of measured LADs and the dredging volume and have not investigated the relation between the amount of measured LADs and the plowing activity. The same is the case for the investigation of the interval between dredging activities, where we have not investigated the interval between plowing activities. It would have been fitting to include this in the research but we do not expect that it would produce new insights.

The analysis of the relation between the characteristics of discharge peaks and the subsequent dredging or plowing is probably not optimal as well. We used the dredging volume and plowing activity in the first complete calendar month subsequent to the month in which the discharge peak occured. If the peak occurs very early in the month, the subsequent dredging or plowing occurs probably mainly in the month of the dredging peak and is not included in the analysis. Another consequense is that after some peaks the dredging volumes and plowing activity are regarded earlier than after other peaks. From early on in the research the data was stored per calendar month, so initially it made sense to do analysis with the monthly data. For more in-depth analysis it would make more sense to take the dredging volume or plowing activity from the first 30 days after a peak instead. The first 40 or 50 days after a peak could also work, since it was stated by the contractor that in the most extreme case it would take about a month to seven weeks after a discharge peak to completely restore the the bed level along the whole Waal (see Section 3.3). If this period of days becomes to long it could start to cover other discharge peaks, which is undesirable. In this research we have not taken this into account.

6

Conclusions and recommendations

6.1. Conclusions

In this section we summarize the main conclusions that can be drawn from this research by answering the research questions.

Answers to the first sub-question: How can dredging volumes and plowing activity be quantified and what are the associated uncertainties?

The most obvious way to analyse dredging volumes seems initially to use sail tracks, which are a log of the dredging vessel and plowing vessel in which information is stored for every minute.

However, it was found that the sail tracks contain much erroneous information. In an attempt to make the data set usable, it has been reduced by Van der Werff ten Bosch and Tuijnder (2016) and Nibbeling (2020), which means that mainly the erroneous information has been deleted. As a result the reduced data set contains no erroneous information but the dredging volumes following from it are largely underestimated.

We have thus analysed dredging volumes by using BRW data, which is a record kept by the contractor containing dredging volumes together with the date and location on which these volumes have been dredged. This data set is also not completely reliable since data is missing for certain months. However, the total monthly dredging volume (over the whole Waal) equals more or less the total monthly dredging volume of the original (unreduced) sail tracks. This indicates that the months for which BRW data is available are rather complete. For analyses in which no information about the dredging location is needed we completed the months with missing data with the total dredging volumes from the original (unreduced) sail tracks. For analyses in which information about dredging locations is needed this is not possible.

For analysing plowing activity sail tracks are the only option. Plowing cannot be expressed by a volume and therefore we expressed the amount of plowing by the amount of reduced sail tracks that show plowing activity. The used unit does not have much meaning but it still makes it possible to look at the ratio between months. We used the reduced sail tracks instead of the original sail tracks to make analysis of the plowing locations possible. Although information thus has been removed, the ratio of the amount of sail tracks between months has stayed largely the same. Since the amount of plowing is expressed in an amount of sailtracks, using the reduced sail tracks has not much negative concequences.

We determined the total dredging volumes and amount of sail tracks with a plowing activity (over the whole length of the Waal) per calendar month. We did the same for the monthly dredging volumes and plowing activity per Rhine-kilometer. The Rhine-kilometer (abbreviated as rkm) gives information about the location on the Waal. The upstream en of the Waal is located at rkm 867.4 and the downstream en of the Waal is located at rkm 952.6.

For several months no information about dredging volumes or plowing activity is available. We defined the discharge peaks as used in the analyses in this research such that only discharge peaks are taken into account that are followed by a month in which data is available. This means that some discharge peaks are not taken into account.

Answers to the second sub-question: What are hotspots for sediment management and what is their relation with Least Available Dephts and the river geometry?

Multiple locations are dredged continuously with the purpose of preventing the bed level from becoming too high there after discharge peaks. These locations are called hotspots. According to the data the most important hotspots are situated at the end of the submerged bendway weirs near Erlecom (rkm 876), at the end of the fixed layer near Nijmegen (rkm 885) and at the end of the fixed layer near St. Andries (rkm 928). At the end of these fixed layers a large erosion pit occurs at the outside of the bend and a large bar occurs at the inside of the bend (White and Blom, 2020). The accretion at the inner bend is the reason for large dredging volumes and plowing activity. The accretion probably occurs with the following reason. In river bends sediment is transported from the outer bend to the inner bend due to the helical flow pattern that occurs in bends. The fixed layers and submerged bendway weirs have been constructed with the goal of reducing the amount of sediment being eroded at the outer bend and thus the amount of sediment being transported from the outside to the inside of the bend. This results in less accretion at the inner bend and thus a wider navigation channel. Sediment transport in downstream direction mainly occurs at the inside of the fixed layer, where the bed is not fixed (White and Blom, 2020). This has as a result that there is no sediment supply in the outer bend at the downstream end of the fixed layer, which means that the sediment load is below the transport capacity. Thus a large erosion pit occurs. The sediment transported from this erosion pit towards the inner bend due to the helical flow pattern is likely the main reason for the accretion at the inner bend. The sediment being suppied at the inner bend probably contributes to the accretion.

These three locations are also situated at a crossing between bends, where usually accretion occurs. This however is most likely because of the fact that bendway weirs and fixed layers are situated in bends and therefore end where the bend ends as well.

The contractor also defines certain hotspots. How the hotspots according to the contractor match with the hotspots following from the analysed data is summarized in Table 6.1.

Table 6.1: Hotspots according to contractor and analysed data

Hotspots according to contractor	Hotspots according to analysed data
Bend at Millingerwaard. Located at rkm 869, 870 and 871	Around rkm 869.
Crossing between bends at Erlecom and Bemmelse Waard. Located at rkm 876 and a small part of 877.	End of fixed layer at Erlecom. This is a hotspot with a large dredging effort. Located at rkm 876.
Bend at Bemmelse Waard/Lent. Located at rkm 880, 881 and a small part of 882.	-
-	End of fixed layer at Nijmegen. This is a hotspot with a large dreding effort. Located at rkm 885.
Winssen. Located at rkm 894, 895 and a small part of 986.	-
Bend at Tiel/Dreumelse Waard. Located at rkm 914, 915, 916, 917 and 918.	-
Dreumelse Waard/Ophemert. Located at rkm 918, 919 and 920.	Around rkm 919.
Crossing between the bends at St. Andries and Opijnen. This is the hotspot with the largest required dredging and plowing effort. Located at rkm 928 and a small part of 929.	End of fixed layer at St. Andries. This is the hotspot with the largest required dredging and plowing effort. Located at rkm 928.

It follows from Table 6.1 that the contractor defines hotspots at Winssen (rkm 894, 895 and a small part of 986) and at the bend between Tiel and Dreumelse Waal (rkm 914, 915, 916, 917 and 918) which are not as obvious in the data as the hotspots at rkm 876, 885 and 928. In the data also a significant hotspot is aparent at the end of the fixed layer near Nijmegen (rkm 885) which is not defined as a hotspot by the contractor. The reason is that the contractor also dredges preventively at rkms that they do not define as hotspots. In this report the term ’hotspots’ is used for rkm 876, 885 and 928 but in reality a lot more rkms are dredged preventively.

We expected that locations with regular little depth need more dredging than locations with regularly large depth. At the hotspots most Least Available Depths (LADs) are measured, which agrees with our expetation. LADs are the daily locations with the smallest depth along the Waal. However, there seems to be no positive relation between the amount of measured LADs at a certain rkm and month on one side and the dredging volume at that same rkm and month on the other side. Since continuous preventive dredging and plowing is carried out at the hotspots, we expected that these hotspots destort the results. However, there is still no positive relation between the amount of measured LADs and the dredging volume when the hotspots are not taken into account. This has the following possible reasons.

- The fact that LADs are measured at a certain location does not necessarily mean that at that location dredging is necessary, since the contractor is contractually obliged to maintain a certain bed level and not a certain water depth.
- Dredging does not always take place on the right location. The contractor uses only one dredging vessel which makes it impossible to dredge at several locations at once.
- There are no-dredging zones present at some locations in the Waal.
- In reality a lot more rkms are dredged preventively than the three hotspots defined in this research.
- Since this analysis takes all months into account, months with missing data about dredging volumes are also taken into account.

Answers to the main research question: How are dredging volumes and plowing activity in the Waal influenced by the hydrograph and the river geometry?

Two types of morphological phenomena are distinguised in the context of this research (Klaassen and Sloff, 2000):

- Stationary phenomena which are non-migrating bars that are mainly the result of the geometry of the main channel, like bends and crossing between bends.
- Non-stationary phenomena which propagate through the river, like dunes moving in downstream direction over the river bed.

Dredging is mostly used for lowering stationary phenomena and plowing for both non-stationary phenomena and assisting the dredging vessel at stationary phenomena. The locations where both the dredging and plowing vessel are active most are at locations where stationary phenomena need to be lowered, which primarily occur at the end of the submerged bendway weirs and fixed layers. These are the locations of the hotspots according to the analysed data.

From analysing the characteristics of the river geometry at the dredging and plowing locations, the following can be concluded.

- Dredging takes place quite uniformly over the Upper, Middle and Lower Waal. Since the Upper Waal is quite a bit shorter than the Middle Waal and the Lower Waal, dredging is more prominent in the Upper Waal relative to the other reaches This is probably due to stationary phenomena being prevalent in the Upper Waal and two of the three dredging hotspots being located in the Upper Waal.
- Most plowing takes place in the Lower Waal. This is probably partly due to the non-stationary phenomena occuring in the Lower Waal but mostly due to the plowing hotspot being located there.

- Most dredging takes place at the crossing between bends, which is probably due to the hotspots being located at crossings.
- Most plowing takes place in gentle bends, which is probably due to many gentle bend being located in the Lower Waal,
- After most peaks a significant part of dredging and plowing takes place at the hotspots, wich is at the end of the submerged bendway weirs and fixed layers (rkm 876, 885 and 928).
- When the peak discharge becomes very large, relatively more dredging and plowing starts to take place at other locations along the waal compared to the hotspots. This happens due to dredging and plowing becoming necessary at locations outside of the hotspots after these large discharge peaks.

We expected that dredging volumes and plowing activity increase after discharge peaks. Therefore, the relation between characteristics of the discharge peaks on one side and the dredging volume and plowing activity (in the first calendar month after each peak) on the other side has been investigated. The discharge peak characteristics that we used are:

- The peak discharge,
- The duration of the discharge peak,
- The decrease rate of the discharge peak,
- The peak discharge when regarding only peaks above 4000 m^3/s,
- The relative size of the discharge peak (the peak discharge minus the low discharge subsequent to the peak).

As discharge peaks increase (in respect to all above mentioned characteristics) the dredging volumes and plowing activity do not increase. An explanation is that dredging volumes are determined in the first full calendar month subsequent to the discharge peak. When a discharge peak occurs late in a month, the dredging volumes and plowing activity are regarded earlier after the peak than when a discharge peak occurs early in a month. A second explanation is that the data is not complete enough. Since some month are missing data, it might be the case that the months with available data are not complete either. This could lead to an underestimation of the dredging volumes and plowing activity after certain discharge peaks. A third and likely explanation is the preventive dredging and plowing at hotspots. However, the dredging volume and plowing activity still do not increase with increasing discharge peaks, when the dredging volumes and plowing activity at hotspots are not taken into account. This could be due to the fact that in reality a lot more rkms are dredged and plowed preventively than the three hotspots defined in this research.

There also is no relation between increasing discharge peaks and the interval between dredging activities, which is amost always between 1 and 2 days. The interval between dredging activities is however smaller at the hotspots than at other locations along the Waal. Since no dredging activities are carried out in weekends an interval of approximately 1.4 days makes sense and proves that continuous preventive dredging takes place.

In our final analysis we regarded all months for which data is available (instead of only looking at discharge peaks). It followed from this analysis that there is no relation between the monthly maximum discharge and the dredging volume or plowing activity in the subsequent month. The most likely reason is again the continuous preventive sediment management carried out by the contractor.

Overall it can be concluded that due to preventive sediment management at hotspots, the dredging volume and plowing activity cannot increase much after discharge peaks. The fact that the contractor uses only one dredging vessel and one plowing vessel contributes to this. However, after discharge peaks sediment management shift slightly from the hotspots to other locations along the Waal.

6.2. Recommendations

Firstly, the problems treated in the discussion (chapter 5) could be improved on in further research.

The information from sail tracks is rather unreliable. It is advisable for Rijkswaterstaat to look into a way of obtaining a more reliable log from the dredging and plowing vessels in the future.

For this research we made an attempt to obtain dredging volumes from multibeam measurements but due to time consumption the attempt was dropped. Approximately every 2 weeks the contractor supplies Rijkswaterstaat with a multibeam measurement of the bed level along the Waal. The differences between subsequent bed levels at locations where dredging or plowing is known to be carried out could provide another data set with dredging volumes.

The contractor has to meet a performance-based contract. In this contract a reference level is indicated above which no sediment is alowed to be present. We expect the dredging and plowing to concentrate at locations where the bed gets close to or exceeds this reference level. It might be interesting to investigate the relation between dredging volumes and plowing activity on one side and the bed level relative to the reference level on the other side, since a positive link is expected between these two variables. However, multibeam measurements would not be the recommended data set for this analysis, because the contractor uses these multibeam measurements to show Rijkswaterstaat that the bed level complies with the contract. Using a more frequent measurement of the bed level would be preferrable.

In this research we indicated geometrical characteristics along the Waal. Together with the information we obtained in this research about dredging locations and plowing locations along the Waal, this gives an interesting overview of expected locations of accretion. In a previous research about wavelets Van Denderen (2020) has indicated locations with regular accretion and erosion. A comparison between the results from these two researches would be interesting, since it might help in explaining locations of accretion and erosion indicated by Van Denderen (2020) but also in explaining dredging and plowing locations.

We indicated in this research the geometrical characteristics, dredging locations and plowing locations per rkm. The locations of accretion and erosion are indicated by Van Denderen (2020) on a much larger resolution. If the resolution of the geometrical characteristics, dredging locations and plowing locations from this research would be increased, a comparison with the results by Van Denderen (2020) becomes even more useful.

In this research the dredging volumes are regarded per kilometer. This makes it difficult to analyse the exact influence of no-dredging zones on LAD locations and the sediment management at those locations, since the no-dredging zones are only about 100 m long. A more in-depth analysis of the influence of no-dredging zones on LAD locations and sediment management, where dredging volumes and plowing activity are regarded on a larger resolution (per 100 m or smaller) could produce interesting results.

In the analysis of the influence of the hydrograph on sediment management in this research, we focused on the influence that discharge peaks (being the height, length and decrease rate of the peak) have on sediment management. The influence of the river discharge in general on sediment management is but briefly treated and more attention could have been payed to this. This topic could be interesting for future research.

Predicitions have been made about the impact of RfR measures on dredging volumes in earlier research. Such predictions were for instance made by Van Adrichem (2013) and Kisoensingh (2015). In this research we obtained some overviews of total dredging volumes in recent years after the implementation of the last RfR measure in 2014. A comparison between the results from this research with predicitions about dredging volumes would be interesting, since it would indicate if the implemented RfR measures have had the expected impact on sediment management.

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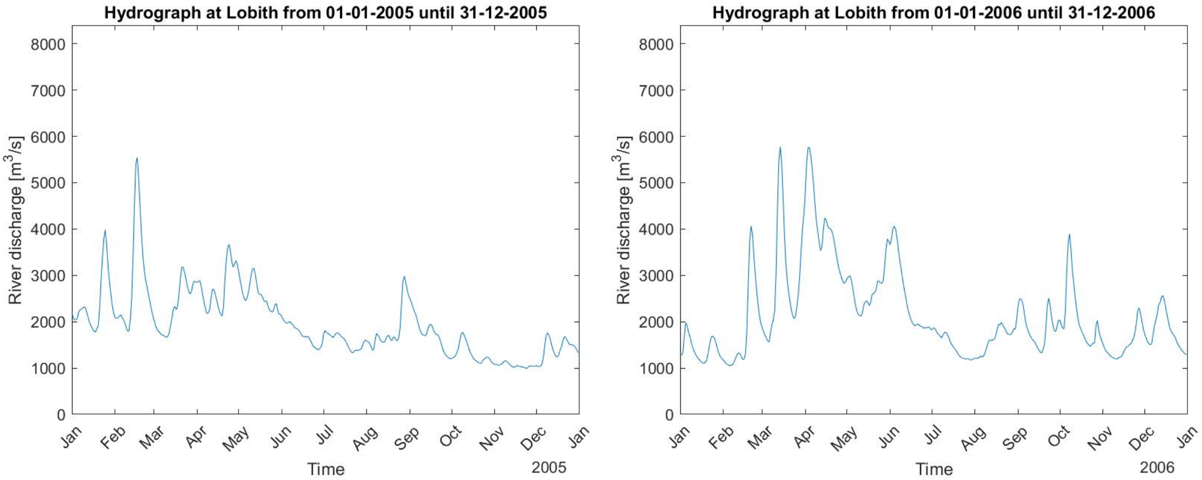
A

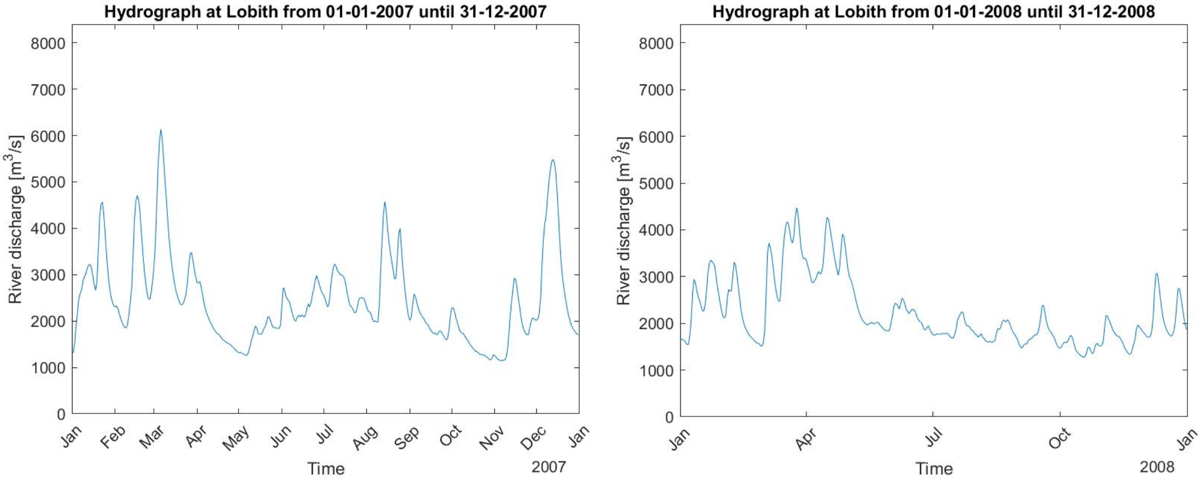
The hydrograph

A.1. Yearly hydrographs



(a) 2005

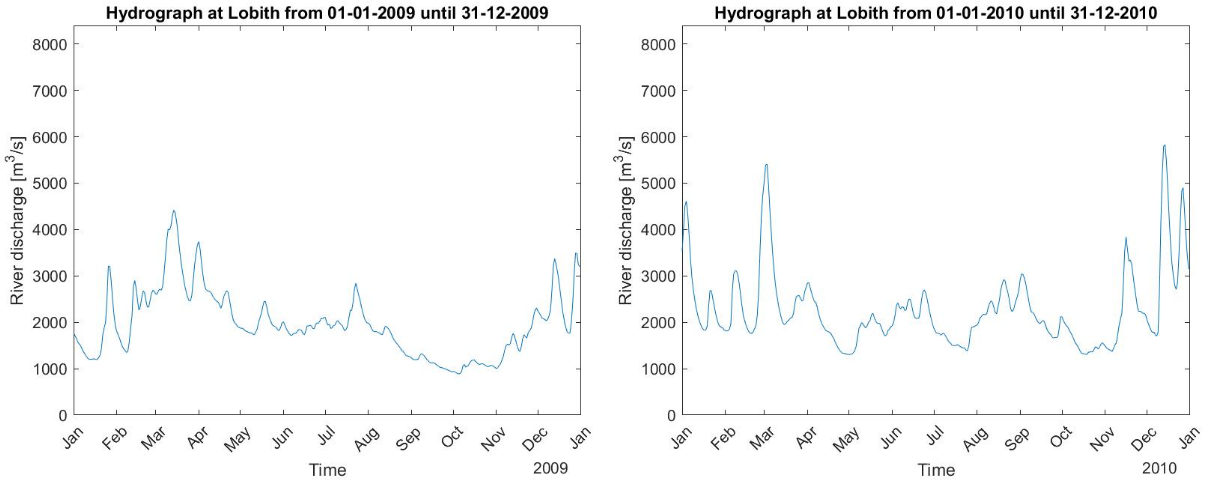
(b) 2006



(c) 2007

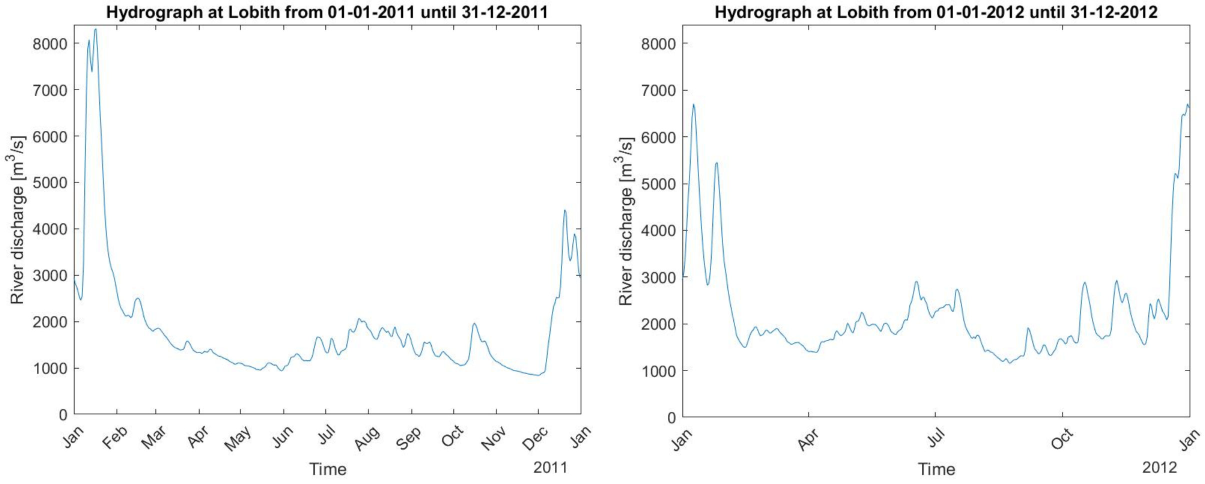
(d) 2008

Figure A.1: The hydrograph at Lobith per year for the period 2005-2008



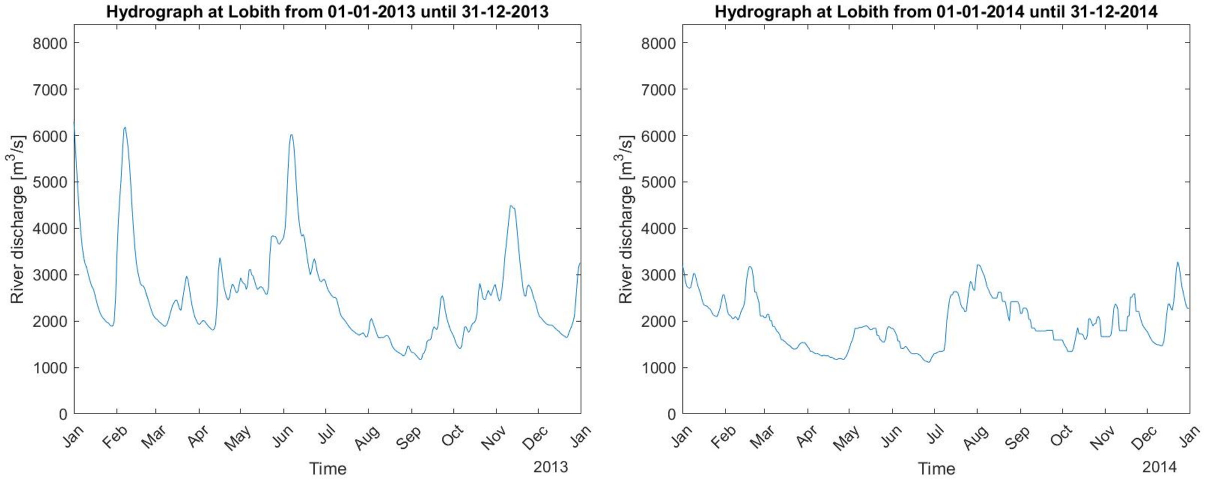
(a) 2009

(b) 2010



(c) 2011

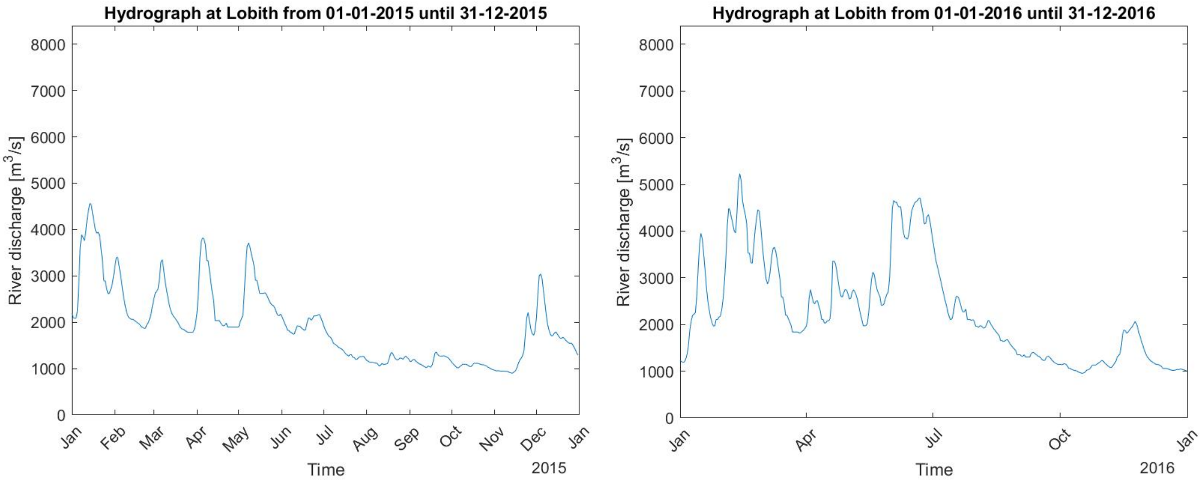
(d) 2012



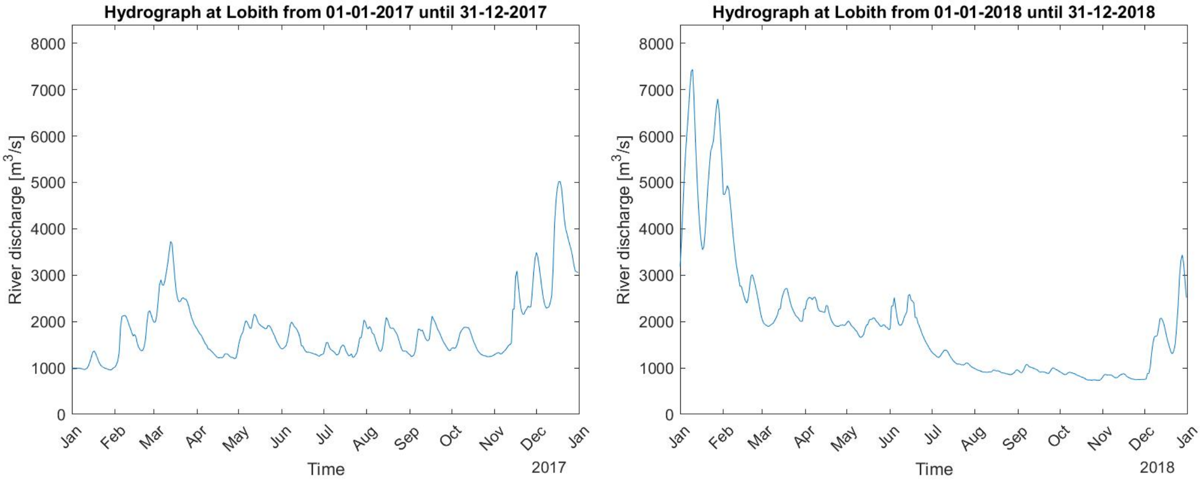
(e) 2013

(f) 2014

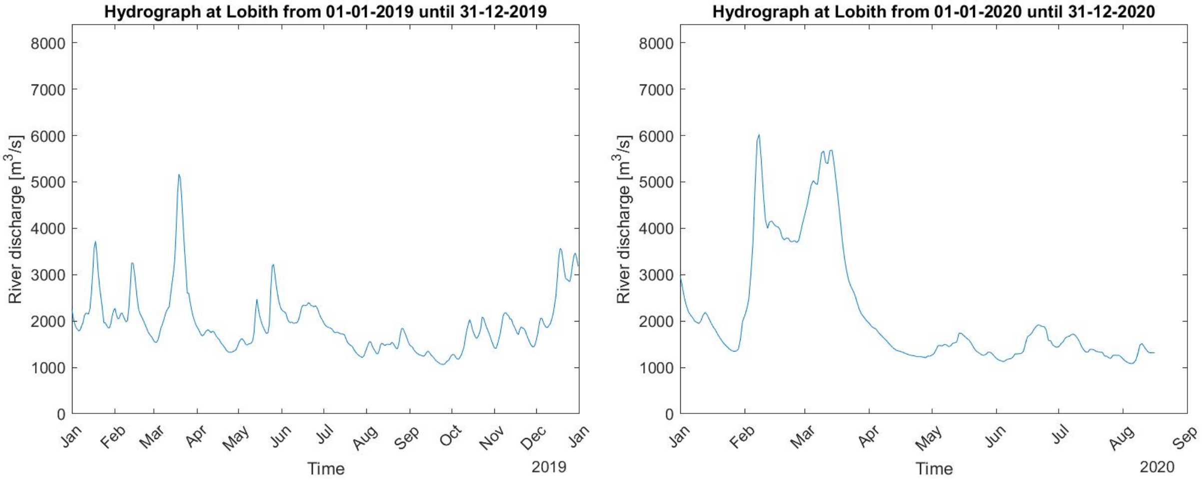
Figure A.2: The hydrograph at Lobith per year for the period 2009-2014



(a) 2015 (b) 2016



(c) 2017 (d) 2018



(e) 2019 (f) 2020

Figure A.3: The hydrograph at Lobith per year for the period 2015-2020

A.2. Statistics of the hydrograph

Table A.1: Statistics of the hydrograph for the period 2005-2020

Statistic	Discharge	Used data set
Mean discharge	2108 m^3/s	Daily averaged discharges
Standard deviation	974 m^3/s	Daily averaged discharges
Maximum discharge	8388 m^3/s	All corrected measurements
Minimum discharge	709 m^3/s	All corrected measurements

A.3. Yearly statistics of the hydrograph

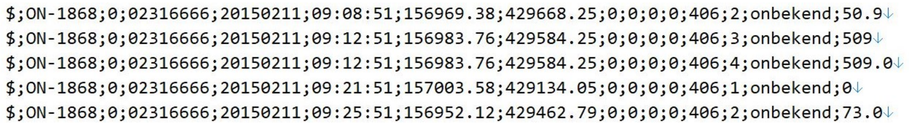
Table A.2: Yearly statistics of the hydrograph

Year	Mean discharge (of daily averaged discharges)	Std. discharge (of daily averaged discharges)	Max. discharge (of all corrected measurements)	Min. discharge (of all corrected measurements)
2005	1962 m^3/s	738 m^3/s	5622 m^3/s	972 m^3/s
2006	2163 m^3/s	956 m^3/s	5828 m^3/s	1042 m^3/s
2007	2466 m^3/s	971 m^3/s	6174 m^3/s	1135 m^3/s
2008	2216 m^3/s	710 m^3/s	5412 m^3/s	1251 m^3/s
2009	1963 m^3/s	714 m^3/s	4452 m^3/s	873 m^3/s
2010	2280 m^3/s	844 m^3/s	5910 m^3/s	1285 m^3/s
2011	1821 m^3/s	1274 m^3/s	8388 m^3/s	821 m^3/s
2012	2246 m^3/s	1122 m^3/s	6750 m^3/s	1142 m^3/s
2013	2580 m^3/s	1030 m^3/s	6524 m^3/s	1131 m^3/s
2014	1958 m^3/s	530 m^3/s	3342 m^3/s	1083 m^3/s
2015	1915 m^3/s	821 m^3/s	4625 m^3/s	883 m^3/s
2016	2294 m^3/s	1091 m^3/s	5268 m^3/s	939 m^3/s
2017	1825 m^3/s	738 m^3/s	5089 m^3/s	936 m^3/s
2018	1953 m^3/s	1365 m^3/s	7553 m^3/s	709 m^3/s
2019	1949 m^3/s	644 m^3/s	5226 m^3/s	1040 m^3/s
2020	2165 m^3/s	1268 m^3/s	6142 m^3/s	1038 m^3/s

B

Sail tracks

The sail tracks are stored in separate files for each day and vessel. Usally such a file thus contains multiple sail tracks but the exact amount of sail tracks per file is highly variable. A typical name for a file containing sail tracks is *20180703_Wilma_RD.trk*. The fist part of the file name indicates the date at which the sail track is measured and the second part indicates the name of the vessel (Van der Werff ten Bosch and Tuijnder, 2016). The third part (in this case 'RD') is not always present in the file name and has no known meaning (Van der Werff ten Bosch and Tuijnder, 2016). The extension of the file is .trk which refers to 'vaartrack' (Van der Werff ten Bosch and Tuijnder, 2016). The name of the vessel naturally indicates to which vessel the sail tracks in the file belong and thus indicates if the sail tracks belong to a dredging vessel or a plowing vessel. An example of a couple of sail tracks as they are stored in the .trk files is shown in Figure B.1.



```
$;ON-1868;0;02316666;20150211;09:08:51;156969.38;429668.25;0;0;0;0;406;2;onbekend;50.9↓
$;ON-1868;0;02316666;20150211;09:12:51;156983.76;429584.25;0;0;0;0;406;3;onbekend;509↓
$;ON-1868;0;02316666;20150211;09:12:51;156983.76;429584.25;0;0;0;0;406;4;onbekend;509.0↓
$;ON-1868;0;02316666;20150211;09:21:51;157003.58;429134.05;0;0;0;0;406;1;onbekend;0↓
$;ON-1868;0;02316666;20150211;09:25:51;156952.12;429462.79;0;0;0;0;406;2;onbekend;73.0↓
```

Figure B.1: Example of a couple of sail tracks

In the sail tracks each column contains specific information. What information each column contains is clarified in Table B.1.

Table B.1: Information per column for each sail track (Nibbeling, 2020)

Column number:	1	2	3	4	5	6	7	8	9	10	11	12	13	14	15	16
Column indication:	$	Contract	Positioning	Vessel-ID	Date	Time	x-coordinate	y-coordinate	Suction depth	Plowing depth	Course	Botom depth	Voyage Number	Activity	Dredging grid	Hopper volume
Stored information:	$	ON-1868	0	02316666	20150211	06:04:51	156969.16	429646.00	0	0	0	0	406	2	onbekend	50.9

Most columns do not contain useful information for this study, because the data is not measured or no useful data is stored. The useful columns are:

- Date (column 5);
- Time (column 6);
- x-coordinate (column 7);
- y-coordinate (column 8);
- Activity (column 14);
- Hopper volume (column 16).

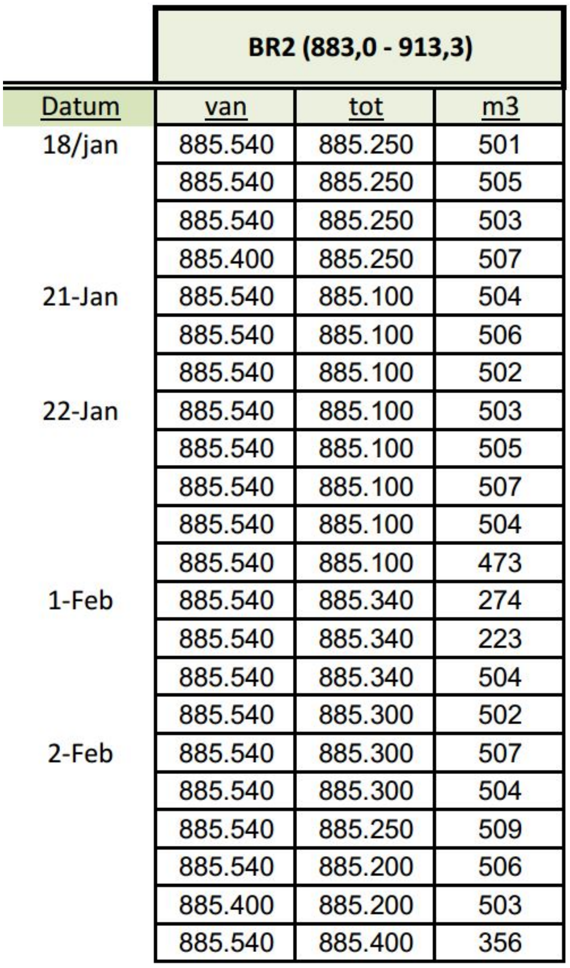
The column containing information about the activity (column 14) shows numbers. These numbers represent the following activities (Van der Werff ten Bosch and Tuijnder, 2016):

- 1: sailing with an empty hopper or in case of a plowing vessel just sailing;
- 2: dredging or in case of a plowing vessel plowing;
- 3: sailing with a loaded hopper;
- 4: dumping;
- 5: unknown;
- 6: probably an indication for pause.

C

Spreadsheet BRW data

Figure C.1 shows a part of the 2016 BRW preadsheet to give an impression of how the data is stored. Each row represents a dredging cycle. The leftmost column shows the date on which the dredging cycle has taken place. The second column shows the most downstream location on which the dredging vessel has been during a cycle and the third column shows the most upstream location the dredging vessel has been a cycle. The rightmost column shows the dredged volume of sedement during the cycle.



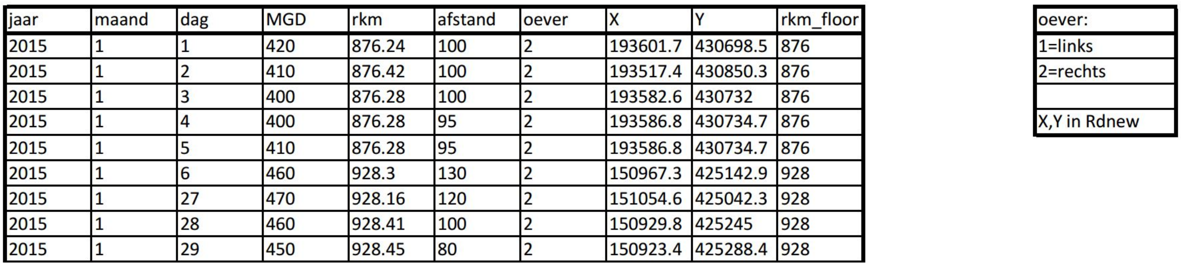
	BR2 (883,0 - 913,3)		
Datum	van	tot	m3
18/jan	885.540	885.250	501
	885.540	885.250	505
	885.540	885.250	503
	885.400	885.250	507
21-Jan	885.540	885.100	504
	885.540	885.100	506
	885.540	885.100	502
22-Jan	885.540	885.100	503
	885.540	885.100	505
	885.540	885.100	507
	885.540	885.100	504
	885.540	885.100	473
1-Feb	885.540	885.340	274
	885.540	885.340	223
	885.540	885.340	504
	885.540	885.300	502
2-Feb	885.540	885.300	507
	885.540	885.300	504
	885.540	885.250	509
	885.540	885.200	506
	885.400	885.200	503
	885.540	885.400	356

Figure C.1: Part of the 2016 BRW spreadsheet

D

Spreadsheet Least Available Depths

Figure D.1 shows a part of the 2015-2018 LAD preadsheet to give an impression of how the data is stored. The first three columns show the date on which an LAD has been measured. The column ’MGD’ shows the measured depth of an LAD in cm. The columns ’rkm’ and ’rkm_floor’ show the location on which an LAD has been measured in the Rhine-kilometer scale with both a different amount of decimals. The columns ’X’ and ’Y’ show the location on which an LAD has been measured in coordinates. The columns ’afstand’ and ’oever’ show respectively the distance from the bank in m and the side of the river at which the LAD is measured (1 = left and 2 = right).



jaar	maand	dag	MGD	rkm	afstand	oever	X	Y	rkm_floor
2015	1	1	420	876.24	100	2	193601.7	430698.5	876
2015	1	2	410	876.42	100	2	193517.4	430850.3	876
2015	1	3	400	876.28	100	2	193582.6	430732	876
2015	1	4	400	876.28	95	2	193586.8	430734.7	876
2015	1	5	410	876.28	95	2	193586.8	430734.7	876
2015	1	6	460	928.3	130	2	150967.3	425142.9	928
2015	1	27	470	928.16	120	2	151054.6	425042.3	928
2015	1	28	460	928.41	100	2	150929.8	425245	928
2015	1	29	450	928.45	80	2	150923.4	425288.4	928

oever:
1=links
2=rechts

X,Y in Rdnew

Figure D.1: Part of the 2015-2018 LAD spreadsheet

E

Explanation scripts

Each of the following sections shortly explains how a MATLAB script is used to process the available data and to eventually create graphs.

E.1. Script reduced sail tracks

Section 2.3 elaborated on how the sail tracks have been edited by Van der Werff ten Bosch and Tuijnder (2016) and Nibbeling (2020) to obtain the reduced sail tracks. In the original data (the unreduced sail tracks) the hopper volume is only shown in the sail tracks when the vessel has finished dredging and is sailing towards a dumping location (and the activity of the vessel is 'sailing full'). In the process of editing the sail tracks for the period 2015-2020, Nibbeling (2020) divided the hopper volume after dredging by the amount of preceding sail tracks with a dredging activity and added this value to each of these sail tracks with a dredging activity. This resulted in an approximation of the dredged volume per sail track with a dredging activity. Nibbeling (2020) did the same for the sail tracks with a dumping activity so the approximated dumping volume per sail track was obtained. The hopper volumes during sailing between dredging and dumping are deleted which means that if we add all volumes for sail tracks with a dredging (or dumping) activity, we obtain the total dredged volume.

The distribution of the hopper volume over the preceding dredging sail tracks and over the subsequent dumping sail tracks has not been done by Van der Werff ten Bosch and Tuijnder (2016) in the process of editing the sail tracks for the period 2005-2015. To be able to conveniently obtain dredging volumes from reduced sail tracks from this period, we use the same script Nibbeling (2020) used for distributing the hopper volume on the reduced sail tracks from the period 2005-2015.

Now the dredging volumes and dumping volumes per month are obtained from the reduced sail tracks. We use a script that filters out the sail tracks with the activity 'dredging' and 'dumping'. Then we use another script that loops through the dates of the dredging sail tracks and dumping sail tracks separately and adds up all hopper volumes for each month. In this way we obtain a total dredging volume and a total dumping volume (over the whole Waal) for each month.

E.2. Script BRW data

We use a script that sorts all BRW dredging volumes per date. Then the script adds up the BRW dredging volumes over all rkms for each month.

E.3. Script original sail tracks

We use a script that loops through the sail tracks and adds up all unique values of the recorded hopper volumes for each day. The script then adds up the daily dredging volumes for each month. As explained in Section E.1, the original sail tracks only show the hopper volumes after dredging and before dumping (when the activity of the vessel is 'sailing full'). Only a few dredging cycles are carried out per day and the hopper volume after dredging usually differs for each dredging cycle, which makes this approach quite reliable.

E.4. Script plowing activity

We use a script to filter out the sail tracks with the activity 'plowing'. Then we use a script that loops through the dates of the plowing sail tracks in the same way as the script used for the reduced dredging sail tracks. The only difference is that for each month no dredging volumes but the amount of sail tracks is added together.

E.5. Script dredging locations according to reduced sail tracks

We use a script that filters out the sail tracks with the activity 'dredging'and 'dumping'. Then we use another script that loops through the dates of the dredging sail tracks and dumping sail tracks seperately and adds up the hopper volumes for each rkm and each month. The script also subdivides the hopper volumes per side of the river. For this the six longitudinal grid cells are used to locate sail tracks left or right. For the sail tracks with a dredging activity, the script calculates the dredging volume per date, river kilometer and side of the river. For the sail tracks with a dumping activity, the script calculates the dumping volume per date, river kilometer and side of the river.

E.6. Script dredging locations according to BRW data

We make a new spreadsheet in Excel with rearranged information from the BRW spreadsheet. In this spreadsheet we determine the lowest rkm at which has been dredged during a dredging cycle. Every dredging volume is shown in a row and each row contains its own date, dredging volume and rkm. Then we use a script that loops through this spreadsheet. This script works in exactly the same way as the script used for the reduced sail tracks to sort the dredged volumes per rkm and month.

E.7. Script dredging intervals according to BRW data

We use a script that orders the BRW data on date. The scipt determines all unique dates per month and places them in chronological order. Then the scipt determines the amount of days between each of these dates and finally it computes the average value is per month.

F

Total dredging volumes and plowing activity

F.1. Total dredging and dumping volumes

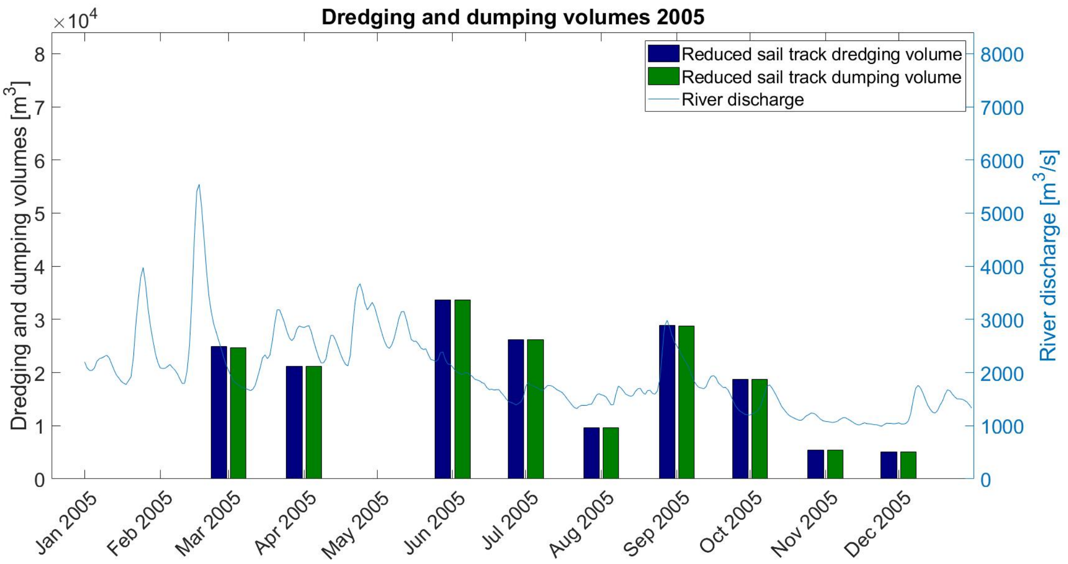


Figure F.1: 2005

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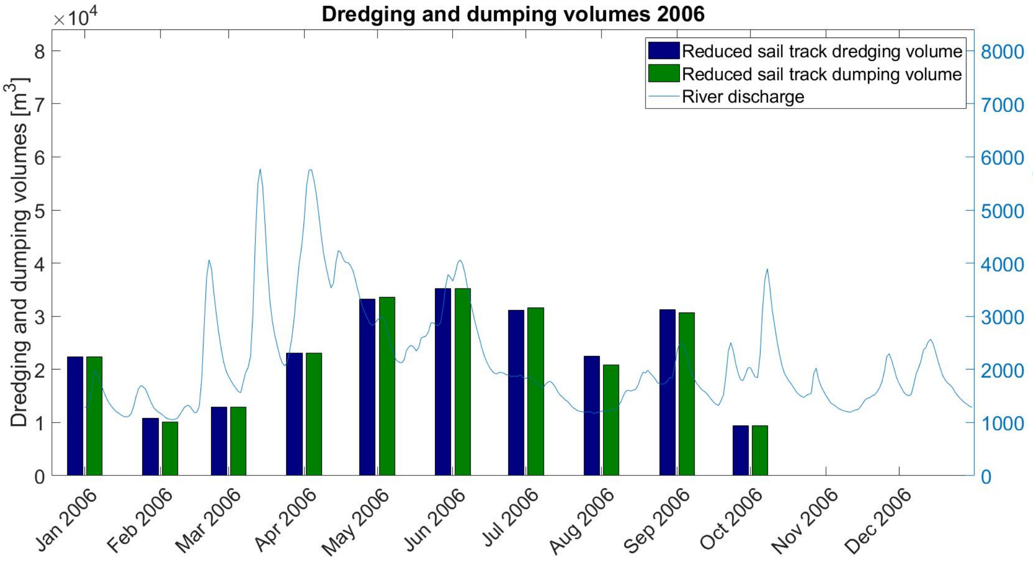


Figure F.2: 2006

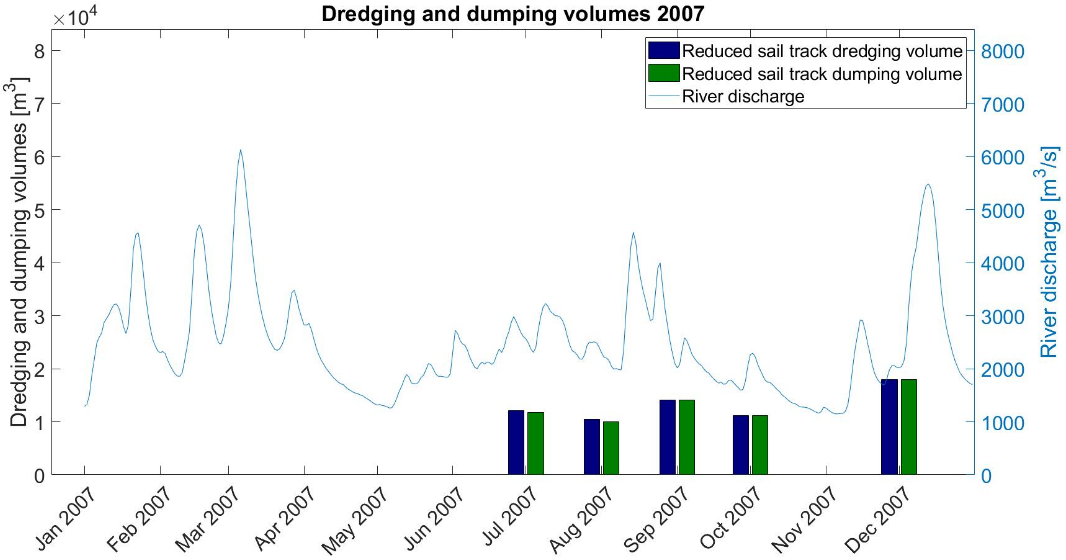


Figure F.3: 2007

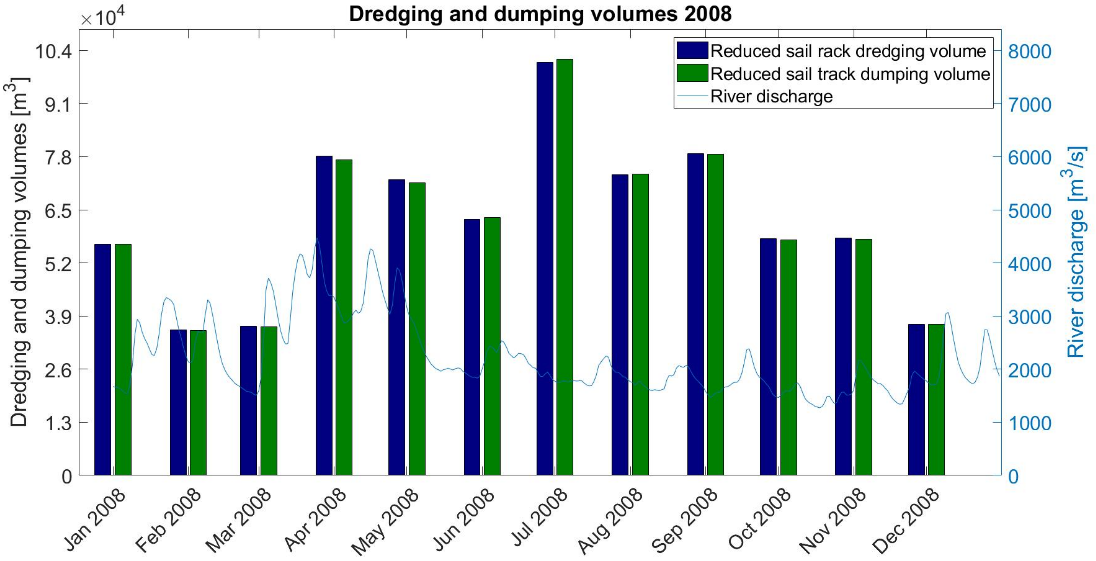


Figure F.4: 2008

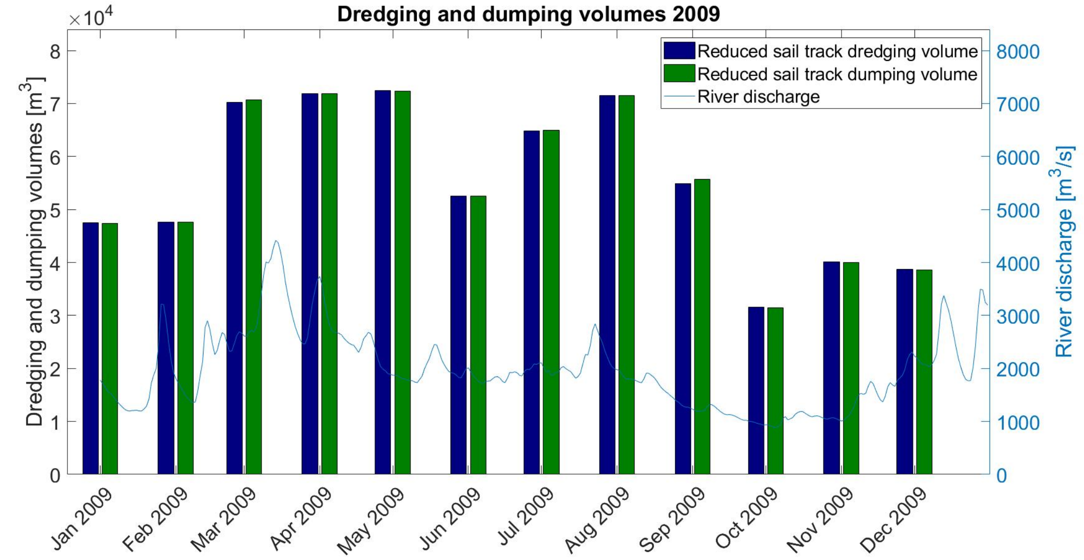


Figure F.5: 2009

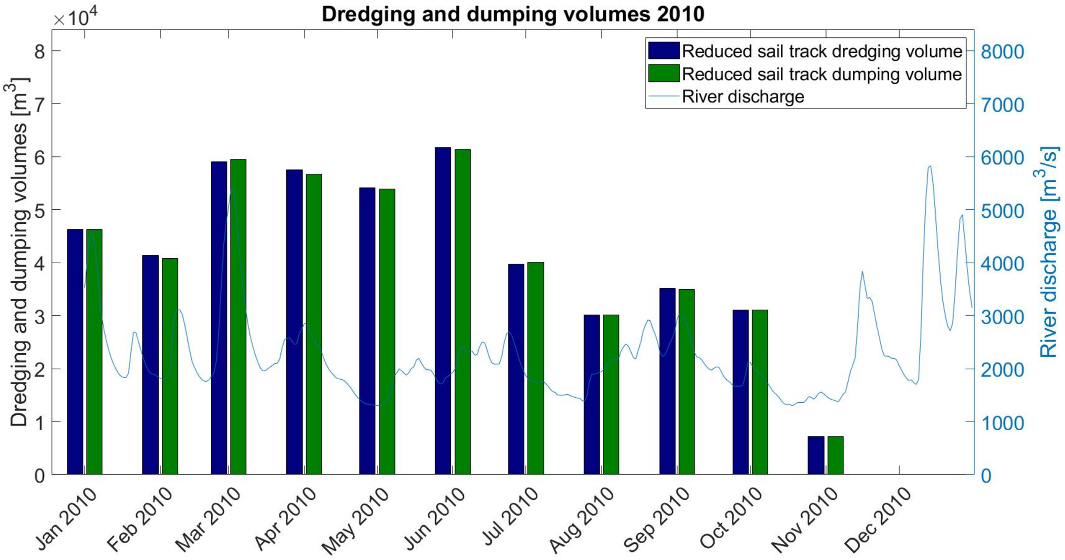


Figure F.6: 2010

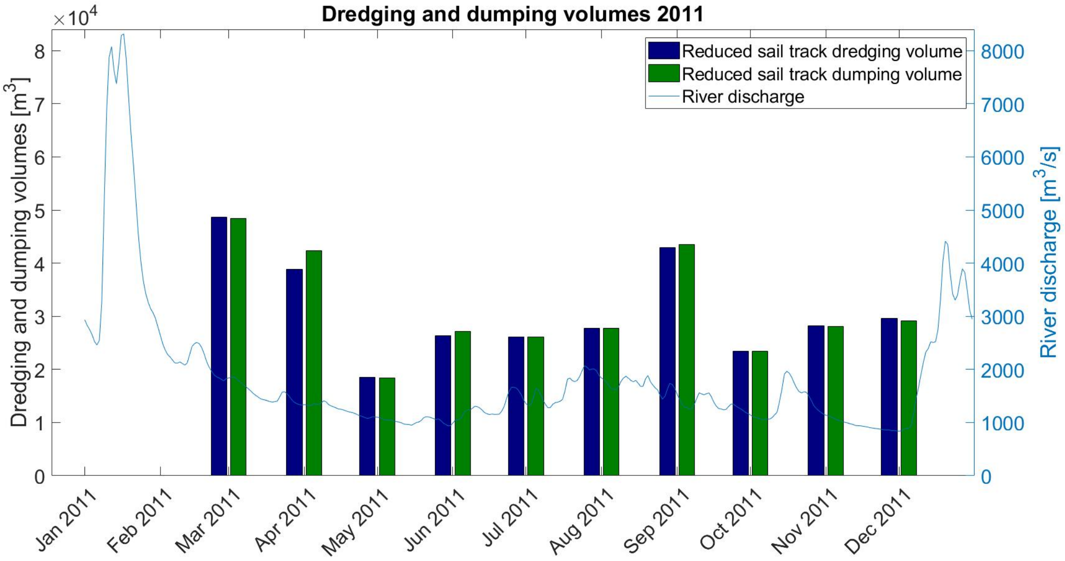


Figure F.7: 2011

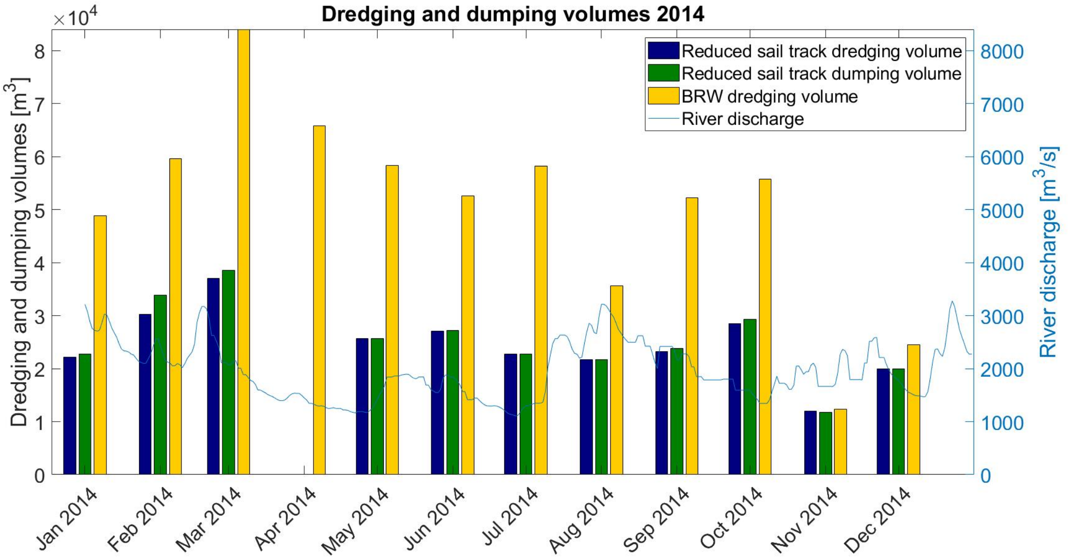


Figure F.10: 2014

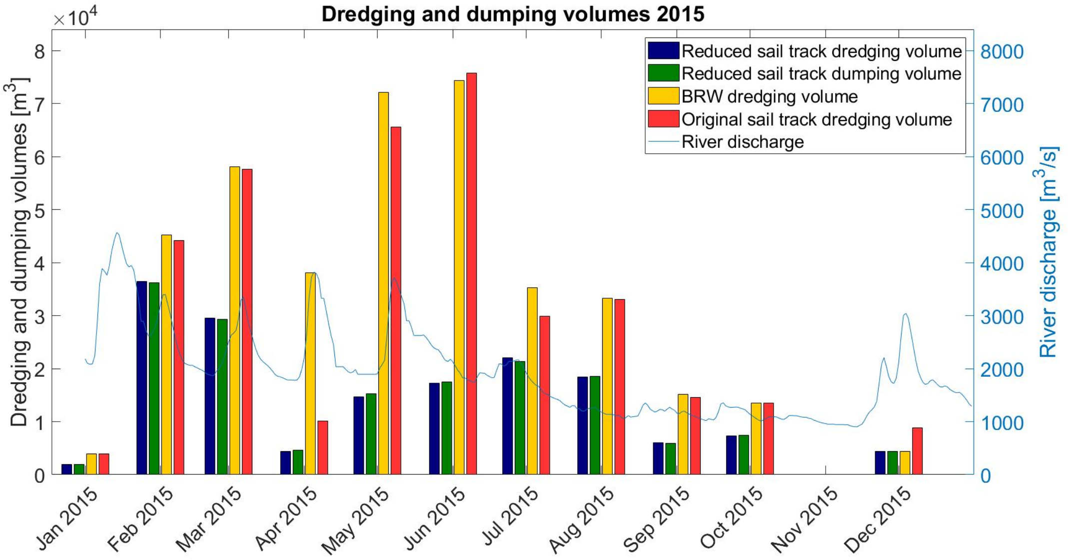


Figure F.11: 2015

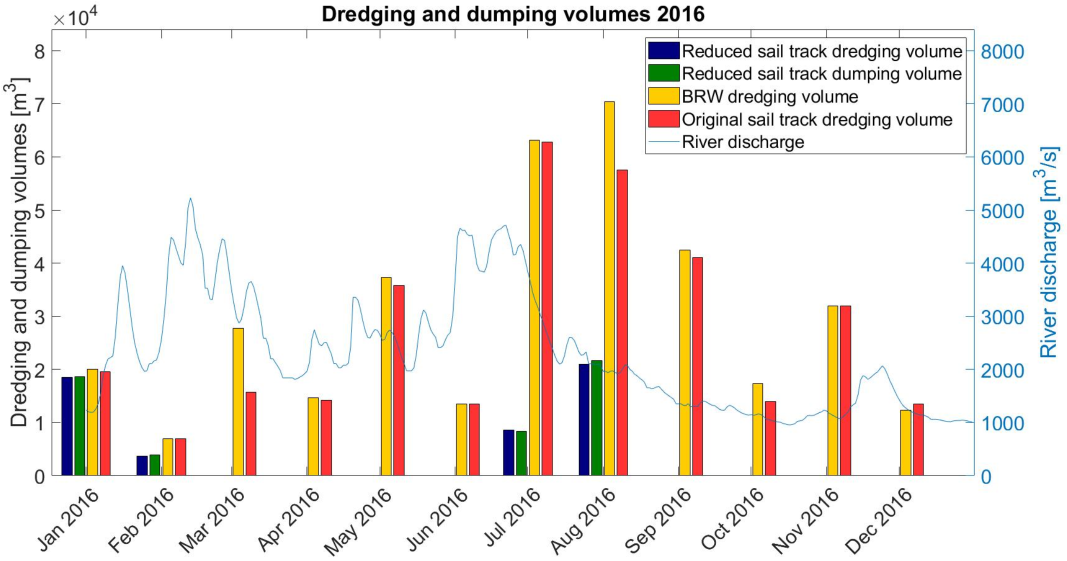


Figure F.12: 2016

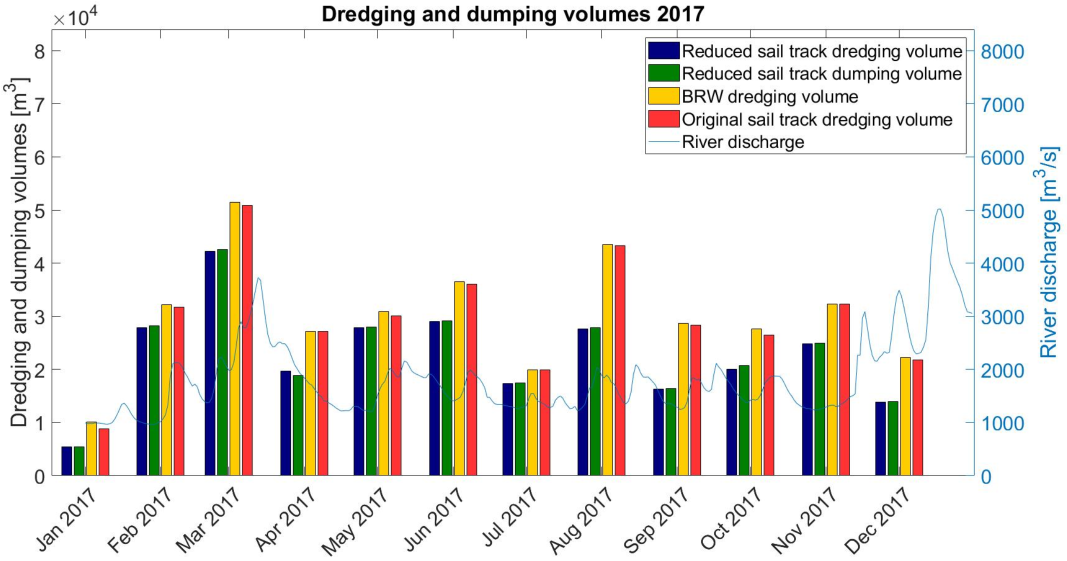


Figure F.13: 2017

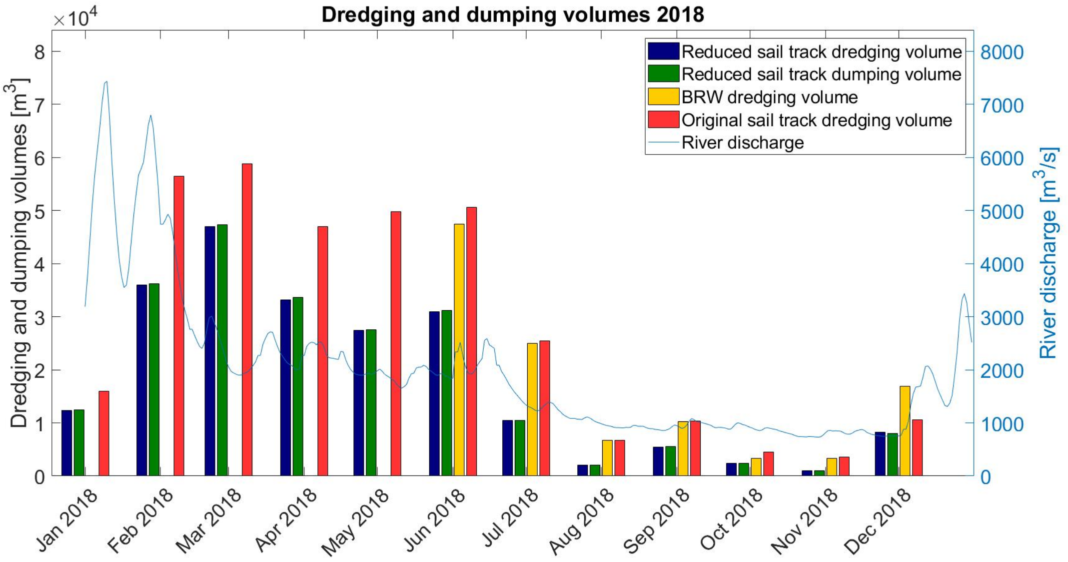


Figure F.14: 2018

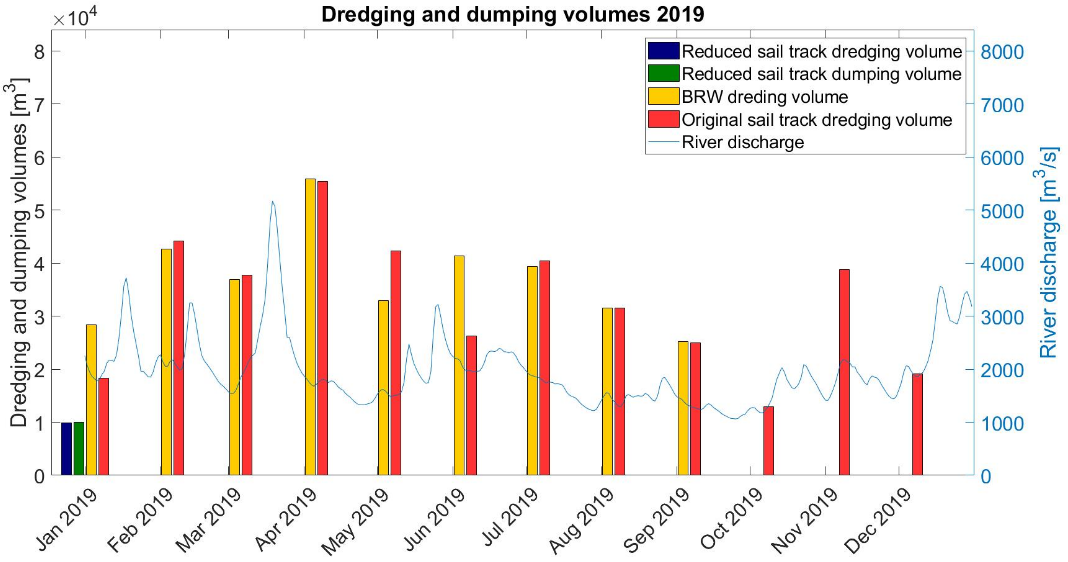


Figure F.15: 2019

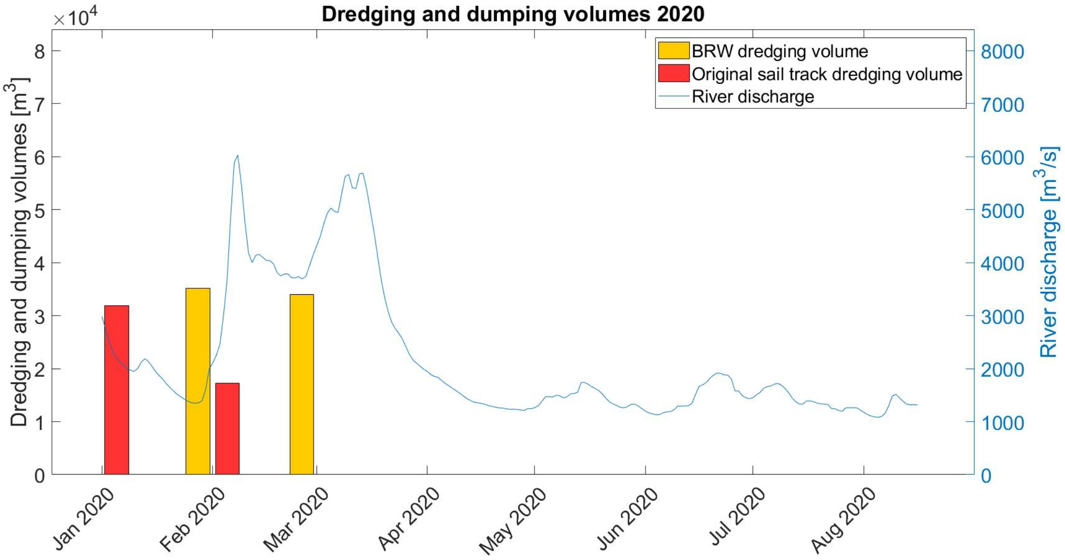


Figure F.16: 2020

F.2. Total plowing activity

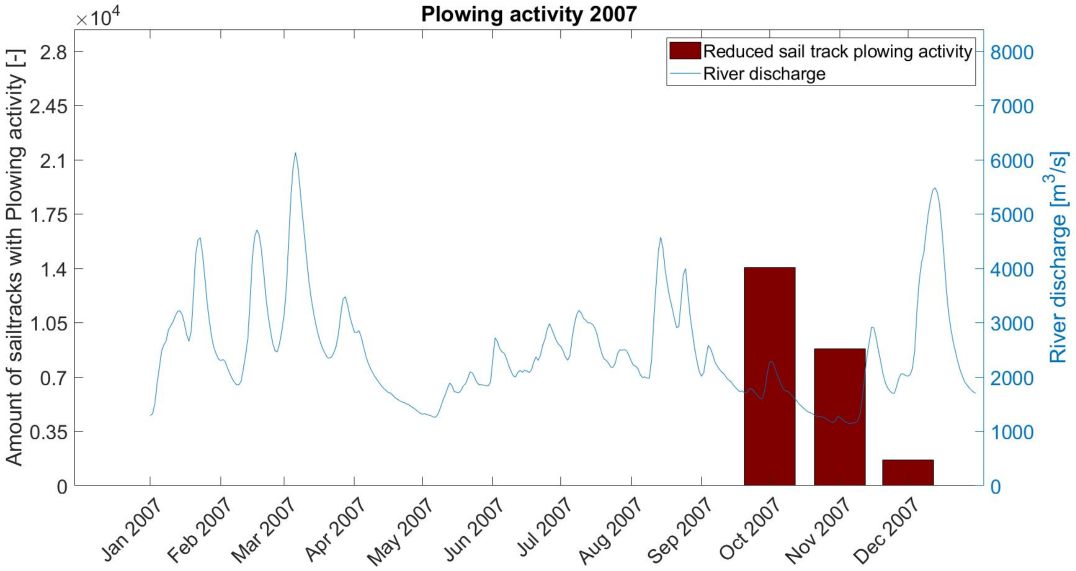


Figure F.17: 2007

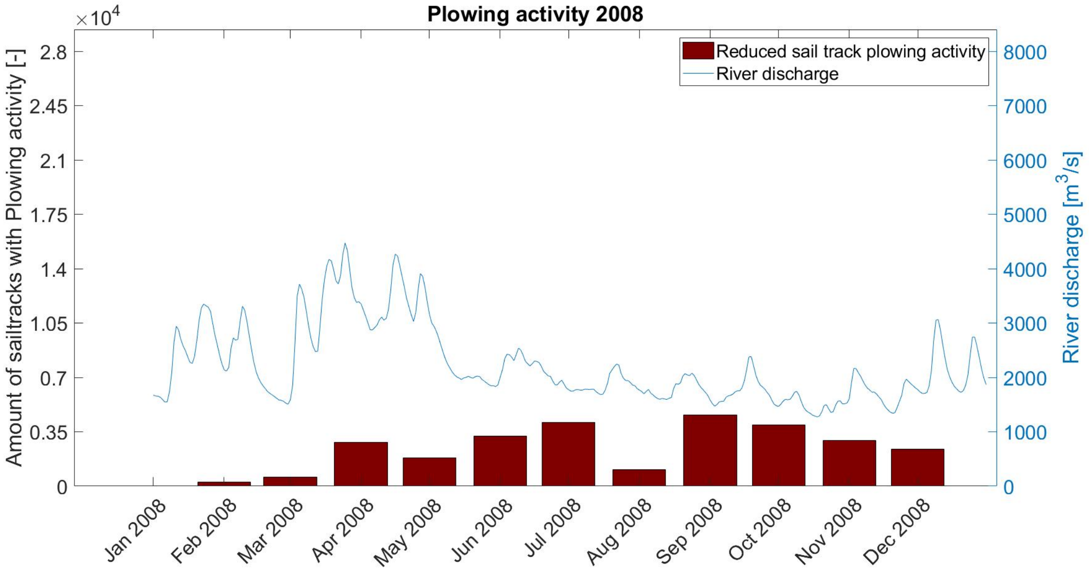


Figure F.18: 2008

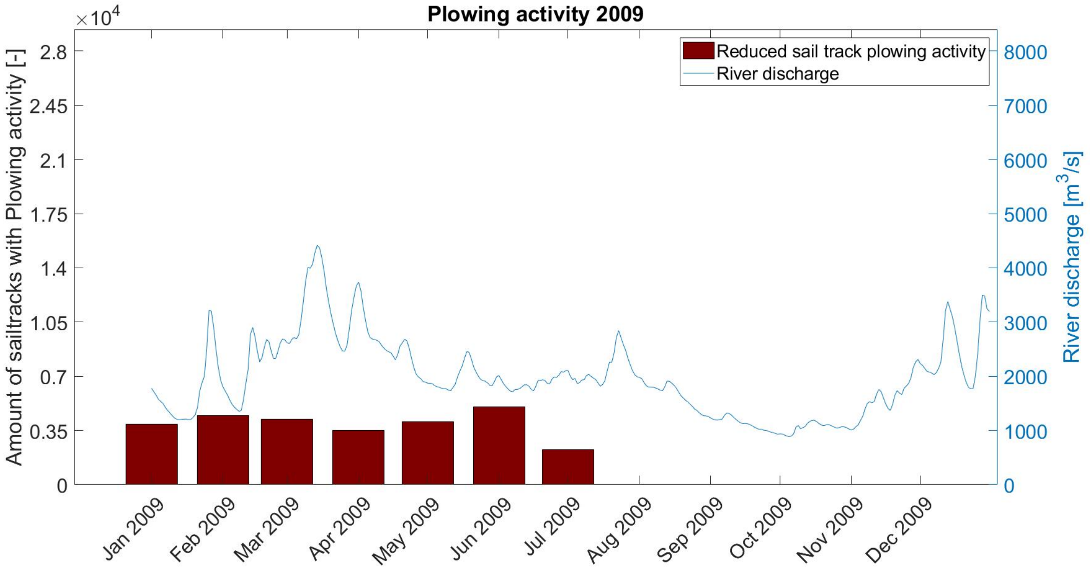


Figure F.19: 2009

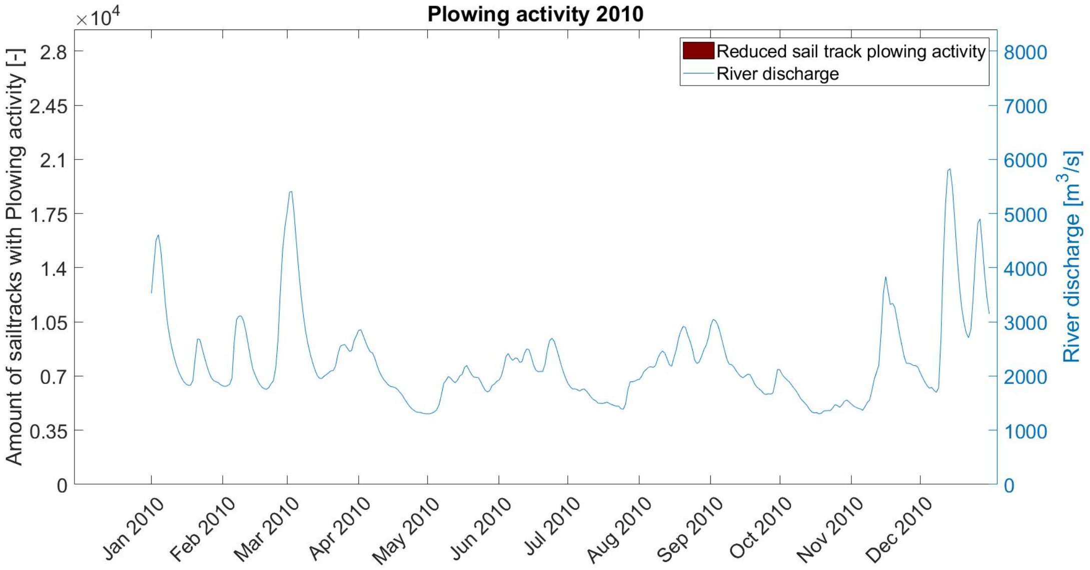


Figure F.20: 2010

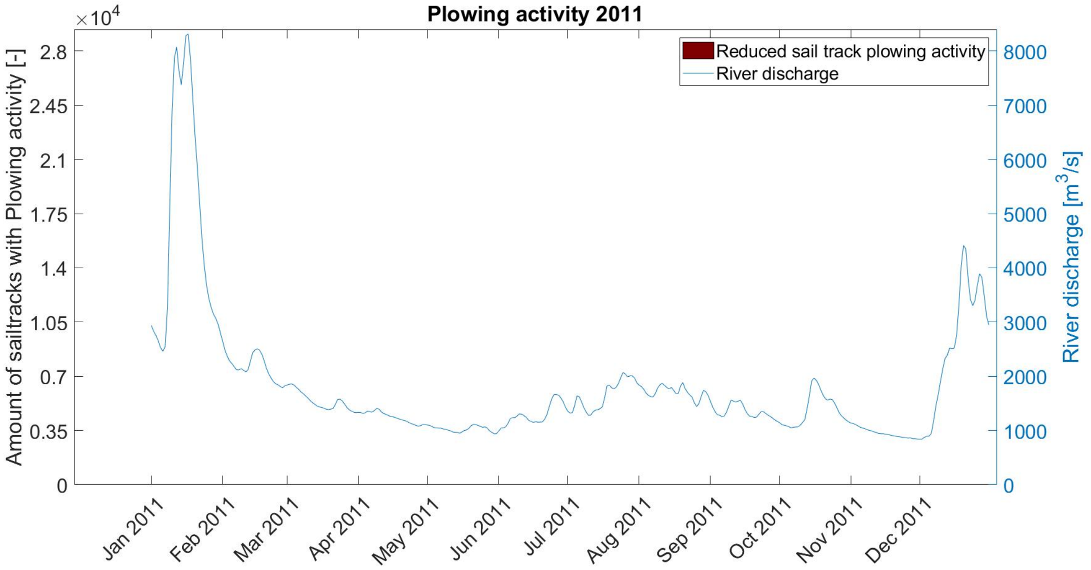


Figure F.21: 2011

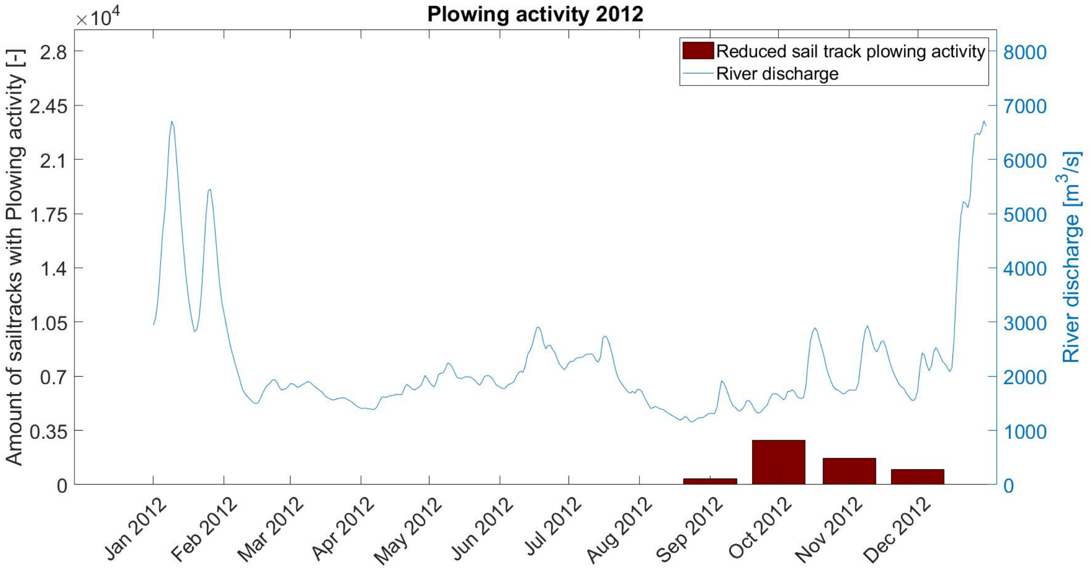


Figure F.22: 2012

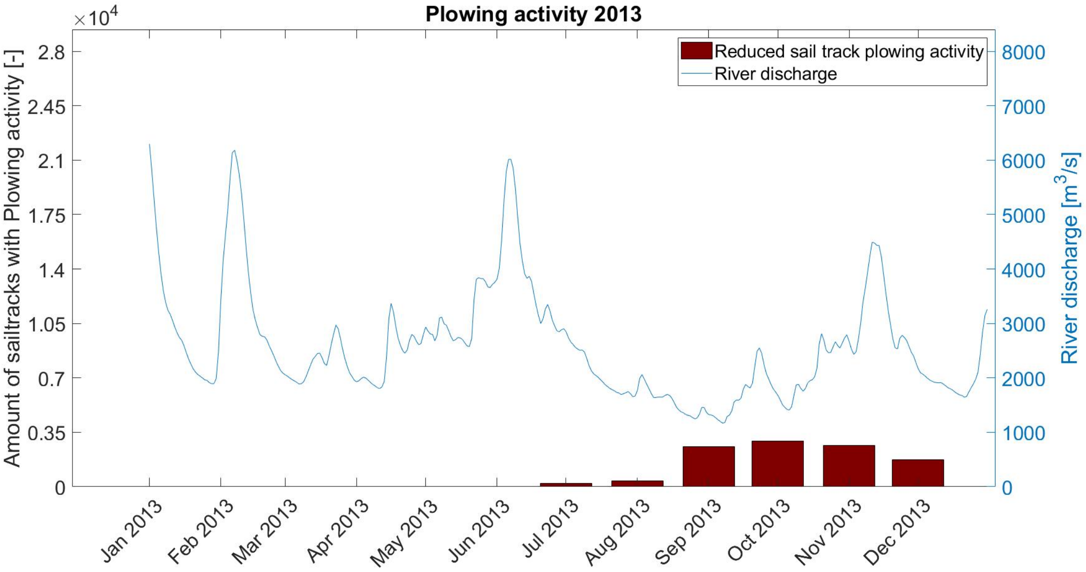


Figure F.23: 2013

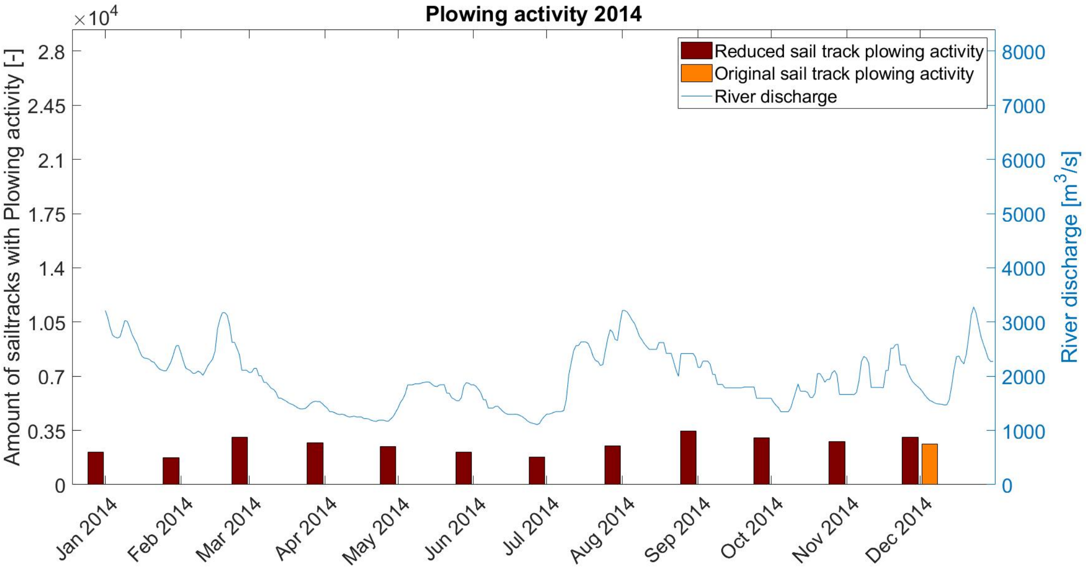


Figure F.24: 2014

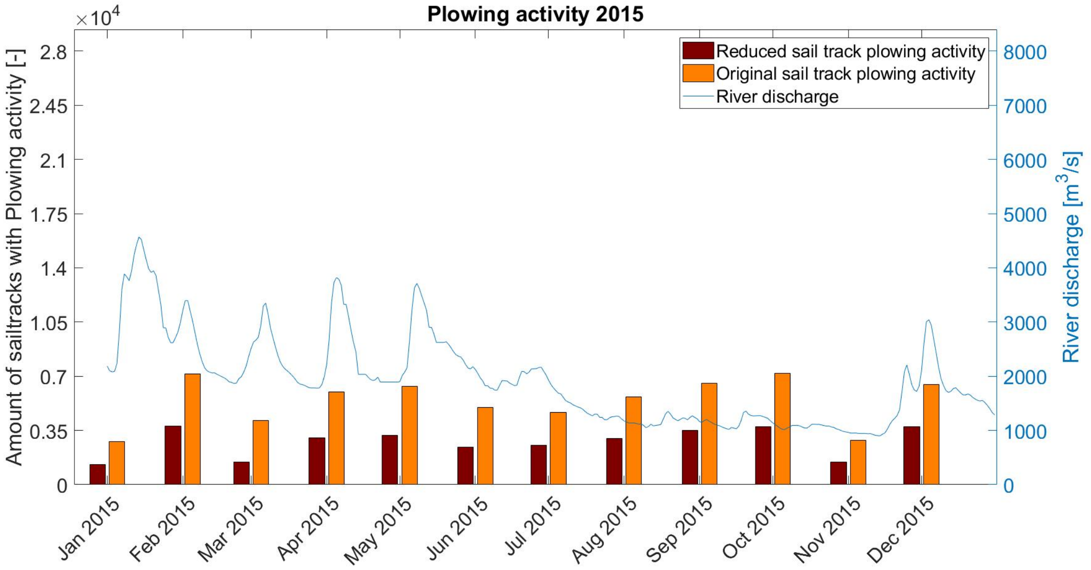


Figure F.25: 2015

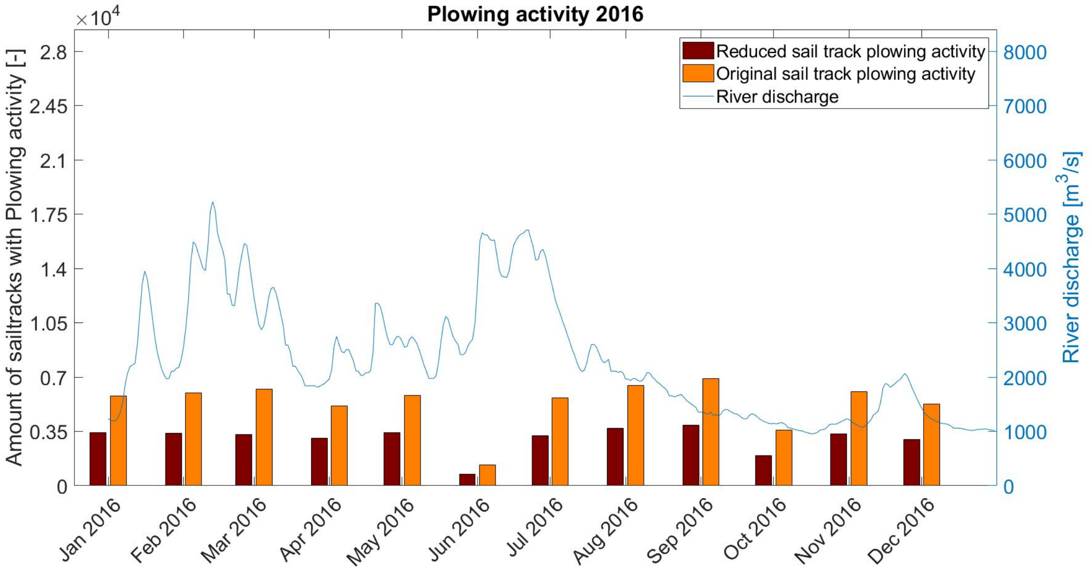


Figure F.26: 2016

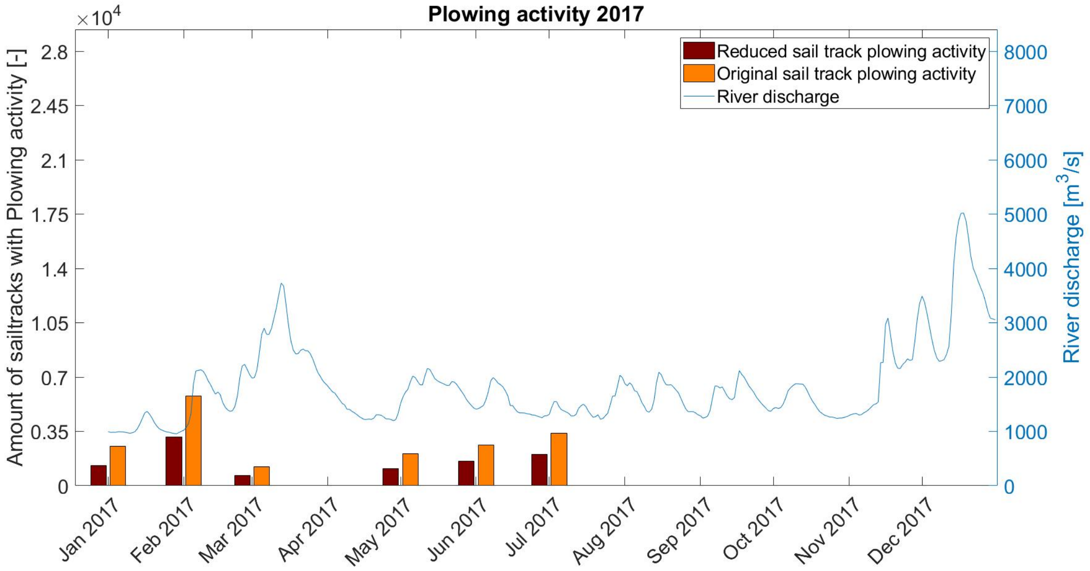


Figure F.27: 2017

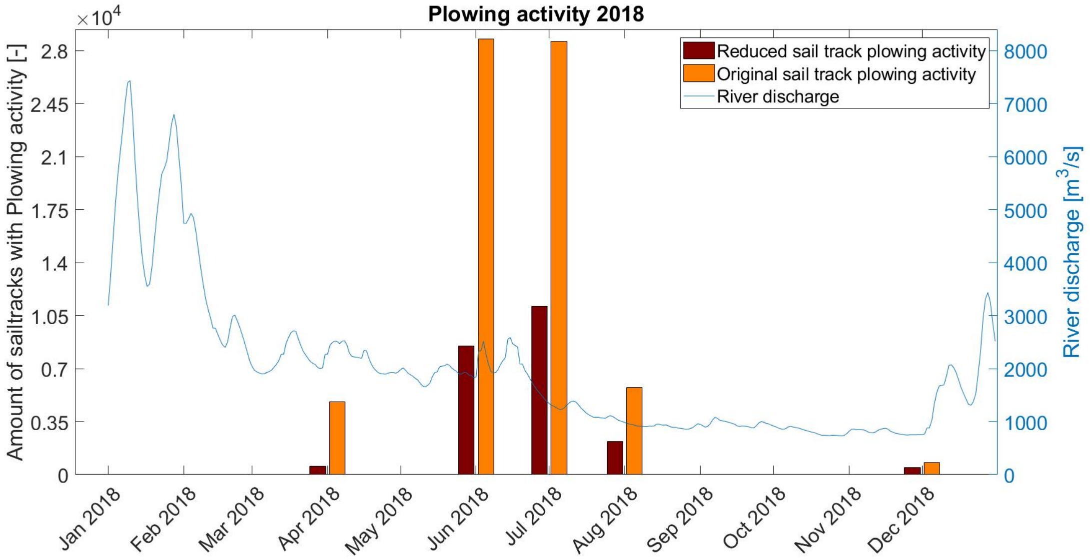


Figure F.28: 2018

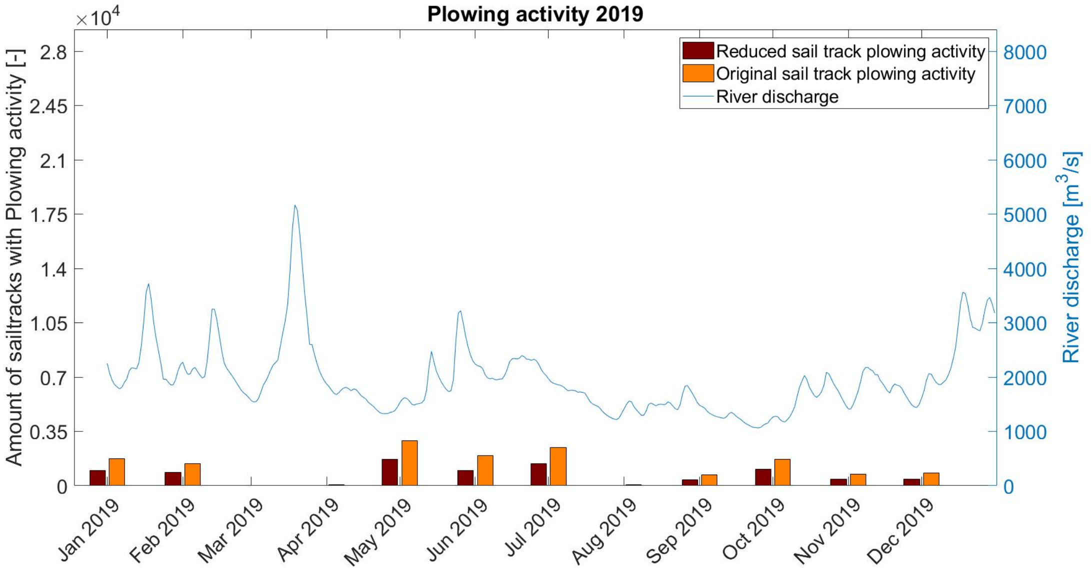


Figure F.29: 2019

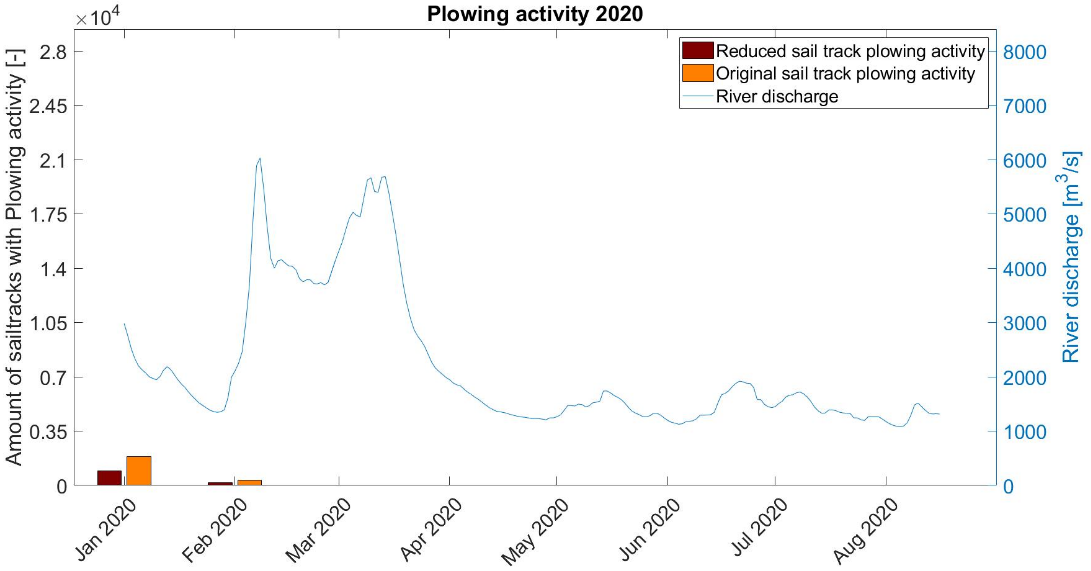


Figure F.30: 2020

G

Hotspots according to the contractor

An overview of the Waal including the hotspots as indicated by the contractor is shown in Figure G.1.

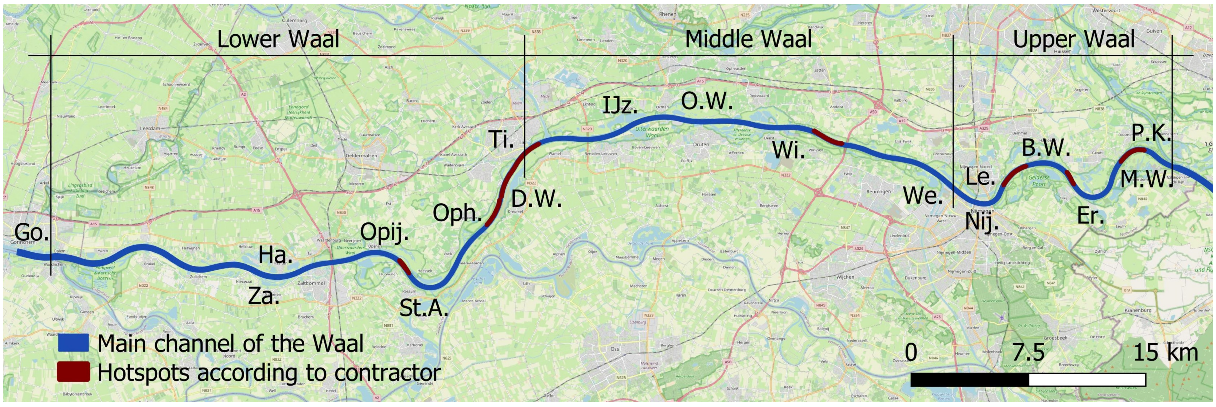


Figure G.1: Overview of the Waal river including the hotspots according to the contractor

H

Dredging, dumping and plowing locations

H.1. Dredging and dumping locations according to reduced sail tracks

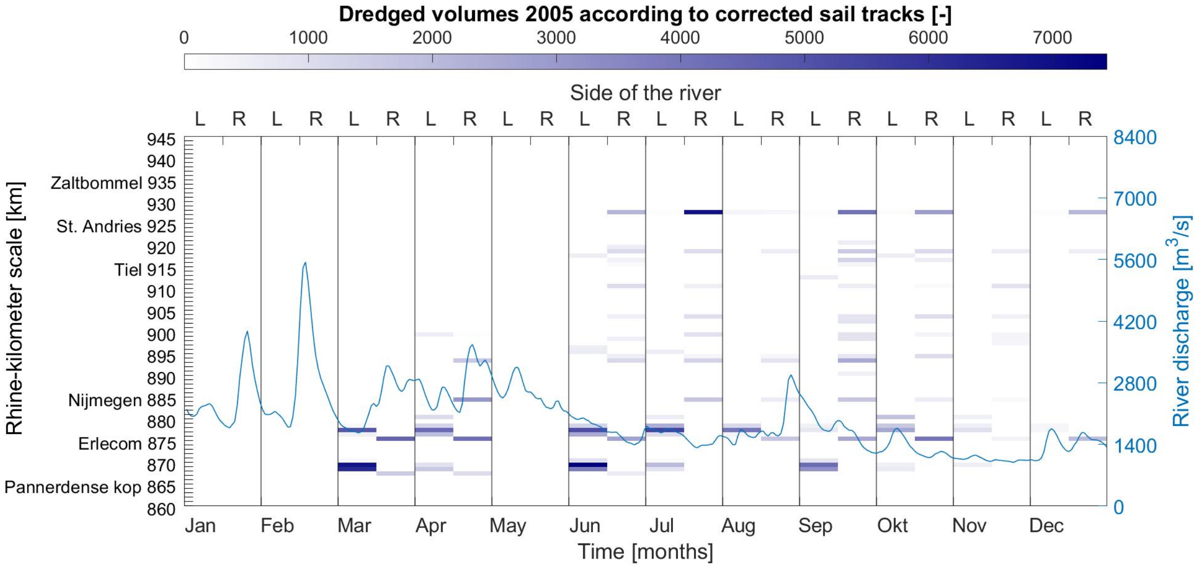


Figure H.1: 2005

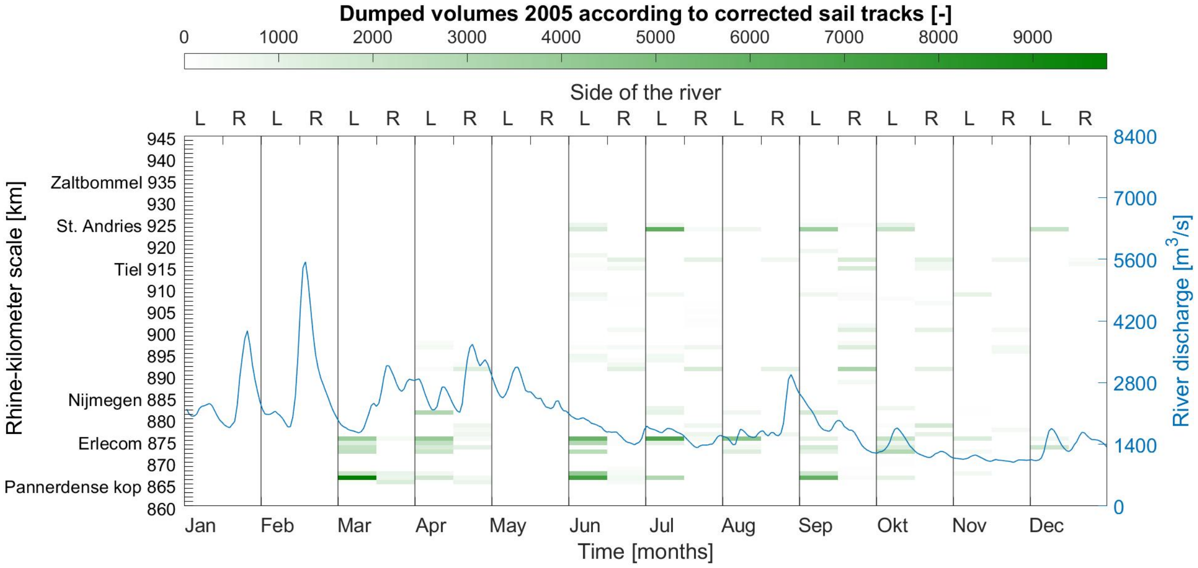


Figure H.2: 2005

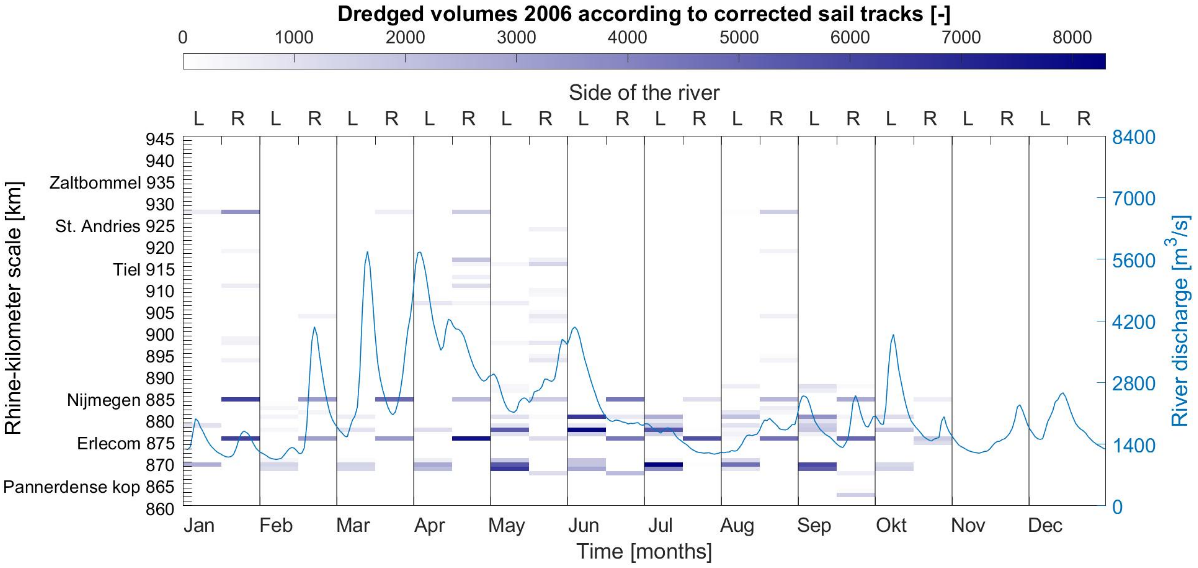
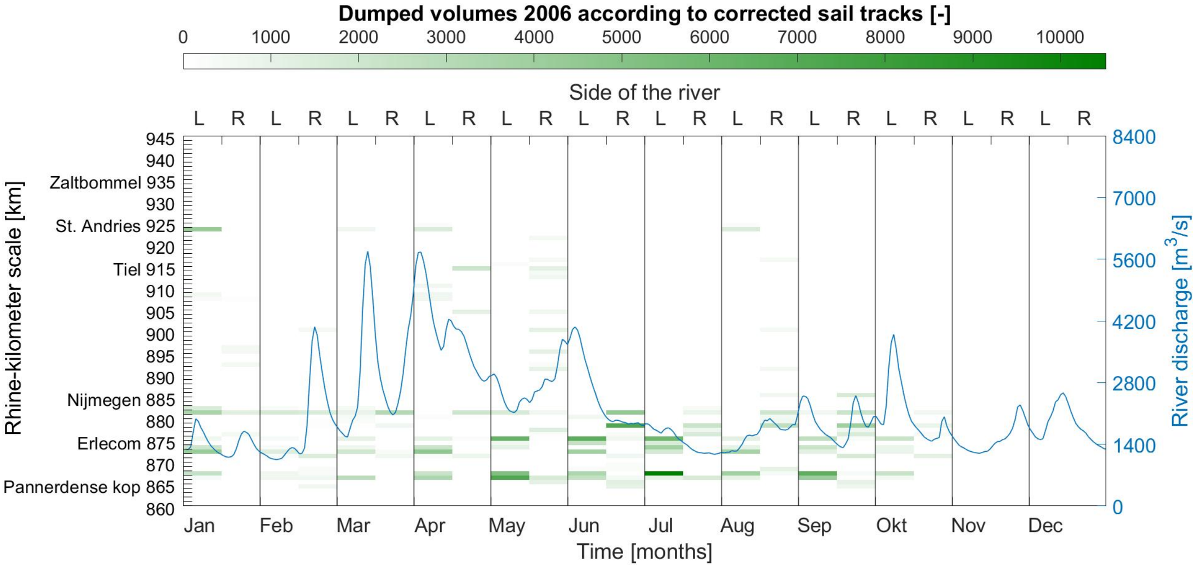


Figure H.3: 2006



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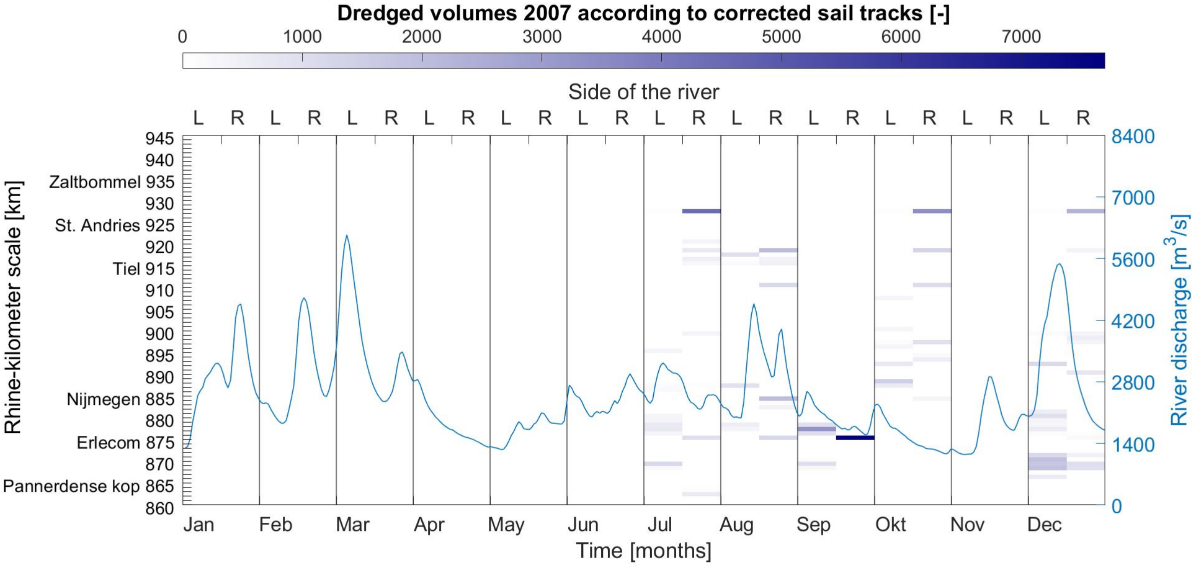

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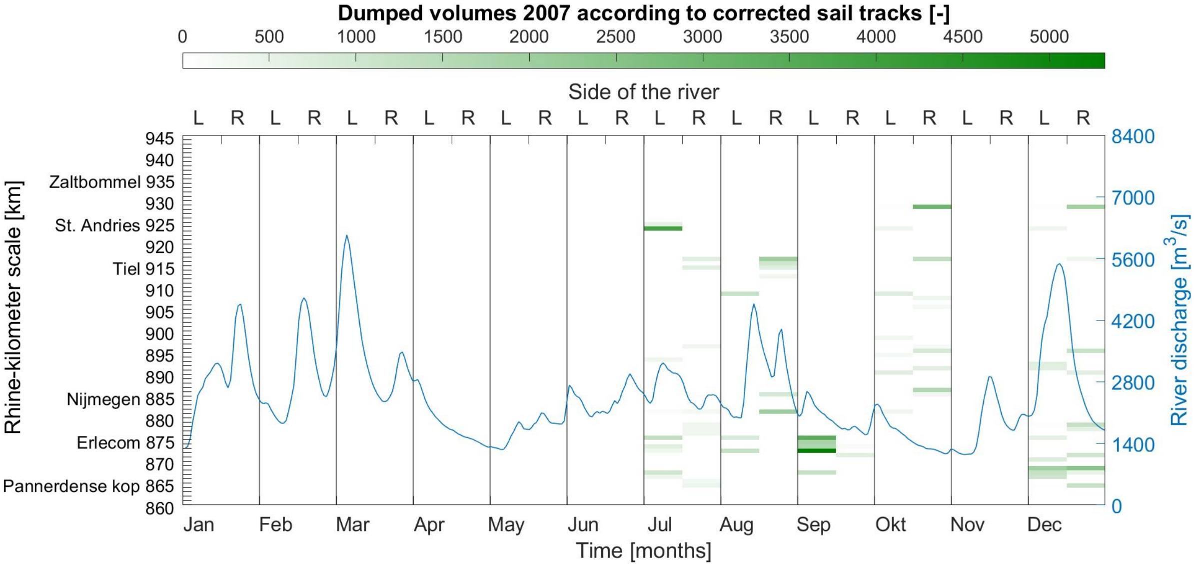

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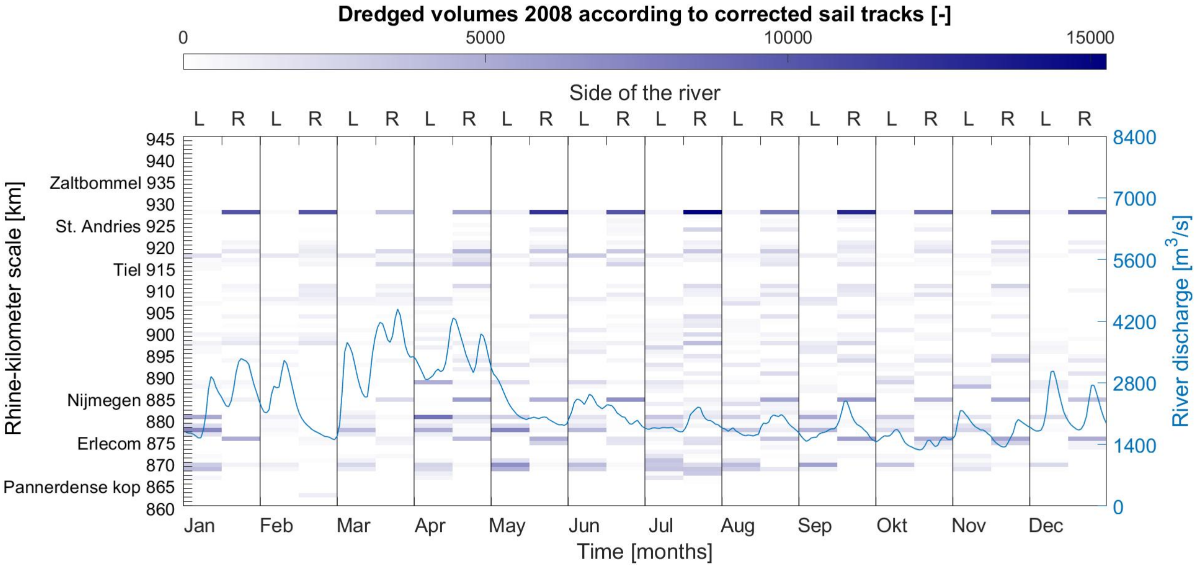
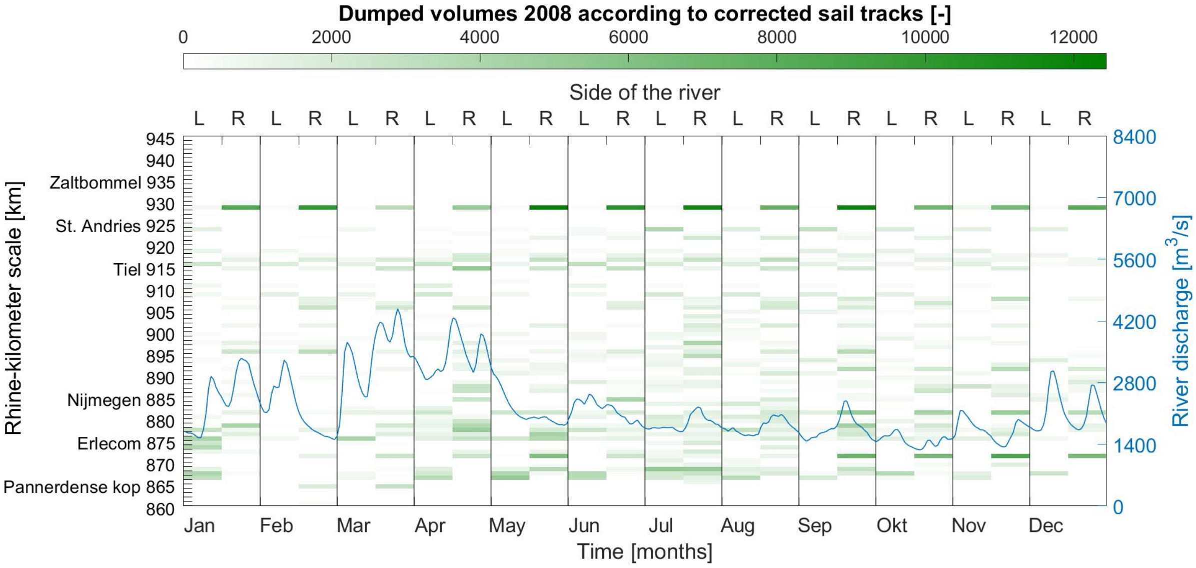


Figure H.7: 2008



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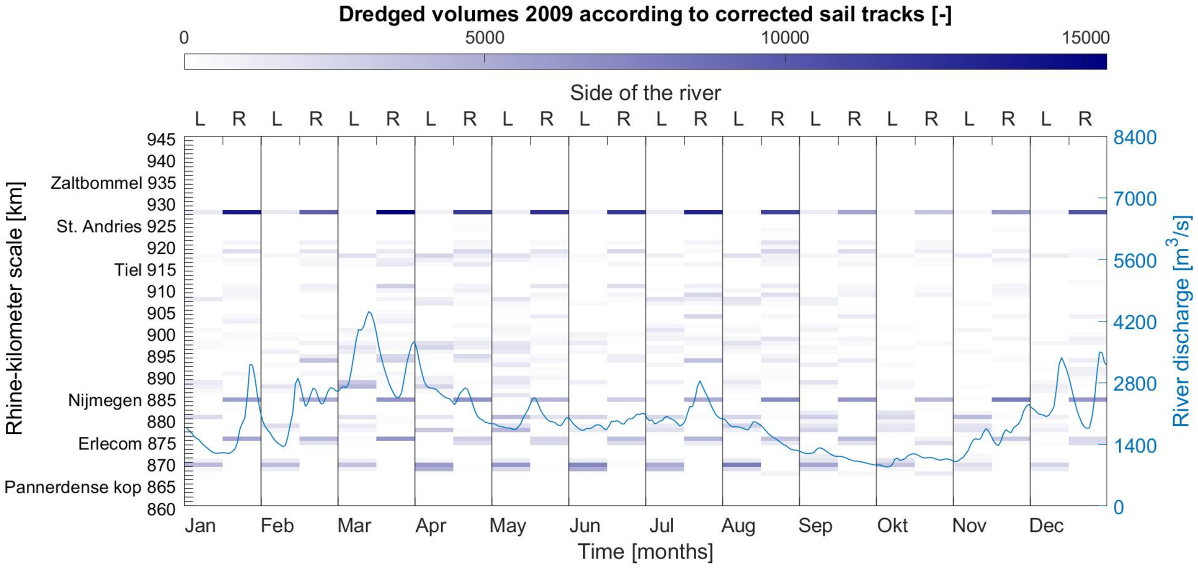


Figure H.9: 2009

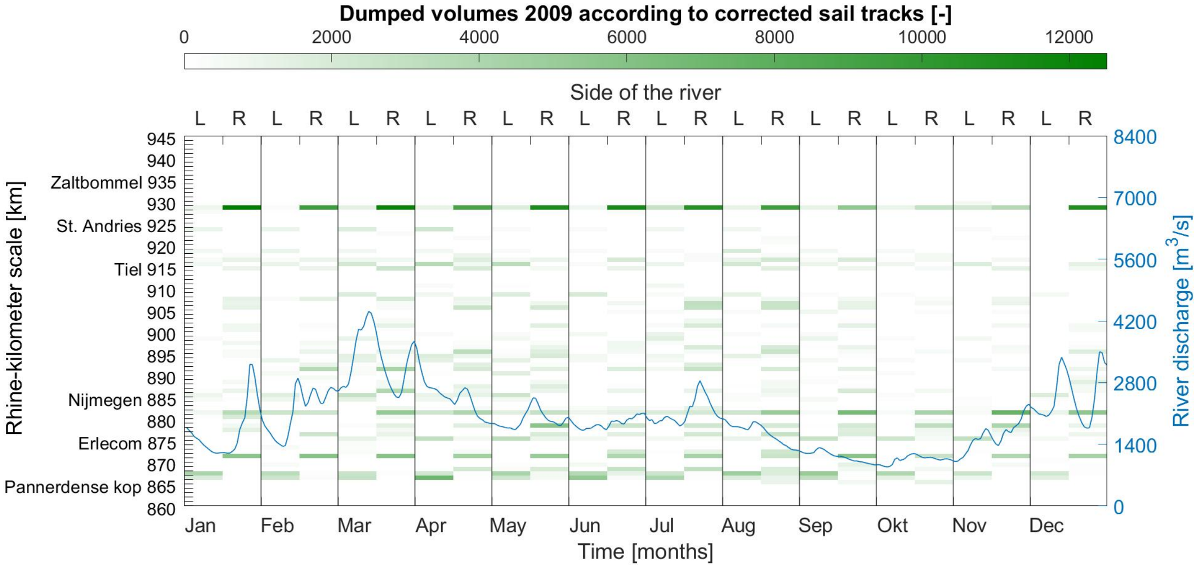


Figure H.10: 2009

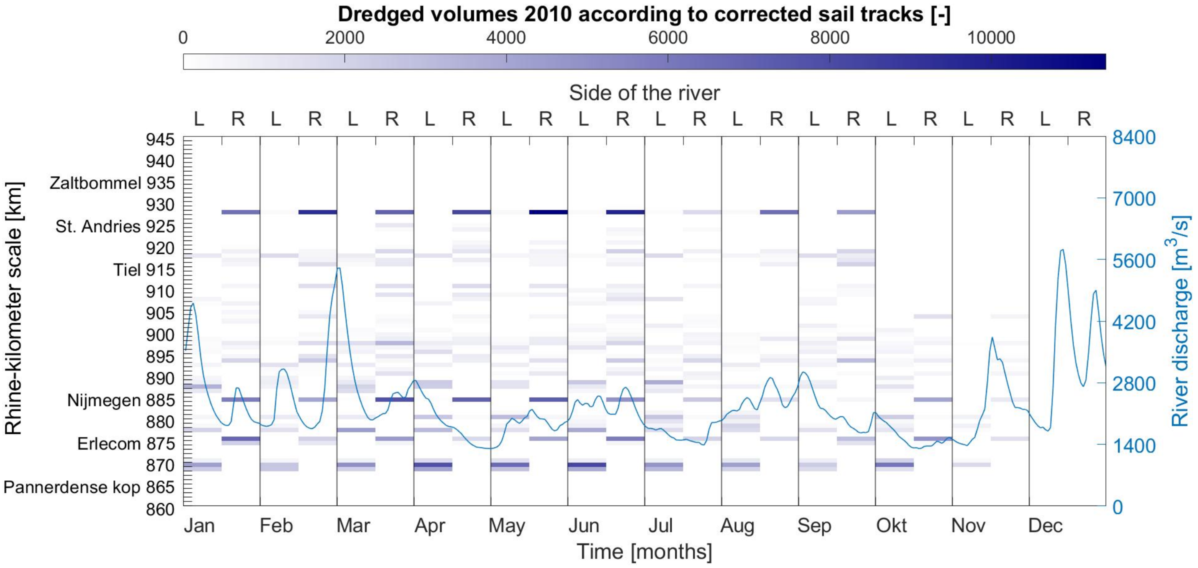


Figure H.11: 2010

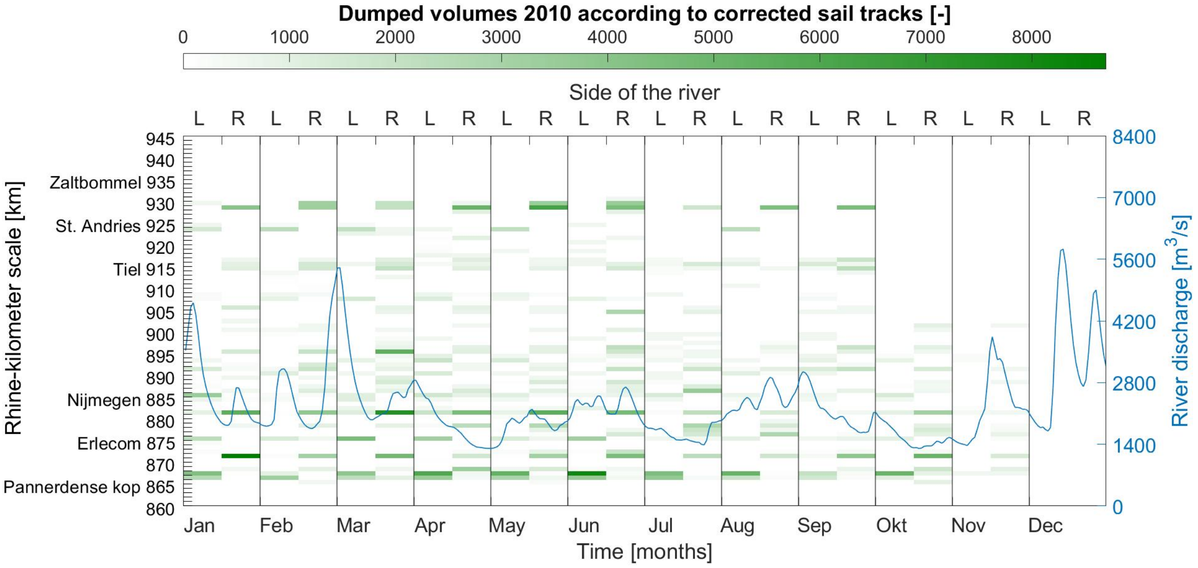


Figure H.12: 2010

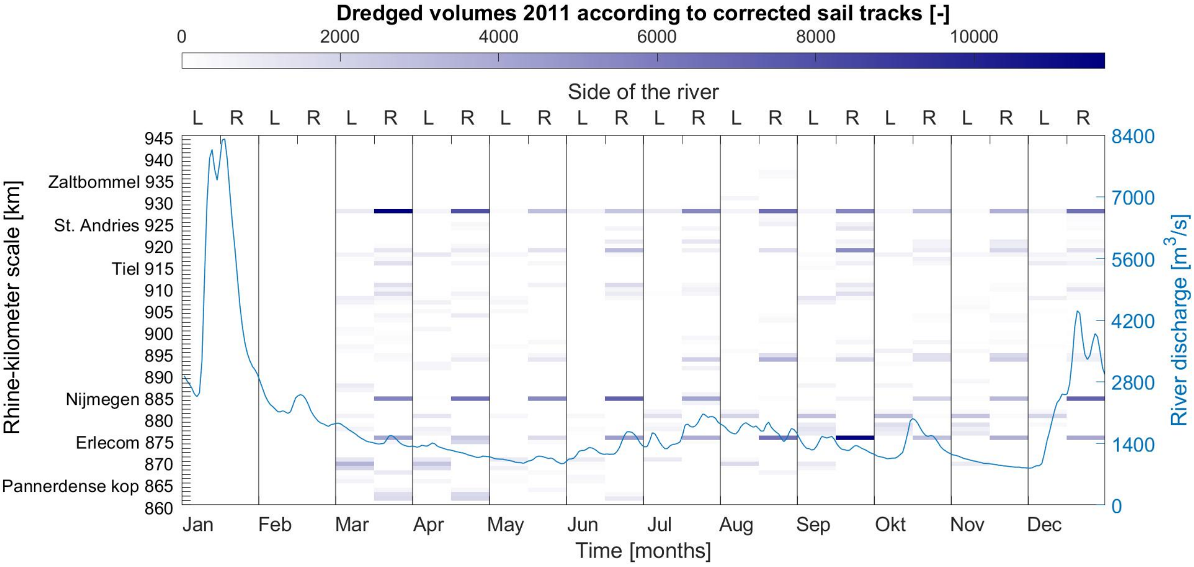
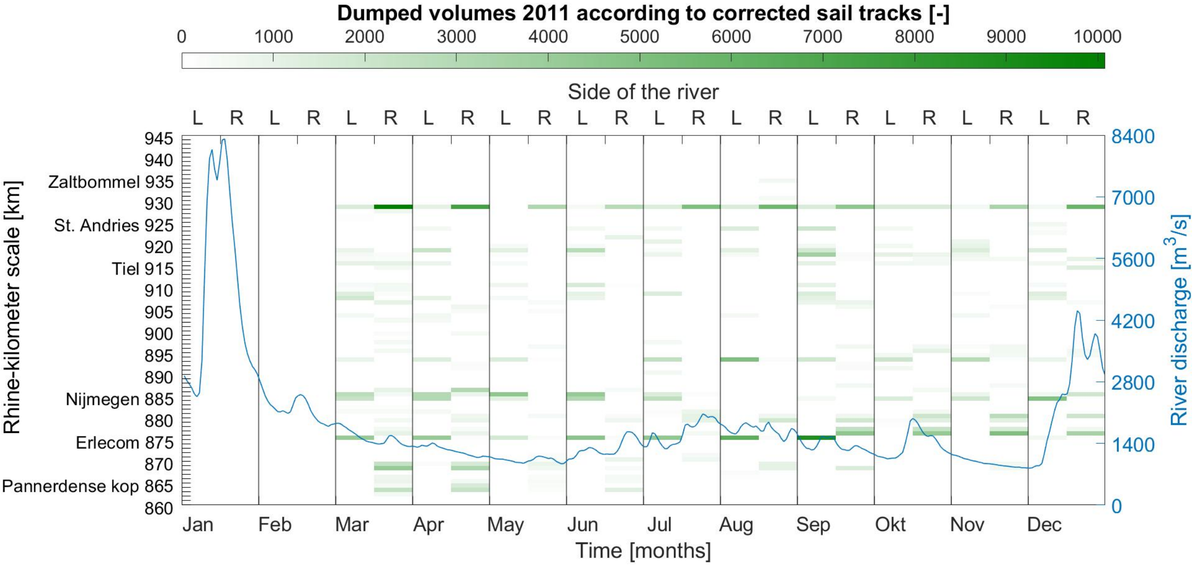


Figure H.13: 2011



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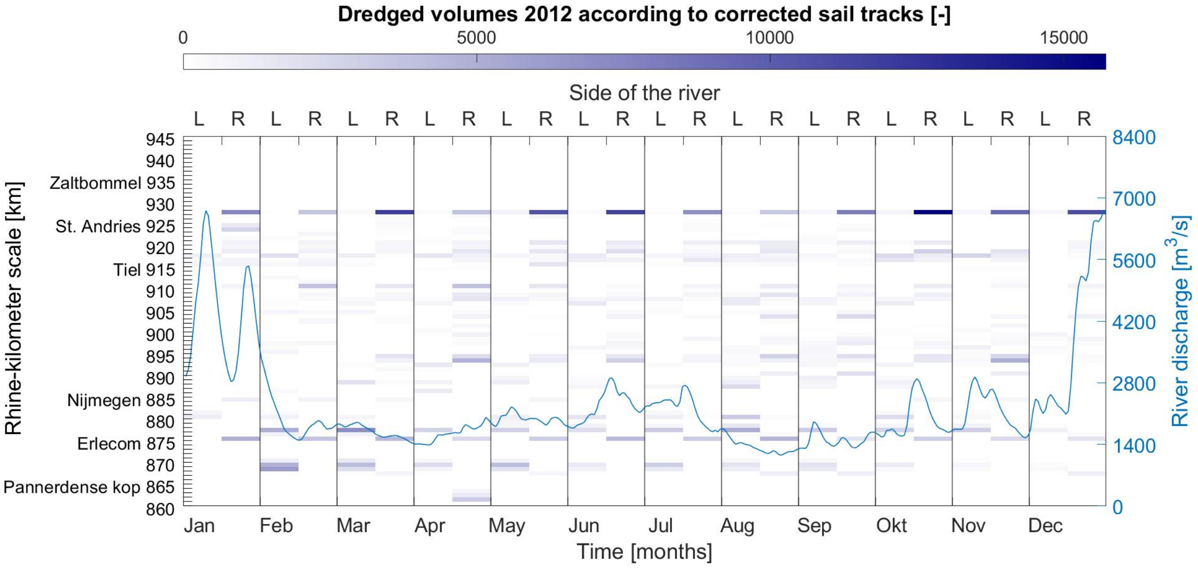
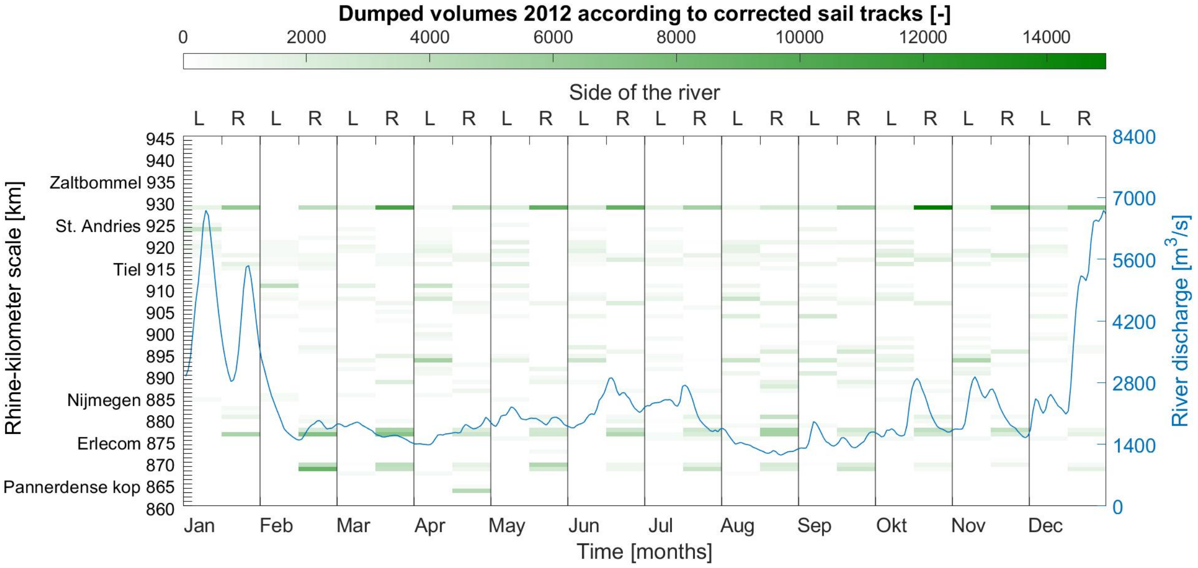


Figure H.15: 2012



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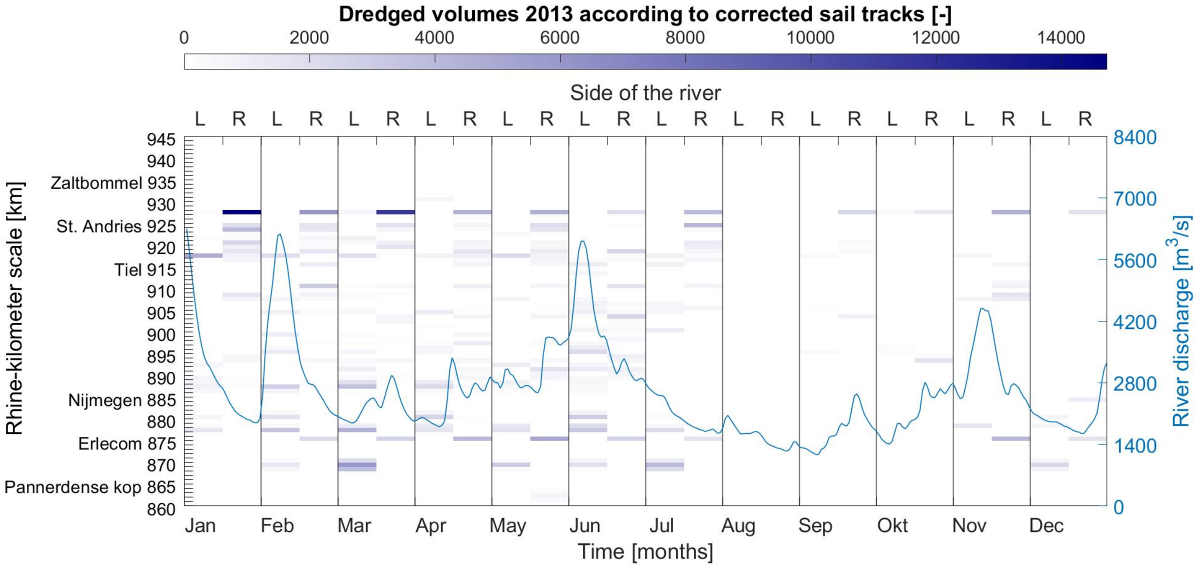


Figure H.17: 2013

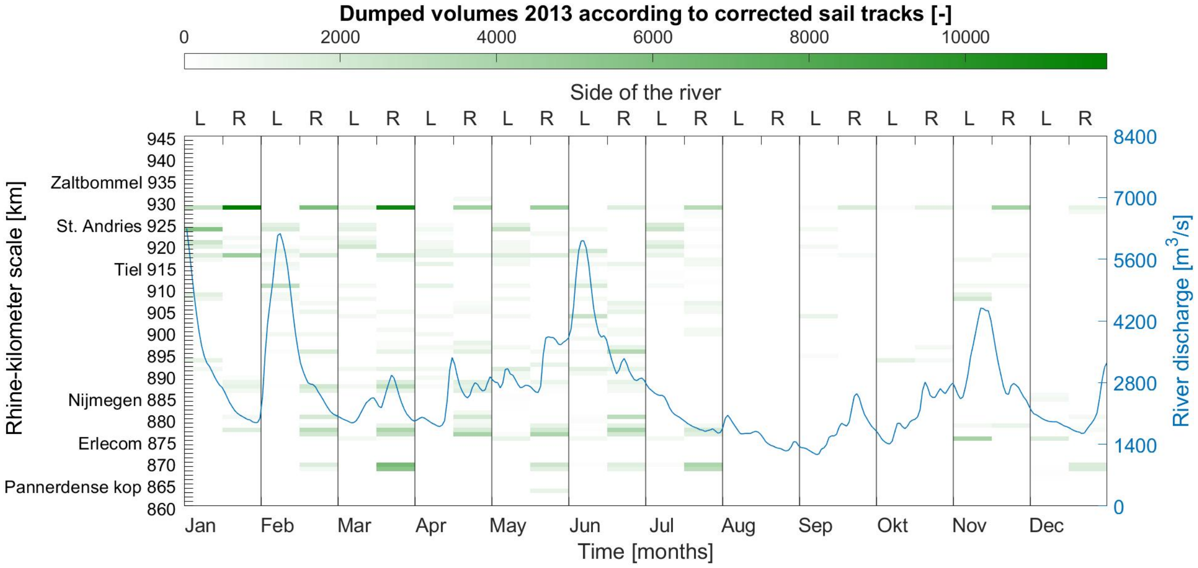


Figure H.18: 2013

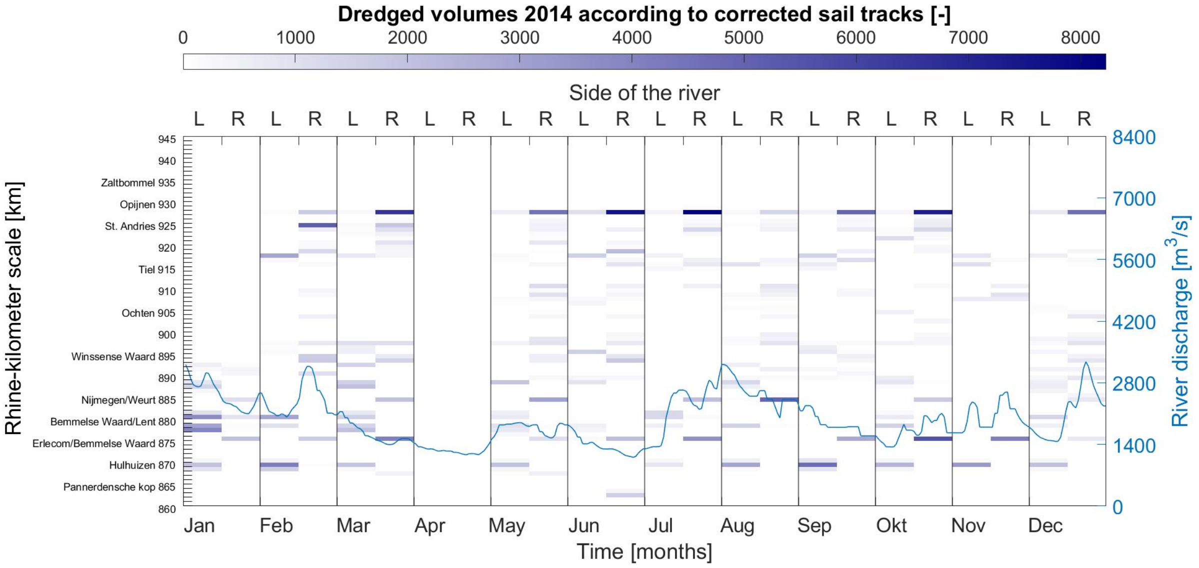


Figure H.19: 2014

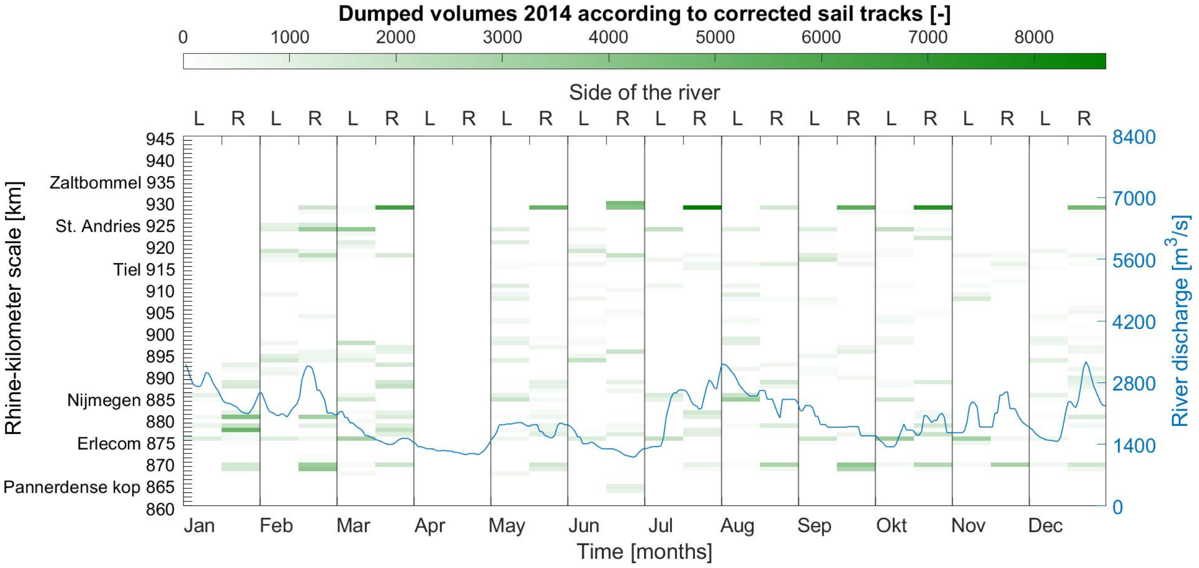


Figure H.20: 2014

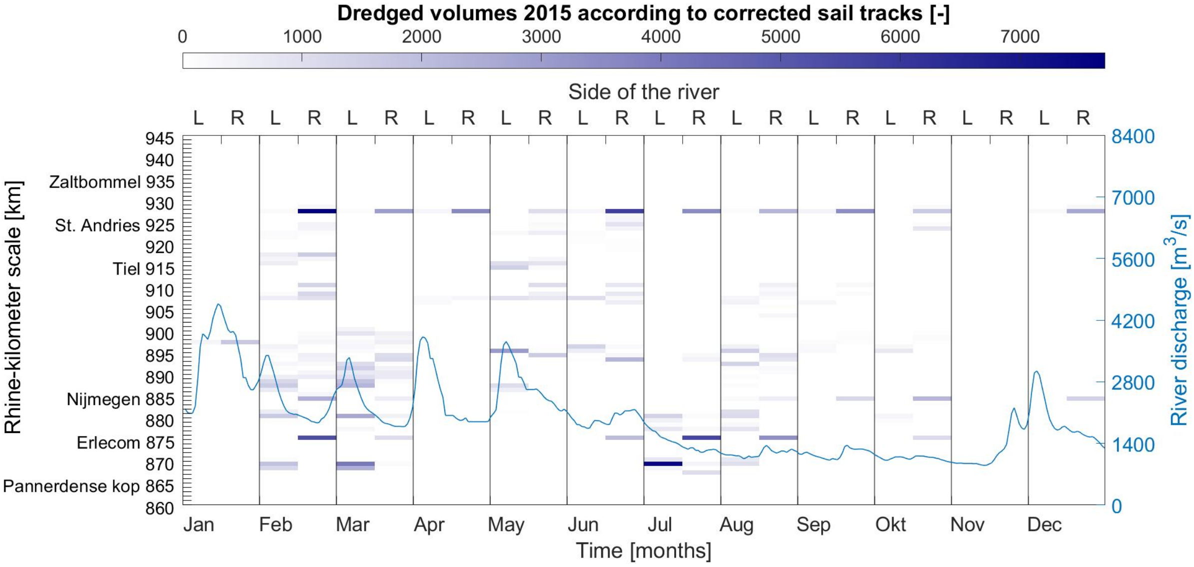


Figure H.21: 2015

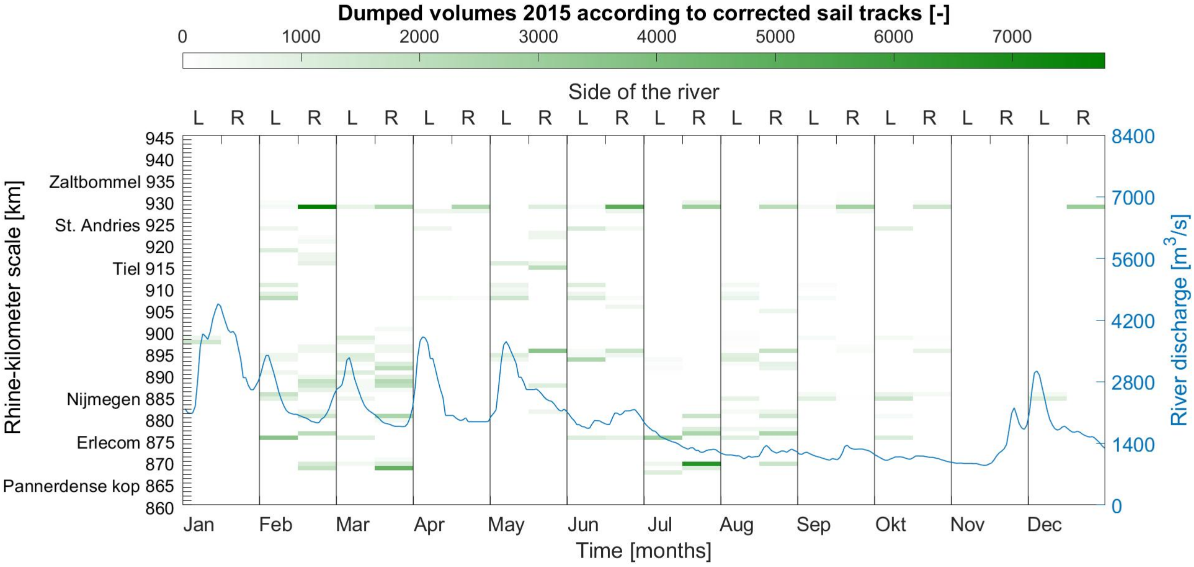


Figure H.22: 2015

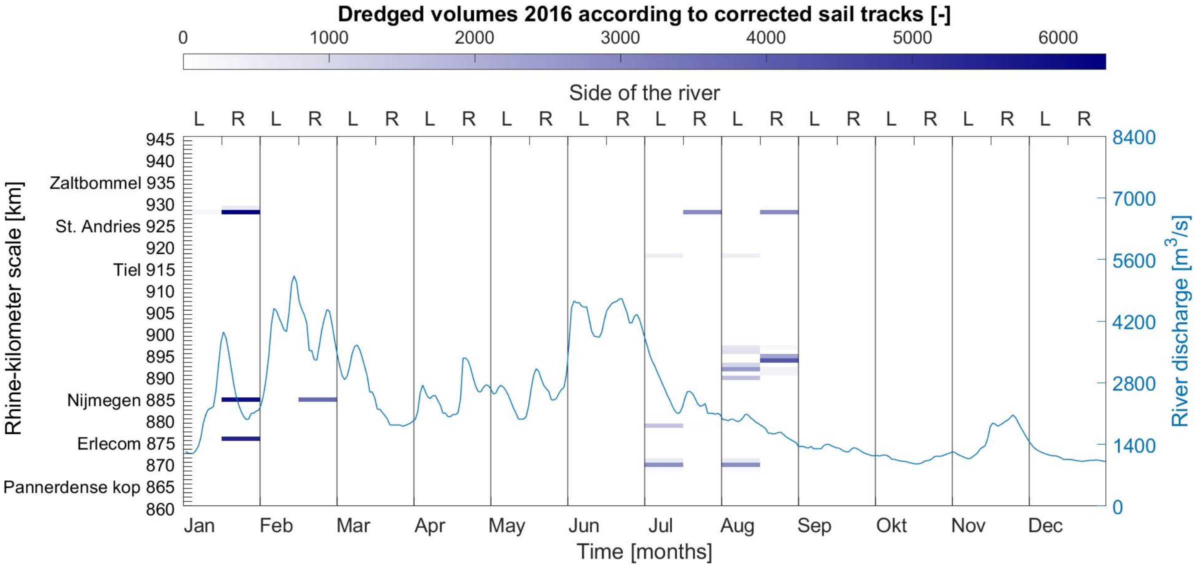


Figure H.23: 2016

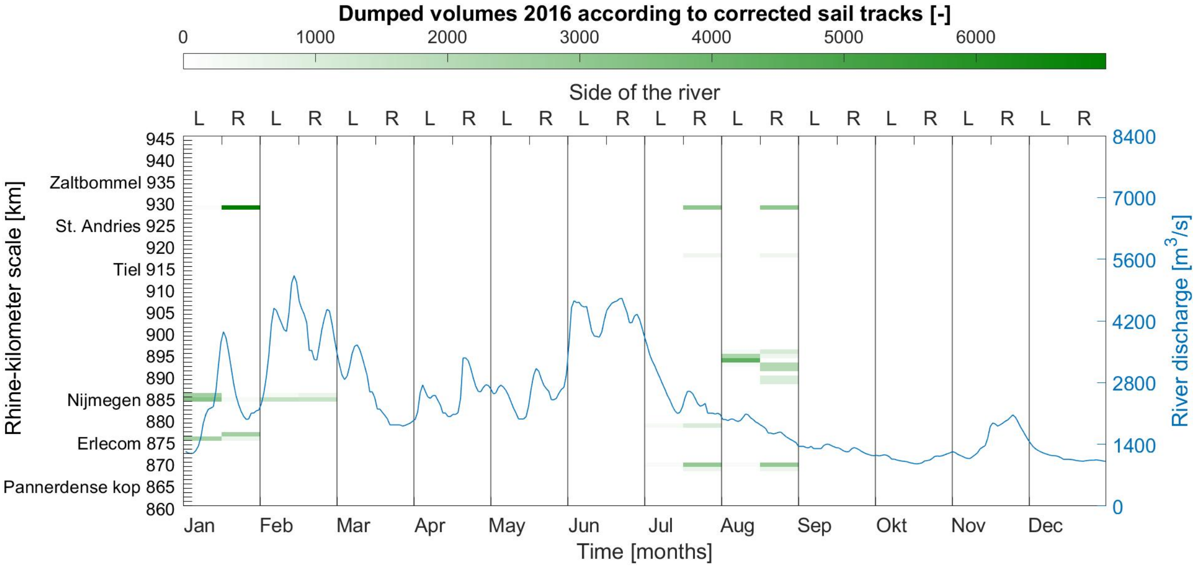


Figure H.24: 2016

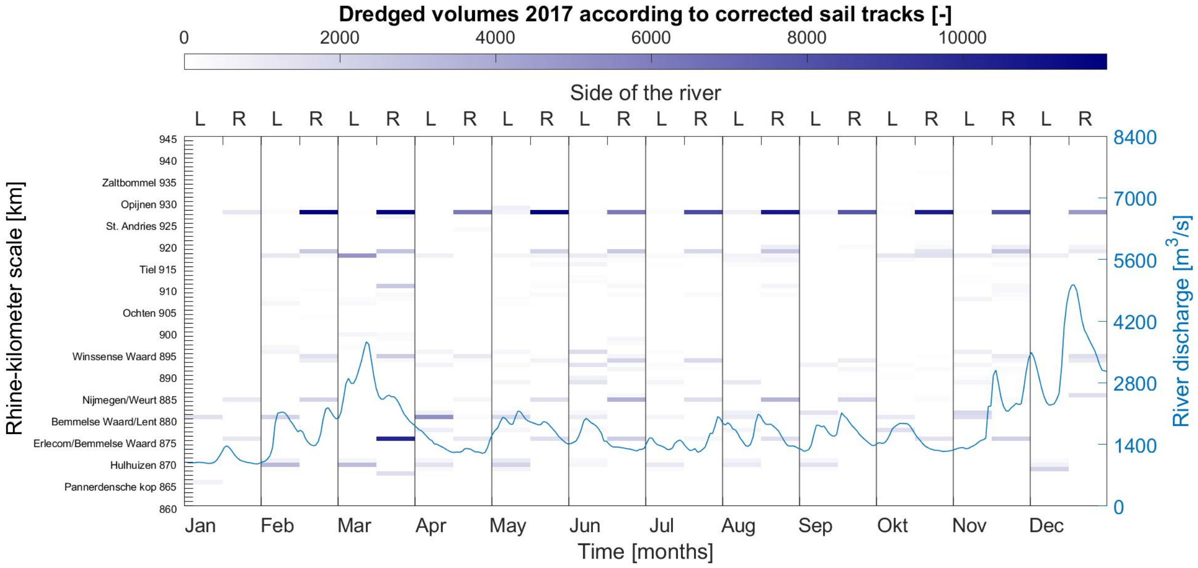


Figure H.25: 2017

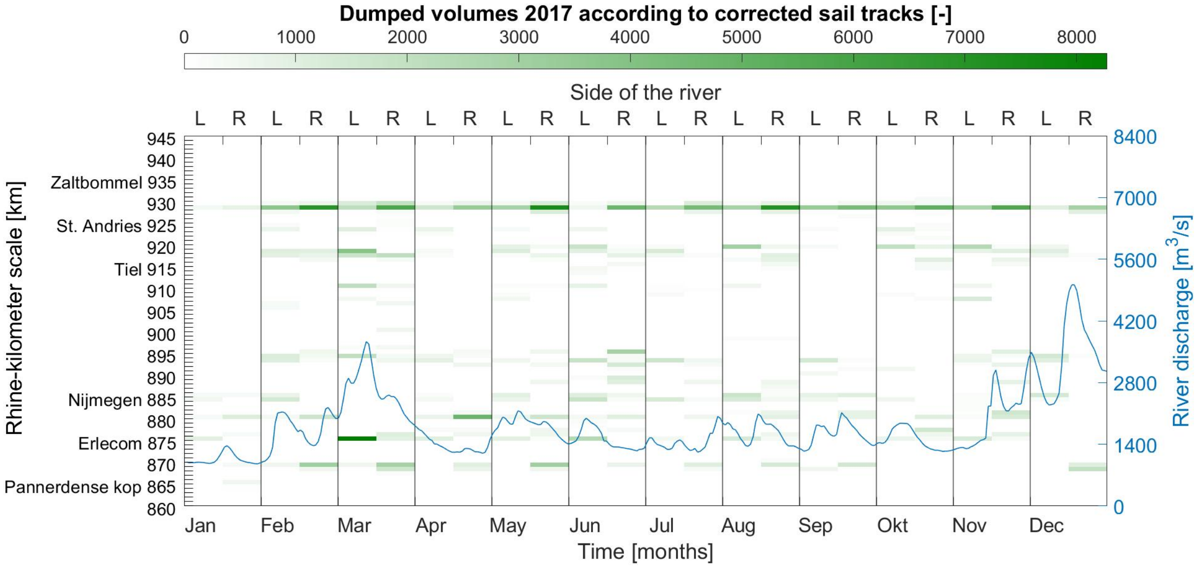


Figure H.26: 2017

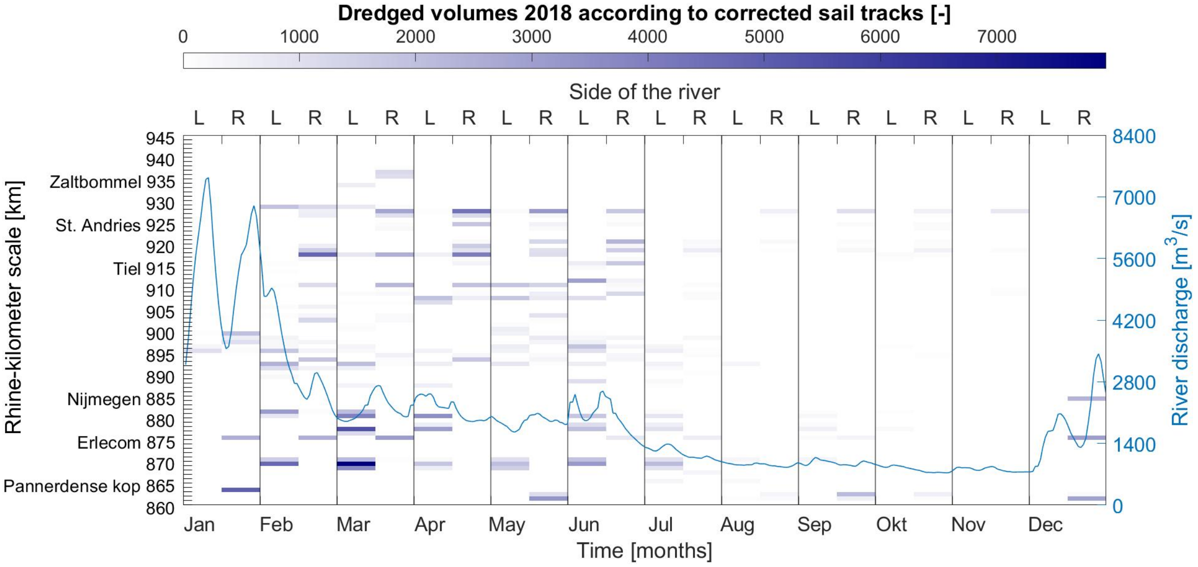


Figure H.27: 2018

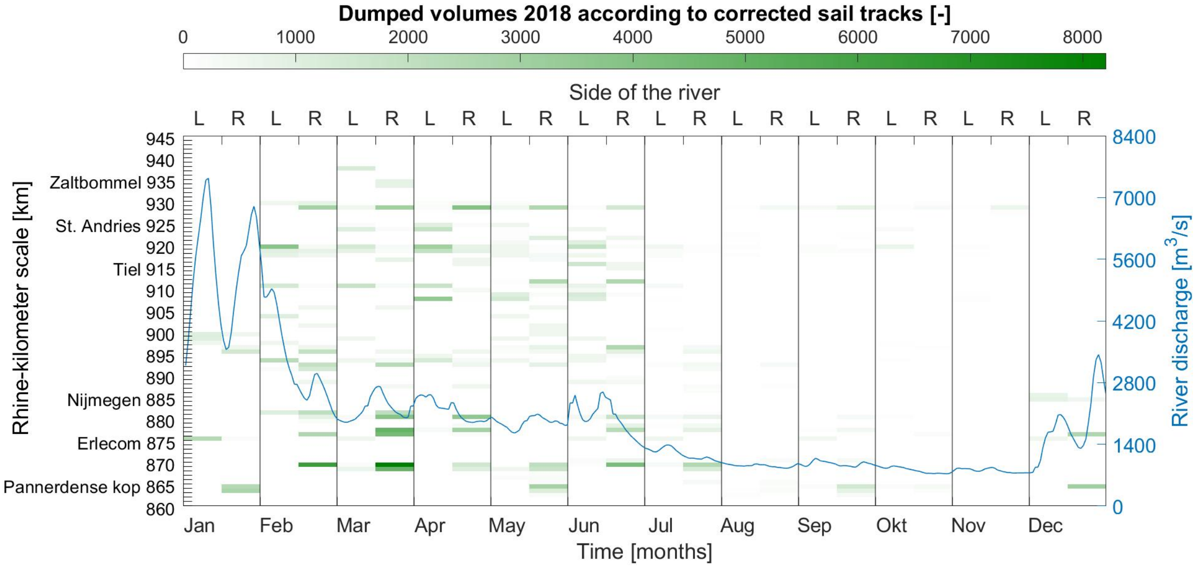


Figure H.28: 2018

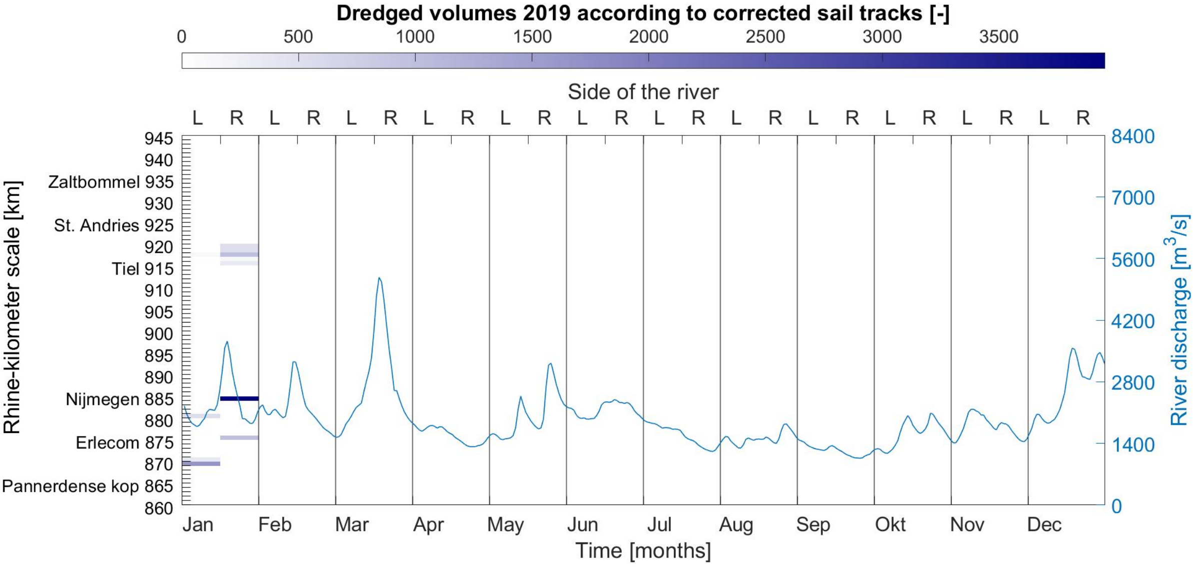


Figure H.29: 2019

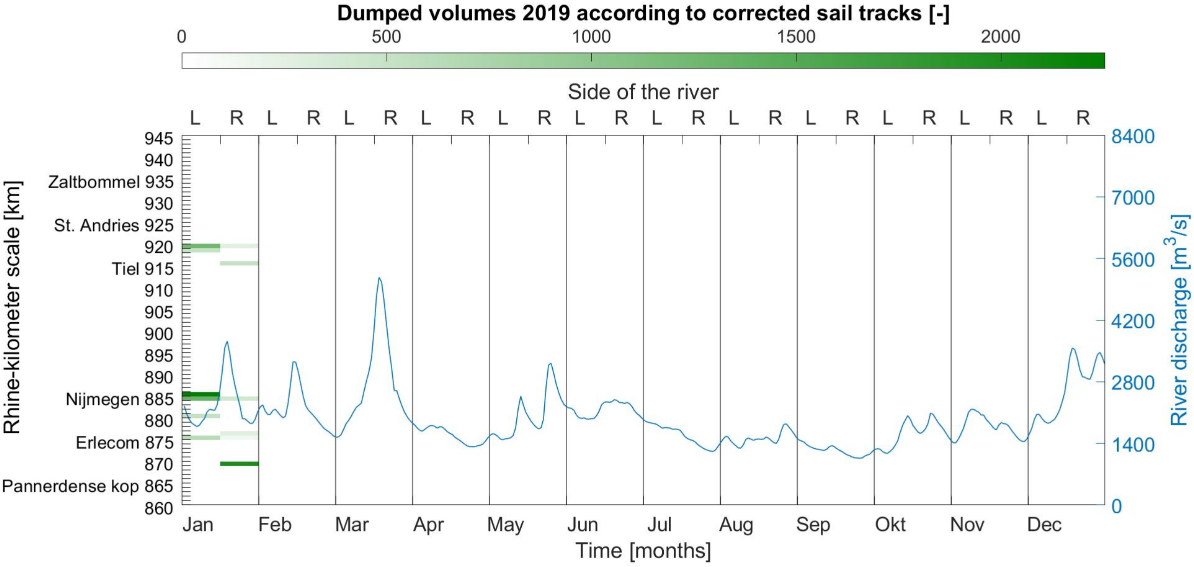


Figure H.30: 2019

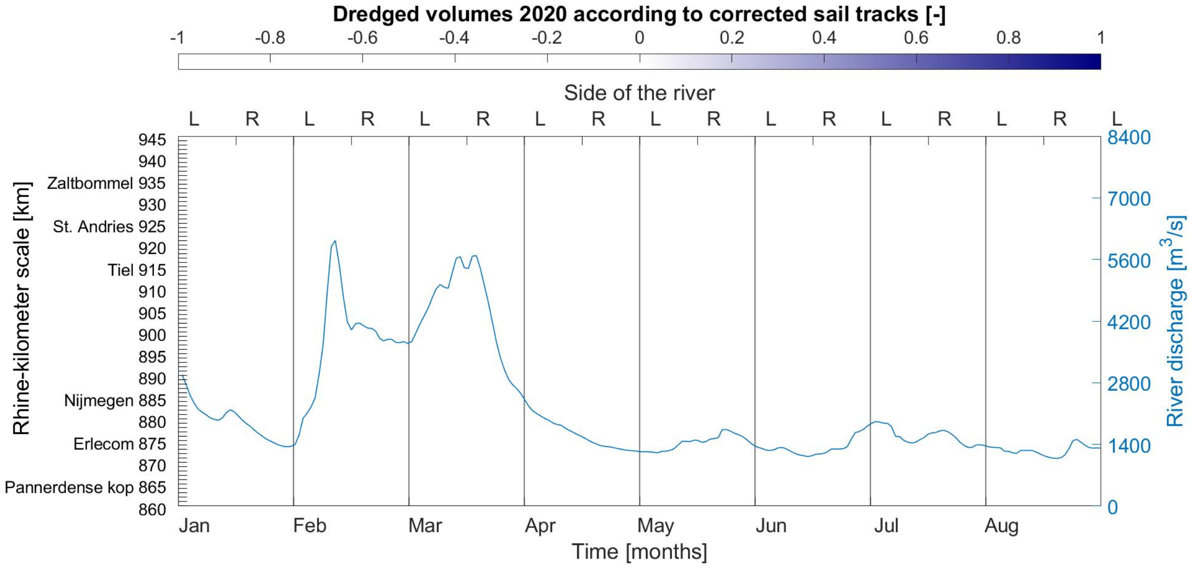


Figure H.31: 2020

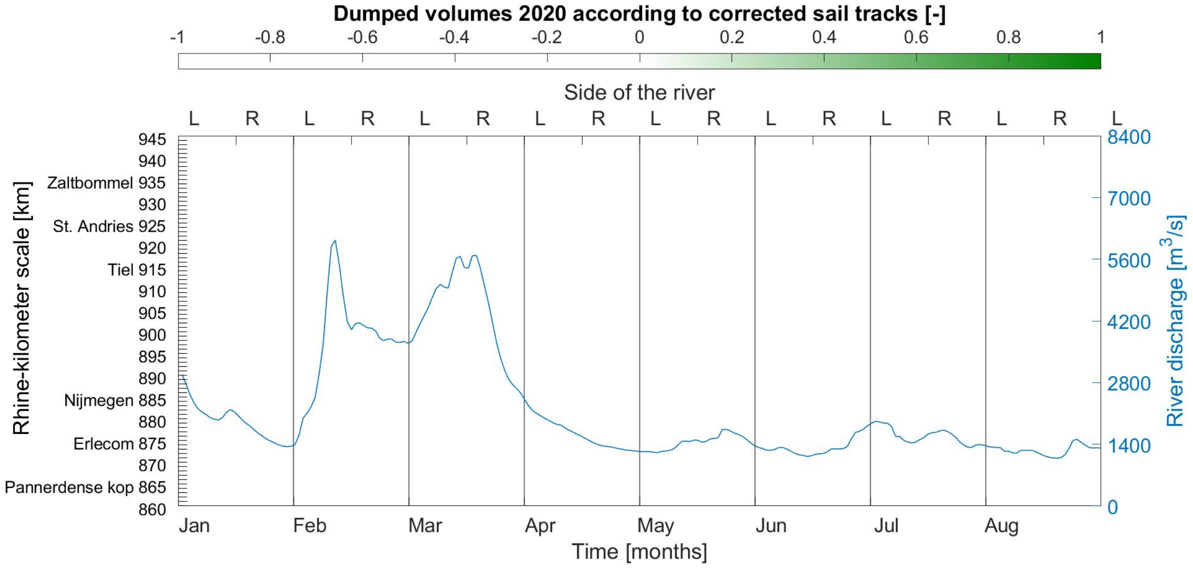


Figure H.32: 2020

H.2. Dredging locations according to BRW data

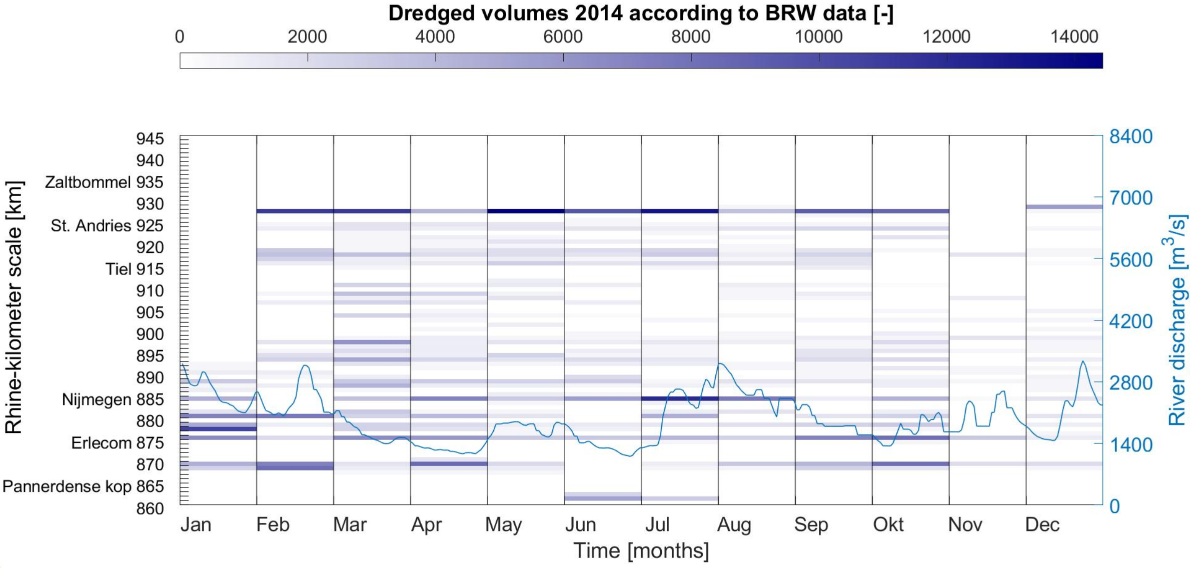


Figure H.33: 2014

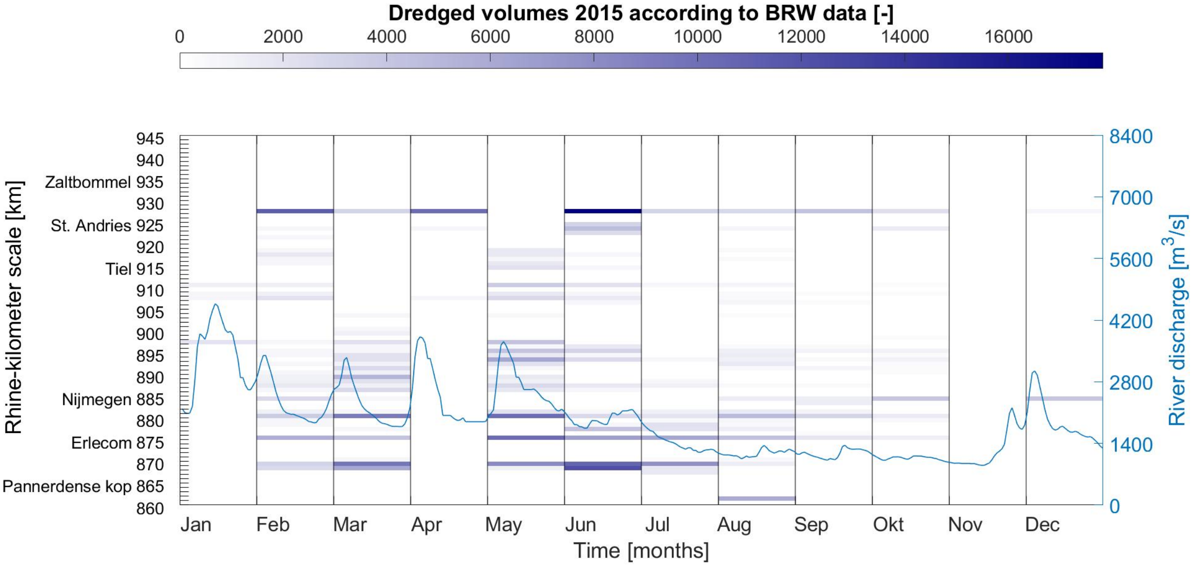


Figure H.34: 2015

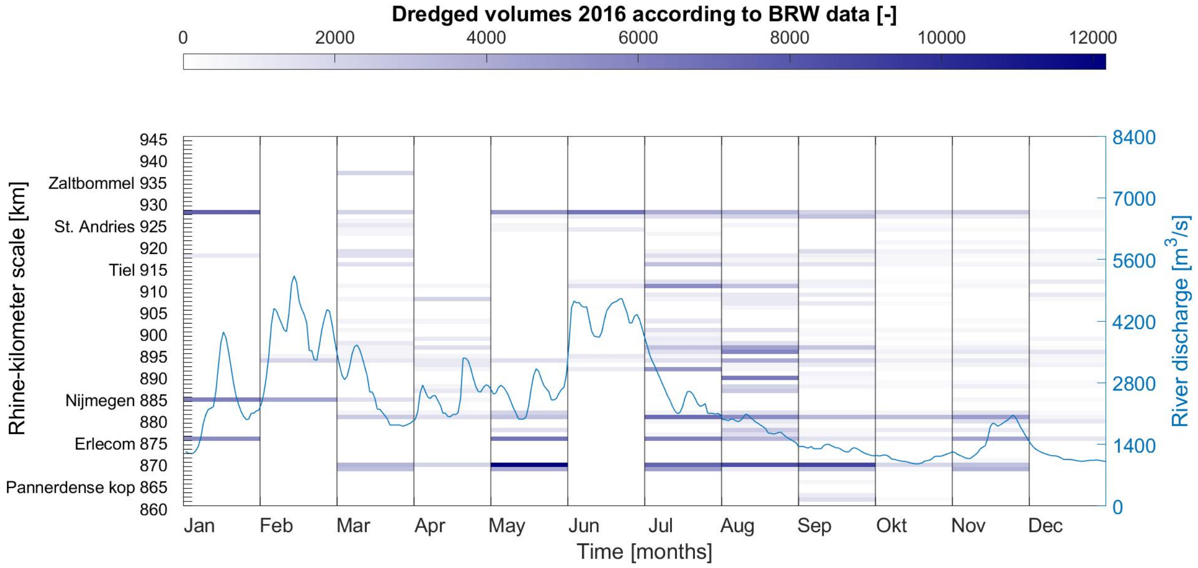


Figure H.35: 2016

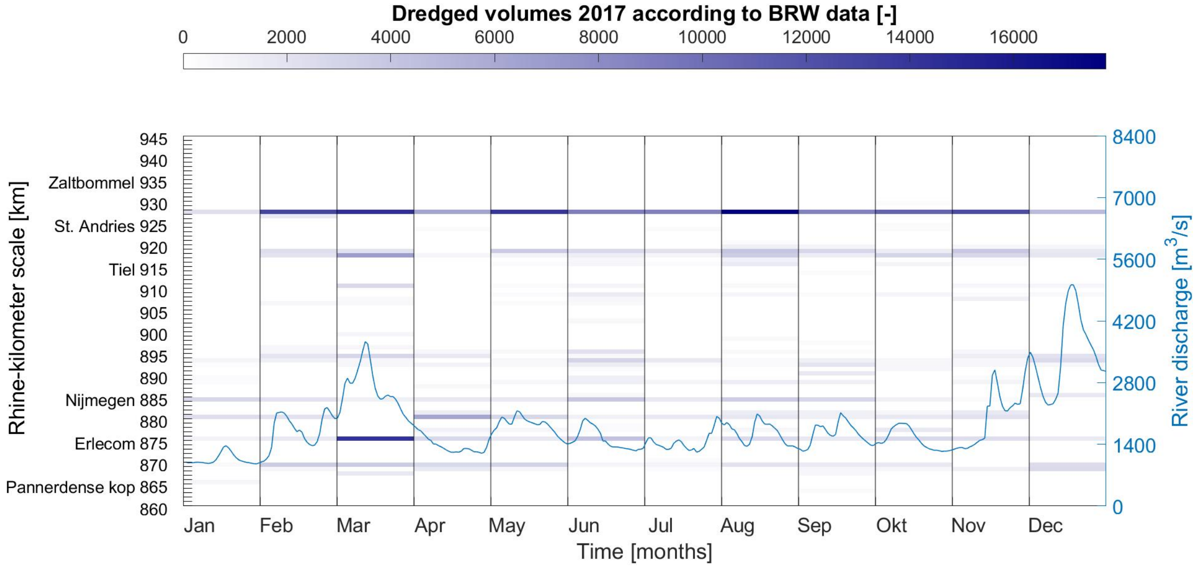


Figure H.36: 2017

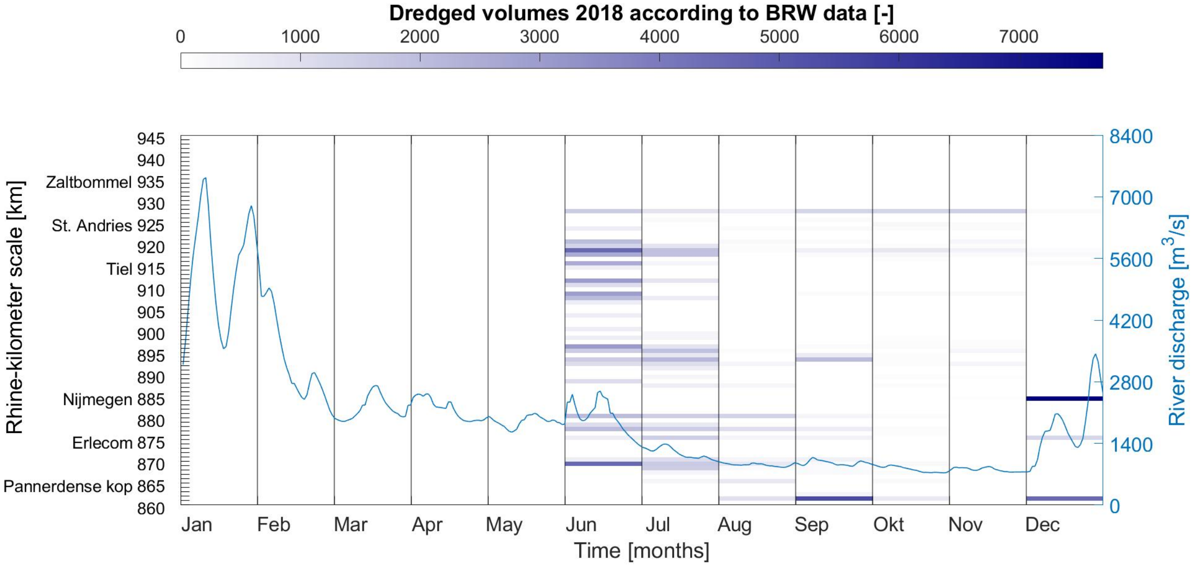


Figure H.37: 2018

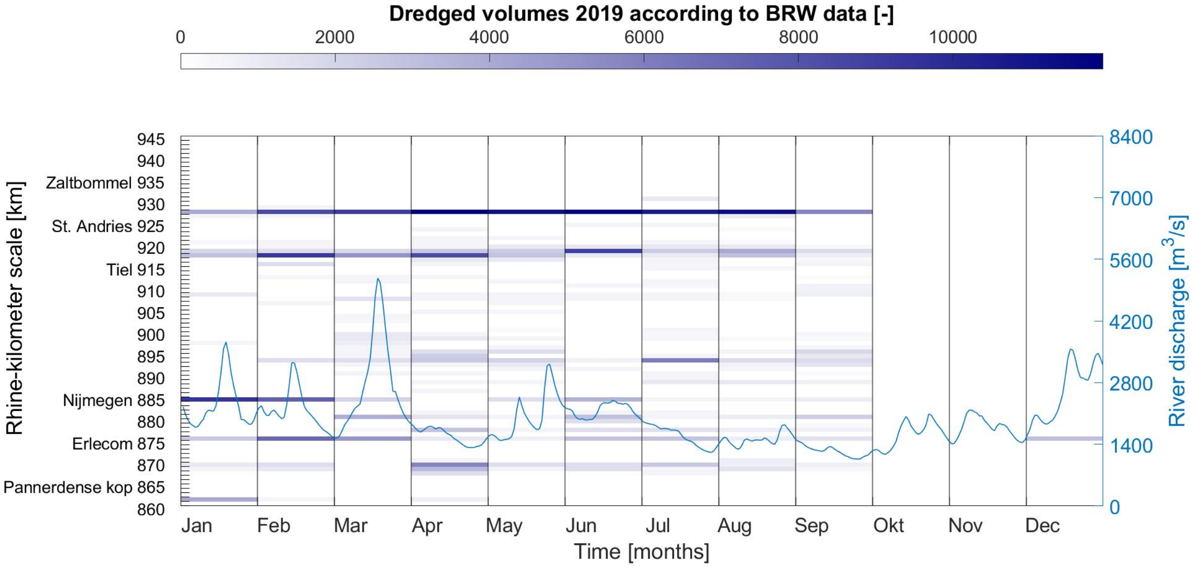


Figure H.38: 2019

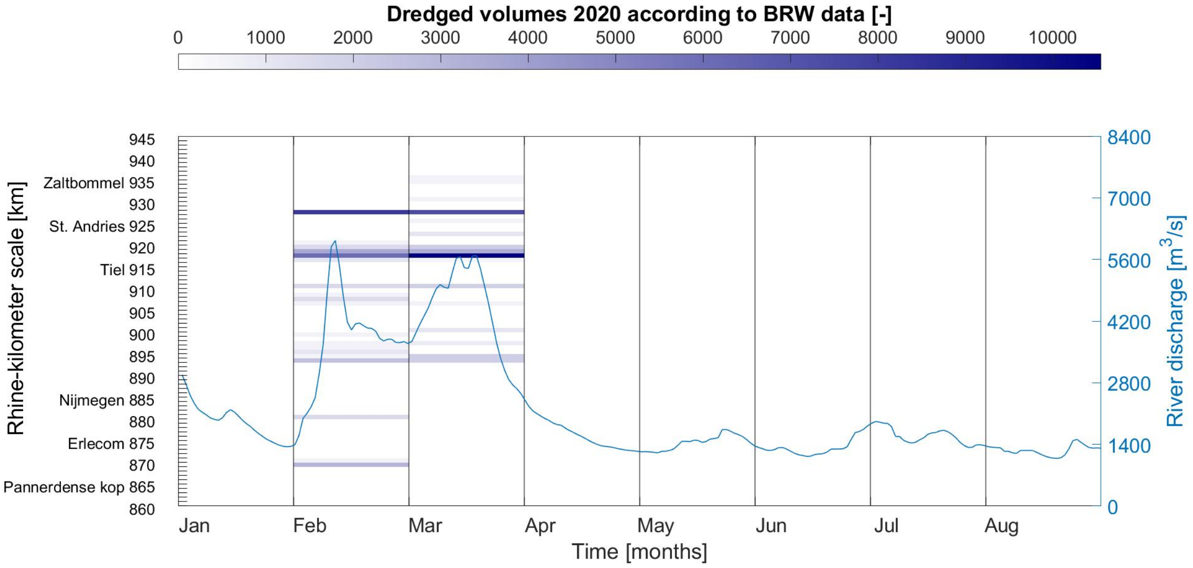


Figure H.39: 2020

H.3. Plowing locations according to reduced sail tracks

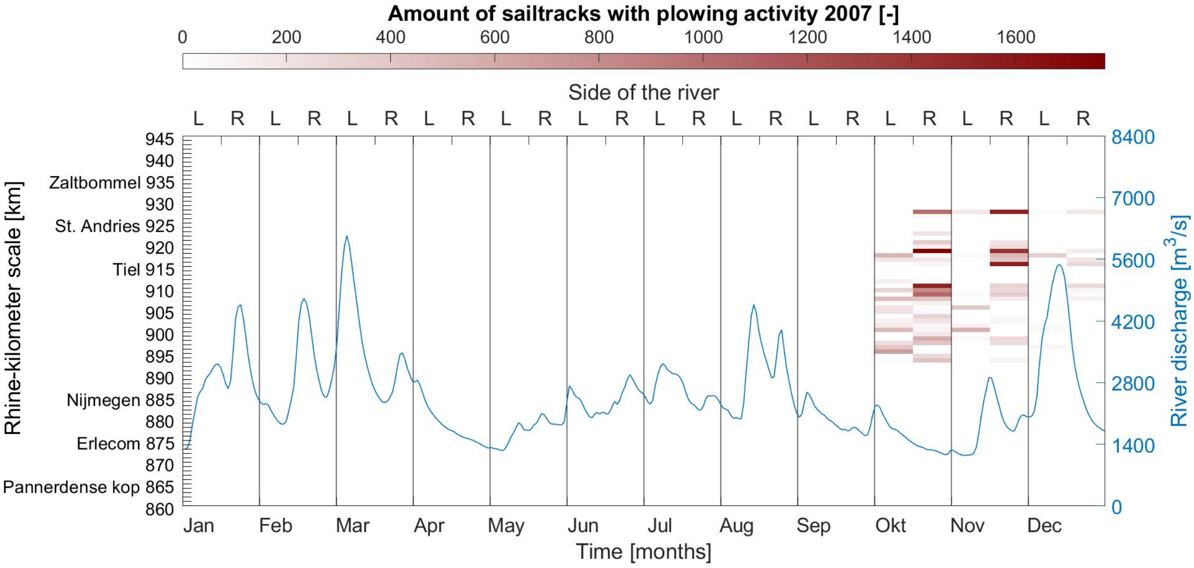


Figure H.40: 2007

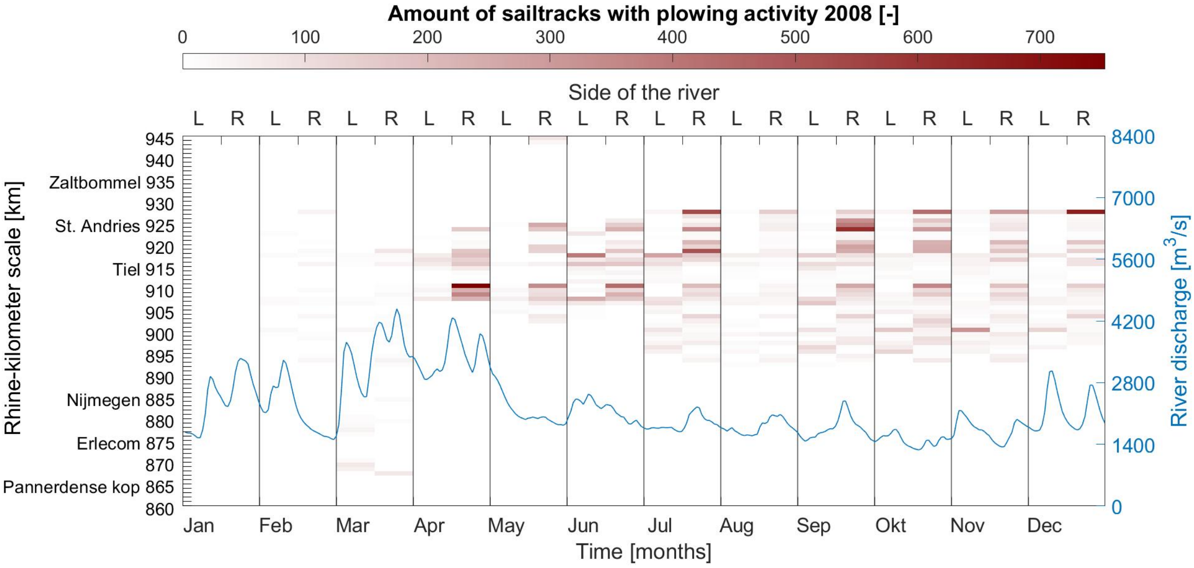


Figure H.41: 2008

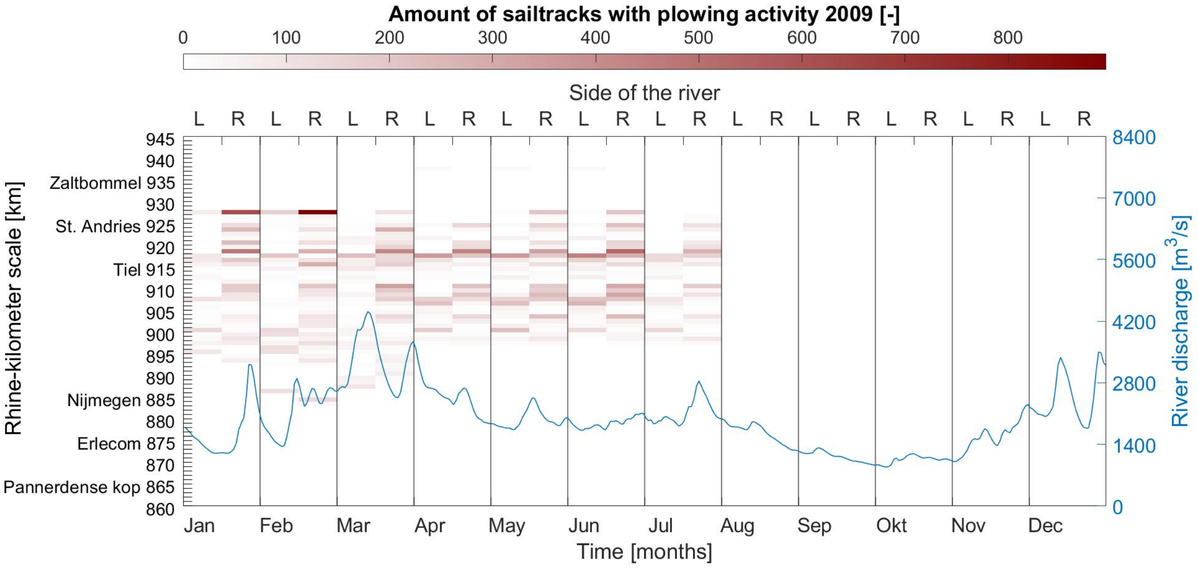


Figure H.42: 2009

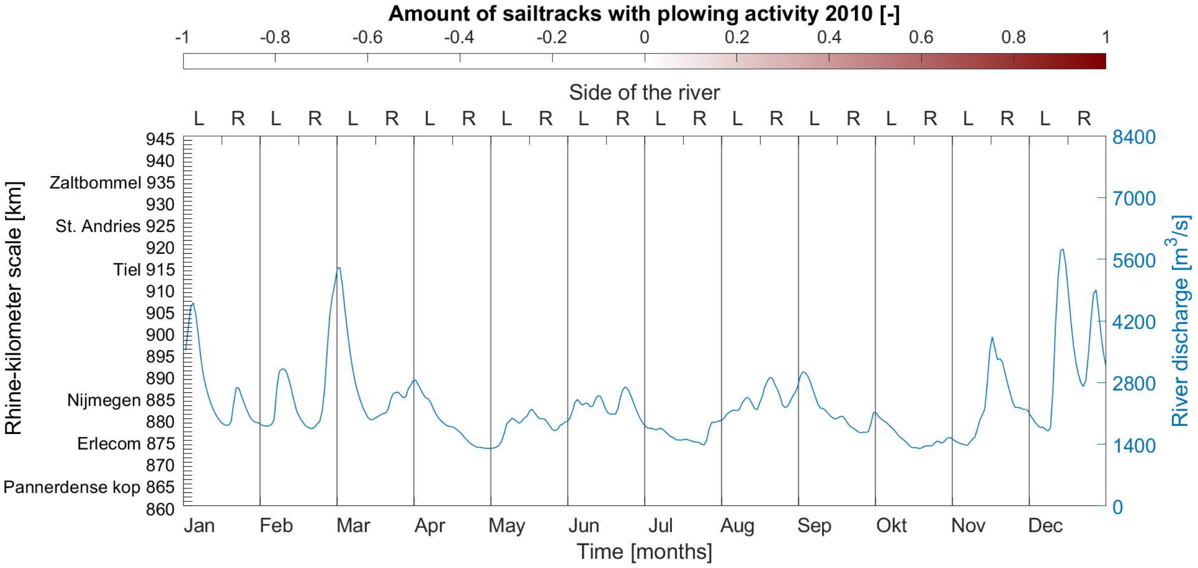


Figure H.43: 2010

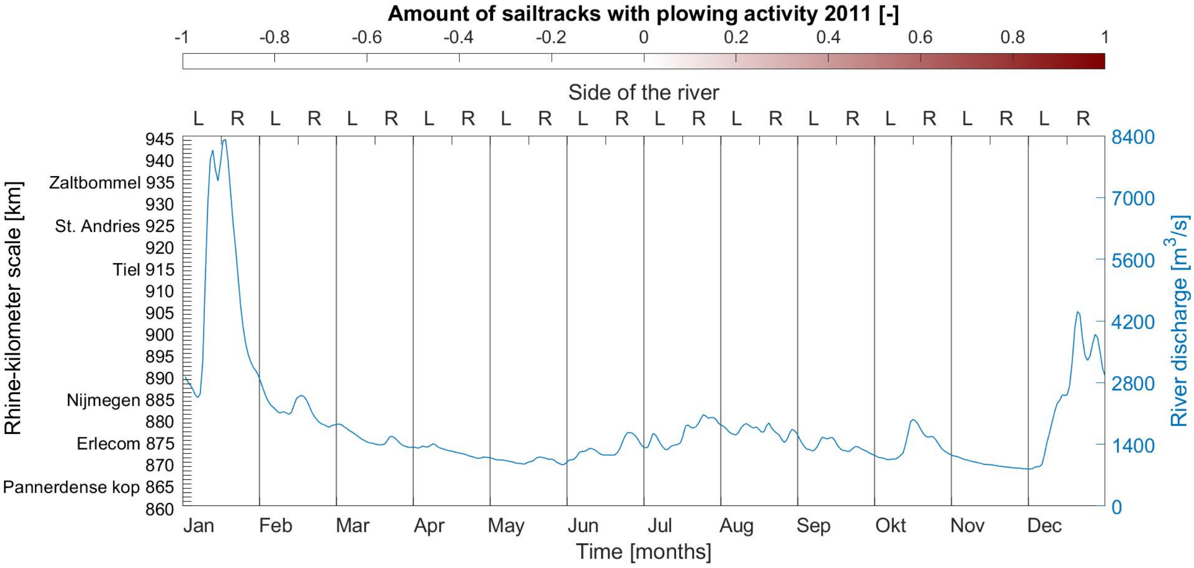


Figure H.44: 2011

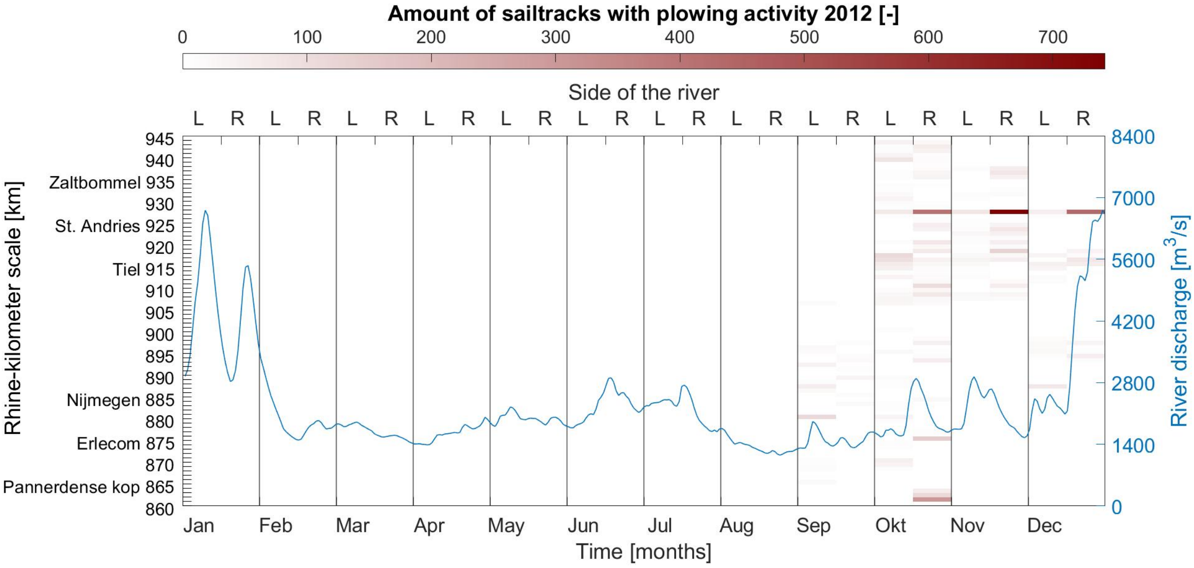


Figure H.45: 2012

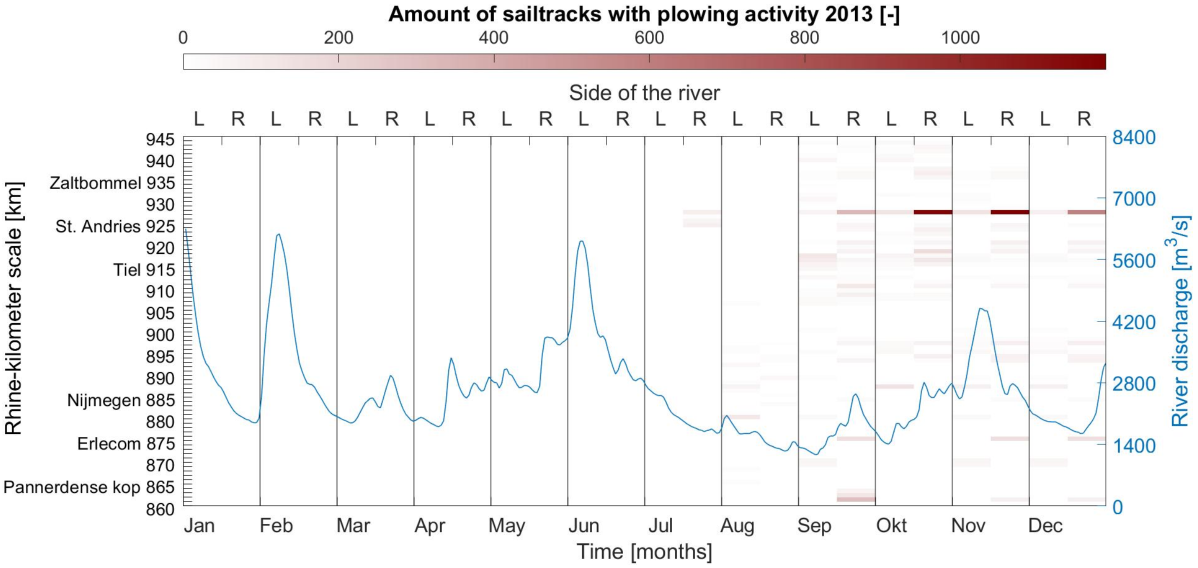


Figure H.46: 2013

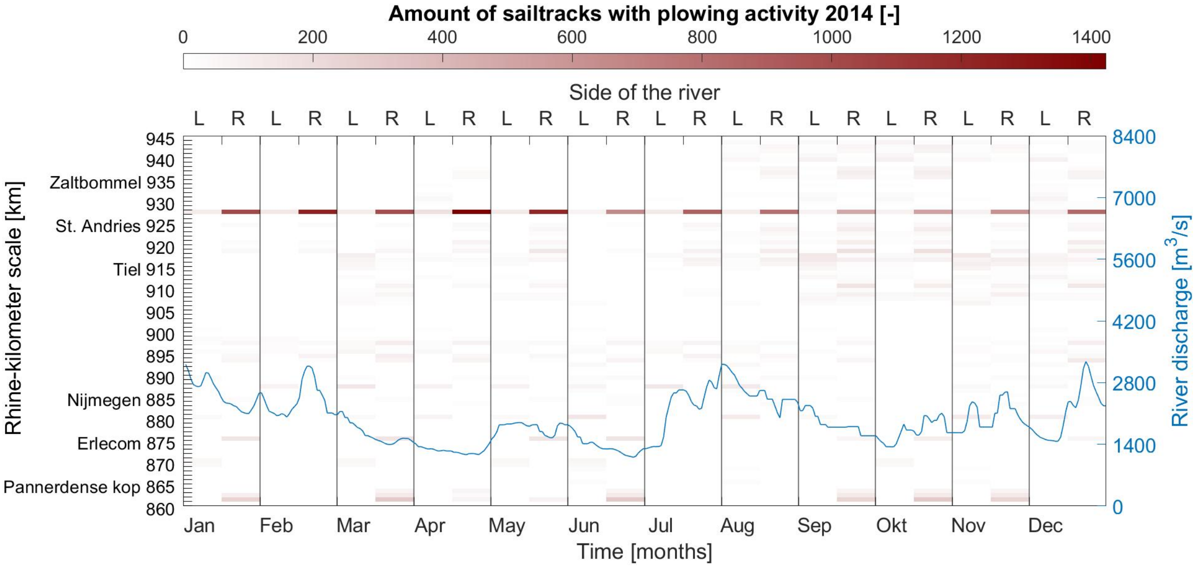


Figure H.47: 2014

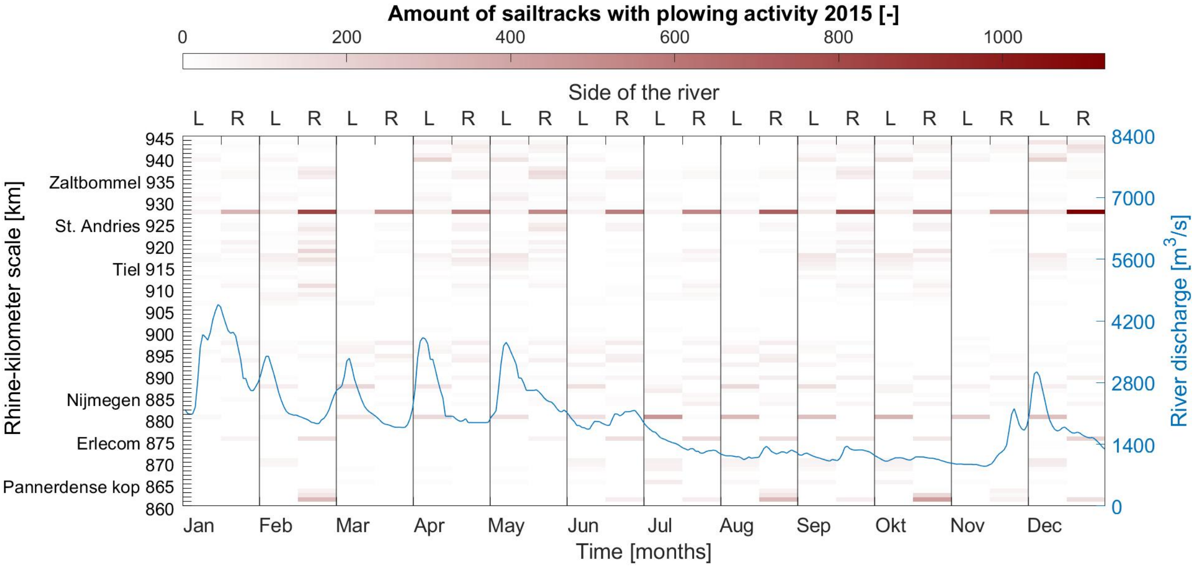


Figure H.48: 2015

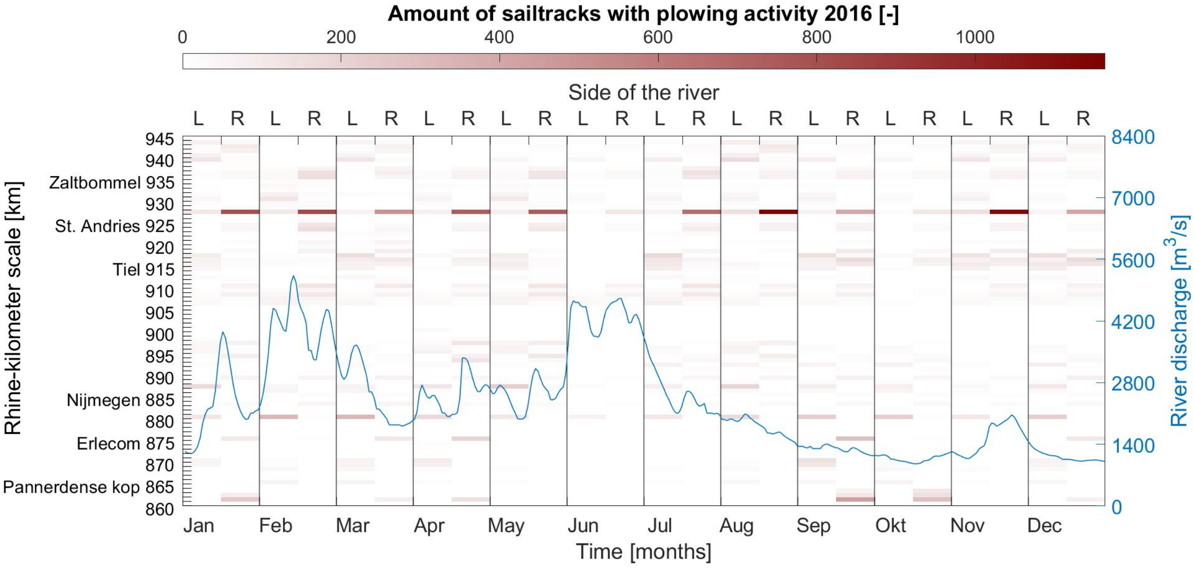


Figure H.49: 2016

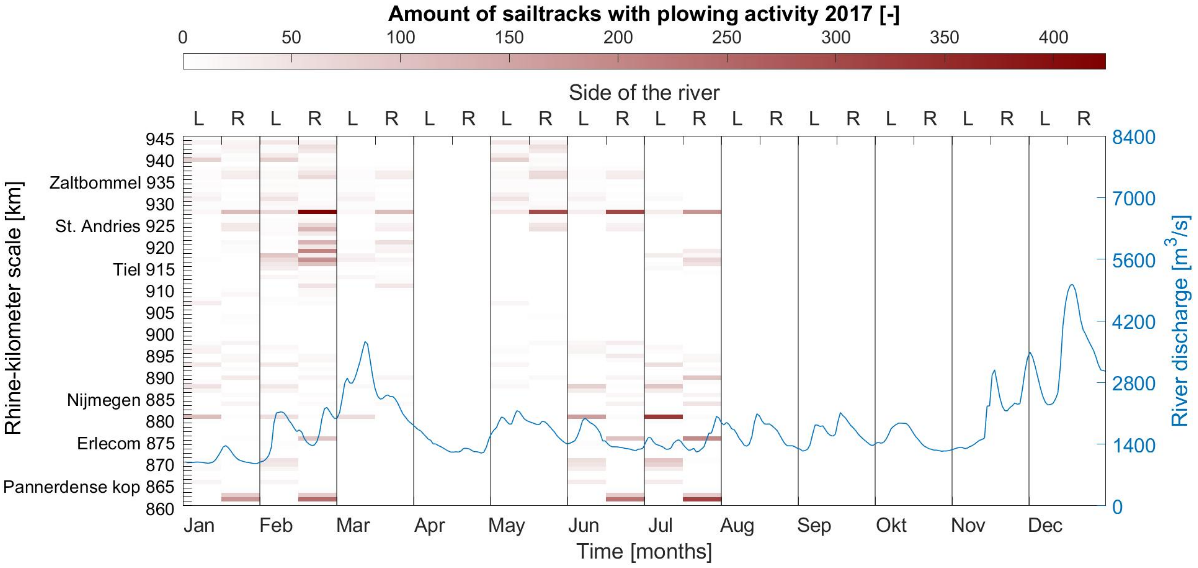


Figure H.50: 2017

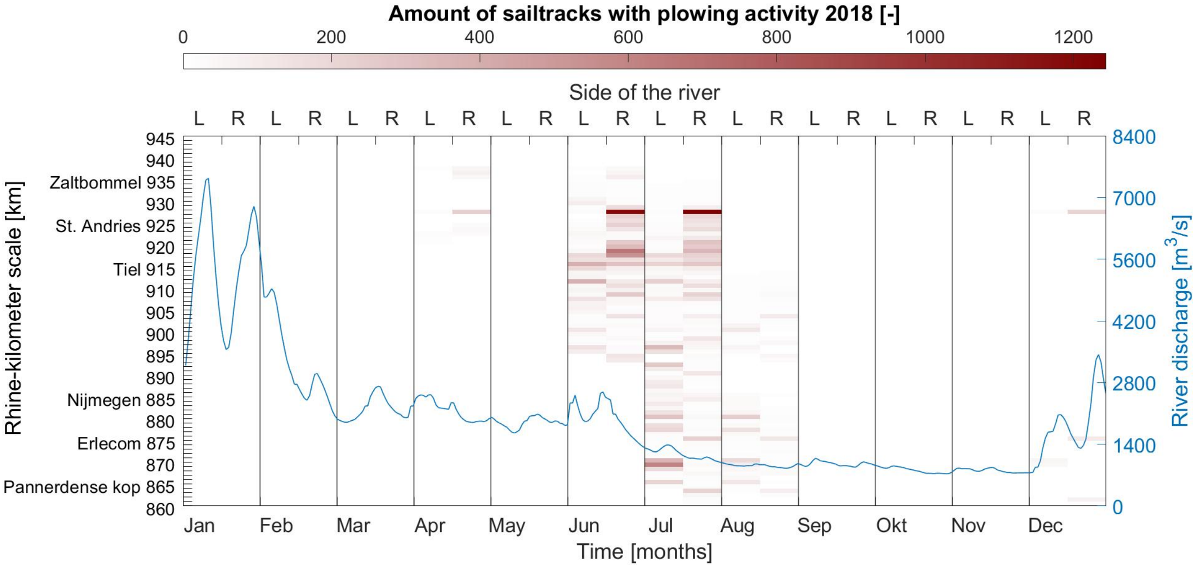


Figure H.51: 2018

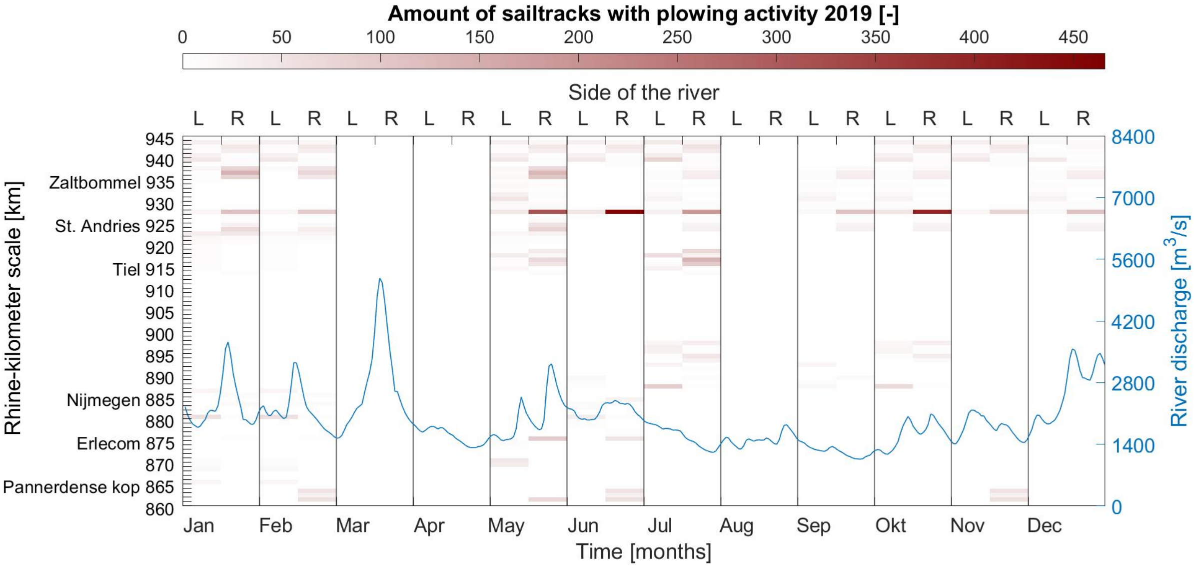


Figure H.52: 2019

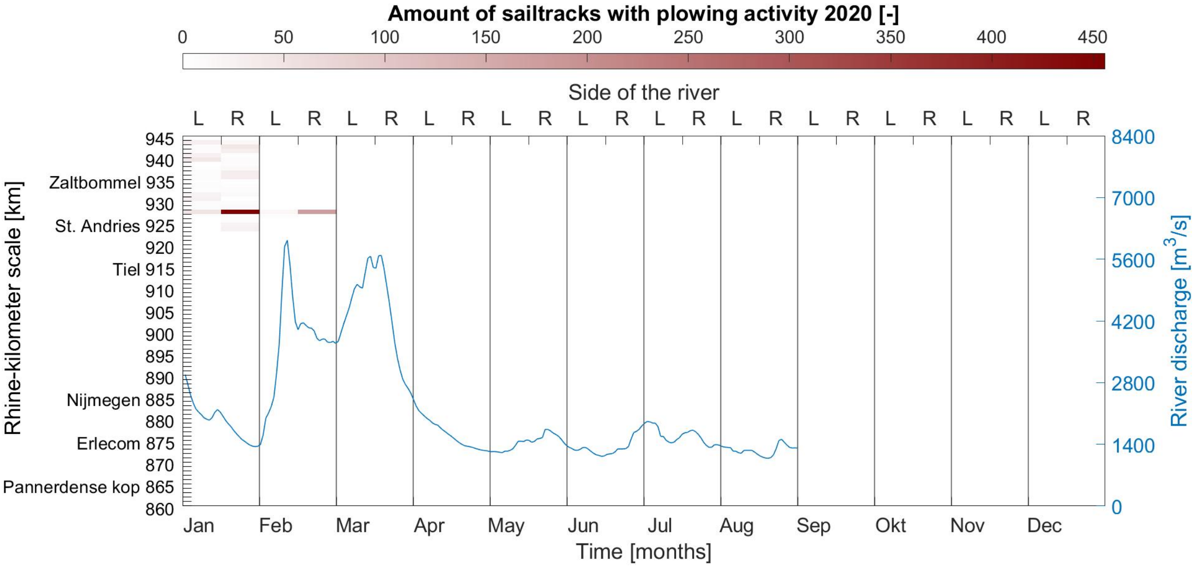


Figure H.53: 2020

I

Relocation of sediment

When we compare fgures about dredging locations with figures about dumping locations according reduced sail tracks (see Section H.1), it seems that on some locations sediment primarily is dredged on one side of the river and dumped on the other side of the river. In bends for instance sedimentation occurs in the inside of the bend and erosion occurs on the outside of the bend (see Section 4.2). It thus makes sense that the inside of the bend is dredged and subsequently the hopper is emptied in the outside of the bend.

On other locations dredging and dumping happens in another way. Dredging and dumping happens on the same side of the river. This happens if a locations of sedimentation and erosion follow each other on the same side of the river over a small distance. This is for instance the case at the end of the fixed layer near St. Andries, where a bar occurs at the right side of the river (this is treated in more detail in section 3.6). The river then turns toward the left and erosion occurs at the right side of the river.

Figure I.1 shows these two situations at St. Andries. In this figure each dot indicates a sail track. Each dot thus represents 2 minutes of activity. In this figure all sail tracks from the year 2008 are shown. The blue dots indicate sail tracks with a dredging activity and the green dots indicate sail tracks with a dumping activity. The red arrows indicate the relocation of sediment.

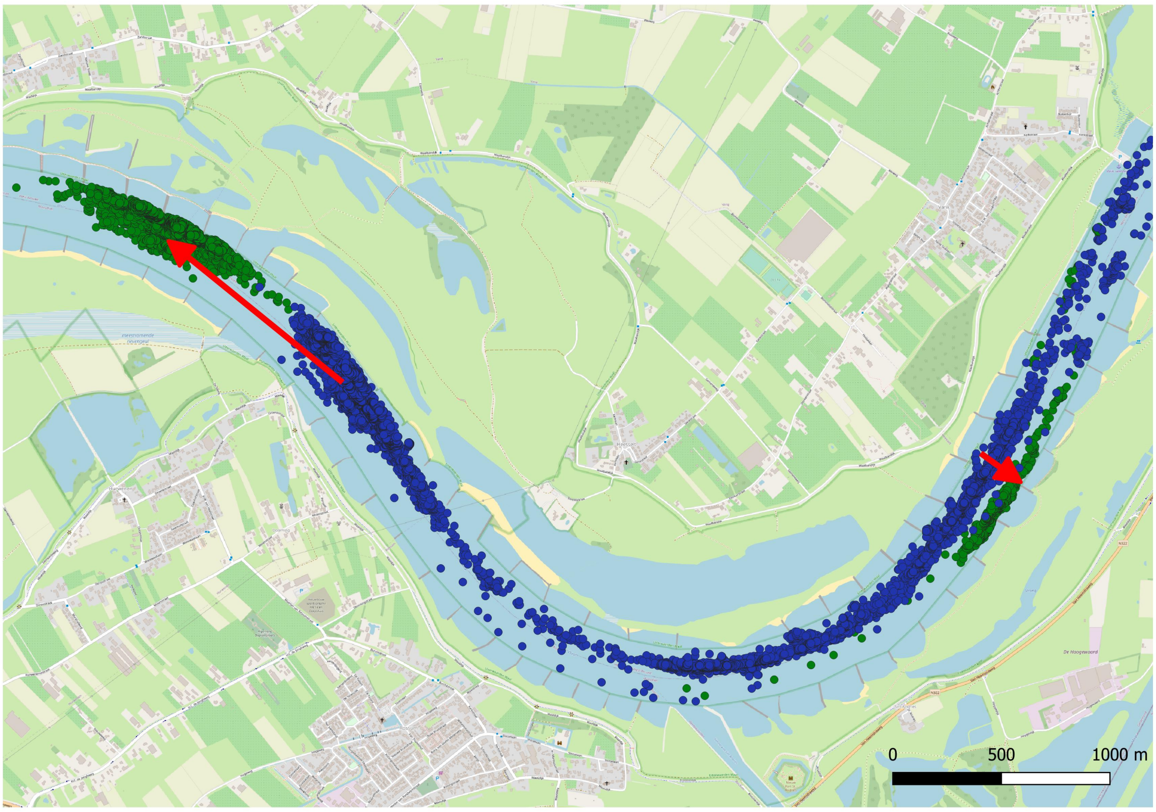


Figure I.1: Sediment relocation at St. Andries according to all reduced sail tracks from 2008 (Blue dots: dredging, Green dots: dumping)

We isolate the sail tracks of one specific day from the reduced sail tracks. By chronologically ordering the sail tracks we can show the sailing route and order of activities of the vessel. Figure I.2 shows such a sailing route for the dredging vessel on 18 March 2015. Again the blue dots indicate dredging sail tracks and the green dots indicate dumping sail tracks. The pink arrows indicate the order in which the sail tracks succeed each oter.

In this figure we see that the vessel dredges the inside of the bend and sails toward the outside of the bend to dump the sediment in a couple of minutes (a sail track is stored for every 2 minutes). We indicated with the red circle two blue dots that represent dredging activity. Because the vessel sails toward these locations in the outside of the bend, it makes sense that these two dots should represent dumping activity. This shows yet another way in which the sail tracks are unreliable.

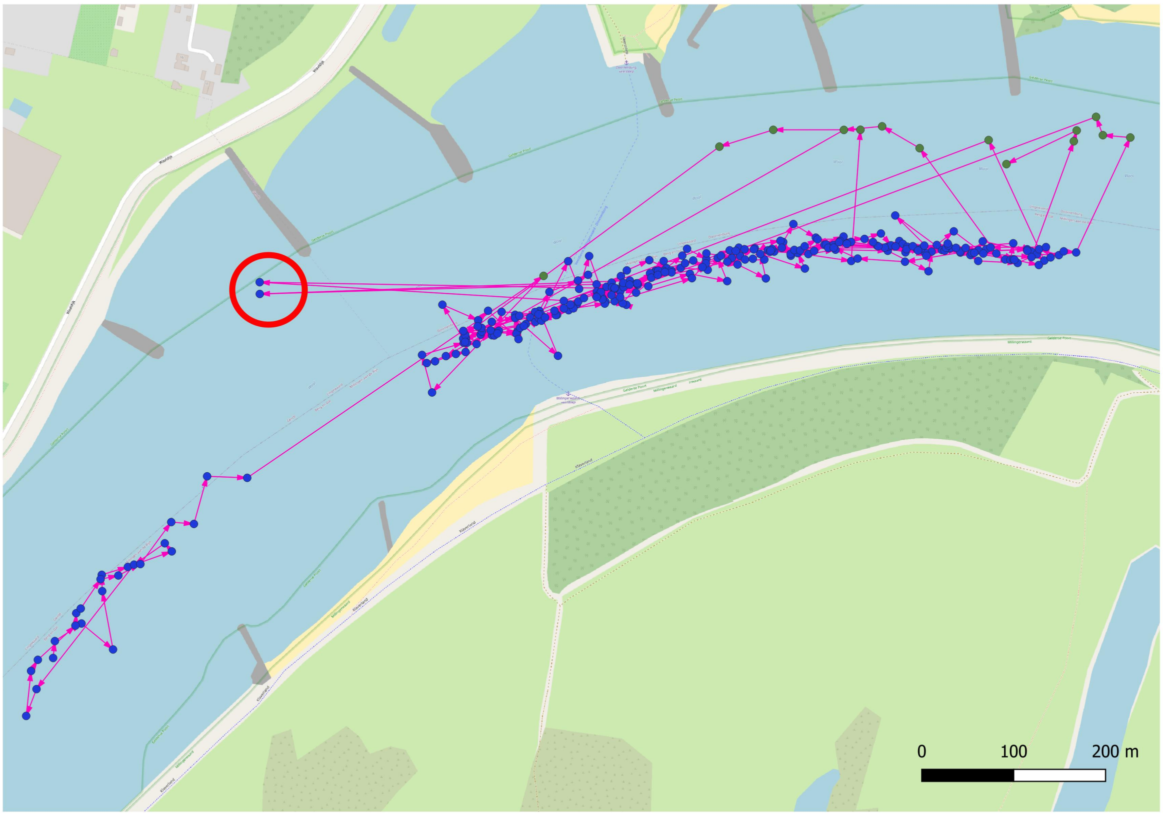


Figure I.2: Sailing route of dredging vessel on 18 March 2015 (Blue dots: dredging, Green dots: dumping)

J

Least Available Depth locations

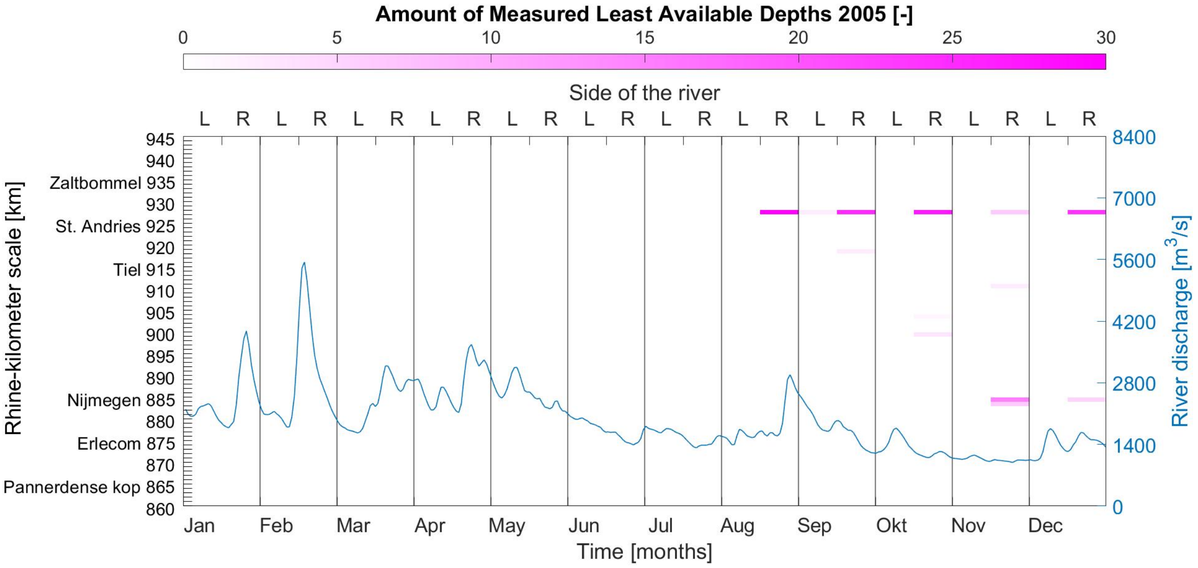


Figure J.1: 2005

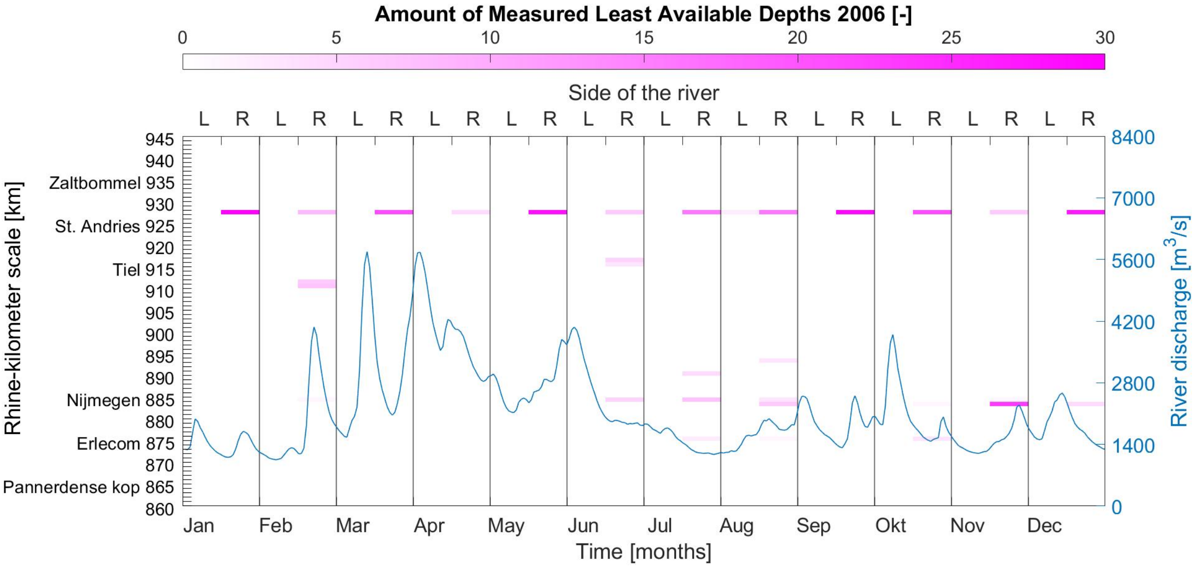


Figure J.2: 2006

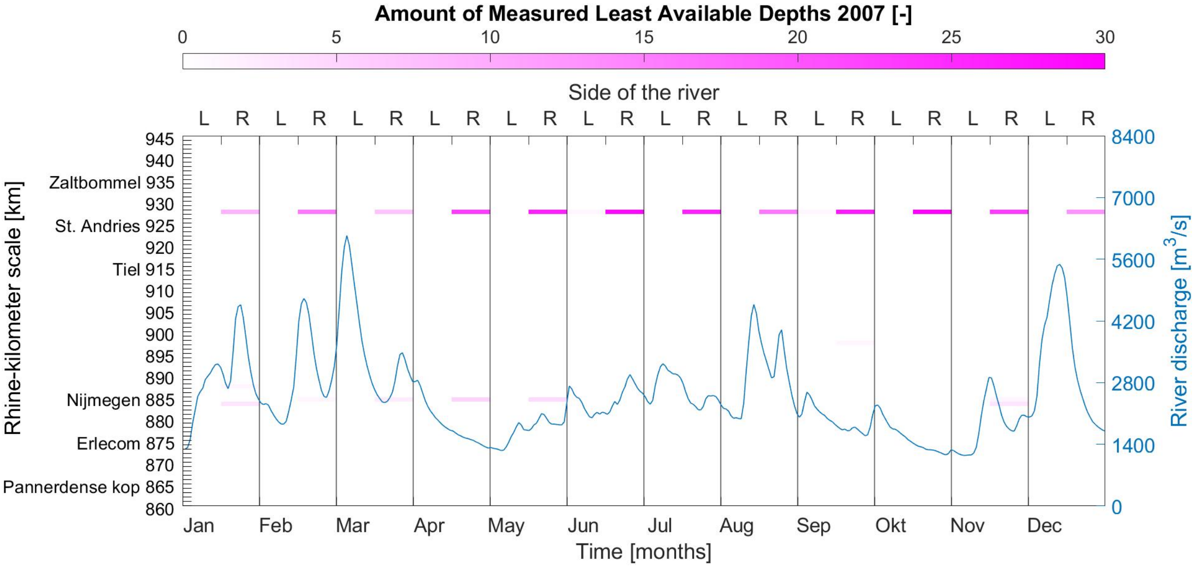


Figure J.3: 2007

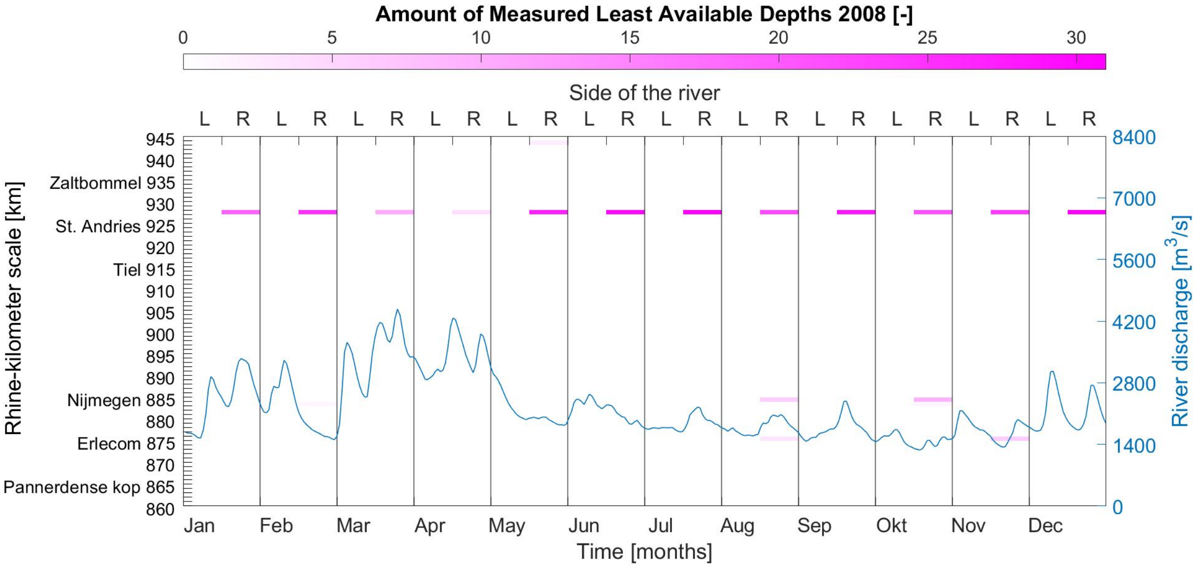


Figure J.4: 2008

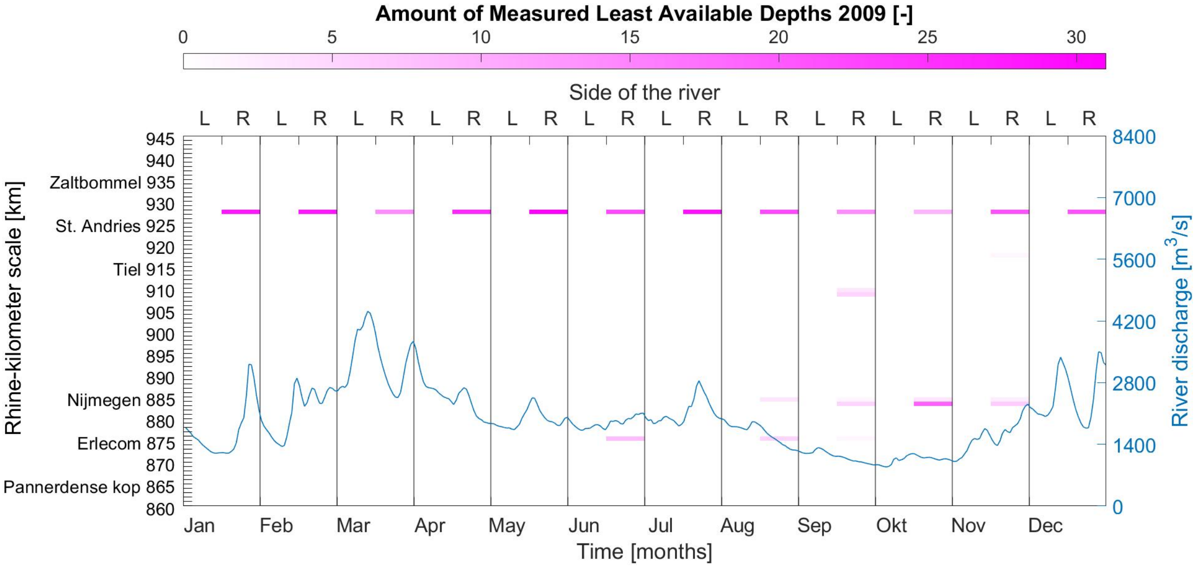


Figure J.5: 2009

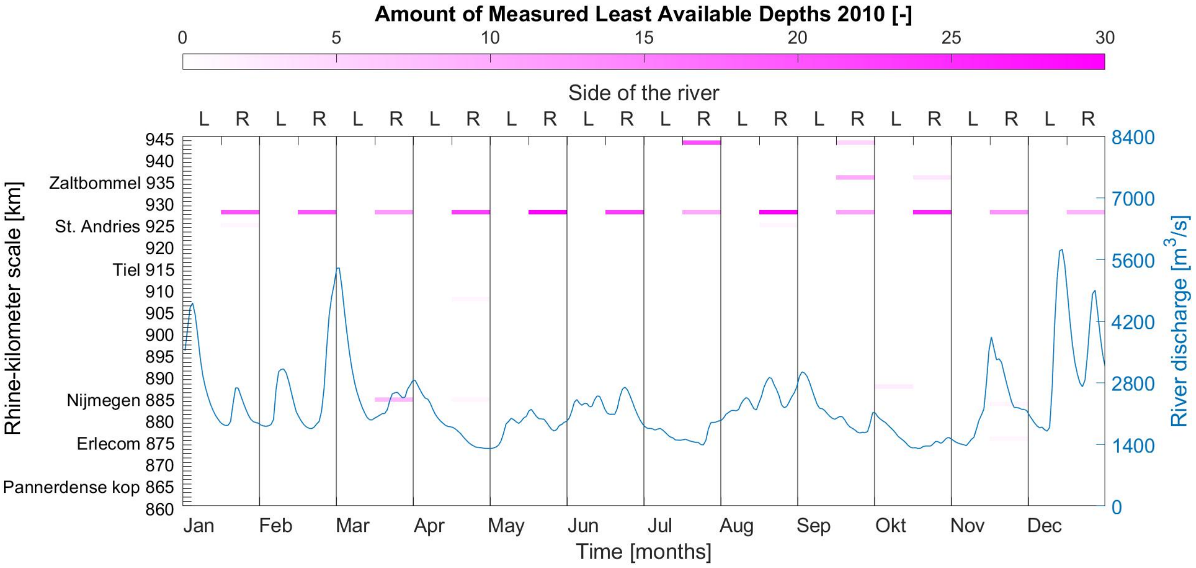


Figure J.6: 2010

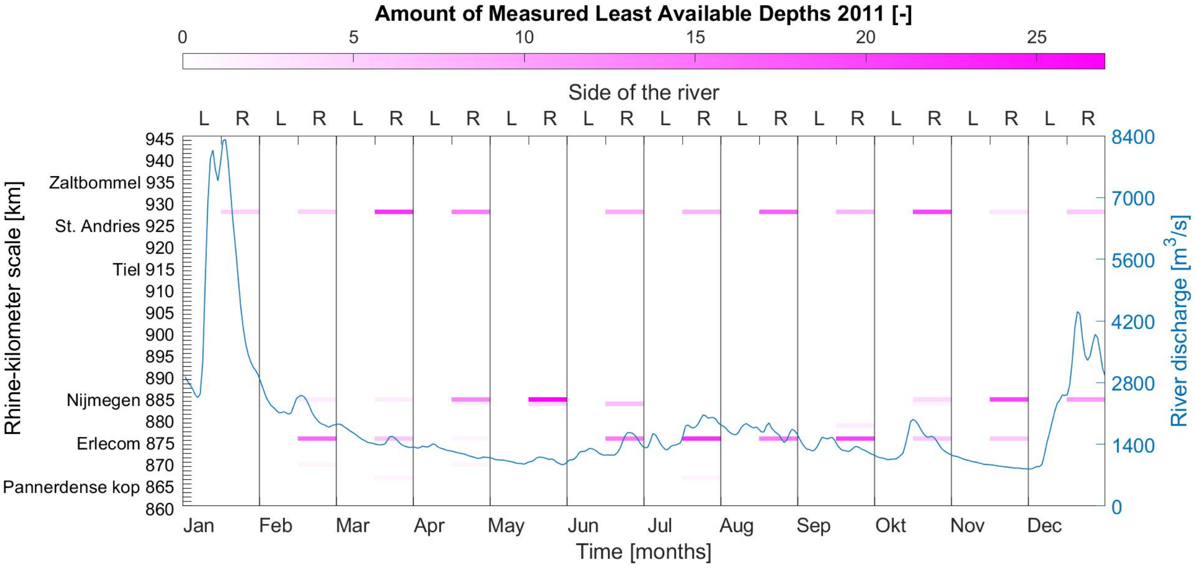


Figure J.7: 2011

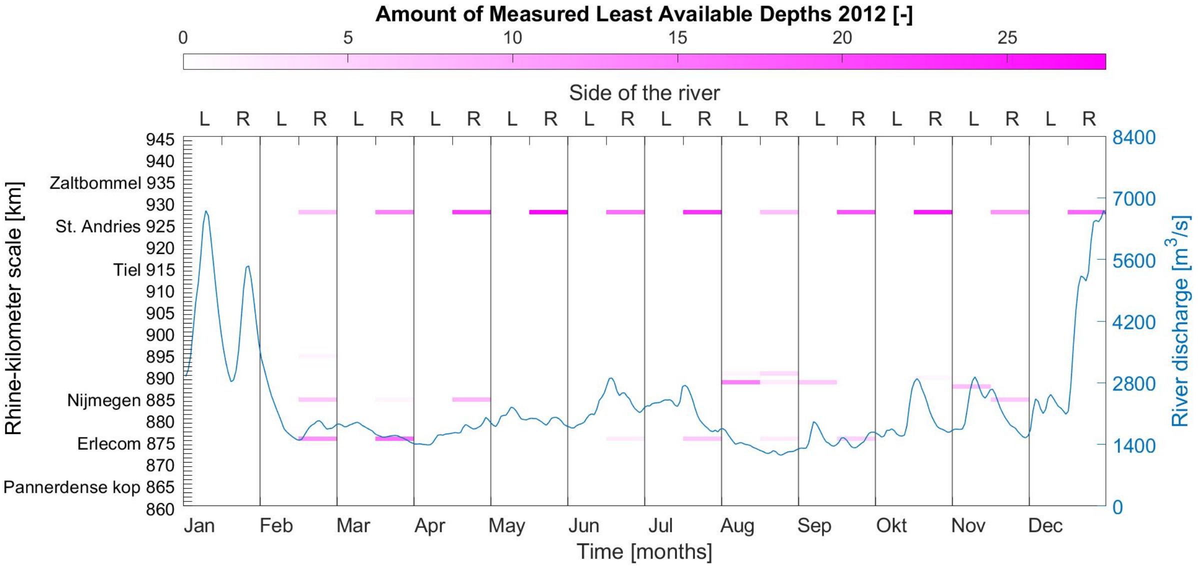


Figure J.8: 2012

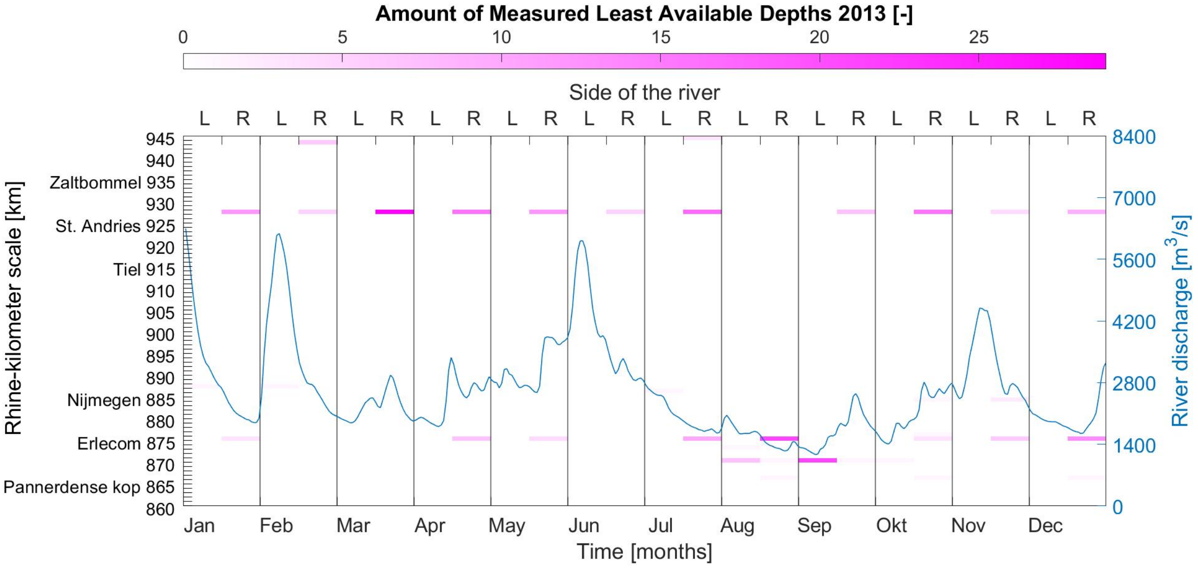


Figure J.9: 2013

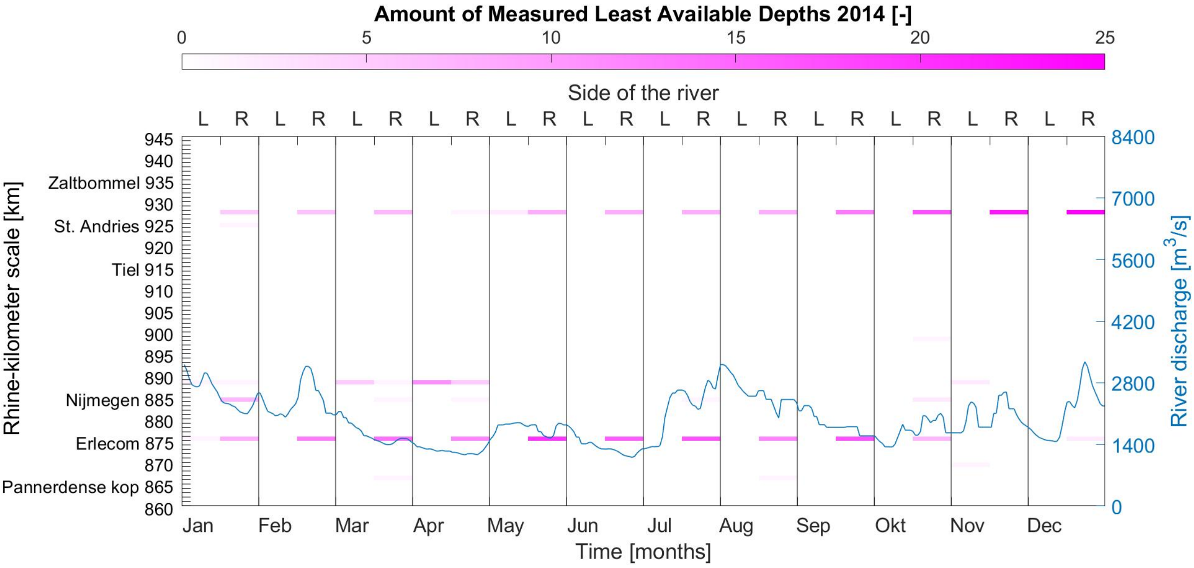


Figure J.10: 2014

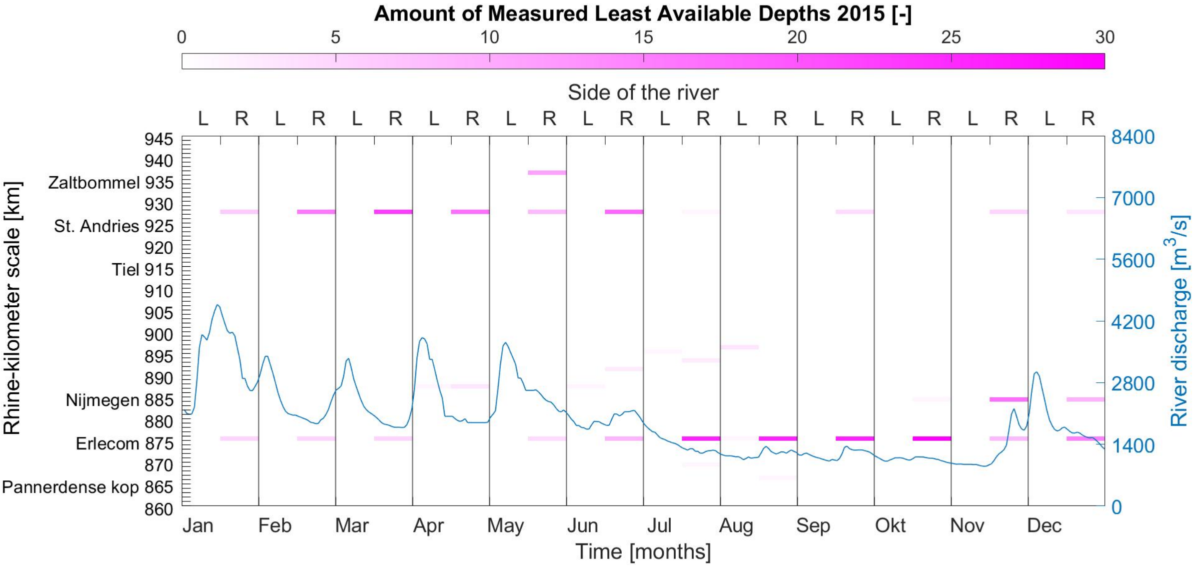


Figure J.11: 2015

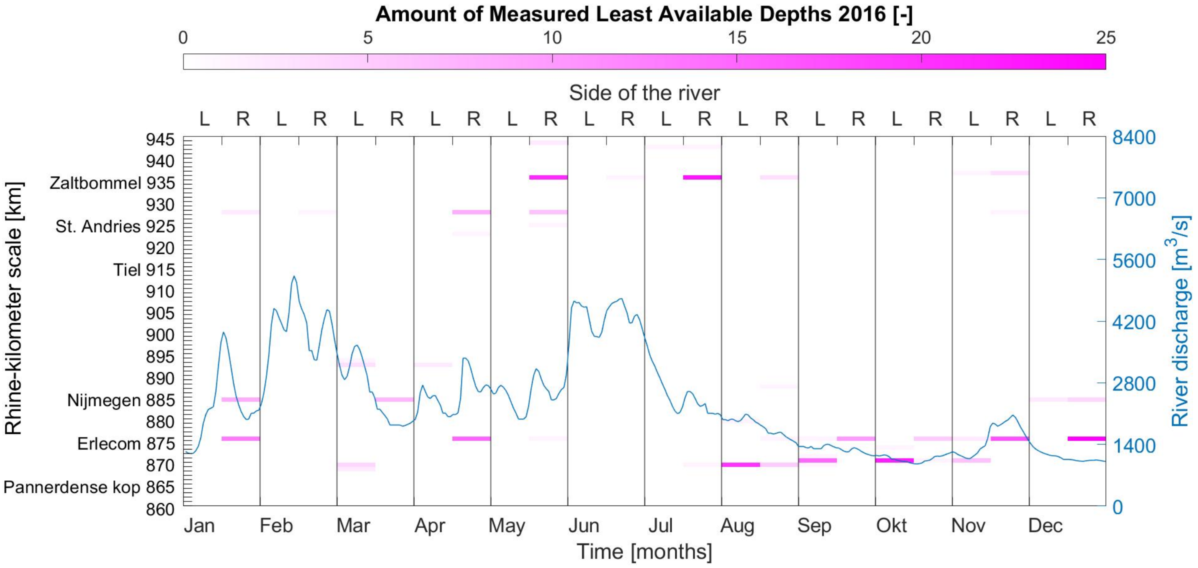


Figure J.12: 2016

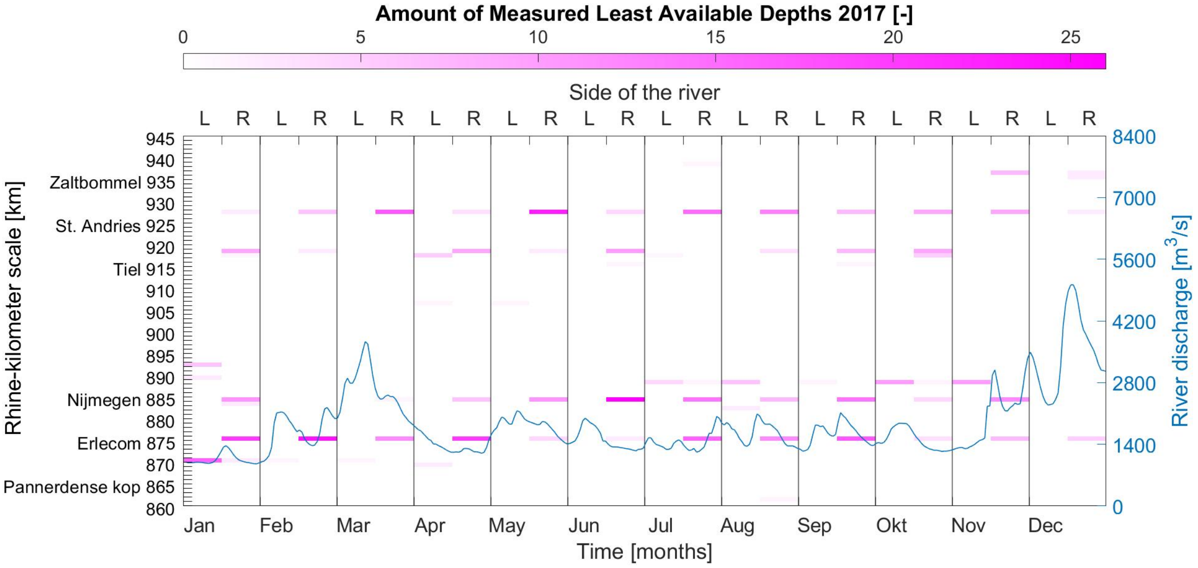


Figure J.13: 2017

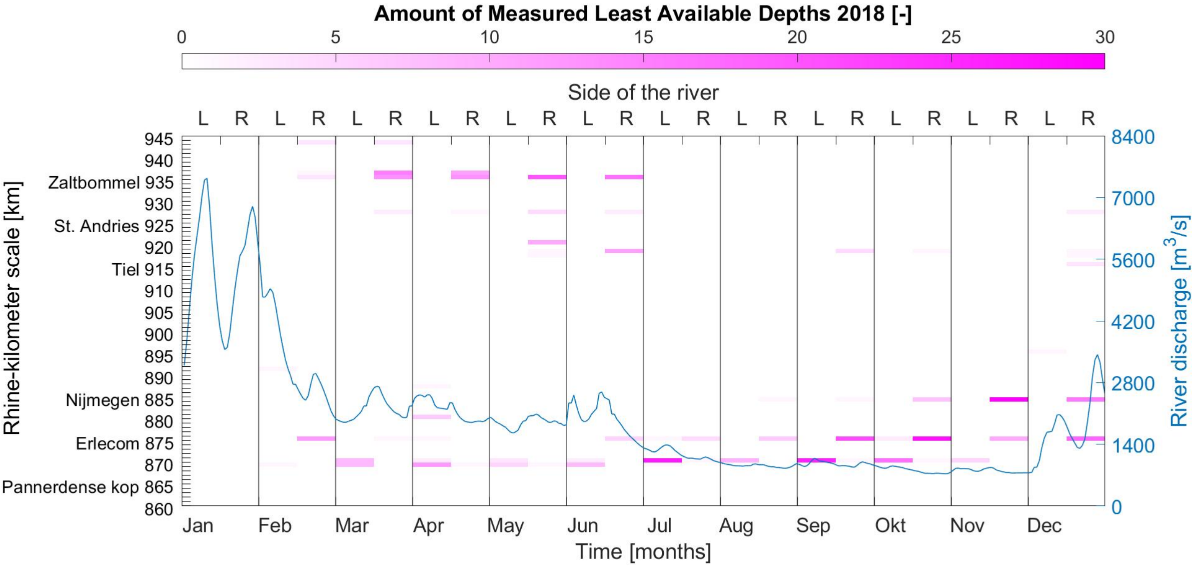


Figure J.14: 2018

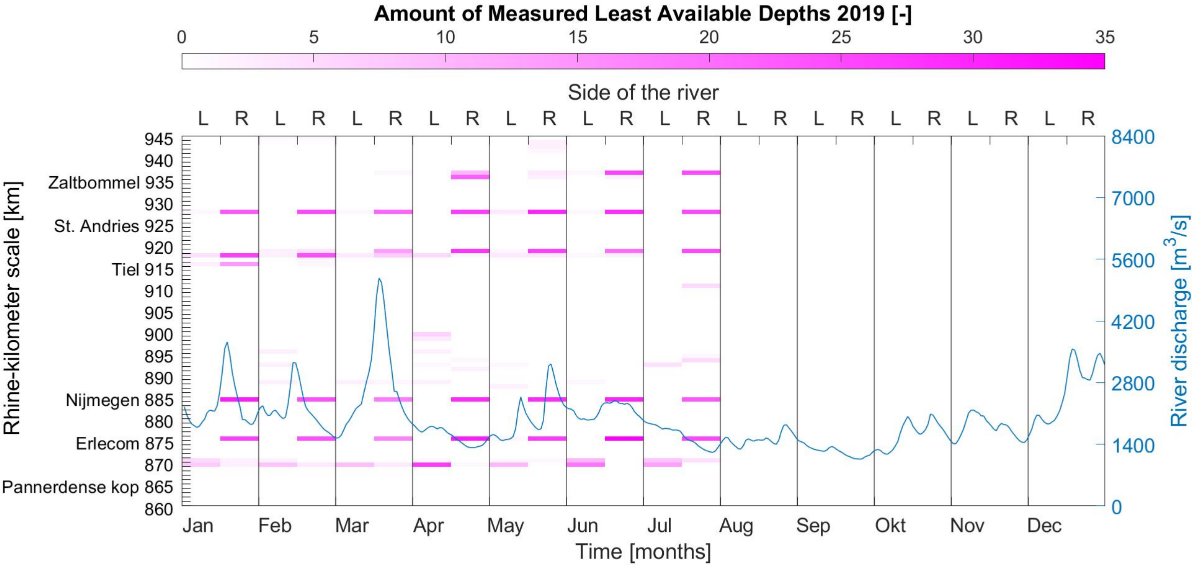
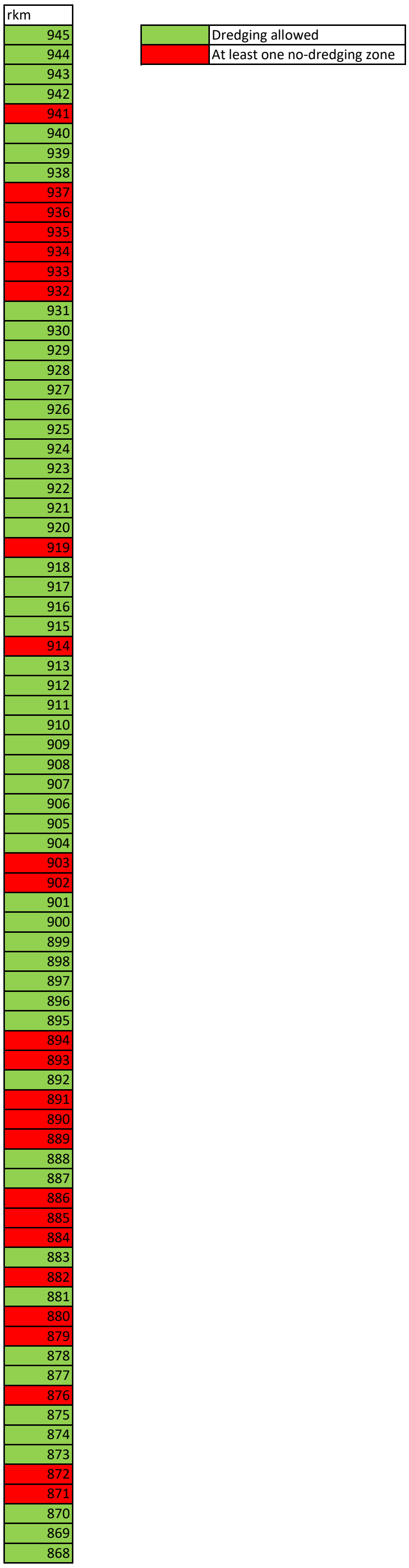


Figure J.15: 2019

K

No-dredging zones



rkm	
945	🟩
944	🟩
943	🟩
942	🟩
941	🟥
940	🟩
939	🟩
938	🟩
937	🟥
936	🟥
935	🟥
934	🟥
933	🟥
932	🟥
931	🟩
930	🟩
929	🟩
928	🟩
927	🟩
926	🟩
925	🟩
924	🟩
923	🟩
922	🟩
921	🟩
920	🟩
919	🟥
918	🟩
917	🟩
916	🟩
915	🟩
914	🟥
913	🟩
912	🟩
911	🟩
910	🟩
909	🟩
908	🟩
907	🟩
906	🟩
905	🟩
904	🟩
903	🟥
902	🟥
901	🟩
900	🟩
899	🟩
898	🟩
897	🟩
896	🟩
895	🟩
894	🟥
893	🟥
892	🟩
891	🟥
890	🟥
889	🟥
888	🟩
887	🟩
886	🟥
885	🟥
884	🟥
883	🟩
882	🟥
881	🟩
880	🟥
879	🟥
878	🟩
877	🟩
876	🟥
875	🟩
874	🟩
873	🟩
872	🟥
871	🟥
870	🟩
869	🟩
868	🟩

🟩	Dredging allowed
🟥	At least one no-dredging zone

Figure K.1: Rkms that contain no-dredging zones

L

Discharge peaks

We define the discharge peaks as peaks with a discharge larger than 3000 m^3/s that are significantly higher than the preceding and subsequent discharge (at least 1500-2000 m^3/s larger) and which are not clearly part of a larger peak. We only take peaks into account that occur in or are followed by a month for which data about dredging volumes and plowing activity is available. Since we use different data sets for dredging (BRW data) and plowing (reduced sail tracks) the amount of usable discharge peaks differs for plowing and dredging.

All regarded peaks that meet these demands and have available data in the subsequent month about dredging volumes (period 2014-2020) are:

- 1 January 2014: 3298 m^3/s;
- 19 February 2014: 3229 m^3/s;
- 1 Augustus 2014: 3270 m^3/s;
- 14 January 2015: 4625 m^3/s;
- 6 March 2015: 3406 m^3/s;
- 5 April 2015: 3855 m^3/s;
- 8 May 2015: 3758 m^3/s;
- 5 December 2015: 3078 m^3/s;
- 16 January 2016: 3993 m^3/s;
- 13 February 2016: 5268 m^3/s;
- 22 June 2016: 4758 m^3/s;
- 14 March 2017: 3779 m^3/s;
- 18 December 2017: 5089 m^3/s;
- 10 January 2018: 7553 m^3/s;
- 28 December 2018: 3487 m^3/s;
- 18 January 2019: 3772 m^3/s;
- 13 February 2019: 3324 m^3/s;
- 19 March 2019: 5226 m^3/s;
- 13 December 2019: 3616 m^3/s;
- 7 February 2020: 6142 m^3/s.

All regarded peaks that meet these demands and have available data in the subsequent month about plowing activity (period 2007-2020) are:

- 23 January 2008: 3373 m^3/s;
- 25 March 2008: 4512 m^3/s;
- 10 December 2008: 3110 m^3/s;
- 26 January 2009: 3297 m^3/s;
- 14 March 2009: 4452 m^3/s;
- 1 January 2014: 3298 m^3/s;
- 19 February 2014: 3229 m^3/s;
- 1 Augustus 2014: 3270 m^3/s;
- 14 January 2015: 4625 m^3/s;
- 6 March 2015: 3406 m^3/s;
- 5 April 2015: 3855 m^3/s;
- 8 May 2015: 3758 m^3/s;
- 5 December 2015: 3078 m^3/s;
- 16 January 2016: 3993 m^3/s;
- 13 February 2016: 5268 m^3/s;
- 22 June 2016: 4758 m^3/s;
- 14 March 2017: 3779 m^3/s;
- 18 December 2017: 5089 m^3/s;
- 10 January 2018: 7553 m^3/s;
- 28 December 2018: 3487 m^3/s;
- 18 January 2019: 3772 m^3/s;
- 13 February 2019: 3324 m^3/s;
- 19 March 2019: 5226 m^3/s;
- 13 December 2019: 3616 m^3/s;
- 7 February 2020: 6142 m^3/s.

M

The influence of the hydrograph on the river morphology

At high discharges flood plains and side channels start to convey water. The discharge is diverted from the main channel to these flood plains and side channels. Here accretion waves are initiated. Further downstream the flow is diverted back into the main channel or the floodplains might become narrower at some point. Here erosion waves are initiated. These accretion and erosion waves are initiated because of the local gradients in flow velocity which in term lead to larger local gradients in sediment transport (Van Vuren, Paarlberg, and Havinga, 2015). The waves then propagate downstream as dunes.

High discharges have an influence on other morphological processes as well, mostly because the floodplains start to convey water which means that the flow velocity in the main channel decreases. Thus siltation in main channel occurs. Dunes (which are non-stationary phenomena) are created due to the termporary high discharge which start to propagate downstream. They flatten again but continue to propagate at falling discharge. At high discharge groyne fields erode and erosion pits near groyne heads deepen. The groyne flames however grow (groyne flames are sediment deposition downstream of erosion pits in groyne fields). At falling discharge the groyne flames erode, usually with deposition in the main channel as a result where it will start to propagate as dunes.

Dunes are also initiated due to the river bed continuously adapting to the discharge. This happens because the equilibrium depth of the river changes with the discharge (Van Vuren, Paarlberg, and Havinga, 2015). The initiated dunes can keep growing when the water level decreases after a high discharge event (Bardoel, 2010). Also the river bed responds faster to high water conditions than to low water conditions because more transport of sediment is possible at high water conditions (Bardoel, 2010).

N

Geometry analyses

N.1. Geometrical characteristics

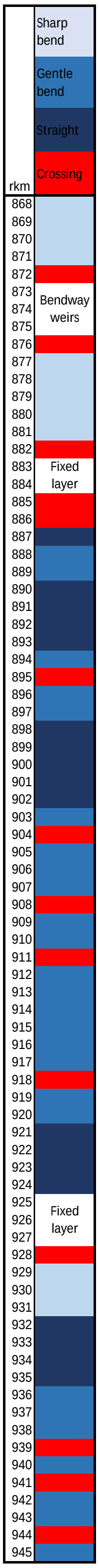
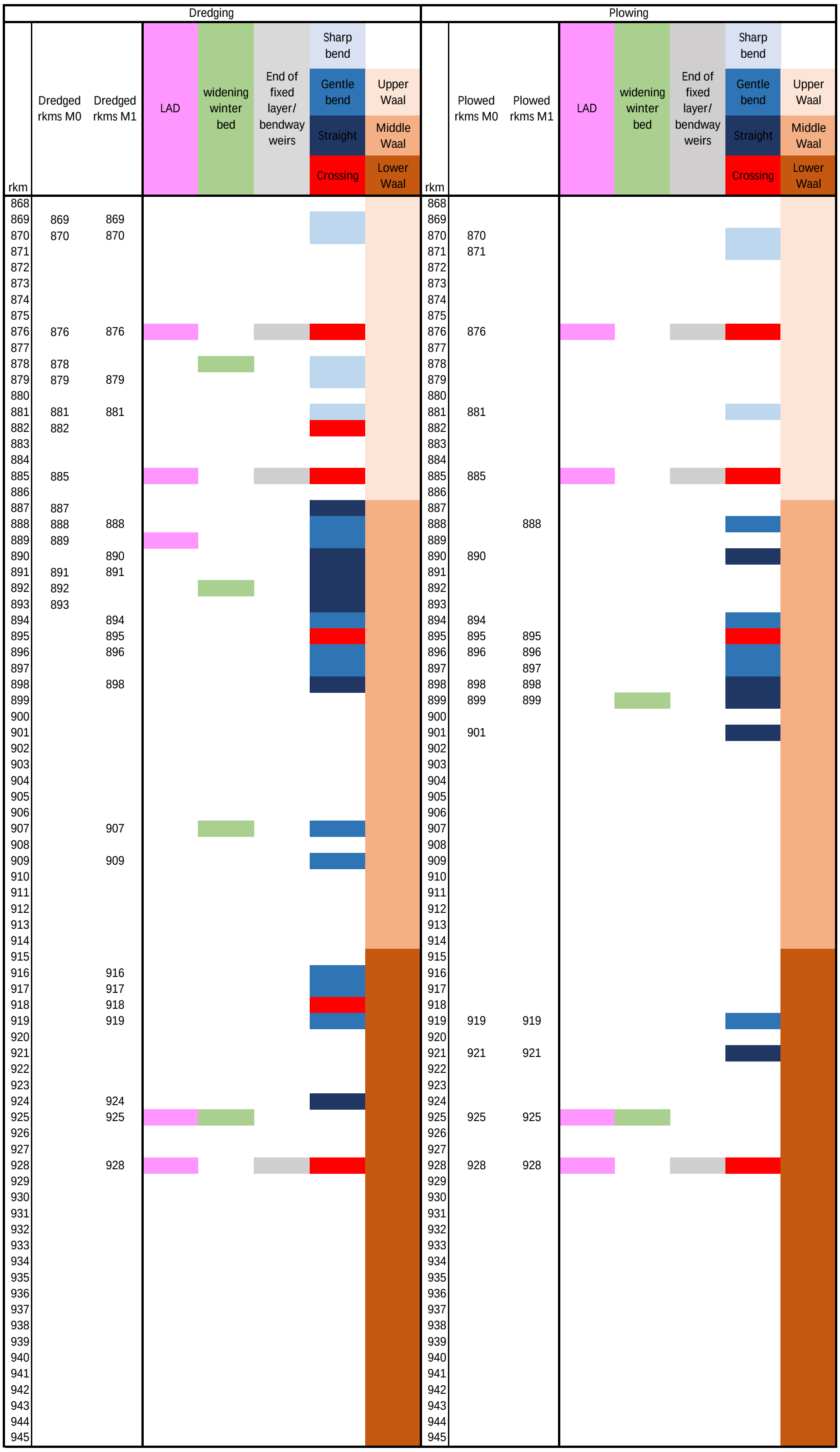


Figure N.1: Geometrical characteristics along the Waal per rkm

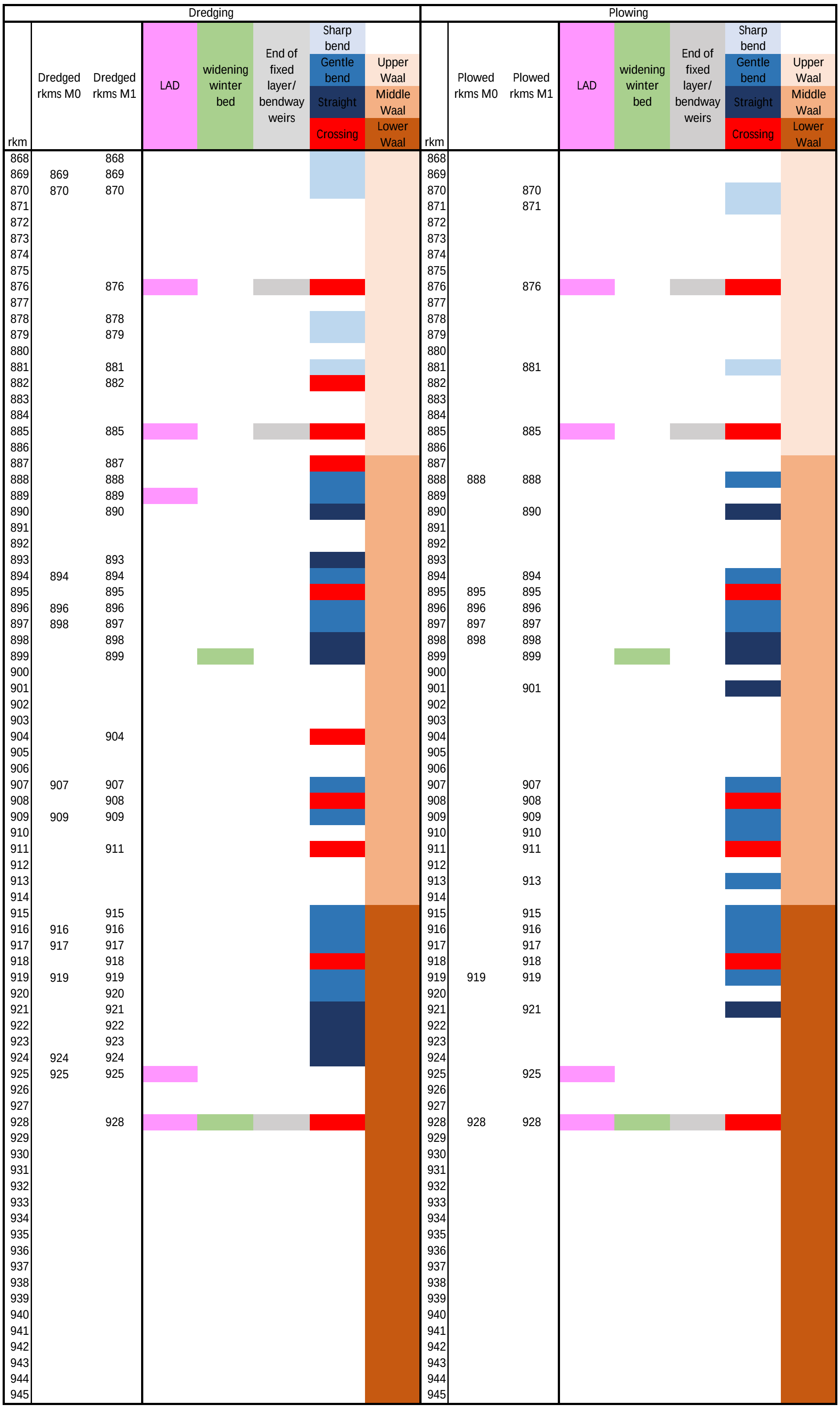
N.2. Geometry analyses per peak



Dredging							
rkm	Dredged rkms M0	Dredged rkms M1	LAD	widening winter bed	End of fixed layer/ bendway weirs	Sharp bend Gentle bend Straight Crossing	Upper Waal Middle Waal Lower Waal
868							Upper Waal
869	869	869				Sharp bend	
870	870	870				Sharp bend	
871							
872							
873							
874							
875							
876	876	876	■		■	Crossing	
877							
878	878			■		Sharp bend	
879	879	879				Sharp bend	
880							
881	881	881				Sharp bend	
882	882					Crossing	
883							
884							
885	885		■		■	Crossing	
886							
887	887					Straight	Middle Waal
888	888	888				Gentle bend	
889	889		■			Gentle bend	
890		890				Straight	
891	891	891				Straight	
892	892			■		Straight	
893	893					Straight	
894		894				Gentle bend	
895		895				Crossing	
896		896				Gentle bend	
897						Gentle bend	
898		898				Straight	
899							
900							
901							
902							
903							
904							
905							
906							
907		907		■		Gentle bend	
908							
909		909				Gentle bend	
910							
911							
912							
913							
914							
915							Lower Waal
916		916				Gentle bend	
917		917				Gentle bend	
918		918				Crossing	
919		919				Gentle bend	
920							
921							
922							
923							
924		924				Straight	
925		925	■	■			
926							
927							
928		928	■		■	Crossing	
929							
930							
931							
932							
933							
934							
935							
936							
937							
938							
939							
940							
941							
942							
943							
944							
945							

Plowing							
rkm	Plowed rkms M0	Plowed rkms M1	LAD	widening winter bed	End of fixed layer/ bendway weirs	Sharp bend Gentle bend Straight Crossing	Upper Waal Middle Waal Lower Waal
868							Upper Waal
869							
870	870					Sharp bend	
871	871					Sharp bend	
872							
873							
874							
875							
876	876		■		■	Crossing	
877							
878							
879							
880							
881	881					Sharp bend	
882							
883							
884							
885	885		■		■	Crossing	
886							
887							Middle Waal
888		888				Gentle bend	
889							
890	890					Straight	
891							
892							
893							
894	894					Gentle bend	
895	895	895				Crossing	
896	896	896				Gentle bend	
897		897				Gentle bend	
898	898	898				Straight	
899	899	899		■		Straight	
900							
901	901					Straight	
902							
903							
904							
905							
906							
907							
908							
909							
910							
911							
912							
913							
914							
915							Lower Waal
916							
917							
918							
919	919	919				Gentle bend	
920							
921	921	921				Straight	
922							
923							
924							
925	925	925	■	■			
926							
927							
928	928	928	■		■	Crossing	
929							
930							
931							
932							
933							
934							
935							
936							
937							
938							
939							
940							
941							
942							
943							
944							
945							

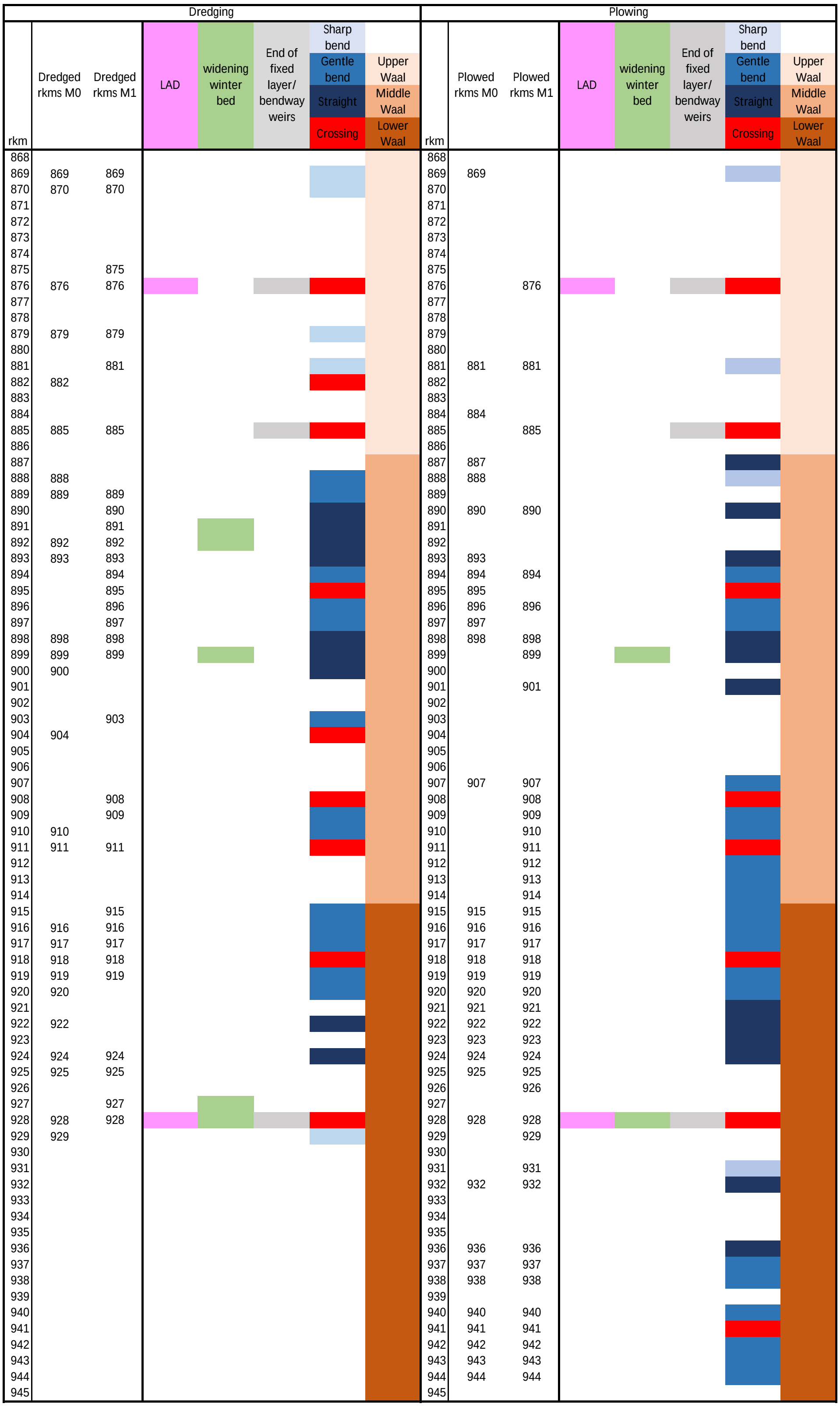
Figure N.2: Geometry analysis of dredging and plowing locations after the peak in January 2014 (peak discharge: 3298 m^3/s)



Dredging							
rkm	Dredged rkms M0	Dredged rkms M1	LAD	widening winter bed	End of fixed layer/ bendway weirs	Sharp bend Gentle bend Straight Crossing	Upper Waal Middle Waal Lower Waal
868		868				Sharp bend	Upper Waal
869	869	869				Sharp bend	
870	870	870				Sharp bend	
871							
872							
873							
874							
875							
876		876	■		■	Crossing	
877							
878		878				Sharp bend	
879		879				Sharp bend	
880							
881		881				Sharp bend	
882		882				Crossing	
883							
884							
885		885	■		■	Crossing	
886							
887		887				Crossing	Middle Waal
888		888				Gentle bend	
889		889	■			Gentle bend	
890		890				Straight	
891							
892							
893		893				Straight	
894	894	894				Gentle bend	
895		895				Crossing	
896	896	896				Gentle bend	
897	898	897				Gentle bend	
898		898				Straight	
899		899		■		Straight	
900							
901							
902							
903							
904		904				Crossing	
905							
906							
907	907	907				Gentle bend	
908		908				Crossing	
909	909	909				Gentle bend	
910							
911		911				Crossing	
912							
913							
914							
915		915				Gentle bend	Lower Waal
916	916	916				Gentle bend	
917	917	917				Gentle bend	
918		918				Crossing	
919	919	919				Gentle bend	
920		920				Gentle bend	
921		921				Straight	
922		922				Straight	
923		923				Straight	
924	924	924				Straight	
925	925	925	■				
926							
927							
928		928	■	■	■	Crossing	
929							
930							
931							
932							
933							
934							
935							
936							
937							
938							
939							
940							
941							
942							
943							
944							
945							

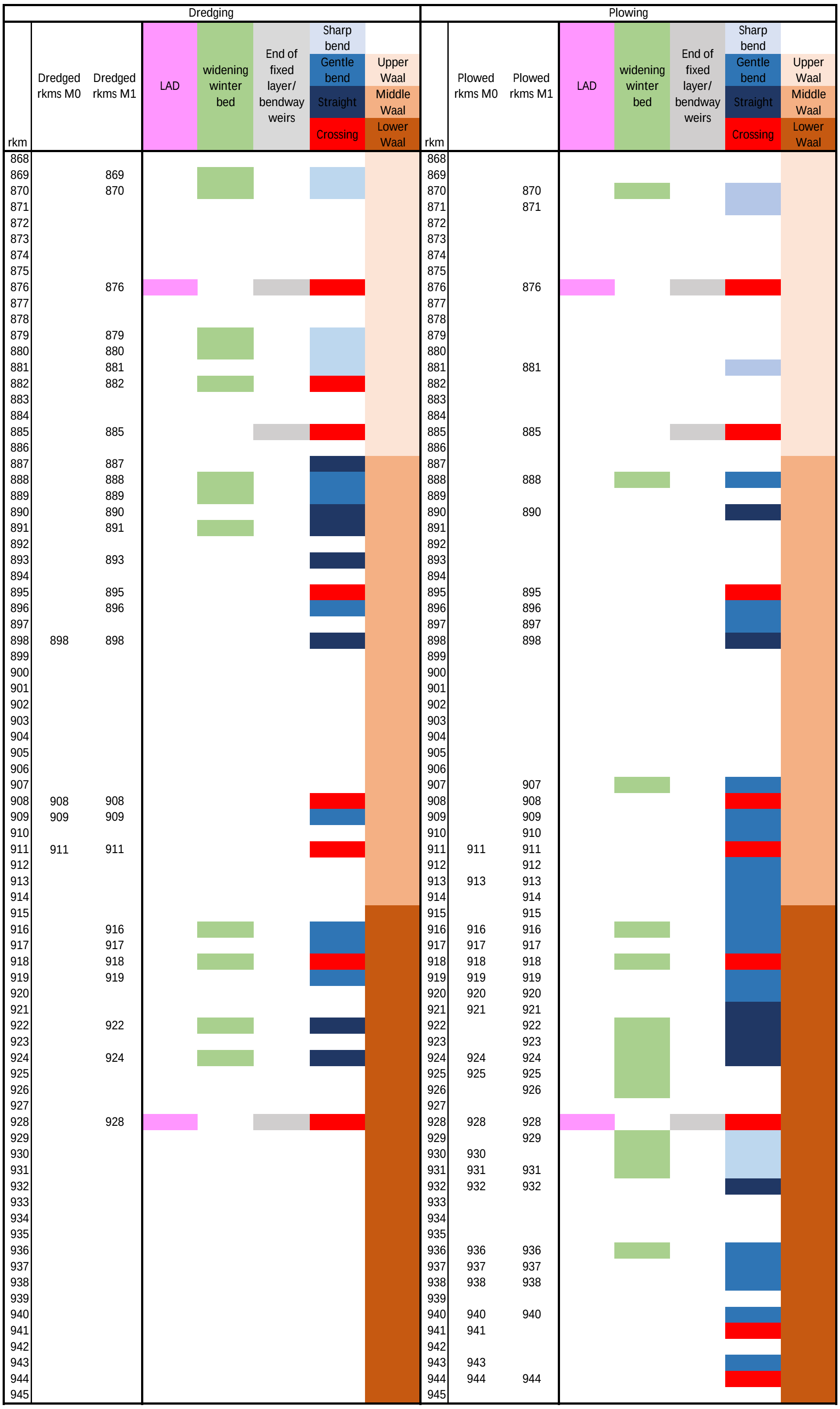
Plowing							
rkm	Plowed rkms M0	Plowed rkms M1	LAD	widening winter bed	End of fixed layer/ bendway weirs	Sharp bend Gentle bend Straight Crossing	Upper Waal Middle Waal Lower Waal
868							Upper Waal
869							
870		870				Sharp bend	
871		871				Sharp bend	
872							
873							
874							
875							
876		876	■		■	Crossing	
877							
878							
879							
880							
881		881				Sharp bend	
882							
883							
884							
885		885	■		■	Crossing	
886							
887							Middle Waal
888	888	888				Gentle bend	
889							
890		890				Straight	
891							
892							
893							
894		894				Gentle bend	
895	895	895				Crossing	
896	896	896				Gentle bend	
897	897	897				Gentle bend	
898	898	898				Straight	
899		899		■		Straight	
900							
901		901				Straight	
902							
903							
904							
905							
906							
907		907				Gentle bend	
908		908				Crossing	
909		909				Gentle bend	
910		910				Gentle bend	
911		911				Crossing	
912							
913		913				Gentle bend	
914							
915		915				Gentle bend	Lower Waal
916		916				Gentle bend	
917		917				Gentle bend	
918		918				Crossing	
919	919	919				Gentle bend	
920							
921		921				Straight	
922							
923							
924							
925		925	■				
926							
927							
928	928	928	■	■	■	Crossing	
929							
930							
931							
932							
933							
934							
935							
936							
937							
938							
939							
940							
941							
942							
943							
944							
945							

Figure N.3: Geometry analysis of dredging and plowing locations after the peak in February 2014 (peak discharge: 3229 m^3/s)



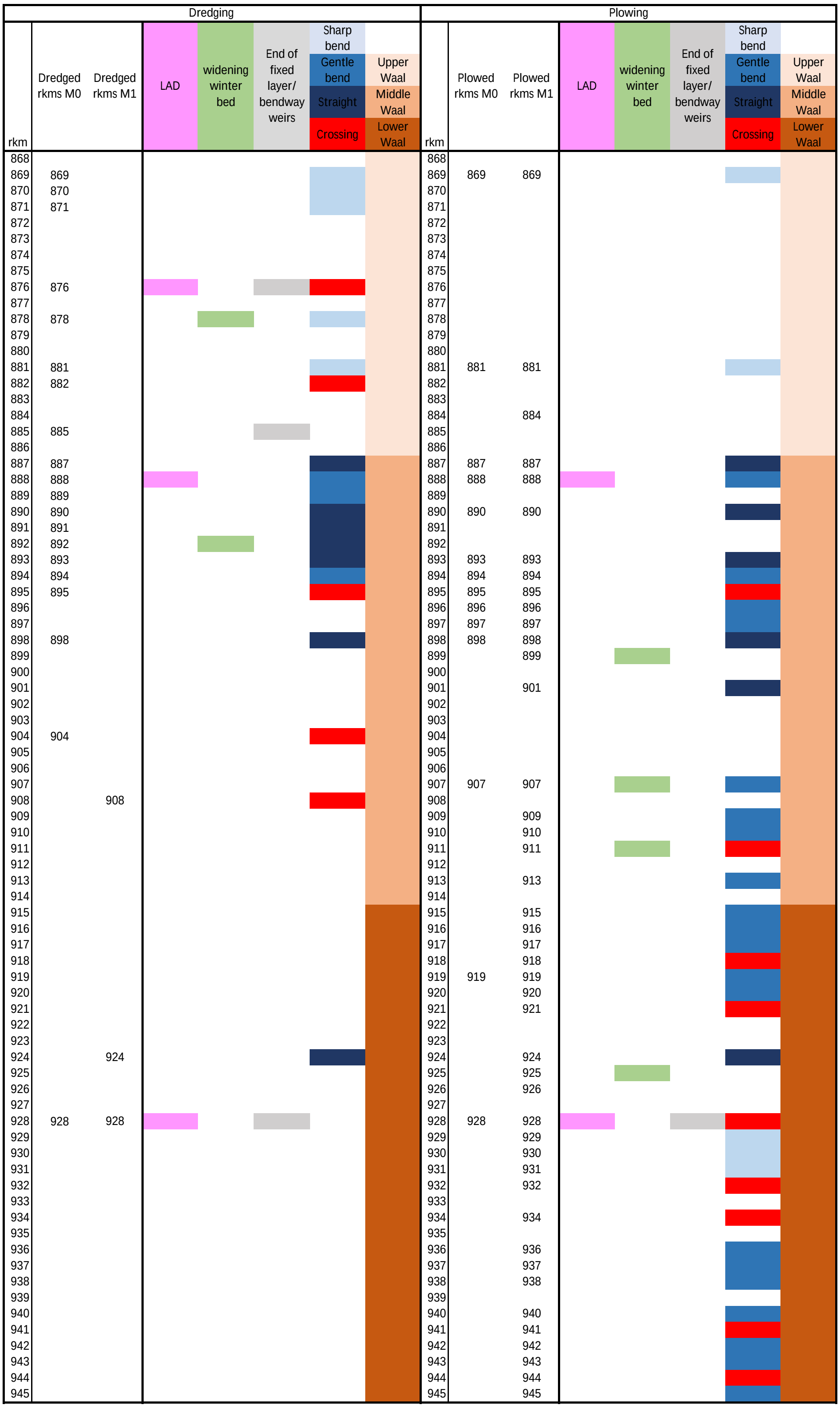
Dredging								Plowing							
rkm	Dredged rkms M0	Dredged rkms M1	LAD	widening winter bed	End of fixed layer/ bendway weirs	Sharp bend Gentle bend Straight Crossing	Upper Waal Middle Waal Lower Waal	rkm	Plowed rkms M0	Plowed rkms M1	LAD	widening winter bed	End of fixed layer/ bendway weirs	Sharp bend Gentle bend Straight Crossing	Upper Waal Middle Waal Lower Waal
868							Upper Waal	868							Upper Waal
869	869	869				Sharp bend		869	869					Sharp bend	
870	870	870				Sharp bend		870							
871								871							
872								872							
873								873							
874								874							
875		875						875							
876	876	876	■		■	Crossing		876		876	■		■	Crossing	
877								877							
878								878							
879	879	879				Sharp bend		879							
880								880							
881		881				Sharp bend		881	881	881				Sharp bend	
882	882					Crossing		882							
883								883							
884								884	884						
885	885	885			■	Crossing		885		885			■	Crossing	
886								886							
887							Middle Waal	887	887					Straight	Middle Waal
888	888					Gentle bend		888	888					Sharp bend	
889	889	889				Gentle bend		889							
890		890				Straight		890	890	890				Straight	
891		891		■		Straight		891							
892	892	892		■		Straight		892							
893	893	893				Straight		893	893					Straight	
894		894				Gentle bend		894	894	894				Gentle bend	
895		895				Crossing		895	895					Crossing	
896		896				Gentle bend		896	896	896				Gentle bend	
897		897				Gentle bend		897	897					Gentle bend	
898	898	898				Straight		898	898	898				Straight	
899	899	899		■		Straight		899		899		■		Straight	
900	900					Straight		900							
901								901		901				Straight	
902								902							
903		903				Gentle bend		903							
904	904					Crossing		904							
905								905							
906								906							
907								907	907	907				Gentle bend	
908		908				Crossing		908		908				Crossing	
909		909				Gentle bend		909		909				Gentle bend	
910	910					Gentle bend		910		910				Gentle bend	
911	911	911				Crossing		911		911				Crossing	
912								912		912				Gentle bend	
913								913		913				Gentle bend	
914								914		914				Gentle bend	
915		915				Gentle bend	Lower Waal	915	915	915				Gentle bend	Lower Waal
916	916	916				Gentle bend		916	916	916				Gentle bend	
917	917	917				Gentle bend		917	917	917				Gentle bend	
918	918	918				Crossing		918	918	918				Crossing	
919	919	919				Gentle bend		919	919	919				Gentle bend	
920	920					Gentle bend		920	920	920				Gentle bend	
921								921	921	921				Straight	
922	922					Straight		922	922	922				Straight	
923								923	923	923				Straight	
924	924	924				Straight		924	924	924				Straight	
925	925	925						925	925	925					
926								926		926					
927		927		■				927							
928	928	928	■	■	■	Crossing		928	928	928	■	■	■	Crossing	
929	929					Sharp bend		929		929					
930								930							
931								931		931				Sharp bend	
932								932	932	932				Straight	
933								933							
934								934							
935								935							
936								936	936	936				Straight	
937								937	937	937				Gentle bend	
938								938	938	938				Gentle bend	
939								939							
940								940	940	940				Gentle bend	
941								941	941	941				Crossing	
942								942	942	942				Gentle bend	
943								943	943	943				Gentle bend	
944								944	944	944				Gentle bend	
945								945							

Figure N.4: Geometry analysis of dredging and plowing locations after the peak in August 2014 (peak discharge: 3270 m^3/s)



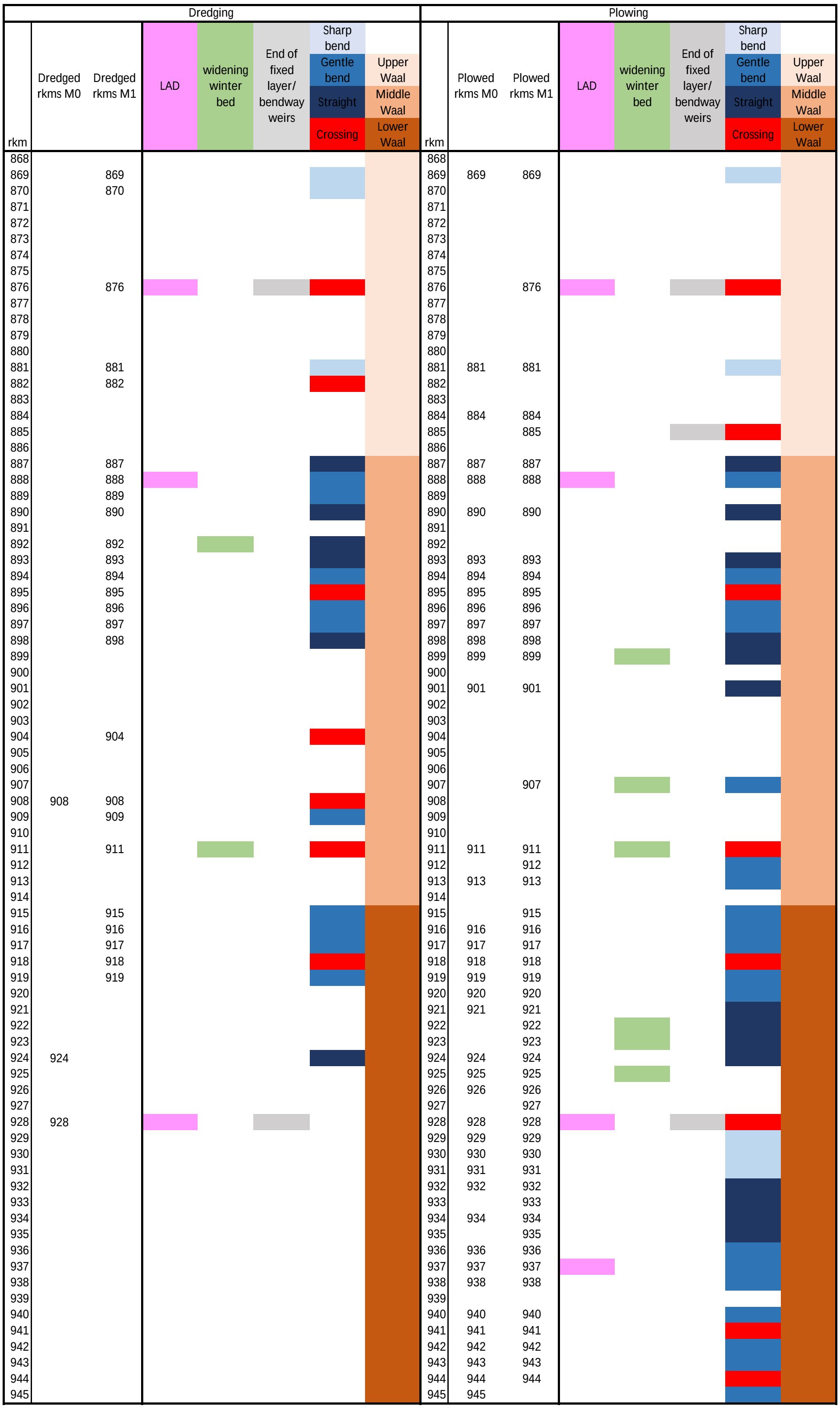
Dredging								Plowing							
rkm	Dredged rkms M0	Dredged rkms M1	LAD 🟪	widening winter bed 🟩	End of fixed layer/ bendway weirs ⬜	Sharp bend ▫ Gentle bend 🟦 Straight ⬛ Crossing 🟥	Upper Waal ░ Middle Waal 🟧 Lower Waal 🟫	rkm	Plowed rkms M0	Plowed rkms M1	LAD 🟪	widening winter bed 🟩	End of fixed layer/ bendway weirs ⬜	Sharp bend ▫ Gentle bend 🟦 Straight ⬛ Crossing 🟥	Upper Waal ░ Middle Waal 🟧 Lower Waal 🟫
868							░	868							░
869		869		🟩		▫	░	869							░
870		870		🟩		▫	░	870		870		🟩		▫	░
871							░	871		871				▫	░
872							░	872							░
873							░	873							░
874							░	874							░
875							░	875							░
876		876	🟪		⬜	🟥	░	876		876	🟪		⬜	🟥	░
877							░	877							░
878							░	878							░
879		879		🟩		▫	░	879							░
880		880		🟩		▫	░	880							░
881		881				▫	░	881		881				▫	░
882		882		🟩		🟥	░	882							░
883							░	883							░
884							░	884							░
885		885			⬜	🟥	░	885		885			⬜	🟥	░
886							░	886							░
887		887				⬛	🟧	887							🟧
888		888		🟩		🟦	🟧	888		888		🟩		🟦	🟧
889		889		🟩		🟦	🟧	889							🟧
890		890				⬛	🟧	890		890				⬛	🟧
891		891		🟩		⬛	🟧	891							🟧
892							🟧	892							🟧
893		893				⬛	🟧	893							🟧
894							🟧	894							🟧
895		895				🟥	🟧	895		895				🟥	🟧
896		896				🟦	🟧	896		896				🟦	🟧
897							🟧	897		897				🟦	🟧
898	898	898				⬛	🟧	898		898				⬛	🟧
899							🟧	899							🟧
900							🟧	900							🟧
901							🟧	901							🟧
902							🟧	902							🟧
903							🟧	903							🟧
904							🟧	904							🟧
905							🟧	905							🟧
906							🟧	906							🟧
907							🟧	907		907		🟩		🟦	🟧
908	908	908				🟥	🟧	908		908				🟥	🟧
909	909	909				🟦	🟧	909		909				🟦	🟧
910							🟧	910		910				🟦	🟧
911	911	911				🟥	🟧	911	911	911				🟥	🟧
912							🟧	912		912				🟦	🟧
913							🟧	913	913	913				🟦	🟧
914							🟧	914		914				🟦	🟧
915							🟫	915		915				🟦	🟫
916		916		🟩		🟦	🟫	916	916	916		🟩		🟦	🟫
917		917				🟦	🟫	917	917	917				🟦	🟫
918		918		🟩		🟥	🟫	918	918	918		🟩		🟥	🟫
919		919				🟦	🟫	919	919	919				🟦	🟫
920							🟫	920	920	920				🟦	🟫
921							🟫	921	921	921				⬛	🟫
922		922		🟩		⬛	🟫	922		922		🟩		⬛	🟫
923							🟫	923		923		🟩		⬛	🟫
924		924		🟩		⬛	🟫	924	924	924		🟩		⬛	🟫
925							🟫	925	925	925		🟩			🟫
926							🟫	926		926		🟩			🟫
927							🟫	927							🟫
928		928	🟪		⬜	🟥	🟫	928	928	928	🟪		⬜	🟥	🟫
929							🟫	929		929		🟩		▫	🟫
930							🟫	930	930			🟩		▫	🟫
931							🟫	931	931	931		🟩		▫	🟫
932							🟫	932	932	932				⬛	🟫
933							🟫	933							🟫
934							🟫	934							🟫
935							🟫	935							🟫
936							🟫	936	936	936		🟩		🟦	🟫
937							🟫	937	937	937				🟦	🟫
938							🟫	938	938	938				🟦	🟫
939							🟫	939							🟫
940							🟫	940	940	940				🟦	🟫
941							🟫	941	941					🟥	🟫
942							🟫	942							🟫
943							🟫	943	943					🟦	🟫
944							🟫	944	944	944				🟥	🟫
945							🟫	945							🟫

Figure N.5: Geometry analysis of dredging and plowing locations after the peak in January 2015 (peak discharge: 4625 m^3/s)



Dredging								Plowing							
rkm	Dredged rkms M0	Dredged rkms M1	LAD	widening winter bed	End of fixed layer/ bendway weirs	Sharp bend Gentle bend Straight Crossing	Upper Waal Middle Waal Lower Waal	rkm	Plowed rkms M0	Plowed rkms M1	LAD	widening winter bed	End of fixed layer/ bendway weirs	Sharp bend Gentle bend Straight Crossing	Upper Waal Middle Waal Lower Waal
868							Upper Waal	868							Upper Waal
869	869					Sharp bend		869	869	869				Sharp bend	
870	870					Sharp bend		870							
871	871					Sharp bend		871							
872								872							
873								873							
874								874							
875								875							
876	876		■		■	Crossing		876							
877								877							
878	878			■		Sharp bend		878							
879								879							
880								880							
881	881					Sharp bend		881	881	881				Sharp bend	
882	882					Crossing		882							
883								883							
884								884		884					
885	885				■			885							
886								886							
887	887					Straight	Middle Waal	887	887	887				Straight	Middle Waal
888	888		■			Gentle bend		888	888	888	■			Gentle bend	
889	889					Gentle bend		889							
890	890					Straight		890	890	890				Straight	
891	891					Straight		891							
892	892			■		Straight		892							
893	893					Straight		893	893	893				Straight	
894	894					Gentle bend		894	894	894				Gentle bend	
895	895					Crossing		895	895	895				Crossing	
896								896	896	896				Gentle bend	
897								897	897	897				Gentle bend	
898	898					Straight		898	898	898				Straight	
899								899		899		■			
900								900							
901								901		901				Straight	
902								902							
903								903							
904	904					Crossing		904							
905								905							
906								906							
907								907	907	907		■		Gentle bend	
908		908				Crossing		908							
909								909		909				Gentle bend	
910								910		910				Gentle bend	
911								911		911		■		Crossing	
912								912							
913								913		913				Gentle bend	
914								914							
915							Lower Waal	915		915				Gentle bend	Lower Waal
916								916		916				Gentle bend	
917								917		917				Gentle bend	
918								918		918				Crossing	
919								919	919	919				Gentle bend	
920								920		920				Gentle bend	
921								921		921				Crossing	
922								922							
923								923							
924		924				Straight		924		924				Straight	
925								925		925		■			
926								926		926					
927								927							
928	928	928	■		■			928	928	928	■		■	Crossing	
929								929		929				Sharp bend	
930								930		930				Sharp bend	
931								931		931				Sharp bend	
932								932		932				Crossing	
933								933							
934								934		934				Crossing	
935								935							
936								936		936				Gentle bend	
937								937		937				Gentle bend	
938								938		938				Gentle bend	
939								939							
940								940		940				Gentle bend	
941								941		941				Crossing	
942								942		942				Gentle bend	
943								943		943				Gentle bend	
944								944		944				Crossing	
945								945		945				Gentle bend	

Figure N.6: Geometry analysis of dredging and plowing locations after the peak in March 2015 (peak discharge: 3406 m^3/s)



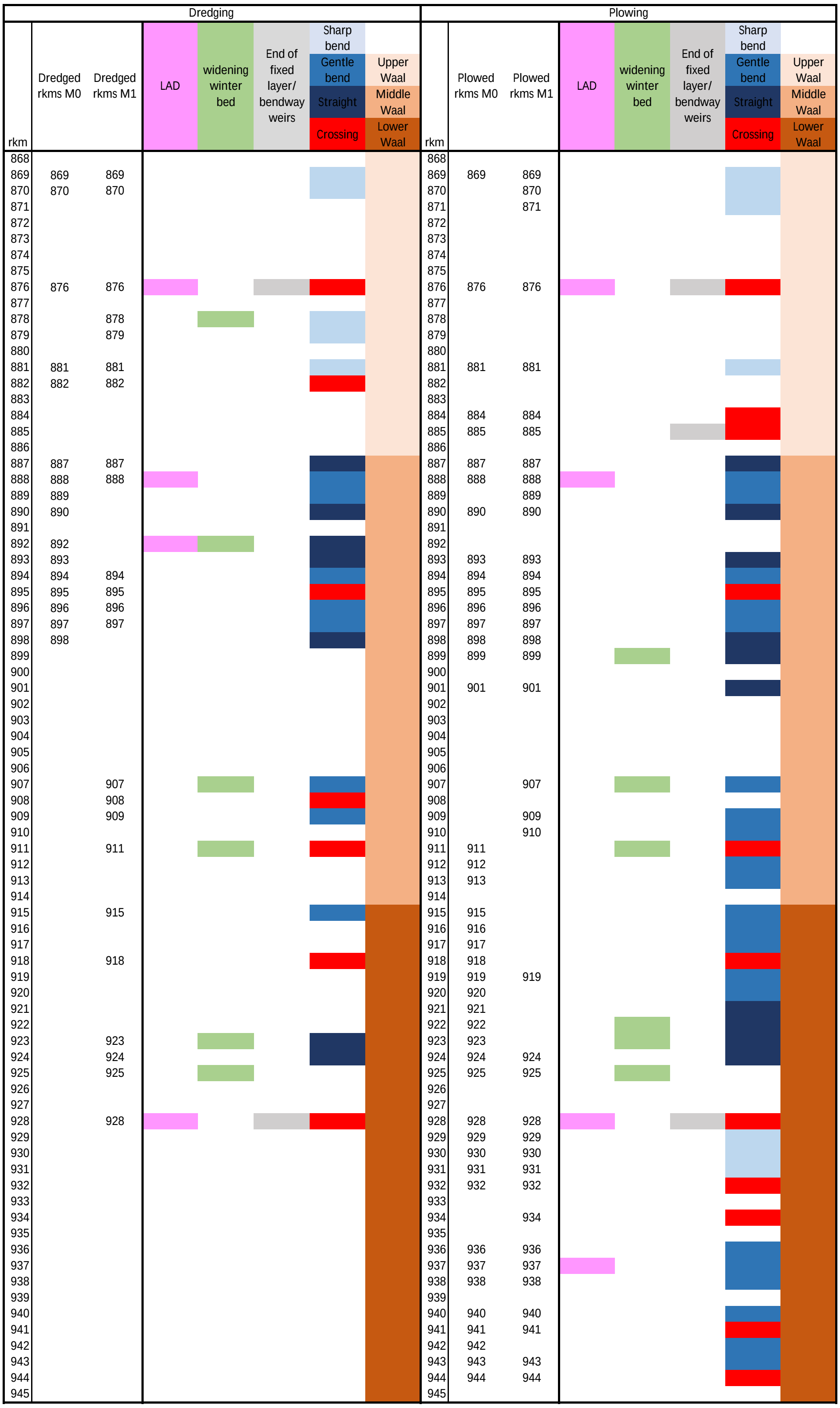
Dredging

rkm	Dredged rkms M0	Dredged rkms M1	LAD	widening winter bed	End of fixed layer/ bendway weirs	Sharp bend / Gentle bend / Straight / Crossing	Upper Waal / Middle Waal / Lower Waal
868							
869		869				Sharp bend	Upper Waal
870		870				Sharp bend	
871							
872							
873							
874							
875							
876		876	■		■	Crossing	
877							
878							
879							
880							
881		881				Sharp bend	
882		882				Crossing	
883							
884							
885							
886							
887		887				Straight	Middle Waal
888		888	■			Gentle bend	
889		889				Gentle bend	
890		890				Straight	
891							
892		892		■		Straight	
893		893				Straight	
894		894				Gentle bend	
895		895				Crossing	
896		896				Gentle bend	
897		897				Gentle bend	
898		898				Straight	
899							
900							
901							
902							
903							
904		904				Crossing	
905							
906							
907							
908	908	908				Crossing	
909		909				Gentle bend	
910							
911		911		■		Crossing	
912							
913							
914							
915		915				Gentle bend	Lower Waal
916		916				Gentle bend	
917		917				Gentle bend	
918		918				Crossing	
919		919				Gentle bend	
920							
921							
922							
923							
924	924					Straight	
925							
926							
927							
928	928		■		■		
929							
930							
931							
932							
933							
934							
935							
936							
937							
938							
939							
940							
941							
942							
943							
944							
945							

Plowing

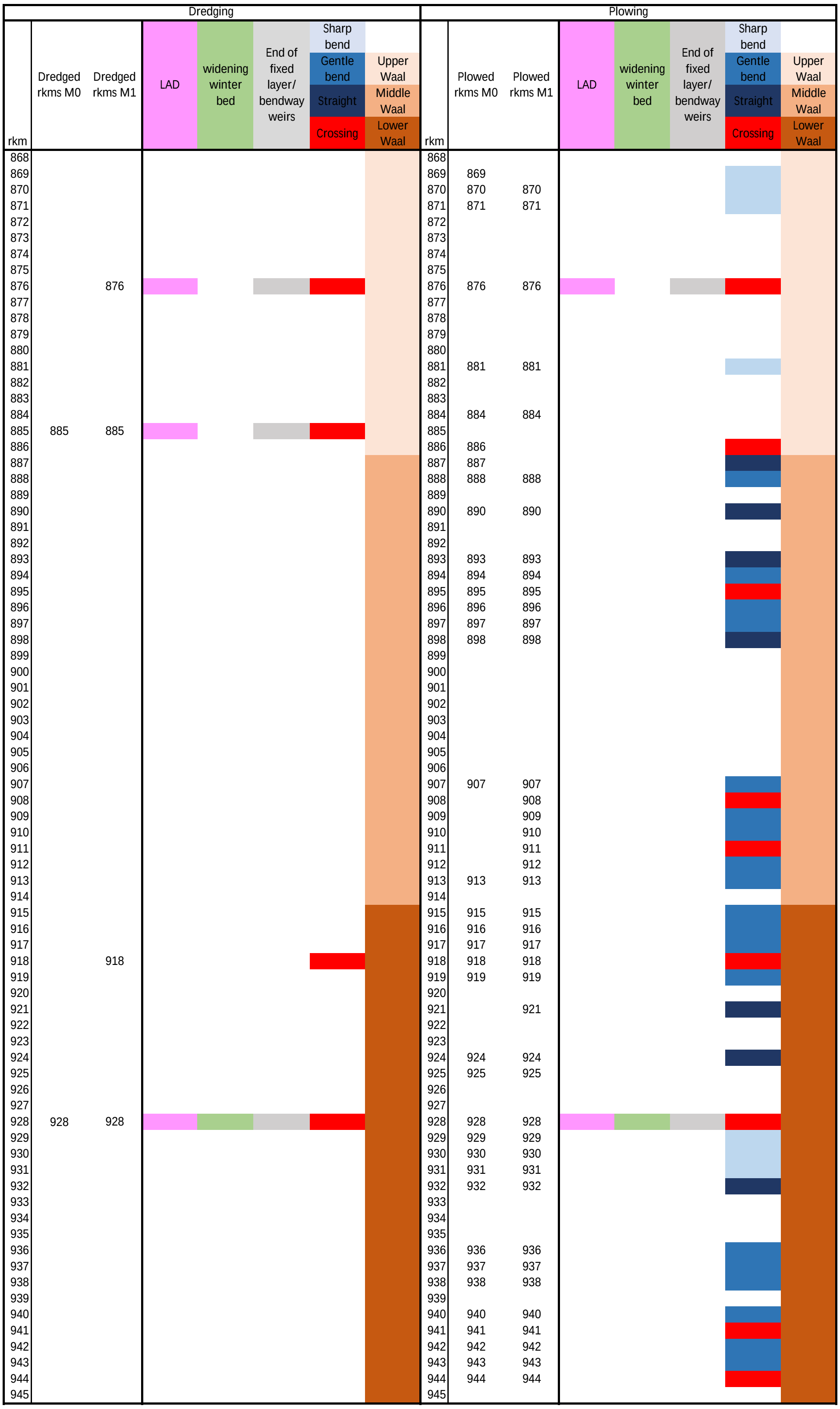
rkm	Plowed rkms M0	Plowed rkms M1	LAD	widening winter bed	End of fixed layer/ bendway weirs	Sharp bend / Gentle bend / Straight / Crossing	Upper Waal / Middle Waal / Lower Waal
868							
869	869	869				Sharp bend	Upper Waal
870							
871							
872							
873							
874							
875							
876		876	■		■	Crossing	
877							
878							
879							
880							
881	881	881				Sharp bend	
882							
883							
884	884	884					
885		885			■	Crossing	
886							
887	887	887				Straight	Middle Waal
888	888	888	■			Gentle bend	
889							
890	890	890				Straight	
891							
892							
893	893	893				Straight	
894	894	894				Gentle bend	
895	895	895				Crossing	
896	896	896				Gentle bend	
897	897	897				Gentle bend	
898	898	898				Straight	
899	899	899		■		Straight	
900							
901	901	901				Straight	
902							
903							
904							
905							
906							
907		907		■		Gentle bend	
908							
909							
910							
911	911	911		■		Crossing	
912		912				Gentle bend	
913	913	913				Gentle bend	
914							
915		915				Gentle bend	Lower Waal
916	916	916				Gentle bend	
917	917	917				Gentle bend	
918	918	918				Crossing	
919	919	919				Gentle bend	
920	920	920				Gentle bend	
921	921	921				Straight	
922		922		■		Straight	
923		923		■		Straight	
924	924	924				Straight	
925	925	925		■			
926	926	926					
927		927					
928	928	928	■		■	Crossing	
929	929	929				Sharp bend	
930	930	930				Sharp bend	
931	931	931				Sharp bend	
932	932	932				Straight	
933		933				Straight	
934	934	934				Straight	
935		935				Straight	
936	936	936				Gentle bend	
937	937	937	■			Gentle bend	
938	938	938				Gentle bend	
939							
940	940	940				Gentle bend	
941	941	941				Crossing	
942	942	942				Gentle bend	
943	943	943				Gentle bend	
944	944	944				Crossing	
945	945					Gentle bend	

Figure N.7: Geometry analysis of dredging and plowing locations after the peak in April 2015 (peak discharge: 3855 m^3/s)



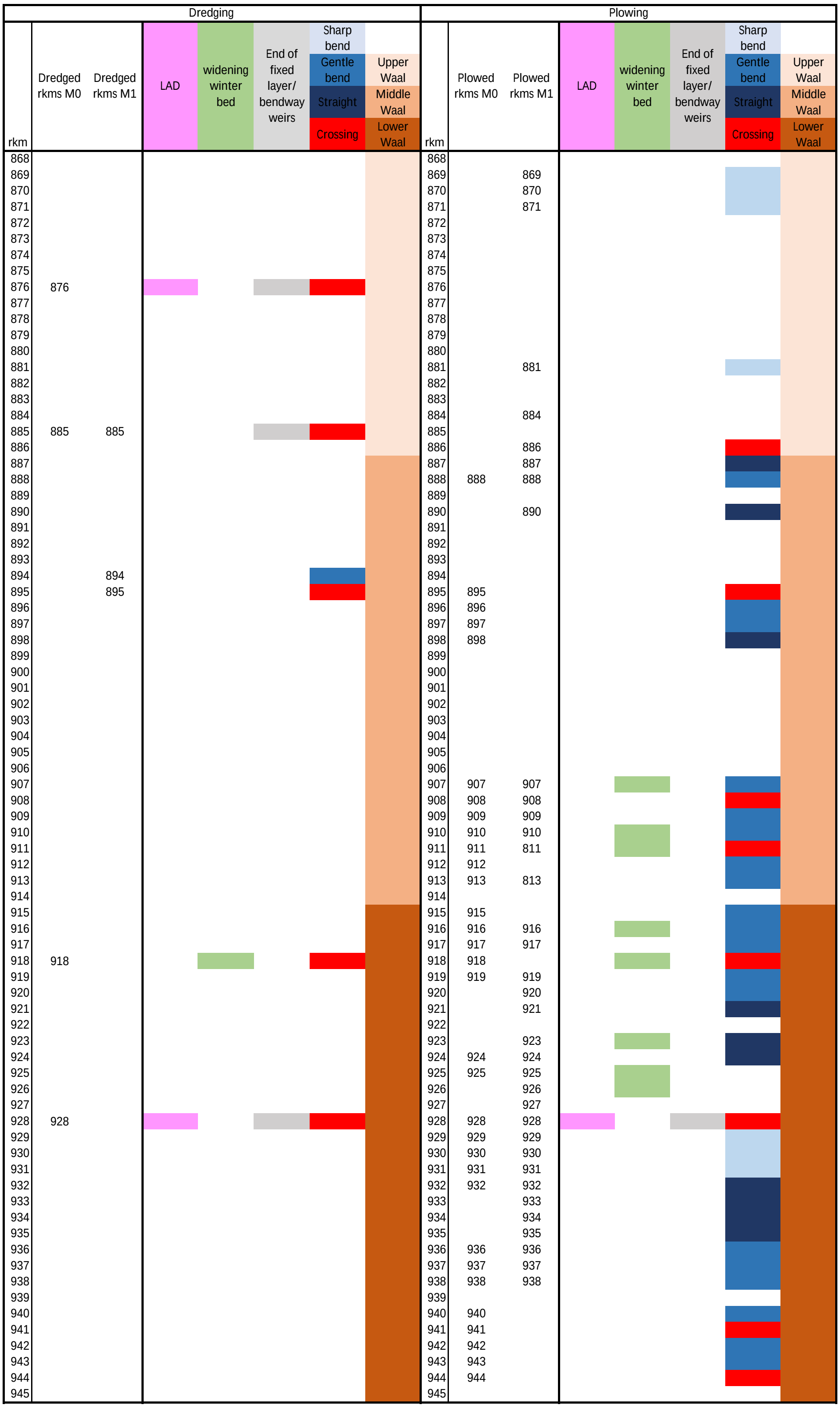
Dredging								Plowing							
rkm	Dredged rkms M0	Dredged rkms M1	LAD	widening winter bed	End of fixed layer/ bendway weirs	Sharp bend Gentle bend Straight Crossing	Upper Waal Middle Waal Lower Waal	rkm	Plowed rkms M0	Plowed rkms M1	LAD	widening winter bed	End of fixed layer/ bendway weirs	Sharp bend Gentle bend Straight Crossing	Upper Waal Middle Waal Lower Waal
868							Upper Waal	868							Upper Waal
869	869	869				Sharp bend		869	869	869				Sharp bend	
870	870	870				Sharp bend		870		870				Sharp bend	
871								871		871				Sharp bend	
872								872							
873								873							
874								874							
875								875							
876	876	876	■		■	Crossing		876	876	876	■		■	Crossing	
877								877							
878		878		■		Sharp bend		878							
879		879				Sharp bend		879							
880								880							
881	881	881				Sharp bend		881	881	881				Sharp bend	
882	882	882				Crossing		882							
883								883							
884								884	884	884				Crossing	
885								885	885	885			■	Crossing	
886								886							
887	887	887				Straight	Middle Waal	887	887	887				Straight	Middle Waal
888	888	888	■			Gentle bend		888	888	888	■			Gentle bend	
889	889					Gentle bend		889	889	889				Gentle bend	
890	890					Straight		890	890	890				Straight	
891								891							
892	892		■	■		Straight		892							
893	893					Straight		893	893	893				Straight	
894	894	894				Gentle bend		894	894	894				Gentle bend	
895	895	895				Crossing		895	895	895				Crossing	
896	896	896				Gentle bend		896	896	896				Gentle bend	
897	897	897				Gentle bend		897	897	897				Gentle bend	
898	898					Straight		898	898	898				Straight	
899								899	899	899		■		Straight	
900								900							
901								901	901	901				Straight	
902								902							
903								903							
904								904							
905								905							
906								906							
907		907		■		Gentle bend		907		907		■		Gentle bend	
908		908				Crossing		908							
909		909				Gentle bend		909		909				Gentle bend	
910								910		910				Gentle bend	
911		911		■		Crossing		911	911			■		Crossing	
912								912	912					Gentle bend	
913								913	913					Gentle bend	
914								914							
915		915				Gentle bend	Lower Waal	915	915					Gentle bend	Lower Waal
916								916	916					Gentle bend	
917								917	917					Gentle bend	
918		918				Crossing		918	918					Crossing	
919								919	919	919				Gentle bend	
920								920	920					Gentle bend	
921								921	921					Straight	
922								922	922			■		Straight	
923		923		■		Straight		923	923			■		Straight	
924		924				Straight		924	924	924				Straight	
925		925		■				925	925	925		■			
926								926							
927								927							
928		928	■		■	Crossing		928	928	928	■		■	Crossing	
929								929	929	929				Sharp bend	
930								930	930	930				Sharp bend	
931								931	931	931				Sharp bend	
932								932	932	932				Crossing	
933								933							
934								934		934				Crossing	
935								935							
936								936	936	936				Gentle bend	
937								937	937	937	■			Gentle bend	
938								938	938	938				Gentle bend	
939								939							
940								940	940	940				Gentle bend	
941								941	941	941				Crossing	
942								942	942					Gentle bend	
943								943	943	943				Gentle bend	
944								944	944	944				Crossing	
945								945							

Figure N.8: Geometry analysis of dredging and plowing locations after the peak in May 2015 (peak discharge: 3758 m^3/s)



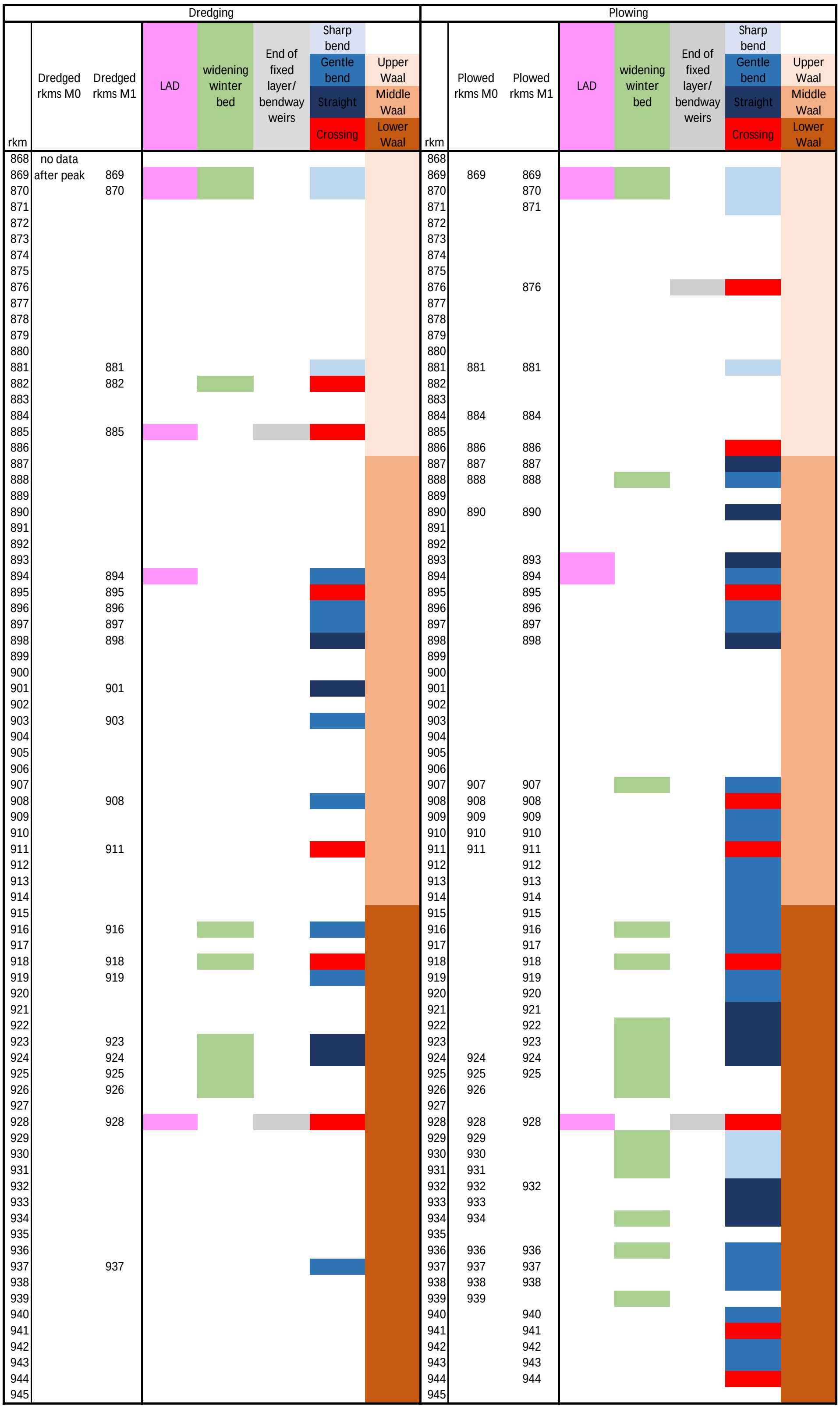
Dredging								Plowing							
rkm	Dredged rkms M0	Dredged rkms M1	LAD	widening winter bed	End of fixed layer/ bendway weirs	Sharp bend Gentle bend Straight Crossing	Upper Waal Middle Waal Lower Waal	rkm	Plowed rkms M0	Plowed rkms M1	LAD	widening winter bed	End of fixed layer/ bendway weirs	Sharp bend Gentle bend Straight Crossing	Upper Waal Middle Waal Lower Waal
868							Upper Waal	868							Upper Waal
869							Upper Waal	869	869					Sharp bend	Upper Waal
870							Upper Waal	870	870	870				Sharp bend	Upper Waal
871							Upper Waal	871	871	871				Sharp bend	Upper Waal
872							Upper Waal	872							Upper Waal
873							Upper Waal	873							Upper Waal
874							Upper Waal	874							Upper Waal
875							Upper Waal	875							Upper Waal
876		876	■		■	Crossing	Upper Waal	876	876	876	■		■	Crossing	Upper Waal
877							Upper Waal	877							Upper Waal
878							Upper Waal	878							Upper Waal
879							Upper Waal	879							Upper Waal
880							Upper Waal	880							Upper Waal
881							Upper Waal	881	881	881				Sharp bend	Upper Waal
882							Upper Waal	882							Upper Waal
883							Upper Waal	883							Upper Waal
884							Upper Waal	884	884	884					Upper Waal
885	885	885	■		■	Crossing	Upper Waal	885							Upper Waal
886							Upper Waal	886	886					Crossing	Upper Waal
887							Middle Waal	887	887					Straight	Middle Waal
888							Middle Waal	888	888	888				Gentle bend	Middle Waal
889							Middle Waal	889							Middle Waal
890							Middle Waal	890	890	890				Straight	Middle Waal
891							Middle Waal	891							Middle Waal
892							Middle Waal	892							Middle Waal
893							Middle Waal	893	893	893				Straight	Middle Waal
894							Middle Waal	894	894	894				Gentle bend	Middle Waal
895							Middle Waal	895	895	895				Crossing	Middle Waal
896							Middle Waal	896	896	896				Gentle bend	Middle Waal
897							Middle Waal	897	897	897				Gentle bend	Middle Waal
898							Middle Waal	898	898	898				Straight	Middle Waal
899							Middle Waal	899							Middle Waal
900							Middle Waal	900							Middle Waal
901							Middle Waal	901							Middle Waal
902							Middle Waal	902							Middle Waal
903							Middle Waal	903							Middle Waal
904							Middle Waal	904							Middle Waal
905							Middle Waal	905							Middle Waal
906							Middle Waal	906							Middle Waal
907							Middle Waal	907	907	907				Gentle bend	Middle Waal
908							Middle Waal	908		908				Crossing	Middle Waal
909							Middle Waal	909		909				Gentle bend	Middle Waal
910							Middle Waal	910		910				Gentle bend	Middle Waal
911							Middle Waal	911		911				Crossing	Middle Waal
912							Middle Waal	912		912				Gentle bend	Middle Waal
913							Middle Waal	913	913	913				Gentle bend	Middle Waal
914							Middle Waal	914							Middle Waal
915							Lower Waal	915	915	915				Gentle bend	Lower Waal
916							Lower Waal	916	916	916				Gentle bend	Lower Waal
917							Lower Waal	917	917	917				Gentle bend	Lower Waal
918		918				Crossing	Lower Waal	918	918	918				Crossing	Lower Waal
919							Lower Waal	919	919	919				Gentle bend	Lower Waal
920							Lower Waal	920							Lower Waal
921							Lower Waal	921		921				Straight	Lower Waal
922							Lower Waal	922							Lower Waal
923							Lower Waal	923							Lower Waal
924							Lower Waal	924	924	924				Straight	Lower Waal
925							Lower Waal	925	925	925					Lower Waal
926							Lower Waal	926							Lower Waal
927							Lower Waal	927							Lower Waal
928	928	928	■	■	■	Crossing	Lower Waal	928	928	928	■	■	■	Crossing	Lower Waal
929							Lower Waal	929	929	929				Sharp bend	Lower Waal
930							Lower Waal	930	930	930				Sharp bend	Lower Waal
931							Lower Waal	931	931	931				Sharp bend	Lower Waal
932							Lower Waal	932	932	932				Straight	Lower Waal
933							Lower Waal	933							Lower Waal
934							Lower Waal	934							Lower Waal
935							Lower Waal	935							Lower Waal
936							Lower Waal	936	936	936				Gentle bend	Lower Waal
937							Lower Waal	937	937	937				Gentle bend	Lower Waal
938							Lower Waal	938	938	938				Gentle bend	Lower Waal
939							Lower Waal	939							Lower Waal
940							Lower Waal	940	940	940				Gentle bend	Lower Waal
941							Lower Waal	941	941	941				Crossing	Lower Waal
942							Lower Waal	942	942	942				Gentle bend	Lower Waal
943							Lower Waal	943	943	943				Gentle bend	Lower Waal
944							Lower Waal	944	944	944				Crossing	Lower Waal
945							Lower Waal	945							Lower Waal

Figure N.9: Geometry analysis of dredging and plowing locations after the peak in December 2015 (peak discharge: 3078 m^3/s)



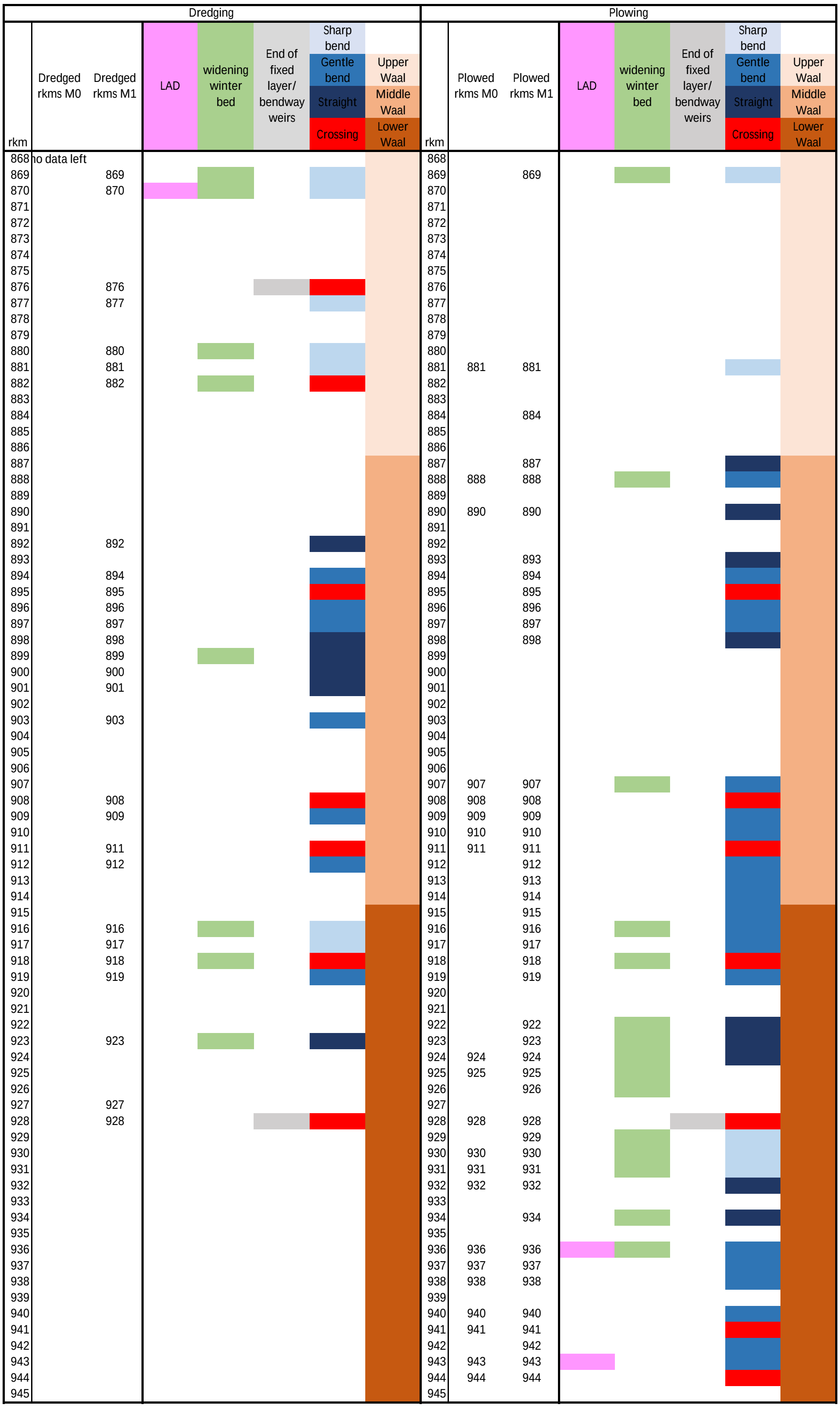
Dredging								Plowing							
rkm	Dredged rkms M0	Dredged rkms M1	LAD	widening winter bed	End of fixed layer/ bendway weirs	Sharp bend Gentle bend Straight Crossing	Upper Waal Middle Waal Lower Waal	rkm	Plowed rkms M0	Plowed rkms M1	LAD	widening winter bed	End of fixed layer/ bendway weirs	Sharp bend Gentle bend Straight Crossing	Upper Waal Middle Waal Lower Waal
868							Upper Waal	868							Upper Waal
869							Upper Waal	869		869				Sharp bend	Upper Waal
870							Upper Waal	870		870				Sharp bend	Upper Waal
871							Upper Waal	871		871				Sharp bend	Upper Waal
872							Upper Waal	872							Upper Waal
873							Upper Waal	873							Upper Waal
874							Upper Waal	874							Upper Waal
875							Upper Waal	875							Upper Waal
876	876		■		■	Crossing	Upper Waal	876							Upper Waal
877							Upper Waal	877							Upper Waal
878							Upper Waal	878							Upper Waal
879							Upper Waal	879							Upper Waal
880							Upper Waal	880							Upper Waal
881							Upper Waal	881		881				Sharp bend	Upper Waal
882							Upper Waal	882							Upper Waal
883							Upper Waal	883							Upper Waal
884							Upper Waal	884		884					Upper Waal
885	885	885			■	Crossing	Upper Waal	885							Upper Waal
886							Upper Waal	886		886				Crossing	Upper Waal
887							Middle Waal	887		887				Straight	Middle Waal
888							Middle Waal	888	888	888				Gentle bend	Middle Waal
889							Middle Waal	889							Middle Waal
890							Middle Waal	890		890				Straight	Middle Waal
891							Middle Waal	891							Middle Waal
892							Middle Waal	892							Middle Waal
893							Middle Waal	893							Middle Waal
894		894				Gentle bend	Middle Waal	894							Middle Waal
895		895				Crossing	Middle Waal	895	895					Crossing	Middle Waal
896							Middle Waal	896	896					Gentle bend	Middle Waal
897							Middle Waal	897	897					Gentle bend	Middle Waal
898							Middle Waal	898	898					Straight	Middle Waal
899							Middle Waal	899							Middle Waal
900							Middle Waal	900							Middle Waal
901							Middle Waal	901							Middle Waal
902							Middle Waal	902							Middle Waal
903							Middle Waal	903							Middle Waal
904							Middle Waal	904							Middle Waal
905							Middle Waal	905							Middle Waal
906							Middle Waal	906							Middle Waal
907							Middle Waal	907	907	907		■		Gentle bend	Middle Waal
908							Middle Waal	908	908	908				Crossing	Middle Waal
909							Middle Waal	909	909	909				Gentle bend	Middle Waal
910							Middle Waal	910	910	910		■		Gentle bend	Middle Waal
911							Middle Waal	911	911	811		■		Crossing	Middle Waal
912							Middle Waal	912	912					Gentle bend	Middle Waal
913							Middle Waal	913	913	813				Gentle bend	Middle Waal
914							Middle Waal	914							Middle Waal
915							Lower Waal	915	915					Gentle bend	Lower Waal
916							Lower Waal	916	916	916		■		Gentle bend	Lower Waal
917							Lower Waal	917	917	917				Gentle bend	Lower Waal
918	918			■		Crossing	Lower Waal	918	918			■		Crossing	Lower Waal
919							Lower Waal	919	919	919				Gentle bend	Lower Waal
920							Lower Waal	920		920				Gentle bend	Lower Waal
921							Lower Waal	921		921				Straight	Lower Waal
922							Lower Waal	922							Lower Waal
923							Lower Waal	923		923		■		Straight	Lower Waal
924							Lower Waal	924	924	924				Straight	Lower Waal
925							Lower Waal	925	925	925		■			Lower Waal
926							Lower Waal	926		926		■			Lower Waal
927							Lower Waal	927		927					Lower Waal
928	928		■		■	Crossing	Lower Waal	928	928	928	■		■	Crossing	Lower Waal
929							Lower Waal	929	929	929				Sharp bend	Lower Waal
930							Lower Waal	930	930	930				Sharp bend	Lower Waal
931							Lower Waal	931	931	931				Sharp bend	Lower Waal
932							Lower Waal	932	932	932				Straight	Lower Waal
933							Lower Waal	933		933				Straight	Lower Waal
934							Lower Waal	934		934				Straight	Lower Waal
935							Lower Waal	935		935				Straight	Lower Waal
936							Lower Waal	936	936	936				Gentle bend	Lower Waal
937							Lower Waal	937	937	937				Gentle bend	Lower Waal
938							Lower Waal	938	938	938				Gentle bend	Lower Waal
939							Lower Waal	939							Lower Waal
940							Lower Waal	940	940					Gentle bend	Lower Waal
941							Lower Waal	941	941					Crossing	Lower Waal
942							Lower Waal	942	942					Gentle bend	Lower Waal
943							Lower Waal	943	943					Gentle bend	Lower Waal
944							Lower Waal	944	944					Crossing	Lower Waal
945							Lower Waal	945							Lower Waal

Figure N.10: Geometry analysis of dredging and plowing locations after the peak in January 2016 (peak discharge: 3993 m^3/s)



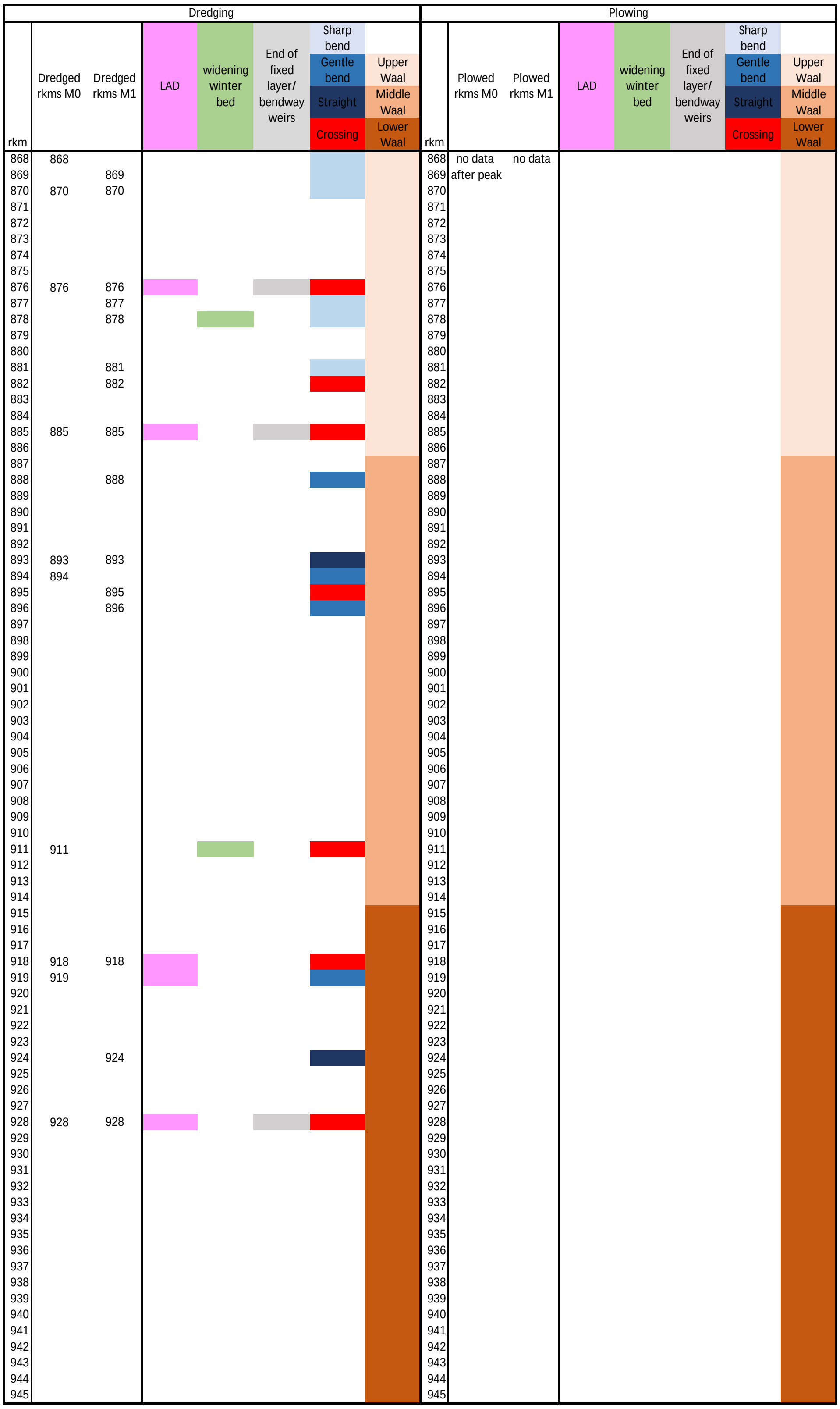
Dredging								Plowing							
rkm	Dredged rkms M0	Dredged rkms M1	LAD 🟪	widening winter bed 🟩	End of fixed layer/ bendway weirs ▨	Sharp bend ○ Gentle bend ◐ Straight ● Crossing 🟥	Upper Waal ░ Middle Waal ▒ Lower Waal ▓	rkm	Plowed rkms M0	Plowed rkms M1	LAD 🟪	widening winter bed 🟩	End of fixed layer/ bendway weirs ▨	Sharp bend ○ Gentle bend ◐ Straight ● Crossing 🟥	Upper Waal ░ Middle Waal ▒ Lower Waal ▓
868	no data						░	868							░
869	after peak	869	🟪	🟩		○	░	869	869	869	🟪	🟩		○	░
870		870	🟪	🟩		○	░	870		870	🟪	🟩		○	░
871							░	871		871				○	░
872							░	872							░
873							░	873							░
874							░	874							░
875							░	875							░
876							░	876		876			▨	🟥	░
877							░	877							░
878							░	878							░
879							░	879							░
880							░	880							░
881		881				○	░	881	881	881				○	░
882		882		🟩		🟥	░	882							░
883							░	883							░
884							░	884	884	884					░
885		885	🟪		▨	🟥	░	885							░
886							░	886	886	886				🟥	░
887							▒	887	887	887				●	▒
888							▒	888	888	888		🟩		◐	▒
889							▒	889							▒
890							▒	890	890	890				●	▒
891							▒	891							▒
892							▒	892							▒
893							▒	893		893	🟪			●	▒
894		894	🟪			◐	▒	894		894	🟪			◐	▒
895		895				🟥	▒	895		895				🟥	▒
896		896				◐	▒	896		896				◐	▒
897		897				◐	▒	897		897				◐	▒
898		898				●	▒	898		898				●	▒
899							▒	899							▒
900							▒	900							▒
901		901				●	▒	901							▒
902							▒	902							▒
903		903				◐	▒	903							▒
904							▒	904							▒
905							▒	905							▒
906							▒	906							▒
907							▒	907	907	907		🟩		◐	▒
908		908				◐	▒	908	908	908				🟥	▒
909							▒	909	909	909				◐	▒
910							▒	910	910	910				◐	▒
911		911				🟥	▒	911	911	911				🟥	▒
912							▒	912		912				◐	▒
913							▒	913		913				◐	▒
914							▒	914		914				◐	▒
915							▓	915		915				◐	▓
916		916		🟩		◐	▓	916		916		🟩		◐	▓
917							▓	917		917				◐	▓
918		918		🟩		🟥	▓	918		918		🟩		🟥	▓
919		919				◐	▓	919		919				◐	▓
920							▓	920		920				◐	▓
921							▓	921		921				●	▓
922							▓	922		922		🟩		●	▓
923		923		🟩		●	▓	923		923		🟩		●	▓
924		924		🟩		●	▓	924	924	924		🟩		●	▓
925		925		🟩			▓	925	925	925		🟩			▓
926		926		🟩			▓	926	926			🟩			▓
927							▓	927							▓
928		928	🟪		▨	🟥	▓	928	928	928	🟪		▨	🟥	▓
929							▓	929	929			🟩		○	▓
930							▓	930	930			🟩		○	▓
931							▓	931	931			🟩		○	▓
932							▓	932	932	932				●	▓
933							▓	933	933					●	▓
934							▓	934	934			🟩		●	▓
935							▓	935							▓
936							▓	936	936	936		🟩		◐	▓
937		937				◐	▓	937	937	937				◐	▓
938							▓	938	938	938				◐	▓
939							▓	939	939			🟩			▓
940							▓	940		940				◐	▓
941							▓	941		941				🟥	▓
942							▓	942		942				◐	▓
943							▓	943		943				◐	▓
944							▓	944		944				🟥	▓
945							▓	945							▓

Figure N.11: Geometry analysis of dredging and plowing locations after the peak in February 2016 (peak discharge: 5268 m^3/s)



Dredging								Plowing							
rkm	Dredged rkms M0	Dredged rkms M1	LAD	widening winter bed	End of fixed layer/ bendway weirs	Sharp bend Gentle bend Straight Crossing	Upper Waal Middle Waal Lower Waal	rkm	Plowed rkms M0	Plowed rkms M1	LAD	widening winter bed	End of fixed layer/ bendway weirs	Sharp bend Gentle bend Straight Crossing	Upper Waal Middle Waal Lower Waal
868	no data left						Upper Waal	868							Upper Waal
869		869		■		Sharp bend	Upper Waal	869		869		■		Sharp bend	Upper Waal
870		870	■	■		Sharp bend	Upper Waal	870							Upper Waal
871							Upper Waal	871							Upper Waal
872							Upper Waal	872							Upper Waal
873							Upper Waal	873							Upper Waal
874							Upper Waal	874							Upper Waal
875							Upper Waal	875							Upper Waal
876		876			■	Crossing	Upper Waal	876							Upper Waal
877		877				Sharp bend	Upper Waal	877							Upper Waal
878							Upper Waal	878							Upper Waal
879							Upper Waal	879							Upper Waal
880		880		■		Sharp bend	Upper Waal	880							Upper Waal
881		881				Sharp bend	Upper Waal	881	881	881				Sharp bend	Upper Waal
882		882		■		Crossing	Upper Waal	882							Upper Waal
883							Upper Waal	883							Upper Waal
884							Upper Waal	884		884					Upper Waal
885							Upper Waal	885							Upper Waal
886							Upper Waal	886							Upper Waal
887							Middle Waal	887		887				Straight	Middle Waal
888							Middle Waal	888	888	888		■		Gentle bend	Middle Waal
889							Middle Waal	889							Middle Waal
890							Middle Waal	890	890	890				Straight	Middle Waal
891							Middle Waal	891							Middle Waal
892		892				Straight	Middle Waal	892							Middle Waal
893							Middle Waal	893		893				Straight	Middle Waal
894		894				Gentle bend	Middle Waal	894		894				Gentle bend	Middle Waal
895		895				Crossing	Middle Waal	895		895				Crossing	Middle Waal
896		896				Gentle bend	Middle Waal	896		896				Gentle bend	Middle Waal
897		897				Gentle bend	Middle Waal	897		897				Gentle bend	Middle Waal
898		898				Straight	Middle Waal	898		898				Straight	Middle Waal
899		899		■		Straight	Middle Waal	899							Middle Waal
900		900				Straight	Middle Waal	900							Middle Waal
901		901				Straight	Middle Waal	901							Middle Waal
902							Middle Waal	902							Middle Waal
903		903				Gentle bend	Middle Waal	903							Middle Waal
904							Middle Waal	904							Middle Waal
905							Middle Waal	905							Middle Waal
906							Middle Waal	906							Middle Waal
907							Middle Waal	907	907	907		■		Gentle bend	Middle Waal
908		908				Crossing	Middle Waal	908	908	908				Crossing	Middle Waal
909		909				Gentle bend	Middle Waal	909	909	909				Gentle bend	Middle Waal
910							Middle Waal	910	910	910				Gentle bend	Middle Waal
911		911				Crossing	Middle Waal	911	911	911				Crossing	Middle Waal
912		912				Gentle bend	Middle Waal	912		912				Gentle bend	Middle Waal
913							Middle Waal	913		913				Gentle bend	Middle Waal
914							Middle Waal	914		914				Gentle bend	Middle Waal
915							Lower Waal	915		915				Gentle bend	Lower Waal
916		916		■		Sharp bend	Lower Waal	916		916		■		Gentle bend	Lower Waal
917		917				Sharp bend	Lower Waal	917		917				Gentle bend	Lower Waal
918		918		■		Crossing	Lower Waal	918		918		■		Crossing	Lower Waal
919		919				Gentle bend	Lower Waal	919		919				Gentle bend	Lower Waal
920							Lower Waal	920							Lower Waal
921							Lower Waal	921							Lower Waal
922							Lower Waal	922		922		■		Straight	Lower Waal
923		923		■		Straight	Lower Waal	923		923		■		Straight	Lower Waal
924							Lower Waal	924	924	924		■		Straight	Lower Waal
925							Lower Waal	925	925	925		■			Lower Waal
926							Lower Waal	926		926		■			Lower Waal
927		927					Lower Waal	927							Lower Waal
928		928			■	Crossing	Lower Waal	928	928	928			■	Crossing	Lower Waal
929							Lower Waal	929		929		■		Sharp bend	Lower Waal
930							Lower Waal	930	930	930		■		Sharp bend	Lower Waal
931							Lower Waal	931	931	931		■		Sharp bend	Lower Waal
932							Lower Waal	932	932	932				Straight	Lower Waal
933							Lower Waal	933							Lower Waal
934							Lower Waal	934		934		■		Straight	Lower Waal
935							Lower Waal	935							Lower Waal
936							Lower Waal	936	936	936	■	■		Gentle bend	Lower Waal
937							Lower Waal	937	937	937				Gentle bend	Lower Waal
938							Lower Waal	938	938	938				Gentle bend	Lower Waal
939							Lower Waal	939							Lower Waal
940							Lower Waal	940	940	940				Gentle bend	Lower Waal
941							Lower Waal	941	941	941				Crossing	Lower Waal
942							Lower Waal	942		942				Gentle bend	Lower Waal
943							Lower Waal	943	943	943	■			Gentle bend	Lower Waal
944							Lower Waal	944	944	944				Crossing	Lower Waal
945							Lower Waal	945							Lower Waal

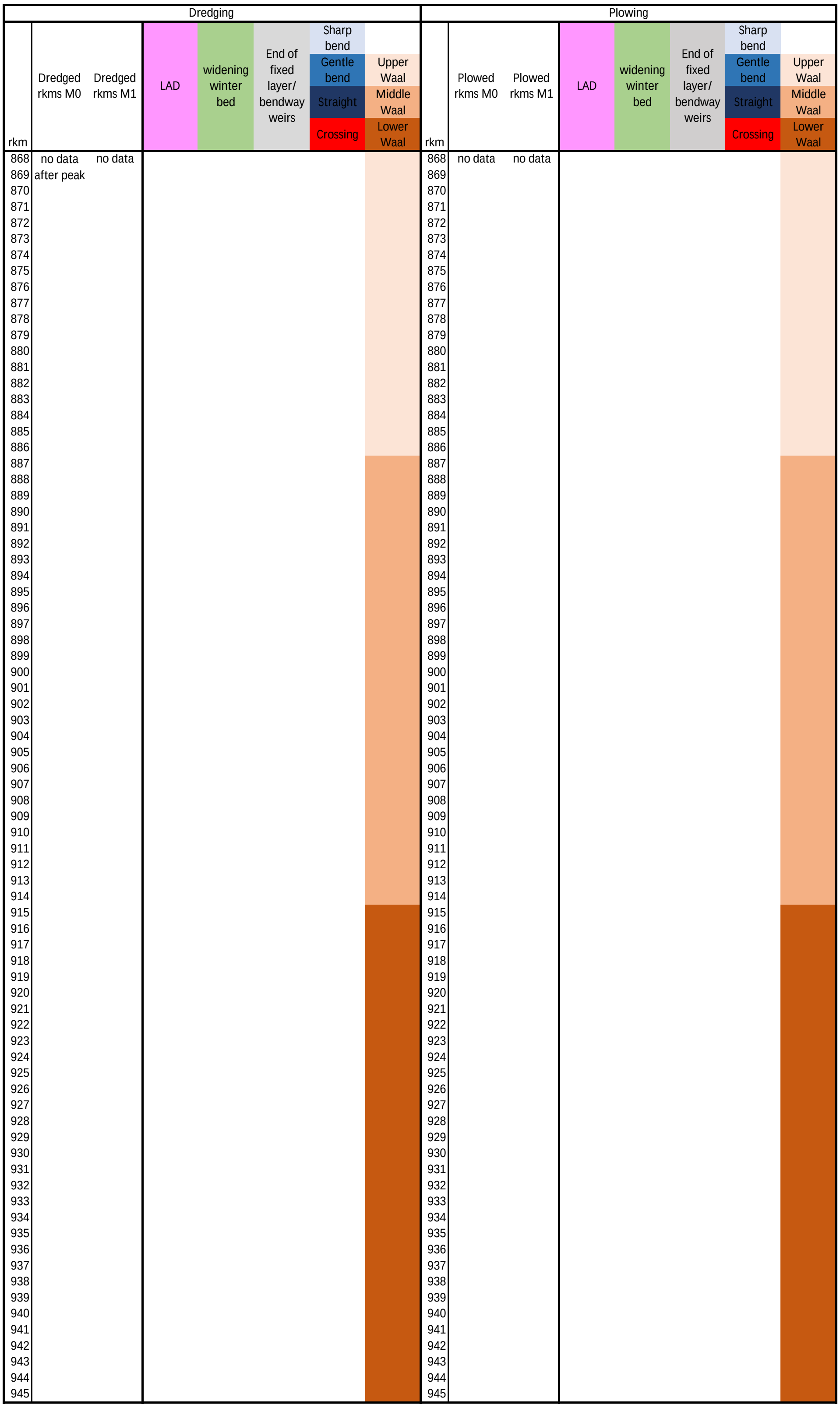
Figure N.12: Geometry analysis of dredging and plowing locations after the peak in June 2016 (peak discharge: 4758 m^3/s)



Dredging							
rkm	Dredged rkms M0	Dredged rkms M1	LAD	widening winter bed	End of fixed layer/ bendway weirs	Sharp bend Gentle bend Straight Crossing	Upper Waal Middle Waal Lower Waal
868	868					Sharp bend	Upper Waal
869		869				Sharp bend	
870	870	870				Sharp bend	
871							
872							
873							
874							
875							
876	876	876	■		■	Crossing	
877		877				Sharp bend	
878		878		■		Sharp bend	
879							
880							
881		881				Sharp bend	
882		882				Crossing	
883							
884							
885	885	885	■		■	Crossing	
886							
887							Middle Waal
888		888				Gentle bend	
889							
890							
891							
892							
893	893	893				Straight	
894	894					Gentle bend	
895		895				Crossing	
896		896				Gentle bend	
897							
898							
899							
900							
901							
902							
903							
904							
905							
906							
907							
908							
909							
910							
911	911			■		Crossing	
912							
913							
914							
915							Lower Waal
916							
917							
918	918	918	■			Crossing	
919	919		■			Gentle bend	
920							
921							
922							
923							
924		924				Straight	
925							
926							
927							
928	928	928	■		■	Crossing	
929							
930							
931							
932							
933							
934							
935							
936							
937							
938							
939							
940							
941							
942							
943							
944							
945							

Plowing							
rkm	Plowed rkms M0	Plowed rkms M1	LAD	widening winter bed	End of fixed layer/ bendway weirs	Sharp bend Gentle bend Straight Crossing	Upper Waal Middle Waal Lower Waal
868	no data	no data					Upper Waal
869	after peak						
870							
871							
872							
873							
874							
875							
876							
877							
878							
879							
880							
881							
882							
883							
884							
885							
886							
887							Middle Waal
888							
889							
890							
891							
892							
893							
894							
895							
896							
897							
898							
899							
900							
901							
902							
903							
904							
905							
906							
907							
908							
909							
910							
911							
912							
913							
914							
915							Lower Waal
916							
917							
918							
919							
920							
921							
922							
923							
924							
925							
926							
927							
928							
929							
930							
931							
932							
933							
934							
935							
936							
937							
938							
939							
940							
941							
942							
943							
944							
945							

Figure N.13: Geometry analysis of dredging and plowing locations after the peak in March 2017 (peak discharge: 3779 m^3/s)



Dredging								Plowing							
rkm	Dredged rkms M0	Dredged rkms M1	LAD	widening winter bed	End of fixed layer/ bendway weirs	Sharp bend Gentle bend Straight Crossing	Upper Waal ░ Middle Waal ▒ Lower Waal ▓	rkm	Plowed rkms M0	Plowed rkms M1	LAD	widening winter bed	End of fixed layer/ bendway weirs	Sharp bend Gentle bend Straight Crossing	Upper Waal ░ Middle Waal ▒ Lower Waal ▓
868	no data	no data					░	868	no data	no data					░
869	after peak						░	869							░
870							░	870							░
871							░	871							░
872							░	872							░
873							░	873							░
874							░	874							░
875							░	875							░
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935							▓	935							▓
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943							▓	943							▓
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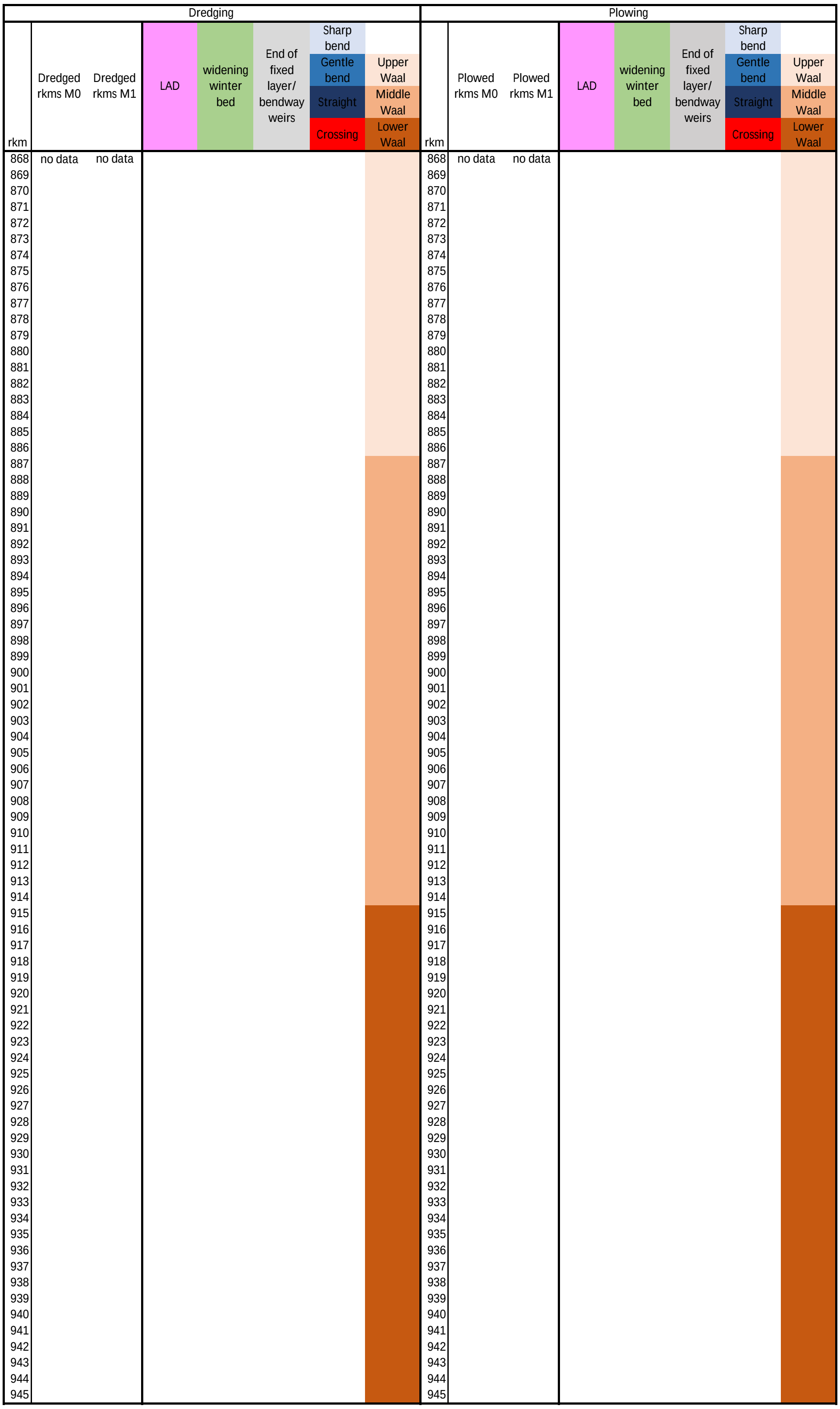
Figure N.14: Geometry analysis of dredging and plowing locations after the peak in December 2017 (peak discharge: 5089 m^3/s)



Dredging								Plowing							
rkm	Dredged rkms M0	Dredged rkms M1	LAD	widening winter bed	End of fixed layer/ bendway weirs	Sharp bend Gentle bend Straight Crossing	Upper Waal Middle Waal Lower Waal	rkm	Plowed rkms M0	Plowed rkms M1	LAD	widening winter bed	End of fixed layer/ bendway weirs	Sharp bend Gentle bend Straight Crossing	Upper Waal Middle Waal Lower Waal
868	no data	no data					░	868	no data	no data					░
869							░	869							░
870							░	870							░
871							░	871							░
872							░	872							░
873							░	873							░
874							░	874							░
875							░	875							░
876							░	876							░
877							░	877							░
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896							▒	896							▒
897							▒	897							▒
898							▒	898							▒
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904							▒	904							▒
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913							▒	913							▒
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915							▓	915							▓
916							▓	916							▓
917							▓	917							▓
918							▓	918							▓
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933							▓	933							▓
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935							▓	935							▓
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937							▓	937							▓
938							▓	938							▓
939							▓	939							▓
940							▓	940							▓
941							▓	941							▓
942							▓	942							▓
943							▓	943							▓
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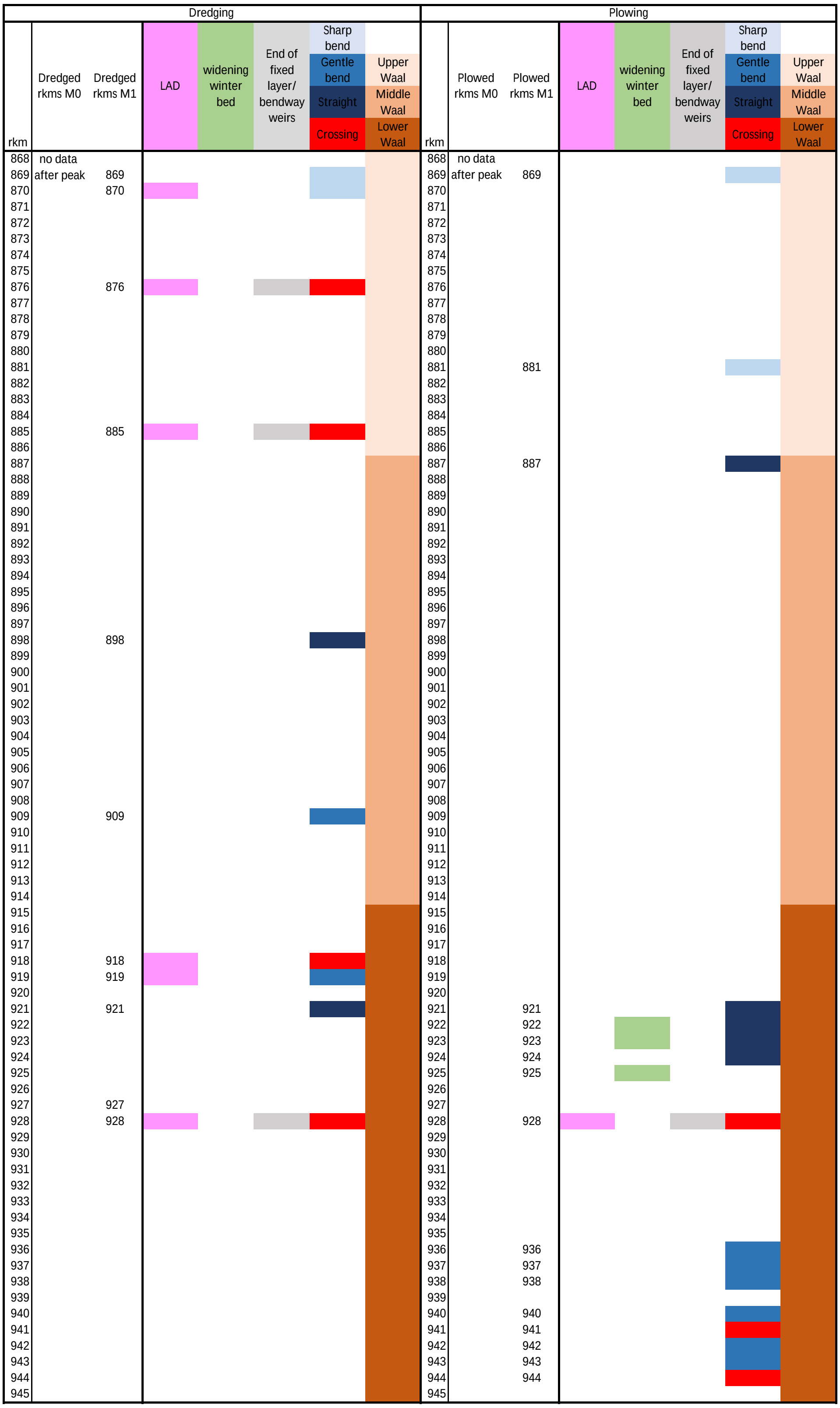
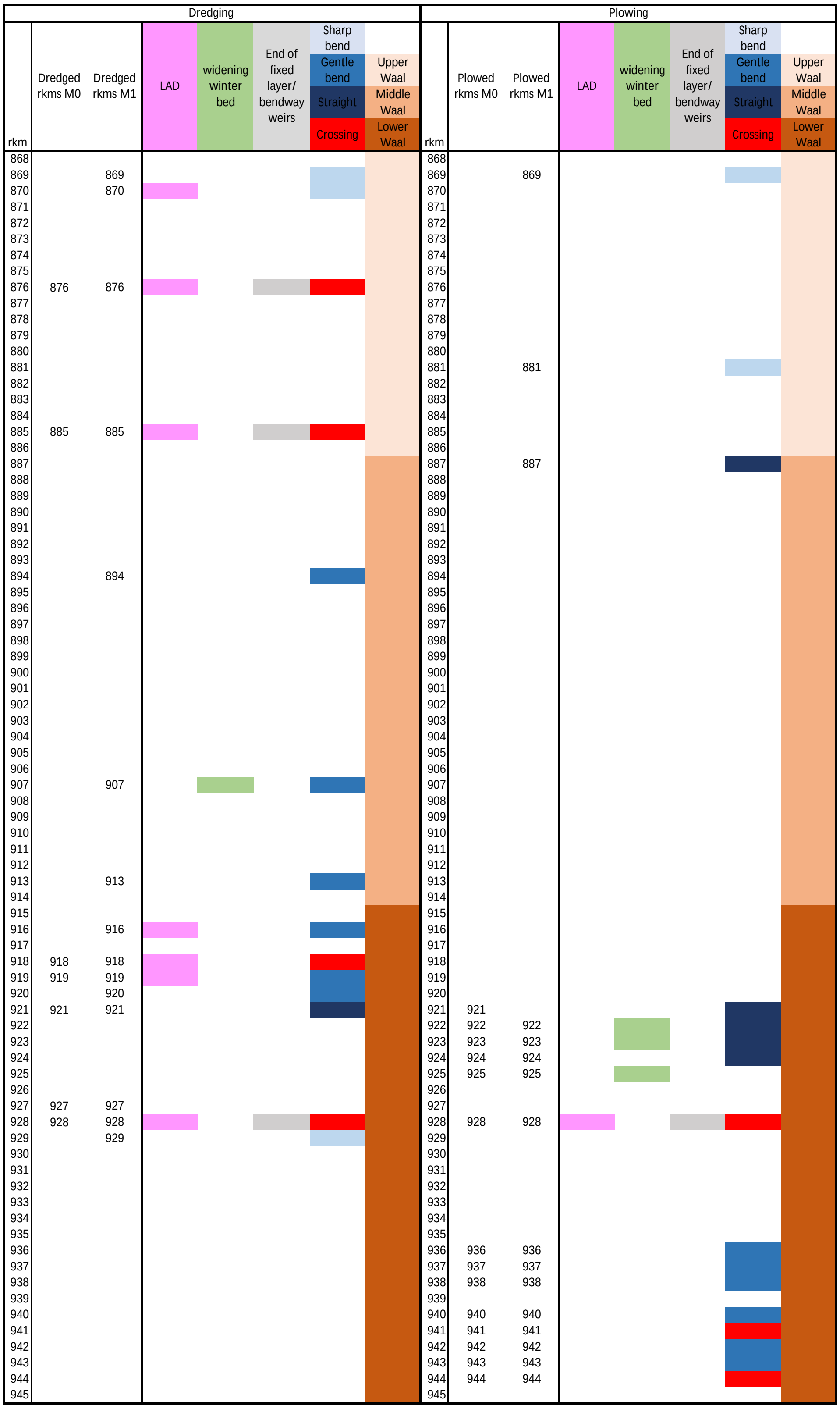
945							▓	945							▓

Figure N.15: Geometry analysis of dredging and plowing locations after the peak in January 2018 (peak discharge: 7553 m^3/s)



Dredging								Plowing							
rkm	Dredged rkms M0	Dredged rkms M1	LAD	widening winter bed	End of fixed layer/ bendway weirs	Sharp bend Gentle bend Straight Crossing	Upper Waal Middle Waal Lower Waal	rkm	Plowed rkms M0	Plowed rkms M1	LAD	widening winter bed	End of fixed layer/ bendway weirs	Sharp bend Gentle bend Straight Crossing	Upper Waal Middle Waal Lower Waal
868	no data						🟨	868	no data						🟨
869	after peak	869				◇	🟨	869	after peak	869				◇	🟨
870		870	🟪			◇	🟨	870							🟨
871							🟨	871							🟨
872							🟨	872							🟨
873							🟨	873							🟨
874							🟨	874							🟨
875							🟨	875							🟨
876		876	🟪		▨	🟥	🟨	876							🟨
877							🟨	877							🟨
878							🟨	878							🟨
879							🟨	879							🟨
880							🟨	880							🟨
881							🟨	881		881				◇	🟨
882							🟨	882							🟨
883							🟨	883							🟨
884							🟨	884							🟨
885		885	🟪		▨	🟥	🟨	885							🟨
886							🟨	886							🟨
887							🟧	887		887				⬛	🟧
888							🟧	888							🟧
889							🟧	889							🟧
890							🟧	890							🟧
891							🟧	891							🟧
892							🟧	892							🟧
893							🟧	893							🟧
894							🟧	894							🟧
895							🟧	895							🟧
896							🟧	896							🟧
897							🟧	897							🟧
898		898				⬛	🟧	898							🟧
899							🟧	899							🟧
900							🟧	900							🟧
901							🟧	901							🟧
902							🟧	902							🟧
903							🟧	903							🟧
904							🟧	904							🟧
905							🟧	905							🟧
906							🟧	906							🟧
907							🟧	907							🟧
908							🟧	908							🟧
909		909				🟦	🟧	909							🟧
910							🟧	910							🟧
911							🟧	911							🟧
912							🟧	912							🟧
913							🟧	913							🟧
914							🟧	914							🟧
915							🟫	915							🟫
916							🟫	916							🟫
917							🟫	917							🟫
918		918	🟪			🟥	🟫	918							🟫
919		919	🟪			🟦	🟫	919							🟫
920							🟫	920							🟫
921		921				⬛	🟫	921		921				⬛	🟫
922							🟫	922		922		🟩		⬛	🟫
923							🟫	923		923		🟩		⬛	🟫
924							🟫	924		924				⬛	🟫
925							🟫	925		925		🟩			🟫
926							🟫	926							🟫
927		927					🟫	927							🟫
928		928	🟪		▨	🟥	🟫	928		928	🟪		▨	🟥	🟫
929							🟫	929							🟫
930							🟫	930							🟫
931							🟫	931							🟫
932							🟫	932							🟫
933							🟫	933							🟫
934							🟫	934							🟫
935							🟫	935							🟫
936							🟫	936		936				🟦	🟫
937							🟫	937		937				🟦	🟫
938							🟫	938		938				🟦	🟫
939							🟫	939							🟫
940							🟫	940		940				🟦	🟫
941							🟫	941		941				🟥	🟫
942							🟫	942		942				🟦	🟫
943							🟫	943		943				🟦	🟫
944							🟫	944		944				🟥	🟫
945							🟫	945							🟫

Figure N.16: Geometry analysis of dredging and plowing locations after the peak in December 2018 (peak discharge: 3487 m^3/s)



Dredging								Plowing							
rkm	Dredged rkms M0	Dredged rkms M1	LAD	widening winter bed	End of fixed layer/ bendway weirs	Sharp bend / Gentle bend / Straight / Crossing	Upper Waal / Middle Waal / Lower Waal	rkm	Plowed rkms M0	Plowed rkms M1	LAD	widening winter bed	End of fixed layer/ bendway weirs	Sharp bend / Gentle bend / Straight / Crossing	Upper Waal / Middle Waal / Lower Waal
868							Upper Waal	868							Upper Waal
869		869				Sharp bend		869		869				Sharp bend	
870		870	■			Sharp bend		870							
871								871							
872								872							
873								873							
874								874							
875								875							
876	876	876	■		■	Crossing		876							
877								877							
878								878							
879								879							
880								880							
881								881		881				Sharp bend	
882								882							
883								883							
884								884							
885	885	885	■		■	Crossing		885							
886								886							
887							Middle Waal	887		887				Straight	Middle Waal
888								888							
889								889							
890								890							
891								891							
892								892							
893								893							
894		894				Gentle bend		894							
895								895							
896								896							
897								897							
898								898							
899								899							
900								900							
901								901							
902								902							
903								903							
904								904							
905								905							
906								906							
907		907		■		Gentle bend		907							
908								908							
909								909							
910								910							
911								911							
912								912							
913		913				Gentle bend		913							
914								914							
915							Lower Waal	915							Lower Waal
916		916	■			Gentle bend		916							
917								917							
918	918	918	■			Crossing		918							
919	919	919	■			Gentle bend		919							
920		920				Gentle bend		920							
921	921	921				Straight		921	921					Straight	
922								922	922	922		■		Straight	
923								923	923	923		■		Straight	
924								924	924	924				Straight	
925								925	925	925		■			
926								926							
927	927	927						927							
928	928	928	■		■	Crossing		928	928	928	■		■	Crossing	
929		929				Sharp bend		929							
930								930							
931								931							
932								932							
933								933							
934								934							
935								935							
936								936	936	936				Gentle bend	
937								937	937	937				Gentle bend	
938								938	938	938				Gentle bend	
939								939							
940								940	940	940				Gentle bend	
941								941	941	941				Crossing	
942								942	942	942				Gentle bend	
943								943	943	943				Gentle bend	
944								944	944	944				Crossing	
945								945							

Figure N.17: Geometry analysis of dredging and plowing locations after the peak in January 2019 (peak discharge: 3772 m^3/s)

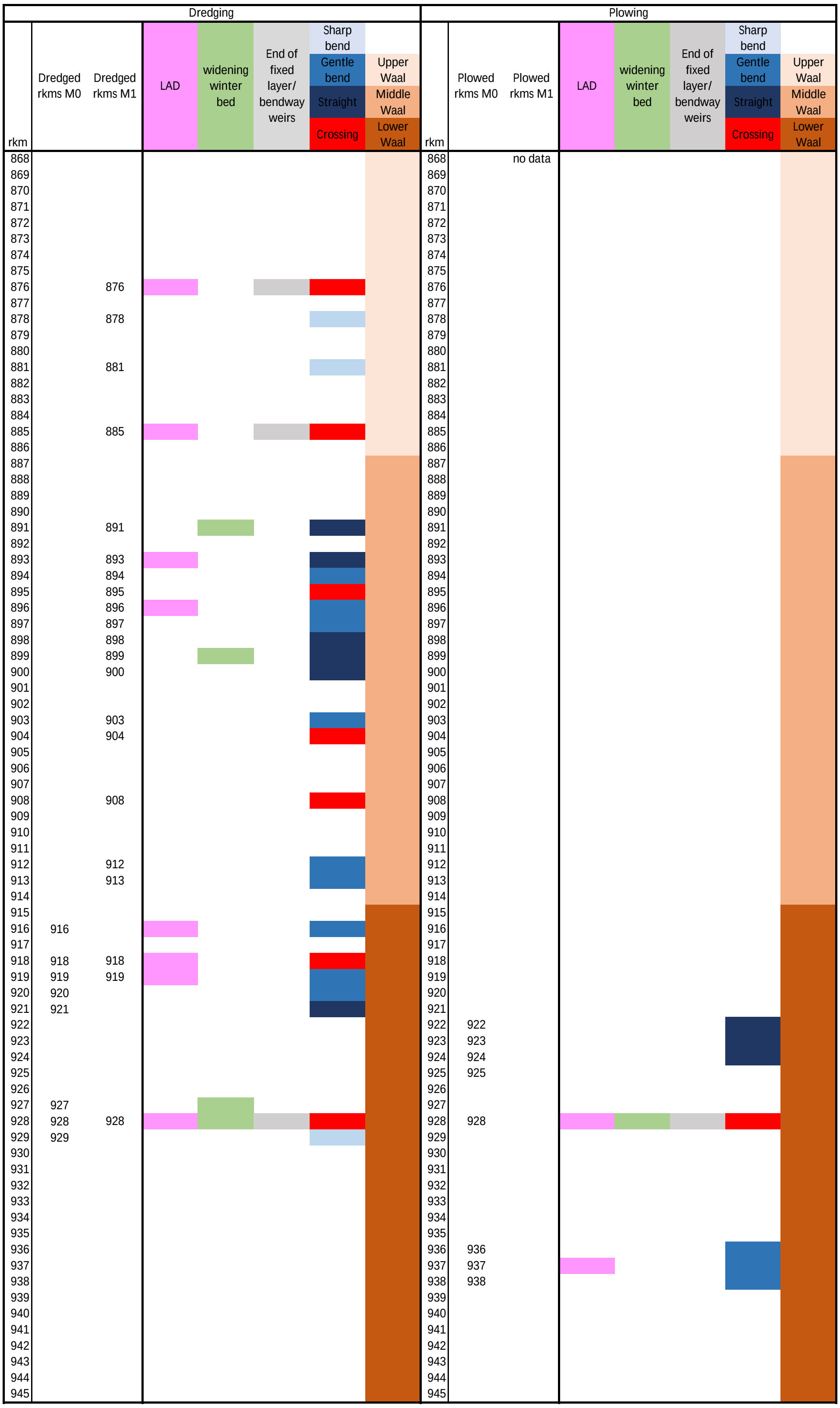
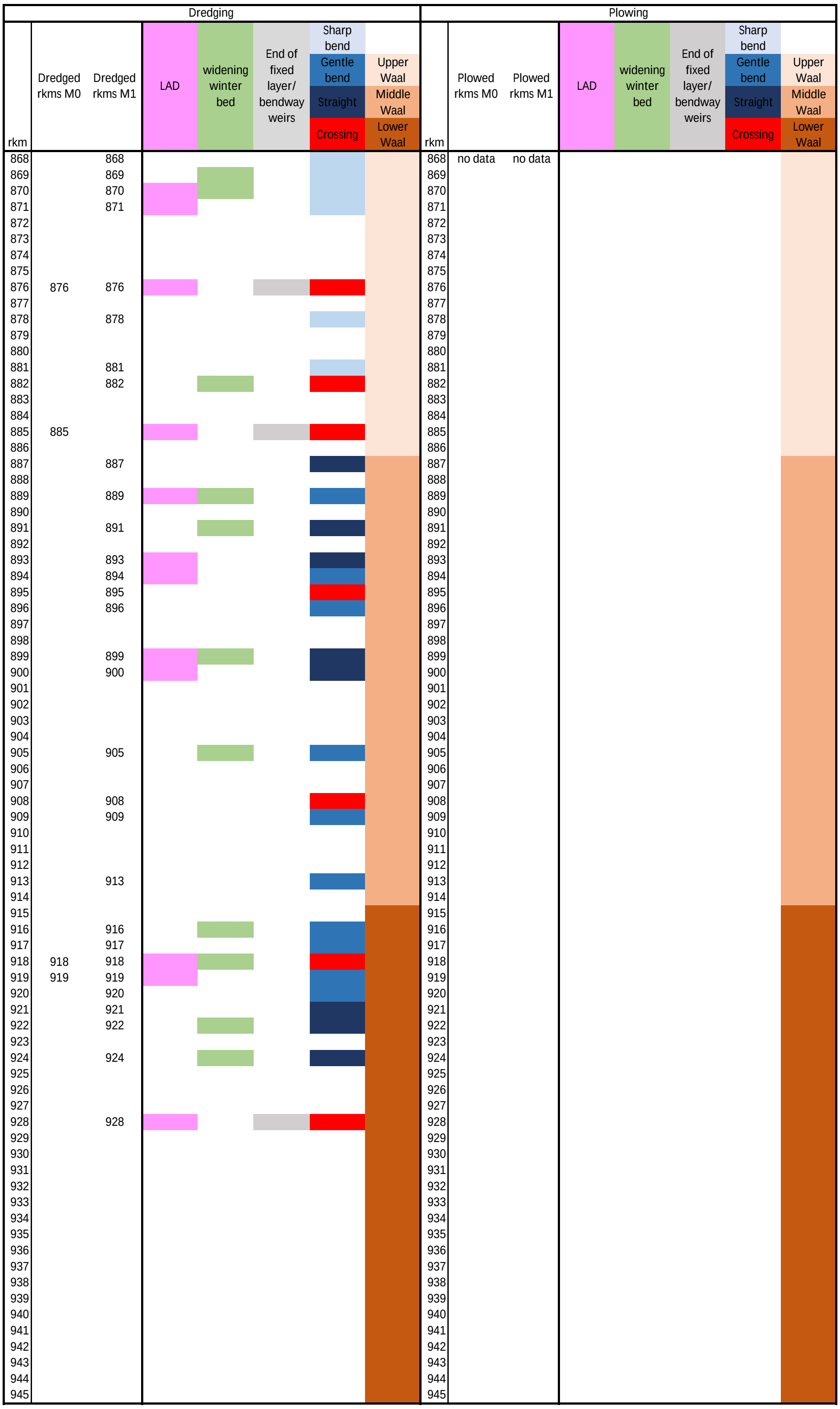
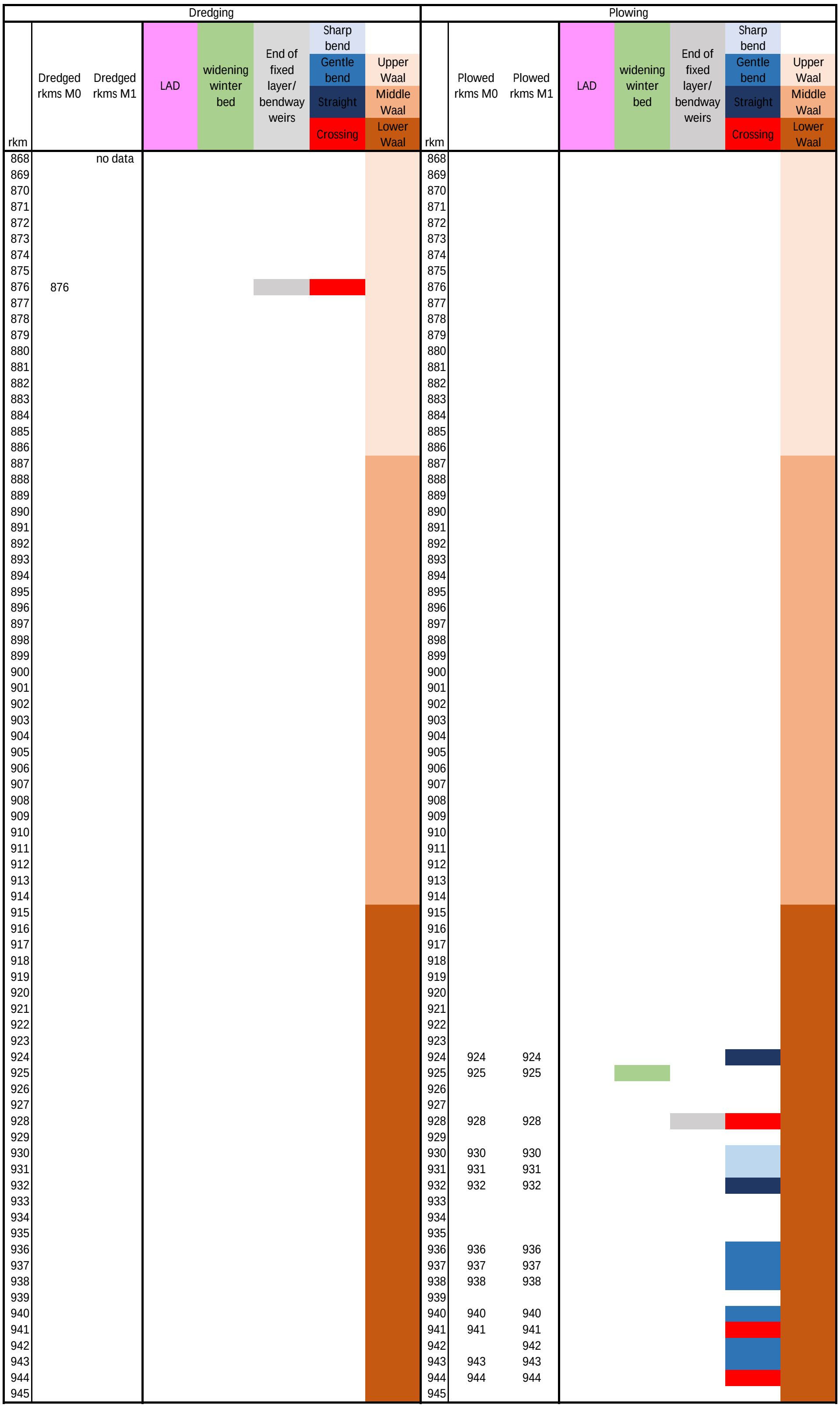


Figure N.18: Geometry analysis of dredging and plowing locations after the peak in February 2019 (peak discharge: 3324 m^3/s)



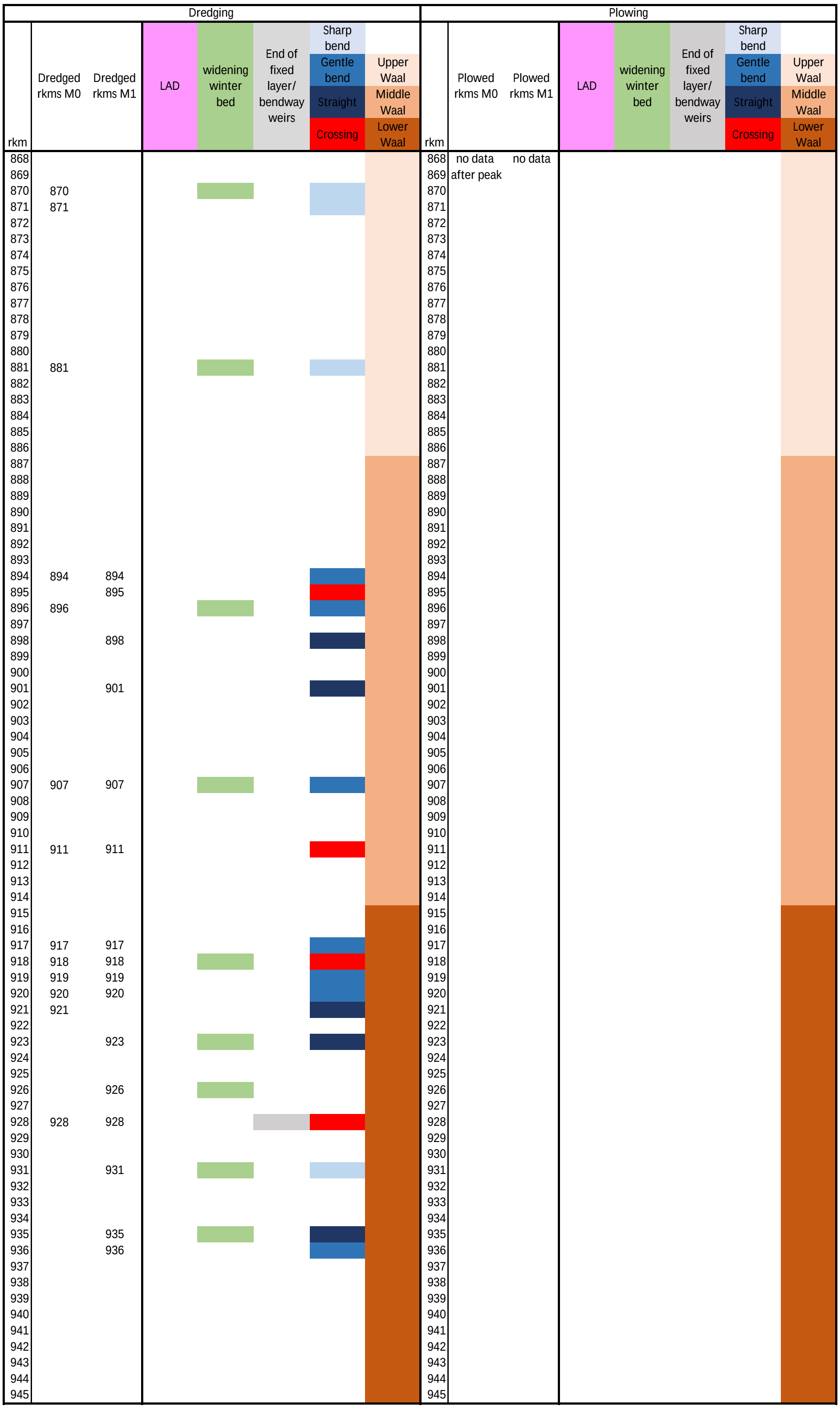
Dredging								Plowing							
rkm	Dredged rkms M0	Dredged rkms M1	LAD 🟪	widening winter bed 🟩	End of fixed layer/ bendway weirs ▨	Sharp bend ░ Gentle bend 🟦 Straight ⬛ Crossing 🟥	Upper Waal 🟨 Middle Waal 🟧 Lower Waal 🟫	rkm	Plowed rkms M0	Plowed rkms M1	LAD	widening winter bed	End of fixed layer/ bendway weirs	Sharp bend ░ Gentle bend 🟦 Straight ⬛ Crossing 🟥	Upper Waal 🟨 Middle Waal 🟧 Lower Waal 🟫
868		868				░	🟨	868	no data	no data					🟨
869		869		🟩		░	🟨	869							🟨
870		870	🟪	🟩		░	🟨	870							🟨
871		871	🟪			░	🟨	871							🟨
872							🟨	872							🟨
873							🟨	873							🟨
874							🟨	874							🟨
875							🟨	875							🟨
876	876	876	🟪		▨	🟥	🟨	876							🟨
877							🟨	877							🟨
878		878				░	🟨	878							🟨
879							🟨	879							🟨
880							🟨	880							🟨
881		881				░	🟨	881							🟨
882		882		🟩		🟥	🟨	882							🟨
883							🟨	883							🟨
884							🟨	884							🟨
885	885		🟪		▨	🟥	🟨	885							🟨
886							🟨	886							🟨
887		887				⬛	🟧	887							🟧
888							🟧	888							🟧
889		889	🟪	🟩		🟦	🟧	889							🟧
890							🟧	890							🟧
891		891		🟩		⬛	🟧	891							🟧
892							🟧	892							🟧
893		893	🟪			⬛	🟧	893							🟧
894		894	🟪			🟦	🟧	894							🟧
895		895				🟥	🟧	895							🟧
896		896				🟦	🟧	896							🟧
897							🟧	897							🟧
898							🟧	898							🟧
899		899	🟪	🟩		⬛	🟧	899							🟧
900		900	🟪			⬛	🟧	900							🟧
901							🟧	901							🟧
902							🟧	902							🟧
903							🟧	903							🟧
904							🟧	904							🟧
905		905		🟩		🟦	🟧	905							🟧
906							🟧	906							🟧
907							🟧	907							🟧
908		908				🟥	🟧	908							🟧
909		909				🟦	🟧	909							🟧
910							🟧	910							🟧
911							🟧	911							🟧
912							🟧	912							🟧
913		913				🟦	🟧	913							🟧
914							🟧	914							🟧
915							🟫	915							🟫
916		916		🟩		🟦	🟫	916							🟫
917		917				🟦	🟫	917							🟫
918	918	918	🟪	🟩		🟥	🟫	918							🟫
919	919	919	🟪			🟦	🟫	919							🟫
920		920				🟦	🟫	920							🟫
921		921				⬛	🟫	921							🟫
922		922		🟩		⬛	🟫	922							🟫
923							🟫	923							🟫
924		924		🟩		⬛	🟫	924							🟫
925							🟫	925							🟫
926							🟫	926							🟫
927							🟫	927							🟫
928		928	🟪		▨	🟥	🟫	928							🟫
929							🟫	929							🟫
930							🟫	930							🟫
931							🟫	931							🟫
932							🟫	932							🟫
933							🟫	933							🟫
934							🟫	934							🟫
935							🟫	935							🟫
936							🟫	936							🟫
937							🟫	937							🟫
938							🟫	938							🟫
939							🟫	939							🟫
940							🟫	940							🟫
941							🟫	941							🟫
942							🟫	942							🟫
943							🟫	943							🟫
944							🟫	944							🟫
945							🟫	945							🟫

Figure N.19: Geometry analysis of dredging and plowing locations after the peak in March 2019 (peak discharge: 5226 m^3/s)



Dredging								Plowing							
rkm	Dredged rkms M0	Dredged rkms M1	LAD	widening winter bed	End of fixed layer/ bendway weirs	Sharp bend Gentle bend Straight Crossing	Upper Waal Middle Waal Lower Waal	rkm	Plowed rkms M0	Plowed rkms M1	LAD	widening winter bed	End of fixed layer/ bendway weirs	Sharp bend Gentle bend Straight Crossing	Upper Waal Middle Waal Lower Waal
868		no data					░	868							░
869							░	869							░
870							░	870							░
871							░	871							░
872							░	872							░
873							░	873							░
874							░	874							░
875							░	875							░
876	876				▨	🟥	░	876							░
877							░	877							░
878							░	878							░
879							░	879							░
880							░	880							░
881							░	881							░
882							░	882							░
883							░	883							░
884							░	884							░
885							░	885							░
886							░	886							░
887							▒	887							▒
888							▒	888							▒
889							▒	889							▒
890							▒	890							▒
891							▒	891							▒
892							▒	892							▒
893							▒	893							▒
894							▒	894							▒
895							▒	895							▒
896							▒	896							▒
897							▒	897							▒
898							▒	898							▒
899							▒	899							▒
900							▒	900							▒
901							▒	901							▒
902							▒	902							▒
903							▒	903							▒
904							▒	904							▒
905							▒	905							▒
906							▒	906							▒
907							▒	907							▒
908							▒	908							▒
909							▒	909							▒
910							▒	910							▒
911							▒	911							▒
912							▒	912							▒
913							▒	913							▒
914							▒	914							▒
915							▓	915							▓
916							▓	916							▓
917							▓	917							▓
918							▓	918							▓
919							▓	919							▓
920							▓	920							▓
921							▓	921							▓
922							▓	922							▓
923							▓	923							▓
924							▓	924	924	924				⬛	▓
925							▓	925	925	925		🟩			▓
926							▓	926							▓
927							▓	927							▓
928							▓	928	928	928			▨	🟥	▓
929							▓	929							▓
930							▓	930	930	930				▢	▓
931							▓	931	931	931				▢	▓
932							▓	932	932	932				⬛	▓
933							▓	933							▓
934							▓	934							▓
935							▓	935							▓
936							▓	936	936	936				🟦	▓
937							▓	937	937	937				🟦	▓
938							▓	938	938	938				🟦	▓
939							▓	939							▓
940							▓	940	940	940				🟦	▓
941							▓	941	941	941				🟥	▓
942							▓	942		942				🟦	▓
943							▓	943	943	943				🟦	▓
944							▓	944	944	944				🟥	▓
945							▓	945							▓

Figure N.20: Geometry analysis of dredging and plowing locations after the peak in December 2019 (peak discharge: 3616 m^3/s)



Dredging							
rkm	Dredged rkms M0	Dredged rkms M1	LAD	🟩 widening winter bed	▩ End of fixed layer/ bendway weirs	▧ Sharp bend 🟦 Gentle bend ⬛ Straight 🟥 Crossing	░ Upper Waal ▒ Middle Waal ▓ Lower Waal
868							░
869							
870	870			🟩		▧	
871	871					▧	
872							
873							
874							
875							
876							
877							
878							
879							
880							
881	881			🟩		▧	
882							
883							
884							
885							
886							
887							▒
888							
889							
890							
891							
892							
893							
894	894	894				🟦	
895		895				🟥	
896	896			🟩		🟦	
897							
898		898				⬛	
899							
900							
901		901				⬛	
902							
903							
904							
905							
906							
907	907	907		🟩		🟦	
908							
909							
910							
911	911	911				🟥	
912							
913							
914							
915							▓
916							
917	917	917				🟦	
918	918	918		🟩		🟥	
919	919	919				🟦	
920	920	920				🟦	
921	921					⬛	
922							
923		923		🟩		⬛	
924							
925							
926		926		🟩			
927							
928	928	928			▩	🟥	
929							
930							
931		931		🟩		▧	
932							
933							
934							
935		935		🟩		⬛	
936		936				🟦	
937							
938							
939							
940							
941							
942							
943							
944							
945							

Plowing							
rkm	Plowed rkms M0	Plowed rkms M1	LAD	🟩 widening winter bed	▩ End of fixed layer/ bendway weirs	▧ Sharp bend 🟦 Gentle bend ⬛ Straight 🟥 Crossing	░ Upper Waal ▒ Middle Waal ▓ Lower Waal
868	no data	no data					░
869	after peak						
870							
871							
872							
873							
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945							

Figure N.21: Geometry analysis of dredging and plowing locations after the peak in February 2020 (peak discharge: 6142 m^3/s)

O

Relation between discharge peak characteristics and sediment management

O.1. Scatter plots for several definitions of peaks

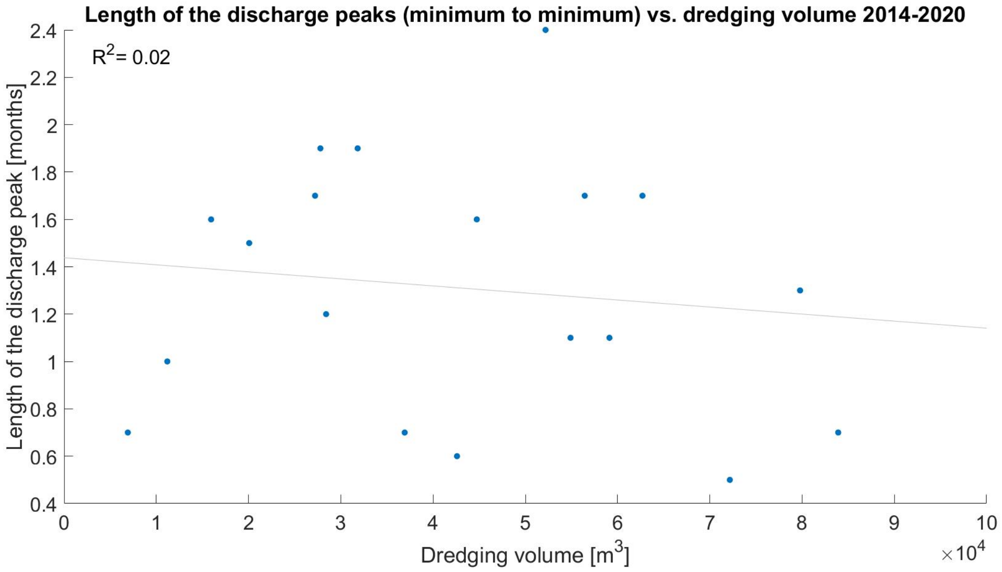

Figure O.1: Discharge peak duration (dredging)

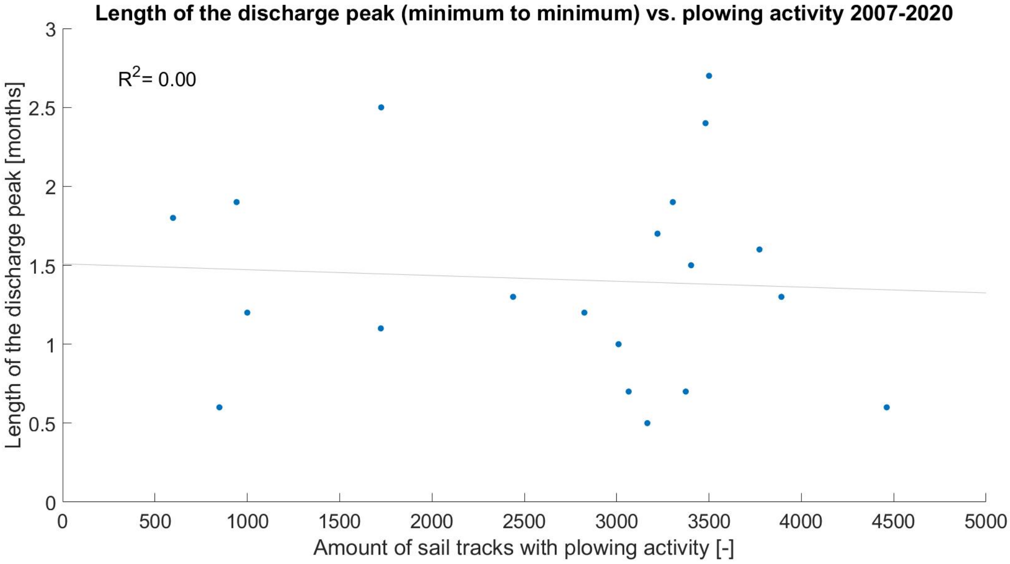

Figure O.2: Discharge peak duration (plowing)

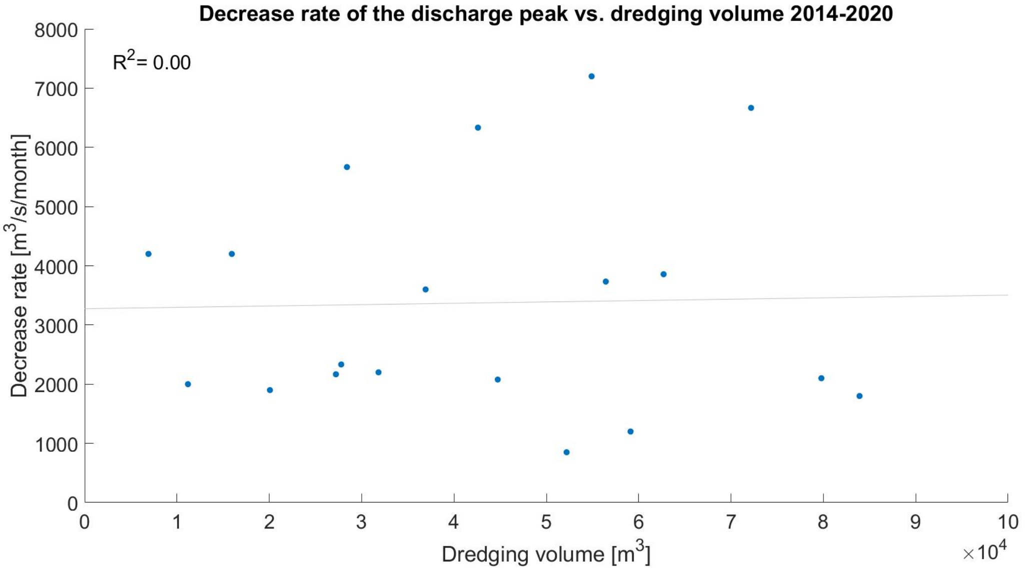

Figure O.3: Discharge peak decrease rate (dredging)

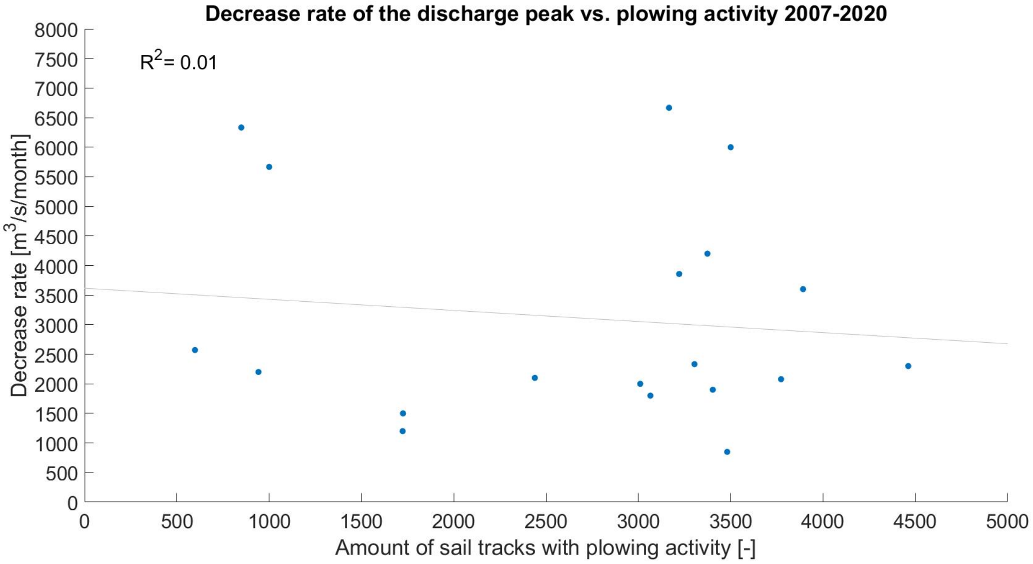

Figure O.4: Discharge peak decrease rate (plowing)

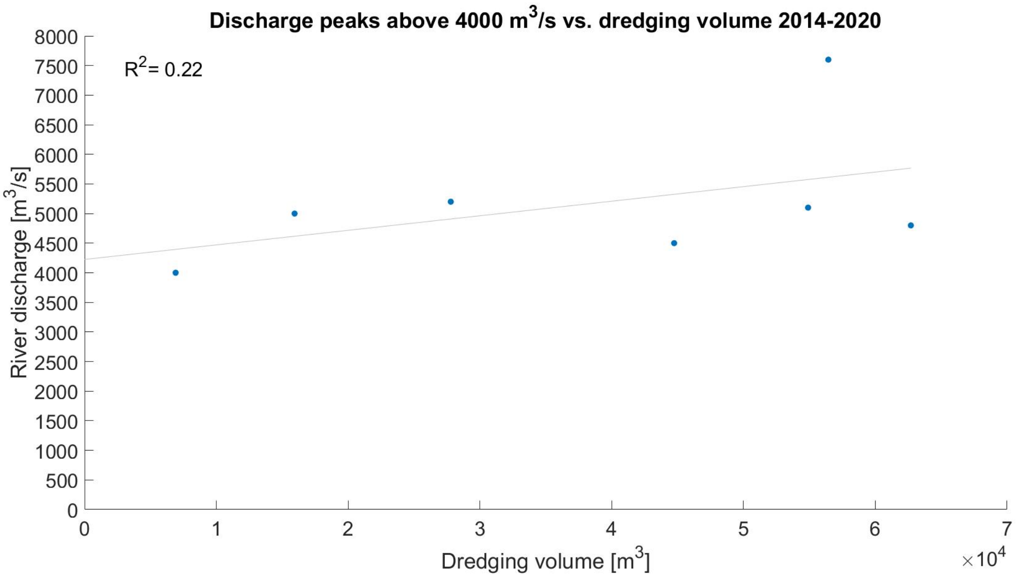

Figure O.5: Discharge peaks of 4000 m^3/s and larger (dredging)

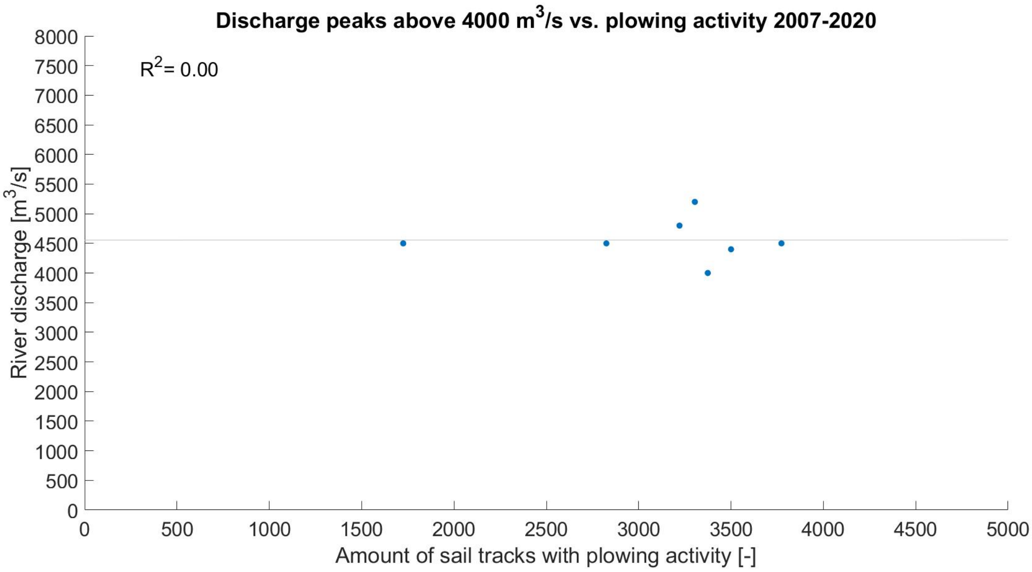

Figure O.6: Discharge peaks of 4000 m^3/s and larger (plowing)

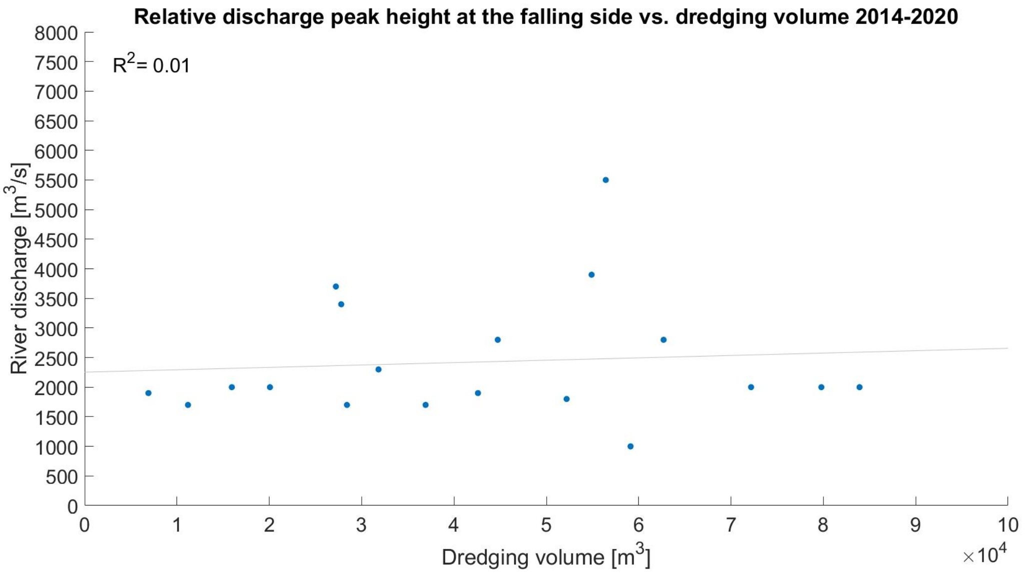

Figure O.7: Relative peak height (dredging)

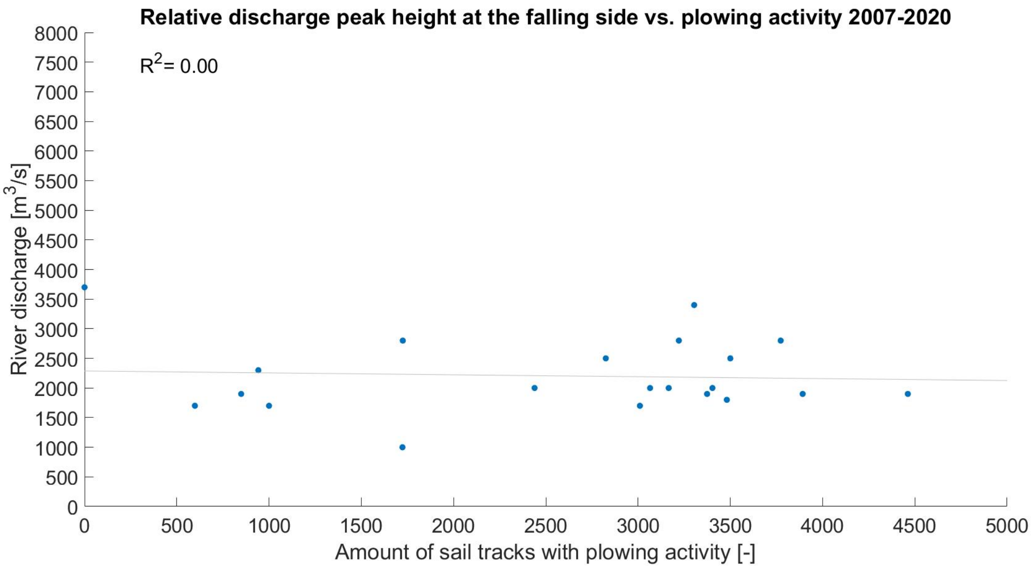

Figure O.8: Relative peak height (plowing)

O.2. Scatter plots for several definitions of peaks without taking hotspots into account

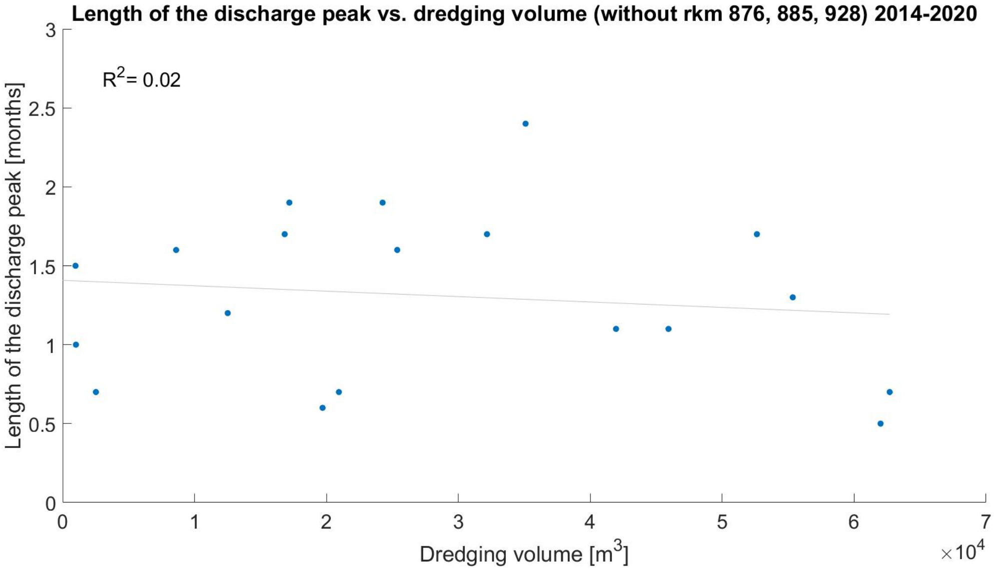

Figure O.9: Discharge peak duration without rkm 876, 885 and 928 taken into account (dredging)

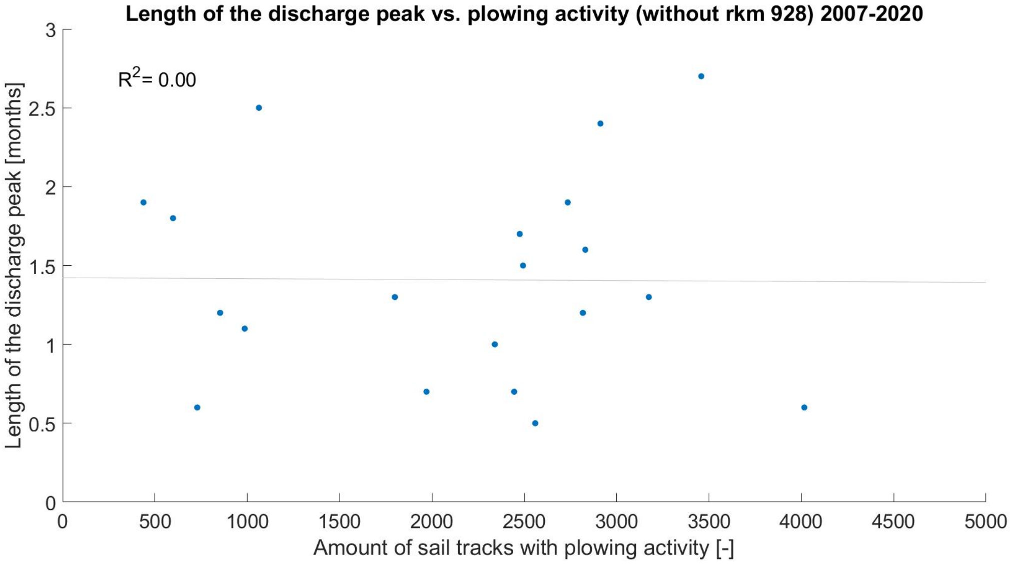

Figure O.10: Discharge peak duration without rkm 928 taken into account (plowing)

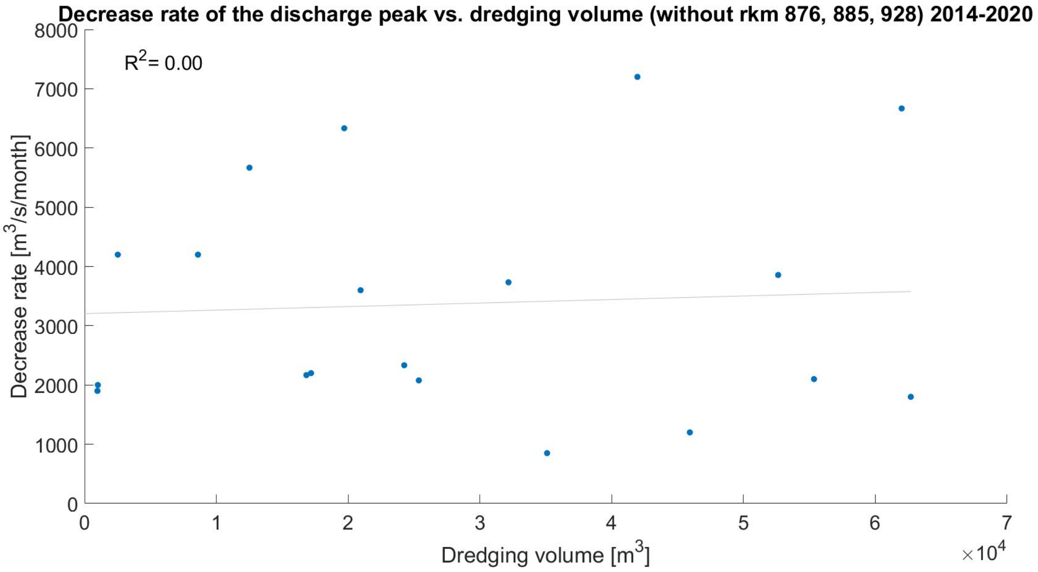

Figure O.11: Discharge peak decrease rate without rkm 876, 885 and 928 taken into account (dredging)

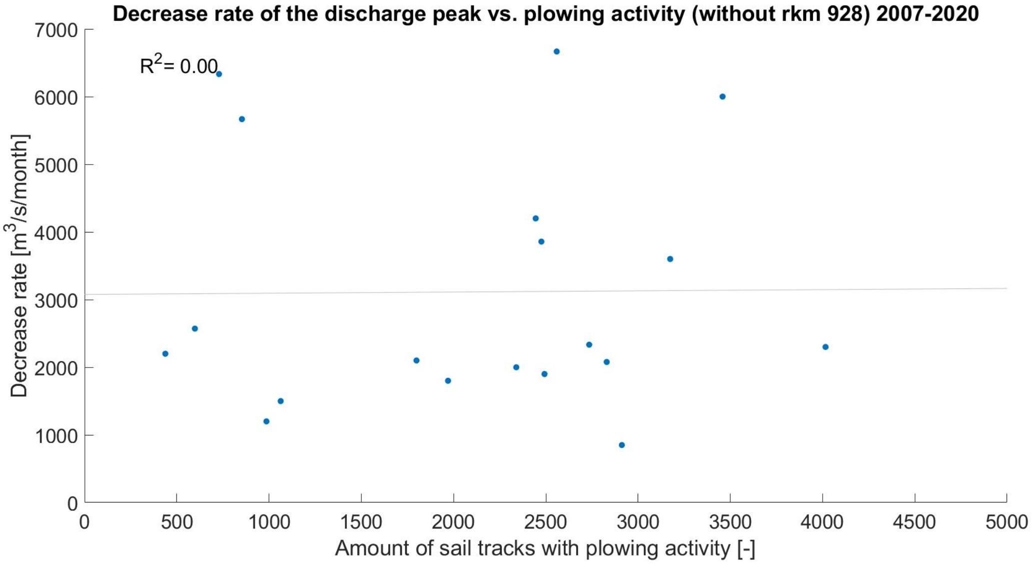

Figure O.12: Discharge peak decrease rate without rkm 928 taken into account (plowing)

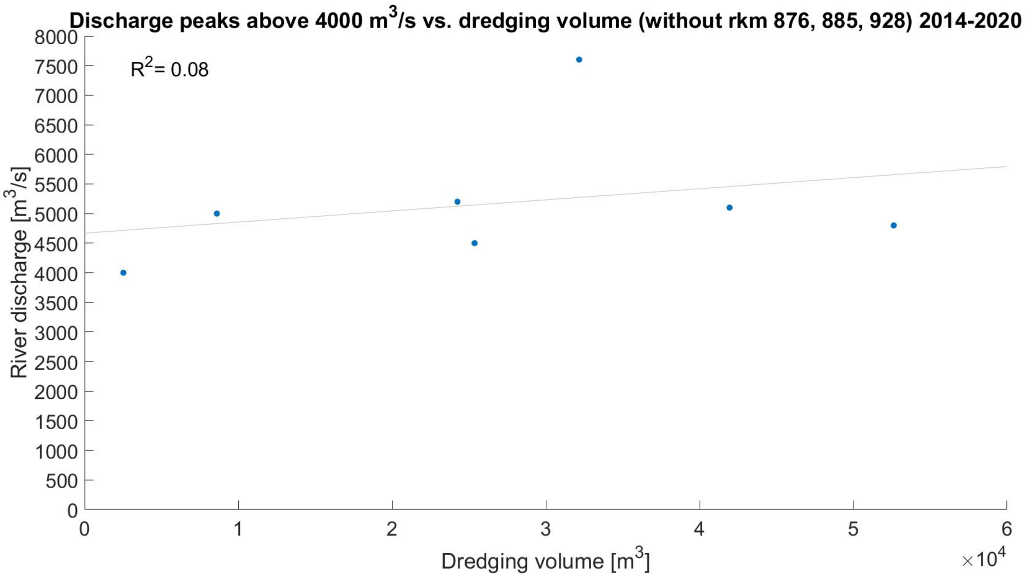

Figure O.13: Discharge peaks of 4000 m^3/s and larger without rkm 876, 885 and 928 taken into account (dredging)

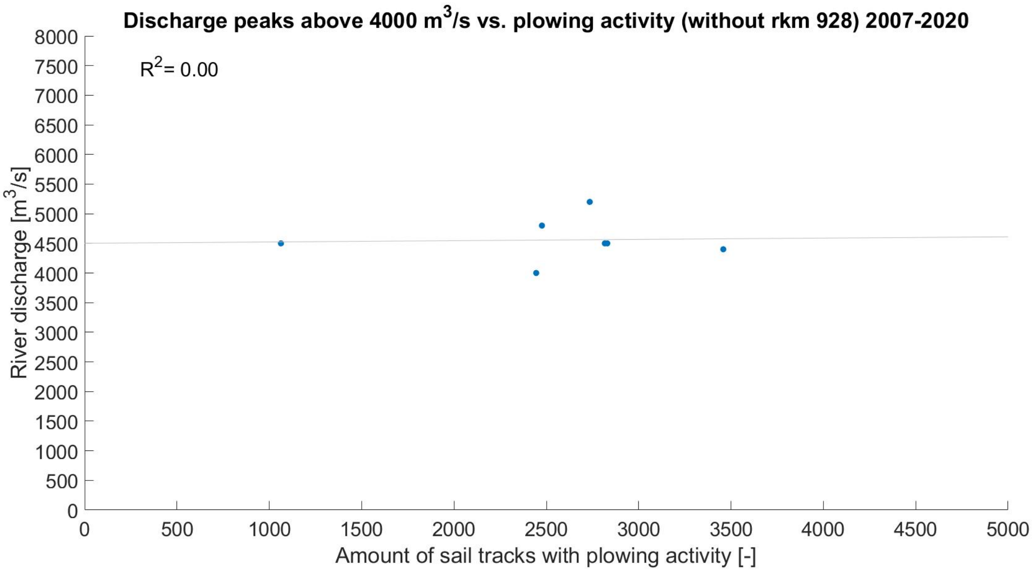

Figure O.14: Discharge peaks of 4000 m^3/s and larger without rkm 928 taken into account (plowing)

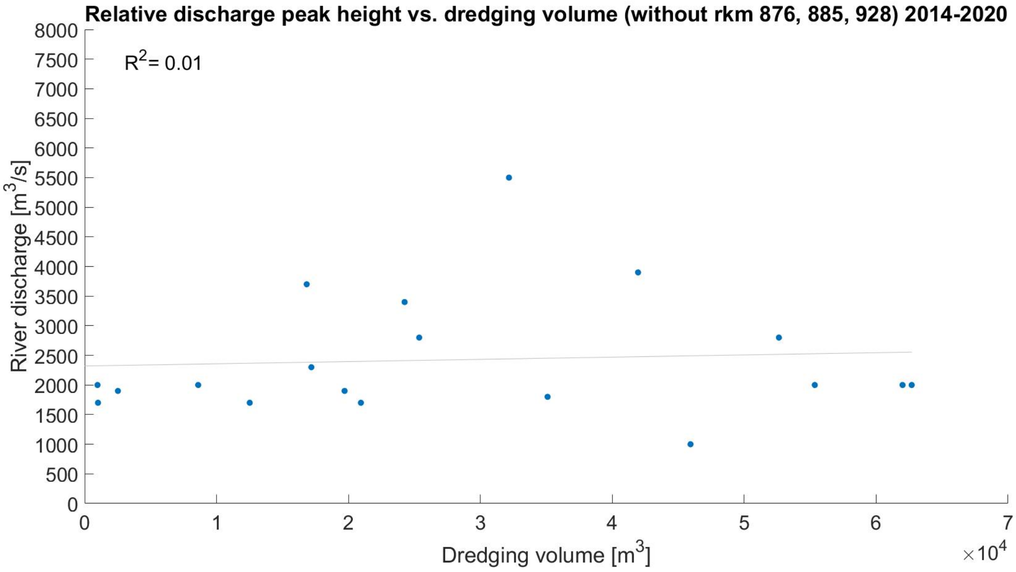

Figure O.15: Relative peak height without rkm 876, 885 and 928 taken into account (dredging)

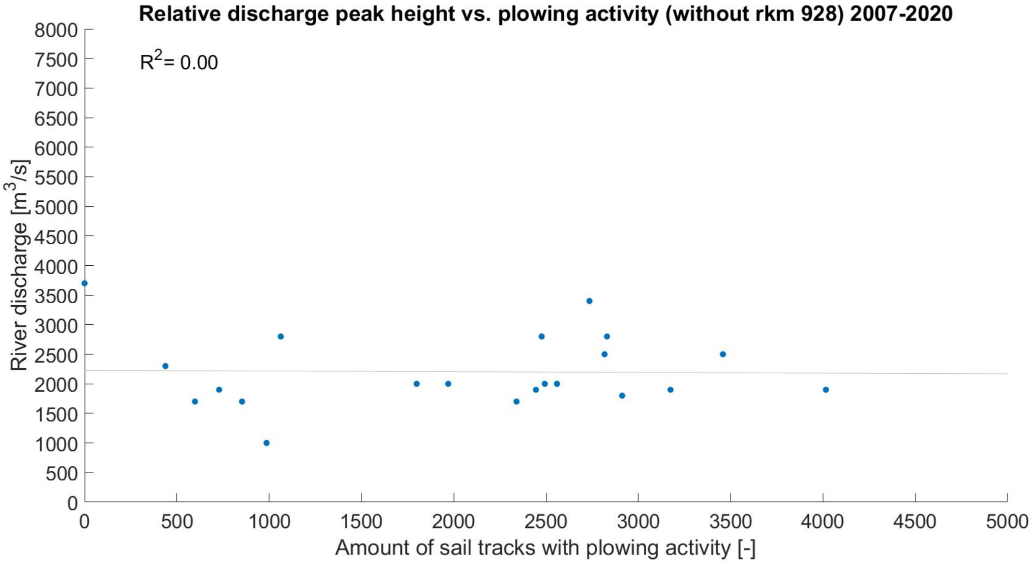

Figure O.16: Relative peak height without rkm 928 taken into account (plowing)

P

Dredging intervals

P.1. Monthly averaged dredging intervals

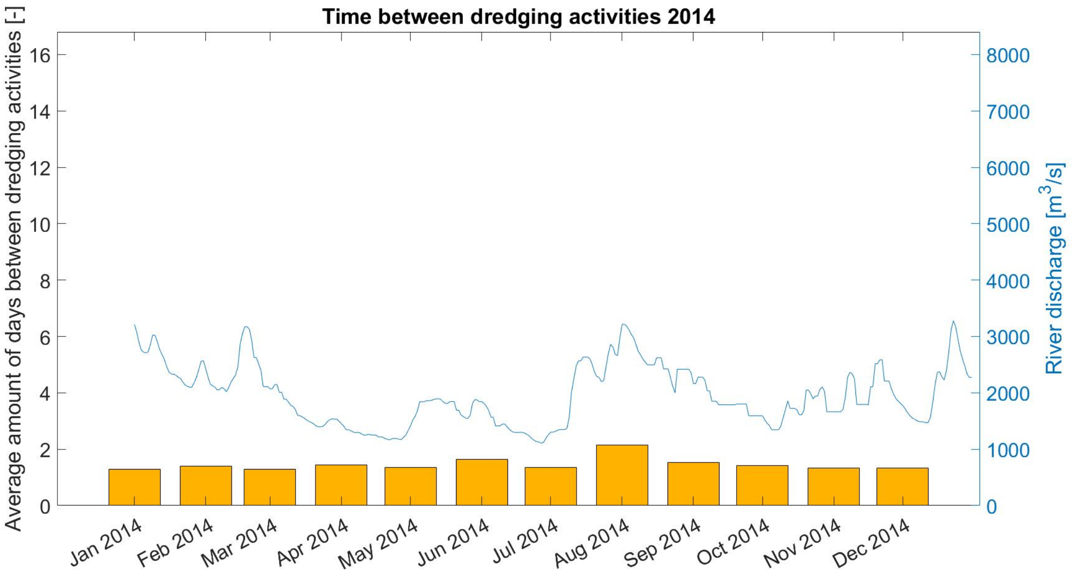

Figure P.1: 2014

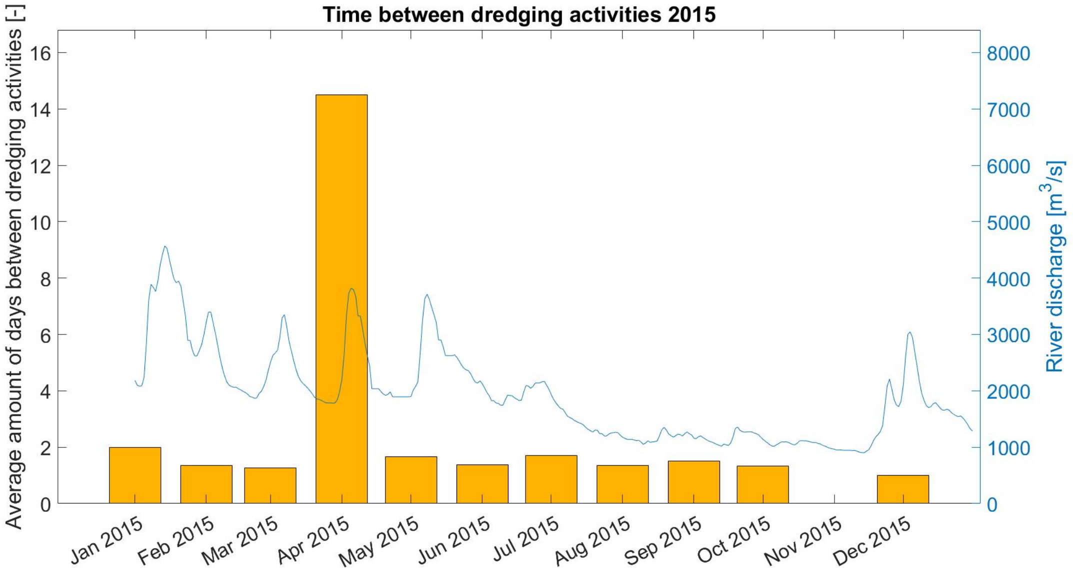

Figure P.2: 2015

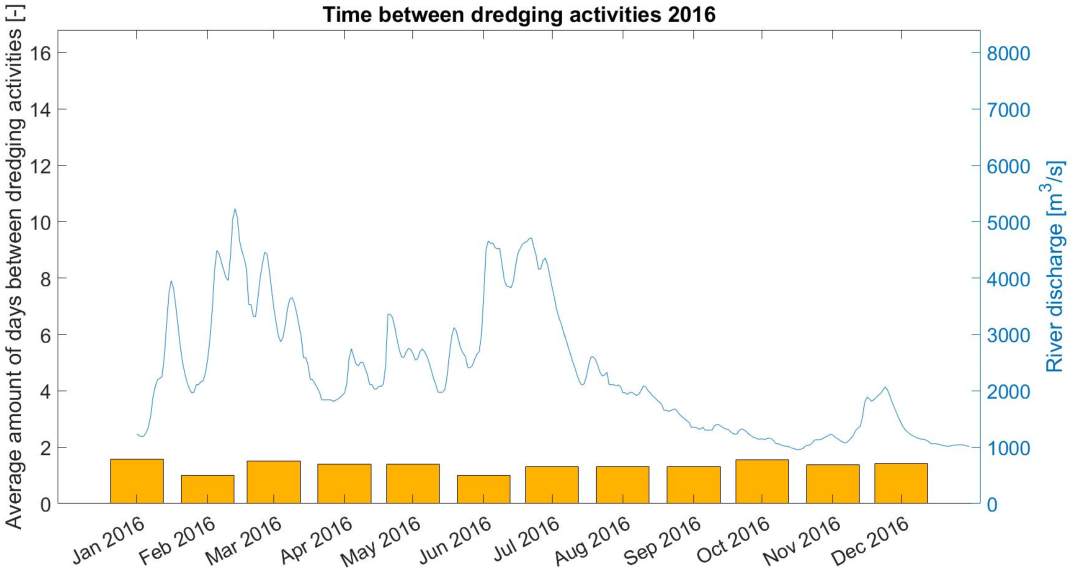

Figure P.3: 2016

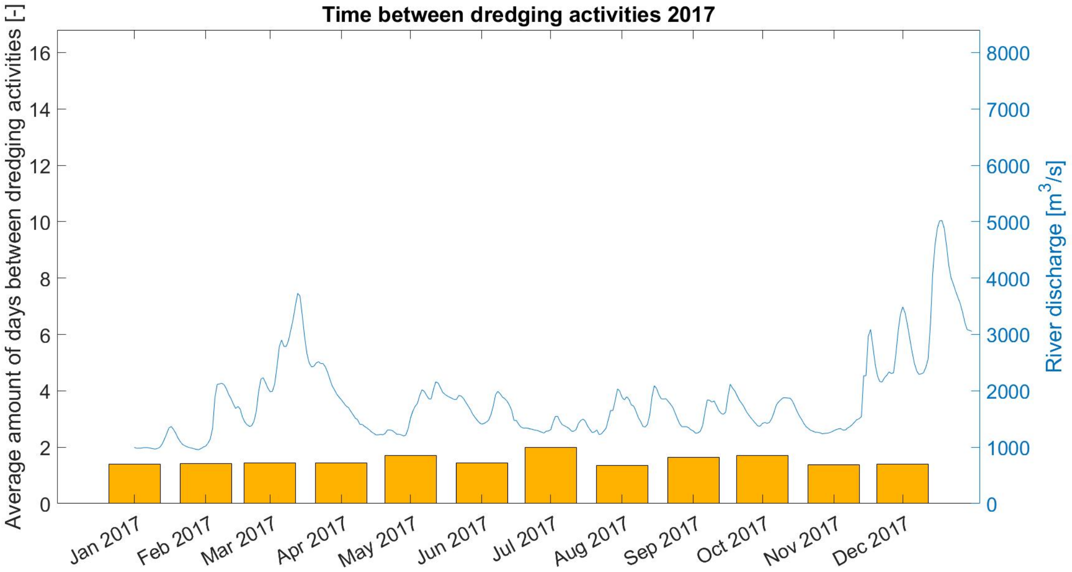

Figure P.4: 2017

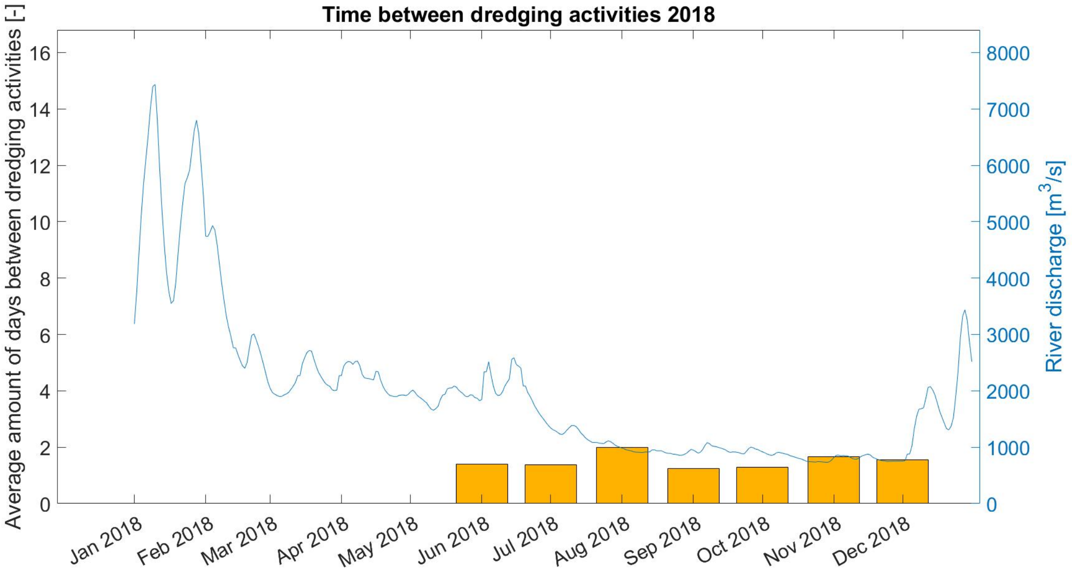

Figure P.5: 2018

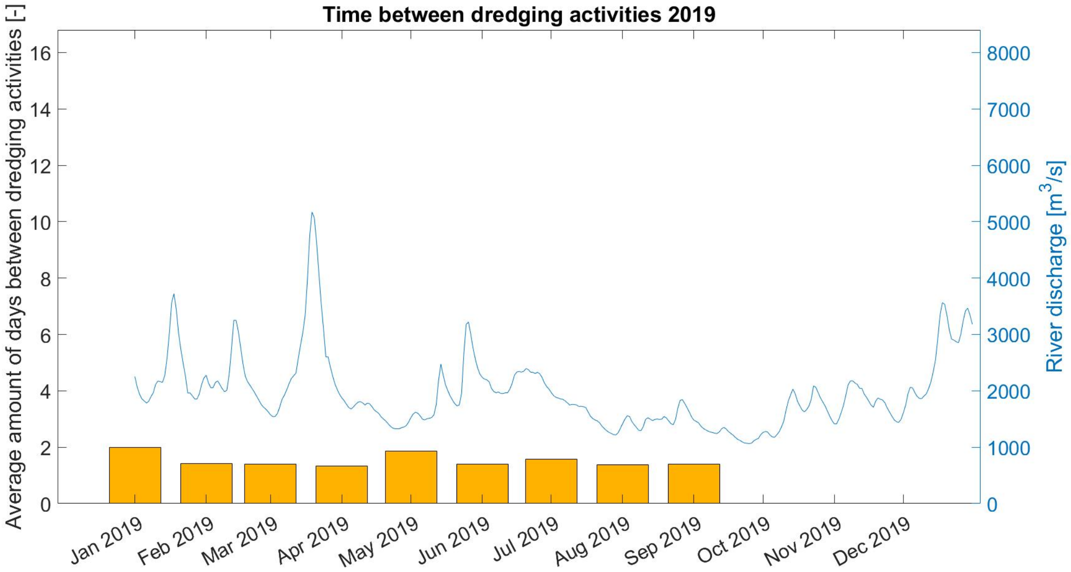

Figure P.6: 2019

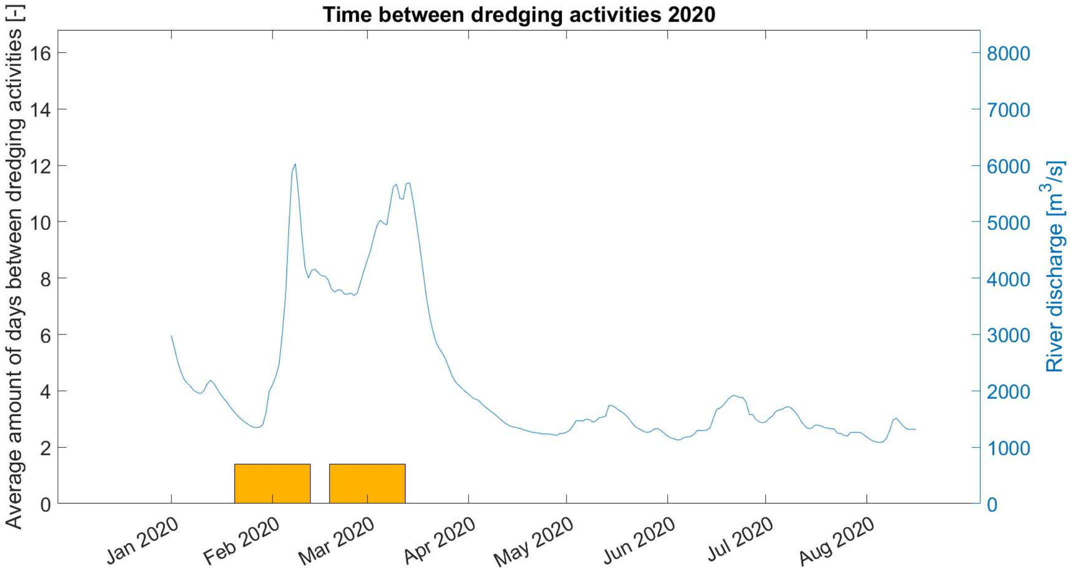

Figure P.7: 2020

P.2. Scatter plots of the dredging interval for several definitions of peaks

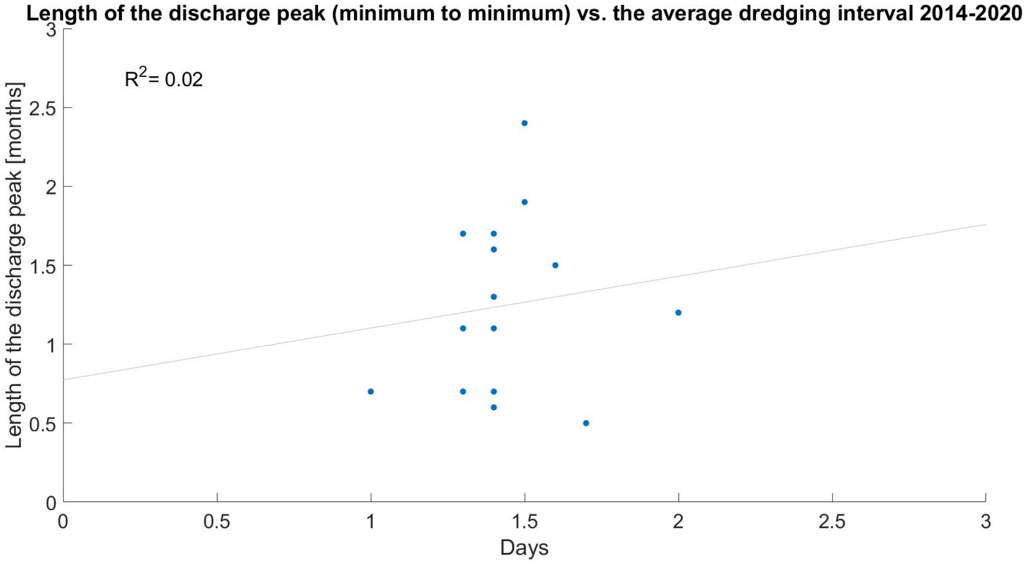

Figure P.8: Discharge peak length (dredging interval)

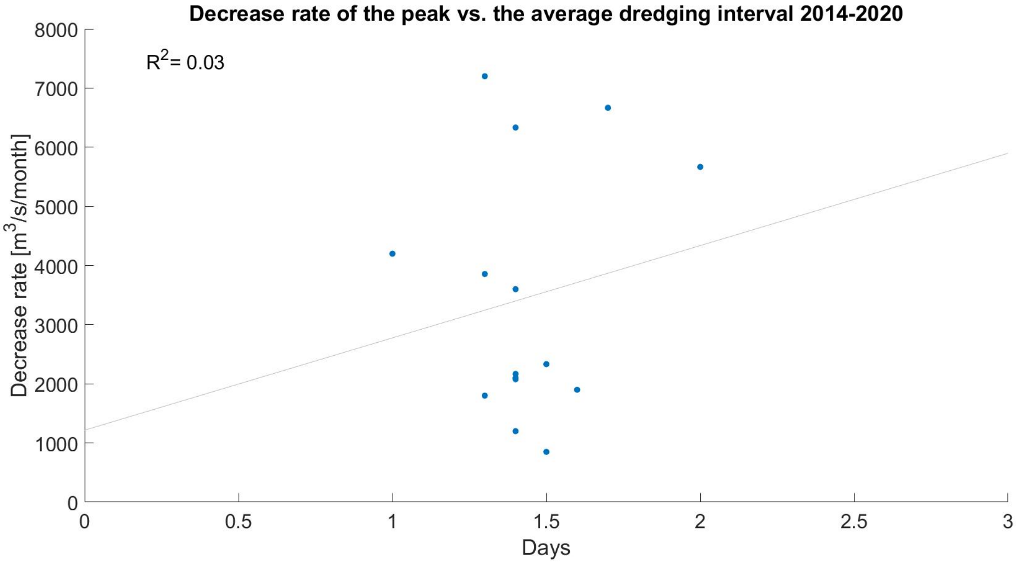

Figure P.9: Discharge peak decrease rate (dredging interval)

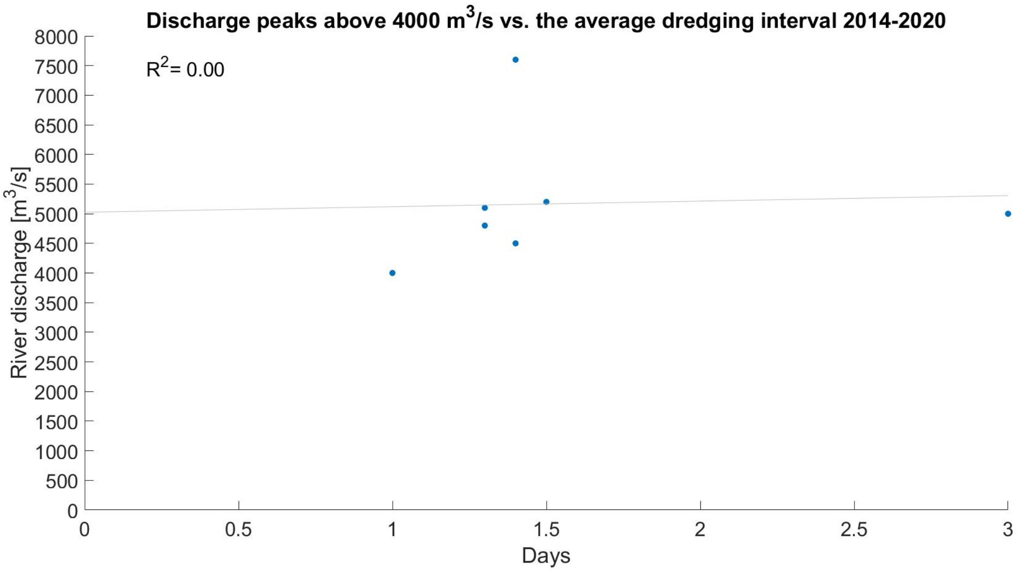

Figure P.10: Discharge peaks of 4000 m^3/s and larger (dredging interval)

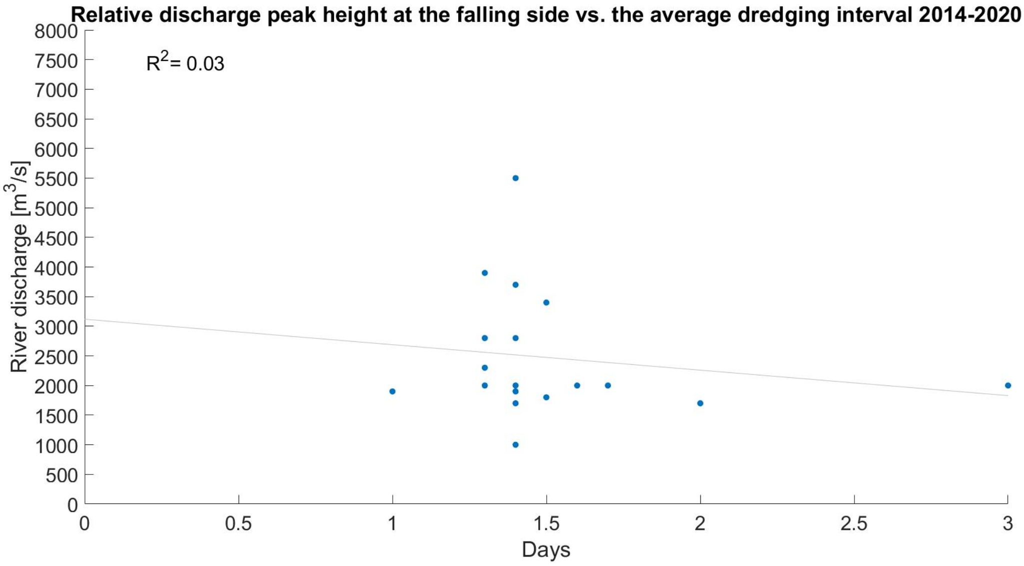

Figure P.11: Relative peak height (dredging interval)

P.3. Scatter plots of the dredging interval for several definitions of peaks without taking hotspots into account

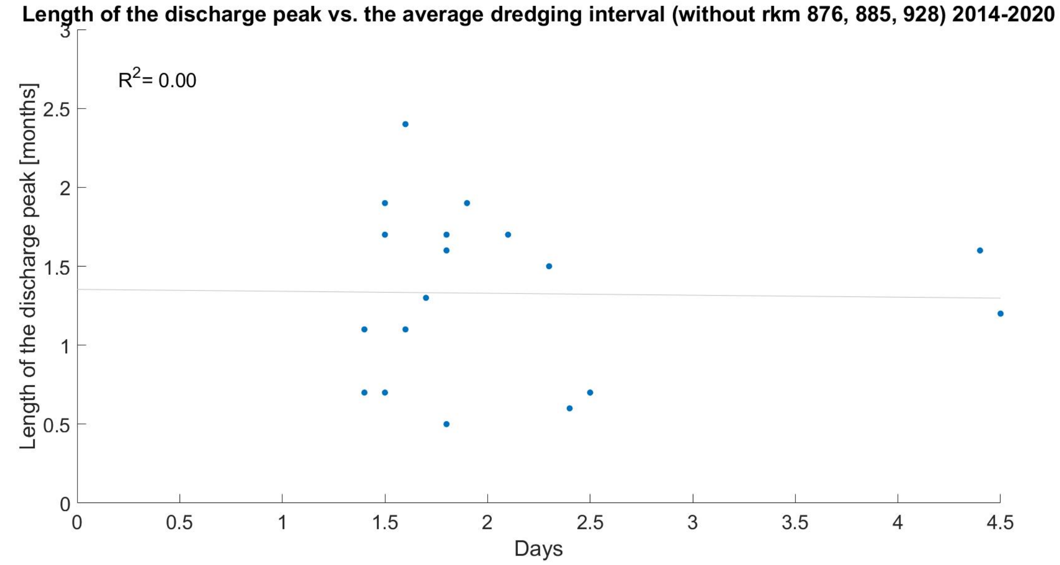

Figure P.12: Discharge peak length without rkm 876, 885 and 928 taken into account (dredging interval)

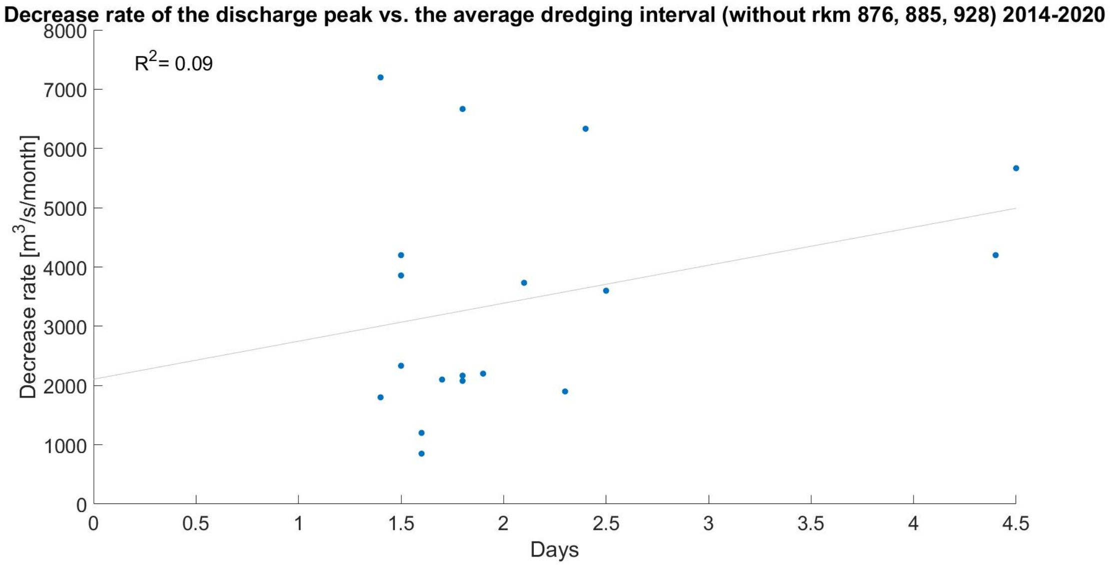

Figure P.13: Discharge peak decrease rate without rkm 876, 885 and 928 taken into account (dredging interval)

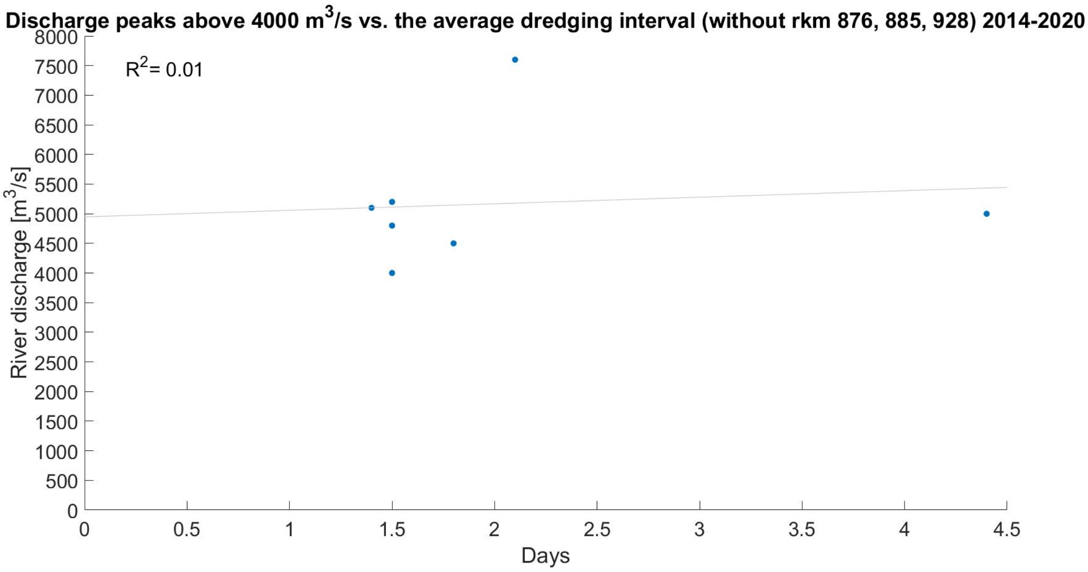

Figure P.14: Discharge peaks of 4000 m^3/s and larger without rkm 876, 885 and 928 taken into account (dredging interval)

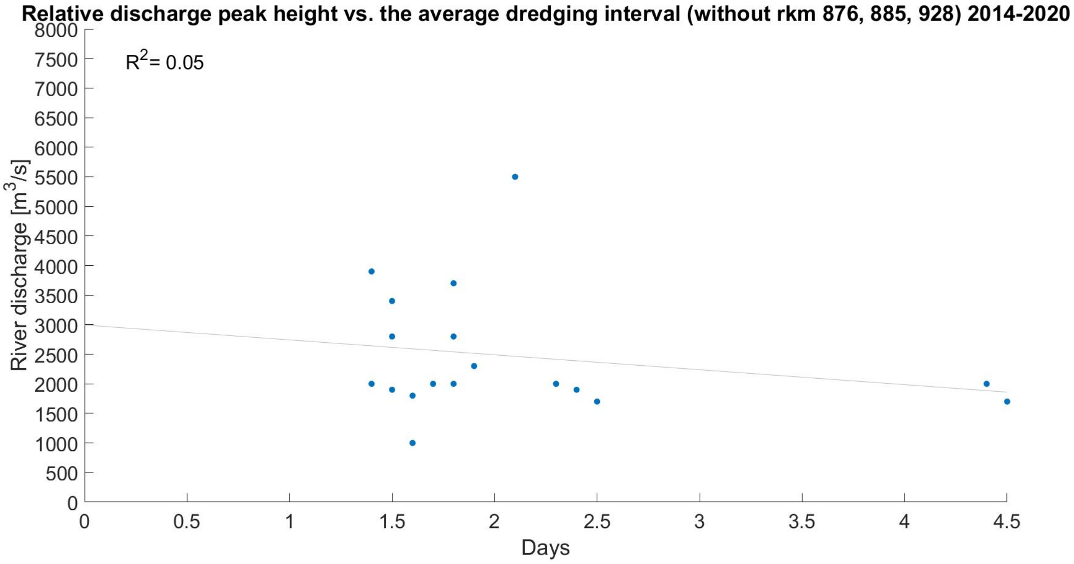

Figure P.15: Relative peak height without rkm 876, 885 and 928 taken into account (dredging interval)