Bachelor Thesis

Validating a 2D water depth chart for cooperative water depth measurement

Roy Dierx

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Client:	Deltares
Supervisor:	Rolien van der Mark
Educational institution:	University of Twente
Supervisor:	Suzanne Hulscher

Abstract

The CoVadem initiative is about cooperative water depth measurement by and for inland skippers. It is a new way in the determination and optimization of vessel routes for the inland shipping sector. A little number of vessels (approximately 75 vessels) have currently joined the initiative and this brings along some obstacles. The vessels do not sail at the exact same location at the exact same moment in time on the river. Therefore, the data from all vessel tracks within a week are combined in grid cells over the domain of the navigation channel of the river. Because of the timescale the morphological processes of a river must be considered. These morphological processes have influence on the grid cell size and the water depth value of this grid cell. In this research an optimal uniform grid size and grid bed level value is investigated by validating this with Multibeam bed level data. Furthermore, a little study is done on the applicability of the validated grid cell size and bed level value to river sections with less data. The hypothesis of an optimal uniform grid size is rejected in this research, but a reliable method is found for the generation of a bed level value in a grid cell. The last conclusion that can be drawn is that the sections with less data can also give reliable bed level values, despite having some gaps in the grid.

Acknowledgements

I would like to thank Rolien van der Mark for her supervision. Because this research is new in many ways, it was sometimes hard to find a method that was useful for gaining a result. She always helped me to get into the right direction for producing useful results. Besides this supervision I would like to thank her for giving me the opportunity to do a research in such an interesting innovative project. I have worked on this research with much pleasure. Furthermore, I would like to thank all other colleagues from Deltares who have shortly helped me along the way of my bachelor thesis. I would also like to thank Suzanne Hulscher for her feedback and critical view on my bachelor thesis.

Finally, I would like to thank my fellow students from Deltares for having pleasant lunches and coffee brakes.

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1. Introduction

1.1. Context

Because of sediment transport and water level changes, water depths in rivers change continuously. For skippers this can be a problem, because they do not have knowledge of what part of the river is the shallowest and how shallow it is. While loading, skippers must take the depth of the river into consideration, having a deeper river, the skipper is able to take a bigger load with him, if the vessel allows this. Nowadays the determination of the amount of load is done by the experience of the skipper and information from Rijkswaterstaat and Elwis (the German version of Rijkswaterstaat). This determination is based on weather and water level forecasts.

On most inland vessels the position and under-keel clearance are measured each second. The vessel does this with equipment that is installed on board. With these data, the skipper has insight in the water depth underneath the vessel. Most vessels do not store data and information is lost immediately after the measurement. The goal of the CoVadem initiative is to collect and analyse all those data from the participating vessels. The data are being filtered, analysed and enriched with relevant additional information sources. By doing so, CoVadem generates almost real-time water depths information and forecast for every route covered by the vessel network. With this information skippers can optimize their loads and travel more efficiently (CoVadem, 2018).

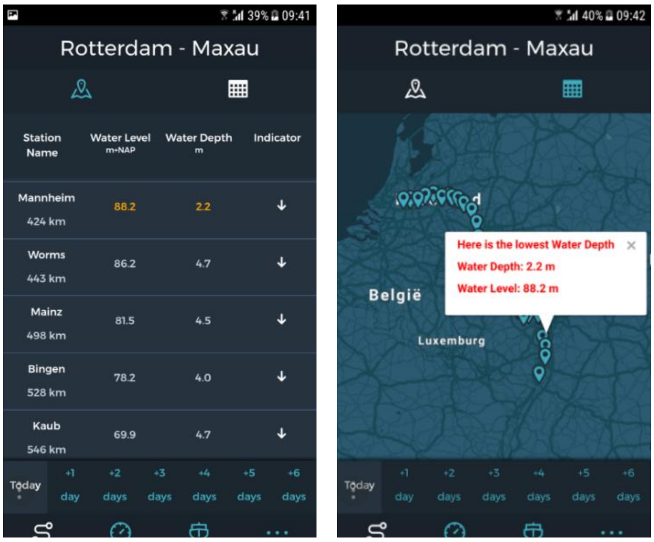


Figure 1-1: Mobile application

Within the project CoVadem+ (van der Mark, 2018) an operational (mobile phone + desktop) application has been developed (Figure 1-1) that shows real-time and forecasted 1D water depths per kilometre, derived from measured under-keel clearances and predicted water levels. This real-time and forecasted 1D water depth is the mean depth of all vessel tracks within a length of 1 kilometre.

The next step in the development of the application is creating an operational 2D water depth map, which displays a real-time and forecast water depth chart. A pilot version of a 2D water depth chart on the River Rhine from Rotterdam to Maxau is currently up and running. For the generation of this 2D water depth chart grid cells with a length of 500 meters in the longitudinal direction of the river and 8 cells across the width of the navigation channel are being used (an example of a 2D water depth chart is shown in Figure 1-2). The goal of this 2D water depth chart is to give an overview of deeper and shallower sections of the navigation channel along and across the river. With this information skippers can determine the route along the river more easily.

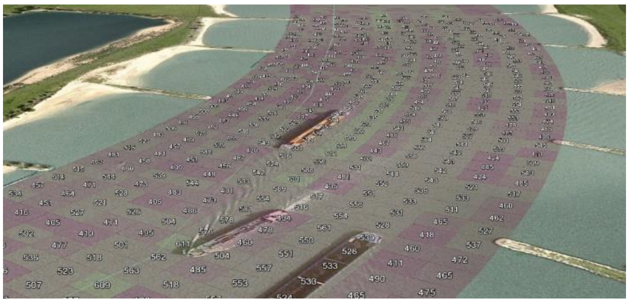


Figure 1-2: Example of a 2D water depth chart in a river

As shown in Figure 1-1 the scope of the research is the River Rhine from Rotterdam to Maxau. In Figure 1-3 a clearer image of the study area is shown. The total study area has a length of 600 km in the Netherlands and Germany.

Figure 1-3: Domain of the study area Maxau-Rotterdam

1.2. Problem Description

For the construction of the 2D water depth chart, mentioned in paragraph 1.1, some problems must be tackled.

The data that is used for the generation of the 2D water depth chart is gained from approximately 75 vessels that have currently joined the CoVadem initiative. These vessels sail on and off the river on a different point in time with different tracks along the river. Besides this, errors in vessel measurements can occur at any moment at any vessel (Abdalla, 2018). These two problems cause for a limited dataset for the generation of a real-time 2D water depth chart from vessel tracks. To tackle the problem of a limited set of data, vessel measurements of one week are being used in the generation of the 2D water depth chart. With one week of data a denser 2D water depth chart can be generated.

Because one week of data is used for the generation of the 2D water depth chart, the morphological processes of the river bed must be considered. These morphological processes consist of the migration of river dunes through the river. River dunes can migrate at a speed of meters a day and differ in shape and size because of sediment transport in a river. An example of river dunes in the River Rhine branches is shown in Figure 1-4. With the vessel tracks being at a different point in time, the river dunes will be located on a different place along the river for each track, because of this migration. If there would be sufficient data over the width of the river in a point of time, it would be possible to map the river dunes with grid cells that are relatively small regarding to the river dunes. This is not the case and therefore the presence and migration of the river dunes must be dealt with otherwise. If a grid cell is still smaller than a dune, it can occur that only data of the crest or the trough of the dune is located in the cell (Figure 1-5). This will give significantly different minimum water depths. Furthermore, a relative big grid cell (Figure 1-6) can miss the detail that is needed for the skipper. In the pilot version of the CoVadem+ application grid cells of 500 meters in length and 8 over the width of the river are being used. Using this length a few river dunes are located in a cell and therefore the migration of these dunes is dealt with. The dimensions that are used for the grid cell in the application are a rough estimation and it is not known if this estimation is optimal.

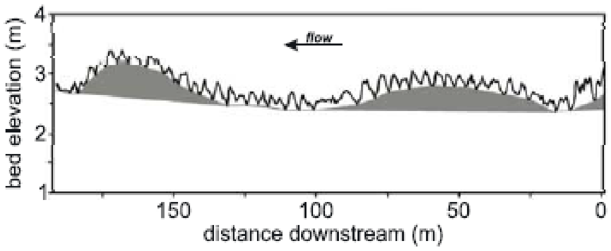


Figure 1-4: An example of river dunes in the River Waal in longitudinal direction (Best, 2005)

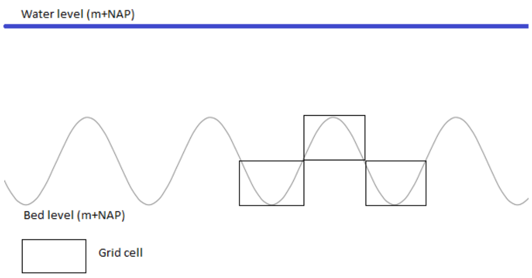


Figure 1-5: Schematic example of a grid cell that is too small

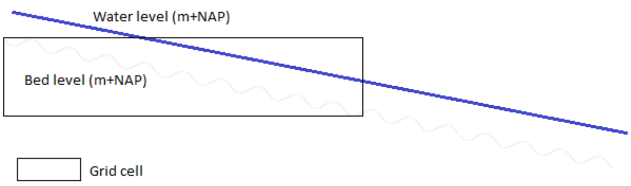


Figure 1-6: Schematic example of a grid cell that is too big

The migration of these river dunes brings along another problem that must be tackled. The skippers want a representation of the minimum water depth. The minimum water depth is dependent on the morphological processes in the river. River dunes that migrate through the river have a big influence on the minimum water depth that is derived from the participating vessels (van der Mark, Vijverberg, & Ottevanger, 2015).

The last problem that occurs in the generation of the minimum water depth chart is the difference in amount of data in the Netherlands and Germany. In the Netherlands there are enough data to give a good minimum water depth. In Germany, a steel factory is located at Duisburg. Different vessels sail up to that steel factory, but few vessels sail further upstream, therefore the minimum water depth chart that can be derived from the vessels is less dense. Besides the few tracks in Germany, there are no Multibeam data to validate the CoVadem data and there is not much known about how alluvial the river bed in Germany is.

For the skippers the water depth of a section of the river is important. Within the CoVadem project this water depth is projected to the skippers in the application. The problem for this research is that water depths change constantly, from different water depths in a certain period of time, no clear conclusions can be drawn. Therefore, the water depths must be translated to a more constant variable. This problem can be addressed using the water levels at NAP from the hydrological stations along the River Rhine. With this water level data and the water depths a bed level at NAP of the River Rhine can be generated. This bed level is far more constant and can be used for answering different sub-questions. Therefor only the bed level of the river will be used for generating results in this research and not the water depth.

1.3. Research Objective

With the above-mentioned problems and requirements in paragraph 1.2, the following research objective can be formulated:

What is the optimal uniform grid, so it is useful for the skipper, the morphological processes are considered, there is sufficient data per grid cell and the grid is applicable both in the Netherlands and in Germany?

For answering this research objective, some sub-questions must be formulated.

1. *What is the best way to generate the maximum bed level value that is assigned to a grid cell?*
2. *What is the optimal grid cell size (length x width) for the representation of the bed level?*
3. *How alluvial is the river bed in Germany and how dense are the data?*

1.4. Theoretical Framework

This paragraph elaborates on the literature that can be used for addressing the sub-questions. Furthermore, prior research in the validation of the CoVadem water depth is documented. This research will partly be the input of this research. The CoVadem project is new in all kind of ways, so there are almost no concrete methods that can be used for conducting the sub-questions.

Prior research

Prior research has been done for the validation of the water depth with CoVadem data (Abdalla, 2018), (van der Mark, Vijverberg, & Ottevanger, 2015) & (van der Mark, 2017). In these researches the participating vessels were validated on their performance of generating accurate data points (Abdalla, 2018). The data that were used for these validations by Abdalla were CoVadem data from 1st September till 15th September 2017 and 1 set of Multibeam data of the River Rhine in that period. The input data that are used for Abdallas research is the same input data in this research. The goal of Abdallas research was validating the performances of each vessels water depth measurements with a focus on the vessel performances at the fixed layers of St. Andries and Nijmegen. These fixed layers consist of an immobile layer of large stones. There is hardly any eroding and aggrading of the river bed over time. With a fixed bed level, the vessels can be validated better on the offset then in case of a high alluvial bed level. This research showed that some vessels resulted in having a really good performance during the entire period; some vessels showed partly good and less good results during this period and others did not show good results at all. So measured data should be validated every day for every vessel, because errors in the vessels measurements can occur at any point any day.

Vessels with good performances can be used for the generation of an accurate maximum bed level chart, also on locations were no Multibeam data is available. The vessels that performed badly on the fixed layers are shown in Table 1-1.

Table 1-1: Vessels with a bad water depth performance on the fixed layers of St. Andries and Nijmegen (Abdalla, 2018)

	Week 1 (1-7 September)	Week 2 (8-14 September)
Vessels	2,28,35,43,52,55	2,12,13,35,52,54,55

Translation to bed level for comparison to individual ship tracks

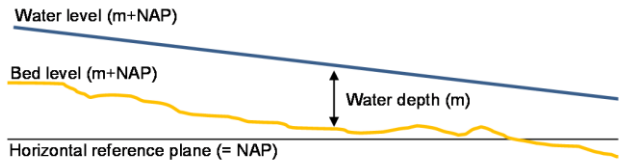


Figure 1-7: Translation of water depth to bed level NAP

For the translation of water depth to a bed level using the CoVadem data some steps are required. The participating vessels measure the under-keel clearance at time and date *t*. This under-keel clearance is translated into a water depth at each measured point along the river by MARIN. The Multibeam data measured the bed level at NAP along the river. For the validation, the CoVadem data must be translated into bed levels at NAP as well. For this translation the measured water levels at point in time *t* at NAP from hydrological stations at river kilometre *x* along the river are used. These measured water levels at a point in time *t* and river kilometre x can be interpolated in time and space. Using these data, the bed level at NAP can be generated for the CoVadem data.

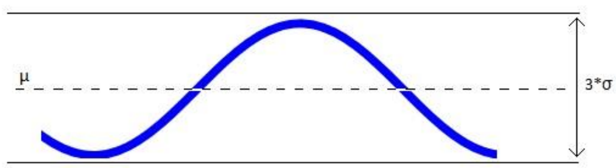
Equation 1: $\textit{Bed level}_{NAP,t,x} = \textit{Water level}_{hydrological\_stations,t,x} - \textit{Water depth}_{CoVadem\_data,t,x}$ (Figure 1-7)

Determination of maximum bed level, accounting for presence of river dunes

For the determination of the river dune height and therefore the maximum bed level of a grid cell, 2 methods can be used:

The first method is to immediately calculate the nth percentile of all data points in a grid cell. These tested percentiles are from 90% till 97.5%. These percentiles are chosen, because the nth percentile must represent a maximum bed level. 97.5% is chosen as the highest percentile, because big errors can occur at any time during the vessels water depth measurement (Abdalla, 2018). With a higher percentile these errors will not be filtered out. A lower percentile is also not useful, because this will not represent a bed level that is high enough. This method is simple and easy to apply and some measured extreme errors are immediately being filtered out without calibrating and validating the measured data first.

The second method is to determine the mean of all CoVadem bed level data points in a grid cell and add half of three times the standard deviation (Figure 1-8). The mean of the CoVadem data points is the bed form-averaged bed elevation (μ) (‘*bodemvorm-gemiddelde bodemligging*’). By calculating the standard deviation (σ) of all the data points in a grid cell, the river dune height can be determined. The river dune height is approximately three times the standard deviation (Nordin, 1966). With the knowledge of the height of a river dune, half of the height can be summed up with the mean bed level and the maximum bed level is determined.



Equation 2:

Maximum bed level = $\mu + 3*\sigma*0.5$

Figure 1-8: Determination of maximum bed level (Method 2)

1.5. Thesis outline

In this paragraph a little description of the thesis outline is given.

The second chapter elaborates on the research methodologies that are set up for addressing the sub-questions. The first paragraph of chapters 3 and 4 consist of a little description of how each methodology is implemented for the first two sub-questions regarding to the available data. Afterwards the results for each sub-question are presented in these chapters. Chapter 5 consists of a little exploration of the river bed of the River Rhine in Germany regarding to the literature and a comparison of the CoVadem data with the literature. In the sixth chapter a conclusion is drawn regarding to the research main question. In chapter 7 the results are being discussed and recommendations are done regarding to further research.

2. Research methodology

For the optimization of grid cells not much research is done. Therefore, this paragraph elaborates on the research methodologies that are set up and will be used for addressing the sub-questions formulated in the introduction. For addressing the sub-questions some data sets are used. The datasets that will be used for conducting the sub-questions and the validation of the sub-questions are discussed. After this, the research method per sub-question is discussed.

2.1. Sub-questions

In this paragraph the research method per sub-question is described.

(1) *What is the best way to generate the maximum bed level value that is assigned to a grid cell?*

The first step in the generation of a maximum bed level value per grid cell, is translating the CoVadem water depth data to bed level data. After this translation, the CoVadem bed level data can be used in the generation of a maximum bed level for a grid cell. For the generation of the water depth chart in the application, all CoVadem data of 1 week is being used. Therefor CoVadem data of 1 week is also used for the generation of a maximum bed level chart.

For the determination of the best way to generate the maximum bed level value that is assigned to a grid cell, two methods are tested. The first method is to directly determine the n^{th} percentile of all the data points in a grid cell. The second method is the determination 1.5 times the standard deviation of all CoVadem data points in a grid cell plus mean bed level.

Before the methods can be tested, the n^{th} percentile that generates the most accurate maximum bed level compared to the actual maximum bed level must be established first. For this research it is assumed that equation 2: *Maximum bed level =* $\mu + 3*\sigma*0.5$ is correct and represents the actual maximum bed level in a grid cell. For the determination of the maximum bed level only the Multibeam data is used. The Multibeam data is the data that represents the best actual bed level, because it is highly detailed. The actual maximum bed level generated with equation 2 is then compared to the maximum bed levels that are calculated by different percentiles using also the Multibeam data.

The last part of this sub-question is validating the CoVadem maximum bed level charts with the maximum bed level generated with the Multibeam data of Rijkswaterstaat. With this validation the pros and cons for generating an accurate maximum bed level chart for each method are written down.

(2) *What is the optimal grid cell size (length x width) for the representation of the bed level?*

For the optimal grid cell size for the representation of the bed level a hypothesis is set up. This hypothesis is that an optimum is expected between the intersection of two errors. The errors that are used for this hypothesis are (1) the resemblance of the CoVadem to the Multibeam data in a grid cell and (2) the amount of detail that is desired to present to the skippers.

1. The resemblance of the CoVadem to the Multibeam data in a grid cell is tested on the mean of all data in a grid cell for the CoVadem and Multibeam data. Next, the error E is established as the difference between both datasets. The result of this error will be the blue line in Figure 2-1. Multibeam and CoVadem data are not obtained on the exact same day, so if less than one river dune is located in a grid cell, a big error can occur if data from another day is used for generating a bed level. With more dunes located in a grid cell, this error will average out and the error will decrease.
2. The amount of detail that is desired to be presented to the skippers is the second factor of importance. For the determination of the amount of detail in a grid cell only the Multibeam data is used. With the Multibeam data the 'actual' river bed will be compared to the generated river beds with different grid sizes. A small grid size will sustain a lot of detail, so a little error will occur. The bigger the cell, the more detail will get lost and a bigger error E will occur. The red line in Figure 2-1 represents this error.

An optimal grid size for these two errors will occur at the point where the red and blue lines intersect.

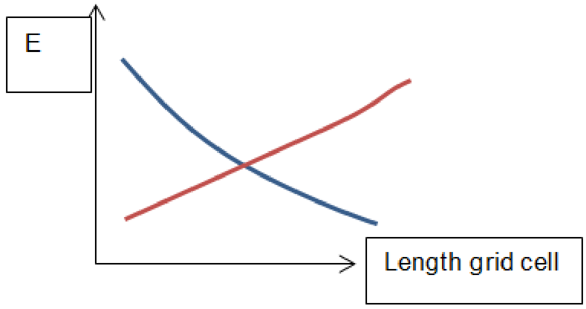


Figure 2-1: Schematic determination of optimal grid cell size

(3) *How alluvial is the river bed in Germany and how accurate is the data?*

For answering how alluvial the river bed is in Germany and how accurate the data is, first a little literature study is done about the river bed of the River Rhine in Germany. After this the data is tested on its accuracy regarding to the literature. The CoVadem data cannot be validated with Multi- or single beam data in Germany, because this data was not available at the time of this research.

2.2. Data

Some datasets are used in this research. The first datasets are the CoVadem data of the actual water depth as derived from measured under-keel clearances. These datasets consist of water depth data and X/Y coordinates in a period of time. For sub-question 1 and 2 a dataset from 1st of September 2017 till 15th September 2017 on the River Rhine from Rotterdam to Lobith is used. For sub-question 3 a dataset from 8th of May 2018 till 8th of June 2018 is used.

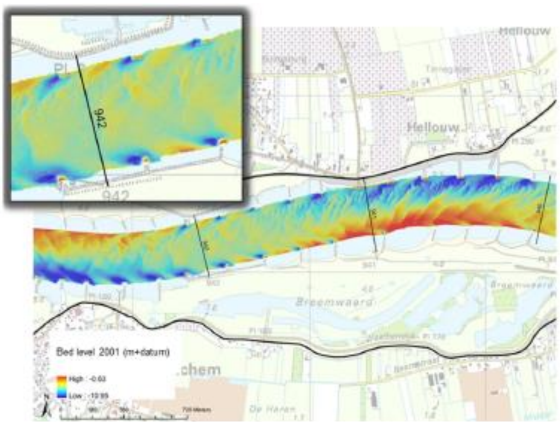


Figure 2-2: Example of Multibeam data on the River-Waal (2001)

For the validation of sub-questions 1 and 2 a dataset from Rijkswaterstaat with echo sound Multibeam data is used. This Multibeam data is a 1 x 1-meter raster file (van der Mark, Vijverberg, & Ottevanger, 2015) from Lobith upstream to Werkendam downstream collected in the period of 1st of September till 15th September 2017. The Multibeam data displays the bed level regarding to NAP (Amsterdam Ordnance Datum). In Figure 2-2 the detail of such a dataset is shown.

The third and last data set that will be used for computing sub-questions is water level data at NAP from measuring stations along the river Rhine. The water levels along the river are measured every ten minutes (van der Mark, Vijverberg, & Ottevanger, 2015).

3. Generation of maximum value per grid cell

In this chapter a result is given for the best way to generate a maximum bed level value for a grid cell. The first paragraph will elaborate on the translation of the CoVadem data points to useable values for the generation of a maximum bed level chart. In the second paragraph the best method for the generation of a maximum bed level chart is calculated.

3.1. Translation from water depth to bed level CoVadem data

Highly detailed Multibeam data was delivered by Rijkswaterstaat. This Multibeam data, as described in chapter 2 Research Methodology, represents the bed level of the River Rhine. The data that is derived from the participating vessels represents the water depth at each data point. For the validation and comparison of the CoVadem data with the Multibeam data, the CoVadem data must be translated to a bed level as well. The translation from water depth at date and time *t* to bed level is done with Equation 1: $Bed\ level_{NAP,t,x} = Water\ level_{hydrological\_stations,t,x} - Water\ depth_{CoVadem\_data,t,x}$. The full description of this translation can be found in Appendix B.1.

3.2. Determination of best method for the maximum bed level

This paragraph elaborates on the determination of the best way to generate a maximum bed level with the CoVadem data points. For this generation 2 methods can be used. Method 1: 'The n^{th} percentile of the CoVadem data' or method 2: '$\mu + 3*\sigma*0.5$ of the CoVadem data'. First a percentile for method 1 must be established. After establishing the percentile for method 1, the 2 methods are compared on different filtering scenarios with the Multibeam data.

3.2.1. Determination of method 1

This paragraph elaborates on the determination of the percentile that represents the best bed level compared to the actual bed level. For this comparison only the Multibeam data is used, because this data is highly detailed.

A code for the determination of the percentile that represents the best maximum bed level is made in Matlab. The Multibeam data is tested on the 90^{th}, 92.5^{th}, 95^{th} & 97.5^{th} percentile. The results of this code are the mean error and the root mean square error of each tested percentile for grid sizes from 150 to 1000 meters in length shown in Figure 3-1 and Figure 3-2. Furthermore, histograms of the difference between the percentiles and actual maximum bed level for grid cells on a 500-meter grid are presented.

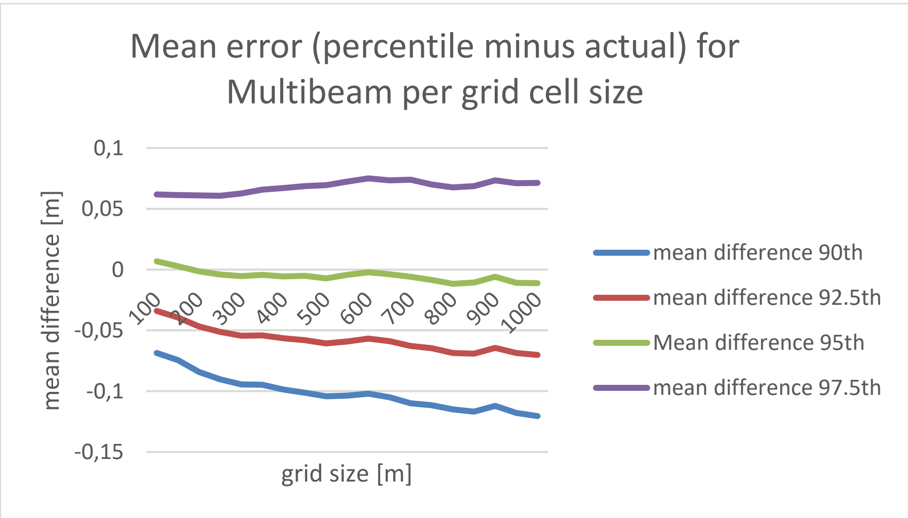


Figure 3-1: Mean error of difference between bed level calculated using the nth percentile and actual

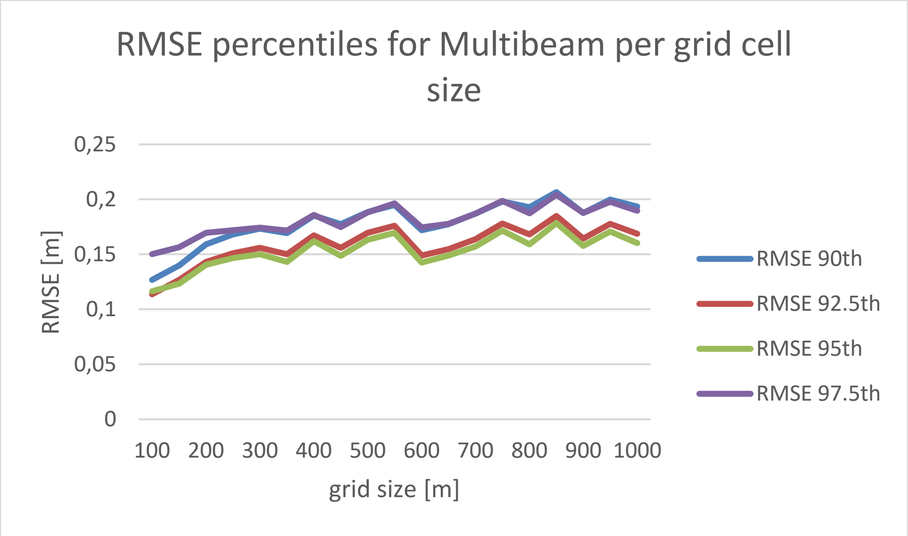


Figure 3-2: Root mean square error of difference between bed level calculated using the nth percentile and actual

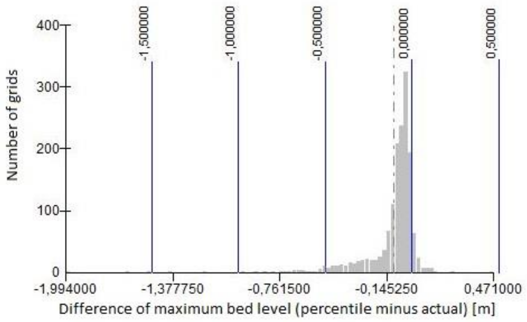


Figure 3-3: Histogram of 90th percentile on a 500m grid

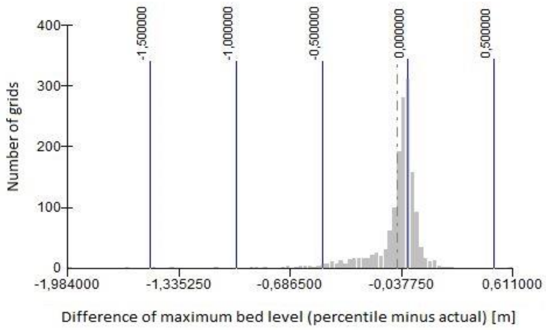


Figure 3-4: Histogram of 92.5th percentile on a 500m grid

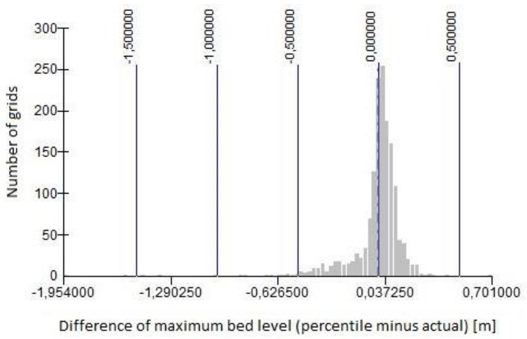


Figure 3-5: Histogram of 95th percentile on a 500m grid

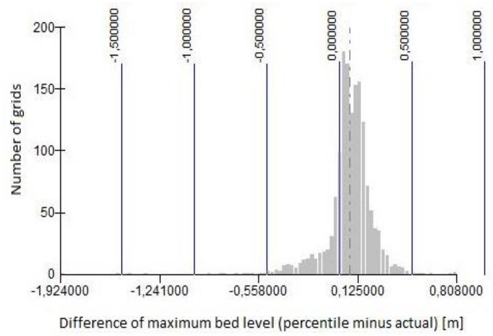


Figure 3-6: Histogram of 97.5th percentile on a 500m grid

From the output graphs in Figure 3-1 to Figure 3-6 two conclusions can be drawn:

1. The output graphs and histograms show that a 95th percentile gives the best mean error and RMSE compared to the actual maximum bed level. The mean almost equals the actual maximum bed level and therefor is the best fit for the total domain.
2. There can also be concluded that a 97.5th percentile is a better option for generating the maximum bed level. The histogram of the 97.5th percentile in Figure 3-6 and the mean error in Figure 3-1 show that most of the grid cells represent a higher maximum bed level. A higher modelled maximum bed level than the actual bed level causes for a bigger under keel clearance. Therefor this option is safer, because it generates less maximum bed levels that are lower than the actual bed level.

For the generation of a maximum bed level with the CoVadem data the 95th percentile is chosen. CoVadem data has less data in a grid cell then the Multibeam data and with a 97.5th percentile, the extreme values of the CoVadem data that are caused by errors will not be filtered out.

3.2.2. Determination of best method

With the percentile of method 1 computed using the Multibeam data, the best method for generating the maximum bed level of a grid cell with the CoVadem data can be determined. For the determination of the best maximum bed level value, the two methods are tested on different scenarios for the total domain.

The scenarios that are set up for this research differ in the amount of filtering of the CoVadem data that is done before generating a maximum bed level. For generating the minimum water depth for the application for the skippers, only the water depths of -999 are filtered out, this is approximately half of all the data. It is not yet decided how other extreme values will be filtered out, therefor only filtering out water depths of -999 is scenario 1. Scenario 2 consists of filtering out the bad vessels that resulted from Abdallas research (Abdalla, 2018). Generations of the maximum bed level for scenario 2 showed some extreme maximum bed level values outside Abdallas research scope. Vessel 21 & 38 caused these extreme values and are therefore also filtered out for scenario 3. After this filter, only a quarter of the total data points remained. The scenarios in short:

1. All CoVadem data without -999 water depths
   a. Week 1
   b. Week 2
2. Excluded bad vessels regarding to Abdallas research
   a. Week 1
3. Excluding bad vessels regarding to Abdallas research and vessels that show sporadically extreme bed level values outside Abdallas research scope
   a. Week 1
   b. Week 2

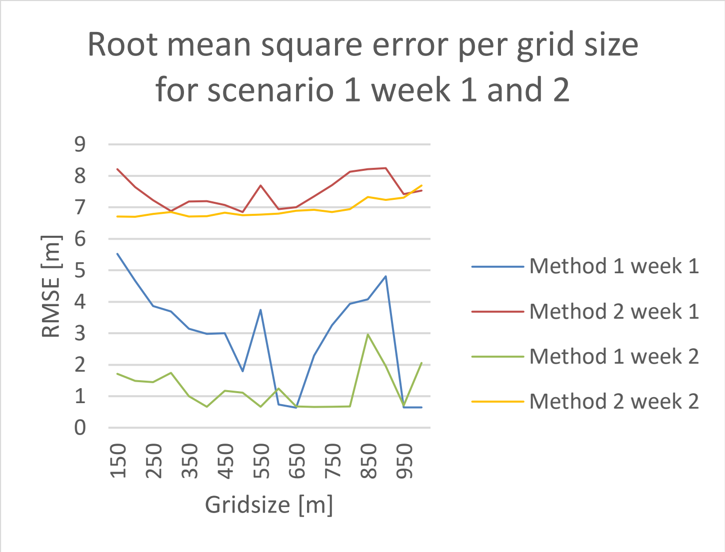
Each scenario is numerically tested on the RMSE and NSE for the two methods for the maximum bed level generation. Each scenario is tested on multiple grid lengths, because the optimal grid size is not established yet. Besides this it is interesting to observe how the CoVadem data performs on different grid lengths regardless to what the optimal grid size is regarding to the Multibeam data. The formulas of the RMSE and NSE are shown in Equation 3 and 4. In these formulas 'model' is the CoVadem data and the 'obs' is the Multibeam data.

Equation 3: $RMSE = \sqrt{\frac{1}{n}\sum_{i=1}^{n}(\text{model}_i - obs_i)^2}$

Equation 4: $NSE = 1 - \frac{\sum_{i=1}^{n}(X_{obs,i} - X_{model})^2}{\sum_{i=1}^{n}(X_{obs,i} - \bar{X}_{obs})^2}$

3.3. Results

In this paragraph the results of the tested methods on the different scenarios are presented. Each method has some pros and cons for different scenarios. These pros and cons are presented in this paragraph together with some supporting figures for a visualisation of the bed level chart. Other graphs and figures that are used to support these results are presented in Appendix A.1 and A.2. The graphs shown in this paragraph are the graphs with the RMSE for different scenarios. The graphs of the NSE are shown in Appendix A.1. The figures in this paragraph and in Appendix A.2 give a visualisation of how the grid would look like in the application on the Midden-Waal and the bends between Nijmegen and Lobith. The grid that is used for this visualisation is a 500-meter grid with 8 cells across the width of the navigation channel.



From this graph it can be concluded that method 1 (95th percentile) is the best option for the generation of the maximum bed level for scenario 1. In week 2 this method gives a relative good result even though all the bad vessels, which are about half of the total vessels, are considered with the generation of the maximum bed level.

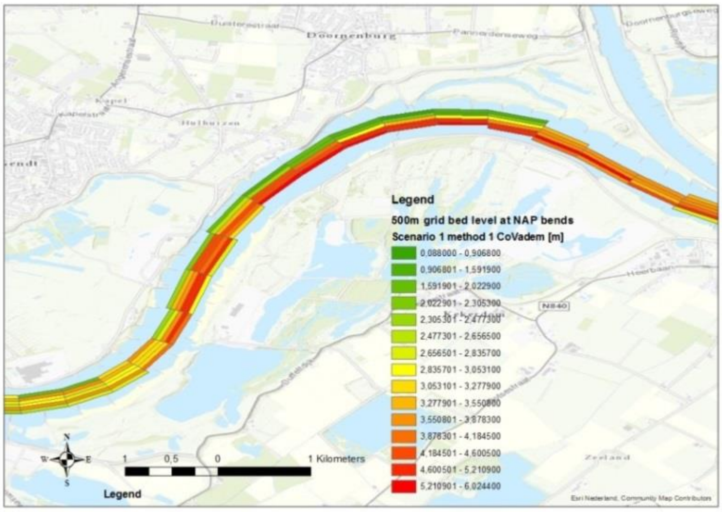


Figure 3-7: Maximum bed level of CoVadem data on the bends scenario 1 method 1 in week 1

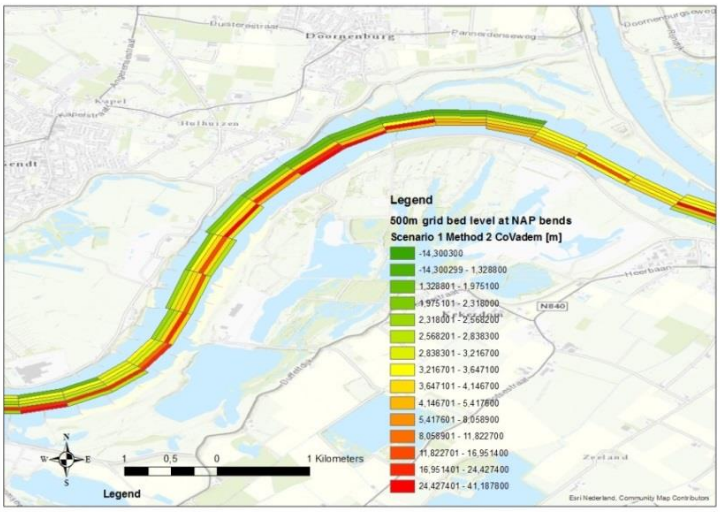
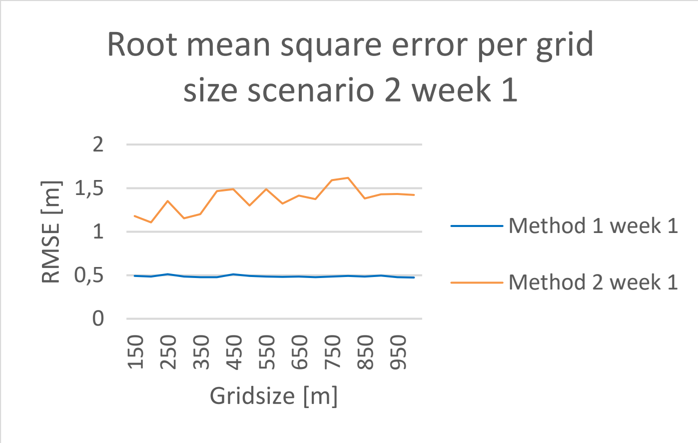


Figure 3-8: Maximum bed level of CoVadem data on the bends scenario 1 method 2 in week 1

From Figure 3-7 and Figure 3-8 and can be concluded that a bed level that is generated using method 1 has less high scale difference in the legend than method 2. This is in line with the results that are presented in the graph for the RMSE of scenario 1. The bad vessels are partly filtered out using method 1. Method 2 results in a river bed chart with extreme values that is not representative for the actual bed level as shown in Figure 3-8.

Using method 2 on the other hand, causes for a clear difference between cells with only good data points and cells with bad data points in it. With method 1 some cells with bad data in it can cause for a plausible bed level, but are in fact not. A skipper can than get stranded on a sand bank.



This graph shows a good RMSE for method 1. The linear blue line of method 1 indicates that the bad data points from the bad remaining bed vessels are filtered out, without any further pre-filtering. The red line of method 2 indicates that there are still bad data points in some grid cells, because extreme data points cause a bad RMSE.

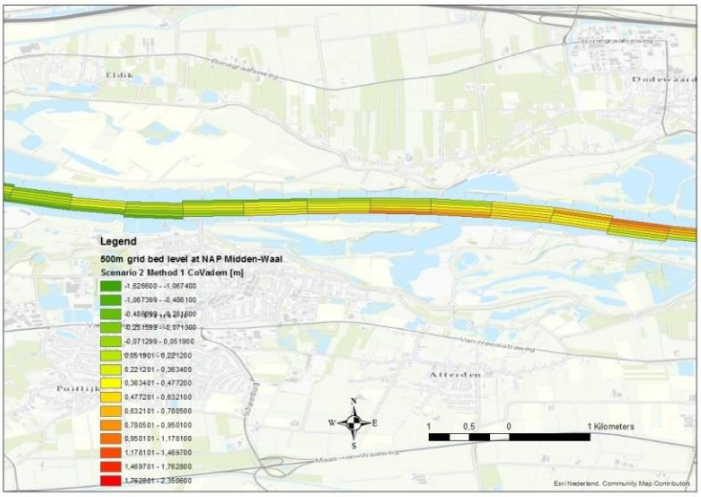


Figure 3-10: Maximum bed level of CoVadem data on the Midden-Waal scenario 2 method 1

In Figure 3-10 and Figure 3-9 the maximum bed level generated with method 1 and 2 for scenario 2 are shown. Because of the pre-filtering of the data, the maximum bed levels of the two different methods are quite alike. The only big difference is the red grid cell in Figure 3-9. This grid cell contains some bad data and because of method 2 this grid cell represents a maximum bed level that is way of the actual bed level.

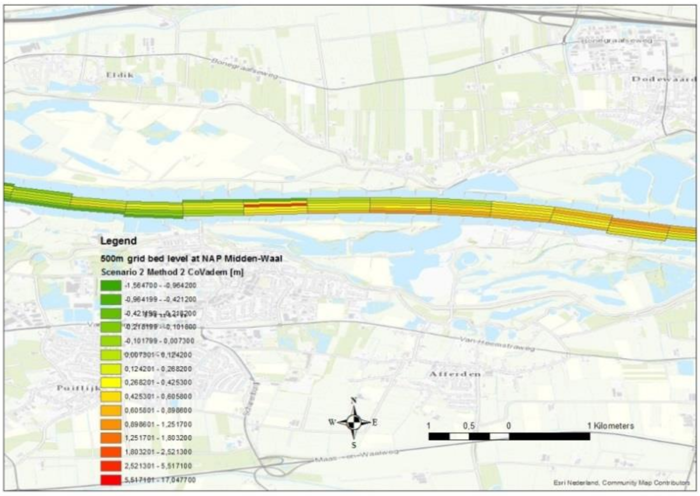
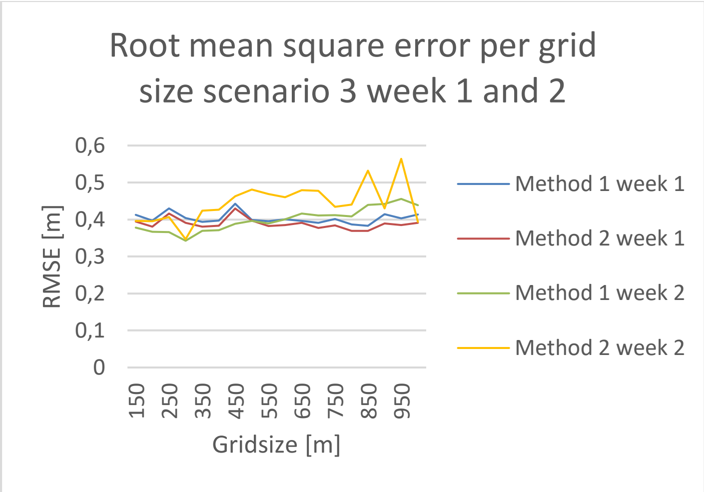


Figure 3-9: Maximum bed level of CoVadem data on the Midden-Waal scenario 2 method 2



From this graph can be concluded that the RMSE of both methods is almost equal. This indicates that with a proper filter method before the generation of the maximum bed level a representative maximum bed level can be generated using both methods.

Method 2 in week 2 shows a worse RMSE, this can indicate on a vessel that passed the filters. This vessel probably does not measure extreme values, but has a wrong offset. This wrong offset causes for a wrong RMSE for the total domain of the River.

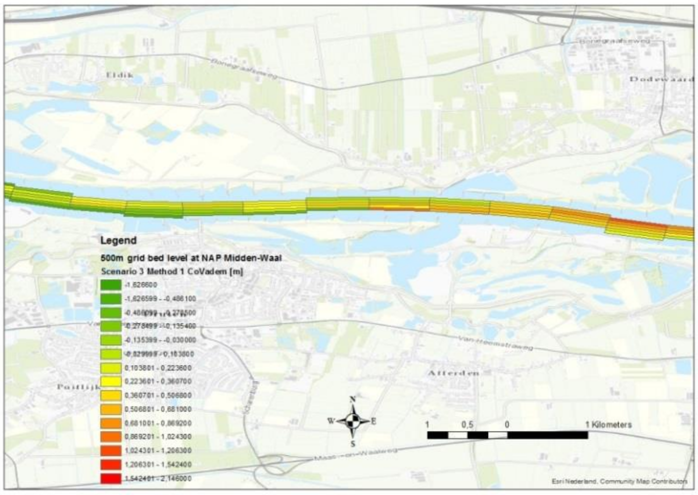


Figure 3-11: Maximum bed level of CoVadem data on the Midden-Waal scenario 3 method 1

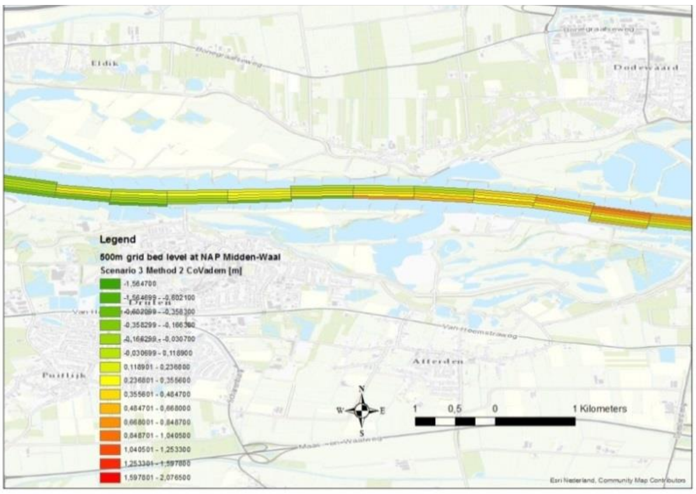


Figure 3-12: Maximum bed level of CoVadem data on the Midden-Waal scenario 3 method 2

3.4. Conclusion

In this paragraph the conclusion for the best method to generate a real-time maximum bed level chart is established. As shown in paragraph 3.3 there are multiple conclusions that can be drawn, each method has its pros and cons at different amount of filtering and the calibration methods.

Currently, there is no calibration of the vessels measurements for the generation of a water depth chart in the application. In the case of no calibration the best way to generate an actual maximum bed level is the calculation of 3* σ*0.5 (method 2) the best method. This method gives a clear bed level chart for the grid cells that have proper data in it and bad grid cells can be filtered out with ease by the skippers.

For the generation of the application with calibration of the vessels' measurements and filtering bad vessels, the best way of calculating a bed level chart is the 95th percentile (method 1). From the research of Abdalla it is concluded that errors in the vessels measurements can occur at any moment. A big error will be detected by the filter or calibration, but a little error can pass the filter method (week 2 is an example of this). Using method 1 this little error will have less influence on the bed level height than method 2. Besides this method 1 and 2 do not differ significantly from each other when the vessels measurements are filtered and calibrated.

4. Optimization of grid cell size

This chapter elaborates on the generation of an optimal grid cell size (length x width). The current water depth chart, which is used in the CoVadem application for the skippers, consists of a 500-meter grid in length along the River Rhine and has 8 cells across the width of the navigation channel in the River Rhine. In the first paragraph a representation of the bed level on the River Midden-Waal for different grid sizes is made using a longitudinal profile (*'Langsprofiel'*). The second paragraph elaborates on the hypothesis of an optimal grid size.

4.1. Representation of bed level

The optimal grid cell size is determined using the bed form-averaged bed elevation (*'bodemvorm-gemiddelde* bodemligging') of the Multibeam and CoVadem data in the grid cells. The bed form-averaged bed elevation is used instead of the maximum bed level, because the maximum bed level will cause bigger errors when increasing the grid size then the bed form-averaged bed elevation (See Figure 1-6 for a visualisation). For the scope of this research question the domains of the straight section of the River Midden-Waal and the bends at Nijmegen are used. These domains are shown in Figure 4-1 and Figure 4-2.

For this research the number of cells across the width of the river are variated between 4 cells and 16 cells in width. The length of the grid cells along the River Rhine is variated from 150 meters to 1000 meters. In Figure 4-1 an example of 8 grid cells in width on the domain of the Midden-Waal is shown.

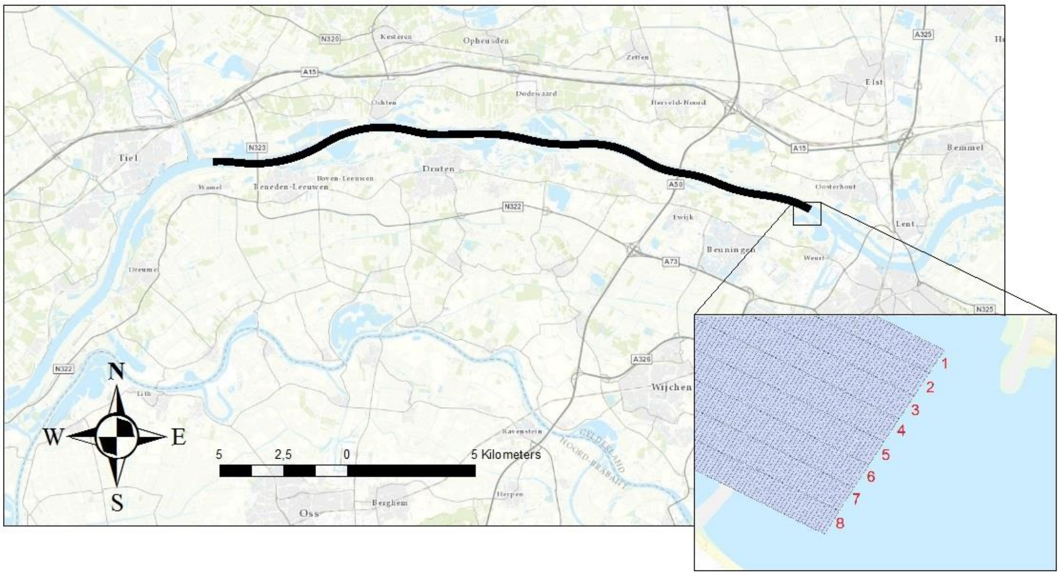


Figure 4-1: Domain River Midden-Waal with 8 longitudinal profiles

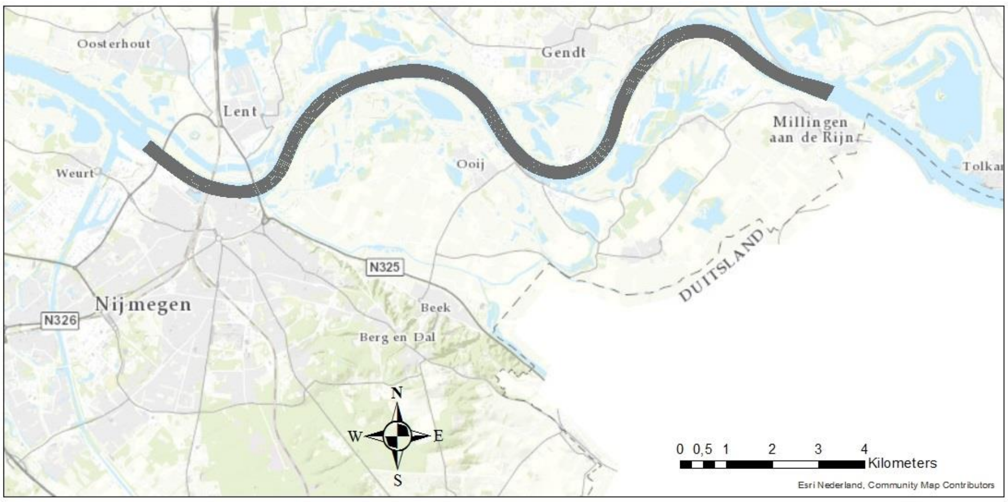


Figure 4-2: Domain bends at Nijmegen on River Rhine

The optimal grid size shows a detailed bed level for the skipper. As can be seen in Figure 4-3, the 5-meter grid (blue line) has a lot of noise. This grid is detailed and represents the actual bed form-averaged bed elevation. For a skipper this is not useful, because it contains too much detail. Besides this there is too little data available for this level of detail. The green line of the 5000-meter grid on the other hand contains too less detail, because it misses bed level elevations and a vessel can get stranded on the river bed.

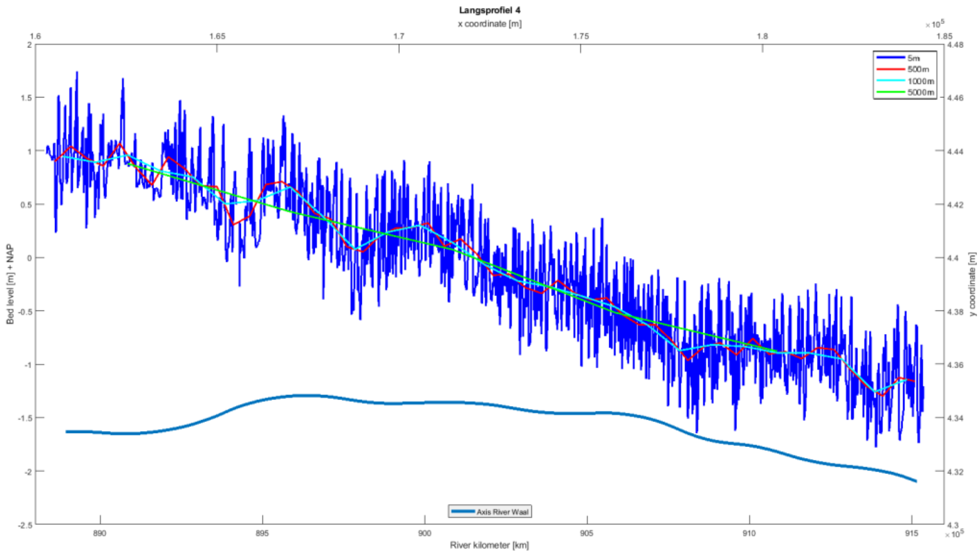


Figure 4-3: Longitudinal profile ('Langsprofiel') of the River Midden-Waal generated with Multibeam data

4.2. Optimizing grid cell size

This paragraph elaborates on the optimization of the grid cell size. This optimization focusses on the intersection between the errors of the resemblance of the CoVadem data to the Multibeam data and the amount of detail that a grid cell displays.

For the error of the amount of detail that a grid cell displays, the grid cells from the longitudinal profiles of the different grid sizes (150 to 1000 meters) are subtracted from the actual bed level (5-meter grid). This means that for example the actual bed level (blue line of a 5-meter grid cell in length in Figure 4-3) is subtracted from the 500-meter grid (the red line in Figure 4-3). With this subtraction a scattered line around zero is generated, as can be seen in Figure 4-4. For this scattered line a confidence interval of 95% is calculated for each grid cell length. The thumb rule is that approximately 95% of the measurements falls within μ +/- 2σ (McClave, Benson, Sincich, & Knypstra, 2011).

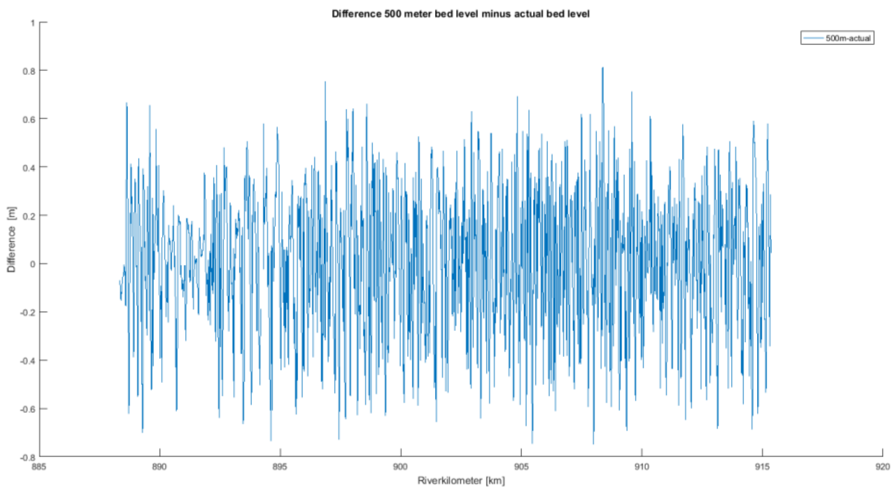


Figure 4-4: Example of difference in bed level for a 500-meter grid regarding to the actual 5m grid bed level

For the error of the resemblance of the CoVadem data regarding to the Multibeam data, the data sets are compared with each other. Before comparing the data sets, the data points from the bad vessels were filtered out of the data set. In Figure 4-5 the longitudinal profiles of the CoVadem and Multibeam data are shown for a 500-meter grid. These lines are subtracted from each other and a confidence interval of 95% is calculated.

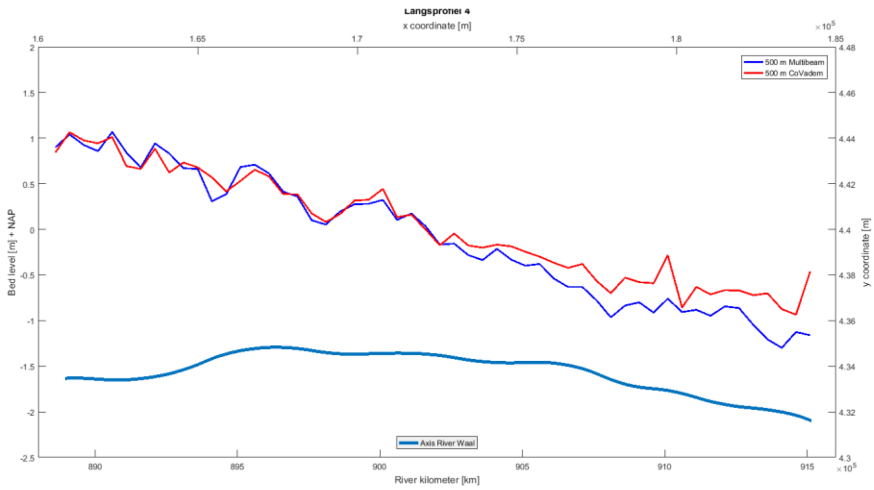


Figure 4-5: Longitudinal profile 500-meter grid of the filtered CoVadem and Multibeam datasets

4.3. Results

In this paragraph the results for the optimal uniform grid cell size are presented. An optimal uniform grid cell is detailed enough to represent uplifts caused by large river dunes, but does not filter out the slope of the river. Besides this, the grid cell with CoVadem data still must represent the actual river bed.

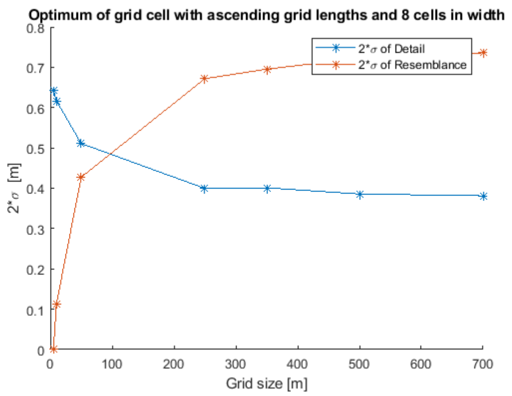


Figure 4-6: Optimum of a grid cell with ascending grid lengths and 8 cells in width

In Figure 4-6 an optimum for the two errors is found near the grid cell length of 100 meters for 8 cells in width on the straight section of the Midden-Waal. The errors of the varying cells in width are plotted separately in Figure 4-7. The literature (Figure 1-4 and Figure 2-2) shows that the wavelength of the river dunes in the River Midden-Waal is approximately 100 to 150 meters. The optimum found in Figure 4-6 does not represent a grid cell with more than one river dune in a grid cell. It can be concluded that the optimum that is generated from the intersection of the two different errors is not the optimum that is wanted.

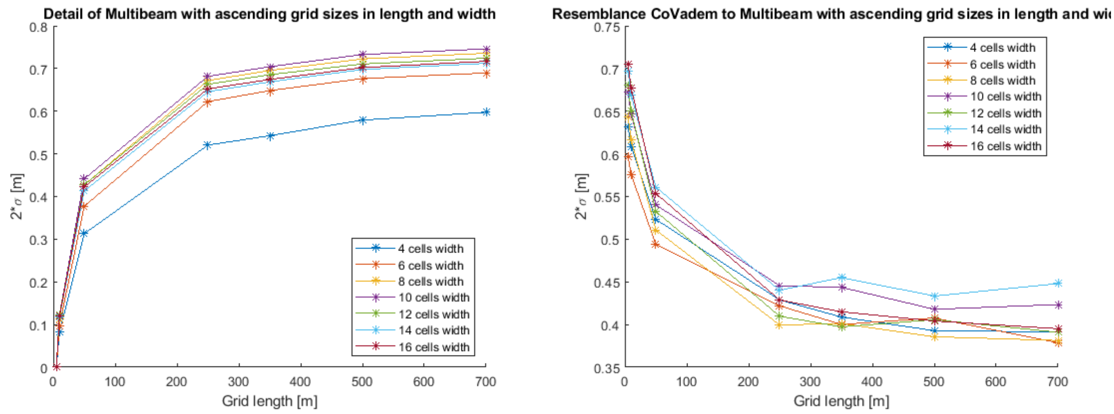


Figure 4-7: Detail and Resemblance of the CoVadem and Multibeam data with ascending grid sizes in length and width on the domain of the straight section of the Midden-Waal

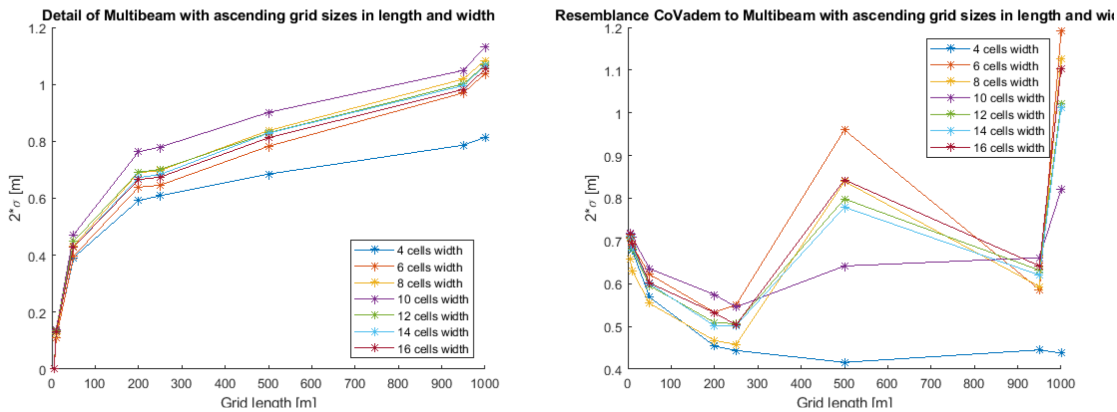


Figure 4-8: Detail and Resemblance of the CoVadem and Multibeam data with ascending grid sizes in length and width on the domain of the bends at Nijmegen

Besides the intersection of the two errors at the straight domain of the River Midden-Waal, the intersection of the two errors at the bends near Nijmegen also result in an optimum around grid cells with a length of 100 to 150 meters. Therefore, it can be concluded that the intersection of the two errors do not give useful results for this research. Despite no useful conclusions can be drawn from the intersection of the two errors, some observations can be done from the error of the detail and resemblance separately.

The error of detail shows a bad standard deviation for the ascending grid lengths with 8 grid cells over the width of the navigation channel at both domains. In the application 8 cells in the width of the navigation channel is used. From Figure 4-7 and Figure 4-8 can be concluded that this width is not optimal, the bed levels of the ascending grid cells have a big variance to the 5-meter grid.

The error of resemblance on the other hand shows a good result for the grid with a length of 500 meter and 8 grid cells over the width of the navigation channel at the straight section of the Midden-Waal (Figure 4-7). This indicates that the CoVadem data with these dimensions represents the most accurate bed level regarding to the actual bed level, because it has the smallest error.

4.4. Conclusions

In this paragraph a conclusion is drawn from the results that are represented in paragraph 4.3.

From the calculation of an optimal uniform grid cell in length and width no conclusion can be drawn regarding to the hypothesis. The errors intersect at a point that is not useful for the generation of a maximum bed level chart. The migration of the river dunes and the total length of one river dune are not considered if the optimum that is found will be used. Therefore, the hypothesis can be rejected.

On the other hand, conclusions can be drawn from the errors separately. The downside to these conclusions is that the conclusions that will be drawn are subjective. The conclusions that can be drawn from these errors are as follows:

The grid cell size that is used in the application has a bad standard deviation regarding to the detail of the river bed that it represents. Regarding to this error, the optimal grid size is not the grid size that is currently used, but a grid size with 4 cells in the width of the navigation channel.

Another conclusion that can be drawn is that the currently used grid size gives the best result regarding to the similarity between the CoVadem data and the actual bed level.

5. Evaluation of River Rhine in Germany

In this chapter the bed level of the River Rhine in Germany is evaluated. For the validation of the CoVadem data on the River Rhine in Germany no data are available. Therefore, first the alluviality and bed level of the River Rhine in Germany must be mapped using the available literature (CHR, 2009) & (Hillebrand & Frings, 2017) of the River Rhine in Germany. The second paragraph elaborates on the comparison of a constructed bed level with CoVadem data to the literature. The third paragraph elaborates on how applicable the generation of a bed level chart is in Germany using the method that is validated on the River Rhine in the Netherlands.

5.1. Literature study on the river bed of the River Rhine in Germany

The River Rhine in Germany can be divided into 3 major parts:
From Basel downstream to Bingen its name is Upper Rhine and the next stretch to Cologne is named Mid-Rhine. From Cologne to Lobith it is called Lower Rhine. For the scope of this research the River Rhine from Maxau (360 km) till Emmerich (852 km) is of importance.

The riverbed is characterized by its geometry and geology. Over long reaches the Rhine is an alluvial river flowing on its own mainly Pleistocene deposits. This holds for the Upper Rhine, the Northern Middle Rhine and the Lower Rhine, whereas, due to the morph tectonic uplift of the Rhenish massif, a bedrock channel with rocky islands and irregular cross sections has developed over a length of some tenth of kilometres between Bingen and St. Goar (river km 527 & 554) at the Southern Middle Rhine.

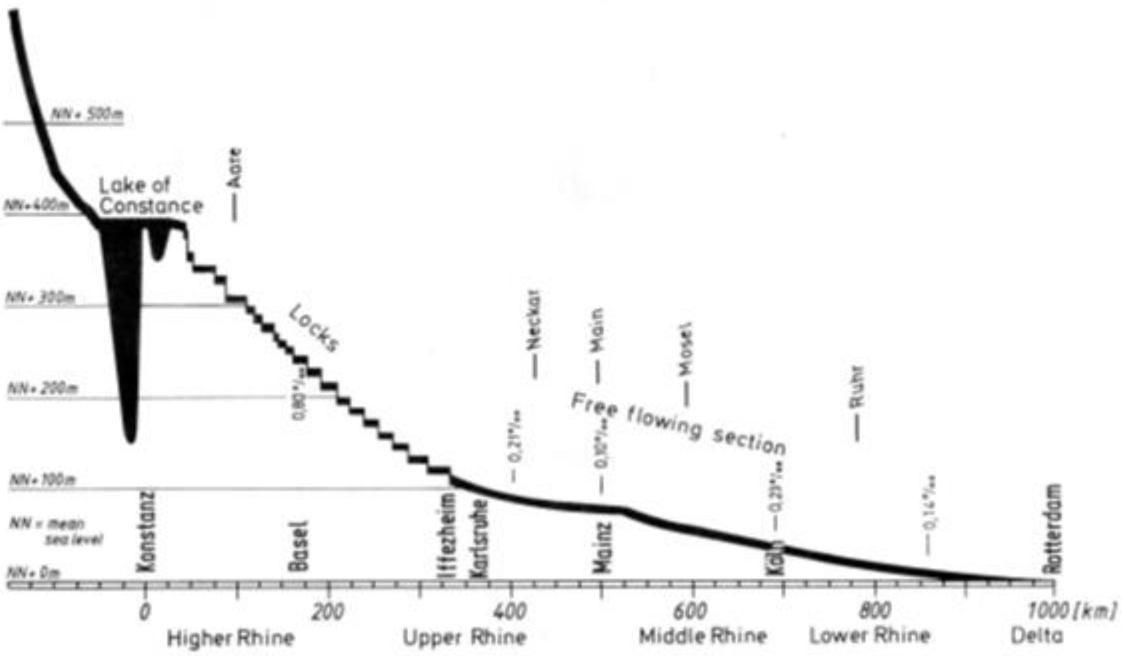


Figure 5-1: Longitudinal profile of the River Rhine and locations (CHR, 2009)

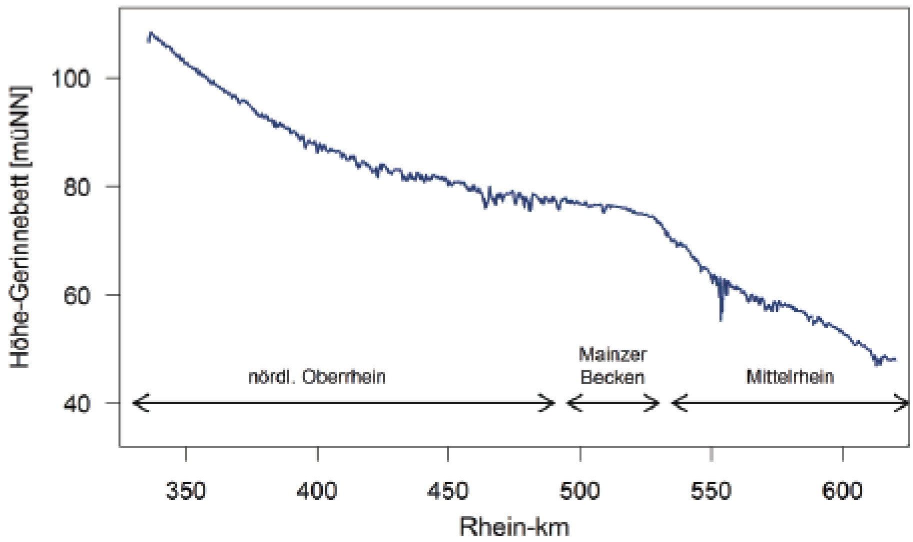


Figure 5-2: Longitudinal profile Upper and Middle Rhine (Hillebrand & Frings, 2017)

Between Iffezheim and Mannheim (river km 325 & 423) bed sediments of the Upper Rhine consist mainly of gravel whereas further downstream the portion of sand increases steadily as shown in Figure 5-3.

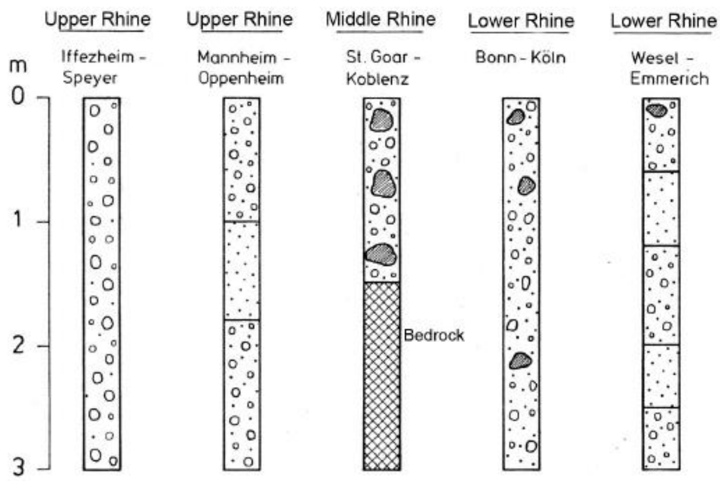


Figure 5-3: Sediments along the River Rhine

Between Basel and Mainz, the Rhine flows through the vast tectonic valley of the Upper Rhine graben before entering the Rhenish massif. The uplift of the Rhenish massif forced it to cut a deep and rather straight gorge into the rising block. Especially crucial for navigation is the transition zone between the Upper Rhine graben and the Rhenish massif. Here in the Mainz basin the river is very wide and the resulting small water depth at low flow velocity is further restricted by the development of large dunes. This is partly suspended when passing the "Binger Loch" at the entrance of the Rhine gorge. The rest is transported on a rocky and cobbly river bottom through the narrow gorge.

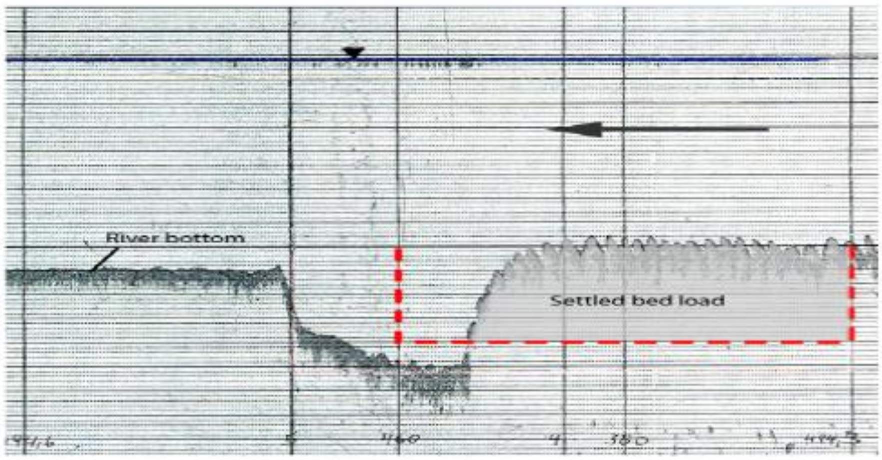


Figure 5-4: 'Binger Loch', a bedload trap at river kilometre 530 of the River Rhine

The ‘Binger Loch’ is a huge bedload trap. This human made trench is 160 m wide, 250 m in length and 1.4 m deep into the river bed. The sudden widening of the cross section forces the bedload to settle in the trench.

The trench was made because of artificial bed load supply in the form of dredging and re-dumping bed sediment. Because of the development of the Rhine into an efficient inland waterway during the last two centuries, the flow and sediment transport was changed severely. The free-flowing section of the river was characterised by a severe bed load deficit leading to bed degradation and falling water levels, whereas in the impounded section further upstream deposition of fine grained sediments occurs. To stop bed degradation and to improve navigation, a strategy has been developed using sediment management. The local dredging and re-dumping provide the base for achieving a dynamic stabilization over the length of the Rhine on top of the authentic bedload.

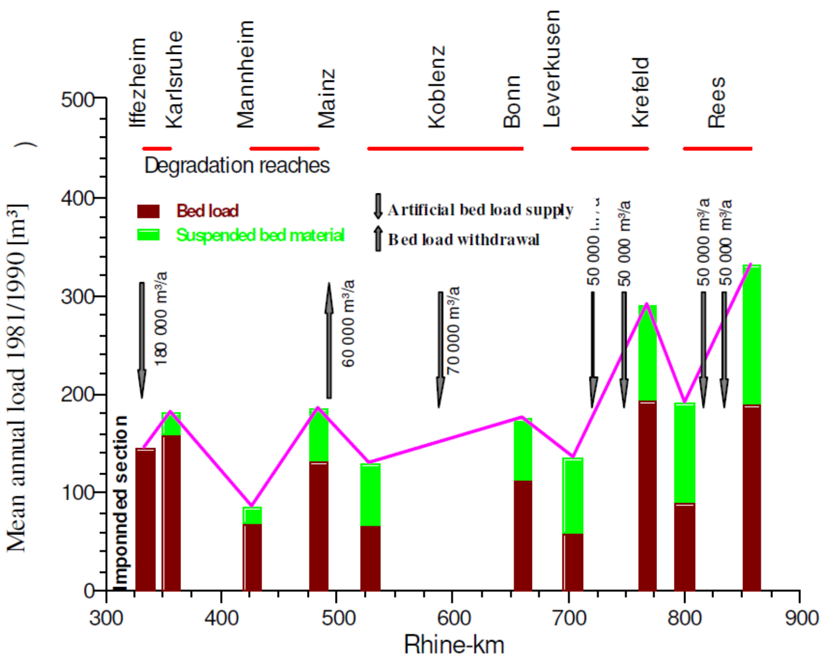


Figure 5-5: Bedload distribution and bedload management measures at the Rhine between Iffezheim and the German/Dutch border

A study showed that the migration rates of gravel supplied at Iffezheim vary between two and six kilometres per year. This is due to the dumped material that does not move downstream as a compact sediment wave, but is spread during transport over the whole distance (dispersion). Along with this dispersion a maximum depth of 1.3 m below the surface of the supplied gravel was observed. It can be assumed that migrating bed forms contribute to the mixing of the supplied gravel with the river bedload. In Figure 5-6 the bed elevation and gravel dunes on the River Rhine at Mainz are represented. It can be concluded that the river bed in the Upper Rhine is highly alluvial, with river dunes rising up to 1 meter in difference from crest to through over a length of 100 meters.

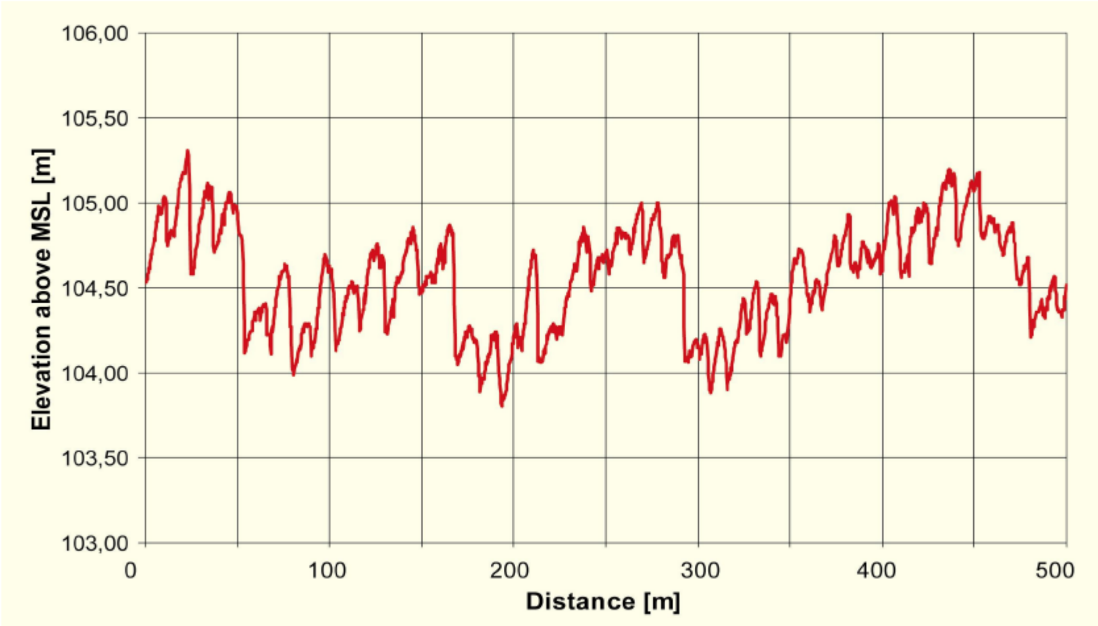


Figure 5-6: Bed form development at high discharge at the upper Rhine

5.2. Construction of the CoVadem bed level and comparison with the literature

This paragraph elaborates on the construction of the maximum bed level using the CoVadem data of the 8th of May till the 8th of June 2018 and a comparison of this constructed maximum bed level with the literature from paragraph 4.1.

The generation of the maximum bed level in the German section of the River Rhine from Emmerich to Maxau is done with the same method as the generation of the maximum bed level in the Dutch section of the River Rhine in Chapter 1. Firstly, the bad data points are filtered out from the data set. Secondly, the water depth of each CoVadem data point is translated to a bed level using Equation 1: $\textit{Bed level}_{NAP,t,x} = \textit{Water level}_{hydrological\_stations,t,x} - \textit{Water depth}_{CoVadem\_data,t,x}$. Next, the 95th percentile of all data points within a grid cell is used for the generation of a maximum bed level per grid cell.

For the German section of the Rhine no data is available for the validation of the CoVadem data and therefor the CoVadem data is compared to the literature. This means: Do the figures that are made, look plausible according to the literature.

The first comparison with the literature is the comparison of the longitudinal profile (Figure 5-1). For this comparison the maximum bed level of 4 longitudinal profiles on NHN (mean sea level) are generated from Maxau to Emmerich with an interval of 1 kilometre. The longitudinal profile from the first week of CoVadem data is displayed in Figure 5-7, the longitudinal profiles from the other weeks are showed in Appendix A.3. This figure shows that the CoVadem data from Karlsruhe downstream to Koln is almost similar to the literature, but further downstream an error occurs.

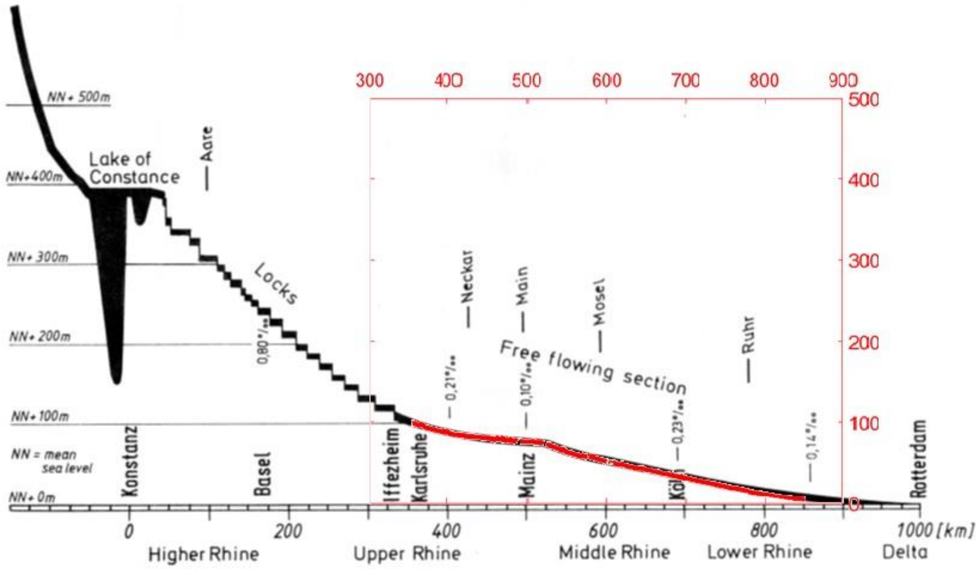


Figure 5-7: Comparison of the longitudinal profile generated with 1 week (8th to 14th May) of CoVadem data (red) with the longitudinal profile from the literature (black)

The literature for the bed form development as shown in Figure 5-6 it compared with the bed form development that is measured with the CoVadem data. Two sections of the river are used at which 2 or 3 vessels follow the same track. These sections are between Mainz and Bingen at which the flow velocity is at its lowest and big river dunes are formed and near Kaub, were the River Rhine flows through the Rhenish Massif on a rocky non-alluvial river bed. These bed form developments are shown in Figure 5-8 and Figure 5-9.

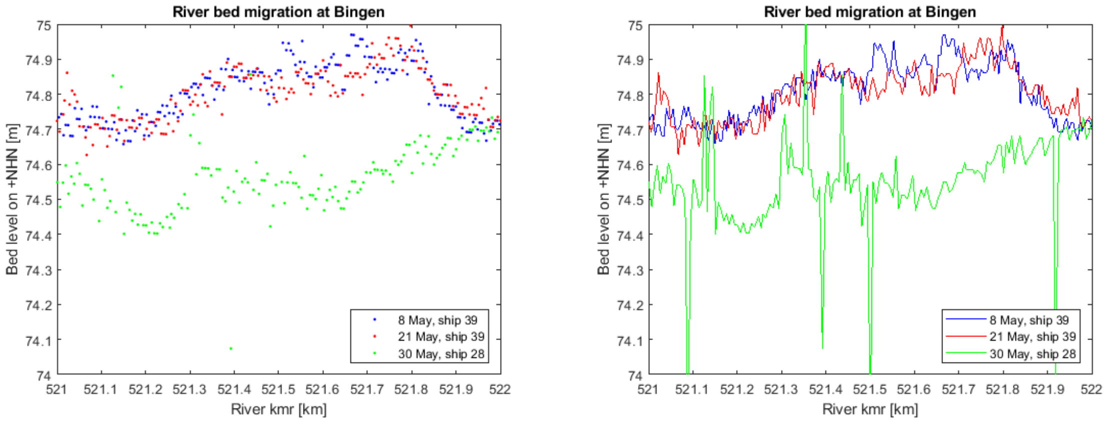


Figure 5-8: River bed constructed on different days using CoVadem data on an alluvial river bed

From the above shown figures can be concluded that the bed form development on the alluvial part of the river does not show the amount of alluviality that follows from the literature. The river dunes only rise up to a difference of 20 centimetres between the crest and the through of the river dune. Besides this the migration of these river dunes cannot be concluded these figures. Between the 8th and 21st of May the river bed does not show a high alluviality and migrating dunes. Between the 21st and 30th of May it does show a difference in bed level, but this migration cannot be linked to any high discharge rates that could have been the cause to this bed level difference. Because the blue and red line are measurements from ship 39 and the green line from ship 28, the differences in bed level measurements are probably caused because of measurements errors at the ships.

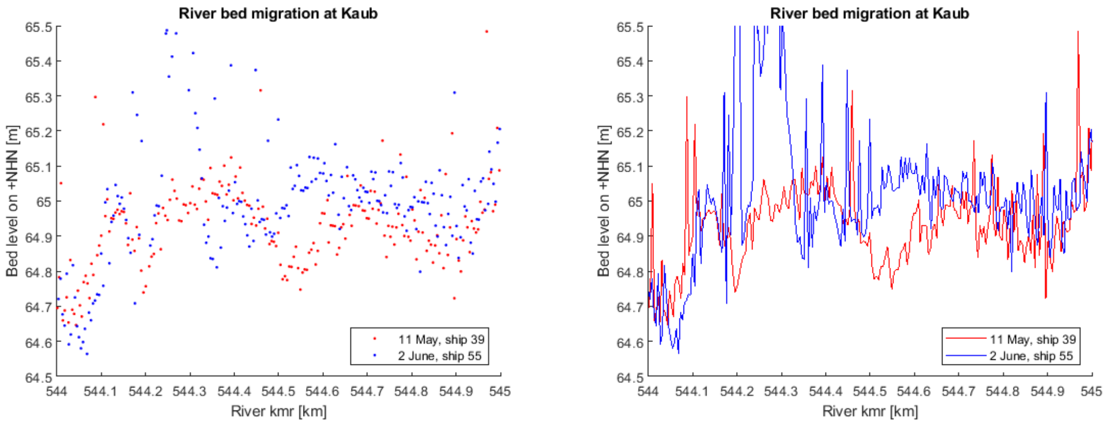


Figure 5-9: River bed constructed on different days using CoVadem data on a rock-based river bed

Besides the construction of the alluvial river bed, the rock-based river bed at the Rhenish Massif is constructed with the CoVadem data. This river bed should show little variances in the river bed on different days. Figure 5-9 shows a river bed that has a high alluvial character, while it is not supposed to be.

The data that is shown in Figure 5-8 and Figure 5-9 are derived from different ships; ships can have errors in the data and there is no good data to validate the results with. Therefor no clear conclusions can be drawn from the above shown figures, because it is only speculation.

The alluviality of the river sections regarding to the literature could not be constructed with the migration of river dunes on a river section of approximately 1 kilometre. For this reason, a construction of the river bed is made using all the available useful data in the period from the 8th of May till the 4th of June. The section of the River Rhine with an alluvial river bed should show a big variance in bed level height along the river and the Rhenish Massif with a rock-based river bed should give a little variance in bed level height along the river.

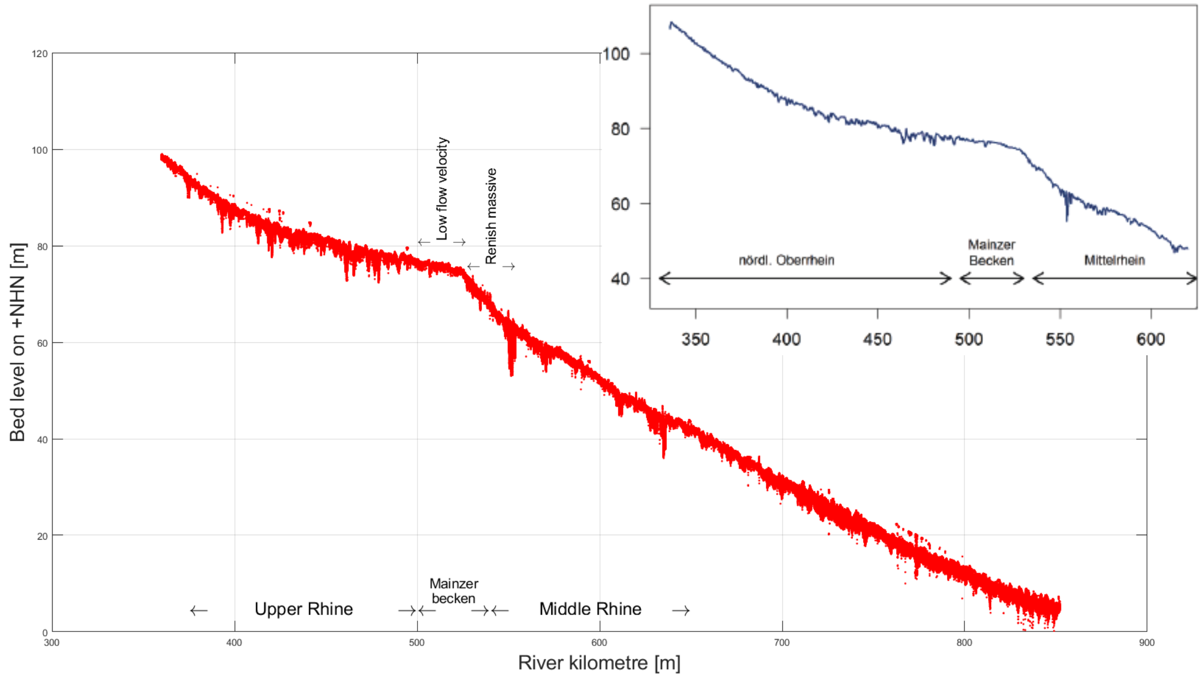


Figure 5-10: Constructed bed level using all useful data points on the River Rhine from the 8th of May till the 4th of June

In Figure 5-10 the river bed in the longitudinal direction of the River Rhine is shown with all useful data points. Some ships showed a big scattering of the data points, an example of such bad data is shown in Figure 5-11. The data points of these vessels are not reliable and are therefore filtered out. Some scattering can be seen in the constructed river bed, but those are the result of deeper river sections. These deeper river sections also follow out of the literature visualised in Figure 5-2.

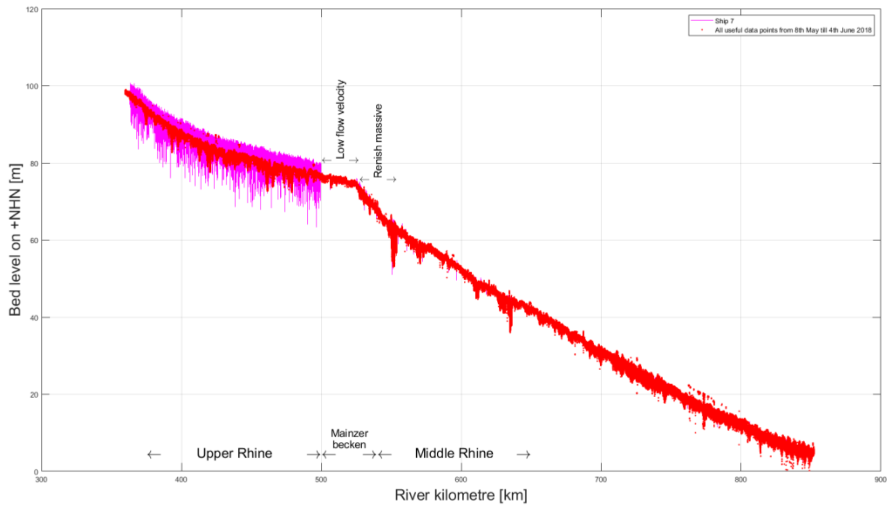


Figure 5-11: Example of a ship with bad data points (Ship 7)

From the above shown figure a bigger variance can be seen in the Upper Rhine and Lower Rhine (river kilometre 700 and rising) then the variance at the Rhenish Massif. This visualisation on the other hand is not that reliable, because the differences are little. Therefore, the variance of the data on River Rhine in Germany is also tested numerically as shown in Figure 5-12. For this variance two periods of time are used. The first period is a week of data (blue dots) and the second period is a month of data (red dots). The variance is calculated for all data points within 100 meters in the longitudinal direction of the river. A river section with a high alluvial character should contain a bigger variance between the data points then a river section with a rock-based river bed.

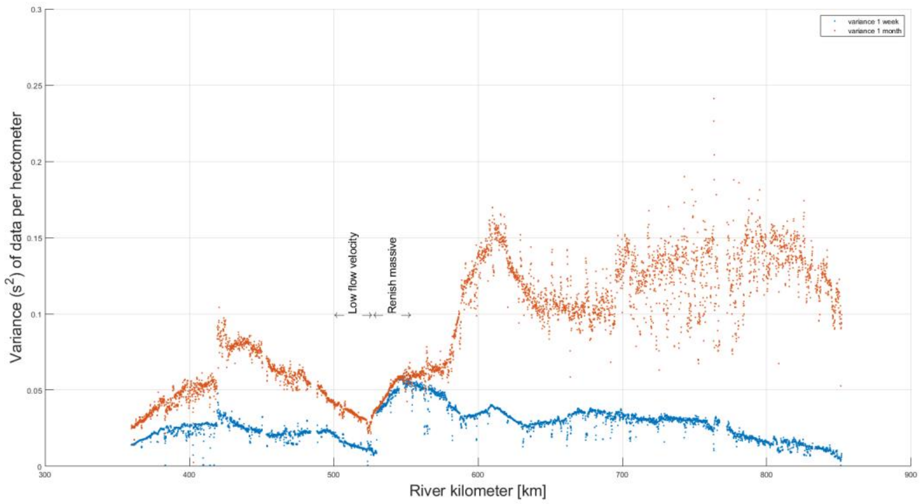


Figure 5-12: Variance of a week of data and a month of data per hectometre on the River Rhine

From Figure 5-12 can be concluded that within a week the variance along the River Rhine shows a big variance of the data points at the Rhenish Massif and a lower variance at the alluvial sections of the River Rhine. This big variance is in line with the literature: 'Due to the morph tectonic uplift of the Rhenish massif, a bedrock channel with rocky islands and irregular cross sections has developed over a length of some tenth of kilometres between Bingen and St. Goar (river km 527 & 554)' (CHR, 2009).

The variance using a month of data shows the same variance of the data points at the Rhenish Massif, but a bigger variance at the alluvial sections of the river. Therefore, it can be concluded that over time the Rhenish Massif has a little variance and is not alluvial, while the other sections of the river show a bigger alluviality. The big variance of the data at the Rhenish Massif with one week of data can be caused because of the big slope of the river at that section. Overall the variance of the River Rhine in Germany shows a plausible result.

5.3. Density of data in Germany

The last part of this chapter consists of a short evaluation on the generation of a bed level chart in Germany compared to the Netherlands. It is known that less vessels sail upstream of the River Rhine in Germany and therefore less data are available at this section, but it is not known how big this difference is compared to the Netherlands. Furthermore, the validated bed level chart (grid size & maximum bed level value) in the Netherlands is tested on the data in Germany.

Figure 5-13 shows an overview of the amount of data points per kilometre in the River Rhine with a week of data. The differences between the Netherlands and Germany are relatively big. Especially between river kilometre 350 and 700, very little data is available.

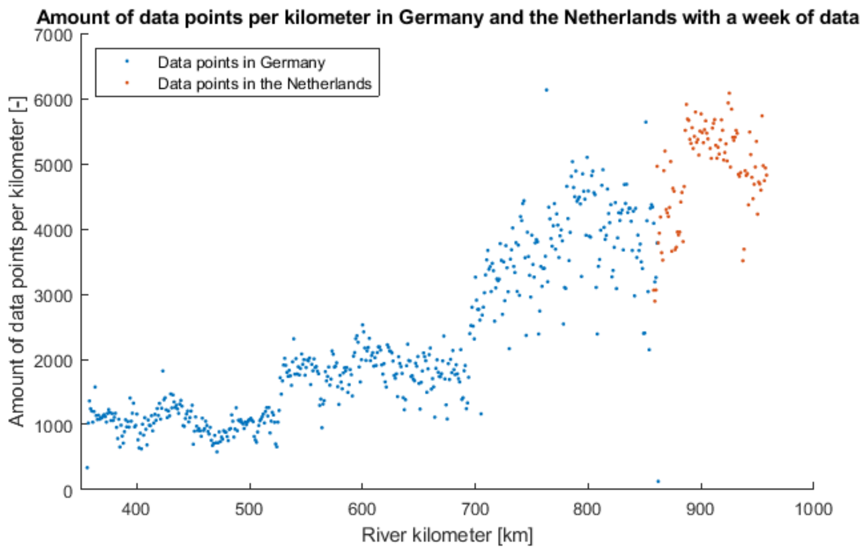


Figure 5-13: Amount of data points per kilometre in Germany and the Netherlands with a week of data

Because of this little amount of data points, gaps occur in the generation of the bed level chart as shown in Figure 5-14. Because this section of the river is highly alluvial, as shown in the previous paragraph, it is no option to fill these gaps with extra data from other weeks, because the bed form development will not be considered.

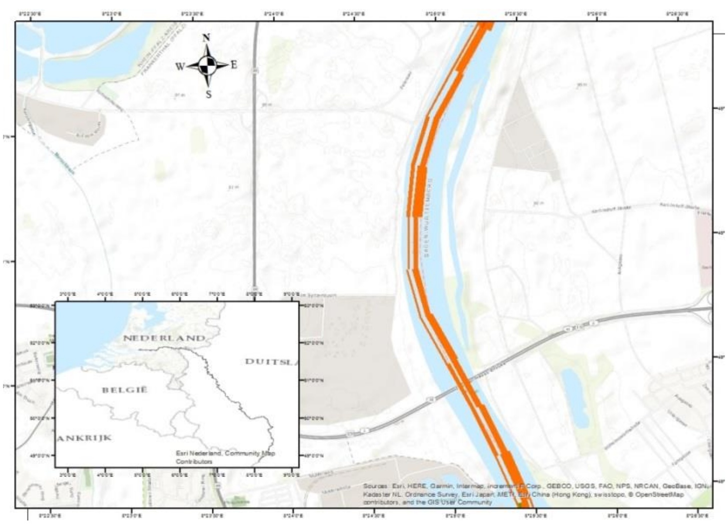


Figure 5-14: Gaps caused by data-poor grid cells

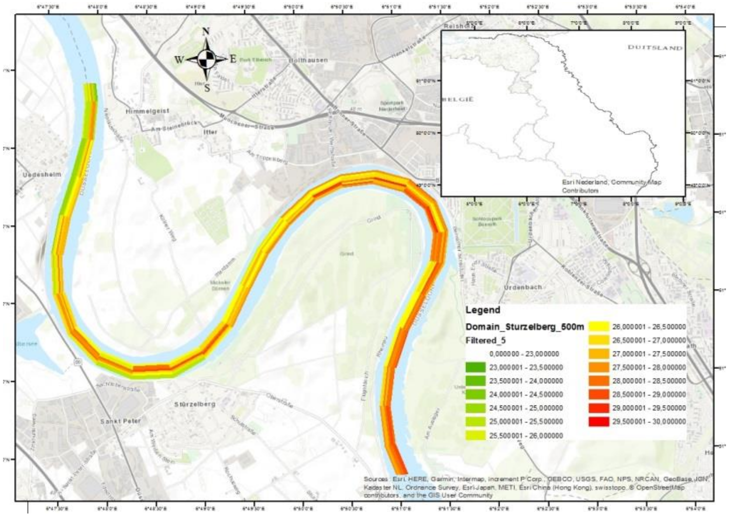


Figure 5-15: Generation of bed level chart with CoVadem data at river km 730

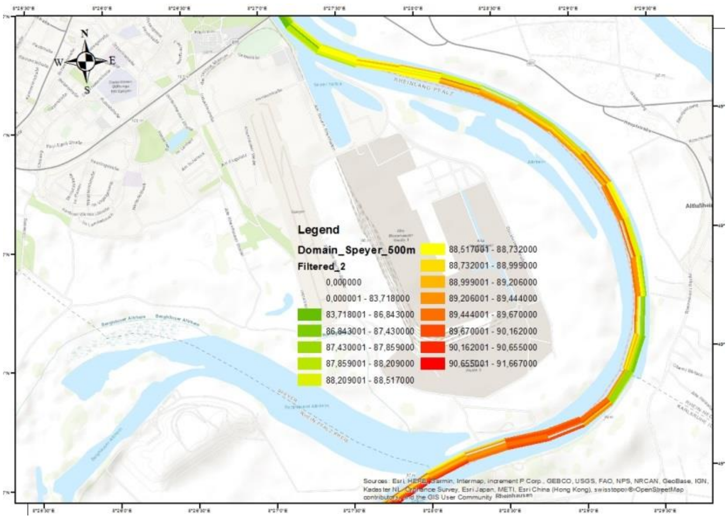


Figure 5-16: Generation of bed level chart with CoVadem data at river km 400

Figure 5-16 shows that at the upstream section of the River Rhine, still a dense bed level chart can be generated in the bends. In comparison to the bed level chart that is generated at the downstream section of the River Rhine (Figure 5-15), it only has a few value-poor grid cells. Overall it shows a representative bed level, with a deeper bed level on the outside of the bends and a shallower bed level on the inside of the bend. It can be concluded that the validated bed level chart from the Netherlands is also applicable in Germany. More visualisations of the maximum bed level in Germany are shown in Appendix A.4.

5.4. Conclusion

From the paragraphs 5.1, 5.2 and 5.3 can be concluded that the River Rhine in Germany partly has a high alluvial character and the approach of the generation of a bed level chart should therefore be the same as the generation of a bed level chart in the Netherlands. The problem that occurs is that the bed level chart becomes less dense further upstream, because of less data. Despite of less data in the upstream section, the bed level chart still looks plausible and therefor there can be concluded that the generation of a bed level chart in the upstream section partly is still useful.

6. Conclusion

In this chapter a conclusion is drawn for the research question that is set in paragraph 1.3 Research Objective. The research question is as follows:

What is the optimal uniform grid, so it is useful for the skipper, the morphological processes are considered, there is sufficient data per grid cell and the grid is applicable both in the Netherlands and in Germany?

For answering the research question, several sub-questions are set up and the conclusions are combined in this paragraph for giving an answer to the research question.

For finding an optimal uniform grid cell size, a hypothesis was set up. This hypothesis implied that an optimum should occur at the intersections of two errors. The optimum that was found was less than the length of one river dune and therefore the morphological processes were not considered. The optimum that was found was not the optimum that is useful for the generation of a bed level chart and therefore the hypothesis of an optimal grid cell size found by the intersection of two errors is rejected.

Another part of the optimal uniform grid is the maximum bed level value that is assigned to a grid cell. Two methods are tested and validated on their performances of the generation of a maximum bed level for a grid cell. The results showed that both methods have their pros and cons, but the best fit, for the representation of the actual maximum bed level, is the calculation of the 95^{th} percentile of all data points in a grid cell. It should be noted that this method is the best fit when the vessels measurement performances are calibrated constantly.

The last part of the optimal uniform grid is the applicability of the grid in the Netherlands and Germany. The grid for the generation of a bed level chart shows reliable results in the Netherlands, but less good results in Germany. The bed level chart that can be generated in Germany looks very plausible, so despite that some sections on the river are missing data and therefore no dense bed level chart can be generated, the uniform grid is also applicable in Germany.

7. Discussion and recommendations

7.1.Discussion

In this paragraph the methods that are used and the results that are generated in this research are being discussed. The methods and results are discussed per sub-question.

Generation of maximum bed level

For the determination of the percentile for method 1 for the generation of the maximum bed level in a grid cell, Multibeam data of the River Rhine in the Netherlands are used. These Multibeam data are considered to be the actual river bed. This is true for the period in time that the Multibeam data are derived, but because of the alluvial character of the river, the river bed can have differences over time. For this reason, a second set of Multibeam data should be used to verify the conclusion that the 95th percentile of all data points in a grid cell represents the best actual maximum bed level.

The generation of the maximum bed level is tested and validated on 2 CoVadem datasets in two subsequent weeks and 1 Multibeam data set from the same period. Because the datasets are from the same period, the differences in the generation of the maximum bed level are not tested on differences between a high and low discharge. These high or low discharges, cause differences in the migration speed of the river dunes and therefore the morphological processes can have differences. Also for the verification of the method for the generation of the maximum bed level, more sets of CoVadem data with corresponding Multibeam data should be tested. For this research only one sample is used, more samples from periods with extremely high or low discharge can give a different result.

The CoVadem data is not from the exact same moment in time as the Multibeam. The data sets differ at a maximum of 1 week, during this week the river bed may change because of bed form migration, which affects the comparison.

The maximum bed levels are partly tested on different grid cell lengths, because there was lack of a big data set. With differing between the grid cell lengths more insight was created on the performances of the CoVadem data. With more datasets, the CoVadem data can be tested better on the grid cell length that is preferred in the application and less on other grid cell lengths, but because there was only 2 weeks of data this was not possible.

Optimization of grid cell size

For the optimization of the grid cell size only two domains are used on the river with the same morphological characteristics. The only difference between the two domains is that one domain is straight and the other has some bends in it. On another domain with different morphological characteristics and different data sets, it is possible to find another optimum. If another method is tested for trying to find an optimum of the grid cell's size, it is useful to use more differences in the data sets.

Evaluation of River Rhine in Germany

The data that are derived from the German section of the River Rhine are not validated properly on the vessels measurement performances as the data that are derived in the Netherlands. The data in the Netherlands are validated on their performances regarding to the fixed layers near St. Andries and Nijmegen (Abdalla, 2018). The data that are derived in Germany are only visually validated on bad vessel measurements. Vessels with a bad offset are not being filtered out, because these differences cannot be seen and it is not known what the actual bed level is, because no Multi- or single beam data are available. Therefore, every conclusion that is drawn from the evaluation of the River Rhine must be put into question.

7.2. Recommendations

This paragraph elaborates on the recommendations that can be done regarding to the improvements that are pointed out in the discussion and regarding to recommendations for future research on the generation of a water depth chart for inland skippers.

From the discussion can be recommended that the generation of the maximum bed level assigned to a grid cell must be investigated on a bigger domain with more data sets. Than a better conclusion can be drawn about how well the bed level chart functions over the time on the different sections of the River Rhine.

Another recommendation that follows from the discussion is that the data in Germany should be validated on a bigger scale. The data in Germany are only validated on the literature that was available about the global bed level, but it is not tested on the actual bed level from Multi- or single beam data.

From the filtering methods that are used for the different scenarios for generating a maximum bed level chart another recommendation can be given. The difference between scenario 2 and 3 showed that vessels can still have sudden bad measurements outside the fixed layers were the vessels can be validated on their performances. Therefore, it is important that the vessels are validated on their measurement performances as frequently as possible. Bad ships with extreme water depths can be filtered out easily, because these data will stand out regarding to the value of a grid cell. A little script which filters out extreme values can already be very useful.

The data especially in the upstream sections of Germany show a big number of gaps in the data sets. Further research needs to be done on the interpolation between the grid cells and extrapolation to the shore of the river.

The pilot version of the 2D water depth chart is now running on the River Rhine from Maxau to Rotterdam. The validations that are done now are only done for the River Rhine and the 2D chart seems to work properly. A next step can be validating the method for the generation of an optimal uniform grid cell on other rivers like the Meuse and the Ijssel or even rivers from different continents and countries.

The data in the upstream section of the River Rhine is scarce. Some sections on the other hand still give a plausible bed level chart and these sections can be used for the application. Further research can be done on what amount of data is needed to give a good estimation for a dense bed level chart.

8. References

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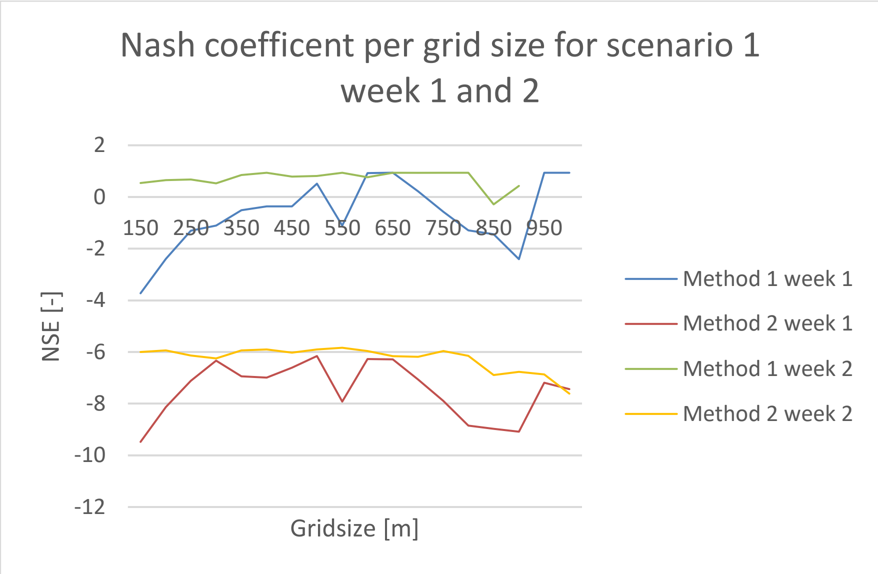
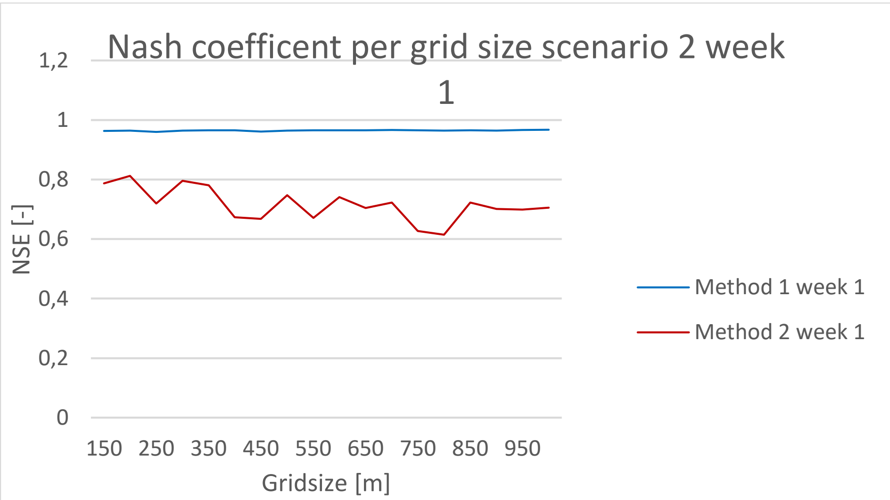
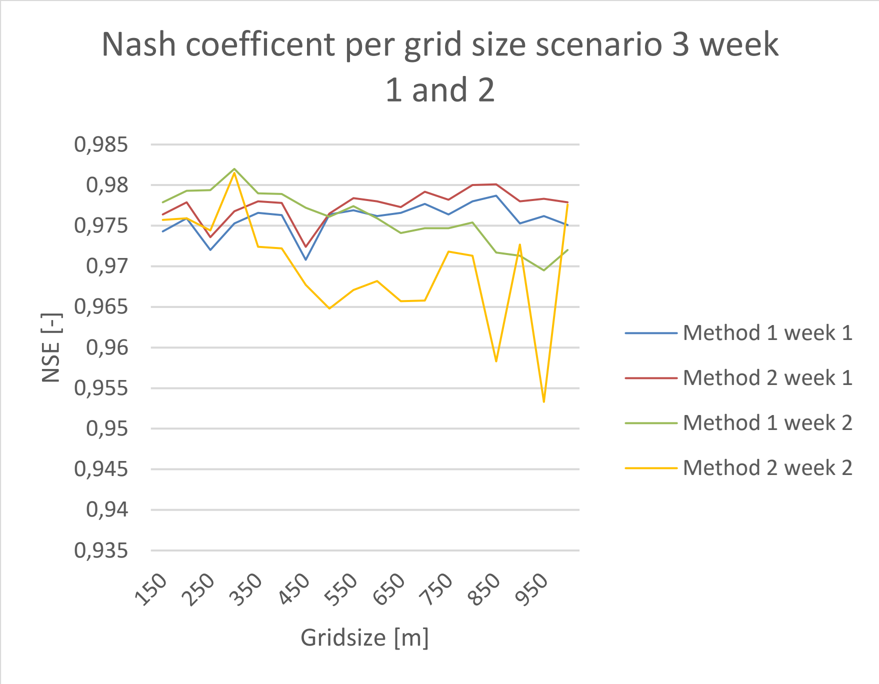
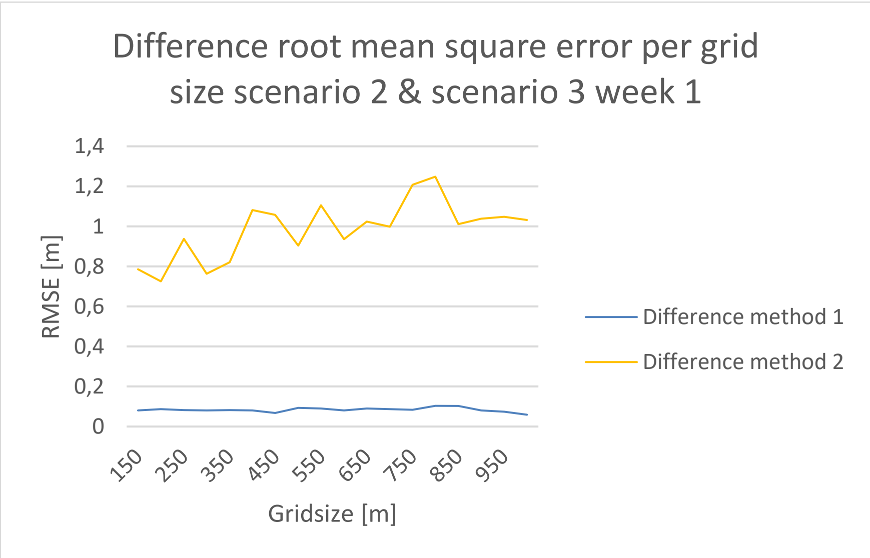
Appendix A Generation of maximum value per grid cell

A.1. Graphs of RMSE and NSE for determination best method






Nash coefficent per grid size scenario 3 week 1 and 2
0,985
0,98
0,975
0,97
0,965
0,96
0,955
0,95
0,945
0,94
0,935
NSE [-]
150
250
350
450
550
650
750
850
950
Gridsize [m]
Method 1 week 1
Method 2 week 1
Method 1 week 2
Method 2 week 2


Difference root mean square error per grid size scenario 2 & scenario 3 week 1
1,4
1,2
1
0,8
0,6
0,4
0,2
0
RMSE [m]
150
250
350
450
550
650
750
850
950
Gridsize [m]
Difference method 1
Difference method 2

A.2. Visualisations of the maximum bed level for different scenarios in a 500-meter grid

In this Appendix multiple figures are shown. This reader's guide can be useful, for a quick interpretation of the results of the figures.

Reader's guide

Figure A-1 to Figure A-4:
These figures display the generated maximum bed level chart at the Midden-Waal and the bends between Nijmegen and Lobith for the Multibeam data using method 1 and 2. These figures are used as reference to the scenarios 1 till 3. The legend consists of a green-to-red colour scale. The green colour displays the lowest bed level at NAP, so the deepest part of the river. The red colour displays the highest bed level at NAP, so the shallowest part of the river.

Figure A-5 to Figure A-8, Figure A-13 to Figure A-16 and Figure A-21 to Figure A-24:
These figures display the generated maximum bed level chart at the Midden-Waal and the bends between Nijmegen and Lobith for the CoVadem data using method 1 and 2. The legend consists of a green-to-red colour scale. The green colour displays the lowest bed level at NAP, so the deepest part of the river. The red colour displays the highest bed level at NAP, so the shallowest part of the river.

Figure A-9 to Figure A-12, Figure A-17 to Figure A-20 and Figure A-25 to Figure A-28:
These figures display the difference between the CoVadem data and Multibeam data for method 1 and 2. The legend consists of a red-to-green colour scale. The red colour displays a CoVadem bed level that is lower than the Multibeam data at NAP. In the translation to the water depth it displays a deeper water depth. This is not preferable; therefore the red colour is used. The colour green displays a CoVadem bed level that is higher than the Multibeam data at NAP. Not preferable as well, but less bad than a bed level that is too deep.

Multibeam

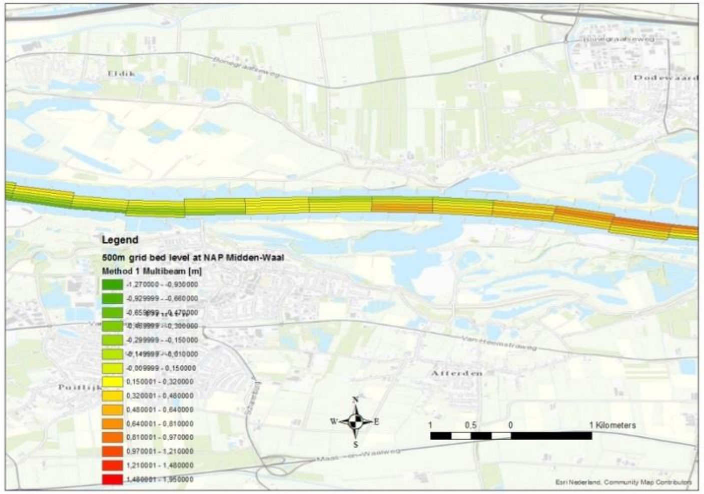


Figure A-1: Maximum bed level of Multibeam data on the Midden-Waal using Method 1

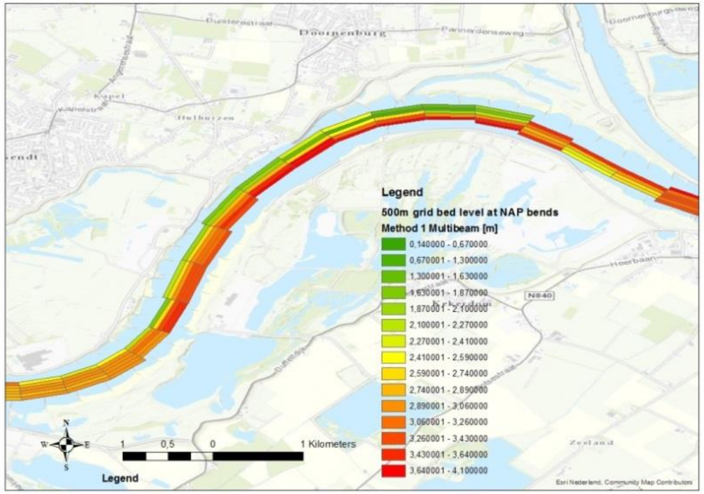


Figure A-2: Maximum bed level of Multibeam data on the bends using Method 1

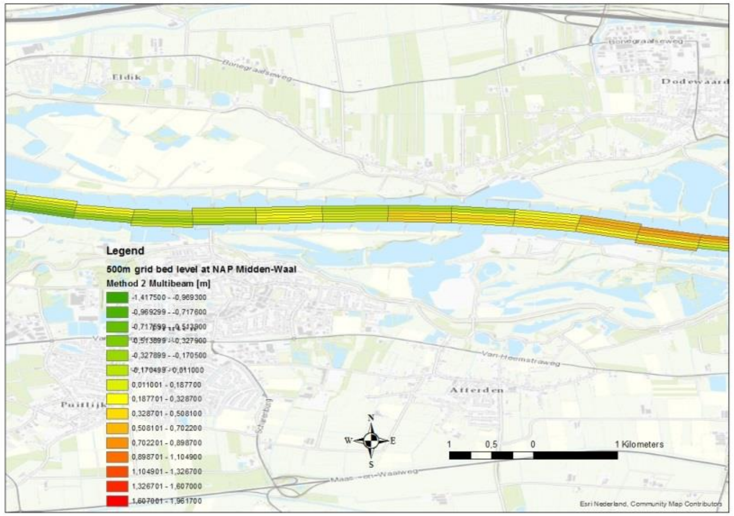


Figure A-3: Maximum bed level of Multibeam data on the Midden-Waal using Method 2

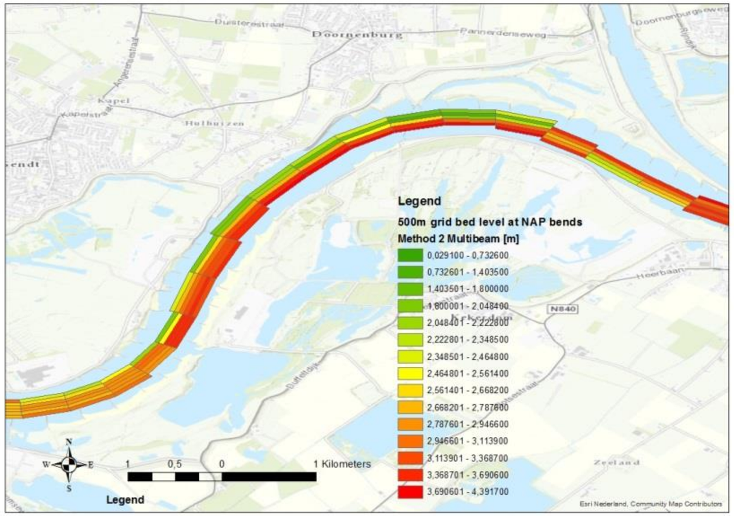


Figure A-4: Maximum bed level of Multibeam data on the bends using Method 2

Scenario 1

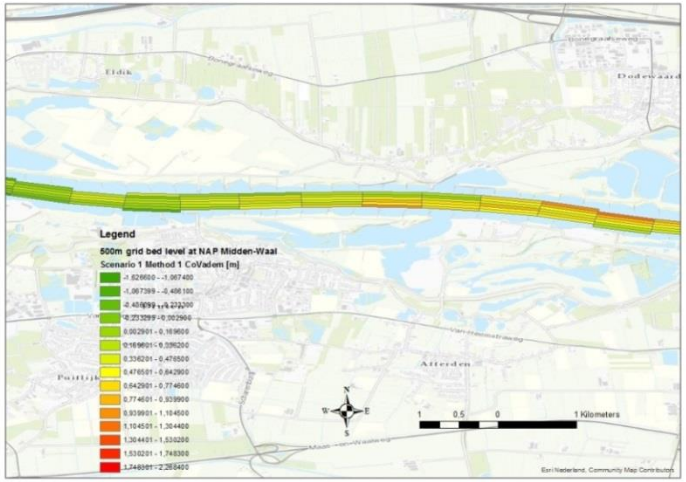


Figure A-5: Maximum bed level of CoVadem data on the Midden-Waal scenario 1 method 1

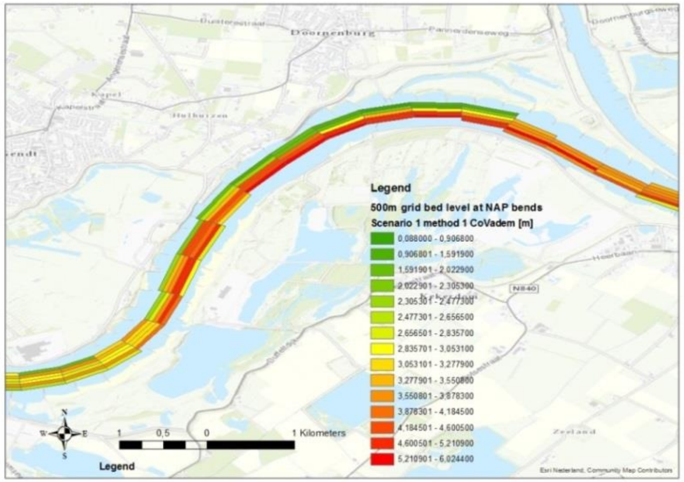


Figure A-6: Maximum bed level of CoVadem data on the bends scenario 1 method 1

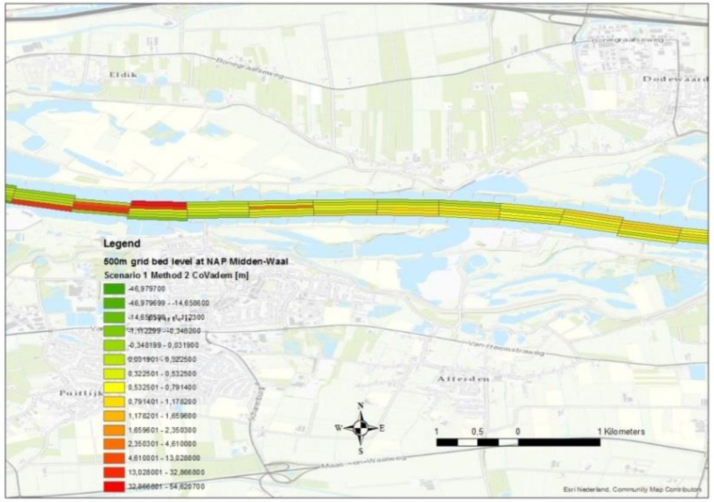


Figure A-7: Maximum bed level of CoVadem data on the Midden-Waal scenario 1 method 2

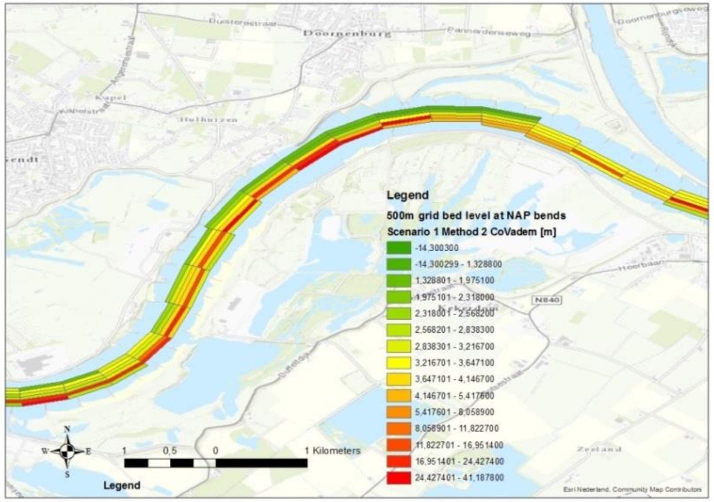


Figure A-8: Maximum bed level of CoVadem data on the bends scenario 1 method 2

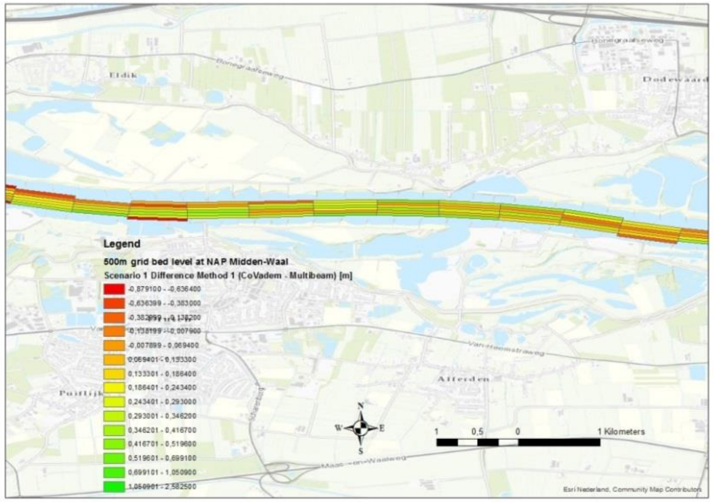


Figure A-9: Difference CoVadem minus Multibeam on the Midden-Waal scenario 1 method 1

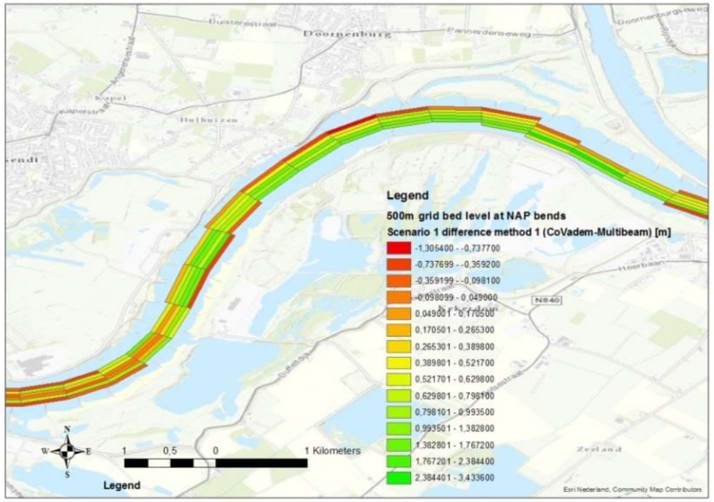


Figure A-10: Difference CoVadem minus Multibeam on the bends scenario 1 method 1

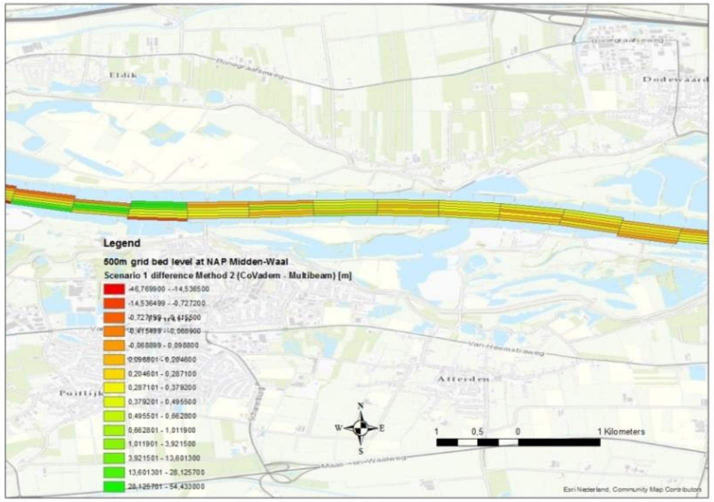


Figure A-11: Difference CoVadem minus Multibeam on the Midden-Waal scenario 1 method 2

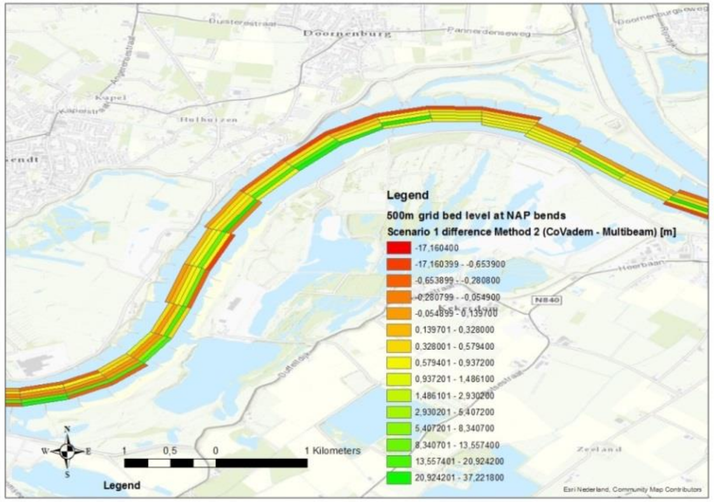


Figure A-12: Difference CoVadem minus Multibeam on the bends scenario 1 method 2

Scenario 2

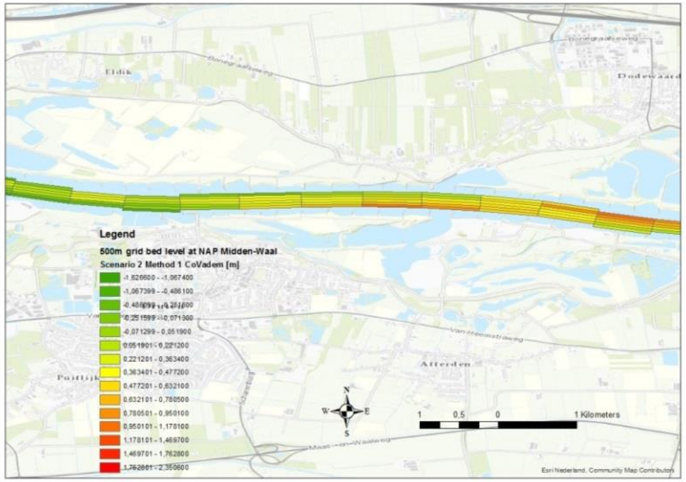


Figure A-13: Maximum bed level of CoVadem data on the Midden-Waal scenario 2 method 1

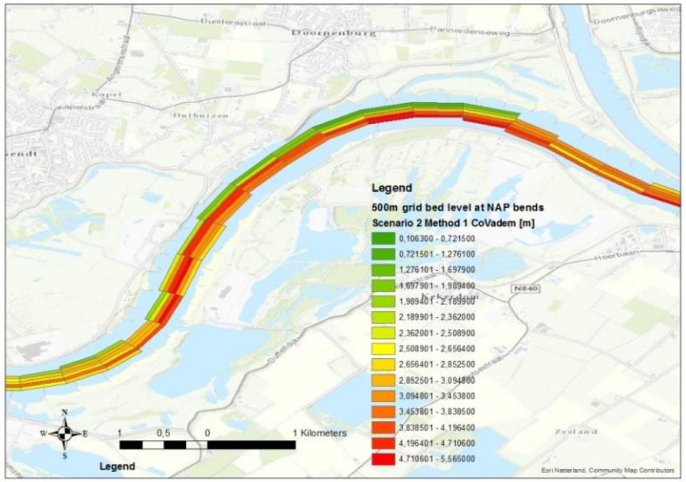


Figure A-14: Maximum bed level of CoVadem data on the bends scenario 2 method 1

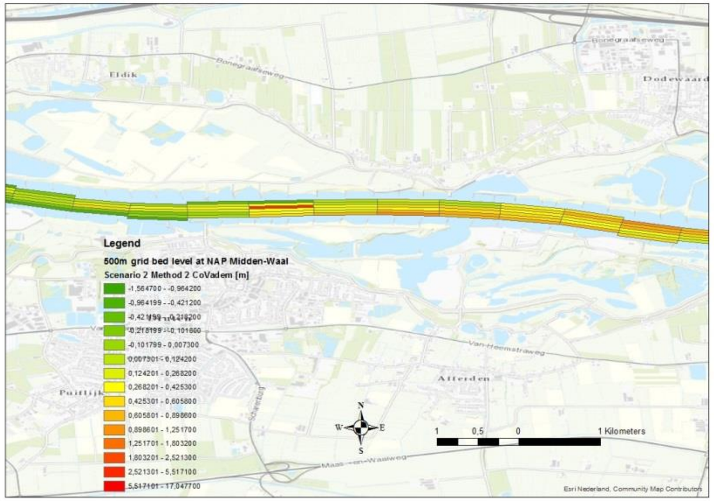


Figure A-15: Maximum bed level of CoVadem data on the Midden-Waal scenario 2 method 2

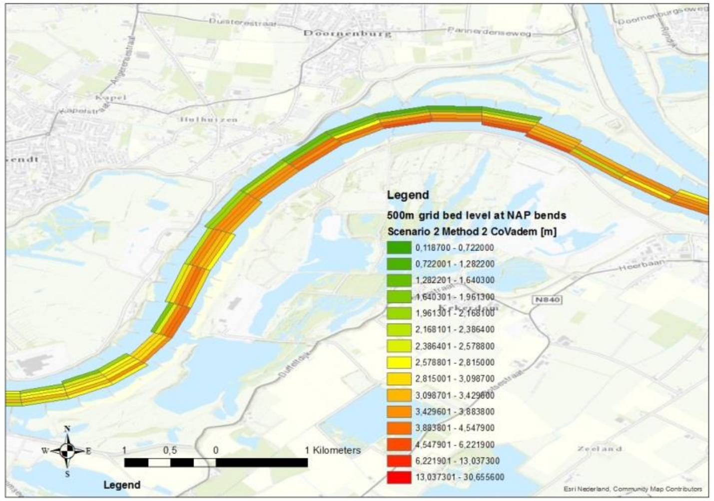


Figure A-16: Maximum bed level of CoVadem data on the bends scenario 2 method 2

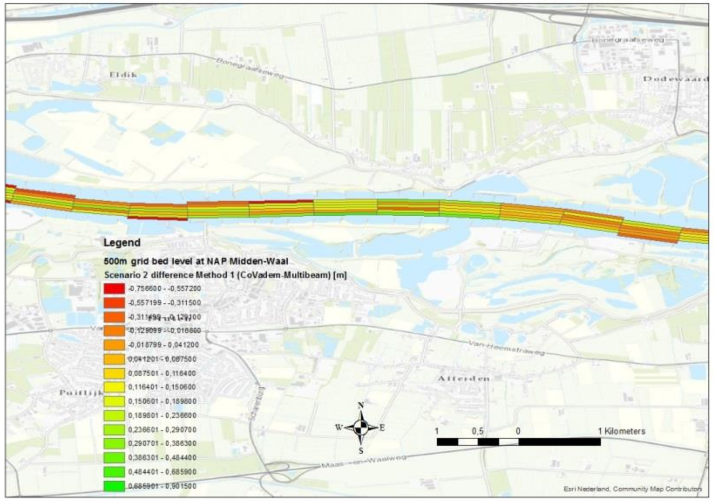


Figure A-17: Difference CoVadem minus Multibeam on the Midden-Waal scenario 2 method 1

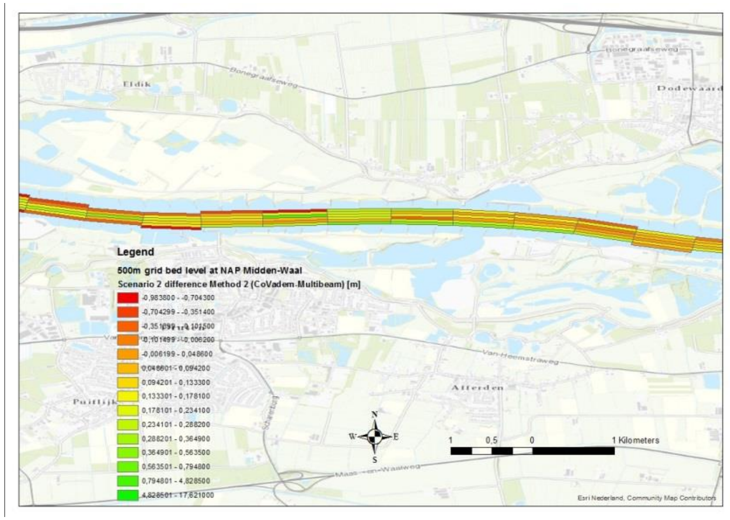


Figure A-19: Difference CoVadem minus Multibeam on the Midden-Waal scenario 2 method 2

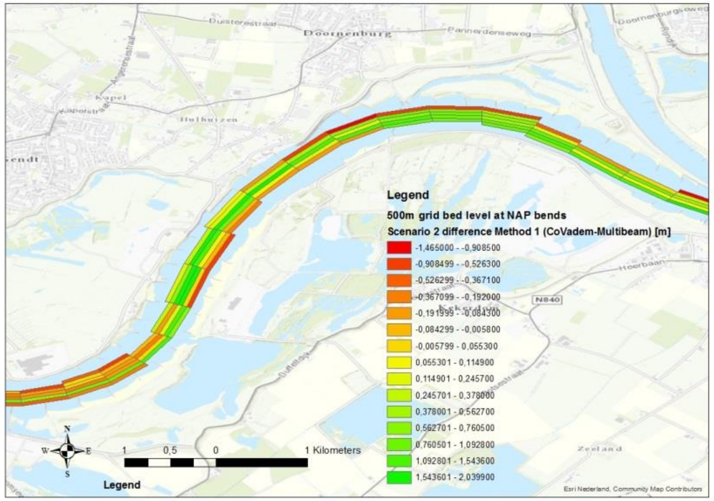


Figure A-18: Difference CoVadem minus Multibeam on the bends scenario 2 method 1

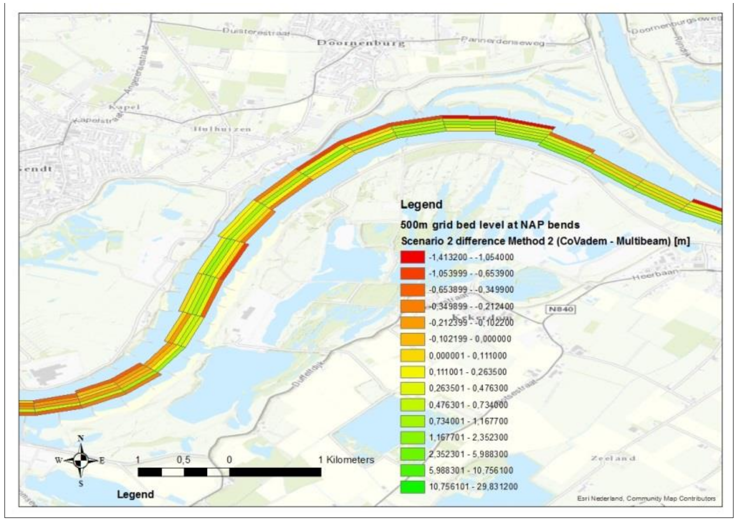


Figure A-20: Difference CoVadem minus Multibeam on the bends scenario 2 method 2

Scenario 3

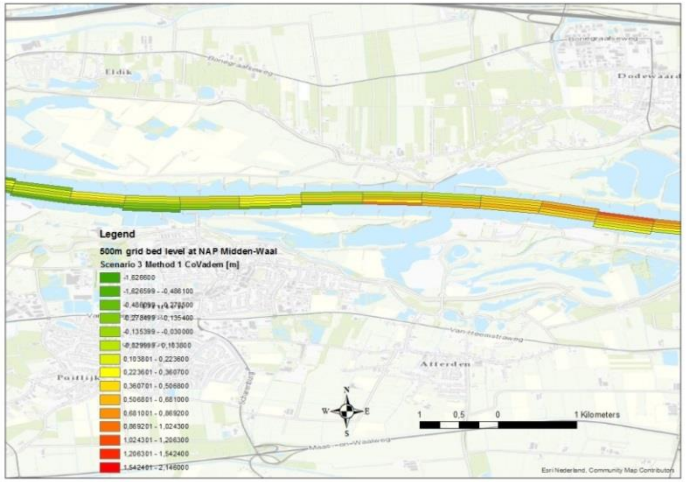


Figure A-21: Maximum bed level of CoVadem data on the Midden-Waal scenario 3 method 1

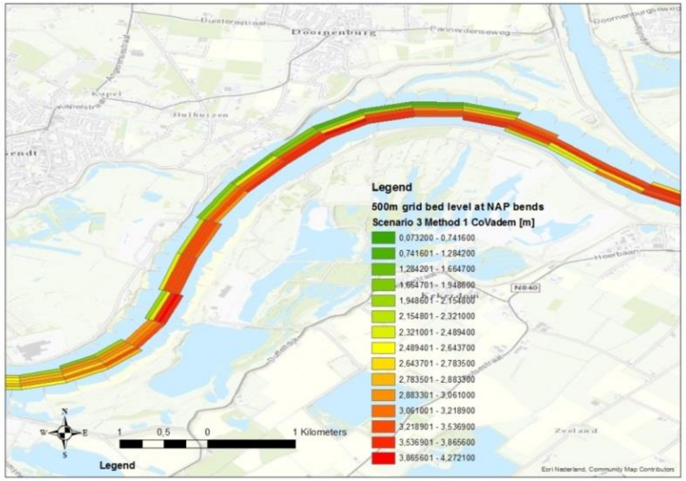


Figure A-22: Maximum bed level of CoVadem data on the bends scenario 3 method 1

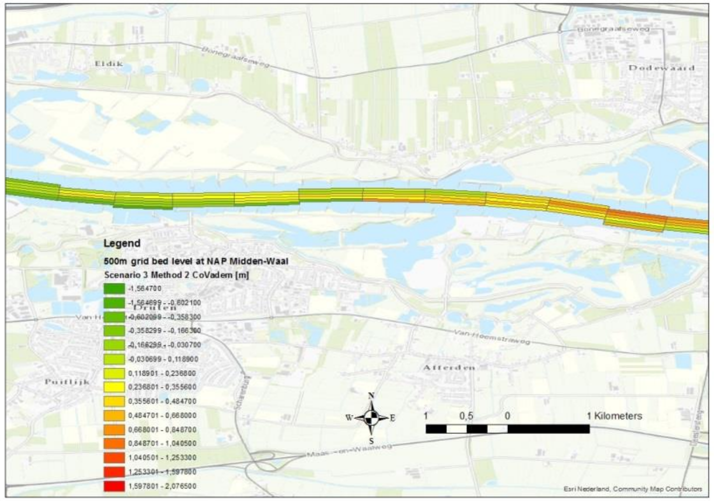


Figure A-23: Maximum bed level of CoVadem data on the Midden-Waal scenario 3 method 2

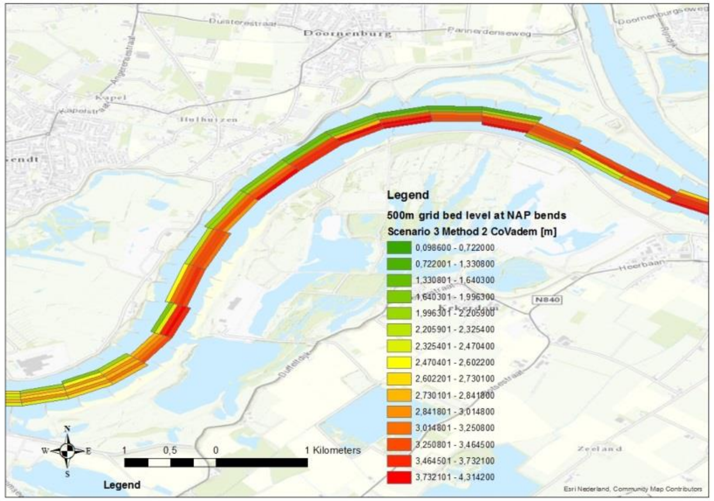


Figure A-24: Maximum bed level of CoVadem data on the bends scenario 3 method 2

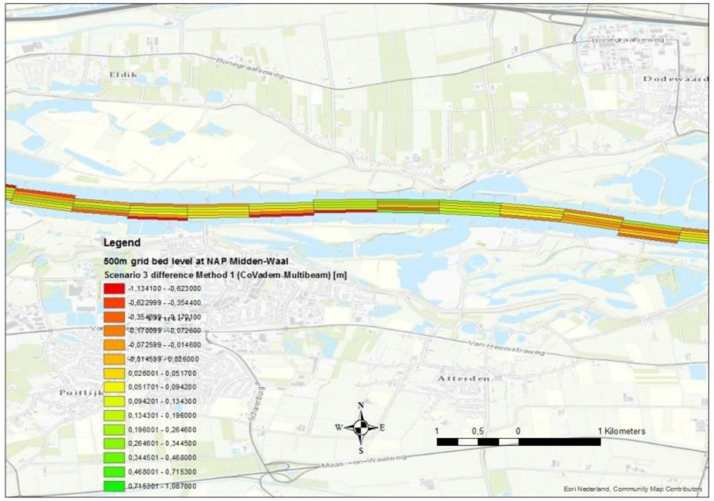


Figure A-25: Difference CoVadem minus Multibeam on the Midden-Waal scenario 3 method 1

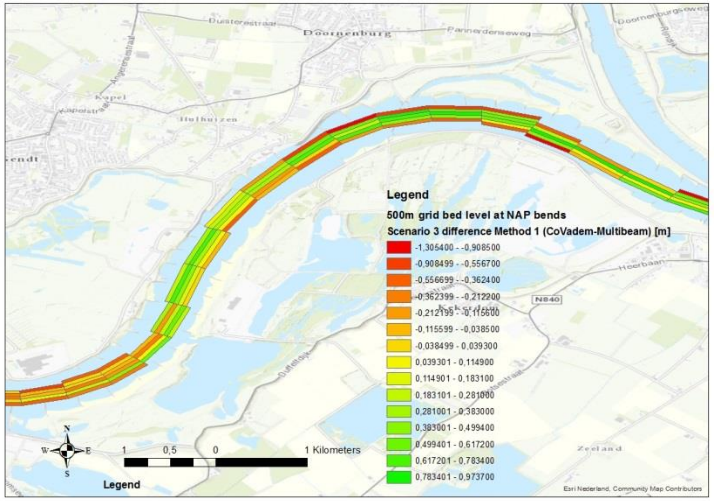


Figure A-26: Difference CoVadem minus Multibeam on the bends scenario 3 method 1

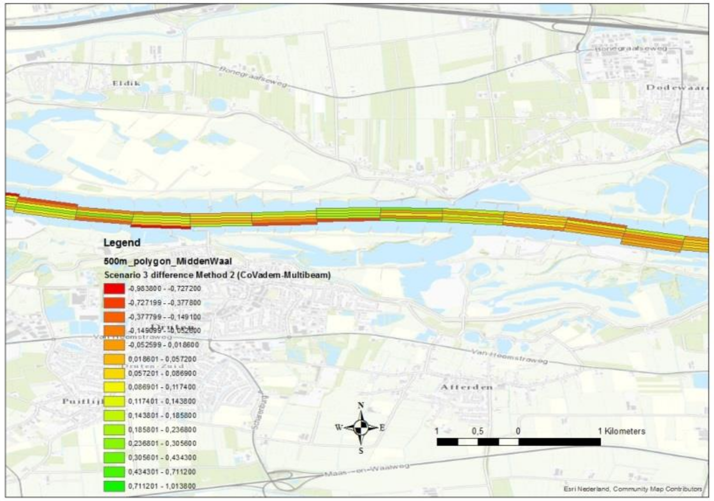


Figure A-27: Difference CoVadem minus Multibeam on the Midden-Waal scenario 3 method 2

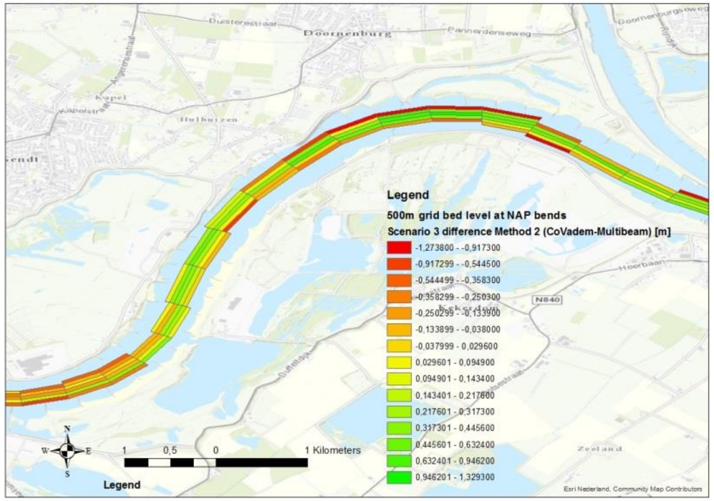


Figure A-28: Difference CoVadem minus Multibeam on the bends scenario 3 method 2

A.3. Longitudinal profiles of the German River Rhine

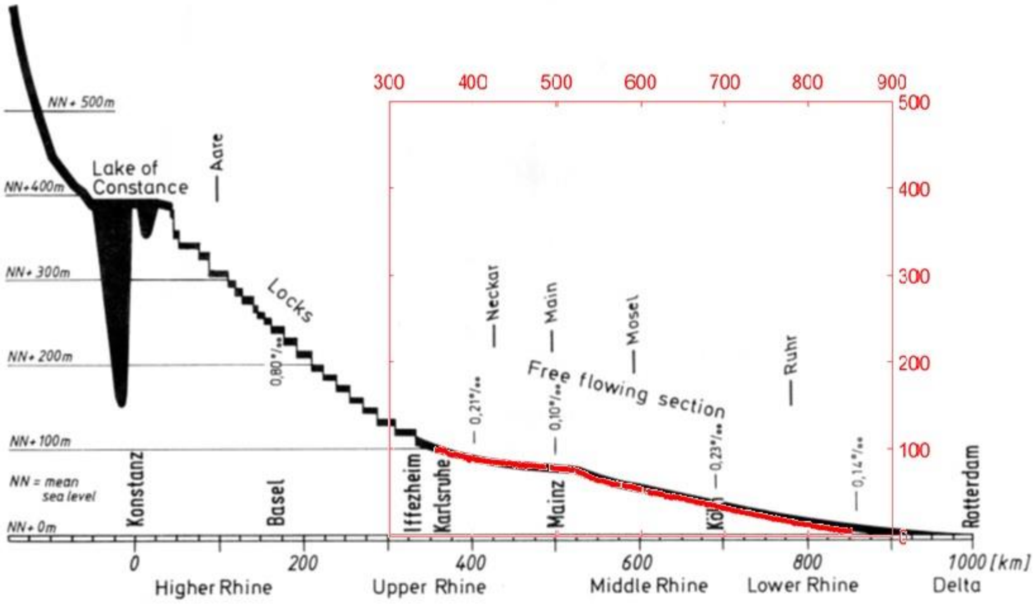


Figure A-29: Comparison of the longitudinal profile of the German River Rhine for week 2

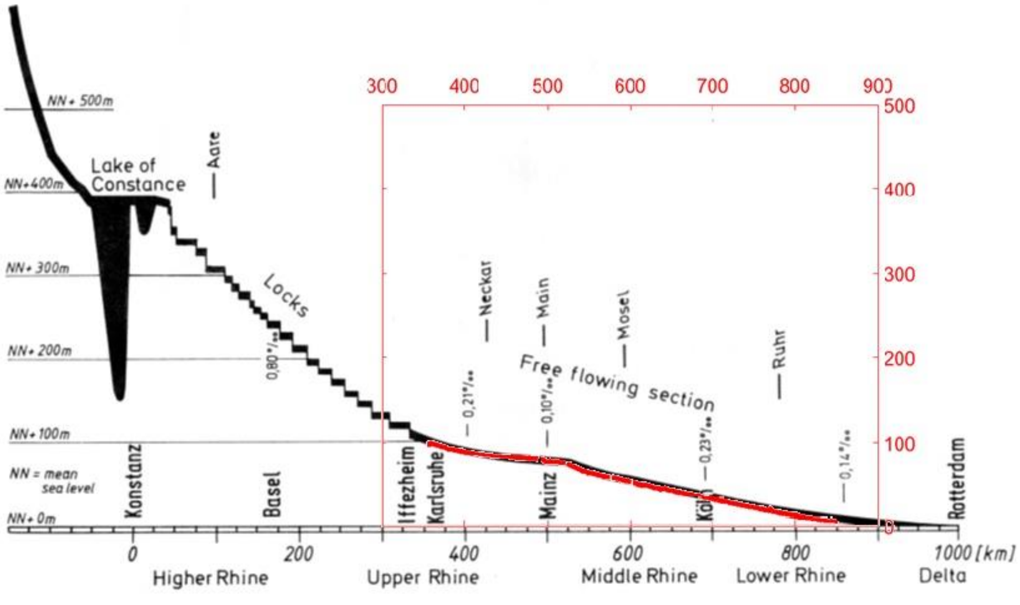


Figure A-30: Comparison of the longitudinal profile of the German River Rhine for week 3

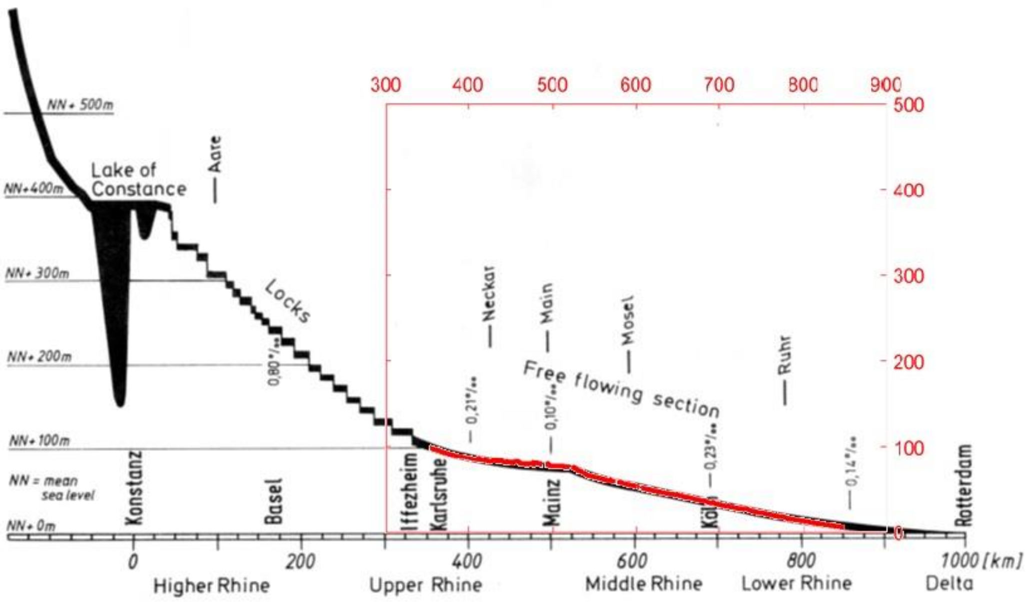


Figure A-31: Comparison of the longitudinal profile of the German River Rhine for week 4

A.4. Visualisations of the maximum bed level for different sections of the River Rhine Germany

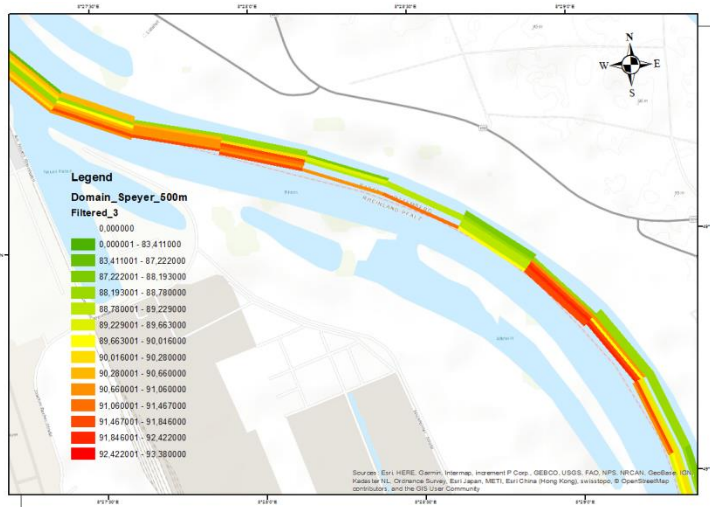


Figure A-32: Maximum bed level Speyer week 2 (15th – 21st May)

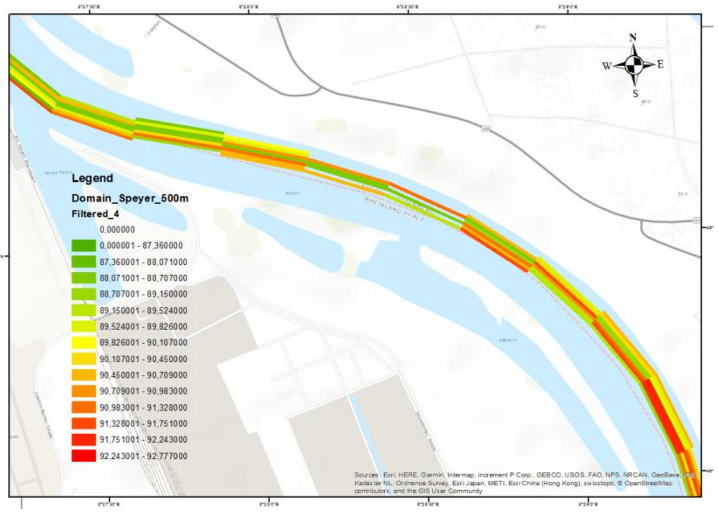


Figure A-33: Maximum bed level Speyer week 3 (22nd to 28th May)

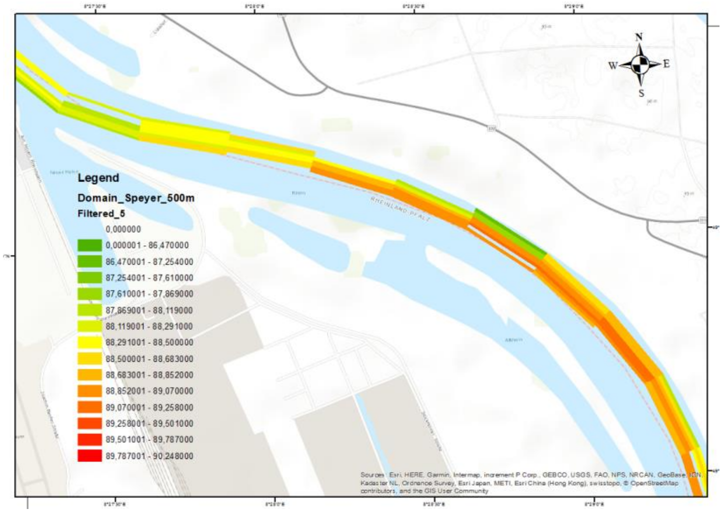


Figure A-34: Maximum bed level Speyer week 4 (29th May – 4th June)

In Figure A-32, Figure A-33 and Figure A-34 generated maximum bed levels at Speyer are shown. Speyer is an upstream section of the River Rhine at river kilometre 400. Week 2 shows bad results, because the differences in the inner and outer bend are too big, so this week does not give reliable results. The other weeks on the other hand show better results. Especially the fourth week shows a representative bed level with smooth transitions between the grid cells. From all three figures can be concluded that value poor grid cells occur along the grid, so there is little data in all weeks.

On the next page maximum bed levels at Koln (river kilometre 690) are shown. At this further downstream section with more vessel tracks in a week, a denser bed level chart can be generated than the bed level chart that is generated at Speyer.

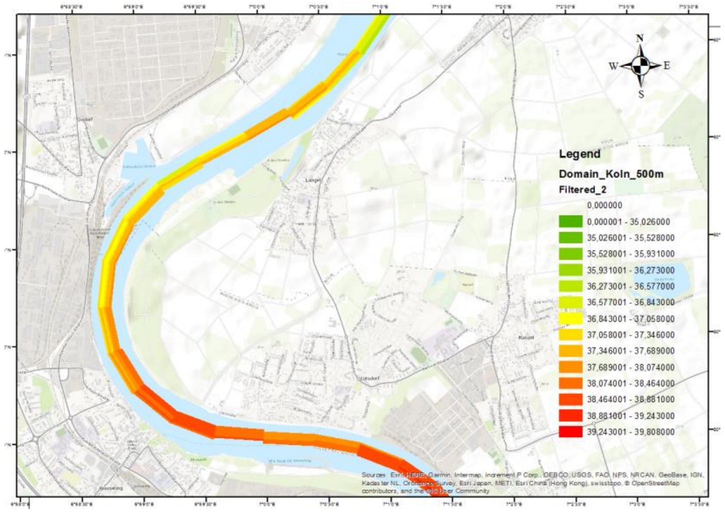


Figure A-35: Maximum bed level Koln week 1 (8th – 14th May)

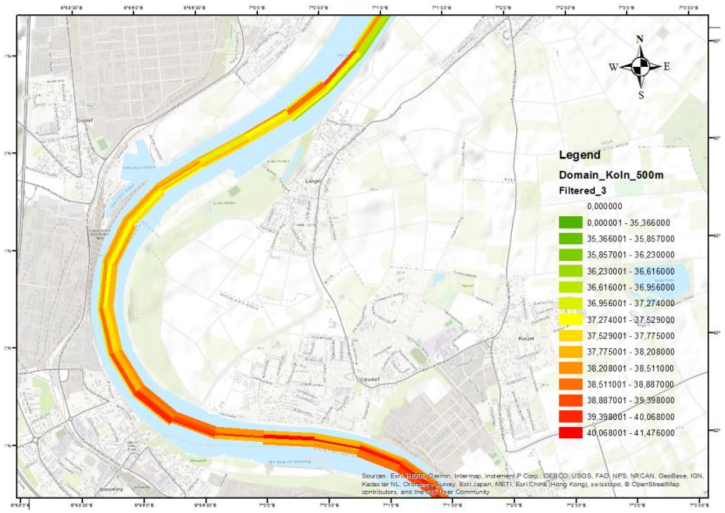


Figure A-36: Maximum bed level Koln week 2 (15th – 21st May)

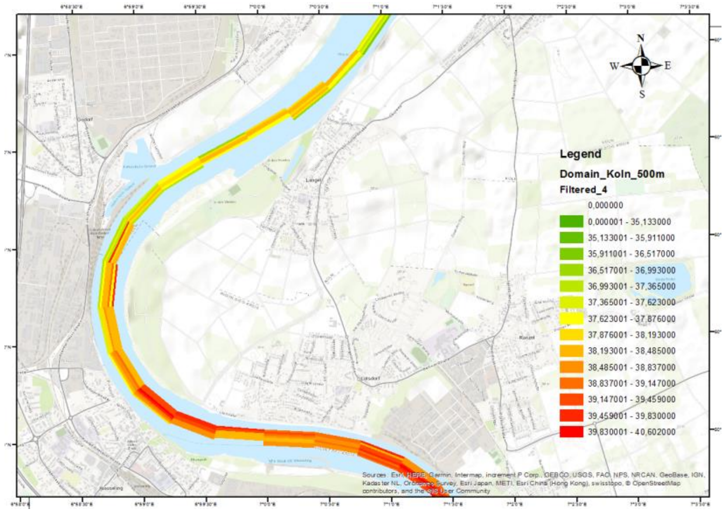


Figure A-37: Maximum bed level Koln week 3 (22nd – 28th May)

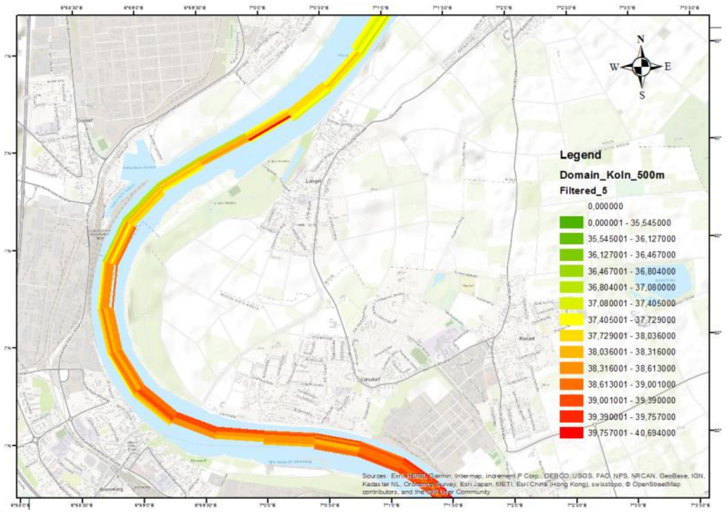


Figure A-38: Maximum bed level Koln week 4 (29th May – 4th June)

Appendix B Matlab code description

B.1. Description of translation water depth to bed level

The first step consists of filtering out negative values for the water depth. Approximately half of the CoVadem data represents a negative water depth of -999 m. These are caused by an error in the translation from under keel clearance to water depth and are therefore not useful for this research. These values are also being filtered out in the generation of the real-time water depth chart in the application for the skippers.

For next steps another data set is used. This dataset consists of the water levels at 8 hydrological stations for every 10 minutes. The locations of these hydrological stations along the River Rhine are shown in Figure B-1. Besides the water levels, the locations of these stations in the Cartesian coordinate system and the place on the River Rhine in kilometres are known as shown in Appendix B.2.

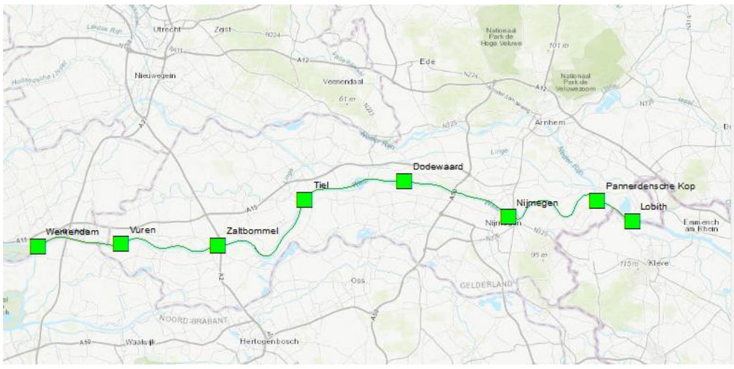


Figure B-1: Hydrological stations along the River Rhine

For the determination of the water level at NAP for each data point, the water levels at the hydrological stations must be linear interpolated in time and space. For these interpolations a code is constructed in Matlab.

Interpolation in time

For the linear interpolation in time, each CoVadem data point is interpolated in time with the water level data from hydrological stations. This resulted in a matrix with water levels on all hydrological stations at the time of each data point.

Interpolation in space

The interpolation in space is the next part in the transformation from water depth to bed level for each data point. This interpolation in space is done in two steps. The first step is to calculate the place on the river in kilometres for each CoVadem data point. For this step, a delivered dataset is used. This dataset represents points on the river-axis of the River Rhine each hectometre. These points have an X- and Y-coordinate the same as each CoVadem data point. With this dataset the distance on the River Rhine for each CoVadem data point can be calculated. A visualisation of this interpolation is shown in Figure B-2.

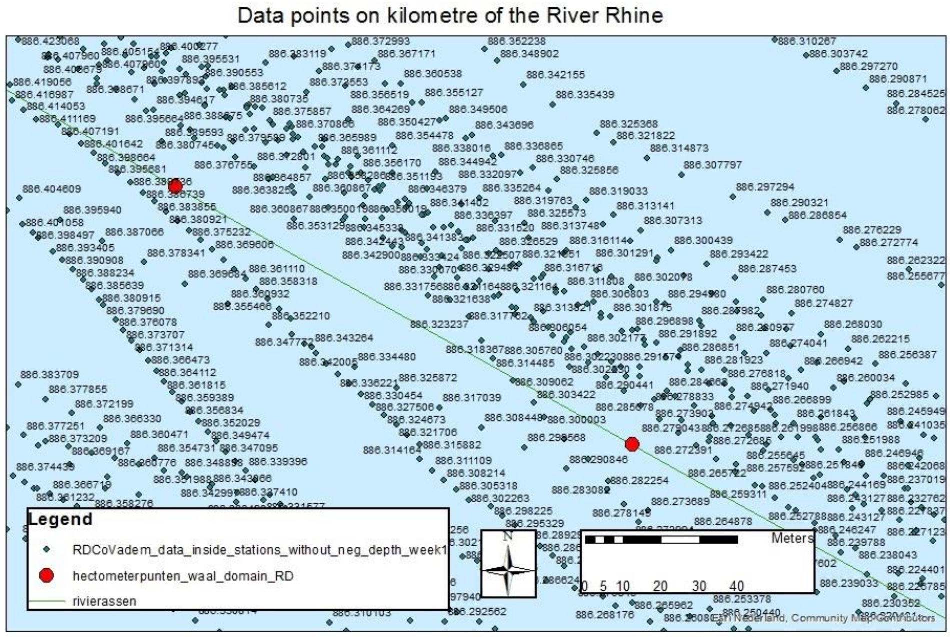


Figure B-2: Data points on kilometre of the River Rhine

The second step is the calculation of the water level at NAP for each CoVadem data point and from there the generation of the bed level at NAP. This is done with again a linear interpolation in space. The distance in river kilometres of the CoVadem data point is known, as is the distance in river kilometres of each hydrological station. With the generated water levels at the hydrological stations for each data point in the time, the water level at each data point can be generated using interpolation in space.

After these steps equation 1 is used for the translation of the CoVadem data water depth data to bed level at NAP so it can be validated with the Multibeam data.

Equation 1: $Bed\ level_{NAP,t,x} = Water\ level_{NAP,t,x} - Water\ depth_{CoVadem\_data,t,x}$

For the generation of a real-time water depth chart, CoVadem data of 1 week is being used. Therefor the last step in the translation to a useful data set is splitting the CoVadem data to a scope of one week. CoVadem data from 1 September 2017 till 15 September 2017 is available, so 2 weeks are generated from this data set as is shown in Table B-1.

Table B-1: Dates weeks

Week	Date
1	1 September – 7 September 2017
2	8 September – 14 September 2017

B.2. Locations of hydrological stations and CoVadem data points on the River Rhine

Table B-2: Locations of hydrological stations on the River Rhine in the Netherlands

Hydrological station	River km [km]
Lobith	862
Pannerdensche Kop	867
Nijmegen	884
Dodewaard	900
Tiel	915
Zaltbommel	933
Vuren	948
Werkendam	961

Table B-3: Locations of hydrological stations on the River Rhine in Germany

Hydrological station	River km [km]
Maxau	359,8
Philippsburg	385,5
Speyer	397,8
Mannheim	422,6
Worms	440,9
Nierstein	478,7
Mainz	496,8
Bingen	525
Kaub	544,5
Boppard	568,5
Braubach	578,3
Koblenz	589,2
Andernach	610
Oberwinter	635
Bonn	655
Koln	689,2
Dusseldorf	744,3
Ruhrort	780,7
Wesel	814,3
Rees	837
Emmerich	852