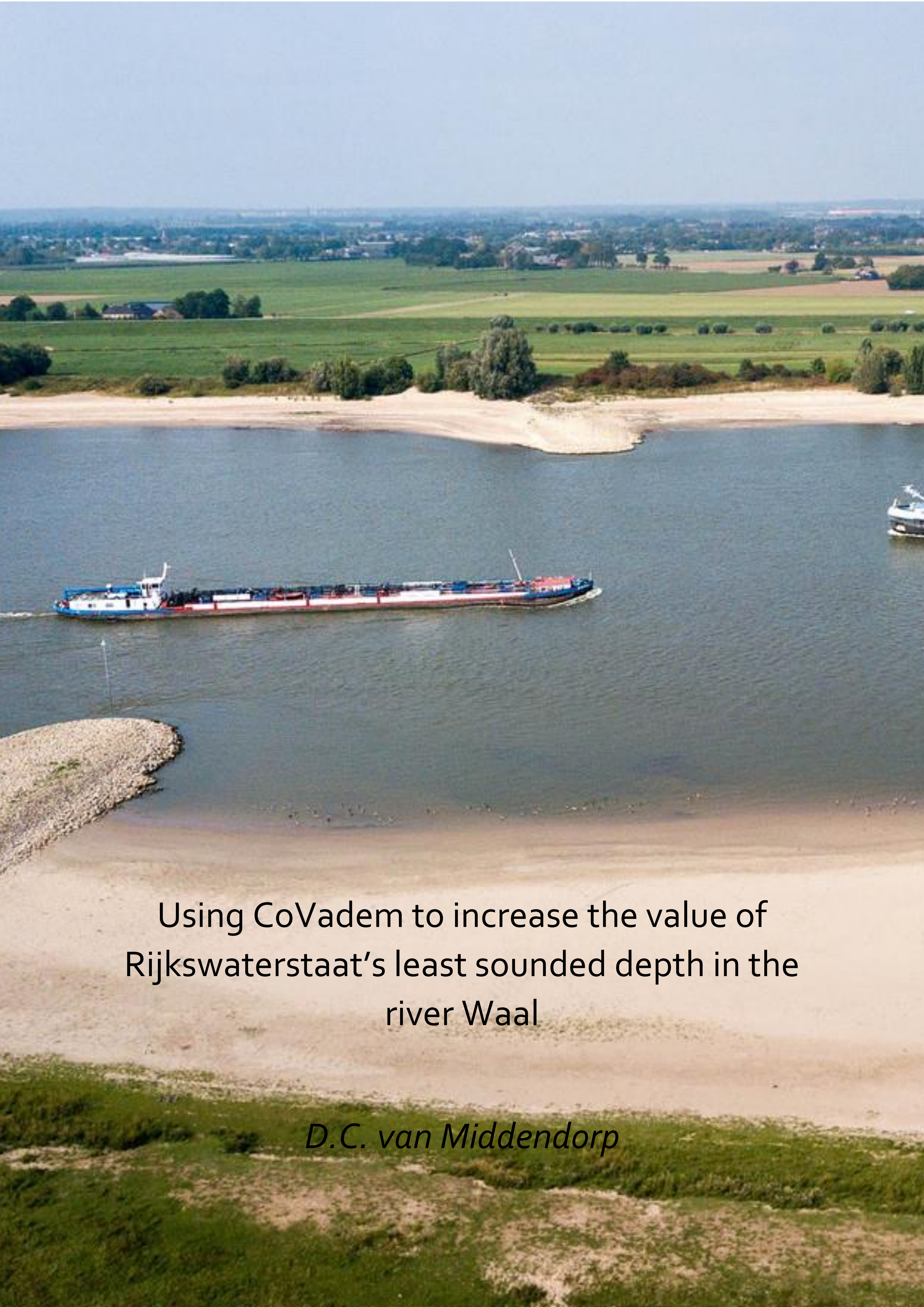

Using CoVadem to increase the value of Rijkswaterstaat's least sounded depth in the river Waal

D.C. van Middendorp

Using CoVadem to increase the value of Rijkswaterstaat's least sounded depth in the river Waal

Master thesis Civil Engineering and Management

University of Twente

31 August 2020

Civil Engineering and Management
Faculty of Engineering Technology,
River and Coastal Engineering
University of Twente
P.O Box 217
7500 AE Enschede
The Netherlands

Author:
Name: D.C. (Daniëlle) van Middendorp
Email: d.c.vanmiddendorp@student.utwente.nl

Graduation committee:
Prof. dr. S.J.M.H (Suzanne) Hulscher (University of Twente)
Dr. ir. R.P.(Pepijn) van Denderen (University of Twente)
Dr. ir. C.F. (Rolien) van der Mark (Deltares)

PREFACE

You just opened my master thesis "Using CoVadem to increase the value of Rijkswaterstaat's least sounded depth in the river Waal". This report is the final product of my master thesis for the MSc Civil Engineering and Management at the University of Twente, where I conducted my research at the Water Engineering and Management (WEM) department.

I would like to thank my graduate committee for their support and advice during the graduation period. Pepijn van Denderen for his daily guidance, insights and feedback. Rolien van der Mark (Deltares) for bringing up the topic and guiding me to focus on practice. And Suzanne Hulscher for her valuable feedback, support and supervision throughout my graduation period. Furthermore, I like to thank CoVadem for providing the data and insight into the topic.

I hope you enjoy reading this thesis and I hope this report inspires to continue the research with CoVadem and other kinds of data to make navigation safer, more skipper-friendly and more sustainable.

SUMMARY

In the river sections of the IJssel, Pannerdensch Kanaal, Neder-Rijn, Lek, and Waal Rijkswaterstaat systematically performs soundings to determine the lowest water depth in the fairway (MGD) when the water levels are low and become critical for navigation. The MGD provides valuable information, however, it also has limitations. The main limitations for the skippers are that the location is not published, i.e. it does not indicate whether vessels can navigate around the shallow area and that the accuracy of the MGD is unknown. CoVadem water depth information might help. The CoVadem data are water depth data continuously collected by the commercial fleet and therefore contains a lot of water depth measurements. However, little is still known about its accuracy and application possibilities. We present the findings of the research on how and to what extend the use of CoVadem data can increase the value of the MGD to make shipping more efficient during low water periods.

To analyse how CoVadem data could be used to increase the value of Rijkswaterstaat's MGD, first, the accuracy of both the CoVadem data and the MGD data is investigated by comparing these data to multibeam bed level data. The accuracy as expressed in Root Mean Square Error (RMSE) of MGD is 23 centimetres and the RMSE of CoVadem data is reduced from 41 centimetres to 30 centimetres by filtering on the horizontal dilution of precision (Hdop). Then, the CoVadem data is compared to the MGD by dividing the river into large grid cells to reduce the impact of limited data coverage. We determined the lowest measured water depth for each grid cell to compare with the measured MGD. The error between the MGD and CoVadem was with an RMSE of 53 centimetres in the same order of magnitude.

Finally, knowing how accurate both datasets are and how the CoVadem data can reproduce the MGD, we concluded on how CoVadem can increase the value of MGD in practice. CoVadem can increase the value of the MGD by foreseeing trends and can estimate where the MGD would have taken place, however, the quality of the data at this stage not accurate enough to be able to replace the MGD measurements. However, CoVadem can be very useful by supporting the measurement procedure by foreseeing patterns and help RWS patrol boats to search more targeted for MGD locations. The potential of the CoVadem data is big, but coverage, especially around MGD data points, should be higher. Which makes CoVadem very promising for further investigation to detect low water depths and provide vital information maximum cargo load in navigation.

TABLE OF CONTENTS

1 INTRODUCTION

The river Waal is the main distributary branch of the river Rhine in the Netherlands. It is the major waterway connecting the port of Rotterdam to Germany. Every year 100.000 vessels sail under the Waal bridge near Nijmegen, this means an average of 300 vessels per day. For all inland skippers in these vessels, water depth is important information, since it determines how much load can be taken. However, water depth changes both over time and location. The water depth is the distance between the bed level and the water level and both are changing continuously.

The water level rises and falls due to varying discharges and may change with several centimetres or decimetres a day depending on the location in the river and the season. Bed level change processes take place on different time scales. On a short timescale (days), river bedforms may migrate several meters. The bedforms respond to the flow by growing or dampen out in height and length. With migration rates in the order of several meters a day, shallow sections may migrate significantly within a couple of days (Best, 2005). On a somewhat longer time scale (days to weeks), a flood event may occur, causing sedimentation and erosion due to floodplain overflow. After a flood, this sedimentation-erosion pattern is likely to slowly dampen out and migrate downstream (Wilbers and Brinke, 2003). The sedimentation may become a bottleneck for navigation if the water level drops quickly. Besides, also low waters, simply caused by low discharges may cause problems for navigation.

With small water depths, ships cannot be fully loaded and measures need to be taken to pass the critical sections on the route (Bons *et al.*, 2014). During the summer of 2018, when water levels were very low, vessels could only load one-third of their normal load due to small water depths (Lange and Waterval, 2018). Here we evaluate various types of data to estimate the size and location of the critical sections.

1.1 BACKGROUND

In this research, MGD data from Rijkswaterstaat and commercial CoVadem data are compared. What these data contain and how these data are collected and processed is described in this background section.

1.1.1 MGD

In the river sections of the IJssel, Pannerdensch Kanaal, Neder-Rijn, Lek, and Waal Rijkswaterstaat systematically performs soundings to determine the lowest water depth in the fairway. The publication of the least sounded depth (MGD = 'minst gepeilde diepte') takes place as soon as and as long as the water depth is lower than the limit. In the Waal, this limit is 350 cm in the fairway.

> Fairway**:** The waterway between the imaginary lines that lie 30 metres from the beacons or replacement buoys on the heads of jetties, groynes, and banks, or 5 meters from other floating markers (*Staatscourant*, 1997).

Figure 1: Study area and trajectories of MGD measurements at the Waal

In the river Waal usually, only one MGD is published, which is representative for the full branch. However, during the low water period in 2018 from 20 August to 10 December, the river Waal was split into three trajectories (Figure 1): Millingen to Maas-Waalkanaal, Maas-Waalkanaal to Amsterdam-Rijnkanaal and Amsterdam-Rijnkanaal to Loevestein (Figure 2). This was done for the vessels that did not have to navigate the whole branch.

The MGD is not necessarily an existing water depth, but rather a combination of a measurement, (large) inaccuracies, a safety factor and a prediction. The MGD is measured by Rijkswaterstaat patrol boats using a single-beam echo sounder. There is no compensation to squat. Therefore, the skippers of the patrol boats try to approach the static situation as good as possible by sounding the MGD with little or no velocity.

Besides, the skippers of Rijkswaterstaat's patrol boats observe the lowest water depth and before publication, the observation is rounded down to the nearest decimetre. Finally, for the predicted MGD value, the fluctuations and the trend in observations and the trend in the predicted discharge at Lobith may be taken into account to determine the MGD value that is published, since they only publish one value per day. The MGD is therefore not necessarily an existing water depth, but rather a combination of the measurement and the prediction of the controller on the patrol boat.

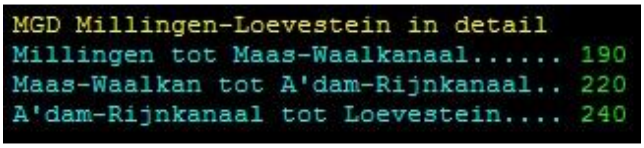

Figure 2: MGD on teletekst 20 August 2018

This method receives complaints from their target audience, the skippers. For example, from skipper and owner of the Trias Obelix joint venture, who grounded two times within three weeks at Nijmegen in the summer of 2018. It was loaded to 2.30 meters on August 5, while the MGD was 2.00 meters at that time. Owner Marcel van Gent stated in Schuttevaer (trade magazine of shipping in the Netherlands) that at that time it was perfectly possible to sail with a draft of 2.3 metres and that the problem was that only one value of MGD is provided for the entire Millingen-Loevestein route. Van Gent stated that if only one shallower location is measured anywhere in the fairway, Rijkswaterstaat will adjust the MGD accordingly. He claims that it could be a small bump that was created somewhere at high water level along the edge of the fairway, where vessels could navigate around (Meulen, 2018).

1.1.2 CoVadem

A solution to these limitations of the MGD may be in CoVadem data. The CoVadem data is water depth data collected by the commercial fleet. Nowadays, vessels are often equipped with modern navigation gear, including a large availability of a variety of sensors. This gear generates highly valuable data on water depths, performance, and operational details. These data, however, is in most cases not stored and valuable information is lost. With the initiative 'CoVadem' the valuable data is stored and collected to provide up-to-date water depth information using Big Data technology. CoVadem is an initiative by MARIN, Deltares, Autena Marine and Bureau Telematica Binnenvaart (*About CoVadem*, 2018). CoVadem does not aim to determine the water depth with a precision equal to that of a multibeam echo sounder, as the singlebeam transducers used are typically less precise. However, the strength of CoVadem is that measurements are performed continuously so that the measurements are always up-to-date (Cotteleer *et al.*, no date). The ambition of CoVadem is that the data collected by the participating ships will be shared with the navigation sector in a condensed way, such that decisions on the loading capacity, the route and the navigation velocity can be made on 'real-time' data (Van der Mark, Vijverberg and Ottevanger, 2015). Therefore data from a growing fleet of 75 vessels is collected, then combined and processed. Eventually, it is communicated as up-to-date water depths.

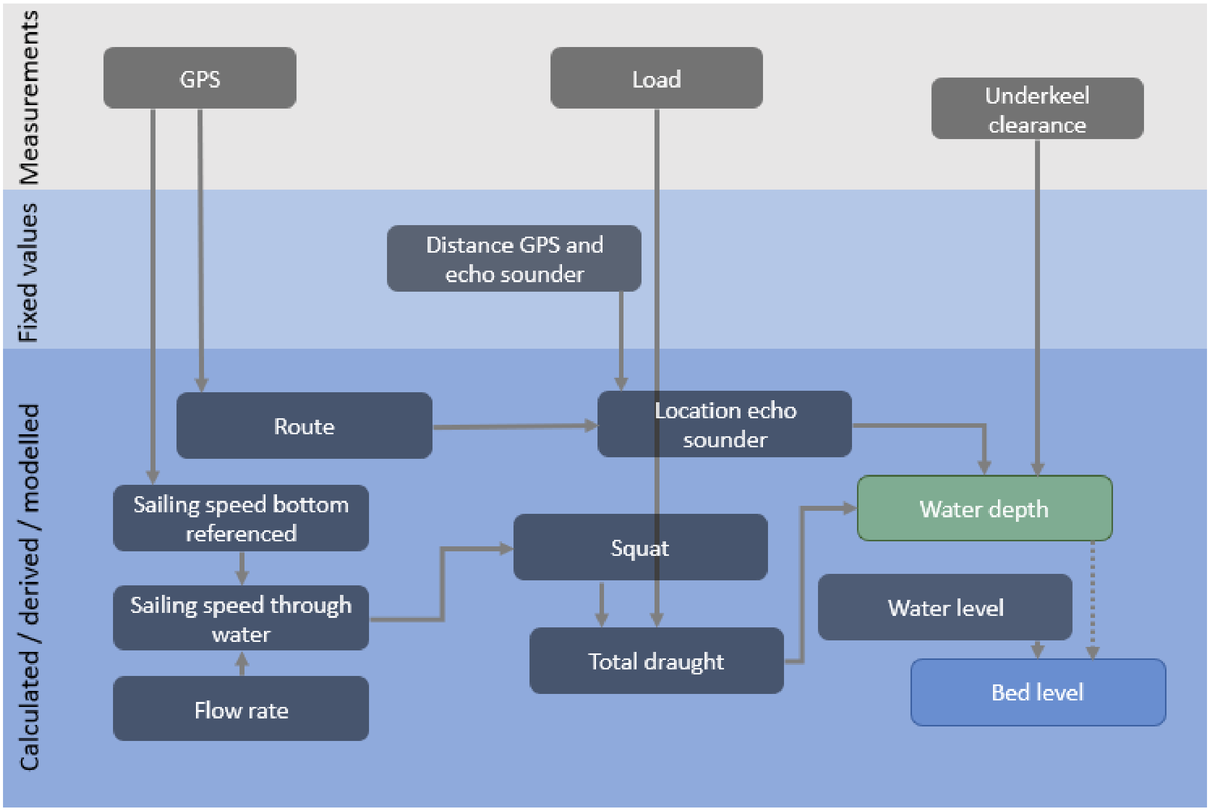

Figure 3: The process of how CoVadem translates measurements to water depth (and bed level) using fixed values, calculations and models (Based on (Niesten and Van der Mark, 2020).

The vessels participating in the CoVadem initiative continuously measure data with sensors that were already on board before they started participating in the project. The under keel clearance is usually measured every few seconds with a single-beam echo sounder, vessel location is measured with a GPS-system and vessel draught is measured before the vessel sails away with a ship cargo meter (a calibrated system of pressure sensors). Only the so-called CoVadem Box has to be placed in each vessel. This box combines existing sensor data, stores them and takes care of the provision of the information to the CoVadem servers.

Figure 3 shows how CoVadem translates the measured GPS, load and underkeel clearance to water depth by correcting for squat, route and ship parameter. Inaccuracies are mainly a result of the unknown accuracy of the equipment of the vessels and the squat calculations

1.1.3 Problem description

The MGD provides valuable information for the skipper. Unfortunately, the location is not published and the accuracy of the MGD is unknown. CoVadem water depth information might help to get more insight into the location of the MGD. However, it is unknown if the accuracy and coverage are sufficient for it to be applicable.

1.1.4 Study area

Rijkswaterstaat classified May to December from 2018 as a low water period (Rura-Arnhem, 2019). This period is right after a period of high water levels and therefore, we focus on this period. In Figure 4, the discharge at Lobith and the MGD values of 2018 are visualised. In this figure also the OLA ('overeengekomen lage afvoer', translated: agreed low discharge) and OLR ('overeengekomen lage rivierstand', translated: agreed low river level) are shown. These values are the theoretical values of a 5% probability to be undershot. So 5% of the time the sailing depth may be less than this agreed standard. However, as can be seen in Figure 4 these administrated limits are undershot more often. This indicates that 2018 was a year with relatively many small water depths.

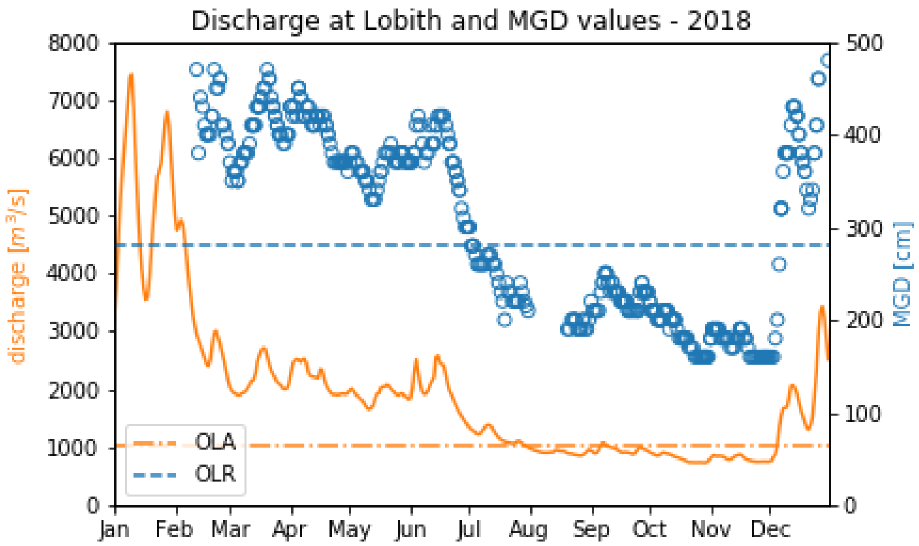

Figure 4: Blue: MGD measured in 2018. Orange the measured discharge at Lobith

In this study, we focus on the river Bovenrijn/Waal from Lobith (upstream) to Loevestein (downstream) (Figure 1). In this area, there is a large amount of CoVadem data available.

Figure 5: MGD locations (black dots) 2018 of which Hulhuizen, Erlecom, Nijmegen, Ophemert/Dreumel, Sint Andries and Haaften are known bottlenecks for the river Waal (Tönis, 2017).

In Figure 5 the locations of the MGD in 2018 are shown. These locations are all dredged often or less often in the past years. Unfortunately, we have no insight in when and where dredging takes place. However, in data from dredging locations from 2014 to 2017 provided by RWS, we see that in this period all MGD locations have been dredged (Figure 6 and 7). These are unexpected changes in the river bed, which cannot be predicted morphodynamically but will cause a disturbance in the river bed.

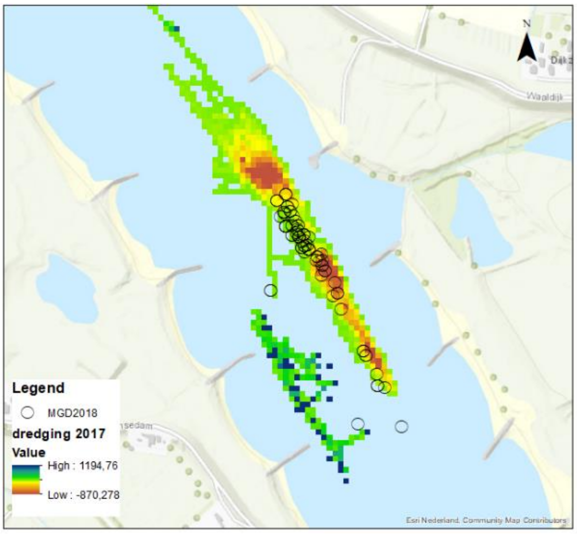

Figure 6: Dredging locations 2017 and MGD locations near Hulhuizen. The colour scale is red (dredging) to blue (dumping)

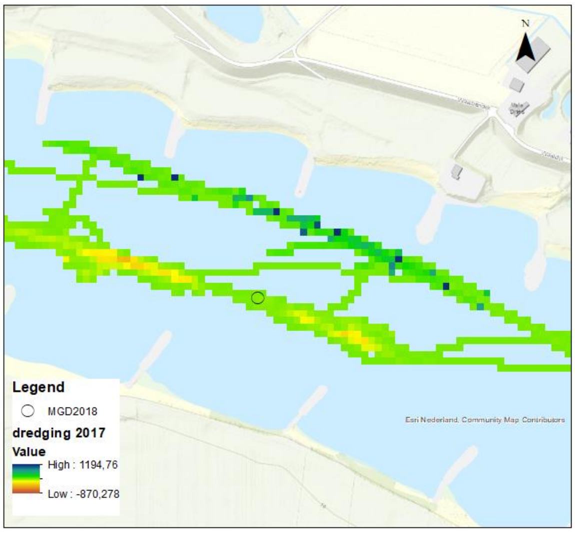

Figure 7: Dredging locations 2017 and MGD locations near Wolferen

1.2 Goal & Research Questions

The goal of this research is to investigate how the use of CoVadem data can increase the value of the MGD provided by Rijkswaterstaat to make shipping more efficient during low water periods. Therefore, the following questions will be answered in this research:

How and to what extent can CoVadem data be used to increase the value of Rijkswaterstaat's MGD (least sounded depth) in the river Waal during low water periods?

a. How accurate are the MGD and CoVadem datasets?
b. How can the MGD of Rijkswaterstaat be reproduced using CoVadem data?

c. How and to what extent can CoVadem data contribute to publishing the shallowest location of the river Waal?

In Figure 8 the relation between the goal, research questions, and the product is visualised.

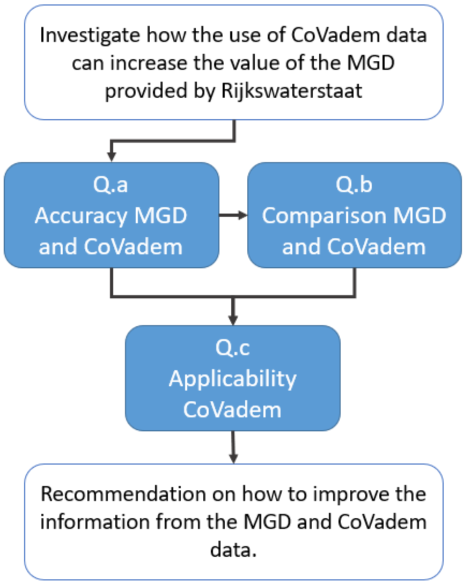

Figure 8: Relation between the goal, the research questions, and the final product

1.3 METHODOLOGY

To analyse how CoVadem data can be used to increase the value of Rijkswaterstaat's MGD, first, the accuracy of both the CoVadem data and the MGD data are investigated by comparing these data to multibeam bed level data (Chapter 4). The multibeam data are biweekly measurements collected by dredgers commissioned by Rijkswaterstaat as part of a performance contract. Water levels determined from water level measurements and stage relation curves ('betrekkingslijnen') are used to perform the comparison between singlebeam water depth and multibeam bed level (Chapter 5). Secondly, the CoVadem data is compared to the MGD by dividing the river into large grid cells to reduce the impact of limited data coverage. We determine the lowest measured water depth for each grid cell a comparison this with the measured MGD (Chapter 6). Finally, knowing how accurate both datasets are and how the CoVadem data can reproduce the MGD, we evaluate the possibilities to apply CoVadem in practice and thereby, to increase the value of the MGD (Chapter 7).

2 BED LEVEL CHANGES

To understand why shallow water depths occur at different locations along the river, bed level changes along the river bed are very important. There two processes affect the dynamic in the river bed. First the natural dynamics in the river bed such as sedimentation and erosion in the bends and secondly the dynamics through interventions such as structures (e.g. groynes and fixed layers), dredging and shipping.

Bedforms respond to the flow by growing or dampen out in height and length. With migration rates in the order of several meters a day, shallow sections may migrate significantly within a couple of days (Best, 2005). On a somewhat longer time scale (days to weeks), a flood event may occur, causing sedimentation and erosion due to floodplain overflow. The bed level variation in the river Waal is in the order of 50 cm with strongly varying discharge (Paarlberg, 2020). The sedimentation and dunes may become a bottleneck for navigation if the water level drops quickly.

The flow pattern in bends and the effect on the morphology of the bends shown in Figure 9. Pools and bars are developing due to eddies in the different cross-sections and inertia of the water particles. The resulting development would be a meandering of the river, which in the river Waal is prevented by groynes and dykes. To avoid the point bar/pool formation and so the restriction of the navigation channel width, bed protections in the form of fixed layers have been placed in the beds of Nijmegen and St. Andries. Bend-weirs with the same effect have been placed in the bend at Erlecom (Hetzer, 2005). During periods of low water, the fixed layer forms an obstacle for navigation, since the Upper-Waal has eroded continuously with 2-3 cm per year, but the fixed layer could not.

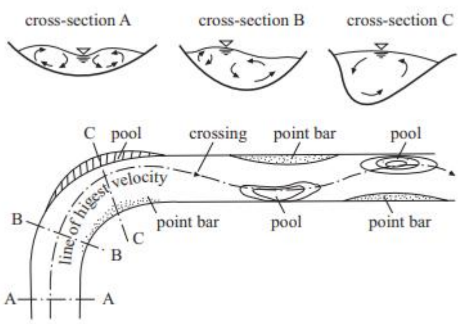

Figure 9: Flow in beds and crossings (Hetzer, 2005),

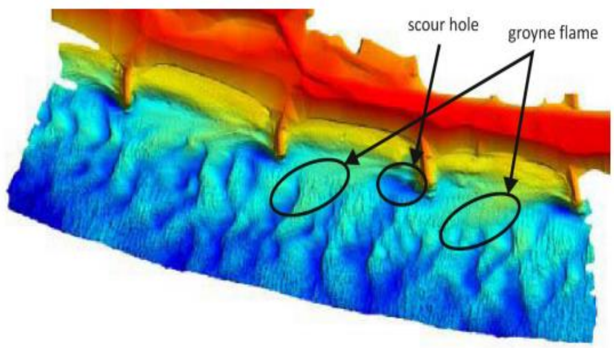

Figure 10: Scour hole and groyne flames (Van Broekhoven, 2007)

Groynes prevent meandering of the river. However, as a consequence of the flow around the groyne head and turbulence caused by the groyne, a scour hole occurs just downstream of the groyne head. A little further downstream of this hole, sedimentation occurs caused by the hole and the widening of the flow into the groyne field. This sedimentation fields are called groyne flames and are found to reach for some ten meters in the transversal direction and may also cause problems for navigation during low flow conditions (Klaassen & Sloff, 2000).

Besides natural river bed dynamics and both natural and intervened morphodynamic effect of river bends also dredging is very important in the river Waal. Almost all known MGD locations are also dredging locations, however, it is unknown when and to what extent this took or will take place. Thereby comes that on multiple locations at the river Waal underpasses of cable pipes are present. At these locations, dredging is not allowed and therefore local shallow water can occur, which cannot be dredged. Finally, navigation itself has an impact on the bed level dynamic by causing bank erosion and different currents in the river bed.

3 METHOD

The research is divided into three parts, each part corresponding to one research question. In Sections 2.1, 2.2 and 2.3, the methods to answer these questions are explained.

3.1 ACCURACY DATASETS

We assess the accuracy of the datasets (Figure 11). The inaccuracies come from technical errors in the equipment, the translation from under keel clearance to water depth (Figure 12), and procedural errors (mainly applicable for MGD). The theoretical inaccuracy is shown in Table 1 (for detailed information about these inaccuracies, see Appendix A).

Table 1: Estimation of inaccuracies (minimum and maximum values) for various sounding techniques. (Wiegmann, 2002)

		Singlebeam with water depth	**Multibeam with RTK position**
		CoVadem & MGD	*Multibeam maintenance sounding (MMS)*
	Source of error		
Location	Influence of the location error measuring on a slope	5 to 10 cm (+/-)	1 to 2 cm (+/-)
Vessel's geometry	Squat	0 to 35 cm (-)	n / a
	Heave	0 to 40 cm (+/-)	n / a
	Draft	0 to 5 cm (+/-)	n / a
	Roll & Pitch	0 to 5 cm (+/-)	0 to 15 cm (+/-)
Reference	Water level as vertical reference	0 to 20 cm (+/-)	n / a
Sounding	Speed of sound	0 to 10 cm (+/-)	0 to 40 cm (+/-)
	Bundle angle	0 to 2 cm (-)	0 to 1 cm (-)

The accuracy of the singlebeam CoVadem and MGD data is studied by comparing the data with multibeam bed level data. The multibeam data available is assumed to be the most accurate data available (Table 1) and therefore, is used as a reference (Appendix B). However, the multibeam is measured after any dredging activities that might lead to differences (Figures 6 and 7). Since the singlebeam measurements of CoVadem and MGD are available in water depth, water levels are used to translate these data to bed level: bed level = water level – water depth (Figure 12). This procedure is explained in Appendix C.

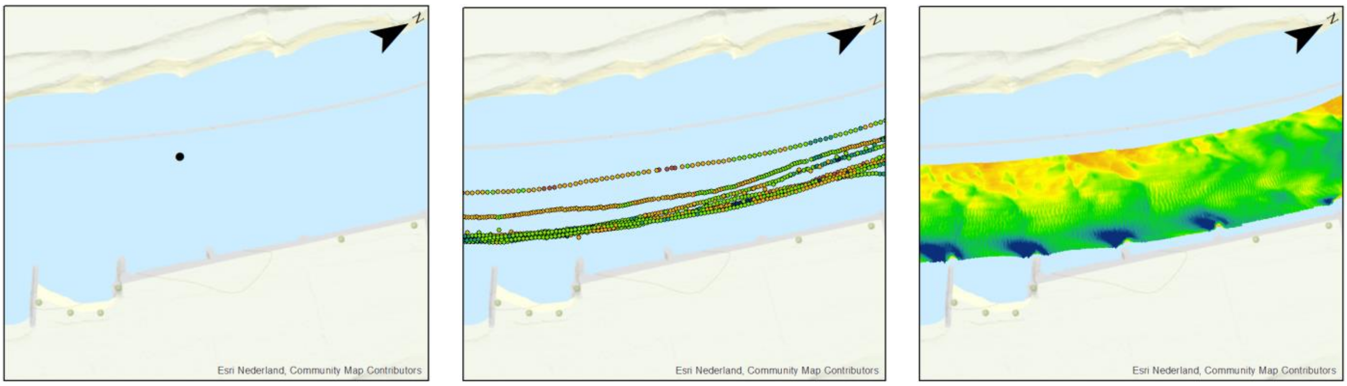

Figure 11: Data at Rhine Kilometre 919 near Dreumel on 19 September 2018. From left to right: MGD (water depth), CoVadem (water depth), multibeam (bed level).

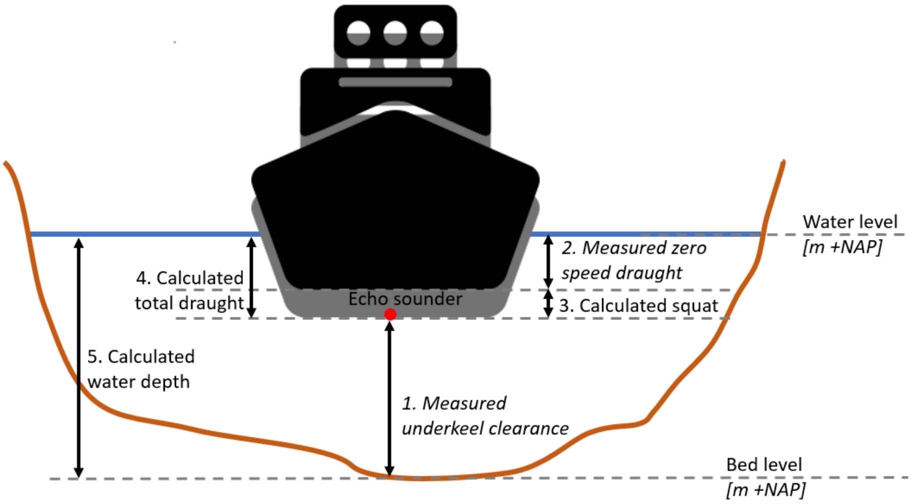

Figure 12: Schematisation of the vessel's under keel clearance with the water level and bed level

The bed levels derived from MGD and water level and the bed levels from the multibeam maintenance soundings are compared. We chose to use multibeam data up to and including five days before the MGD/CoVadem data was measured because otherwise, we have too little data to make a comparison. Multibeam data is collected within a performance contract and dredgers tend to dredge the river right before delivering the multibeam date to meet the requirements in the contracts. Therefore if a multibeam measurement after the MGD/CoVadem measurement would be selected there is a higher chance dredging took place between the measurements. This would likely affect comparisons between the multibeam and MGD at locations such as in Figures 6 and 7.

To quantify the accuracy, the following statistics are calculated: Root Mean Squared Error (RSME); the mean error (μ); the standard error of the difference (σ); and the correction. In addition to the quantification of the accuracy, the difference in bed levels is visualised on the following factors.

- Day from multibeam maintenance sounding: The accuracy depending on the time between MGD measurement and multibeam measurement. If the bed is changing one would expect the accuracy to decrease if the time between the measurements is growing. With this comparison, we will prove that up to five days before the measurement is acceptable.
- Rhine kilometre: The accuracy depending on the location of the MGD measurement. Since both hydrodynamic processes and morphological effect change over the length of the river.
- Discharge and water depth: The accuracy depending on the discharge and the measured singlebeam water depth. With higher discharge and therefore also larger water depths, the bed level changes more than at lower discharges. Also measuring errors may change over water depth.

The CoVadem data is in many cases unfiltered. Therefore, we apply extra filtering to the CoVadem databases on the Hdop and ShipID:

- Hdop: The horizontal dilution of precision. The higher the Hdop value, the bigger the scatter in position error. The theoretical accuracy can be divided into several categories (Table 2).

Table 2: Geometric DOP Rating (Jyothirmaye, Srinivas and Ramu, 2019)

Hdop	Classification
1	Ideal
1-2	Excellent
2-5	Good
5-10	Moderate
10-20	Fair
>20	Poor

- ShipID: We have data from 35 different vessels and they all perform differently because of differences in the measuring equipment and geometry of the vessels. To filter out the ships who are performing the worst, criteria will be made bases on which will be filtered.

For MGD data these comparisons are visualised in scatter figures with a mean since the amount of data is not enough for other visualisations. For CoVadem data the comparison based on these factors is visualised as a violin plot to show the spread and its distribution or as box and whisker plot if it improves the readability (Figures 13 and 14).

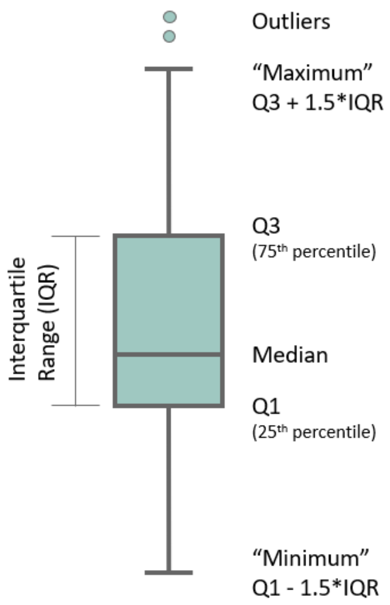

Figure 13: The definition of a box and whisker plot

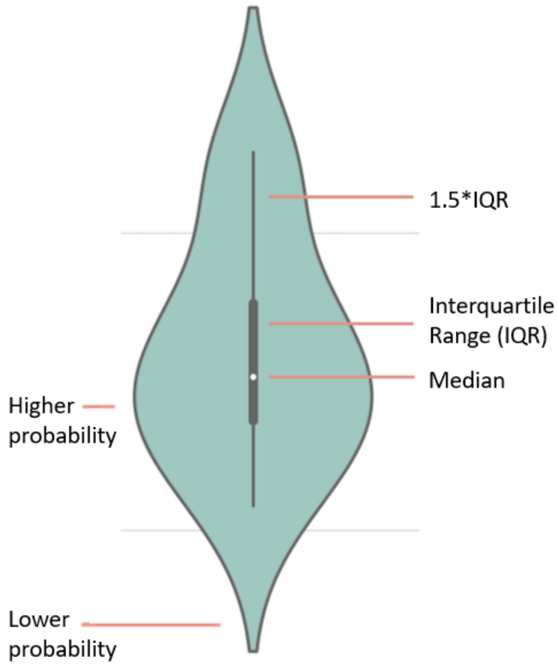

Figure 14: The definition of a violin plot

3.2 Reproducing MGD using CoVadem

A comparison between MGD and CoVadem is performed to check how well CoVadem can reproduce the MGD. Because CoVadem does not measure along the whole length and width of the river, the river is divided into grid cells, to get one (minimum) CoVadem water depth per cell. Since CoVadem data still contains unrealistic outliers, data in the grid cells are processed to filter out these extreme values. The width of the grid cells is half of the river width. The river is split along the river axis, to differentiate between the inner and outer bend. We compare different grid cell lengths. Too small results in too little CoVadem datapoints in the cell and too big loses the value of location accuracy. The chosen cell lengths are 500 m, 750 m, 1000 m 1500 m and 2000 m.

The best way to generate the minimum water depth from CoVadem that is assigned to a grid cell is based on the research of Dierx (2018). In this research, an n^{th} percentile of the CoVadem data was used to assign the maximum bed level. Dierx validated the outcome and concluded that 95% or 97% gives the smallest error between MGD and CoVadem bed levels. Since bed level and water depth are directly dependent through the water level, we used this method to find the minimum water depth. Both filtering values are compared to the following:

- Correlation
- Mean difference between the MGD and the CoVadem data
- The standard deviation of the difference between the MGD and the CoVadem data
- Root Mean Square Error (RMSE)
- Median of the difference between the MGD and the CoVadem data

Based on these results, a grid size and a filtering percentile are selected. For each MGD we compare the MGD with the CoVadem data at the same location (cell) and time (up to 5 days before) as the MGD data.

3.3 APPLICABILITY COVADEM

We investigate the additional value of CoVadem in two steps. Firstly, it is investigated whether a small water depth is missed because the Rijkswaterstaat Patrol boats do not measure along the whole stretch of the river. The comparison between the CoVadem data and the MGD data is repeated but now not limited to the grid cell but over the whole branch. Secondly, the goals of Rijkswaterstaat and the inland waterway transport with the MGD will be investigated closely. Both the currently provided MGD and the opportunities of CoVadem are mirrored to these goals.

Since the location of shallow waters is so important for inland shipping, we analyse the location. Rijkswaterstaat publishes the smallest water depth every day it is below 350 cm as MGD for safety reasons in navigation. They do not publish a location, but only the smallest water depth over the whole river Waal from Millingen to Loevestein. Although the MGD is issued for the navigation industry, this is not quite what the skippers need, since they need the water depth on their route and not necessarily on the whole Waal. There are a lot many vessels that navigate from the direction of Loevestein to Nijmegen and then divert to the South via the lock at Weurt. With an MGD at Nijmegen due to drought, they are officially not allowed to navigate deeper than the MGD, but they could.

.

4 RESULTS: ACCURACY DATASETS

In this chapter, the accuracy of MGD (3.1) and CoVadem (3.2) is presented. Both statistical results and accuracy based on different parts of the data, such as location and water depth, are included.

4.1 ACCURACY MGD

The bed levels derived from the singlebeam MGD water depth measurements and water levels (Appendix B) are compared with the bed levels measured in the multibeam maintenance soundings ('beheerspeilingen').

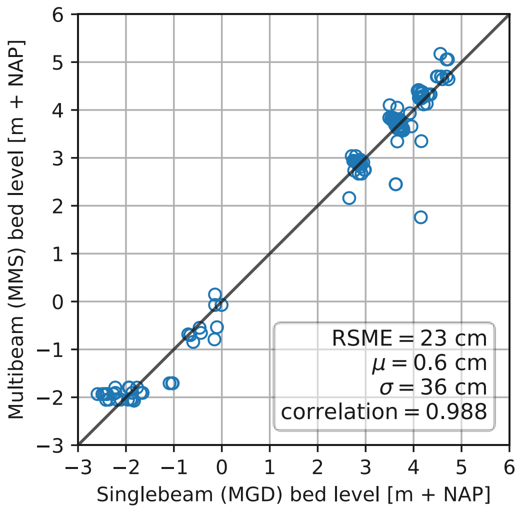

Figure 15: Singlebeam (MGD) bed levels versus multibeam (MMS) bed levels

In Figure 15, the values of the singlebeam MGD bed levels and their corresponding multibeam routine management sounding (MMS) bed levels are shown. The Pearson product-moment correlation coefficient of 0.99 means the data are strongly related. From the procedure, the MGD was expected to be higher than the actual bed level, since the water depth is rounded down and processed conservatively. However, the comparison shows that this effect is not large.

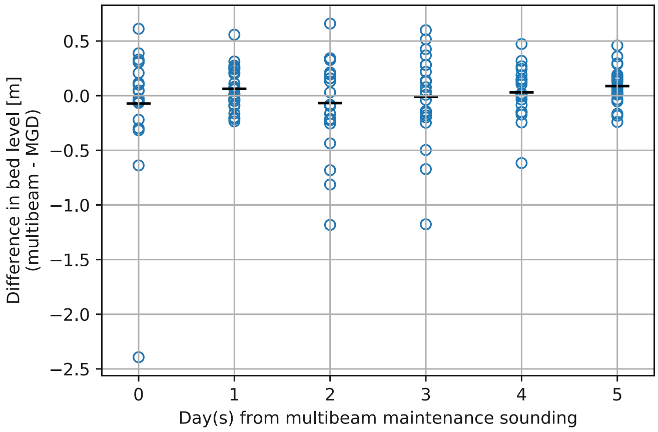

Figure 16: Difference in bed level (multibeam - MGD) per day from multibeam maintenance sounding. The black stripe is the median.

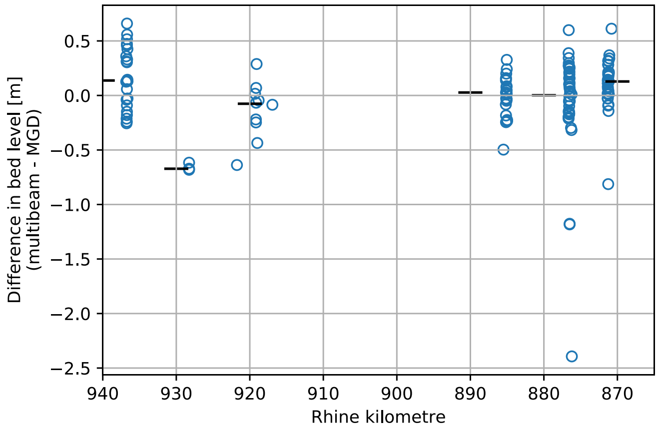

Figure 17: Difference in bed level (multibeam - MGD) over Rhine kilometre. The black stripe is the median per 10 kilometres. Left Lobith, and right Loevestein.

Figure 16 shows the differences in bed level between the day of measurement of the singlebeam MGD relative to the multibeam routine management sounding. Since the bed level of the river changes in time, it was expected that the accuracy would decline as the difference in days would increase. However, this trend not shown in the data. Also, there is no significant dependency on the accuracy of the location visual in the data (Figure 17). The known bottlenecks Hulhuizen, Erlecom, Nijmegen, Ophemert/Dreumel, Sint Andries and Haaften are clearly visible *(Tönis, 2017)*. Since these are also known dredging locations the outliers may be caused by recent dredging activity. The lack of a relationship between the error and the number of days between measurements and the error and the Rhine Kilometre might suggest that morphological changes are limited and not a significant contribution to the variation in the MGD during low water conditions.

4.2 Accuracy CoVadem

The bed levels derived from the singlebeam CoVadem water depth measurements are compared with the bed level in the multibeam routine management sounding. We first show unfiltered data and then the accuracy of Covadem to make it also applicable in practice. Figure 18 shows the relation between the two datasets.

4.2.1 Filtering conditions

First, all data is analysed to find the criteria on which the data must be filtered. This is only done based on parameters given by CoVadem. The statistics from all data as described in a Root Mean Square Error, mean, standard deviation, and the correlation coefficient is shown in Figure 18.

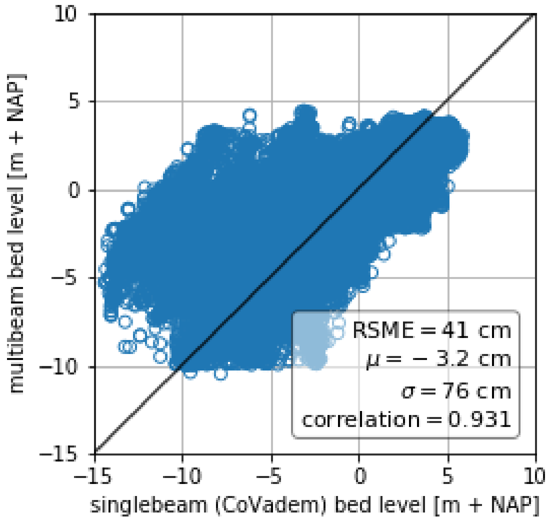

Figure 18: Singlebeam (CoVadem) bed levels versus multibeam (MMS) bed levels before any filtering

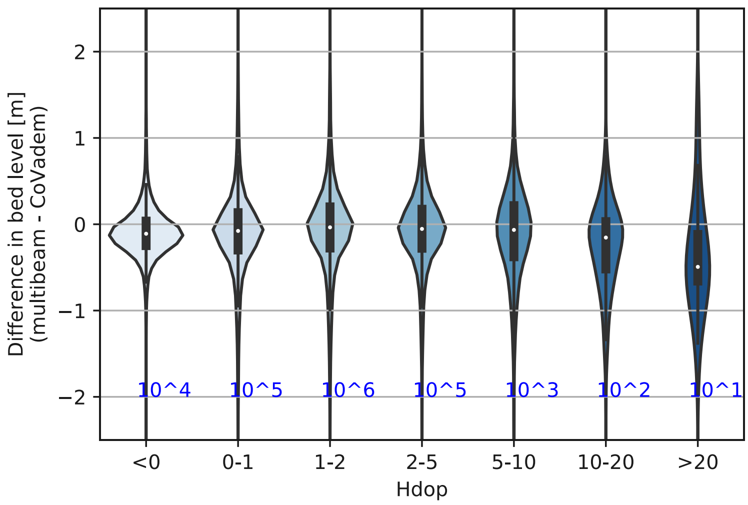

Figure 19: Difference in bed level per Hdop class. The white point is the median the black bar contains 50% of the data. The number below is the number of CoVademe data points.

Discharge

Since the importance of the water depth increases with lower discharges, the accuracy of the data is analysed for different maximum discharges. Figure 20 shows that the accuracy of the CoVadem data increases with lower discharges, which can be explained by the fact that the bed changing less with lower discharges. However, we chose to include all discharges in this research, since also at higher discharges, for example, due to dune movement, small water depths may occur.

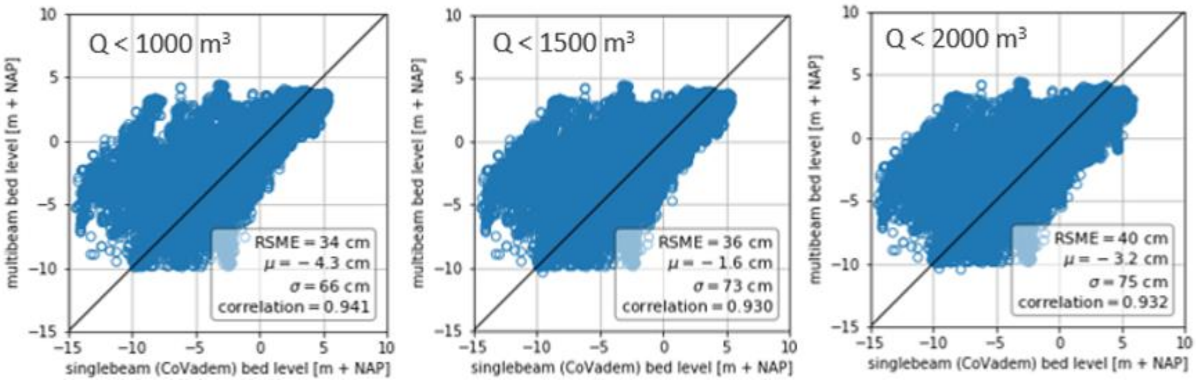

Figure 20: Singlebeam (CoVadem) bed levels versus multibeam (MMS) bed levels before any filtering with different maximum discharges (Q). Left Q<1000 m³/s (49% of the days). Middle Q<1500 m³/s (68%). Left Q<1000 m³/s (87%).

Hdop

The accuracy visual in the data is presented in Figure 19. As can be seen in the figure, if Hdop > 5 the spread of accuracy becomes bigger, and also the mean accuracy drops. Therefore there is chosen to remove the data if Hdop is bigger than five. The meaning of a negative Hdop value is unknown, however, since the difference between singlebeam and multibeam seems to be acceptable these data are not filtered out.

ShipID

All ships participating in the CoVadem initiative perform very differently. Both in the spread in the difference between the singlebeam and multibeam bed level as in the median values (Figure 21 and Figure 22). In Figure 21 the difference and the spread in differences are shown per ship, in Figure 22 we selected four of these ships and shown the histograms of the difference in bed level. Ship 8 and Ship 35 seem normally distributed, but that does not apply to Ship 34 and Ship 67.

Ships with 75th percentile minus 25th percentile (top of the box and bottom of the box) bigger than 0.5 meters are removed. The accuracy of this data is too scattered to give reliable information. In Figure 21 is shown which ships are filtered out and which ships are selected for this accuracy analysis. As can be seen in Figure 21 some ships may benefit from a vertical shift, because the spread is very low and the median is not zero. This is discussed in paragraph 4.3.

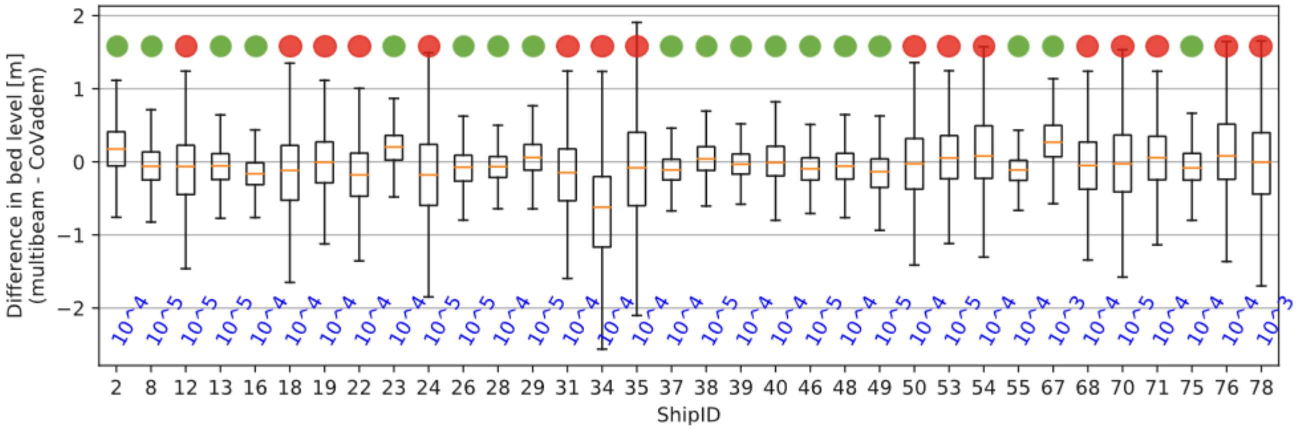

Figure 21: Difference in bed level between CoVadem bed level and multibeam bed level values. Blue value is the number of measurements in the order of magnitude. The green point means the ship remains, the red point means the ship is filtered out.

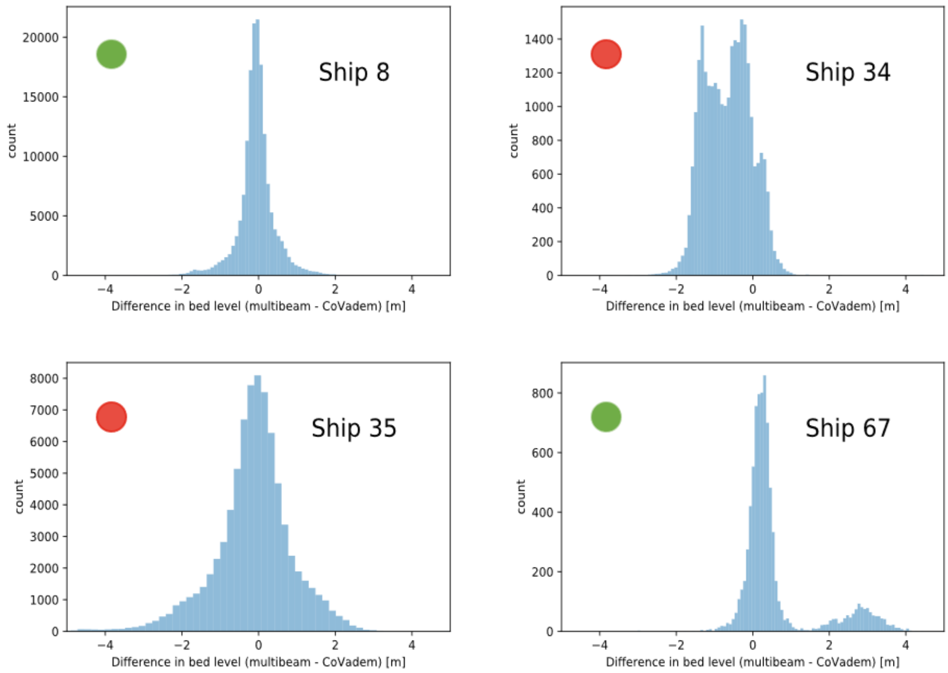

Figure 22: Histograms of difference in bed level of ship 8, 34, 35, and 67. The x-axis is the difference in bed level (multibeam – CoVadem [m]) and the y-axis is the count of the number of measurements with that difference.

4.2.2 Accuracy after filtering

After filtering for Hdop and ShipID, the accuracy improves (Figure 23). The RMSE is reduced to 30 centimetres. However not all outliers are filtered out by the filtering for shipID and Hdop, there is an improvement of the RMSE of more than 10 centimetres. We will compare the magnitude of the error with several river characteristics.

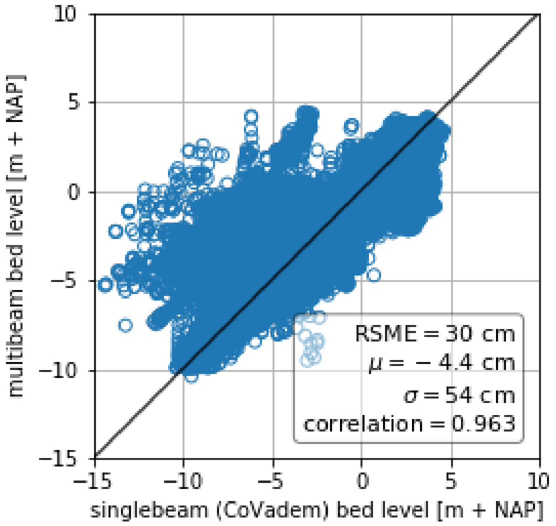

Figure 23: Singlebeam (CoVadem) bed levels versus multibeam (MMS) bed levels after filtering for Hdop and ShipID

Day from multibeam measurement

The accuracy of the CoVadem data is not dependent on what day relative to the routine management sounding the measurement took place (Figure 24).

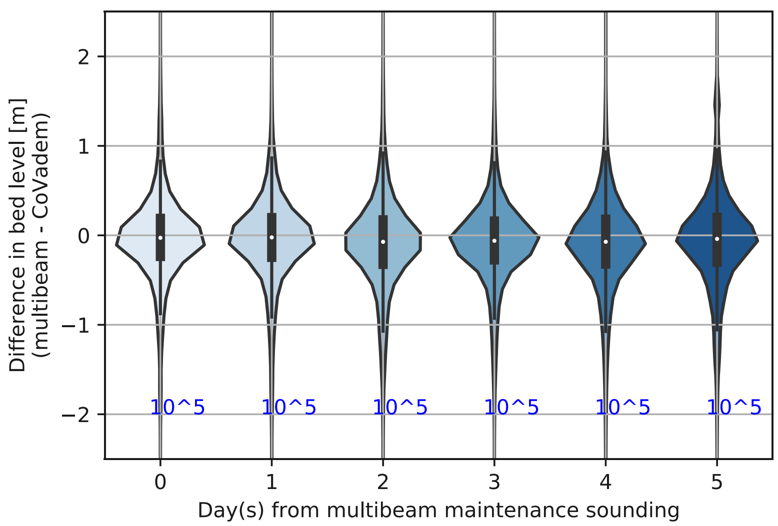

Figure 24: Difference in bed levels per day from the multibeam measurement. The white point is the median the black bar contains 50% of the data. The number below is the number of CoVademe data points.

ShipID

We compare the error again, but now with filtering for Hdop. As can be seen in Figure 25, most vessels show a higher bed level than the multibeam bed level. This indicated that those ships underestimate the water depth and this is a conservative value to avoid grounding.

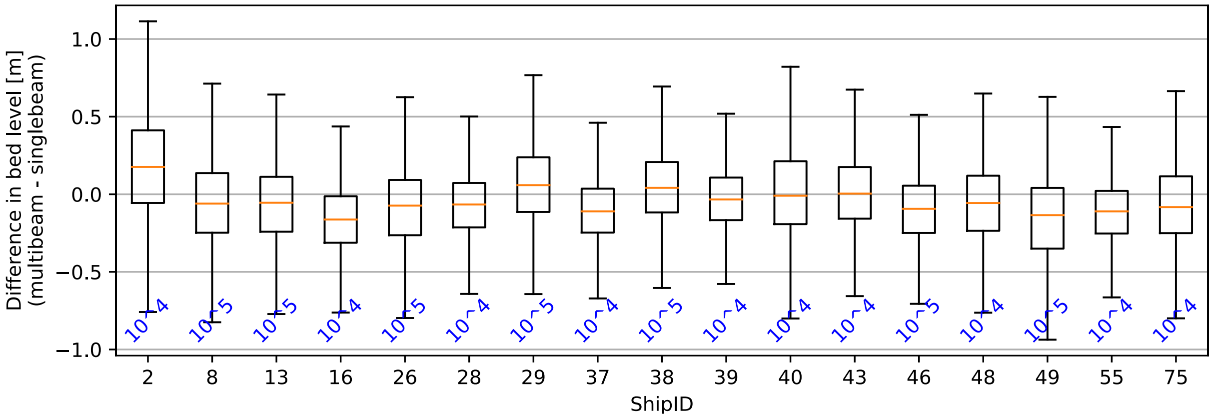

Figure 25: Difference in bed level (multibeam - CoVadem) depending on the ShipID. Blue value is the order of magnitude of the number of measurements.

Discharge

Figure 26 shows that a higher discharge leads to a larger spread in the difference in bed level between multibeam data and CoVadem data. This might be explained by the fact that the river bed level changes are larger with higher discharges. Also, at high discharges, the median value of the difference increases with the number of days that the Covadem data and multibeam data are apart. This small trend is likely not significant concerning the large spread.

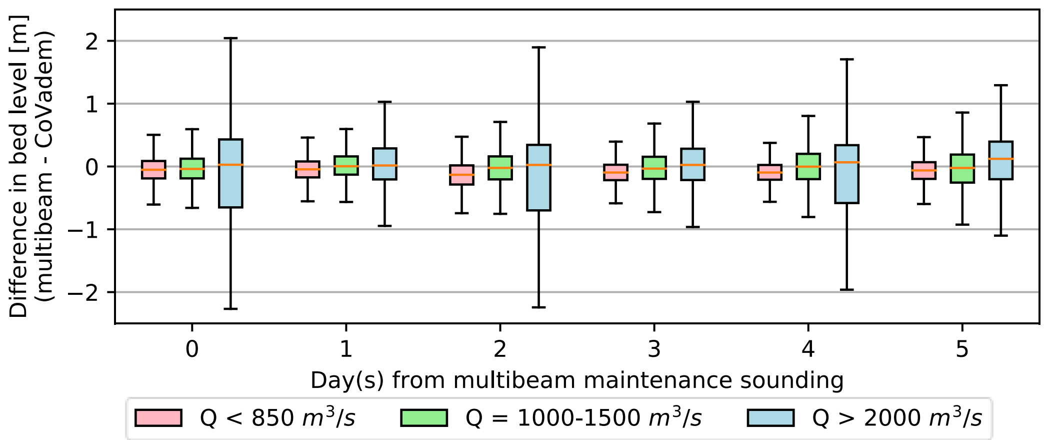

Figure 26: Difference in bed level (multibeam - CoVadem) depending on the number of days between the multibeam measurement and the CoVadem measurement and the discharge at Lobith at that time.

Figure 27 shows that the Root Squared Mean Error reduces to 22 centimetres with maximum discharges of 1000 m^3/s

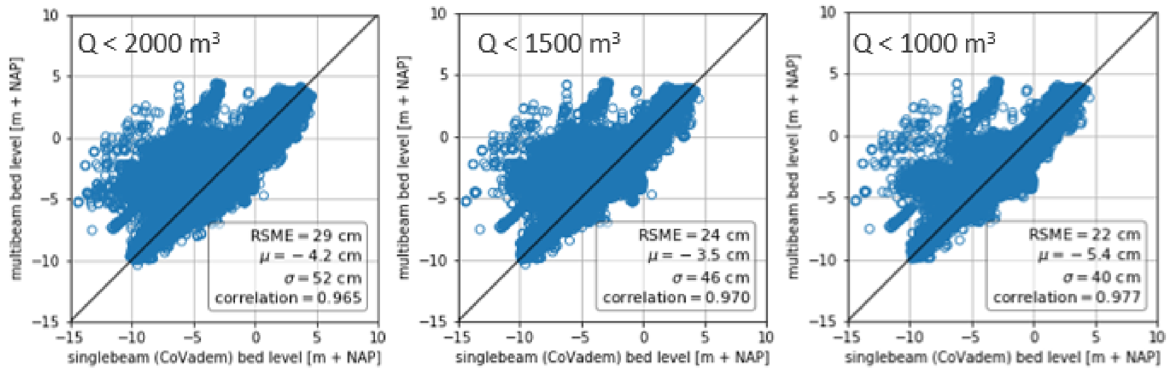

Figure 27: Singlebeam (CoVadem) bed levels versus multibeam (MMS) bed levels before any filtering with different maximum discharges (Q). Left Q<2000 m³/s (87% of the days). Middle Q<1500 m³/s (68%). Left Q<1000 m³/s (49%).

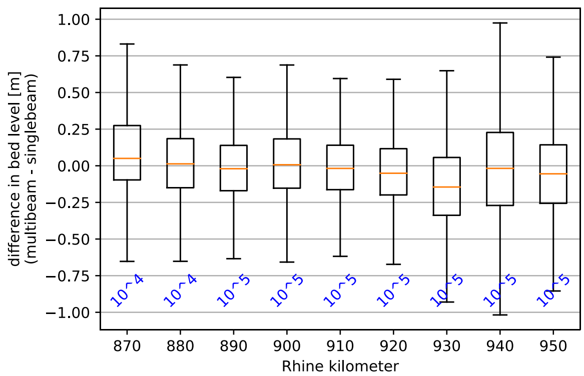

Figure 28: Difference in bed level (multibeam - CoVadem) depending on the location in the river. Blue value is the order of magnitude of the number of measurements.

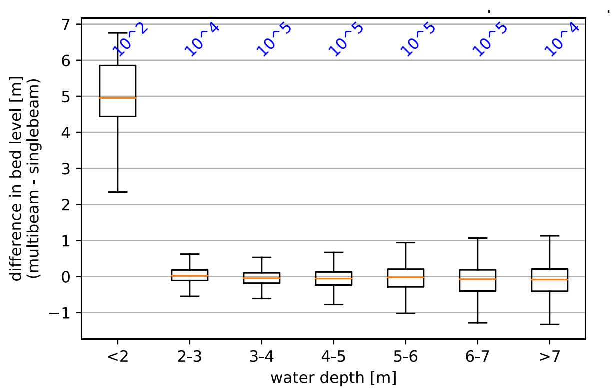

Figure 29: Difference in bed level (multibeam - CoVadem) depending on the CoVadem water depth. Blue value is the order of magnitude of the number of measurements.

Rhine kilometre

The difference in bed level varies as a function of the river kilometre. A small trend from upstream to downstream is visible (Figure 28). At upstream locations, CoVadem is overestimating the water depth and downstream CoVadem is underestimating the water depth. It is not clear what causes this trend, but it might be related to the water depth, flow velocity, salinity and/or dune formation. At the downstream end (rkm>=940), the tide impacts the water level in the river Waal which might explain the change in trend and the increase in spread.

Water depth

In Figure 29 we see that the difference in bed levels with very small CoVadem depths is very large. Small water depths may have a high chance of being a measurement error. Apart from that, the higher the depth the uncertainty of the data increases, which relates to the discharge (Figure 26).

4.3 Conclusion/ discussion

The expected higher bed level (smaller water depth) measured by MGD is not visible in the data. The RMSE of MGD is 23 centimetres. Considering the MGD being a combination of the measurement and the prediction of the controller on the patrol boat, this error is rather low. For CoVadem, the filtering reduces the RSME from 41 to 30 centimetres. The averaged mean is -4 centimetres, which shows a generally 'save' image of the river bed level if measured by CoVadem.

For navigation in low water depths an error of 30 centimetres, with a standard deviation of 54 centimetres, is too high to rely on. So individual data is not reliable, however, combining the data over different grid cells might be a solution to this.

Vertical shift

One option to improve the accuracy of the CoVadem data is to apply to each vessel a correction for the water depth. This can be done if (1) there is a fixed layer in the riverbed, i.e. the bed level is constant in time, (2) the water level is available from a nearby water level gauge, i.e. the water level is accurately known, (3) the majority of the CoVadem fleet passes the location regularly, i.e. the correction factor can be recomputed every track (Cotteleer et al., no date).

We looked at whether the CoVadem data is similar to the multibeam data. Many shipping tracks show a constant shift (Figure 30). However, a lot of the trips do not pass the fixed layers of Nijmegen or Sint Andries, which would mean that these cannot be corrected and this would result in different treatment of the data or removing a lot of the data. Also, the shift is generally not constant in time and space (Figure 30). Also, shifts from previous trips cannot be used (Figure 31) and this is likely a result of the load measurement.

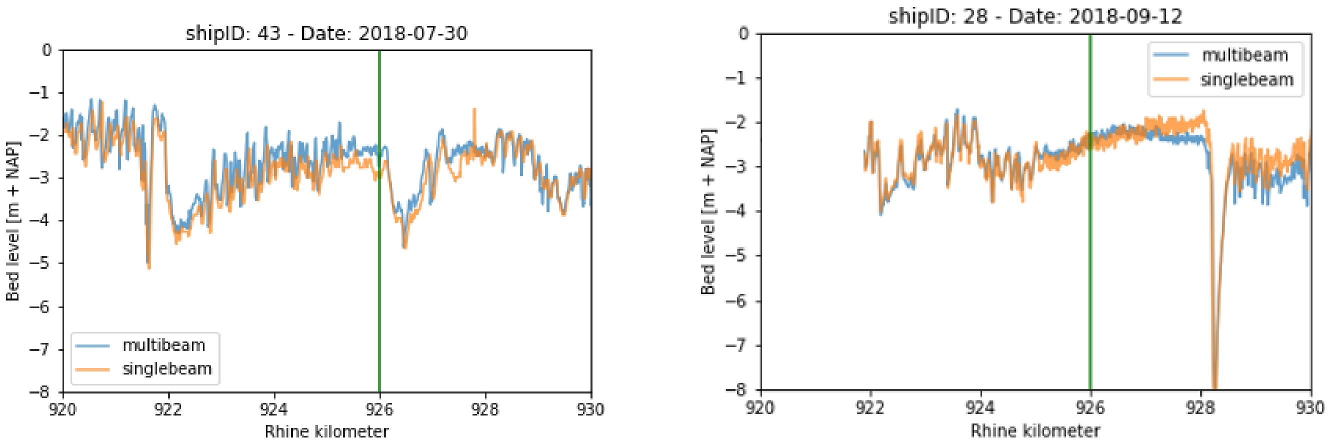

Figure 30: Singlebeam (CoVadem) bed level and corresponding multibeam bed level around the 'vaste laag' near St Andries of two different tracks.

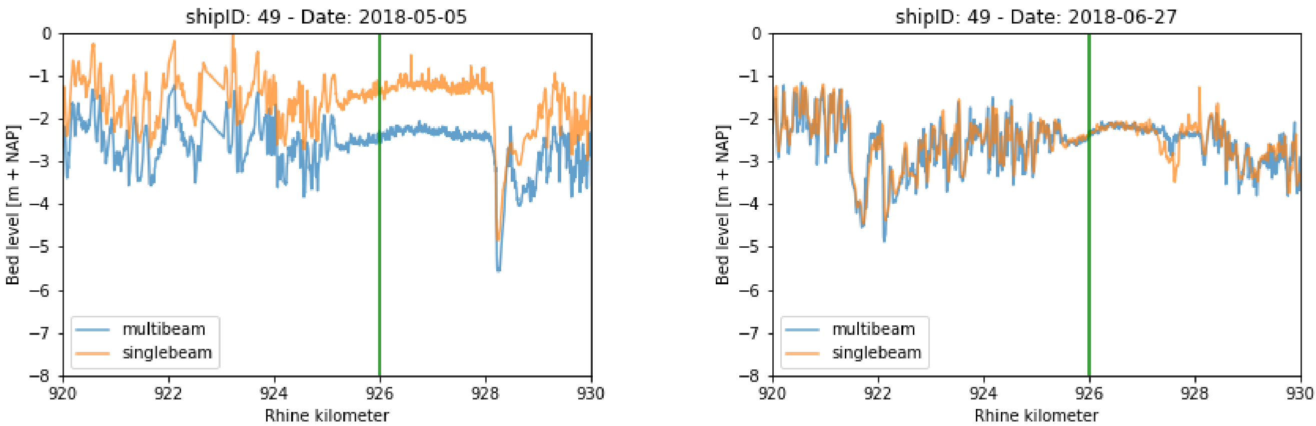

Figure 31: Singlebeam (CoVadem) bed level and corresponding multibeam bed level around the 'vaste laag' near St Andries of ship 49 on different days.

5 RESULTS: REPRODUCING MGD USING COVADEM

This chapter gives the result on how CoVadem can reproduce the MGD and how well CoVadem can do so. First, the procedure to retrieve the minimum water depth is presented (4.1) then the difference between the MGD and CoVadem is presented.

5.1 ASSIGNMENT OF MINIMUM WATER DEPTH

To retrieve the most accurate minimum water depth, first, the size of the grid cell is investigated. Too small results in too little CoVadem data in the cell and too big loses the value of location accuracy.

5.1.1 Grid cell size

The width of the grid cells is half of the river width. The river is split along the river axis, to make a difference between inner and outer bends (Figure 32). The length of the grid cell is mapped as the length of the river axis with a perpendicular line on this axis to the left and right of the river. The grid cells are therefore not all exactly the same size.

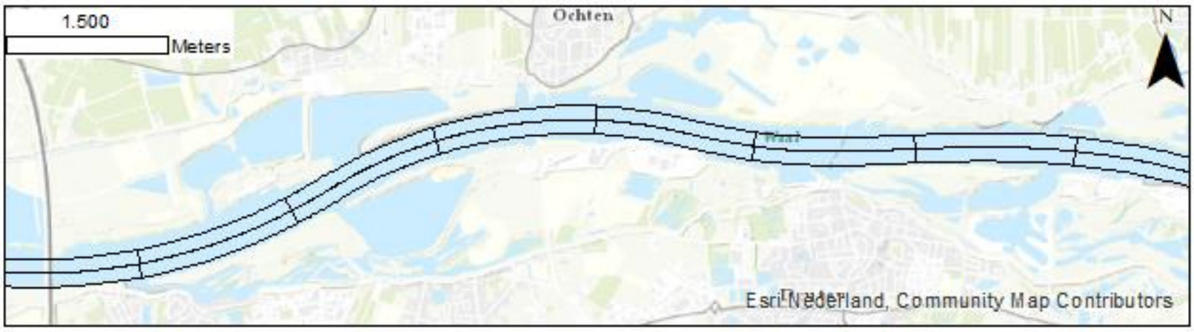

Figure 32: River section divided into grid cells. Cell numbering is from downstream to upstream with the right (south) even numbering and left (north) uneven numbering.

Table 3: Investigating the length of the grid cell

Cell length	Nr of cells without data	The median number of measurements (without zeros)	Nr of cells with more than 100 measurements
500 m	101	119	130
750 m	90	216	188
1000 m	79	244.5	193
1500 m	**65**	**351.0**	**227**
2000 m	56	524.0	252

We compare grid sizes from 500 metres to 2000 metres, based on the number of MGD cells without any CoVadem data, the median number of CoVadem measurements per MGD cell and the number of MGD cells with more than 100 CoVadem measurements. Since only the cells with more than 100 CoVadem measurements can be used, we chose a cell length of 1500 m(Table 3), since there are sufficient MGD points to analyse.

5.1.2 Filtering percentile

In Figure 33, the summary statistics of assigning a water depth for CoVadem data are shown. In general, there is a minimal RSME between the min and 95th percentile. By using this method of using only a percentage of the data to find the minimum water depth the "bad" data that was responsible for the large spread as a function of ShipID is filtered out. So, we chose to not select the shipIDs as in the previous chapter, but only filter out the Hdop values bigger than five. Based on the RSME we chose to use the 97th percentile. This corresponds with the method of Dierx (2018) which validated this method on 95th and 97th percentile.

An RSME of 59 centimetres with comparing CoVadem and MGD is in the same order of magnitude as the combined RSME of MGD versus multibeam (23 centimetres) and CoVadem versus multibeam (30 centimetres). Which means that the data is promising.

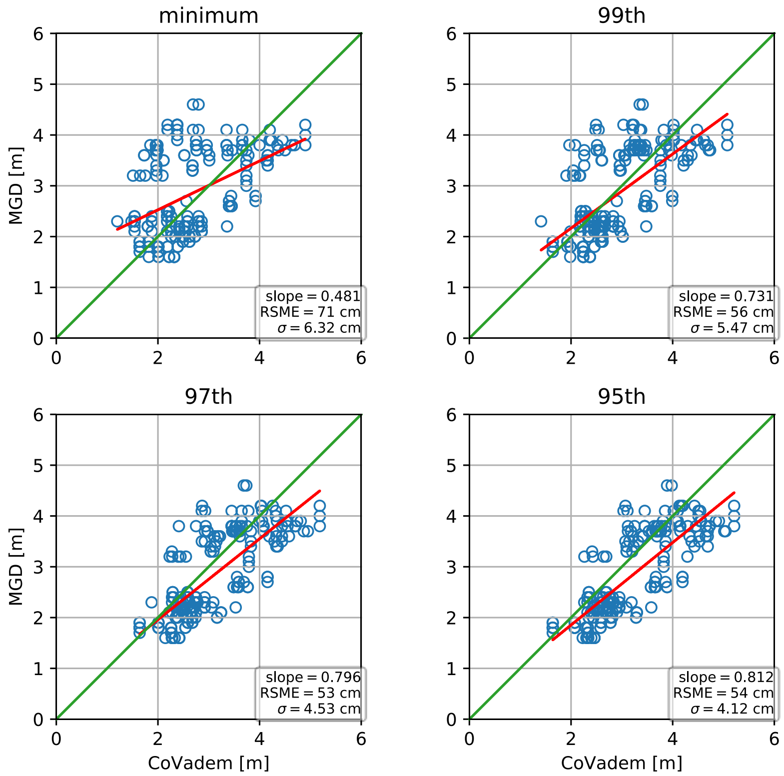

Figure 33: MGD water depth versus CoVadem water depth using different filtering methods without filtering based on shipID

5.2 DIFFERENCES MGD AND COVADEM

In this paragraph, the comparison between MGD and CoVadem is shown. For all MGDs in cells with more than a hundred CoVadem measurements on the CoVadem day and up to five days before the MGD measurement were included. This is 227 of the 335 MGD measurements.

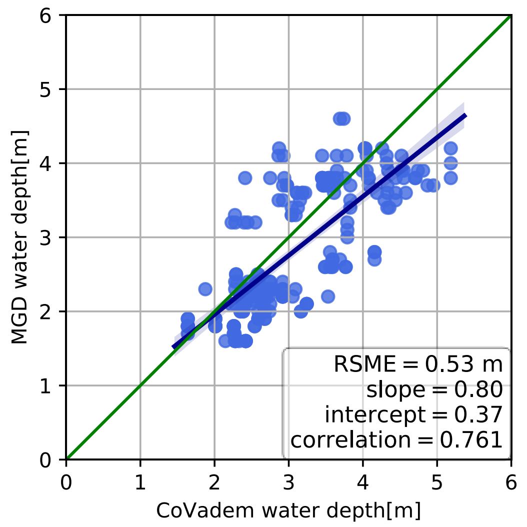

Figure 34: Scatter of CoVadem water depth versus MGD water depth with a grid length of 1500 metre and a filtering percentile of 97.

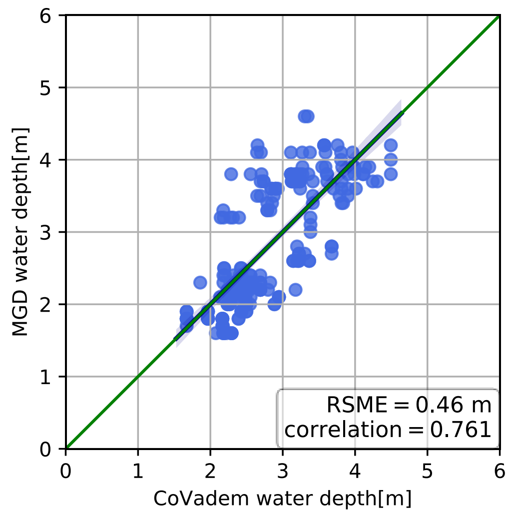

Figure 35: Scatter of CoVadem water depth versus MGD water depth with a grid length of 1500 metre and a filtering percentile of 97. With CoVadem data transposed over the linear fit

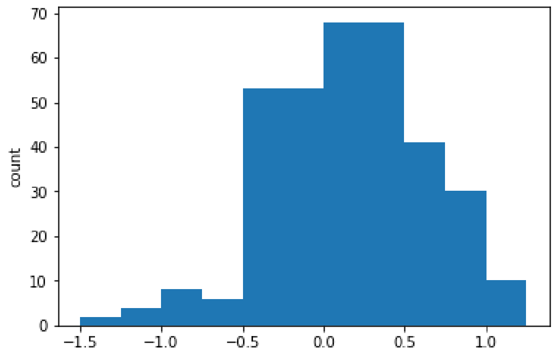

Figure 36: Difference in water depth CoVadem-MGD

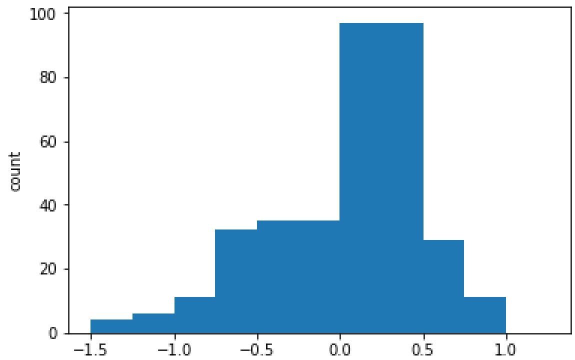

Figure 37: Difference in water depth CoVadem-MGD with correction

In Figure 34, the scatter and regression line of CoVadem water depth versus MGD water depth is shown. The regression line shows that there is a trend visible. A higher CoVadem water depth corresponds with a greater difference between the values. Therefore a correction is proposed to improve CoVadem values as shown in Equation (1). In the following figures, we will show both the uncorrected and corrected CoVadem data.

$$Corrected\ CoVadem\ water\ depth\ [m] = 0.366 + 0.796 * CoVadem\ water\ depth\ [m] \quad (1)$$

The difference between the CoVadem water depth and the MGD water depth varies as a function of MGD water depth (Figure 38, Figure 39 and Figure 40).

In Figure 39 the effect of the correction as proposed in Equation (1) is visible. It shows that for smaller MGDs the correction has a positive impact, and differences reduce. However, for the MGDs with larger water depth, the correction makes the difference between CoVadem and MGD only bigger. Figure 40 shows that by using only the days with an average discharge less than 1500 m^3/s the MGD's with higher water depths will not be taken into account. Because in this situation another correction will provide a better fit, this is not shown. However, from the correction as in Figure 39, we might conclude that the accuracy only increases.

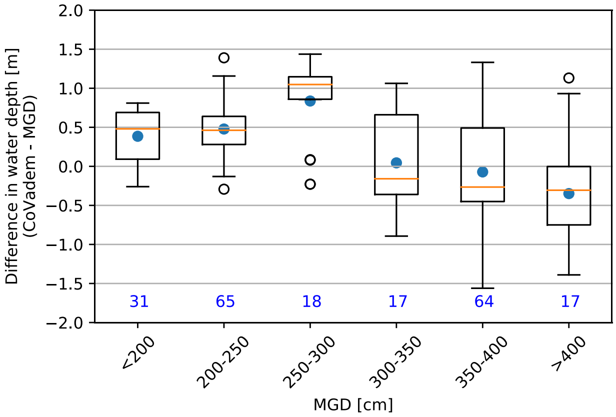

Figure 38: Difference in water depth CoVadem versus MGD per MGD value

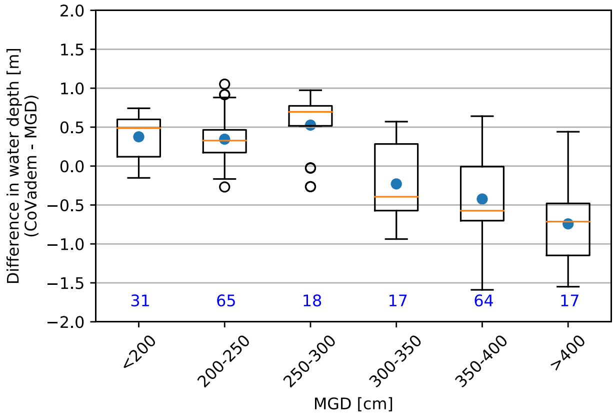

Figure 39: Difference in water depth CoVadem versus MGD per MGD value with correction

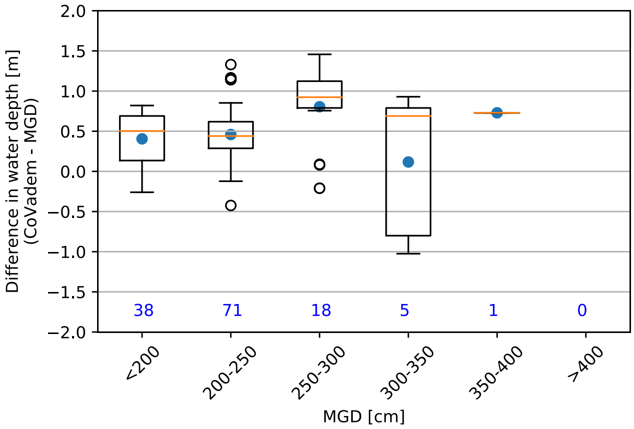

Figure 40: Difference in water depth CoVadem versus MGD per MGD value with correction with discharge smaller than 1500 m^3/s

These figures also show that the correction (Equation 1) changes this difference. It shows that for smaller MGDs, the correction has a positive impact, and differences reduce. However, for the MGDs with larger water depth, the correction makes the difference between CoVadem and MGD only bigger. This might be caused by the water level and the variability of that water level since the CoVadem water depth is not corrected for water level. We relate the water depth difference with the water level at Lobith. We relate each CoVadem datapoint with a daily-averaged water level at Lobith. In Figure 41 and Figure 42, the CoVadem water depth and the MGD water depth are shown as a function of the mean water level difference at Lobith, which is calculated as the difference between the mean water level at Lobith for all the CoVadem measurements in the cell and the water level at Lobith at the day of MGD measurement. This shows that indeed at the larger water depth also the variability of the water level at Lobith is larger. This suggests that the linear correction (Equation 1) could improve by taking into account the daily variation of the water level at Lobith. However, Figure 43 and Figure 44 show that a clear trend is missing.

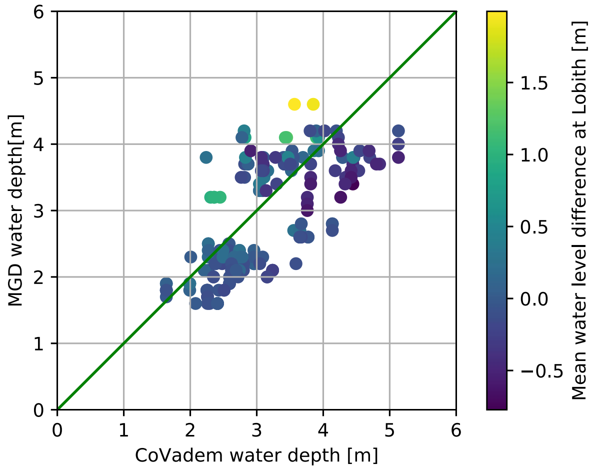

Figure 41: MGD water depth versus CoVadem water depth

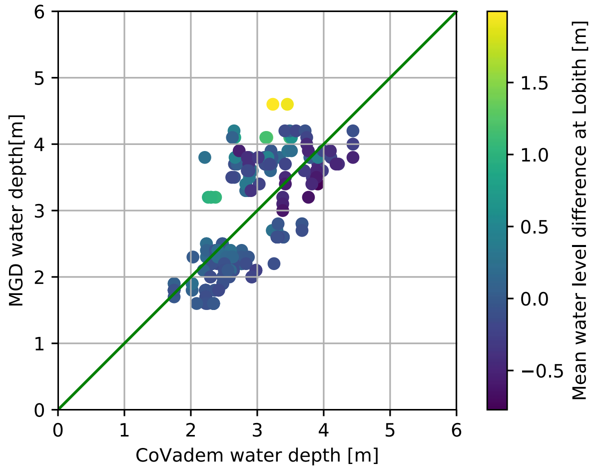

Figure 42: MGD water depth versus CoVadem water depth with correction.

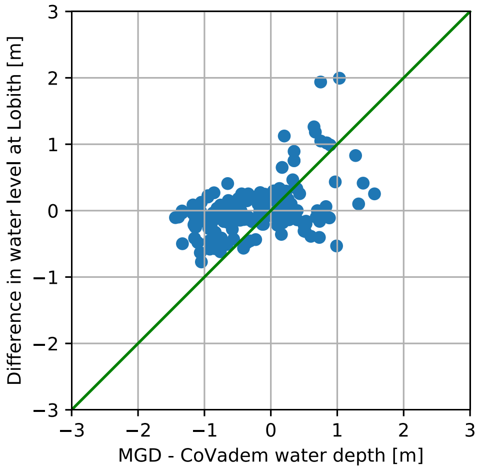

Figure 43: Difference in MGD and CoVadem water depth versus the difference in water level at Lobith. The correlation coefficient of -0.50

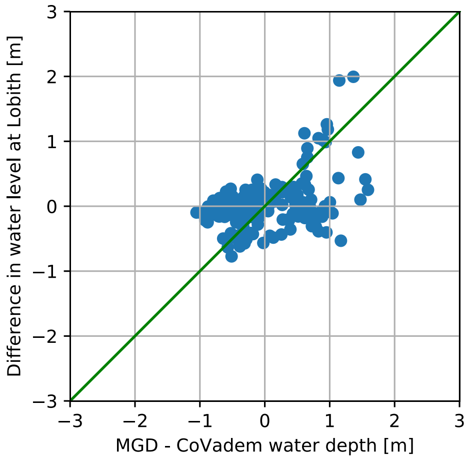

Figure 44: Difference in MGD and CoVadem water depth versus the difference in water level at Lobith with correction as in Equation (1). The correlation coefficient of -0.48

5.3 COMPARISON PER LOCATION

MGD is only measured in 14 different cells (Figure 45 and Figure 46), which means that the locations of the MGD do not vary much. In Figure 45 and Figure 46 the difference in water depth between CoVadem and MGD is visualised per cell where the MGD was measured. A clear separation between cell numbers lower than 60 (downstream Amsterdam-Rijnkanaal) and cell numbers higher than 60 (upstream Amsterdam-Rijnkanaal) is visible. The downstream MGDs are higher than the upstream MGDs. On average the downstream MGDs are underestimated by CoVadem and upstream MGDs are overestimated by CoVadem. If this is related to morphological changes then the linear correction relation could be improved by taking into account the river kilometre. However, an explanation could be that skippers know the bottlenecks at Nijmegen and Erlecom with low water levels. And they sail around the MGD location. In Figure 47 this phenomenon can be recognised.

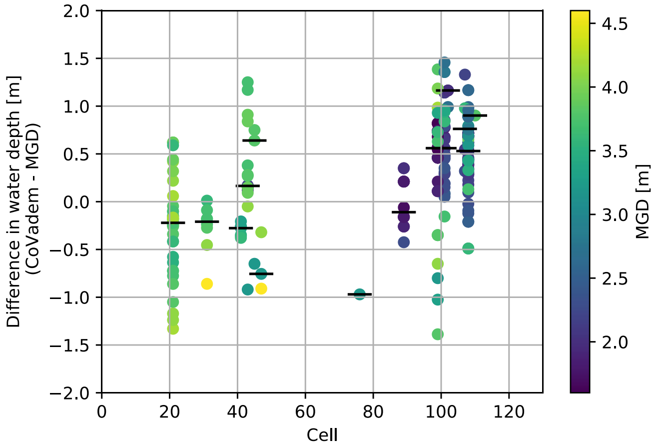

Figure 45: Difference in water depth CoVadem versus MGD per MGD location.

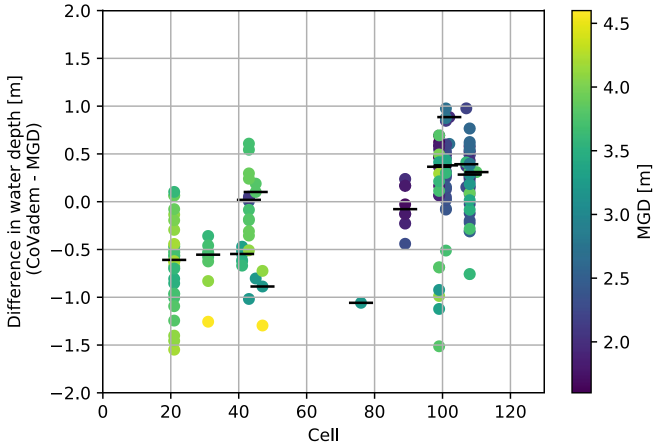

Figure 46: Difference in water depth CoVadem versus MGD per MGD location.

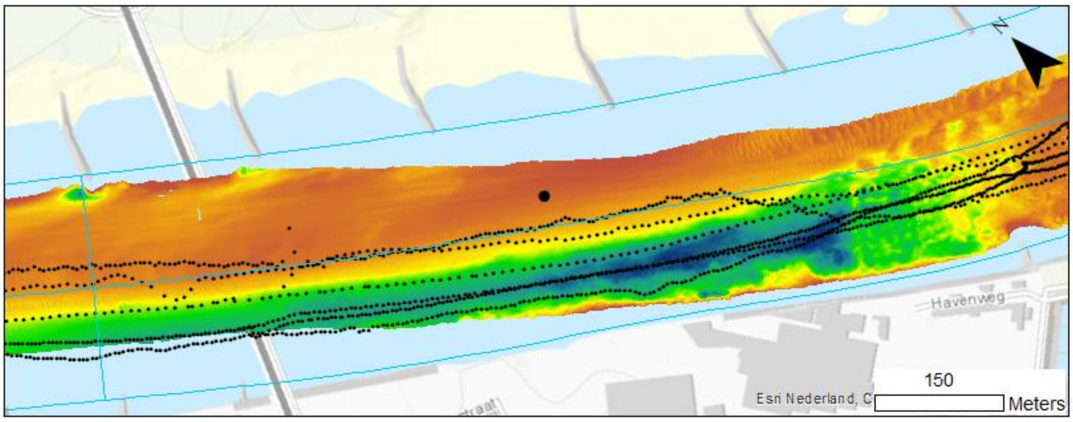

Figure 47: 27 September MGD (bigger point) and CoVadem (smaller points) data downstream the fixed layer at Nijmegen at Rhine Kilometre 885 with an MGD value of 230 cm

5.4 Conclusion/discussion

The difference between MGD and CoVadem water depths result in a Root Mean Square error of 53 without correction and 48 centimetres with a linear correction. Considering the RMSE of both datasets compared with multibeam of 23 centimetres (MGD) and 30 centimetres (CoVadem), this difference is within the added errors.

In the comparison of CoVadem and MGD, CoVadem data up to five days before the MGD measurement are taken. However, no correction for the water level change is performed, which at Lobith can be up to 1.5 meters. In Figure 48 and Figure 49 the relation between the difference in water depth and the difference in water level is shown. This disproves a clear change in accuracy due to the changes in water level. However, we suggest that this needs more attention in future research.

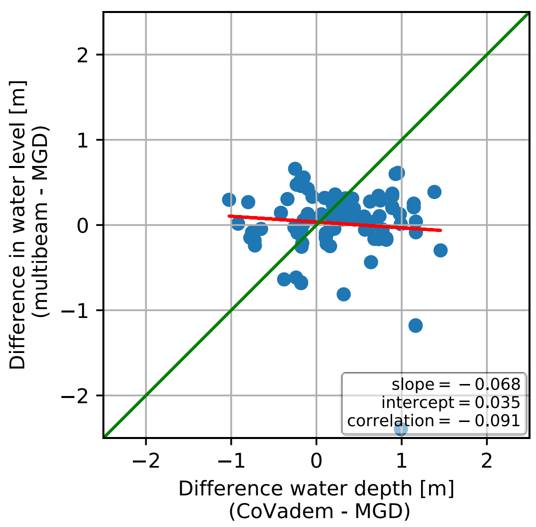

Figure 48: No relation between accuracy relative to multibeam and comparison MGD/CoVadem

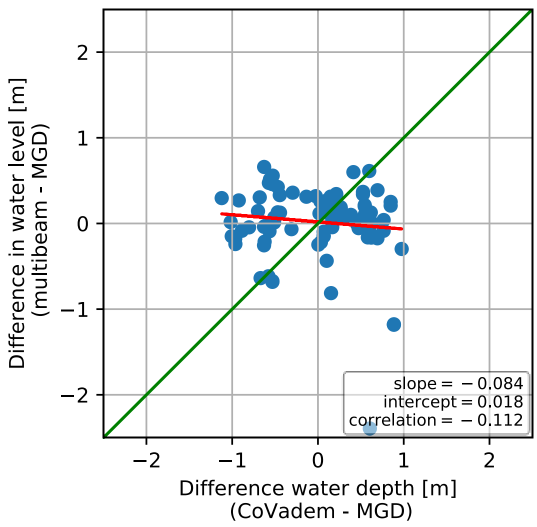

Figure 49: No relation between accuracy relative to multibeam and comparison MGD/CoVadem with correction

6 RESULTS: PUBLISHING SHALLOWEST LOCATION

This chapter focusses on how CoVadem data can contribute to publishing the shallowest location of the river Waal. Therefore subsequently the locations of the MGD are analysed (5.1), other shallow locations are investigated (5.2) and recommendations on implementing CoVadem are given (5.3).

Locations MGD

Locations of MGD are present on locations with two types of bedforms. Dunes that move downstream with stochastically varying dimensions and velocities and fixed structures at the site of structures like fixed layers and groynes or transitions in soil composition like varying gravel plaster, partially covering clay and peat layers. Only at one MGD in 2018, a clear image of a dune can be distinguished (Appendix C). During low water levels, it seems that dunes are not the main cause for MGDs.

Determining the MGD from CoVadem data is difficult because skippers navigate around shallow areas. There is limited coverage of shallow areas and therefore, we use large grid cells to have sufficient data within a cell.

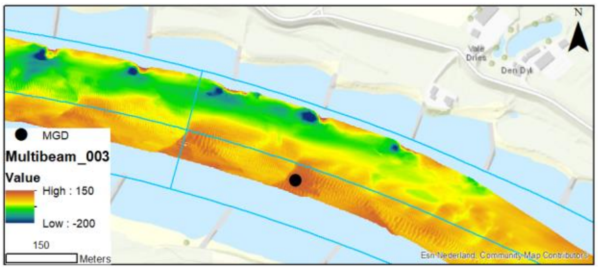

Figure 50: MGD with 320 centimetres water depth measured 7 December 2018 near Wolferen at Rhine Kilometre 896. Multibeam data in cm + NAP.

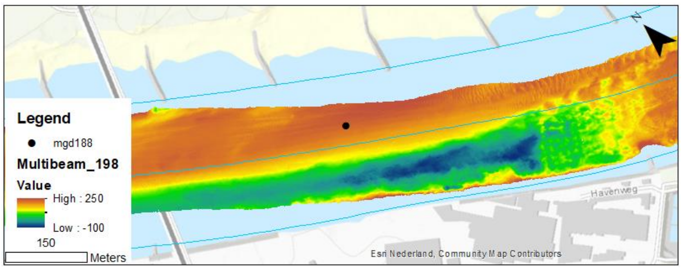

Figure 51: MGD with 230 centimetres water depth measured 28 September 2018 after the fixed layer near Nijmegen at Rhine Kilometre 885. Multibeam data in cm + NAP.

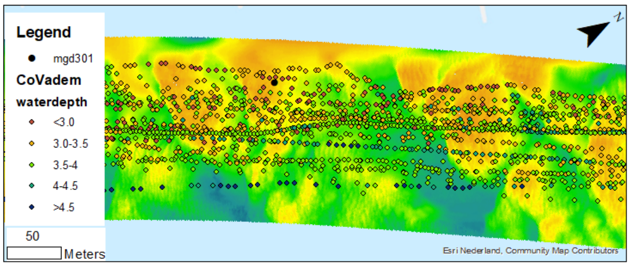

Figure 52: MGD with 320 centimetres water depth measured at 3 December 2018 near Passewaaij at Rhine Kilometre 917 with the CoVadem data included.

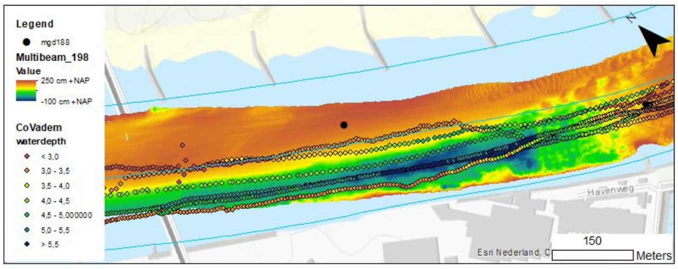

Figure 53: MGD with 230 centimetres water depth measured 27 September after the fixed layer near Nijmegen at Rhine Kilometre 885 with the CoVadem data included. Also a known location for 'continuous' dredging.

In Figure 54 at four different locations, the water depths from May to December 2018 according to CoVadem are shown. From this figure can be concluded that generally, the CoVadem water depth follows the same trend as the MGD water depth. At some locations, for example in cell 68 near Druten, no MGD is measured, but the water depth drops below the MGD water depth on that day. In cell 21, near Haaften, the MGD was measured very often in the months May and June. However, according to CoVadem, the water depths were even lower than the MGD. From this figure, we can conclude that CoVadem might give a good indication of the water depth and location, but we cannot rely on the exact values. These graphs were made without a correction on the CoVadem data that generally overestimates the water depth relatively to the MGD.

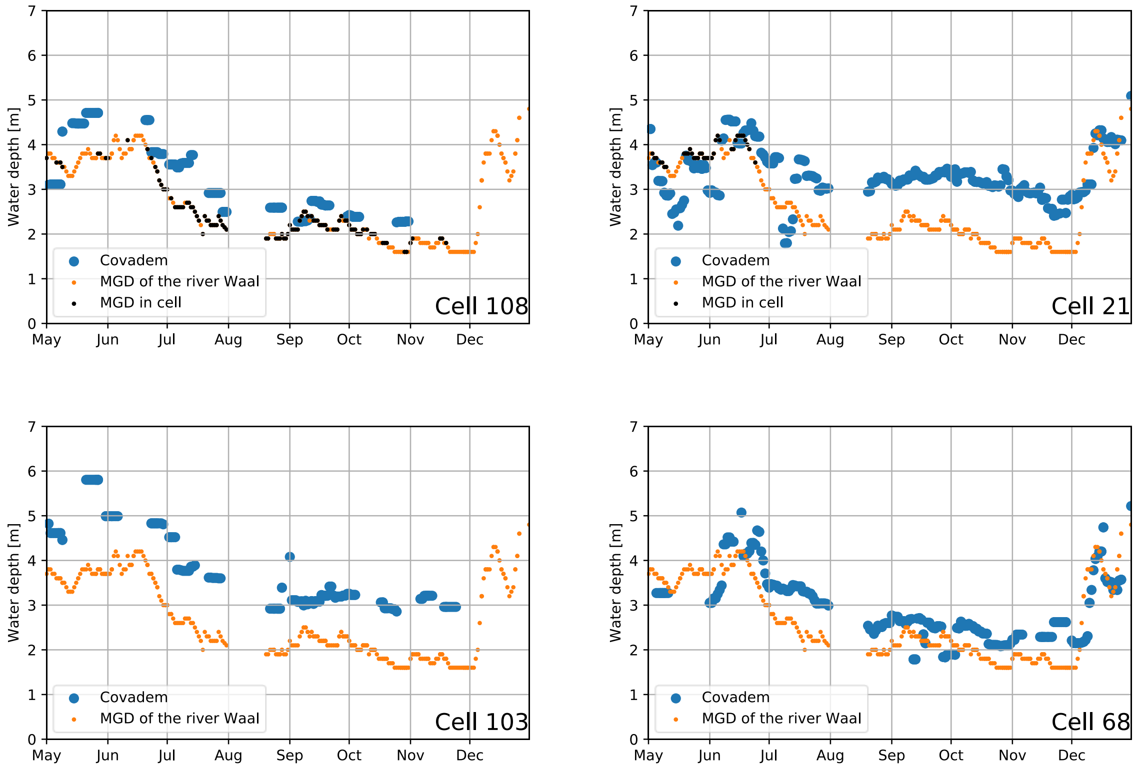

Figure 54: CoVadem water depths per cell from May to December 2018 (blue), the orange points are the MGD water depths on that day, but not at that location. The black points are MGD water depth if that MGD is located in that cell. Cell 108: Hulhuizen, Cell 21: Haaften, Cell 103: inner bend Erlecom, Cell 68: Druten.

In Figure 55 all MGD locations with their occurrence in 2018 are shown. CoVadem can inform their shippers with these locations and emphasise that especially around these areas the measurements are really important.

Figure 55: MGD locations in 2018 and their occurrence

Shallow water at other locations

There are only 9 locations divided over 14 cells where the MGD was measured. And since Rijkswaterstaat does not measure the whole length of the river, but only the locations known for being shallow, this is not surprising. Here, we analyse whether this is likely that Rijkswaterstaat missed shallow water locations. Therefore, we compared each MGD with the CoVadem water depths for each cell with more than 100 measurements. This resulted in figures for each MGD as in Figure 56. We highlighted four different MGDs to show great variability in outcome. The top figures show the point at which the MGD location was according to CoVadem data likely to be the shallowest water level. In Figure 56a the MGD location is the lowest water depth. In Figure 56b the MGD occurs at two separate locations. In Figure 56c and d, the location of the MGD is not the location with the shallowest water according to CoVadem. Figure 56c shows the smallest water depth at a different location. Figure 56d shows that the water depth is at other locations smaller than the MGD.

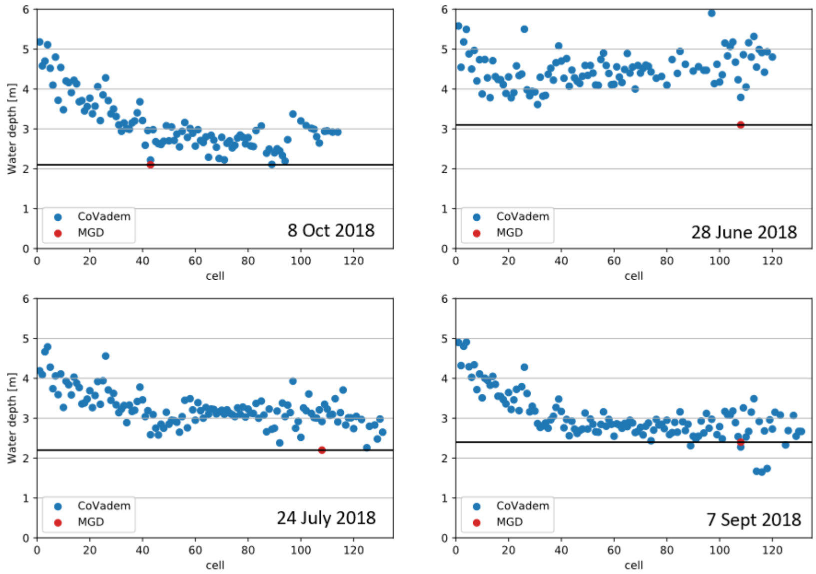

Figure 56: Water depth CoVadem per cell (blue) and MGD water depth with the location (red). Cell is the location in the river. WIth downstream cell 1 and upstream cell 132.

In Figure 57 the minimum water depth per cell from May to December 2018 are shown. From this graph, it can be concluded that MGD detects the same critical locations as CoVadem, and additional it shows shallow locations further upstream Sint Andries (cell 35) and near Lobith (cell 132).

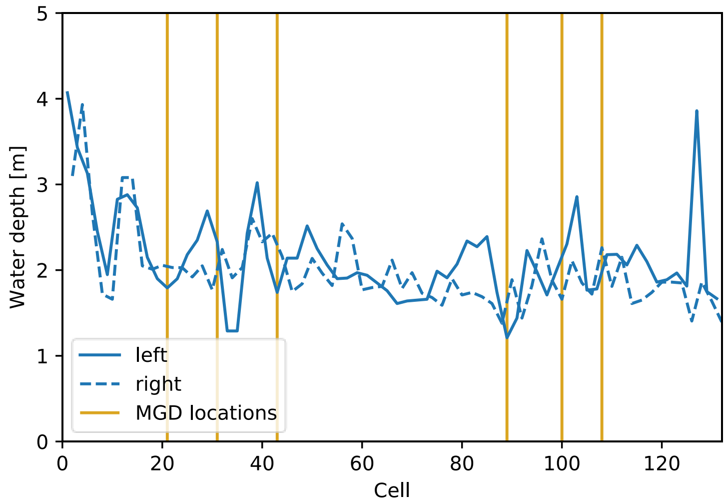

Figure 57: Minimum CoVadem water depth per cell. The dashed line corresponds to the left side of the river (in flow direction) and the solid line corresponds to the right side of the river. The vertical lines are from left to right: Haaften (cell 21), Sint Andries (31) Dreumel (43), Nijmegen(89), Erlecom(101), Hulhuizen (108) Cell 1 is Loevestein and cell 132 in Germany, upstream Lobith

6.1 CONCLUSION/DISCUSSION

As we concluded from Chapter 4, we cannot increase the accuracy of MGD using individual CoVadem measurements. Combining data as shown in Chapter 5, is promising, however, in this stage still too scattered. However, CoVadem can help to determine the locations at which MGDs will occur. CoVadem can still become a useful tool for Rijkswaterstaat in addition to their measurements.

7 DISCUSSION

We will discuss the following topics in this chapter: the scope of this research, the method on defining the accuracy of the MGD and CoVadem water depth, the comparison of CoVadem with MGD and the research limitations.

7.1 SCOPE

In this research we only focussed on the Waal, however, there are more MGD trajectories in the Netherlands and in (almost) every river or canal where vessels navigate, the water depth is important. This research could be repeated on other trajectories. Thereby the variability of the bed is an important factor on how many days of CoVadem data can be used. Also, high coverage is essential for accurate research in other waters.

Thereby, we did not include the legal aspect of the MGD. So considering CoVadem data would improve, it still might not be possible to substitute CoVadem data for MGD measurements for legal reasons. And finally, we used CoVadem data from 2018, and CoVadem is working very hard to increase the accuracy of the data, for example by investigating the vertical shift and investigating the squat calculations. Research with more recent data should show whether accuracy has indeed improved.

Thereby can CoVadem to get insight into the speed of changes of the river bed. Now we only looked at water depth. But this can easily be translated to bed level to be able to detect sanding or moving bedforms.

7.2 ACCURACY MGD AND COVADEM WATER DEPTH

To analyse the accuracy of MGD and CoVadem data, we compared each dataset with multibeam data. We chose to use 5 days of multibeam data before the CoVadem and MGD. This was done because this amount of data was still manageable regarding computing time and computer space. Using fewer days would mean that a changing bed would have less effect on the outcome, however, would also mean fewer data to work with. Using more days would mean more effect of the changing bed in the outcome, but also more data to look at. However, this would probably not improve the accuracy if we only look at low discharges.

One option to improve the accuracy of the CoVadem data is to apply to each vessel a correction for the water depth as explained in Section 4.3. This was not included in this research but is worth investigating. Besides, the downward trend in the difference between CoVadem and multibeam data over the length of the river should be investigated. Furthermore can improve the accuracy of CoVadem data be found in the factors mentioned in the theoretical accuracy in paragraph 3.1 and Appendix A. Especially, squat, which is a calculated value might be worth looking into. Thereby, also multibeam measurements can contain errors, especially in dredging areas, which will remain an error in analysing the accuracy based on multibeam data.

7.3 COMPARISON COVADEM AND MGD

In the comparison of CoVadem and MGD we imposed a linear correction for both data sets. However when the maximum discharge is different or even another year with different conditions, this relation would likely not hold. Therefore, more research is needed to impose such a correction, because CoVadem vessels navigate around the shallowest areas.

For this comparison, the water depths are compared since that is the value we want to know and to eliminate the inaccuracies of water level determination. However, comparing bed levels also might have benefits because the bed level does not change as fast as the water depth during low discharge conditions.

Besides, the width of the cell was probably too big since also ships who were navigating around the small water depth were included in the data, which results in an inaccurate image of the low water depth. However, sizing down the cell width would also result in fewer data per cell. Also, the MGD at near Haaften at Rhine Kilometre 937 is influenced by the tide, comparing water depths over a whole day automatically a misunderstanding of the situation.

Also, the MGD locations regularly dredged. And it is not clear where and when this took place. Therefore it might be that the measurements are correct, however, dredging took place in between the measurements. And since it is not possible to measure MGD and CoVadem at the same place and time, this problem is not easily solved. More research and insight in dredging the river Waal is needed to investigate the consequences of dredging in the comparison between MGD and CoVadem.

7.4 High discharges

In this research, we investigated the period from May to December 2018. In this period the average water level was 1300 m^3/s with a maximum of 3430 m^3/s. The highest discharge corresponding with an MGD was 2590 m^3/s (Figure 58). However, this MGD is still larger than the 350 cm at which the MGD is published. In Appendix D the effect of using a maximum discharge for the comparison between CoVadem and MGD is shown and shows that the difference between MGD and CoVadem decreases when we use a smaller maximum discharge.

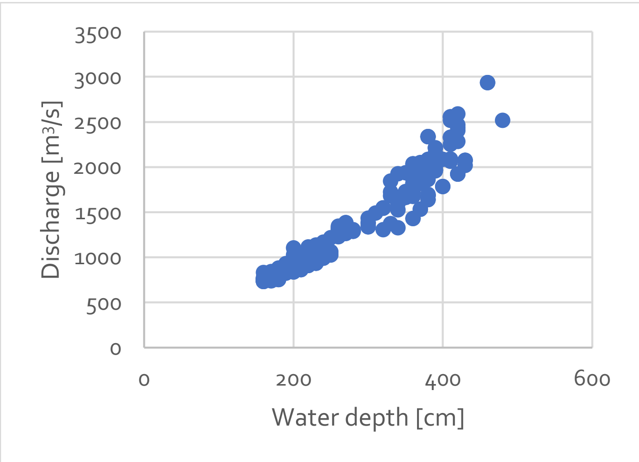

Figure 58: MGD water depth versus discharge

8 CONCLUSION AND RECOMMENDATIONS

8.1 CONCLUSION RESEARCH QUESTIONS

The goal of this research was to investigate how the use of CoVadem data can increase the value of the MGD provided by Rijkswaterstaat to make shipping more efficient during low water periods.

For this goal, first, the accuracy of both datasets was analysed, by comparing the bed levels retrieved from MGD and CoVadem water depths with multibeam bed levels. The accuracy as expressed in Root Mean Square Error (RMSE) of MGD is 23 centimetres and the RMSE of CoVadem data is reduced from 41 centimetres to 30 centimetres by filtering on the horizontal dilution of precision (Hdop) given by the GPS systems and ships with a high spread in the difference between bed levels. The dependency of this accuracy was the biggest on the discharge and water depth, with higher water depths and larger discharges the spread in differences increases. By using a maximum discharge of 1500 m^3/s the RSME is reduced to 34 centimetres and with filtering 22 centimetres. This makes CoVadem accuracy similar to the MGD accuracy and therefore promising to complement.

Due to the large error in both datasets comparing both was difficult. However, the error between the MGD and CoVadem was with an RMSE of 53 centimetres in the same order of magnitude. By putting linear correction RSME reduced to 48 centimetres, but analysing on different factors, linear may not be the best fit. To be able to draft proper conclusions from a comparison first, the accuracy of the data must be tackled.

The location of the shallow water is important for inland shipping since a lot of vessels might not pass the critical location. Therefore the locations of the MGD were analysed. It turned out that dunes or other moving bedforms do not tend to cause shallowest water depth, but the known locations in the inner bend (after a fixed layer) or locations that are known for aggrading after high water levels were the locations where the MGD was found. Looking for other locations missed by Rijkswaterstaat in their search for the MGD, was not doable because of the inaccuracies in the data.

Concluding, CoVadem can increase the value of the MGD by foreseeing trends, however, the quality of the data at this stage not accurate enough be able to replace the MGD measurements, and the question remains if it will ever be. However, this was also not the goal and the potential of the CoVadem data is big, but coverage should be higher.

8.2 RECOMMENDATIONS FOR FURTHER RESEARCH

Since this research shows there is great potential in using CoVadem to detect small water depths, we propose future research on this topic. We propose to focus on the following research directions. (a) Analyse the bed level changes with small discharges. If more is known of the variability during low water levels, better decisions can be made on how many numbers of days the CoVadem data holds accurate information. Adding the water level changes to the CoVadem data might and using data from more days, could result in smaller grid cells lengths and more accurate water depths. (b) A comparison with a smaller width of the grid cells, or different shape. This can be done to be able to localise the small water depths even more precise, so the vessel could sail around the smallest water depth. (c) And the most important proposal for future is to minimise inaccuracies both the MGD and CoVadem data. The vertical shift as discussed in paragraph 4.3 for CoVadem data and the procedure of measuring MGD are the first things to take a look at.

9 REFERENCES

About CoVadem (2018) *CoVadem*. Available at: https://www.covadem.org/over/ (Accessed: 23 January 2019).

Best, J. (2005) 'The fluid dynamics of river dunes: A review and some future research directions', *Journal of Geophysical Research: Earth Surface*, 110(4), pp. 1–21. doi: 10.1029/2004JF000218.

Bons, A. *et al.* (2014) 'EconomyPlanner ; optimal use of inland waterways', in *European Inland Waterway Navigation Conference*.

Cotteleer, A. *et al.* (2017) *Real-time validation of CoVadem derived water depths at locations with a fixated riverbed*. Hydro 2017

Dierx, R. (2018) *Validating a 2D water depth chart for cooperative water depth measurement*. Bachelor Thesis University of Twente

Giri, S.; Van Vuren, S.; Ottevanger, W.; Sloff, K. A Preliminary Analysis of Bedform Evolution in the Waal during 2002–2003 Flood Event Using Delft3D. In Marine and River Dune Dynamics

Hetzer, S. (2005). Navigability of the river Waal. Ms. Thesis report, Universität Stuttgart

Jyothirmaye, S., Srinivas, V. S. and Ramu, B. (2019) 'Fast Satellit Selection Techniques and DOPs for Multi-GNSS Positioning', in *URSI AP-RASC*. New Delhi, India.

Klaassen, G.J. and Sloff, C.J. (2000). *Voorspelling bodemverlaging en herstelrelaties voor baggeren op de Waal, Eenvoudige relaties en benodigd onderzoek*, rapport Q2669, WL, Delft Hydraulics

Lange, I. de and Waterval, D. (2018) 'No Title', *Trouw*, 18 October. Available at: https://www.trouw.nl/home/laagwatermalaise-voor-een-lading-die-ik-normaal-in-een-schip-stop-heb-ik-er-nu-drie-nodig-~a5951cb7/.

Lokin, L., Warmink, J., and Hulscher, S.: River dunes under extreme high and low flows: outline of a research project, EGU General Assembly 2020, Online, 4–8 May 2020, EGU2020-9998, https://doi.org/10.5194/egusphere-egu2020-9998, 2020

Van Broekhoven, R.W.A. (2007), *Het effect van kribverlaging op de afvoercapaciteit van de Waal ten tijde van hoog water,* Ms. Thesis report, TU Delft

Van der Mark, C. F., Vijverberg, T. and Ottevanger, W. (2015) 'Validation of Actual Depth Measurements by Inland Vessels', in *Pianc - The World Association for Waterborne Transport Infrastructure*, pp. 1–5. Available at: www.pianc.org.ar/sr2015.

Meulen, D. van der (2018) *RWS peilt tijdelijk drie MGD's tussen Millingen en Loevestein*, *Schuttevaer*. Available at: https://www.schuttevaer.nl/nieuws/havens-en-vaarwegen/nid29375-rws-peilt-tijdelijk-drie-mgds-tussen-millingen-en-loevestein.html (Accessed: 28 March 2019).

Niesten, I. and Van der Mark, C. F. (2020) *Vervolgonderzoek meerwaarde CoVadem-meetgegevens in het havengebied Rotterdam*. Deltares, Delft

Rura-Arnhem (2019) *Betrekkingslijnen Rijntakken versie 2018*. Rijkswaterstaat Oost-Nederland

Staatscourant (1997) 'Bekendmaking aan de Rijnscheepvaart', p. 30.

Tönis, R. (2017) *Advies Baggeren en terugstorten sediment Boven-Rijn, Waal, Pannerdensch Kanaal - en Nederrijn-Lek voor PC-NAT 2019-2026*.

Wiegmann, N. (2002) *Onderzoek naar het verschil tussen multibeam / singlebeam op de rivieren*.

ministerie van Verkeer en Waterstaat

Wilbers, A. and Brinke, W. ten, (2003) 'The response of subaqueous dunes to floods in sand and gravel bed reaches of the Dutch Rhine', *Sedimentology*, pp. 1013–1034. doi: 10.1046/j.1365-3091.2003.00585.x.

Wilbers, A. (2004) 'The development and hydraulic roughness of subaqueous dunes', Netherlands Geographical Studies 323, ISSN 016-4839, 227, PhD Universiteit Utrecht

Appendix A: THEORETICAL ACCURACY ECHO SOUNDING

In this chapter, the theoretical accuracy of singlebeam and multibeam echo sounding is presented. First, the global theoretical accuracy is described (A.1), then the details per dataset are explained (A.2, A.3, A.4).

A.1 THEORETICAL ACCURACY

Both MGD and CoVadem data are collected using a singlebeam echo sounder, measuring water depth. The multibeam maintenance sounding (MMS) data is collected using a multibeam echo sounder with an RTK positioning, which means that the vertical location is included in the measurement.

In measuring depth, the sources of error can be divided into horizontal (x,y) errors and vertical (z) errors. Both errors, however, result in a vertical error (Table 1). As a result of a horizontal error, a depth is registered in an incorrect position. Which presents itself as a vertical error.

Because vessels only measure the under keel clearance, the distance between the keel and the waterline must be added to obtain water depth (Figure 1). By using the water level as a vertical reference, besides precision in the water level model also heave, draft and squat have a major influence on the calculated water depth and/or bed level. Other sources of error can be the beam angle and the propagation speed of sound through water.

Table 1: Correction table for sounding systems. Values are minimum and maximum values. (Wiegmann, 2002)

		Singlebeam with water depth	**Multibeam with RTK position**
	Source of error		
Location	Influence of the location error measuring on a slope	5 to 10 cm (+/-)	1 to 2 cm (+/-)
Vessel's geometry	Squat	0 to 35 cm (-)	n / a
	Heave	0 to 40 cm (+/-)	n / a
	Draft	0 to 5 cm (+/-)	n / a
	Roll & Pitch	0 to 5 cm (+/-)	0 to 15 cm (+/-)
Reference	Water level as vertical reference	0 to 20 cm (+/-)	n / a
Sounding	Speed of sound	0 to 10 cm (+/-)	0 to 40 cm (+/-)
	Bundle angle	0 to 2 cm (-)	0 to 1 cm (-)

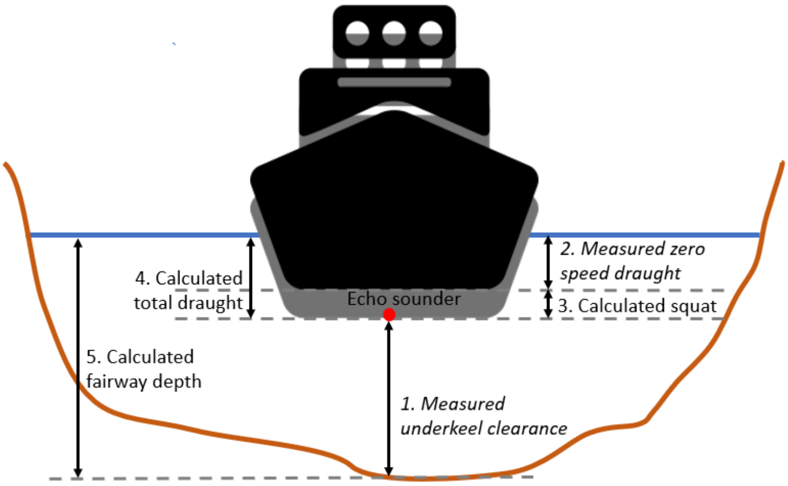

Figure 1: Components of calculated fairway depth (black ship: static vessel; grey ship: moving vessel)

A.1.1 Location

The error causes by location can have two causes. (1) The error caused by the used GPS. In the CoVadem data, a Hdop value is available, which qualitatively describes the error caused by the relative position of GPS satellites. (2) The error caused by a different position of the GPS and the echo sounder (Figure 2).The quantification in the error for different vessel geometries are shown in Figure 3.

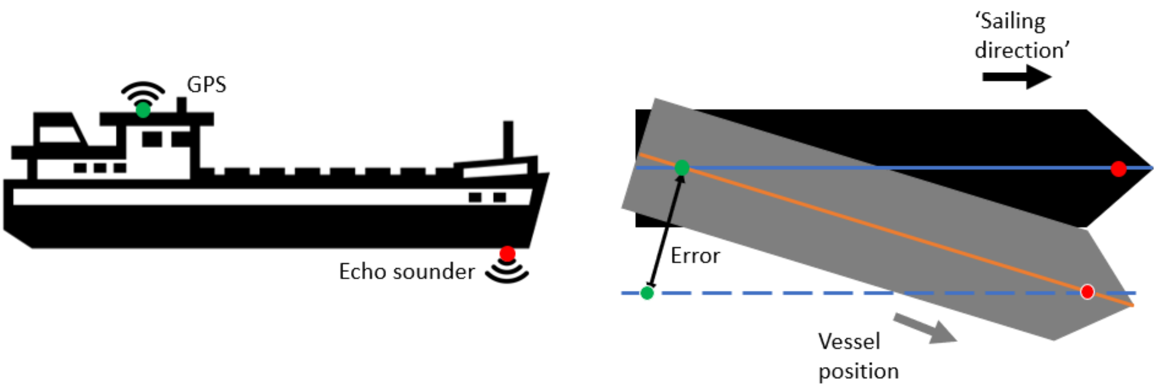

Figure 2: Error caused by the different position of GPS and echo sounder

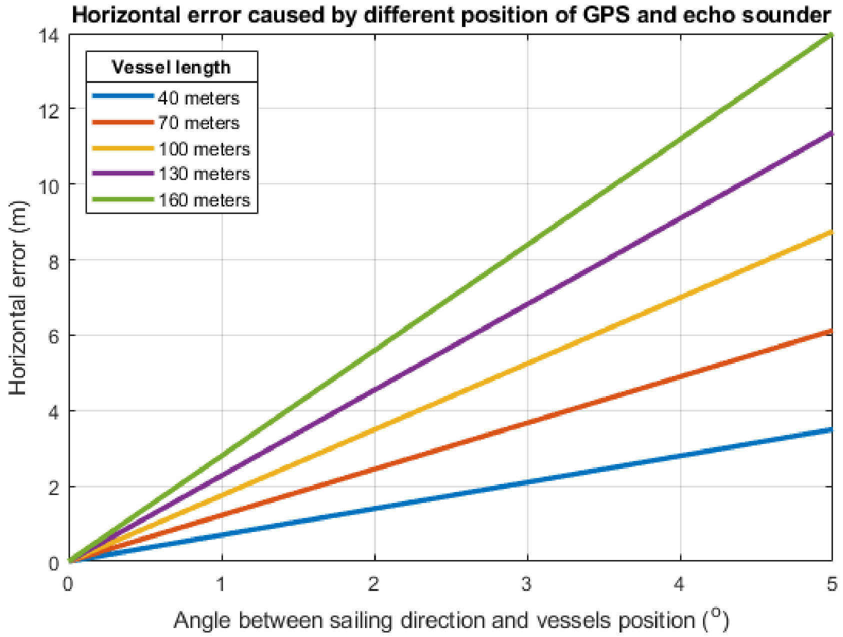

Figure 3: Horizontal error caused by the different position of GPS and echo sounder based the vessel's length and the angle between the 'sailing direction' and the vessel's position

A.1.2 Vessels geometry

Squat

The squat is the increased draught due to the flow of water past the ship hull (Figure 4). The forward speed of the ship pushes the water in front ahead. This water must return at the sides and below the ship. This water motion induces a relative velocity between the ship and the surrounding water that causes a change along with the ship similar to the Bernoulli effect. This phenomenon produces a downward vertical force (sinkage) and a moment about the transverse axis (trim) that can result in different values of the squat at the front and end of the vessel. The combination of sinkage and change in trim is called squat (Ankudinov et al., 1996). From Figure 5 it is clear that the lower the sounded depth the deeper the sinkage and the higher the speed the deeper the sinkage.

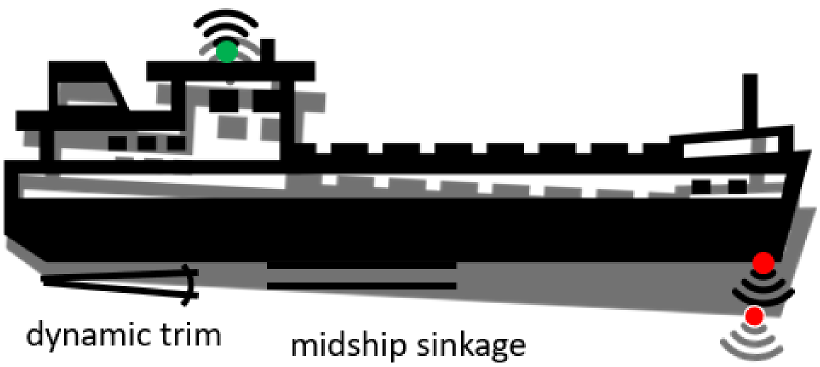

Figure 4: Squat is the combination of dynamic trim and midship sinkage

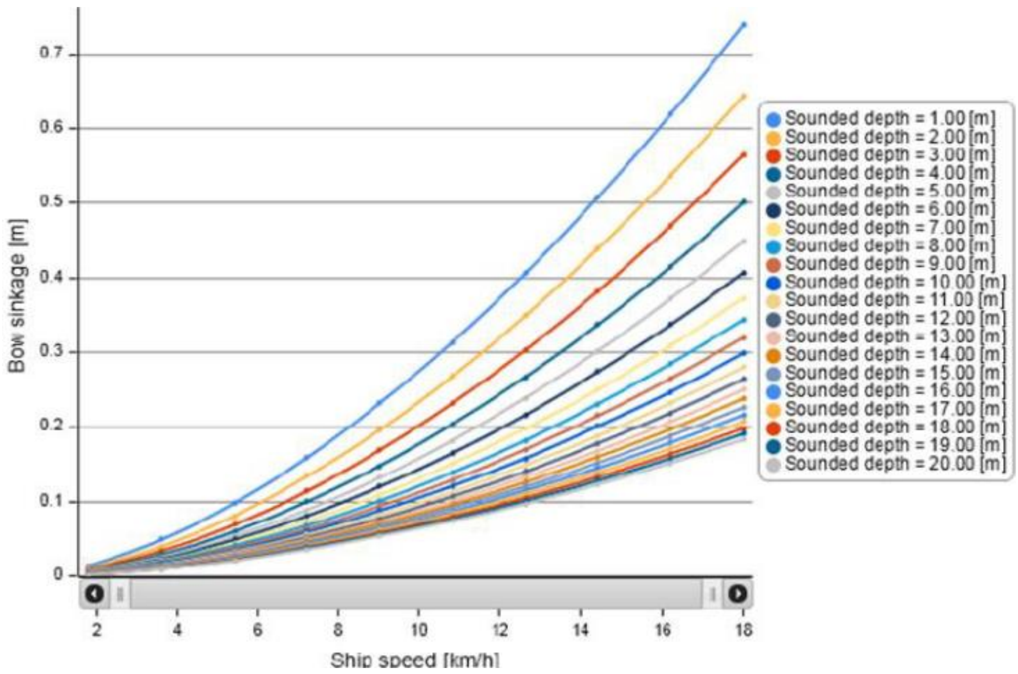

Figure 5: Bow sinkage for constant sounded depth (Bons *et al.*, 2014).

Water level model and heave

Heave usually causes a considerably varying depth of the vessel and thereby the zero point of the echo sounder relative to the water surface (Figure 6). Influences that can cause this deviation with the water level model are wind, varying river discharge, change in the flow profile, and other shipping (Venhorst, 2002). Heave is very difficult to estimate and is afterwards poorly reproducible, so correction afterwards is not possible. In Figure 7 the longitudinal gradient of a section of the river Waal is presented. The blue line shows the height in NAP as obtained from an RTK-dGPS, which not only measures the location but also the height. It can be seen that the actual water level isn't a smooth line. Compared to the interpolation based on different measuring stations, deviations occur.

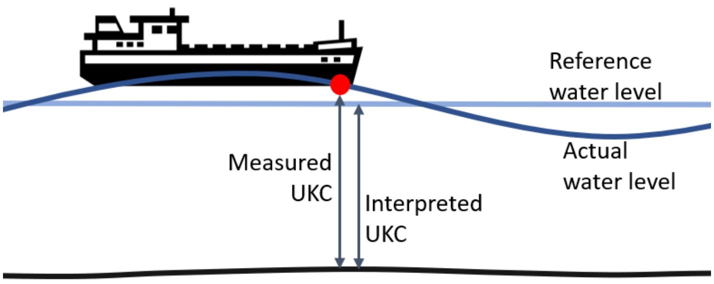

Figure 6: Heave is the difference between measured and interpreted UKC. In this example, water depth is overestimated.

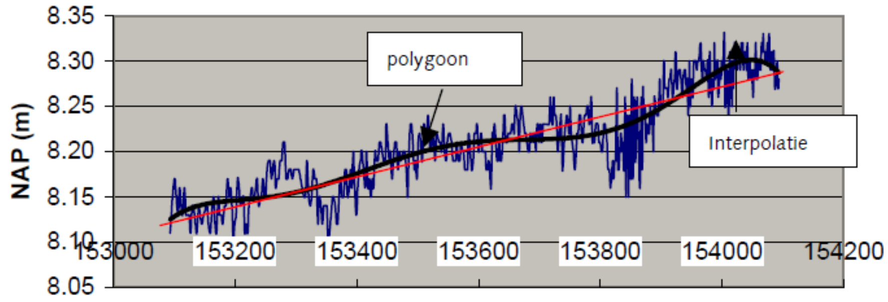

Figure 7: Longitudinal gradient of a section of the river. Blue: measured data; Red and black: interpolated (Wiegmann, 2002)

Initial draft
As long as the water level is the reference for the echo sounder, the initial draft is an important variable. The draft is dependent on the load and measured with a load sensor.

Roll and pitch

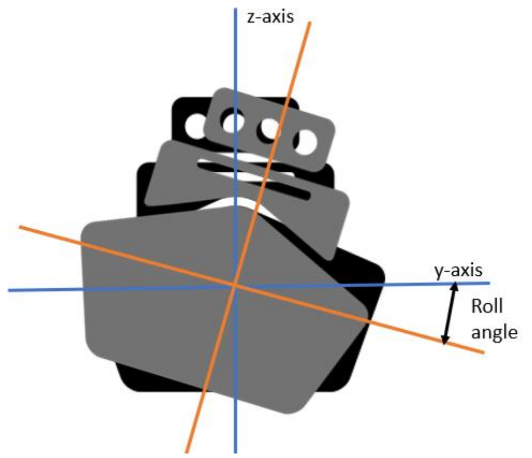

Figure 8: Roll, the tilting rotation of a vessel about its x-axis.

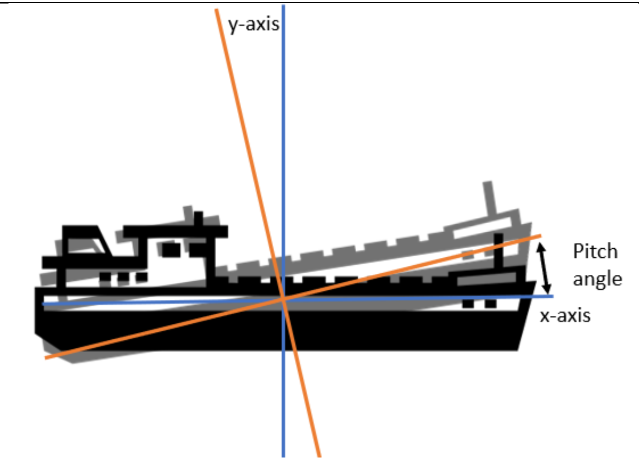

Figure 9: Pitch, the up/down rotation of a vessel about its y-axis.

A.1.3 Reference

By using the water level as a vertical reference, as used by the singlebeam MGD and CoVadem the vertical location of the ship in the water is very important. The squat, draft and heave cause a substantial changing depth of the vessels geometry. Other influences include other vessels passing by and longitudinal differences in water level.

A.1.4 Sounding

Beam angle
The opening angle of the echo sounder transducer, beam angle, is a source of error that will remain. Differences in the beam angle size cause differences in the vertical accuracy of the bottom. Multibeam systems usually use a beam angle of 1.5 degrees. Singlebeam echo sounders usually use a beam angle of around 10 degrees. The smallest depth is measured as a value within the entire footprint. Within the footprint, there is no distinction between mountains and valleys. Small valleys disappear and the depth value of the entire footprint gets the depth of the highest mountain. This phenomenon means that an uneven bed is always measured shallower.

Table 2: Quantification of the squat error on the water depth (Wiegmann, 2002)

Source of error	Singlebeam	Multibeam
Squat	+/- 0 to 35 cm	Not applicable

Propagation speed of sound
Practical experience has shown that the sound variations in sections where salt and freshwater are alternated can cause large to very large (0.4 meters) vertical difference in water depth (Wiegmann, 2002). The multibeam measurement needs a layered sound speed to be accurate. In sections where temperature and salinity are less varying, the inaccuracy is significantly smaller.

A.1.5 Theoretical accuracy per dataset

Multibeam
The multibeam dataset is collected by dredgers commissioned by Rijkswaterstaat as part of the performance contract. With these measurements, dredgers prove that agreed bed levels are met. It is important to keep in mind that dredgers might have dredged the river bed where bed levels were not met. These locations are unknown.

MGD
The skippers of Rijkswaterstaat's patrol boats observe the lowest water depth and before publication, the observation is rounded down to the nearest decimetre. For the predicted MGD value, the fluctuations and the trend in observations and the trend in the predicted discharge at Lobith may be taken into account to determine the MGD value that is published. The MGD is therefore not necessarily an existing water depth, but rather a combination of the measurement and the prediction of the controller on the patrol boat.

CoVadem
Many different vessels with different quality of the equipment. Van der Mark, Vijverberg and Ottevanger (2015) investigated the accuracy of under keel clearances of inland vessels measured using conventional equipment (GPS meter and echo sounder) by comparing these data to highly accurate and detailed multibeam bed level data. The average error is of the order of 20 cm. All the ships measure the same pattern as in the multibeam data: i.e. shallow and deep parts and bedforms. Often a small systematic horizontal shift was visible, probably caused by the fact that the moment in time for both data sets may deviate a couple of days. Also, a small systematic vertical shift was often visible. This may be caused by an incorrect translation from under keel clearance to water depth (Van der Mark, Vijverberg and Ottevanger, 2015).

Appendix B: OBTAIN MULTIBEAM BED LEVEL

Both singlebeam MGD data and CoVadem data are compared with multibeam maintenance soundings (MMS) from Rijkswaterstaat. Since there may be some horizontal errors in the singlebeam (GPS) location, each singlebeam point is compared with an area to obtain the maximal multibeam bed level. This is done with four steps (Figure 10).

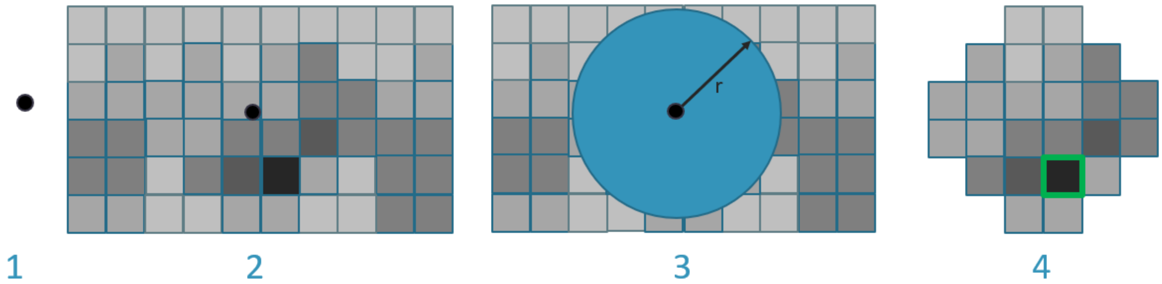

Figure 10: Steps to compare singlebeam measurements with multibeam routine management soundings (1: singlebeam point, 2: raster with bed levels, 3: buffer around the singlebeam point with r= 4 m for CoVadem and r = 12.5 m for MGD, 4: select maximum value of raster as multibeam bed level)

(1) The singlebeam point is selected. The date is checked and if there is an MMS raster available for that date within five days in the past, this raster is used in the following steps. Since dredgers tend to dredge the river just before the MMS are delivered to Rijkswaterstaat, the rasters that are measured after the singlebeam point is measured are not taken into account. If there is no raster available, this singlebeam point is not included in the accuracy analysis. (2) The singlebeam point is projected on a raster with bed levels. (3) A buffer is made around the singlebeam point to account for the eventual horizontal error. The buffer is 8 meters in diameter for CoVadem data, approximate the width of the ship and 25 meter diameter for MGD, since the location is an estimated value in the procedure of measuring the MGD. (4) The buffer polygon determines which raster point of the routine management multibeam raster is used. We chose the highest bed level because this might be the bottleneck for navigation.

Appendix C: Using stage relation curves to translate water depths to bed level

The translation from water depths of MGD and CoVadem to bed level is done by using water level measurements and stage relation curves. In this chapter, these two water level datasets are explained (C.1) and the roadmap of the translation from water depth to bed level is presented (C.2)

C.1 Water level data

C.1.1 Water level measurements

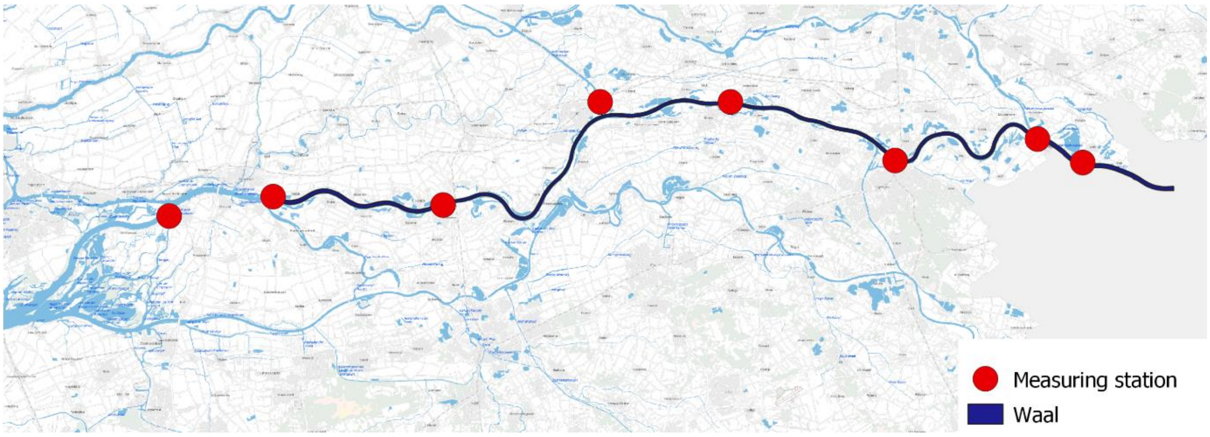

Figure 11: Measuring stations along the Waal (upstream to downstream/right to left : Lobith, Pannerdensche Kop, Nijmegen, Dodewaard, Tiel, Zaltbommel, Vuren, Werkendam)

Along the Waal eight LMW ('Landelijk Meetnet Water'- translated: national water monitoring network)-stations (Figure 11) conduct water level measurements every 10 minutes.

C.1.2 Stage relation curves

A stage relation curve (Dutch: betrekkingslijn) is a graphical representation that indicates which water levels at various level scales correspond to each other at (quasi-) stationary discharge state. The stage relation curves for the Rhine branches give the relation between measuring station Lobith and the water levels on the varying branches. For the stage relation curves version 2018 also the period with low discharges 1 May to 14 December 2018 is used, to obtain curves at lower water levels.

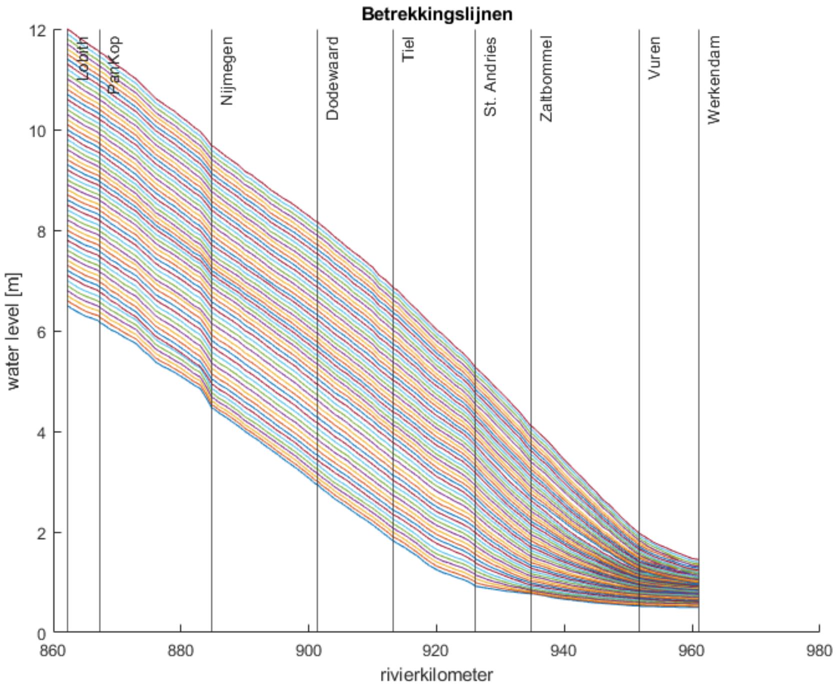

Figure 12: Stage relation curves

The used data contains 56 relation curves, starting at Lobith with a 10 cm interval from 6.5 to 12 meters. For each relation curve, the water levels at every Rhine kilometre and the measuring station is modelled.

C.2 SINGLEBEAM WATER DEPTH TO BED LEVEL

To translate the singlebeam MGD and CoVadem data to bed level per singlebeam point five steps are taken (Figure 13). (1) The x,y location is converted to a Rhine kilometre with an accuracy of 1 metre. By taking this step the lateral water level differences are neglected. (2) Water levels from the same time as the measurement at the upstream and downstream measuring station are determined. We chose not only to look at the water levels at Lobith since measurements closer are available and Figure 14 and Figure 15 show that this indeed minimises the inaccuracy. Water levels are measured every 10 minutes, linear interpolation gives the water level at the time of measurement. (3) If the water level at LMW-station doesn't match the water level at one of the stage relation curves, the two closest curves are used. This means one with higher water levels and one with lower water levels. (4) The water level of the Rhine kilometre before and after the singlebeam point is determined from the stage relation curves. Linear interpolation between the water levels from the two Rhine kilometres and the two-stage relation curves is performed to get a water level at the singlebeam location. (5) The two derived water levels from the upstream LMW-station and the downstream LMW-station are averaged to get the water level relating to the singlebeam measurement.

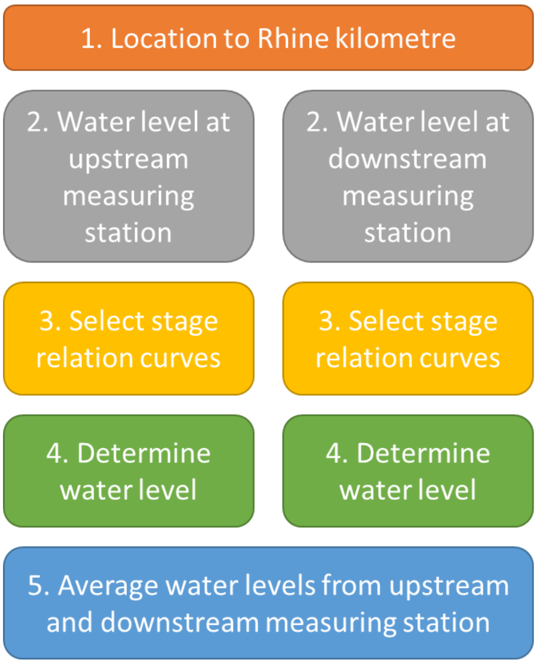

Figure 13: Roadmap to translate singlebeam water depth to bed level

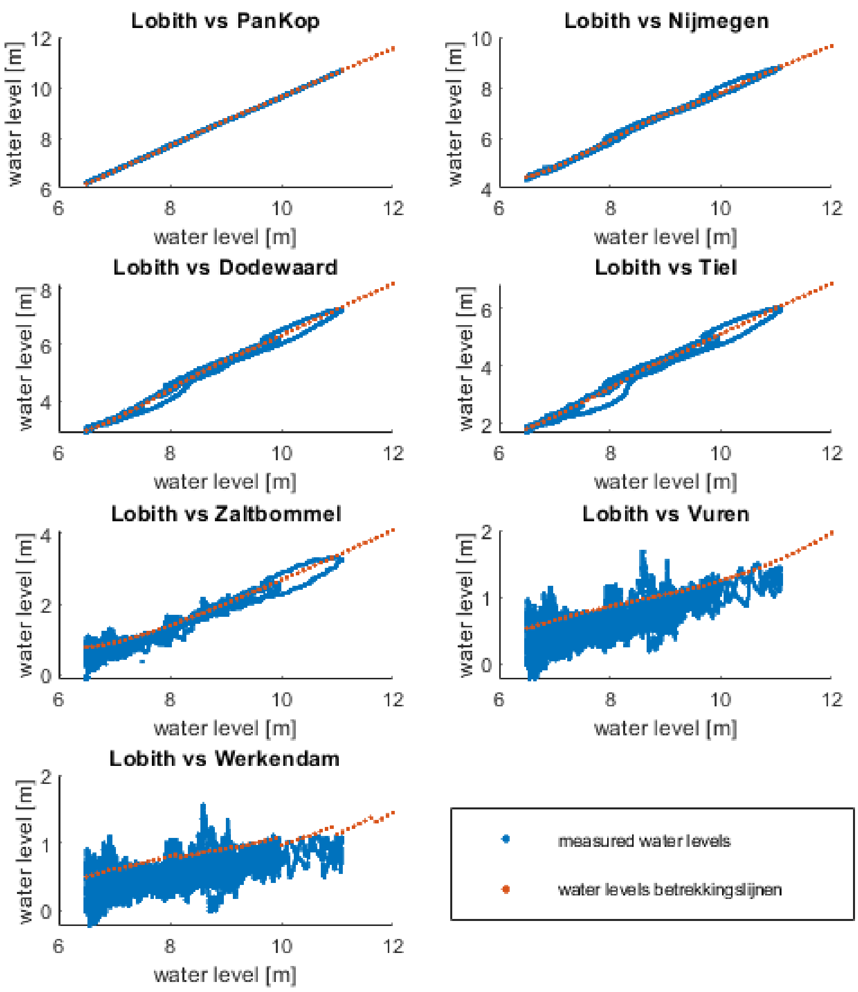

Figure 14: Differences between water levels of stage relation curves (orange) and measured water levels (blue) comparing different LWM-stations from May to December 2018

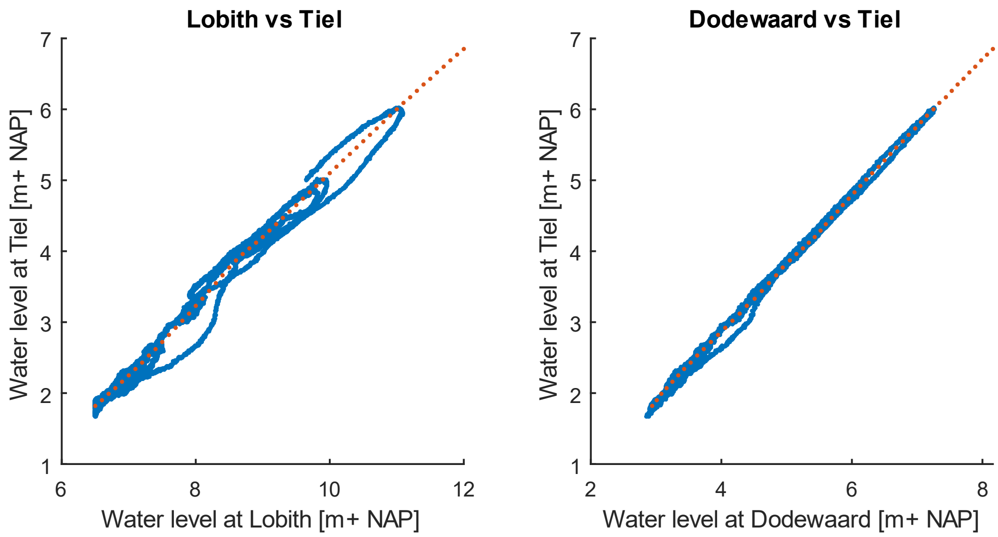

Figure 15: Differences between water levels of stage relation curves (orange) and measured water levels (blue) comparing different LWM-stations from May to December 2018

Appendix D: Maximum discharge

Since the MGD gets more important with lower water depths, we analysed the difference between MGD and CoVadem for different maximum discharges (Figure 16, Figure 17 and Figure 18).

From these figures can be concluded that the Root Squared Mean Error decreases with lower maximum discharges. Also, the 'best' filtering percentile changes from 97^{th} to 99^{th}.

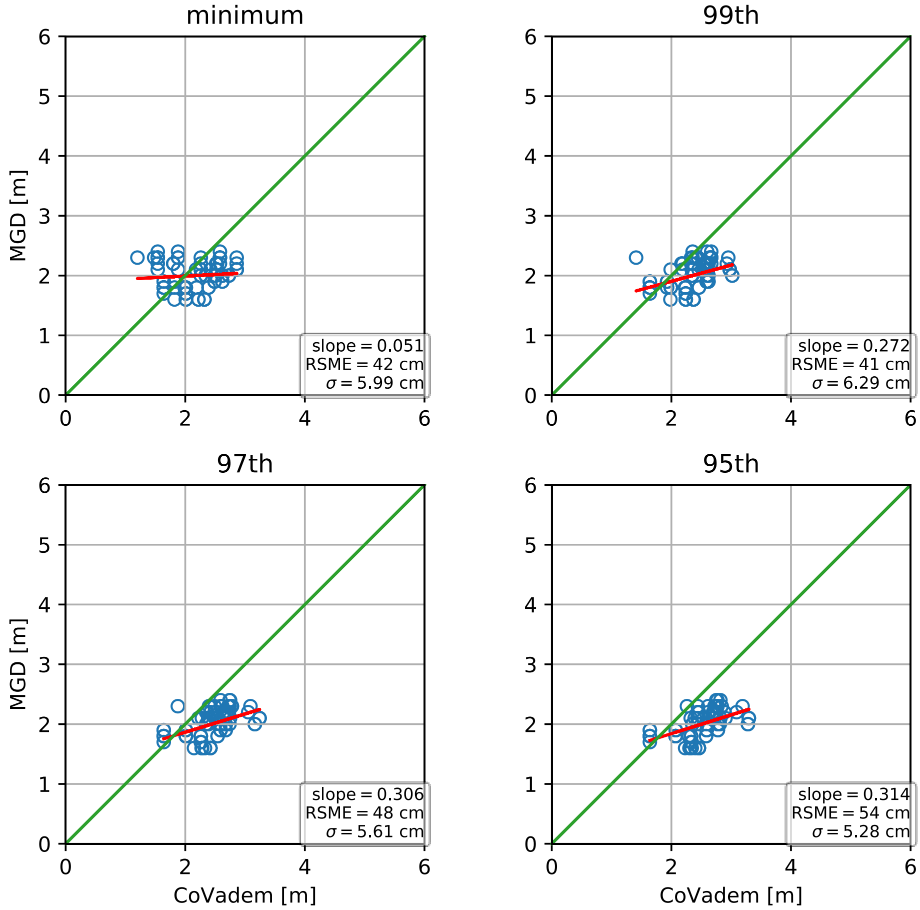

Figure 16: MGD water depth versus CoVadem water depth using different filtering methods without filtering based on shipID with maximum discharge 1000 m³/s

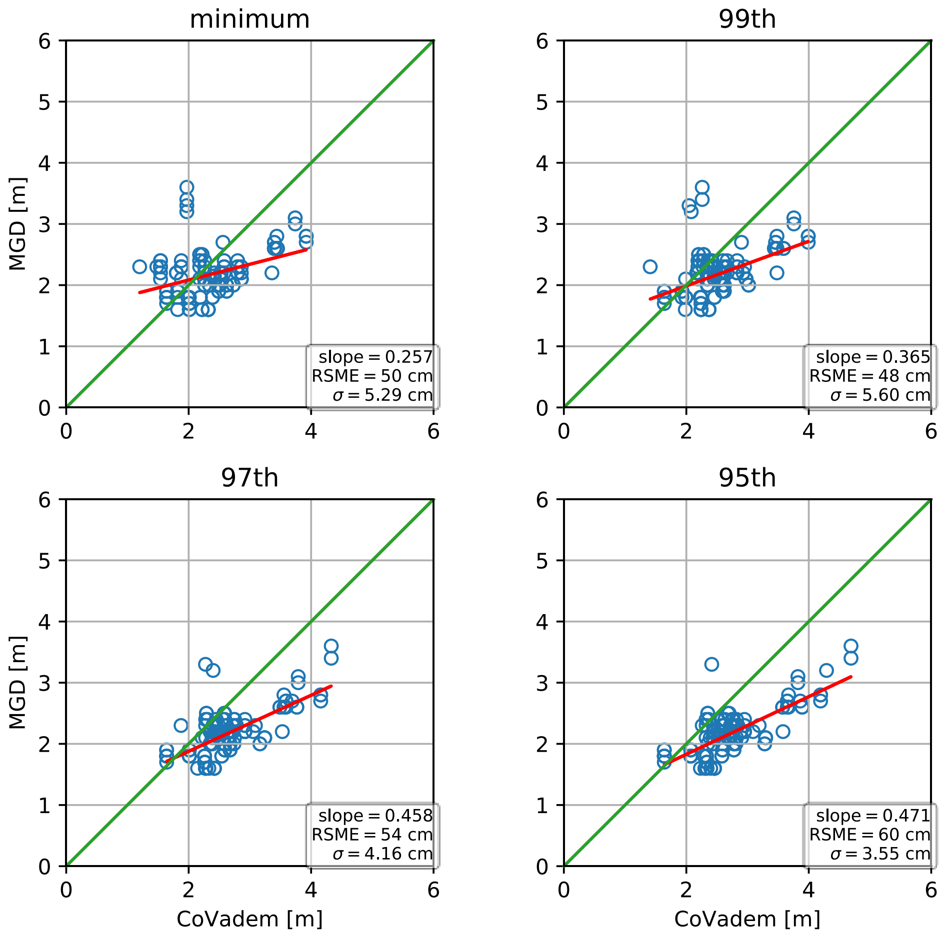

Figure 17: MGD water depth versus CoVadem water depth using different filtering methods without filtering based on shipID with maximum discharge 1500 m³/s

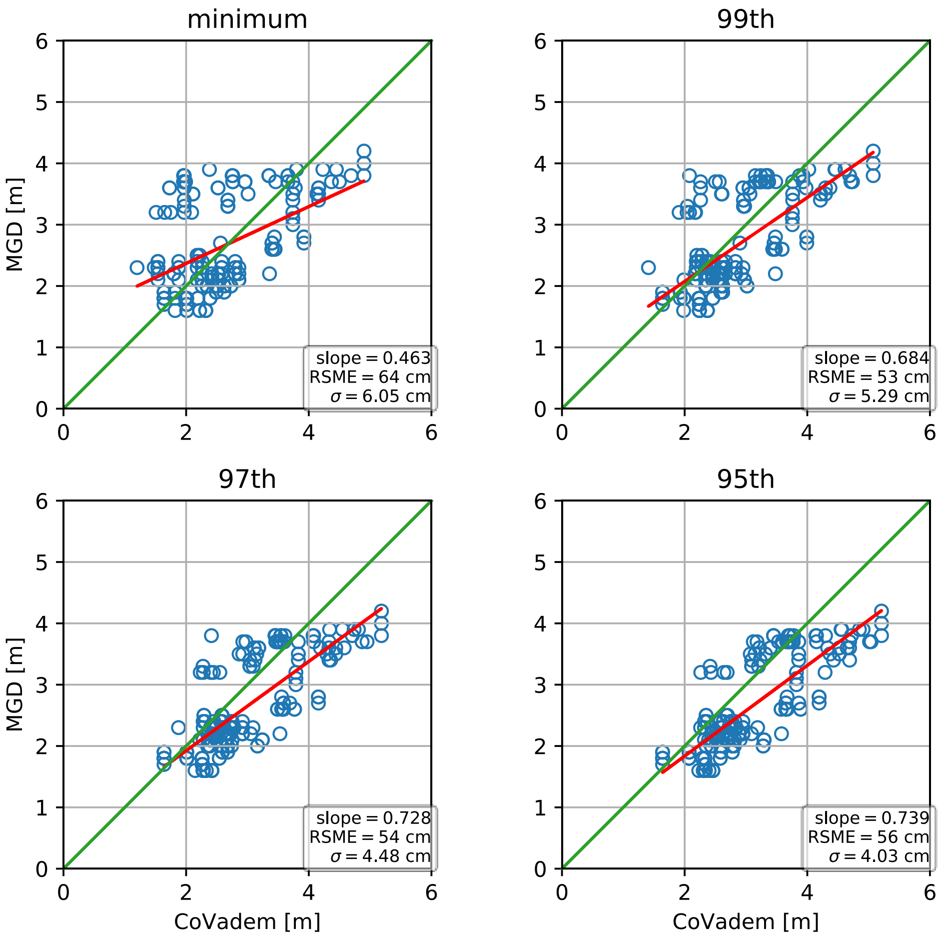

Figure 18: MGD water depth versus CoVadem water depth using different filtering methods without filtering based on shipID with maximum discharge 2000 m³/s

Appendix E: MGD LOCATIONS

Cell	Rhine kilometre	Location	Nr of MGDs in this investigation	Description of location of MGD
21	937	Haaften	37	After high water levels, sanding takes place at this location
31	928	Sint Andries	8	The downstream fixed layer at Sint Andries in inner bend
41	922	Ophemert	7	After high water levels, sanding takes place at this location
43	919	Dreumel	16	Longitudinal training wall
45	919	Dreumel	3	Longitudinal training wall
47	917	Passewaay	3	Groynes near Passewaaij floodplain
76	896	Winssen/wolferen	1	Dune
89	885	Nijmegen	14	Downstream fixed layer at Nijmegen
99	876	Erlecom	34	Downstream bed groynes at Erlecom
101	876	Erlecom	37	Downstream bed groynes at Erlecom
102	876	Erlecom	3	Wrong side of the river?
107	871	Hulhuizen	4	Inner bend Hulhuizen
108	871	Hulhuizen	59	Inner bend Hulhuizen
110	870	Hulhuizen	1	Inner bend Hulhuizen