Exploring the D-RATIN tool

Studying inland navigation potential using a rapid assessment tool

Deltares

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Summary

The economic viability and competitiveness of (sea) ports have an intimate relation with the quality of the inland waterway network that connects the ports to the hinterland. Rivers form the main arteries of this network, but their natural behaviour may create local navigability bottlenecks such as shoals and sharp bends. Traditionally, engineering interventions to maintain and improve river navigability involved relatively complex, time consuming studies. Recent data developments however, have brought rapid assessments within reach.

In line with this data development, the knowledge institution Deltares has developed the D-RATIN tool (**D**eltares - **R**apid **A**ssessment **T**ool for **I**nland **N**avigation). This tool provides quantitative river information regarding geometrical, hydrological and geographical river aspects as well as navigational bottlenecks and the costs of required interventions, based on open source data, which can be used for consultation purposes. The tool allows policymakers to evaluate a river's navigation potential in the planning phase more quickly, due to the reduction of the required input data.

This research aimed to achieve two goals. The main goal was to study whether the tool is able to generate the intended quantitative river and bottleneck data. To achieve this goal the tool has been applied to a case study. This case study tried to determine the economically optimal shipping lane dimensions for the Tocantins River in Brazil. However, the success of the tool is not only determined by the functioning of the tool itself. The role that the tool is able to fulfil within the total framework of an inland navigation study is almost equally important. Therefore, the second goal was to study what role the D-RATIN tool might fulfil within such a study.

The performed study showed that the D-RATIN tool is able to produce quantitative river data that can be used for consultation purposes. Yet, the tool's output results contain significant uncertainties that limit the usability. Therefore, the tool is only able to roughly locate bottleneck locations. However, a proper cost indication is not yet possible, partly because some bugs are found in the cost calculation algorithm. Furthermore, the tool seems to deliver river data to which many elements of a full river study depend on. The earlier availability of this important river data might cause the full river study process to be smoothed and allows for more intensive stakeholder involvement in the planning phase of a river study. Even though the tool only delivers quite specific output results that are highly uncertain.

Acknowledgement

Conducting this research has not been possible without the help of many individuals. Therefore, I would like to express my deepest appreciation to all those who helped me throughout this research.

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1 Introduction

1.1 Context

Inland shipping is a modality that has a lot to offer to freight transport. Not only is this a way of transporting freight cost-efficiently, it also offers high reliability, a high safety level and compared to road transport, emissions are relatively low [1]. It is mainly because of these reasons, combined with the highly navigable waterway network that in the Netherlands about 80% of the bulk cargo is transported by the inland waterways [1].

Although inland navigation plays a key role in freight transport in the Netherlands, many other countries do not use this modality to such a high extent. This is often caused by the poor state of the inland waterways which are not easily navigable. This lack of navigability could be attributed to several factors, of which physical bottlenecks in rivers is the most prevalent. These bottlenecks, such as shoals and sharp bends, are mostly caused by the river's natural behaviour such as erosion. However by dredging and some other related interventions, human interference can resolve these problems, allowing the river to become navigable. This could be beneficial for the viability and competitiveness of ports, which have an intimate relation with the quality of the inland waterway network connecting the port to the hinterland [2]. Secondly, regions surrounding the river and ports may experience positive economic effects as well, from these infrastructural improvements.

Typically, relatively complex and time consuming studies are needed in order to improve river navigability. Also, for the less developed parts of the world, there is a lack of available data in order to perform these studies. However, recent data developments have brought more rapid assessments within reach [2]. In line with this data development, the knowledge institution Deltares has developed the D-RATIN tool (**D**eltares **R**apid **A**ssessment **T**ool for **I**nland **N**avigation). This tool aims to provide quantitative information regarding geometrical, hydrological and geographical river aspects as well as navigational bottlenecks and the costs of required interventions, based on open source data, which can be used for consultation purposes [2]. This allows policymakers to evaluate a river's navigation potential in the planning phase more quickly, because of the reduction in required input data.

To achieve this, D-RATIN performs three steps as presented in Figure 1.1. Firstly, the D-RATIN tool reconstructs the river's bed-levels. The tool offers multiple options to reconstruct these bed levels. Firstly, there is an option for a fully theoretical bed level reconstruction, with the aid of a simplified geometrical and physics-based model. This option will be used when no bathymetric data is available. The second option is based on interpolation. This option interpolates bathymetric data in order to reconstruct the bed levels of the full river section. The third option combines the theoretical data obtained by the first method with a limited amount of available bathymetric data and fuses these two datasets into one bed level model. After the river is reconstructed, a 1D SOBEK model calculates the water depths in the river, by solving the Saint Venant equations. Based on these water depth calculations and the dimensions of the shipping lanes; the third section will apply a route optimization algorithm using a cost-function. This algorithm is based on dredging volume and shipping distance. The algorithm tries to obtain the 'optimal' route and calculates the volume of dredging and the costs of the needed river interventions for a given ship dimension.

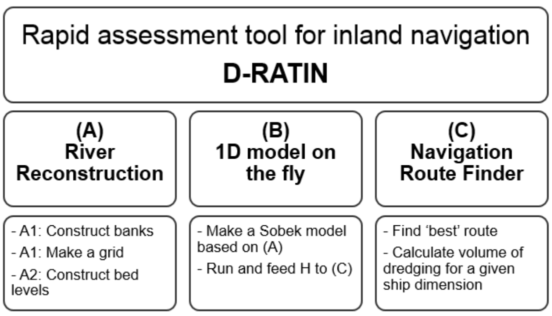

Figure 1.1: conceptual model of the D-RATIN tool

1.2 Related work

The background principles used to reconstruct the river's bed-levels are described in the master's thesis "Combining a Physics-based Model and Spatial Interpolation of Scarce Bed Topography Data in Meandering Alluvial Rivers", conducted by Zervakis [3]. Not only are the background principles described, also the implementation of these principles within the tool and the tool's performance on some river sections in Europe and America are discussed in this study. This information is crucial for a proper interpretation of the output results.

Zervakis performed experiments validating the D-RATIN theory based bed-level results with the actual ground truth. These experiments show that the tool is able to reconstruct general patterns throughout the river section, purely based on physics based model. However, the model does not properly predict the extremer values in the river. For each studied section, Zervakis calculated the Root Mean Square Deviation (RMSE). This value represents the accuracy of the model [4]. For this model the RMSE value differs per scenario, in Zervakis' case it ranged from 0.7m to 4.8.m. This high variation does show that whether the theoretical model generates acceptable results depends highly on the scenario. Zervakis also shows that only few data is required to significantly improve the results, in all cases less than 0.3% of the available data was required to significantly improve the accuracy.

Furthermore, Zervakis addresses some recommendations regarding the use of the bed-level reconstruction model, which are relevant to this research. Firstly Zervakis claims that the grid's resolution does not bear a hindrance in terms of running time. In his research Zervakis has not noticed a significant change in computation times when a finer grid was used. All computations remained within a five-minute range. Hence, Zervakis recommends the use of a fine grid, close to the initial collected data resolution. Yet, Zervakis experiments only involved relatively small river sections, compared to the sections that will be studied in this research.

Secondly, Zervakis concludes that the bed-level calculations only hold true for alluvial rivers that consist out of a single channel, which do not have to sharp bends, that are relatively constant in the width and which have no sandbars in their path. Therefore, the tool is not applicable to sections that include bifurcations. Nevertheless, in case of bifurcations the river can be assessed by dividing the river section into segments, which then can be assessed separately.

1.3 Research goals and questions

This research aims to achieve two goals. The main goal is to study whether the tool is able to generate the projected quantitative river and bottleneck data. To achieve this goal, the tool will be tested in a case study. This case study tries to determine the economically optimal shipping lane dimensions for the Tocantins River in Brazil. However, the success of the tool is not only determined by the functioning of the tool itself. The role that the tool is able to fulfil within the total framework of an inland navigation study is almost equally important. Therefore, the second goal is to study what role the D-RATIN tool might fulfil within such a study. Satisfying these goals will thus not only result in information about the functioning of the tool itself. It will also clarify whether the tool is a useful addition to the current way of studying inland navigation, as well as how it should be used in such a study.

The two goals have been translated to a set of research questions. The main research question aims to fulfil the main goal. This main question will be answered by the first two sub-questions. Sub-question three will address the second research goal. Sub-questions four and five are related to both research goals.

Main research question:

"To what extend is the quantitative data produced by the D-RATIN tool useful in a specific case study?"

Sub-questions:

1. *"Which river case allows this study to properly test the tool?"*
2. *"To what extend can the results generated by the D-RATIN tool make a contribution to obtain the optimal waterway dimensions?"*
    a. *"Which waterway dimensions are required for each barge type?"*
    b. *"How should the tool be used in case of bifurcations in the river?"*
    c. *"Which locations currently obstruct the river from being navigable?"*
    d. *"What are the costs of the needed interventions in the riverbed as well as the costs for other required infrastructure for each relevant vessel class?"*
    e. *"What are the economical profits gained by the done interventions for each relevant vessel class?"*
    f. *"How should the results generated by the D-RATIN tool be interpreted?"*
3. *"What role can de D-RATIN tool fulfil within a full inland navigation study?"*
    a. *"What are the required elements for a full inland navigation study?"*
    b. *"Which elements of a full inland navigation study depend on the information provided by the D-RATIN tool?"*
4. *"What are limitations of the D-RATIN tool? "*
5. *"What are logical improvements of the tool in order to increase its functionality?"*

2 Tocantins River

Since this research aims to test the D-RATIN tool in a case study a river is required that allows to test all the functions of the tool. It is also important that enough information regarding the economic relevance is known for the river. A river that met those requirements and therefore has been chosen is the Tocantins River in Brazil. A full motivation about the river choice can be found in Appendix 11.1.

The Tocantins River, shown in Figure 2.1, is a 2.640 kilometre long river located in Northern Brazil. The river flows from the south to the north through the four Brazilian states of Goiás, Tocantins, Maranhão, and Pará. Although this river is located near the Amazon the Tocantins River actually forms a separate drainage basin. This basin covers an area of around 800.000 square kilometres [5]. The discharge in the river highly fluctuates during the year with a minimum of about 2.500 m^3/s and a maximum of about 25.000 m^3/s. The average monthly discharge, measured at Itupiranga, is presented in Figure 2.2 [6].

Figure 2.1: Tocantins River

According to Arcadis there are opportunities regarding navigational potential of the Tocantins river [7]. The advent of a steel plant in Marabá will lead to a predicted yearly cargo demand of about 32.5 million tonnes. Arcadis advises to prepare the Tocantins River for inland navigation for vessels consisting of 4 barges. The intervention costs, for this vessel type, are estimated around 180 million BRL[1], taking dredging, riverbank strengthening and signalling costs into account. Not only between Marabá and the Ocean does Arcadis see opportunities; they also address the transport opportunities further upstream of the river. However, these opportunities require more radical interventions, like dams. For this research these plans have been neglected. Hence, this research only focuses on the 32.5 million tonnes of cargo that needs to be shipped from Marabá to the ocean and assumes the river upstream to be untouched. The proposed plans by Arcadis are presented in Figure 11.1 in Appendix 11.1. This figure shows that the transport of the 32.5 million tonnes of cargo is only blocked by a relatively short river section, of 46 kilometres, between Marabá and Itupiranga.

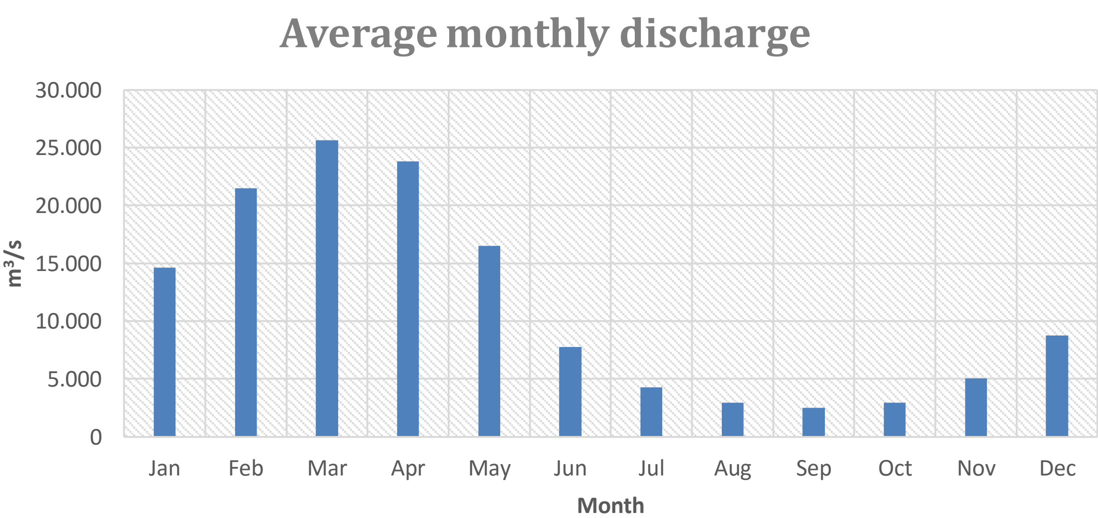

Figure 2.2: Average monthly discharge

[1] *1 euro compares to 3,99 BRL (Brazilian Real)*

3 Optimal shipping lane dimensions

This chapter addresses the search for the optimal shipping lane dimensions for the Tocantins River. These optimal dimensions have been determined by performing a cost-benefit analysis weighing each barge type. To do so firstly the requirements regarding the shipping lane dimensions for each vessel type have been analysed. Then the D-RATIN tool has been used to identify the river bottlenecks. Subsequently the costs to resolve these bottlenecks have been estimated by the D-RATIN tool. Thereafter the calculated benefits gained by the river interventions will be presented. The final paragraph discusses the way the results should be interpreted.

3.1 Waterway dimensions

The waterway dimensions are determined using literature and by the aids of an interview with two Dutch inland shippers, Ida Pals and Stefan van den Brink. During the interview it became clear that transportation by a tug barge configuration, Figure 3.1, is the most suitable method for this river case. Mostly because high amounts, of the same material, are being transported. Barges do have a simple shape and are robust. Therefore, more rapid loading and unloading machines can be used. Contrary to for example the ship the interviewees use, called the Fossa, Figure 3.2, which has a more complex shaped cargo space. Barges do also offer more flexibility in transporting goods. A powerful push boat can carry one to six barges; this allows the boat to adjust its capacity to the required level. In contrast to the Fossa that has a fixed capacity.

Figure 3.2: The Fossa

Figure 3.1: Tug barge configuration

There are different barge configurations on the market. Not only with respect to the dimensions of the single barges. Also regarding the barge composition, the amount of barges hitched to the push boat. The CEMT classification [8] classifies all the barge configurations into 10 categories, presented in Appendix 11.2. This research will study the needed interventions and the corresponding costs for each of these 10 categories. To do so for each class the decisive dimensions, the dimensions of the largest possible vessel within each class, have been taken into account. These decisive dimensions can be found in columns 1 to 4 of Table 3.1

For each of the vessel classes the required waterway dimensions are determined. The waterway width has been based on a basic width, related to the width of the vessel, combined with width additions, for wind, bends and the effects of the streaming water [9]. The required waterway depth is based on the loaded vessel draught plus 40% [9]. The final results are presented in the columns “waterway depth” and “Waterway width corrected” of Table 3.1. The full calculation methods can be found in Appendix 11.2.

Class	Width	Length	Draught Loaded	Loading capacity	waterway depth	waterway width	waterway width corrected
	(m)	(m)	(m)	(tonnes)	(m)	(m)	(m)
I	5,2	55	1,9	400	2,66	24	32
II	6,7	71	2,5	600	3,5	31	41
III	8,2	85	2,6	1250	3,64	38	51
IV	9,5	103	3	1800	4,2	45	59
Va	11,4	136	4	3950	5,6	56	74
Vb	11,4	189	4	7050	5,6	60	79
VIa	22,8	145	4	7050	5,6	101	134
VIb	22,8	194	4	12000	5,6	106	140
VIc	22,8	270	4	18000	5,6	115	152
VIIa	34,2	193	4	18000	5,6	152	200

Table 3.1: Waterway requirements

3.2 Parameter values

To reconstruct the river with the D-RATIN tool input parameters regarding the grid, bathymetry and water-levels are required. These parameters are shown in Table 3.2. To obtain the most accurate results the physical parameter values have been based on literature where possible. The accuracy of each parameter might differ, because not all the parameters where to be determined based on sufficient literature. However, inaccuracies in these physical parameters do not cause this research to fail to achieve the intended goals, as long as realistic values are used. This way the study might perform calculations on a more fictional river than the actual river, but also this fictional river then has realistic properties. This allows the study to still test the tools functioning on a river that, in theory, could exist. A foundation for the parameters that are determined by literature and/or calculation can be found in appendix 11.3.1.

Contrary to the physical parameters, the non-physical parameters cannot be based on literature. These parameters only have been based on visual checks, checking whether the generated output seems to be logical. However, to determine these parameters accurately they need to be calibrated to measurement data, which is not available in this research.

Unless stated differently, all the calculations in this research have been performed with these parameters.

Model part	Parameter	Value	Method
Grid	Refinement threshold	150	visual check
	Spacing	150 m	Calculation time based (Appendix 11.3.1.1)
	Shortening	10 rows	Visual check
	Number of cells	10	Calculation time based
	Smoothing window	10	Visual check (Appendix 11.3.1.1)
Bed levels (theory)	Bankfull discharge	$2{,}5 \cdot 10^4$ m³/s	Assumption (Appendix 11.3.1.2)
	Chézy Roughness coefficient	$4 \cdot 10^1$ $m^{1/2}/s$	Educated guess [10] (Appendix 11.3.1.2)
	Longitudinal river slope	$1 \cdot 10^{-4}$	Calibrated (Appendix 11.3.1.2)
	Sediment median grain size (D50)	$4 \cdot 10^{-5}$ m	Literature [11] (Appendix 11.3.1.2)
	Coefficient related to secondary flow	1,5	Assumption
	Water level downstream	82 m	Estimated (Appendix 11.3.1.2)
	Nr of cells for banks (left)	1	Assumption
	Nr of cells for banks (right)	2	Assumption
	Smoothing window	20	Visual check
Bed levels (measurement)	Power	2	Visual check
	Anisotropy	3	Visual check
	Smoothing window	10	Visual check
Bed levels (fusion)	Distance threshold	300 m	Visual check
	Smoothing window	1	Visual check
Water levels	Discharge	$2{,}5 \cdot 10^3$ m³/s	Literature [6]
	Chézy roughness coefficient	$4 \cdot 10^1$ $m^{1/2}/s$	Educated guess [10]
	Water level down stream	75,2 m	Estimation by calculation (Appendix 11.3.1.3)

Table 3.2: Parameter values

3.3 Navigational bottlenecks

This research tried to obtain the exact bottleneck locations with the D-RATIN tool. The reconstruction of the river bathymetry and water depths worked appropriately, the results of this reconstruction can be found in Appendix 11.3.1. It was also possible to manually integrate the sandbars, as described in Appendix 11.3.2. However, the last model, designed to generate the optimal navigation route, does not work properly for all vessel classes. For the larger classes the algorithm generates paths that, at certain locations, navigate close to the riverbanks, the paths also contain sharp bends, such a path is presented in 11.3.3

Errors do not only occur in the route generation also the corresponding dredging volume and thus output costs are illogical, it turned out that the calculated dredge volume for a Va class vessel was higher than the volume for a Vb class. Even though the Vb class vessels require a larger waterway profile. Besides the calculation errors the tool also shows some limitations in the representation of the results. It appeared not to be possible to determine the exact locations of the navigational bottlenecks. The navigability of the full river can be presented with the tool, as shown in Figure 3.3. However, only the shallow areas that are located on the navigation path form actual bottlenecks. The exact bottleneck locations have therefore been obtained by ArcMap.

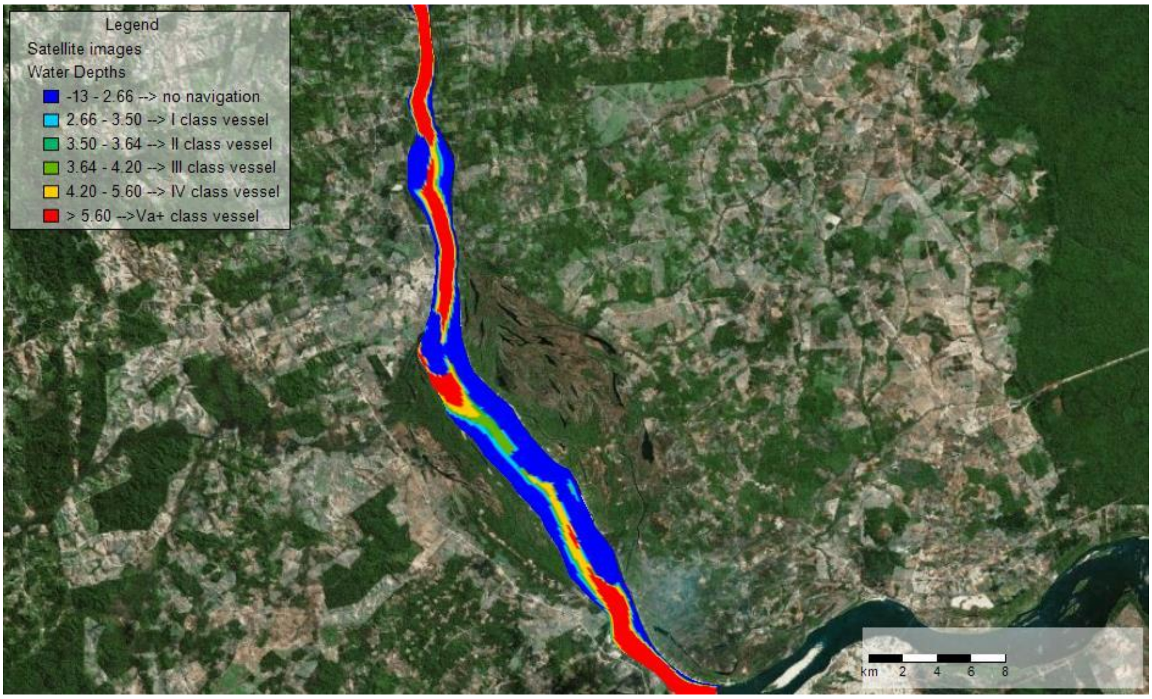

Figure 3.3: Bottleneck visualization by the D-RATIN tool

The resulting bottleneck locations are presented in Appendix 11.3.4 , Figure 3.4 shows a zoomed in example. These figures, in Appendix 11.3.4, show that the Tocantins River is navigable for large sections. Especially the smaller vessel classes do not require rigorous dredging interventions. The figures also show that for vessels larger than the Va class the locations do not change. For these classes the required waterway depth is the same only the waterway width changes and therefore only the amount of dredging differs for these classes. The dredging volumes for each class can be found in Table 11.2.

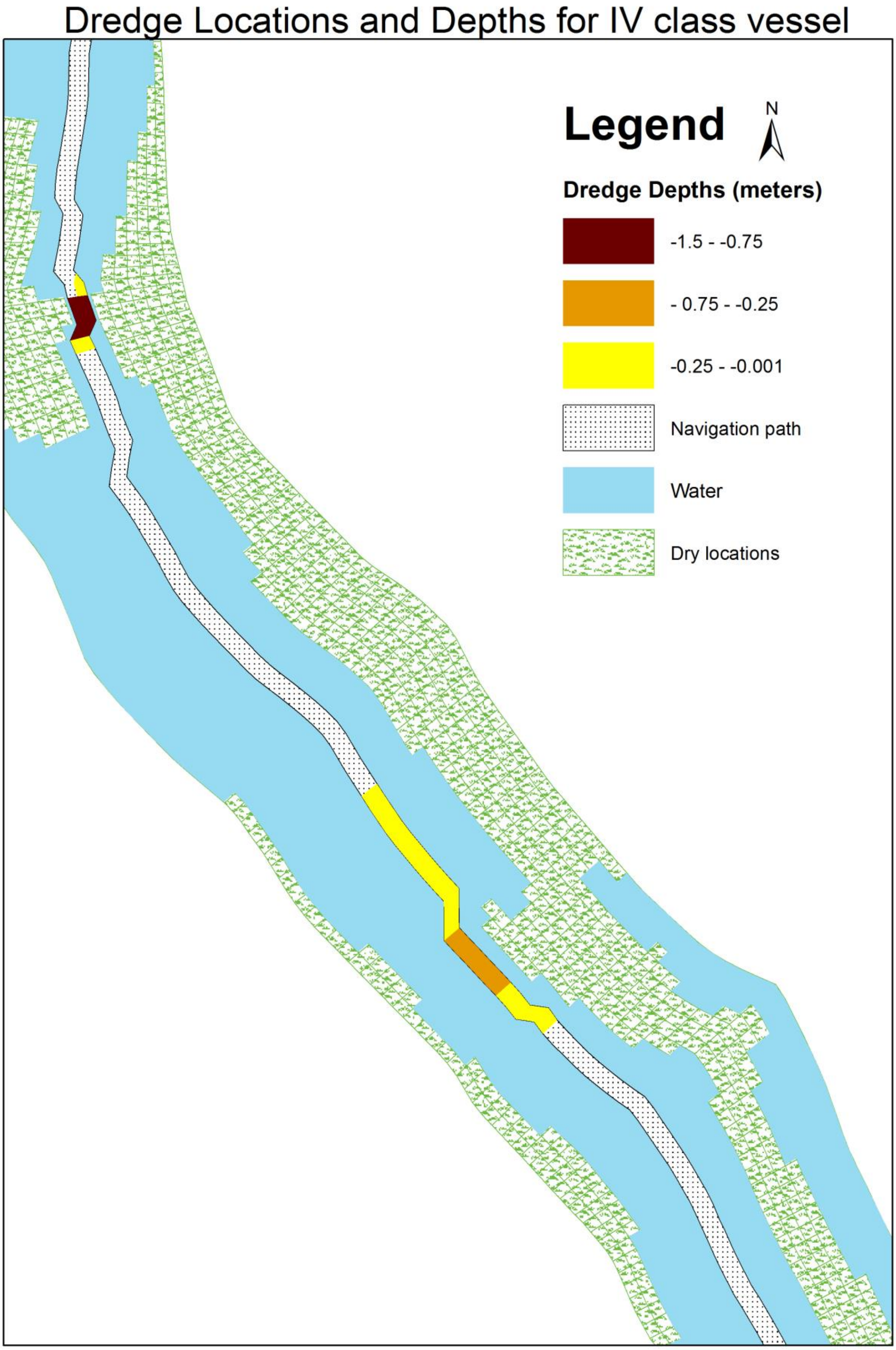

Figure 3.4: Bottleneck visualization by ArcMap

3.4 Cost-benefit analyses

To gain more insight in the impact of the D-RATIN's cost calculations to obtain the optimal river dimensions, a cost-benefit analysis has been performed. All calculations are presented in appendix 11.4. Since the Tocantins River has an exceptionally high transport demand, two scenarios have been calculated. The first scenario is the actual river case with the high demand. The second scenario is a fictional scenario with a more average demand, based on the demands for the other Brazilian rivers studied by Arcadis. The cost benefit analyses showed that the impact of the D-RATIN's cost calculations depends on the scenario. In case of the fictional scenario the calculated costs affect the results more significantly.

The cost benefits result for the first scenario show that for this river section the VIc class vessel is the most profitable option, it also shows that all classes do have a positive net benefit result. However, this does not mean that all ship sizes are profitable in absolute sense. The only costs and benefits that are represented are the costs and benefits relative to the reference scenario. This is the scenario of using the smallest ship size. The presented results are thus the result of the underlying assumptions that led to the smallest vessel class as the reference scenario. The fictional cost-benefit chart can be found in Figure 3.6. In this scenario The IV class vessel appears to be the most profitable. Contrary to the first scenario not all the vessel classes are profitable.

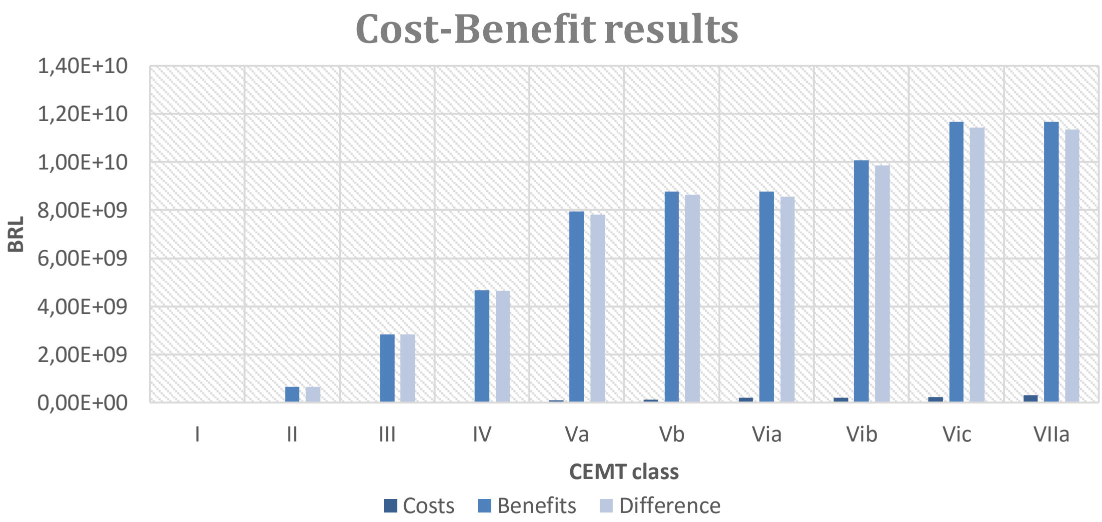

Figure 3.5: Cost-Benefit results

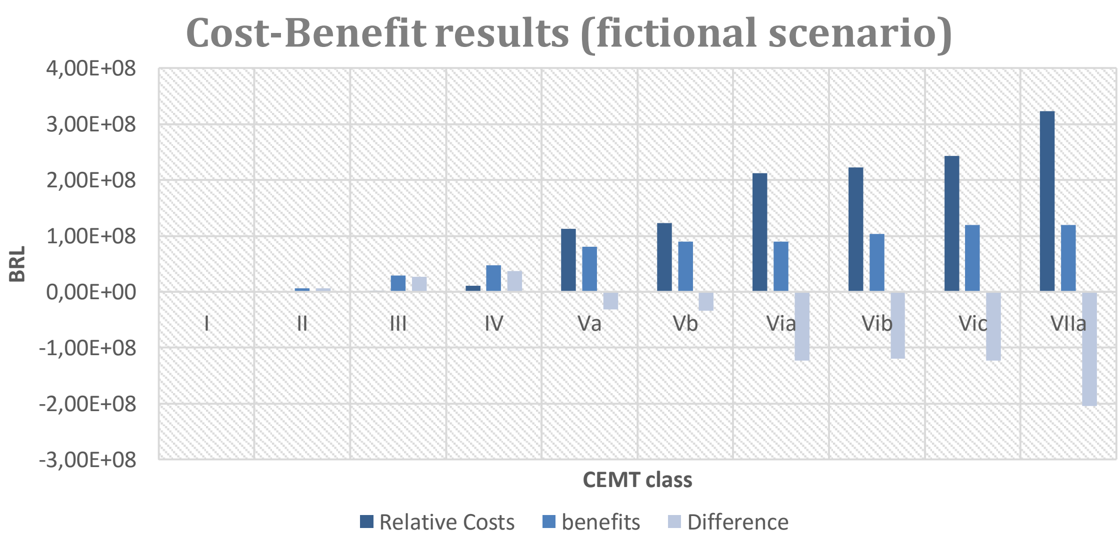

Figure 3.6: Cost-Benefit results (fictional scenario)

3.5 Interpretation of results

The calculated costs should be interpreted carefully, especially because they are calculated with the use of a new tool that has not yet proved its functionality. Although, the tool's output results are not meant for further use, studying how the results should be interpreted provides information about how to use the D-RATIN tool.

3.5.1 Sensitivity analyses

Since this research was not able to determine all parameters with similar accuracy a sensitivity analyses, relative to the III vessel class, has been performed. This class has been chosen since this is the largest vessel class for which the route algorithm does not generate problematic routes. Only the extreme values, of the range in which the parameters will most likely be, have been tested. The results are presented in Table 11.4 in appendix 11.5. It was not possible to derive exact general relations between the cost output and the parameter values. Even though, for each river the same background principles are used, the sensitivities also depend on the river geometry.

The sensitivity analysis shows that not only the physical parameters, regarding the bathymetry, have a substantial influence on the output result. Also the way the grid is defined affects the output costs significantly, the grid spacing in the stream wise direction has the highest grid influence on the output costs. This would mean that, contrary to what has been done in this research, the grid parameters should not only be based upon whether it fits the polygon properly but the generated results should also be calibrated to water depth data.

Some physical parameters, regarding the bed levels, also appear to be highly influential to the cost result. The bankfull discharge and Chézy friction coefficient are most dominant to the cost output. The high sensitivity to the Chézy friction coefficient is mainly caused by its double use in both the bathymetry as well as the water depth calculations. Unfortunately, it is not always possible to determine those parameters accurately.

However, the tool is not that sensitive to all its parameters. For example, the number of cells for the river banks does influence the results significantly less. This lower sensitivity is probably caused by the fact that, in this case, there will hardly be dredged in the absolute riverbanks. The riverbank parameters will only influence the dredging costs indirectly by affecting the water level.

To quantify the error caused by the parameter sensitivity the calibration results obtained by Zervakis [3] have been used. Zervakis calibrated the most sensitive parameters, Bankfull discharge, Chézy friction coefficient, longitudinal river slope, sediment grain size and the related coefficient to secondary flow. For each parameter the highest difference between the initial educated guessed value and the calibrated value has been assumed to be the minimum accuracy of the parameter. The deviation per parameter can be found in Table 11.5 in appendix 11.5.1.

With this parameter accuracy the uncertainty caused by the parameters has been studied. Figure 3.7 shows that this in accuracy is substantial. The obtained bottleneck area ranges between 1.6 km^2 and 3.0 km^2. Hence due to

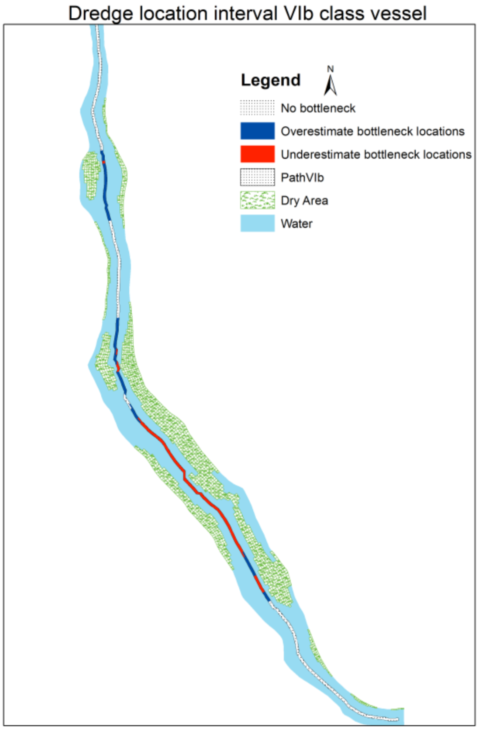

Figure 3.7: Dredging location uncertainty as a result of Parameter errors

the parameter uncertainty about 1.4 km^2 is uncertain whether it forms a bottleneck or not.

This sensitivity analysis showed that the output results can only be considered to be valid when all the physical input parameters, to reconstruct the riverbed, are based on acceptable background knowledge and checked thoroughly also all the non-physical parameters should be calibrated by measurement data. This calibration requires a sufficient amount of data, which might not always be available at open sources. This was the case in this research. The physical parameters have not been properly determined either. Therefore, the obtained costs are not reliable, even if the route algorithm had worked appropriately.

3.5.2 Effects of the added sandbars

The modelled cross-sections that include a sandbar do differ from the reality. This difference is caused by the way the sandbar has been reconstructed. In this model the sandbar has been added to the theoretically reconstructed river. This theoretically reconstruction does not take the sandbar into account. Hence the modelled bed-levels will be higher than the actual bed levels; a schematisation is presented in Figure 11.33. The higher estimate will lead to an overestimated dredging volume.

Not only the bed-level topography is affected by the addition of the sandbars, the sandbars also influence the output of the 1D flow model. Figure 11.32 and Figure 11.31 in Appendix 11.5.2 show a comparison between the water levels along the river, with and without sandbars. This comparison shows that the sandbars cause the water levels to drop. This drop is in line with the theory of Bernoulli [12], which expresses the relation between cross sectional throughput area and the water level. The water levels upstream the sandbars, especially upstream the first sandbar, are raised by the sandbars. This corresponds to the backwater curve theory. Hence it can be concluded that the effects of the added sandbar, on the water level, corresponds with the established theory.

Furthermore, for the implementation of the sandbars assumptions were made regarding the interpolation parameters. A sensitivity analyses showed that the parameter selection does not substantially influence the output results. All parameters only affect the output indirectly by their influence on the water-level; this influence appears to be negligible. The sensitivity to the interpolation parameters can be found in appendix **11.5**, Table 11.6.

The used method to deal with the sandbars has been based on the fact that with this method the tool will not miss any of the bottlenecks, since the water depths are underestimated. However, to quantify the uncertainty of this overestimations an interval has been calculated in which the actual bottleneck locations must most certainly lie. To do so the bottlenecks have not only been obtained by the overestimating method but also by an underestimating method, neglecting all the side streams. Figure 3.8 shows the interval results for a VIb class vessel. The red areas are located by both methods and therefore they are certainly bottlenecks. On the other hand, are the blue areas only located by the overestimating method and thus uncertain.

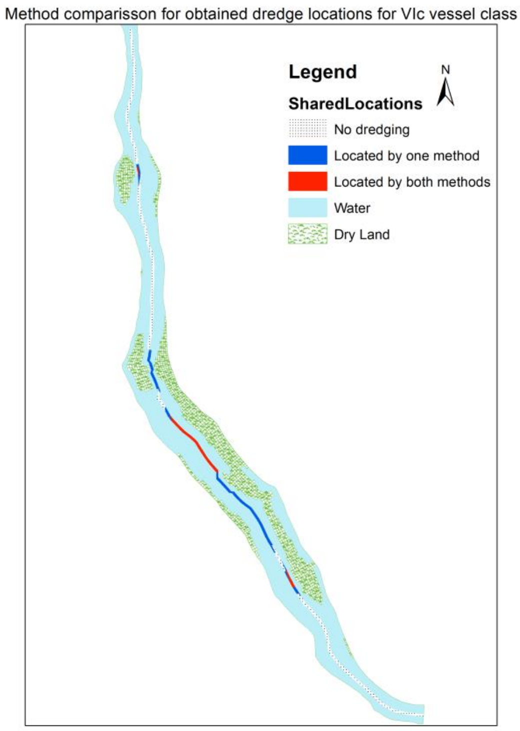

Figure 3.8: Dredging location uncertainty as a result of the sandbar errors

3.5.3 Accuracy of used principles

Inaccuracies might not only be caused by uncertain parameter values, as discussed in paragraph 3.5.1. Also the used theories might not be representing the river accurate enough. This definitely holds true for this research's scenario, in which sandbars occur. These sandbars correspond with some different morphological effects. Therefore, the used theories to reconstruct the bed levels are actually not applicable to these river sections. Reconstructing the sandbars by manually producing height data does not do the full job either, as stated in the previous paragraph.

Furthermore, the validation results of Zervakis [3] show that there is a high variation in the accuracy of the theoretical bed-level reconstruction method. This high variation shows that whether the theoretical model generates acceptable results depends highly on the scenario. However, the RMSE might not even provide representative information regarding the accuracy of using the tool for inland navigation potential research. The RMSE value is strongly determined by the more extreme errors. In this model these errors seem to occur at the extreme bathymetry levels, the river banks and river bottom. Nonetheless, these areas are of less interest for this research. Hence, to draw proper conclusions about the model's accuracy, it should be better to obtain an RMSE value which only considers the points that do matter for this use of the tool.

Moreover, Zervakis showed that the tool is likely to smoothen the riverbed profile. Due to this smoothened profile the tool is likely to overestimate the dredging costs. Figure 3.9 shows that for situations in which the waterway profile is located within the two intersection points, of the theoretical river profile and the actual river profile, the tool will most likely overestimate the dredging locations. Although inaccuracies are not preferable it is better to have an overestimate in these studies, this way no bottlenecks will be missed. This is especially important since the theoretical model will mostly be used in the early stages of the research at which it is more important to not miss any bottlenecks than correctly indicating the costs.

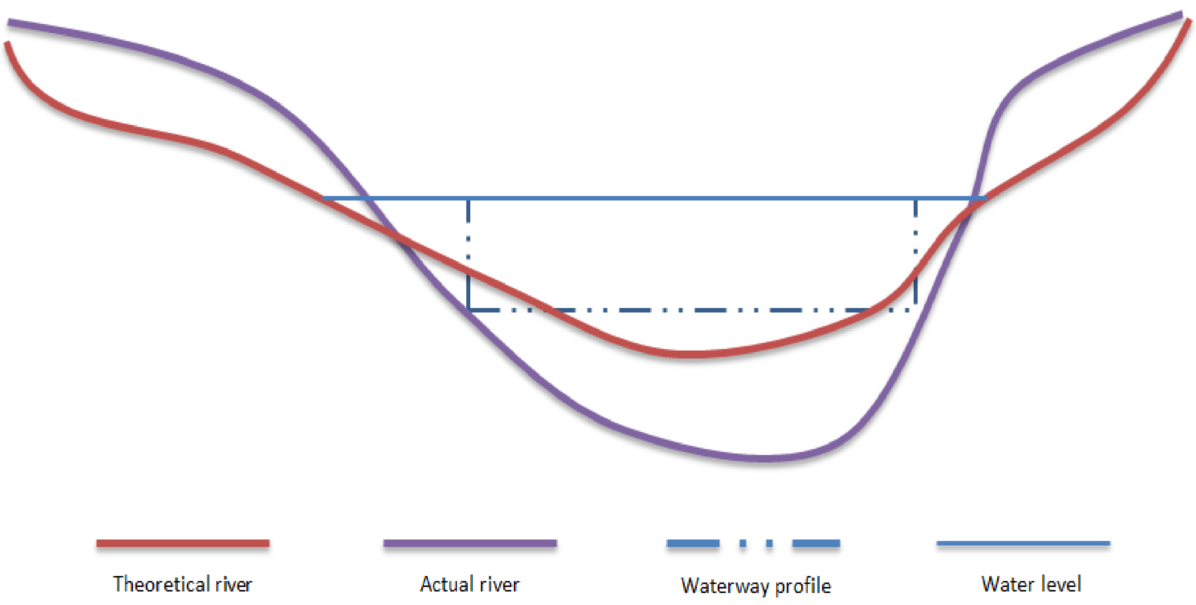

Figure 3.9: schematized example of the impact of the theoretical error

Although the bed-level reconstruction introduces some errors these errors only affect the output results indirectly, by their influence on the water-depths. The inaccuracies regarding the water-depths are therefore more important than the bed-level inaccuracies. To study the effects of bed-level inaccuracies on the water-depth errors, three experiments have been conducted. In the first experiment both the river bed centre as well as the riverbanks have been adjusted, as presented in Figure 11.35. In this situation the water depth error is increased by 2.5% relative to the bed-level error. The second experiment only adjusted the bank heights as presented in Figure 11.38. This experiment showed that the water depth inaccuracies are smaller than the corresponding riverbank inaccuracies. This reduction in the error is caused by the low water depths at the banks. Therefore, some areas become dry and thus the bed level error does not fully impact the water depth. In the third experiment only the river centre has been adjusted, as presented in Figure 11.36. This inaccuracy has a more substantial influence on the water depths; the effects on the water level are presented in Figure 11.37. The initial bed-level error is increased almost 40% in the water depths. It can thus be concluded that the effect of bed-level inaccuracies on the water depths depend on the location within the cross section. The results also show that when errors in both the river centre as well as the riverbanks occur, then the error caused by the centre inaccuracies is compensated by the riverbank errors. All results are presented in Table 3.3.

Model type	**Error scenario**	**Σ(hreal-hpredicted)^2**	**RMSE (meter)**	**Difference to bed level RMSE**
Bed level inaccuracy	higher Riverbanks and lower centre (Figure 11.35)	78	0,11262	
	higher riverbanks (Figure 11.38)	50	0,09027	
	lower Centre (Figure 11.36)	28	0,06729	
Water level inaccuracy	higher riverbanks and lower centre	82	0,11538	3%
	higher riverbanks	28	0,06765	-25%
	lower centre	54	0,09343	39%

Table 3.3: effects of bed level inaccuracy on water depth

Besides the inaccuracies caused by the bed-level theories, also the theory used in the 1D SOBEK model introduces errors to the water depths. Due to the river's bifurcations the used SOBEK model is not a completely valid representation of the river system. Firstly, some errors occur in the calculation of the flow velocity. SOBEK calculates an average velocity over the full cross section, which includes both the main channel and the side channel. However, the mean flow velocity in the main channel is likely to be substantially higher than the side stream's. Therefore, the velocity in the main channel is underestimated by the model and thus the water level is overestimated. Also the water distribution around the bifurcation is affected due to the wrongly calculated velocities, since the main channel will have a higher flow velocity there will be more water flowing through the main channel than is currently calculated.

Another inaccuracy caused by the SOBEK model can be seen in Figure 3.4. Due to the low water-level the side stream is blocked by a threshold, withstanding the water from flowing through the side channel. However, the model does fill the side channel behind this threshold with a water stream. Therefore, the water level in the main channel is underestimated. To gain insight in the corresponding error the SOBEK model has been manually adjusted, such that all the water will be flowing through the main channel. This limitation caused an RMSE error of approximately 0.0145 meter. Figure 3.10 shows the error along the river.

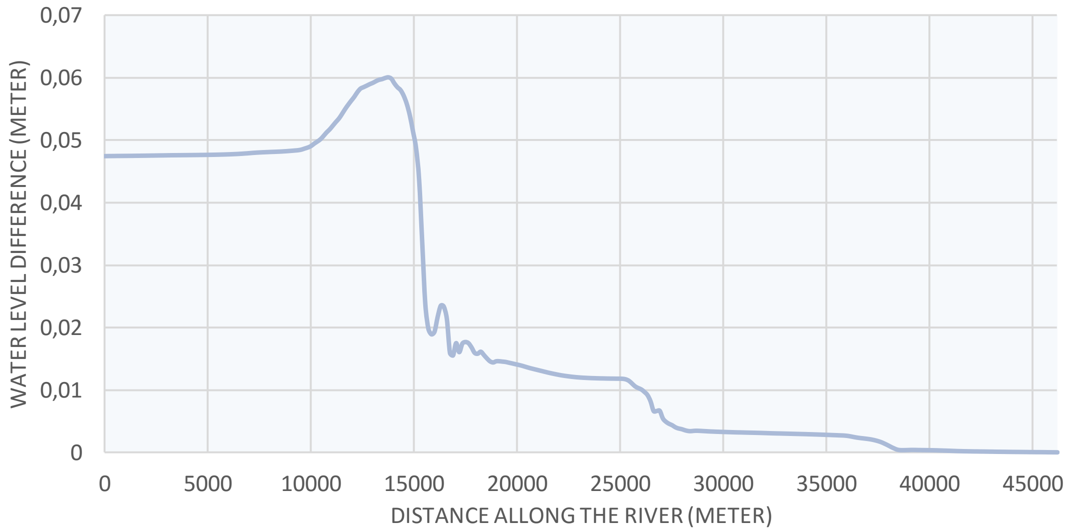

Figure 3.10: Water level error caused by side stream inaccuracy

In some cases, a threshold might be located at the end of the side channel. This way the water will enter the side channel but it will not reach the main channel again. In such a case the side channel functions as a storage area, the cross-sectional area of the side stream should therefore be modelled as a storage area instead of flow area. However, this is not possible in the tool. The SOBEK model in the tool considers the storage area as a flow area causing the water levels to be underestimated.

3.5.4 Validation

Since the research aims for examining data scarce areas it is hard to validate the reconstructed river. Exact water depths or bed level data is not available. Nevertheless, there are some ways to partly validate the gained results, regarding the water depths and the intervention costs.

Firstly relative depths have been validated by the colour differences that are visual in the Google Earth satellite images [13]. These differences are caused by the differences in water depths. This colour difference does allow checking whether the tool estimates the height variations properly. In Appendix 11.2 a centreline has been constructed, representing the centre of the deeper areas of the river. It seems like the model generated by the D-RATIN tool follows this centreline quite well. This would mean that if the absolute water depths are also approximated well the tool provided the required information to locate the bottlenecks properly.

Secondly have the intervention costs been validated by a comparison with Arcadis' cost indications. This comparison showed that the RATIN tool estimates the costs lower than Arcadis has done, respectively 132 million BRL and 180 million BRL [7]. However, if all the costs, calculated with the D-RATIN tool, are corrected for this difference still the same optimal shipping lane dimensions are obtained. Hence, even though there is a significant difference the optimal waterway dimension is not affected. Yet, this only holds true when the chosen parameters are sufficiently accurate estimates, which is not known.

3.5.5 Required additional measurements

The currently calculated river is purely based on river theory. Whether the generated results are within an acceptable margin or not is not known for sure. However, the tests of Zervakis [3] show that the theory, on its own, in most cases does not generate sufficient results. To obtain results with sufficient accuracy additional measurements are required. Zervakis shows that a fusion of the measurements and the theory improves the results significantly.

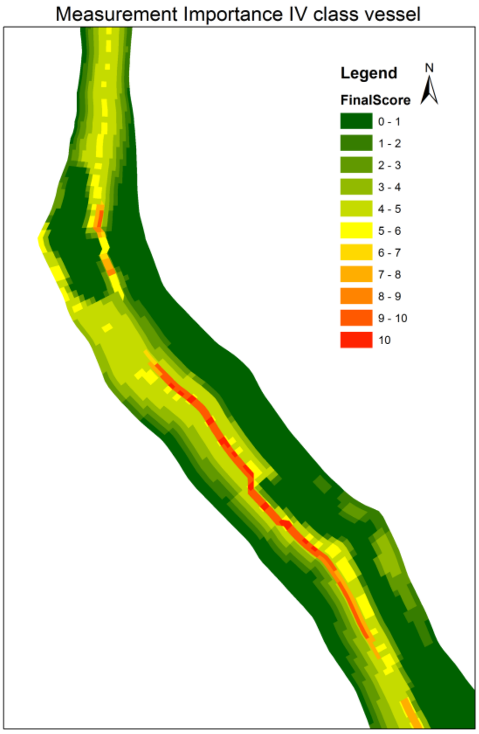

Figure 3.11: Measurement importance zoomed example

To achieve the best improvements with limited measurements the measurements must be performed at strategic locations. As afore mentioned the tool shows the most significant errors at the extreme values of the river. The mid-range bed-levels are determined more accurate. For the navigation potential it is mostly the mid-range and lower range values that are of importance, because these are the locations that will be navigated; A schematization of the important and unimportant bathymetry levels can be found in appendix 11.5 Figure 11.41: schematization of the interesting bathymetry heights. Therefore, measurements are mostly required for the determination of the absolute bottom of the river, instead of for the full cross sections. It can thus be concluded that for this application of the bathymetry model a beam measurement that follows the red line in Figure 11.40 shown in Appendix 11.3.2 will probably be the most efficient option. Another option is a more winding line measurement covering the deeper river locations. This allows for a better reconstruction of the full bottom of the river profile. These measurement approaches are supported by the generated measurement importance maps that are presented in appendix 11.3.4, Figure 3.11 shows a zoomed in example. The used method for generating these importance maps are discussed in Appendix 11.5.5.

Depending on the available time and financial resources the research area can be reduced based upon the importance maps

3.5.6 Optimal shipping lane dimensions

The previous paragraphs showed that many of the elements in the tool contain inaccuracies. A high inaccuracy is caused by the parameter uncertainty. Therefore, these parameters must be determined with great care and if possible they need to be calibrated to measurement data. Also, the sandbar reconstruction introduces a high uncertainty to the cost output results.

However, even though both the parameters and the sandbars cause significant uncertainty, these uncertainties do not strengthen each other. Figure 3.12 graphs the total uncertainty in the bottleneck locations, taking into account the parameter and sandbar uncertainty. This figure shows that combining the two uncertainties does not add extra bottleneck locations. Only the amount of certain locations, locations that are located by both methods, is reduced. Hence it can be concluded that even if the sandbar implementation had not included inaccuracies still the same locations need to be studied due to the parameter uncertainty. The total uncertainty in bottleneck locations for all vessel classes are presented in Appendix 11.3.4.

Besides the parameter and sandbar uncertainty, uncertainties are also caused by the used theories. Some of these inaccuracies overestimate the dredging locations others will lead to an underestimate. Overall it is likely that the summation of the errors in a theoretically reconstructed river will overestimate the dredging locations, due to the dominant errors in the bed-level reconstruction theories. The combination of these theory inaccuracies and the uncertainties caused by the parameter determination and the sandbar implementation limits the tool's ability to determine the optimal shipping lane dimensions. The validation to the Arcadis' results showed that the cost underestimate does not influence the cost benefit outcomes, if the parameters have been determined properly. In this research it has not been possible to properly determine these parameters. Hence, no optimal vessel class can be obtained for the Tocantins River case, based upon the limited data available.

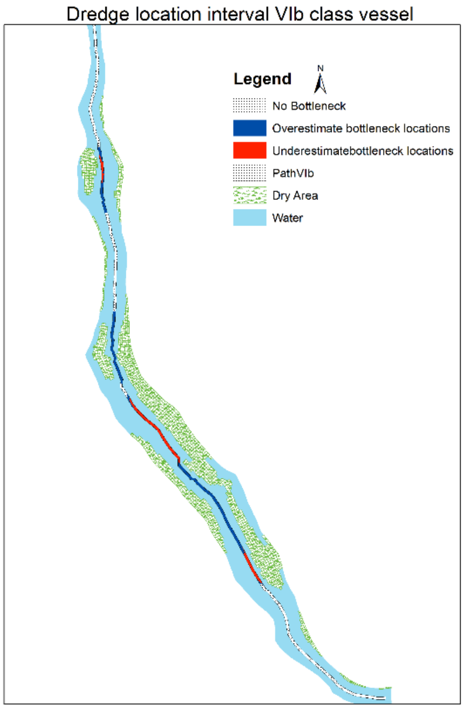

Figure 3.12: Total dredging location uncertainty

Nonetheless, Zervakis shows that the addition of few measurement data can reduce the bed-level inaccuracies significantly. If data is available, the tool might provide results accurate enough to determine an optimal vessel class. The theoretically reconstruction can provide the required information to determine the most efficient measurement approach to optimally improve the bed-level reconstruction with the fusion method.

4 Functioning of D-RATIN tool within a navigation study

To see how the tool might function within a full inland navigation study (FINS) first the process of a full study has been summarised. This has been done with the aid of the report “Guidelines for Sustainable Inland Waterways and Navigation” compiled by PIANC [14]. An overview of their proposed working method is shown in Figure 4.1[14]. Thereafter it has been studied which role the D-RATIN tool might fulfil and how it should fulfil this role within the FINS.

4.1 Aspects of a FINS

Studying inland navigation potential does not only include the physical bottleneck formed by too shallow river parts. A river influences many natural processes like morphologic evolution, hydrologic balance, sediment continuity, habitat provision and chemical and biological processes. These processes can be considered to be the priority functions of the river. The advent of inland navigation has a direct influence on these other functions and vice versa. The river not only fulfils other natural functions also other functions for humans are offered by the river, for example water supply for irrigation. The interactions between all the ecosystem elements form a complex system of relations. To develop a sustainable waterway an optimum must be found between the wanted river interventions and the other river functions. Therefore, the first step in a FINS should be to get to know all the functions that the river fulfils. The outcome of this evaluation depends on the local river characteristics, their relative importance, their interactions and the scope of the project to be undertaken.

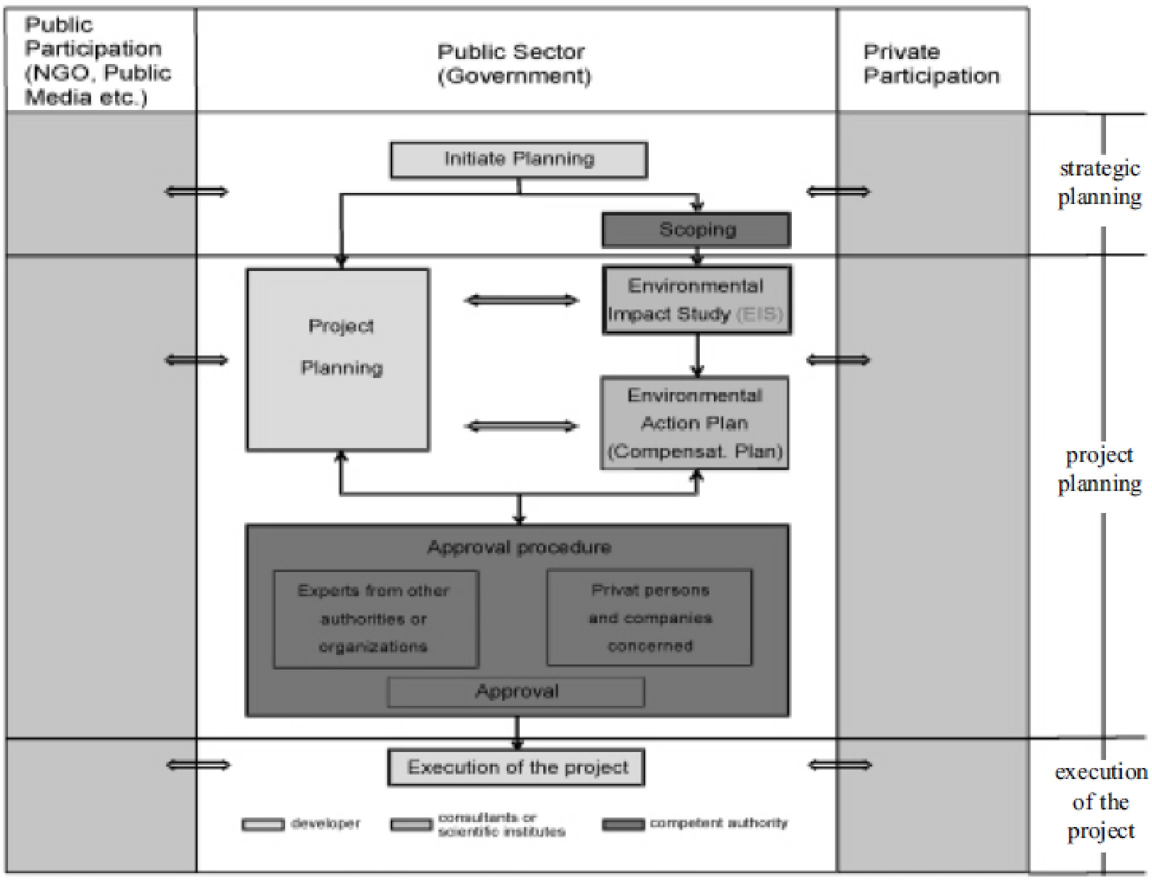

Figure 4.1: schematization of a full inland navigation study [14]

4.2 Use of the tool within FINS

Although the actual research to river interventions is a small part of the FINS it seems to be one of the more critical parts. Many of the different aspects of the study rely on data regarding the river interventions. Without sufficient data the FINS cannot be performed properly, causing politics to disprove the proposed interventions and investors might back off because of the uncertainty in the results. Therefore, the sooner data is available the smoother the FINS can be performed. However, for the objected areas this data is scarce and therefore FINS take a long time. The D-RATIN tool can help provide the required information even in data scarce environments.

Firstly, the tool can be used to reduce the study area from a full river section that might sometimes be more than 1000 kilometres to only the bottleneck locations. Due to the theoretical based model this is even possible without almost any data. As already shown in chapter three it is possible to generate measurement importance maps that can be used to obtain the most efficient measurement strategy. Once the minimal required measurements have been performed the tool can quickly provide the policy makers with some quantitative data regarding the required river interventions.

It is not only the effort of gathering data that is reduced by the D-RATIN tool. The availability of quantitative information in the early stages of the FINS also allows for stakeholder participation in an early stage. The early involvement of stakeholders is more likely to get the main interests, regarding the interventions, pointed in the same direction. This might prevent the FINS from obstruction by stakeholder complaints.

In general, the D-RATIN tool offers some possibilities to ease the FINS process for data scarce areas. It might even become the accelerator within the FINS. However, this valuable role of the D-RATIN tool only holds true when the tool meets its intended goals.

5 D-RATIN limitations

Although the D-RATIN tool seems to have potential in becoming a useful tool for studying data scarce river projects there are some limitations of its use. Firstly, since the tool uses as little data as possible it is highly reliable on the few physical parameters it does require. Therefore, these input data must be known quite exact in order to produce reliable results. Another limitation is formed by the many required non-physical parameters. To calibrate these parameter settings sufficient data is required for independent calibration, limiting the input data reduction. This data might also not be available at open sources. However, one of the main goals was to generate results out of mostly open source data.

Another limitation is formed by the capability of the grid to deal with irregularities in the river's shape. Figure 5.2-13 show that when the river width changes more abrupt the grid is not able to smoothly reconstruct this change. Although the locations of these inaccuracies in the grid do not have a direct impact on the cost output they do have an indirect effect by affecting the bathymetry reconstruction. This grid limitation might cause too many inaccuracies; in case the river significantly deviates in width.

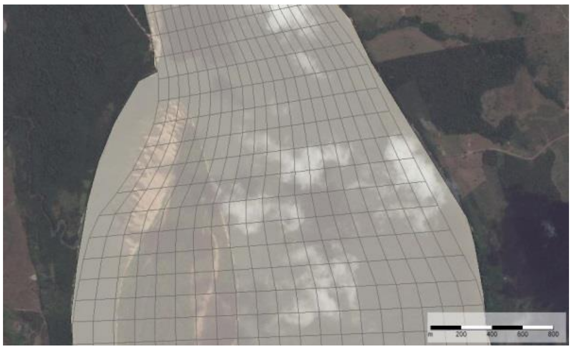

Figure 5.2: Example of a grid error

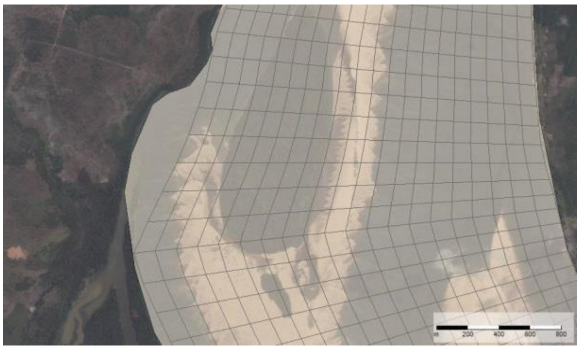

Figure 5.1: example of a grid error (2)

The D-RATIN's capability of determining the optimal shipping lane dimensions with limited data depends on the required accuracy of the results. The performed cost-benefit analyses showed that the influence of the D-RATIN calculation on the cost benefits results, depend on the project characteristics. Due to the high uncertainties in the parameter determination and in the sandbar reconstruction, it is not likely that the tool, in the current state, is able to produce sufficient results for cases in which the cost calculations have a relatively large impact.

Since the tool is based on idealised river cross-section profiles it does not reflect irregularities that might be in the river. Also these idealised river profiles differ from the ground truth situation. Therefore, it is required to take a substantial margin into account for the reduction of the study area. This margin limits the effectiveness of the reduction. However, available local knowledge might slightly reduce the limitation. Combining the tool with local knowledge is essential in order to reduce the study area in the most effective way.

6 Possible improvements

During this research some problems regarding the tool's functioning appeared. This chapter will discuss these problems and, if possible, it will suggest possible improvements.

The first problem that has been noticed is related to the projection systems that the tool can use. Although the tool offers a wide range of systems to load polygons into the map, the tool cannot continue calculations with all these systems. This is caused by the way the systems define their coordinates. The tool is able to calculate with projection systems that express their coordinates in meters, relative to a certain reference point. Nevertheless, some of the available projection systems express their coordinates by latitude and longitude coordinates. Such systems will cause the calculations to fail, since the system is only able to calculate with SI units. Either the tool must automatically transform the projection system or it should not offer all projection systems when loading the river polygon.

Furthermore, the current SOBEK model that is used to calculate the water depths is not a valid model for river systems that contain sandbars. This wrongly modelled system causes errors in the flow velocity and water levels. To resolve these errors, the tool must build a SOBEK model with bifurcations around the sandbar. This way the tool will not consider the main channel and the side stream as one river but as two individual streams that have their own velocity and flow area. Although the error caused by the wrongly model river system is not substantial for obtaining the bottleneck locations it might become substantial when the tool should be used to obtain economic optimal waterway dimensions.

During the search for the navigational bottlenecks it became clear that the tool does not provide any exact information about the locations of these bottlenecks. This information however, could be highly beneficial for the proceeding of the research. Not only does it allow the researchers to validate the output of the tool better, it also provides information about which locations needs further investigation. This appears to be the most important function of the tool. Therefore, it is of importance that the tool will be extended and provides maps, similar to the maps created in ArcMap, which shows the locations of the navigational bottlenecks. The required information is already in the tool, only representation should be implemented.

The most important improvements however, are required in the route algorithm. This route algorithm generates routes that in practice are not realistic for navigation, because the route algorithm searches for the route that requires the least amount of dredging interventions. It is more desirable to let the algorithm find a logical route for shippers than the cheapest route to construct. Moreover, the dredging volume also shows illogical outcomes and should therefore be improved. To resolve the illogical routes, vessel navigation characteristics could be implemented in the tool, which prevent the route from sharp bends.

Finally, if the tool also needs to be able to obtain economic optimal shipping lane dimensions, expansion of the theoretical principals, regarding the sandbars, is required. The method provided by this research might be sufficient to obtain an indication of the bottlenecks. Nonetheless, the inaccuracy of the method is too substantial to properly determine intervention costs that could be used in the search for the optimal waterway dimensions.

7 Conclusion

This research aimed to test the usefulness of the quantitative data produced by the D-RATIN tool. To do so the tool has been applied on the Tocantins River. This river shows a high potential for inland navigation, especially because of the advent of a new steel plant. This steel plant is expected to deliver a demand of about 32,5 million tonnes a year. Therefore, the navigating the Tocantins River has a high economic relevance, which makes it an interesting river to study with the D-RATIN tool.

Applying the tool on the Tocantins River case showed that the results generated by the D-RATIN tool are mostly useable to roughly allocate the bottleneck locations, without much input data. These obtained bottleneck locations can be used to significantly reduce the study area, which sometimes can be several hundreds of kilometres, to only bottleneck locations. Furthermore, generated data can be used to obtain an efficient measurement strategy. With these measurements the riverbed can be reconstructed significantly more accurate, improving the bottleneck allocation.

To produce the bottleneck results, the river's sandbars have been reconstructed with the aid of the interpolation method build in in the tool. Contrary to Zervakis' recommendation to divide the river into segments, since this way of reconstructing the river increases the required assessment effort. Also not enough data is available to properly assess the river in those segments. Although the chosen sandbar reconstruction method allows for a rapid sandbar reconstruction it introduces significant uncertainties to the bottleneck allocation.

While the results can be used to roughly obtain the bottleneck locations, they cannot yet be used to properly calculate the river intervention costs. Firstly, the theoretically generated output data is likely to be too uncertain to calculate the intervention costs accurately enough to be useable in a cost benefit analyses. Secondly, the implemented route algorithm, used to obtain the intervention costs, generates illogical routes and dredging volumes and should therefore first be improved.

Furthermore, the bottleneck results should be obtained and interpreted with great care. The results appear to be highly sensitive to the physical input parameters, which not always can be determined real accurate. Errors also occur due to the limited usability of the implemented theory. Both the bed-level reconstruction theories, as well as the 1D flow model are not completely valid methods to calculate the Tocantins River system. The generated results can only be used appropriate when all those errors and uncertainties are fully understood and taken into consideration.

Despite the significant uncertainties in the output results, the D-RATIN tool might fulfil a crucial role within a full inland navigation study. The early availability of quantitative data allows for more intensive stakeholder participation in an early study phase. The sooner involvement of stakeholders might get the main interests of these stakeholders pointed in the same direction more easily. This will reduce the delays caused by stakeholder complaints. Therefore, the tool could function as an accelerator within the full inland navigation study.

However, to fulfil this role the optimal route finder and the representation of the bottlenecks require improvements. One should try to obtain a route algorithm that generates paths that are logical for shippers to navigate, instead of a cost based route. Another improvement is required in the representation of the river bottlenecks. The tool only provides information regarding the navigability of the full river sections. Yet, only the shallow areas that are located on the navigation path form actual bottlenecks.

Contrary to the expectations the bed-level reconstruction method, regarding the sandbar reconstruction, does not necessarily require improvements to improve the bottleneck allocation; at least not for this case study. The parameter uncertainty appeared to be significantly higher than the error caused by the sandbar reconstruction method. Therefore, improving the sandbar reconstruction only improves the amount of certain bottleneck locations. Yet, the total allocation of certain and possible bottleneck locations will not be improved. Hence, the effort to improve the sandbar reconstruction might be too large relative to the effect of its improvements.

Finally, some limitations of the tool's application are found in this research. Firstly, the high sensitivity to relatively uncertain parameters limits the accuracy that can be achieved. Secondly, the grid is not able to properly reconstruct more rapid river width fluctuations. In case a river substantially fluctuates in width this limitation might add a substantial extra error. Thirdly, the tool is only able to generate general river shapes. Hence, irregularities that might be in the river are not obtained. Therefore, the tool's results should be combined with local knowledge to properly reduce the study area.

Overall, it can be concluded that even though the tool contains a substantial uncertainty it is still able to fulfil an important role within the context of a full inland navigation study, when small improvements are made. The main quality of the tool is the ability to reconstruct general river shapes, only based on theory. These general shapes can be used to provide roughly estimated quantitative data, regarding the bed-levels, water depths and bottlenecks, which are accurately enough to significantly reduce the study area and that can be used to obtain an efficient measurement strategy. The early availability of quantitative river data also allows for more intensive stakeholder involvement in the planning phase of a full river study. Hence, the tool is a valuable addition to a full inland navigation study.

8 Discussion

The conclusions drawn from this research are mostly general conclusions regarding the functioning of the tool. This research tried, as much as possible, not to let the inaccuracies in the generated results affect the validity of these more general conclusions. Besides the accuracy of the generated river data also the used method to obtain this data affected the validity of the conclusions. Mainly the river choice had a significant influence on the results. This chapter discusses the effects of this river choice on the obtained conclusions.

Firstly, the sensitivity analyses showed that the output cost results are dependent on the grid parameters. However, this dependency depends on the height variation of the bed-levels in the stream wise directions. Figure 11.47 shows that if the variation becomes more substantial the grid approach contains a bigger error. For the Tocantins River the height variations where relatively high because of the width variation in the river. Rivers with a more constant width will therefore be less dependent on the grid spacing parameter.

The optimal way to deal with bifurcations depends on the river geometry. In this research the river section had relatively many bifurcations. Therefore, dividing the river into segments, to assess those segments separately, would significantly increase the required research effort. Hence, to assure a rapid assessment the reconstruction of the sandbars by the interpolation method has been used. However, this research showed that this reconstruction method adds a significant uncertainty to the bottleneck allocation. Whether segmenting or sandbar reconstruction is the best method should be determined for each case individually. The method choice should be based upon the availability of data and the river's geometry. If the river contains relatively few bifurcations and the discharge distribution at those bifurcations can be estimated properly than segmenting is the best way to deal with bifurcations. On the other hand, if no data regarding the discharge distribution is known or segmenting increases the required river study effort too much then the sandbar reconstruction method is preferable.

The quantified inaccuracy caused by the parameter uncertainty, has been based on the calibration performed by Zervakis [3]. For each parameter the highest difference between Zervakis' educated guessed value and the calibrated value has been taken to be the uncertainty of the parameter. However, it is likely that in most cases the parameters are determined more exact than these highest uncertainties. For example, in Zervakis' study most cases only had one parameter that actually was significantly off. Contrary to this research that assumed all the parameters to be significantly inaccurate. This assumption not only affects the obtained quantified parameter uncertainty, but it also affects the conclusion that the parameter inaccuracy is dominant to the sandbar inaccuracy. Whether the sandbar implementation requires improvements or whether its inaccuracy indeed is inferior to the parameter inaccuracy therefore depends on the chosen parameter interval. In this study this interval has been chosen to be relatively large, since no sufficient information regarding those parameters was available. Yet, it is likely that in real river studies often more information is available, therefore this interval can be significantly smaller. In these cases, the error caused by the sandbar implementation becomes relatively more important than this research suggests.

Furthermore, this research concluded that the tool is not likely to produce proper cost results that are useful in a cost benefit analyses. Even though, in this study, the validation to Arcadis' results showed that the inaccuracies did not influence the optimal waterway dimensions. This validation however only holds true for cases that have a substantially high demand. The fictive cost-benefit analyses showed that in more general cases the cost calculations have more impact in obtaining the optimal shipping lane dimensions. Moreover, the validation to Arcadis' results is only valid if the parameter values are correct. In this research these parameters have not been determined based on sufficient information. The downstream water level has for example only been based on a simplified Chézy Q-h relation. This combination of factors led to the conclusion that the tool probably is not yet able to provide river data, accurately enough to obtain the optimal waterway dimensions. Yet, if the parameters turn out to be correct, this conclusion might be wrong for cases that have a significantly high cargo demand.

Besides inaccuracies caused by the implementation of the sandbars, this research also addressed the inaccuracies that are caused by the limited implemented theory. The effects of the wrong representation of the river system by the SOBEK model depend on the river's geometry. The error will be less substantial if the river contains relatively few sandbar locations. Moreover, the obtained effects of bed level inaccuracies on the water depth error, discussed in paragraph 3.5.3, only hold true for low water scenarios. The impact of the riverbank inaccuracies will increase for high water scenarios because no areas will become dry land. Nonetheless, in case navigation potential is studied low water level will always be the decisive level.

9 Recommendations

To improve the tool's accuracy more morphological research, regarding the sandbars, is required. This research reconstructed the sandbars by interpolation of manually added height points. Although this improved the results it still has not been based upon any theoretical knowledge. It must therefore be studied whether it is possible to reconstruct sandbar systems by idealized cross sections, as has been done for single channel river sections.

Furthermore, experiments can be performed which determine the tool's accuracy regarding the water depths near the navigation path locations. Currently only the bed-level accuracy of full river sections is known. Though, these full section accuracies contain many points which are not of significant importance for the determination of navigational potential. This research theoretically supports the conclusion that the tool provides more accurate results than the RMSE values obtained by Zervakis suggest. Yet, the accuracy that the tool reaches for navigability study purposes has not been quantified.

This research used a simple grading method to obtain measurement importance maps. However, the grading can be done in many different ways and there probably are better ways to grade the importance of each location. Experiments can be performed that test some of these different grading methods to obtain the most effective measurement strategies out of the importance maps.

Moreover, research can be done to improve the route algorithm. As already has been mentioned in this report it might be possible to implement the vessels manoeuvrability characteristics into the algorithm. However, whether this is actually possible based upon the limited uncertain data is not known. There also should be studied if this kind of algorithm still allows for a rapid assessment.

Finally, the effects of the wrongly modelled river system by the 1D flow model can be further studied. This research only obtained the effects of the error caused by a threshold in the entry of the side channel. The effects of the other model inaccuracies, like the effects of the wrongly obtained flow velocity and the effects of modelling storage areas as flow areas can be further studied. The results of this study show whether the inaccurate representation causes a substantial error when obtaining the optimal shipping lane dimensions.

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11 Appendix

11.1 River selection

This study aims to determine whether the D-RATIN tool satisfies the intended goals and how the tool can be useful within a full river study. Although this will be done by performing a case study, the results thereof will not be used.

A currently unnavigable river of which the navigational potential has already been studied, using a different method, might be the scenario that best fits the needs of this research. This alternative is likely to both raise the important river study questions as well as to offer the option of validating the results gained by the D-RATIN tool.

The “inland waterways strategic plan” produced by Arcadis [7] already provides some estimates about the expected quantities of shipped bulk as well as some cost indications for the river inventions. This allows the study to focus more on the tool’s use instead of becoming an economical study. In this study performed by Arcadis multiple extensions for the Brazilian inland navigation network are mentioned. Examining the navigability of the Paraguay River and the Tocantins River are two of the most suitable options for this research, because of their economic importance and required interventions. The Tocantins river has been chosen to be the most suitable river for this research.

The Tocantins River has a favourable straight forward shape; this is required to be able to use the tool. Arcadis provides some economical information about the required river interventions. The main advantage of the Tocantins River, compared to the Paraguay River, is the high economic impact on a relatively short river section. The Tocantins River expansion stretches over a distance of about 46 kilometres, contrary to the Paraguay River of which the section to be studied is more than 600 kilometre long. Another advantage is the predicted economic importance of the Tocantins River is way higher, because of the advent of a new steel plant. With 32.5 million tons the expected amount of yearly shipped bulk is about one and a half times larger. Finally, the optimal waterway dimensions are the same along the river section.

Furtheremore, has Arcadis assumed a barge dimension, derived from the amount of predicted bulk transport, for which they calculated the costs of the needed river interventions. This is contrary to this research that aims to find an economical optimum for the barge size. The comparison between the outcomes of the Arcadis study and this research could therefore also deliver some information about the usefulness of searching an economical optimal barge size, in the planning phase of navigational strategy studies.

Not only are the Brazilian rivers interesting because of some of their physical aspects, but also the Brazilian country itself has some interesting features with respect to inland navigation. Firstly, the Brazilian waterways show a lot of navigational potential which currently are not exploited. Secondly the Brazilian industry is producing a lot of bulk goods. This can be illustrated by the fact that the iron ore mining industry in Brazil is the 3rd biggest iron ore mining industry in the world [15], producing almost 10% of all the iron ore in the world. Inland shipping has some preferable characteristics, like costs and capacity, for these types of bulk transport [1].

It is the combination of the Brazilian freight transport importance combined with the appealing characteristics of the Tocantins River that led to the selection of this river.

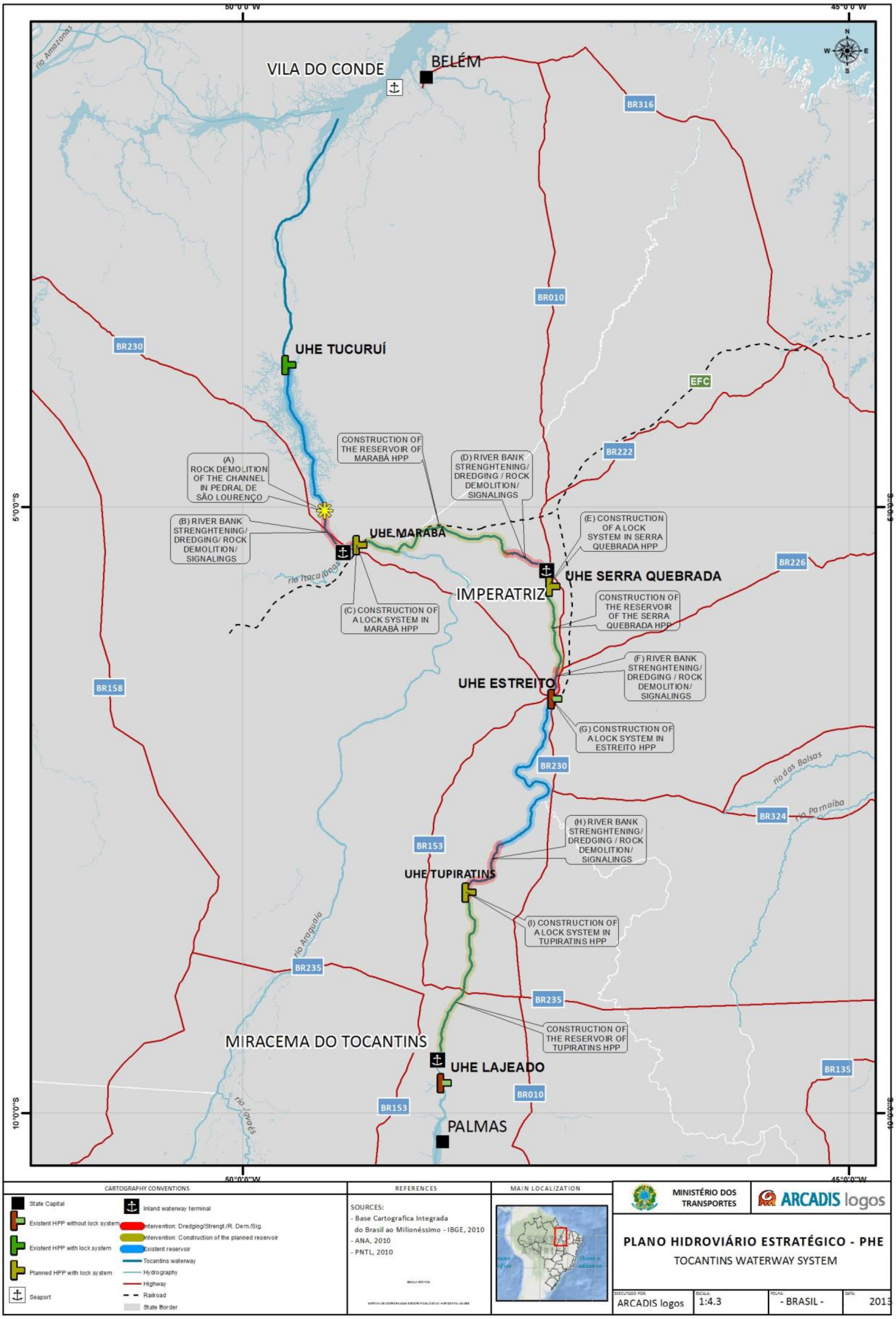

Figure 11.1: Proposed interventions by Arcadis

11.2 Waterway requirements

For each of the 10 CEMT class ship dimensions the corresponding waterway dimensions have been determined. The article “Waterway Guidelines 2011” from Rijkswaterstaat [9], a Dutch governmental body, provides a method to determine canal dimensions. This method does not take the effects of a significant river flow into account. Since a vessel that is navigating the Tocantins River will experience effects of the present flow, these methods cannot be adequately used. In order to resolve this problem the research paper of El-Sersawy, h. and Ahmed, A.F. [16] has been used to correct the results obtained by the methods for canals. El-Sersawy and Ahmed compare multiple width estimation methods for rivers. Unfortunately, these methods are not described in their article and the references cannot be attained as well. Therefore, there is no direct method for rivers accessible. However, comparing their results with the results obtained from a canal situation does provide an indication of the required additional width due to the consequences of the river flow. Hence the width has been determined with the methods provided by Rijkswaterstaat and then these widths have been corrected using the El-Sersawy and Ahmed article.

The method provided by Rijkswaterstaat relates to a trapezoid shaped waterway profile, as presented in Figure 11.3. Since the river’s waterway requires a rectangular profile only the top width of the trapezoid profile has been calculated. The method divides this required upper waterway profile width in 3 sections. One basic width and two additional sections, those are required because of some external effects. The basic width is estimated to be:

$$W_b = 4 * W_{vessel} \tag{1.1}$$

Due to the influence of side wind on the vessel an addition to the standard width is required. This additional width is approximated by the formula:

$$\Delta_{W_{wind}} = 0.05 * L_{vessel} \tag{1.2}$$

Not only has the wind affected the required width of the shipping lane. The orientation of the vessel when it passes bends should be considered as well. Therefore, an additional width, depending on the curvature of the bend, the dimensions of the ship and 2 constants determined by the CEMT class of the vessel has been assigned according to the formula:

$$\Delta_{W_{bend}} = (C_1 + C_2) * L_{vessel}{}^2 / R_{bend} \tag{1.3}$$

The values for the C constants can be found in Table 11.1. The total required width for each CEMT class type of ship, for canals, is given by the summation of these three sections:

$$W_{tot} = W_b + \Delta_{W_{wind}} + \Delta_{W_{bend}} \tag{1.4}$$

The results of this total width calculation for canals can be found in column 7 of Table 3.1.

Now that the width requirement for canals is known these values can be corrected for the effects of the stream, on the vessel’s manoeuvrability, in the Tocantins River. To do so the article of El-Sersawy and Ahmed has been used. In their article they calculate a required shipping lane width for the Nile, taking water flow into account. The correcting factor has been obtained by first calculating the required shipping lane width for the Nile, with the aid of the method provided by Rijkswaterstaat for non-flowing waterways. Then this result has been compared with the result of El-Sersawy and Ahmed whom do take flow into account. The ratio between the two widths has been determined to be the correcting factor, for which all the obtained widths for the Tocantins River will be corrected. This relation only holds true when the assumption is made that the flow characteristics of the Tocantins and the Nile are similar, this however is uncertain. Nevertheless, this calculation method is the best method available, within this limited time period.

To calculate the required waterway depth, the draughts of the vessel and the underkeel clearance have been considered. This underkeel clearance prevents the riverbed from eroding, due to the water-flow caused by the ship. The draught for each barge type is given by the CEMT classification and can be found in the fourth column of Table 3.1. Regarding the underkeel clearance two contradicting papers have been found. Firstly, there is the report of Rijkswaterstaat [9]; this report claims that the underkeel clearance should be about 40% of the ships draught. On the other hand, Robijns [17] executed some small scale experiments and concluded that for barge type vessels the underkeel clearance should be over 10%. This is four times less than Rijkswaterstaat claims. Nevertheless, the underkeel clearance provided by Rijkswaterstaat has been used in this research, mainly because the tool provides only a rough bank level estimate. When taking the 10% obtained by Robijns into account there is no room for errors in the calculations, in contrast to the Rijkswaterstaat method that allows a substantial error.

Duwstellen (Barges)							
CEMT Klass e	AVV Klasse	Karakteristieken maatgevend duwstel**				Classificatie	
		Combinatie	Breedte	Lengte	Diepgang (geladen)	Laadvermoge n	Breedte en lengte
			m	m	m	T	m
0							
I	BO1		5.20	55	1.9	0-400	B<=5.20 en L alle
II	BO2		6.70	61 of 71	2.5	401-600	B 5.21-6.70 en L alle
III	BO3 BO4		7.50 8.20	78 85	2.5 2.6	601-800 801-1250	B 6.71-7.60 en L alle B 7.61-8.40 en L alle
IV	BI	Europa I duwstel	9.50	85 of 90-94 of 99 of 103	3.0	1251-1800	B 8.41-9.60 en L alle
IVb							
Va	BII-1 BIIa-1 BIIL-1	Europa II duwstel Europa IIa duwstel Europa II Lang	11.40 11.40 11.40	92 of 96 - 110 92 of 96 - 110 125-129 of 132-136	3.5 4.0 4.0	1801-2450 2451-3200 3201-3950	B 9.61-15.10 en L <=111.00 B 9.61-15.10 en L <=111.00 B 9.61-15.10 en L 111.01-146.00
Vb	BII-2L	2-baksduwstel lang	11.40	169-177 182-186 of 189	3.5-4.0	3951-7050	B 9.61-15.10 en L >=146.01
VIa	BII-2b	2-baksduwstel breed	22.8	95 of 97-101 106-113 135 of 145	3.5-4.0	3951-7050	B 15.11-24.00 en L <=146.00
VIb	BII-4	4-baksduwstel (incl. 3-baks lang)	22.8	183-194	3.5-4.0	7051-12000 (7051-9000)	B 15.11-24.00 en L 146.01-200
VIc	BII-6l	6-baksduwstel lang (incl 5-baks lang)	22.8	263-270	3.5-4.0	12001-18000 (12001-15000)	B 15.11-24.00 en L >=200.01
VIIa	BII-6b	6-baksduwstel breed (incl. 5-baks breed)	34.2	193	3.5-4.0	12001-18000 (12001-15000)	B >=24.01 en L alle

Figure 11.2: CEMT classification

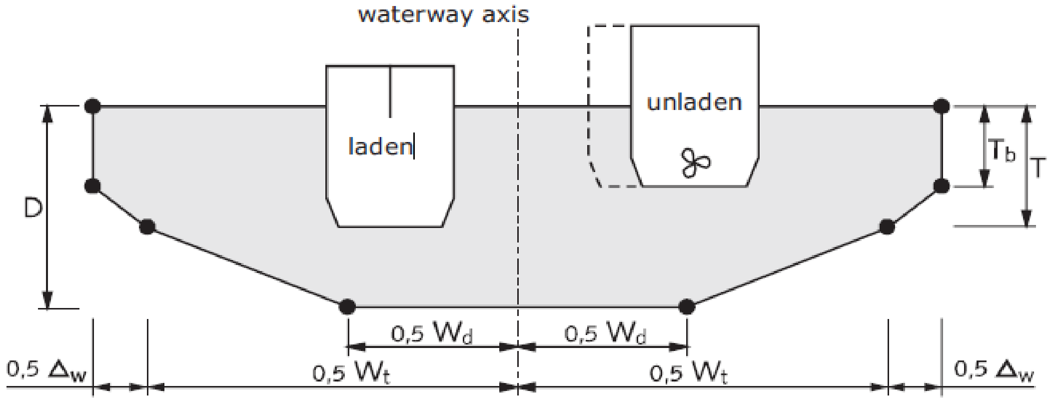

Figure 11.3: waterway profile

CEMT Class	Wd	Wt	Δw	C1	C2
	(m)	(m)	(m)		
I	10,4	20,8	2,75	0,25	0,5
II	13,4	26,8	3,55	0,25	0,5
III	16,4	32,8	4,25	0,25	0,5
IV	19	38	5,15	0,25	0,5
Va	22,8	45,6	6,8	0,25	0,5
Vb	22,8	45,6	9,45	0,2	0,4
Via	45,6	91,2	7,25	0,2	0,4
Vib	45,6	91,2	9,7	0,2	0,4
Vic	45,6	91,2	13,5	0,2	0,4
VIIa	68,4	136,8	9,65	0,2	0,4

Table 11.1: waterway requirements additional information

11.3 Navigational Bottlenecks

11.3.1 Model parameters

11.3.1.1 Grid parameters

The grid parameters have been determined by a trial and error process. Zervakis (2015) claims that the grid size does not influence the computing time, however during this research it became clear that for this case the grid size does matter. This is probably because the study area in this research is significantly larger than in Zervakis' research. The final parameter values are presented in Figure 11.6. The spacing parameters are based on computing time and a visual inspection of the bed-level and water depth results. The smoothing parameter has been visually judged by observing how accurate it fits the polygon. If the smoothing parameter is too low, the grid will overlap itself, which is presented in Figure 11.5. The chosen parameter generates the grid as presented in Figure 11.4 . This grid seems to be fitting the polygon more accurate.

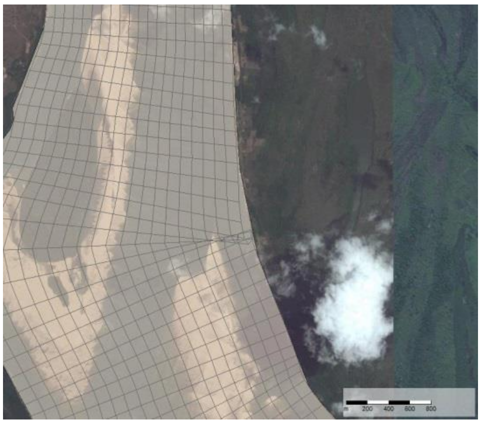

Figure 11.5: too low smoothing grid example

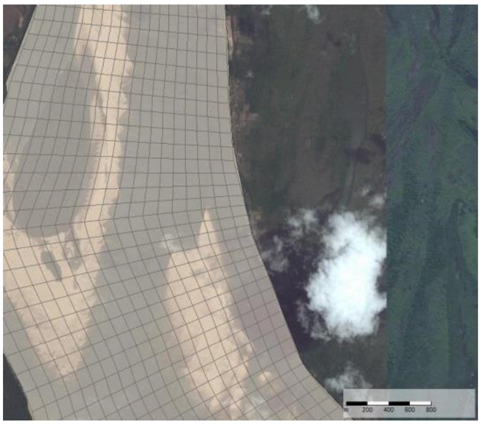

Figure 11.4: sufficient smoothing grid example

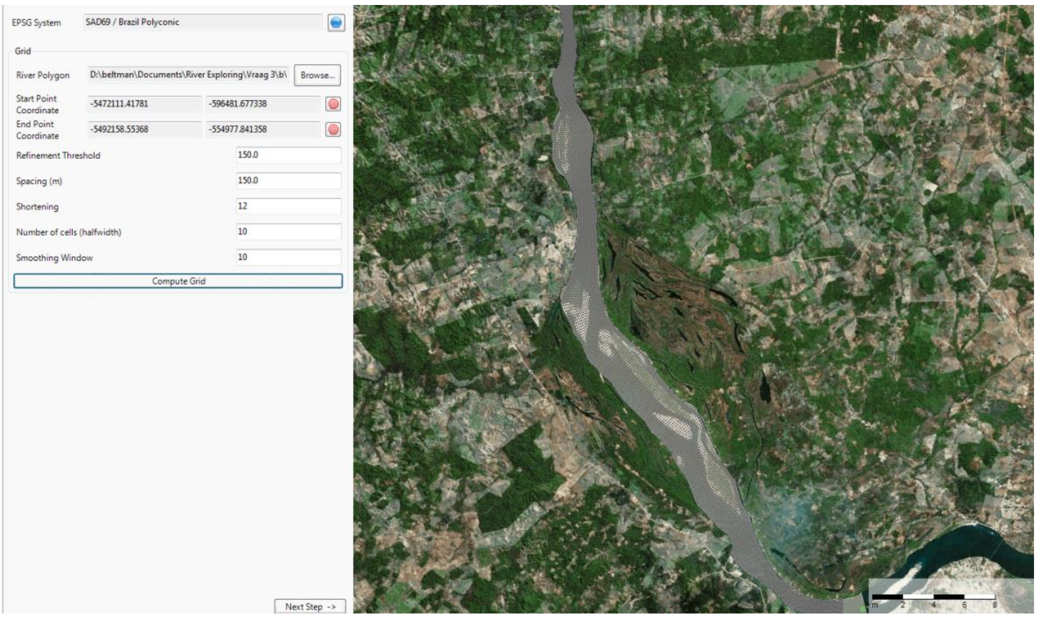

Figure 11.6: Grid parameters

11.3.1.2 Bed level parameters

The physical bed level parameters have been based mostly on available literature about the Tocantins River or rivers in general. The non-physical parameters have again been determined by a trial and error process. The used parameter values can be found in Figure 11.8.

It was not fully possible to determine the bankfull discharge exact. The definition of the bankfull discharge also differs per source. In this research it is assumed that the river reaches its bankfull discharge every year, because of the high fluctuation in discharge. Therefore the average maximum discharge has been determined to be the bankfull discharge. This average is obtained out of the hydrograph presented in Figure 2.2.

Some measurement figures that describe the grain size of the soil of the right river bank, near the Tocantins Dam have been found [11]. These grain sizes have been used as the grain size in this research's river section. However, it is not certain that these grain sizes hold true for the situation more upstream the river.

The average slope has been determined by calibrating the water level slope, generated by the model, to the water level slope given by Google Earth [13]. Google Earth shows that with a discharge of 4300 m^3/s the water level decreases about 1 meter. By trial and error the corresponding bed level slopes have been determined. The obtained water level slope is presented in Figure 11.7.

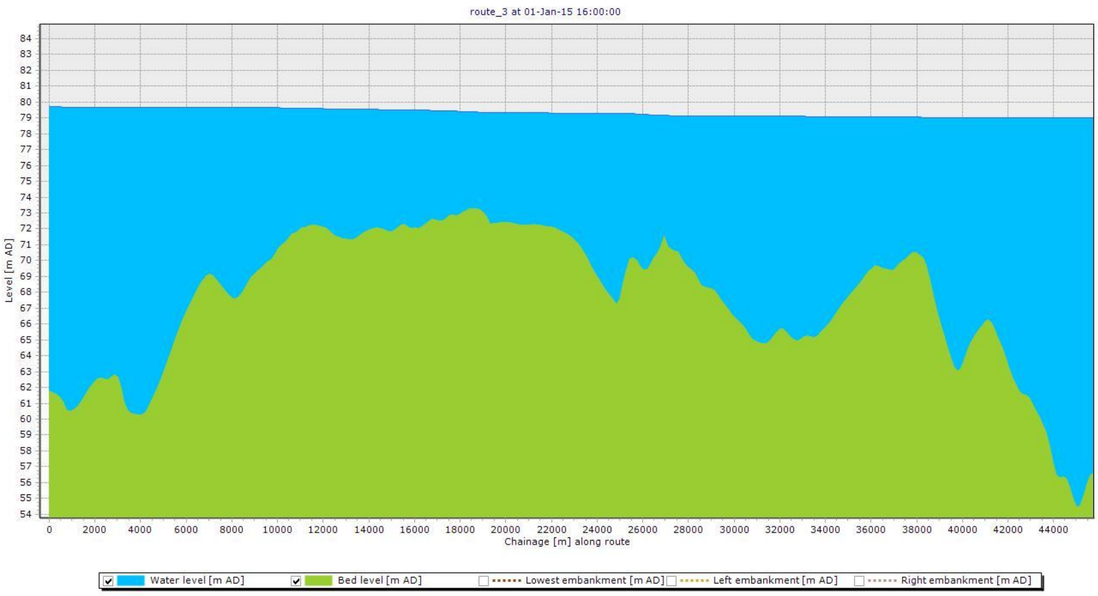

Figure 11.7: River slope calibration by water level

The water levels downstream have been determined using the height maps provided by Google [18]. The bankfull water level has been assumed to be equal to the height of the banks, these heights are provided by the elevation finder [18].

No information is available about the cross section of the Tocantins River. Therefore, the number of cells for the riverbanks have been estimated and adjusted depending on the model output. Still this parameter is quite uncertain and should be defined into more detail for a real case study.

For smoothing the results, the smoothing window has been put to 20. This is an estimation. Unfortunately, it is not possible to calibrate this parameter into more detail since there are no water depths known for the whole river section. The parameter is only checked by reference to the credibility of the outcomes.

To reconstruct the sandbars in the river, the interpolation and fusion options have been used. The parameters have all been determined by trial and error, based on the geometry of the sandbanks, known from Google Earth data. It seems like these obtained parameters properly represent the sandbars as they are shown at satellite images. The sandbar geometry below the water surface is not known and cannot be checked further.

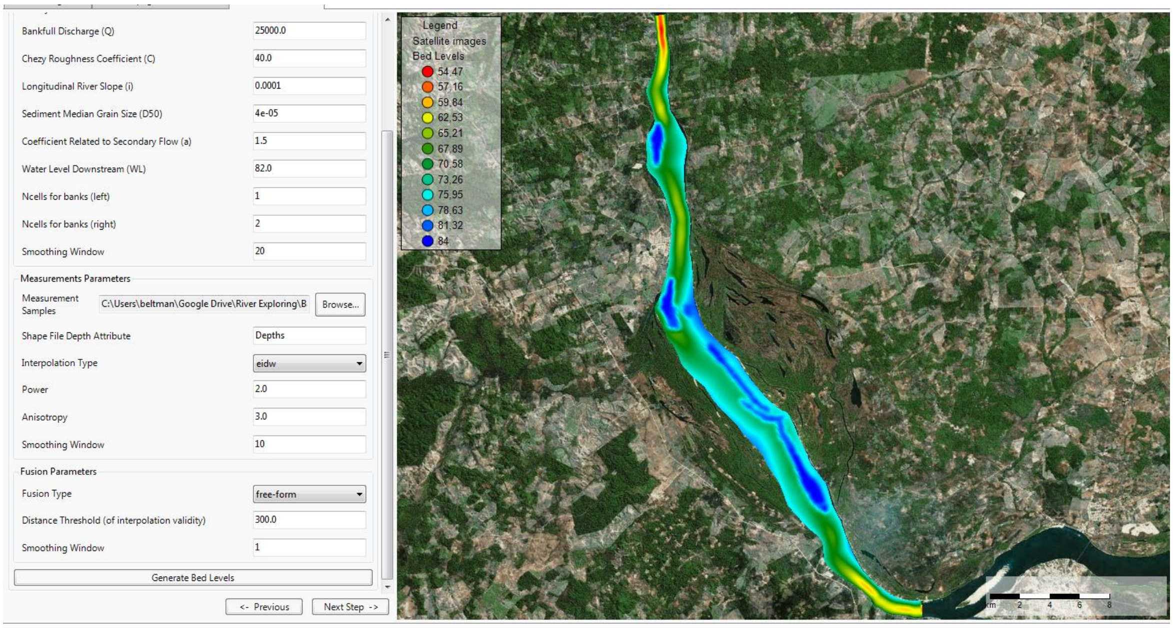

Figure 11.8: bathymetry parameters

11.3.1.3 Water depth parameters

Although the tool suggests the bankfull discharge as input for the water depth calculations, this research does not do so. To successfully ship the 32.5 million tonnes of cargo navigation, this should be able to happen during the entire year. Therefore, the minimum average discharge per year, 2.500 m^3/s has been taken to be the leading discharge for the calculations regarding the navigational potential.

To calculate the water level that corresponds to the minimum discharge of 2.500 m^3/s a simplified Chézy Q-h relation has been used [10]:

$$Waterlevel_{2500} = Waterlevel_{bankfull} - \left(\frac{Q_{bankfull}}{\text{Width}^* \left(\frac{g * I}{c_f} \right)^{0,5}} \right)^{\frac{2}{3}} - \left(\frac{Q_{2.500}}{\text{Width}^* \left(\frac{g * I}{c_f} \right)^{0,5}} \right)^{\frac{2}{3}} \quad (1.5)$$

The friction coefficient has been calculated by [10]:

$$c_f = \frac{g}{C^2} \tag{1.6}$$

The width, 1750 meters, of the river has been obtained with Google Earth.

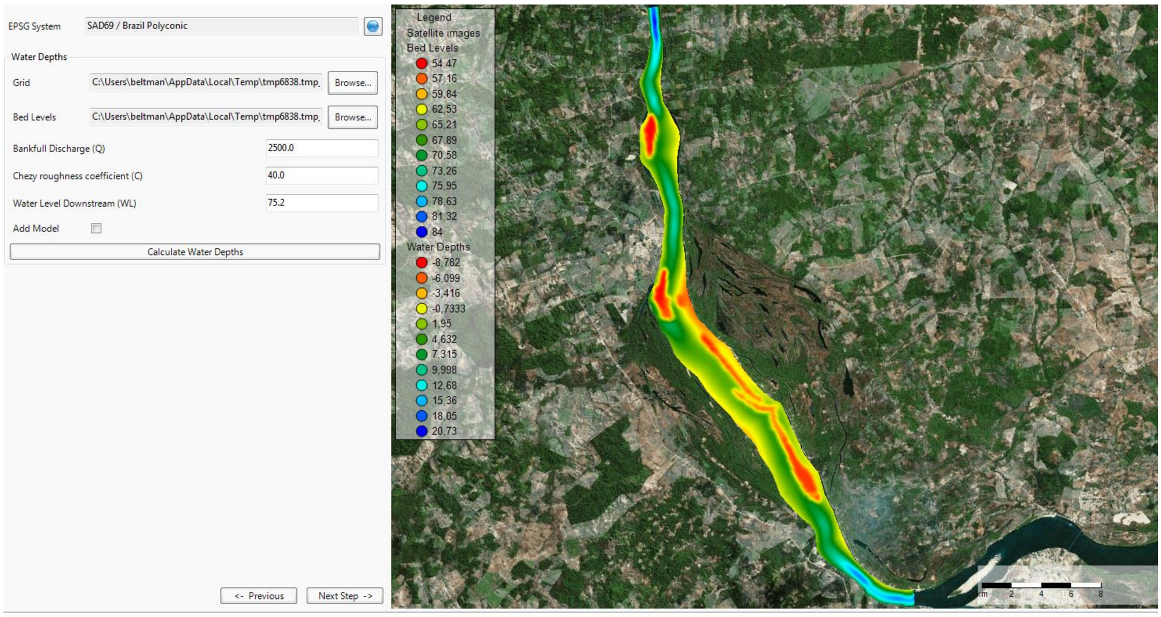

Figure 11.9: Water-depths parameters

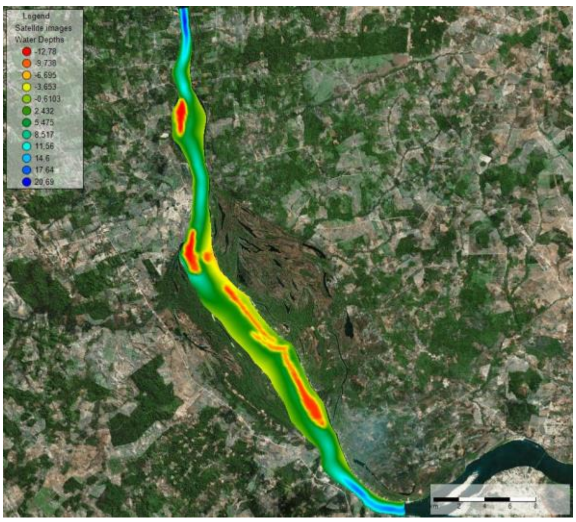

Figure 11.10: water depths including sandbars

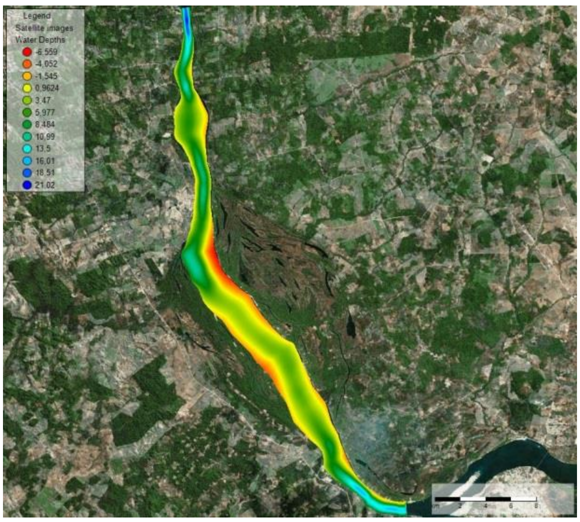

Figure 11.11: water depths excluding sandbars

11.3.2 Sandbar reconstruction method

Currently the tool is not capable to reconstruct the river's bed-levels for sections that contain sandbars. During the search for a suitable river it became clear that there are hardly rivers that do not have those sandbars somewhere in their path. There are multiple ways to deal with sandbars in the D-RATIN tool, of which two options have been considered in this study.

The first option divides the river into sections in which the river's discharge is constant. A new section begins at every point where the main channel's discharge is affected by the presence of a bifurcation by sandbars. In order to successfully apply this method an indication about the discharge distribution around each sandbar is needed. This distribution is hard to obtain for the projected rivers. Literature has been studied to see whether it is possible to estimate the discharge distribution, only based on both channel widths. Gleason and Smith [19] studied such a relation and came up with an equation that estimates the discharge related to the width of the river. Unfortunately, their results show quite some deviation in the predicting performance. It can be concluded that such a relation is a too rough estimation for this research's goals. Another downside of dividing the river into sections is that it increases the amount of work drastically. Only for the relatively short river section that this research analyses it would generates nine sections. This would mean that the required time for the analyses will be increased about nine times, while the initial goals where to develop a tool for quick research. Therefore, this option has not been used. Nevertheless, dividing the river into sections is required when the river merges or demerges.

Another possibility is to manually reconstruct the sandbanks. This can for example be done by implementing sandbar's height points, of which the height is obtained by Google Earth data. Then the interpolation tool can be used to interpolate these points into a sandbank, as presented in Figure 11.12. In the case of the Tocantins River this reconstruction appears to have potential, because the maps of Google provide the required information about the sandbar heights. Implementing these known points could help to improve the output results. The biggest advantages of this method are that it is feasible to use only open source data and contrary to the first option it will most likely not increase the research time significantly.

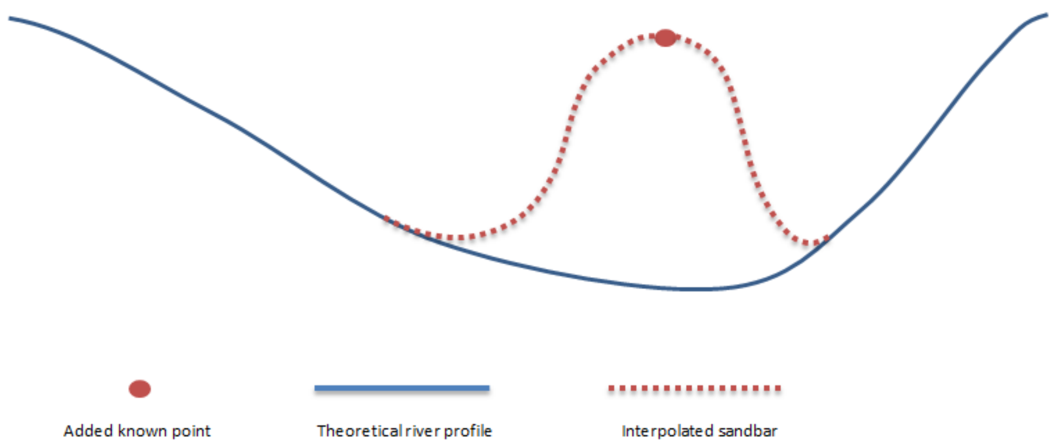

Figure 11.12: Schematization of sandbar interpolation

In this research the second method has been used. In ArcMap height points have been generated of which the height has been gained out of Google Maps data. Figure 11.13 shows the generated height points that are used for the interpolation.

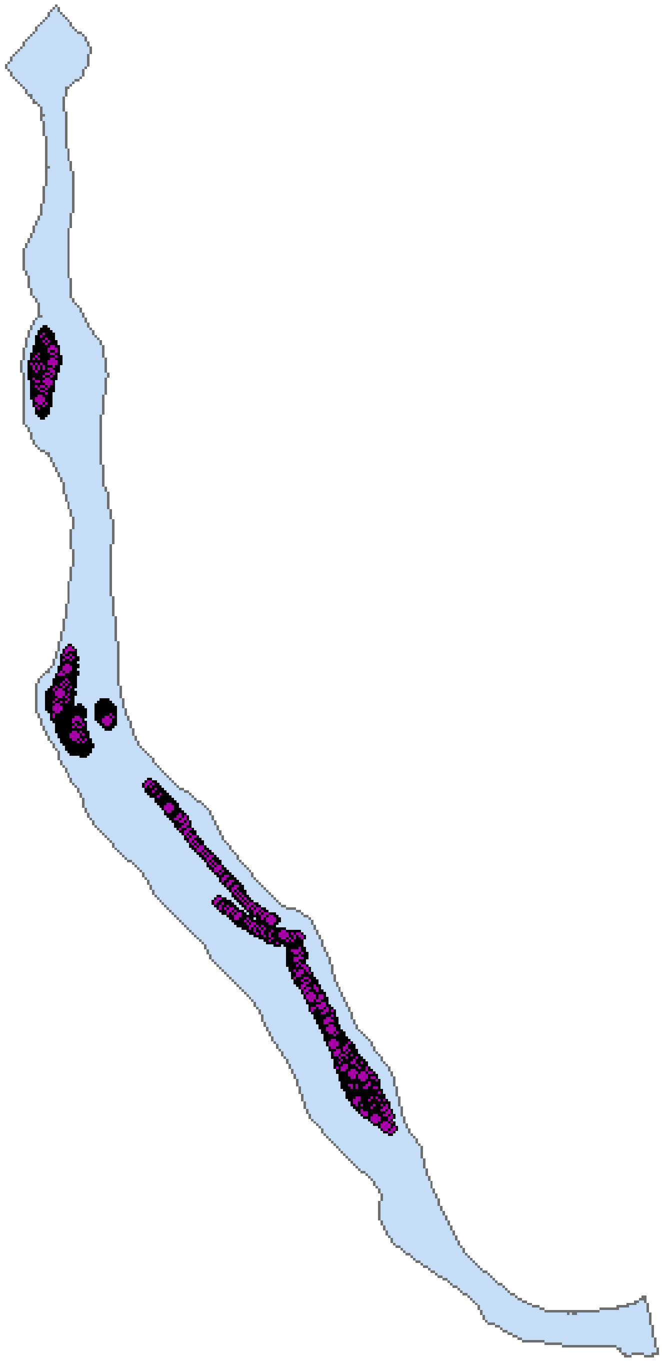

Figure 11.13: Added height points

11.3.3 Route examples

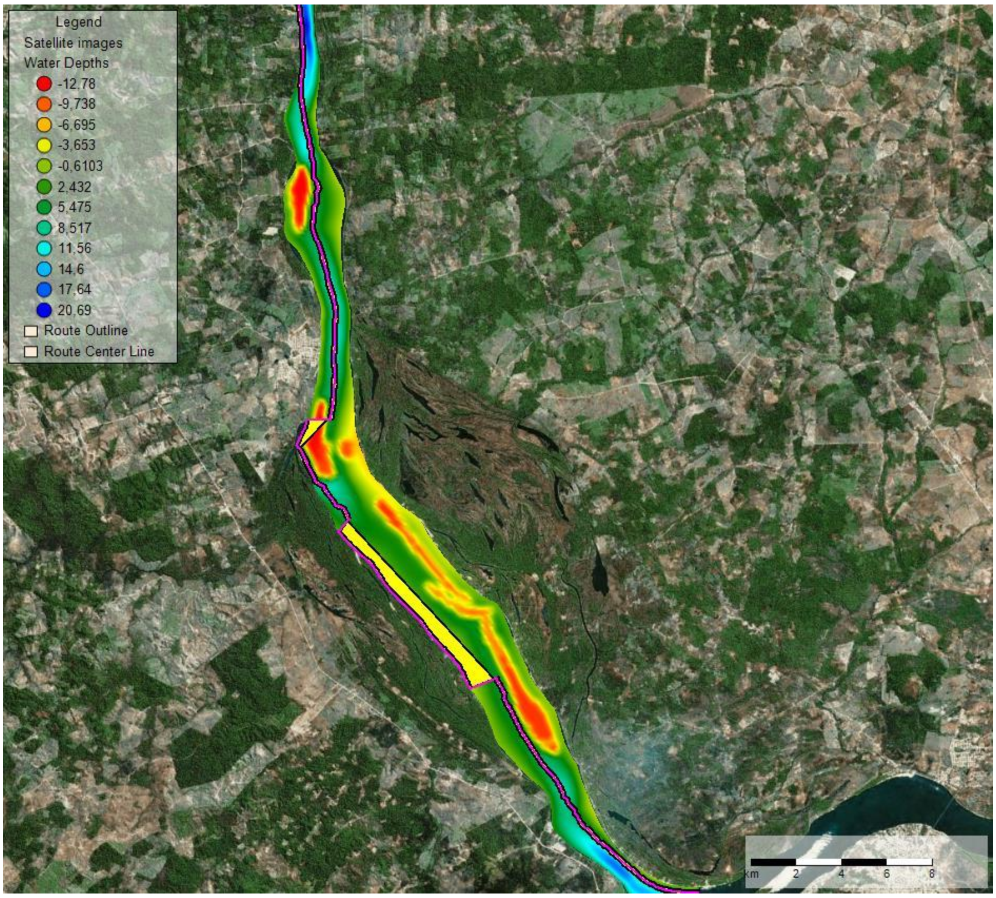

Figure 11.14: Wrongly generated route

11.3.4 Bottleneck locations

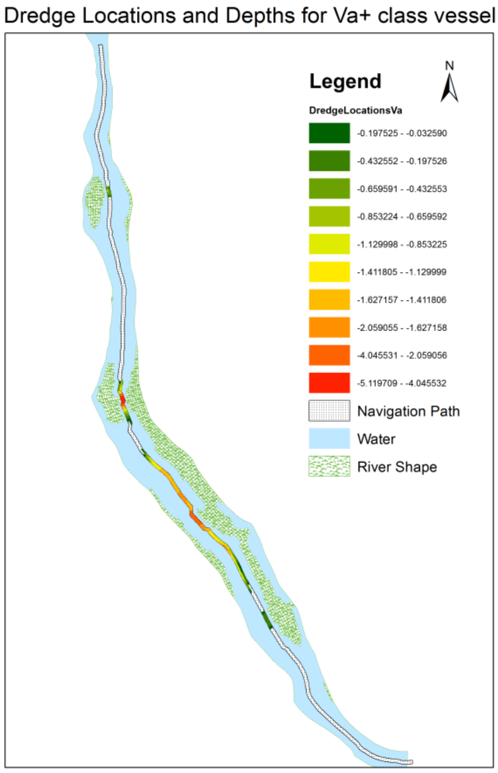

Figure 11.18: Dredge Locations and Depths for Va+ class vessel

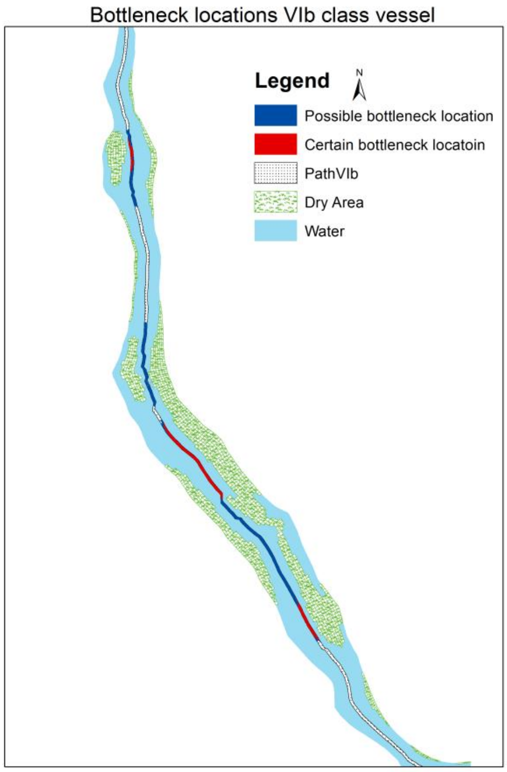

Figure 11.15: Bottleneck location certainty Va+ class vessel

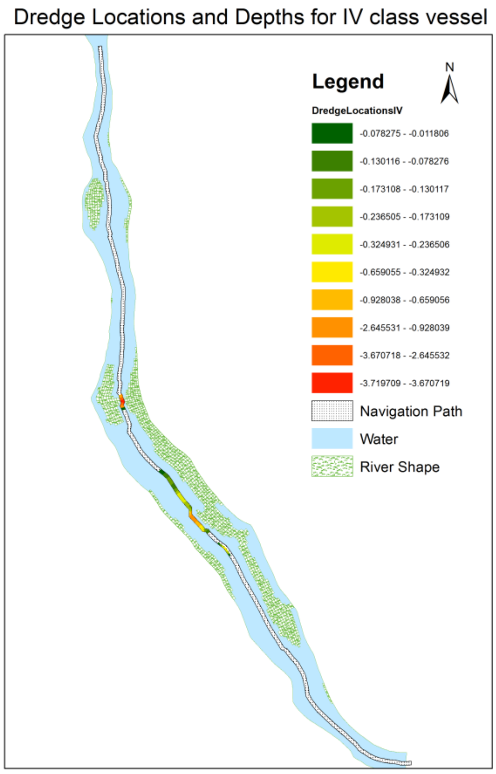

Figure 11.17: Dredge Locations and Depths for IV class vessel

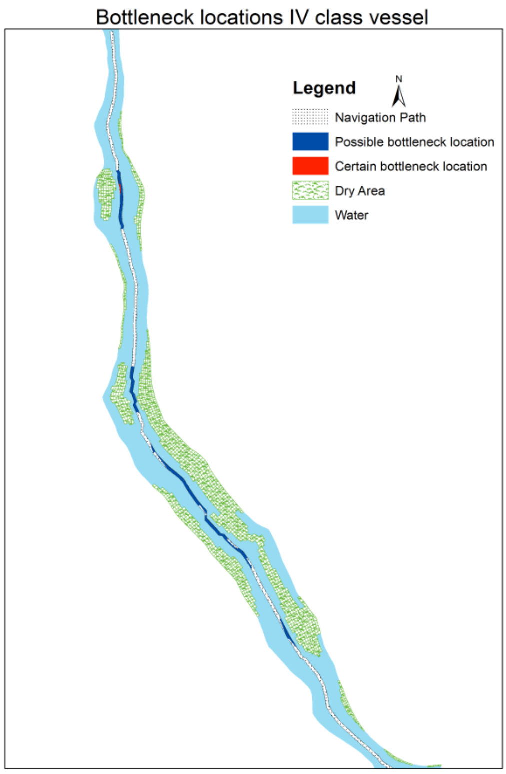

Figure 11.16: Bottleneck location certainty IV class vessel

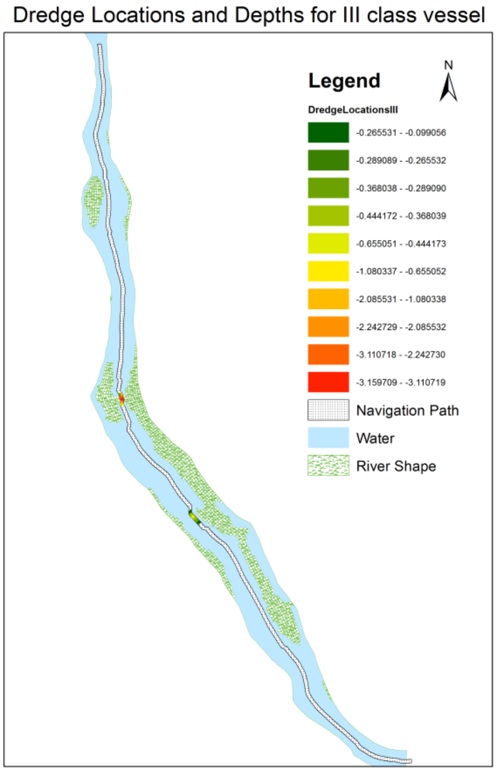

Figure 11.22: Dredge Locations and Depths for III class vessel

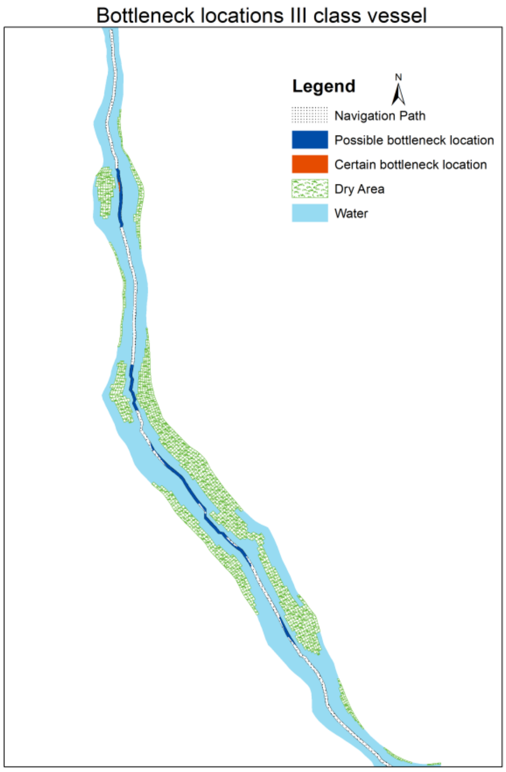

Figure 11.20: Bottleneck location certainty III class vessel

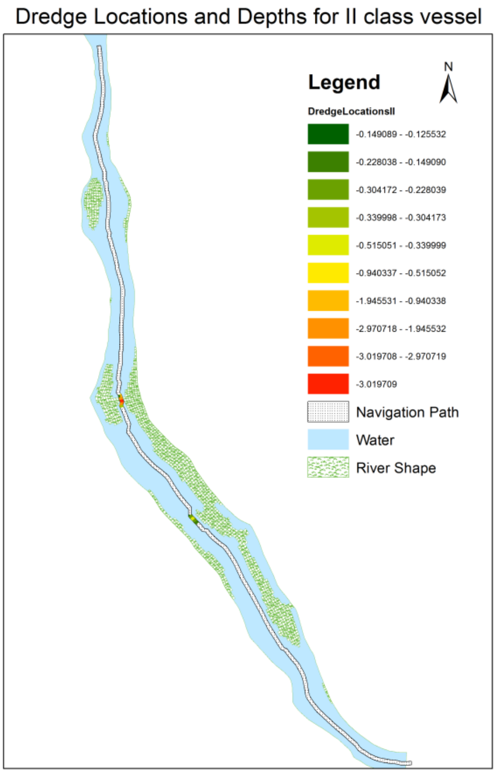

Figure 11.21: Dredge Locations and Depths for III class vessel

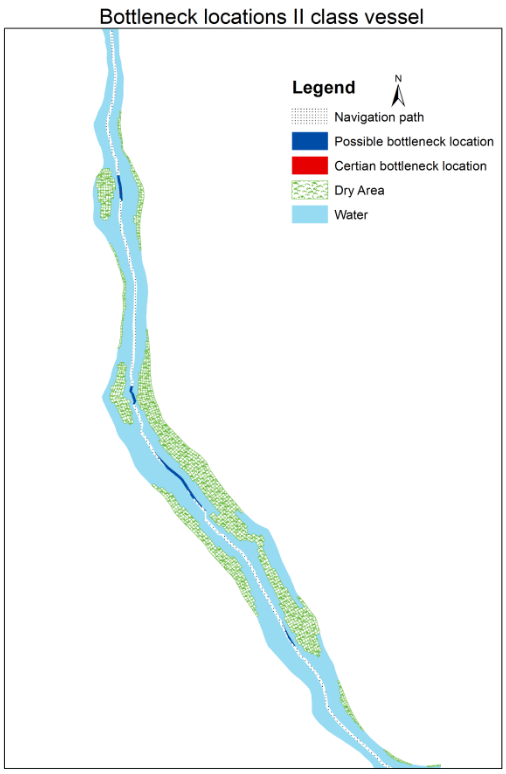

Figure 11.19: Bottleneck location certainty II class vessel

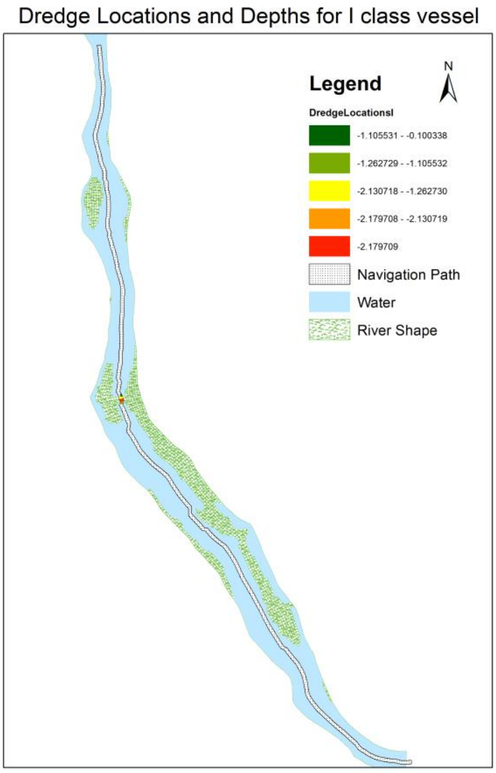

Figure 11.24: Dredge Locations and Depths for I class vessel

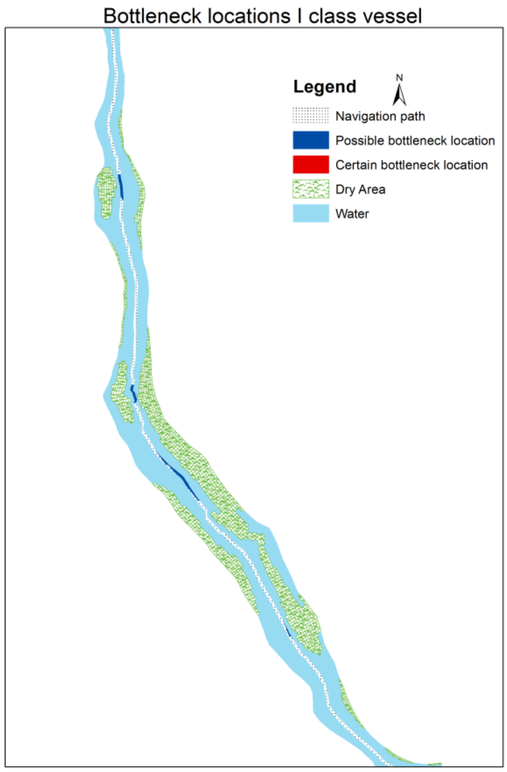

Figure 11.23: Bottleneck location certainty I class vessel

CEMT Class	Dredge volume (m^3)
I	442
II	8267
III	17612
IV	102352
Va	1133716
Vb	1233530
Via	2134534
Vib	2234939
Vic	2435928
VIIa	3242261

Table 11.2: Dredge volume per CEMT class

11.4 Cost-benefits

This cost-benefit study purely aims to test de D-RATIN's performance and is not performed for the generation of the exact cost-benefit results of the Tocantins River. Therefore, to not digress from the set goal assumptions regarding the cost-benefit analysis have been made. There also is not enough knowledge available to properly execute a cost-benefit analysis, without these assumptions.

The most important assumption made in this cost-benefit analyses is that transportation by water in all the scenario's is the most favourable mode of transport. This means that the full demand of 32,5 million tonnes of cargo will be transported by the waterway, no matter what the optimal CEMT class vessel is. There are multiple reasons why this assumption is acceptable. Firstly, most of the Tocantins River is currently navigable. Only 46 km of river need to be prepared for navigation. This makes it plausible that it will be way cheaper than constructing a 450 km long railway, connecting the steel plant to the ports. Roughly estimated will the costs of a railway be 5 billion BRL, based on the costs per kilometre of a planned railway construction in Brazil [20]. The article of Caris et al [21], supports this assumption, it shows that, on average, the infrastructural costs of railways are higher than for waterways. Not only construction costs are way higher, also the operating costs of rail are higher than transportation by water. The advantage of rail lies mainly in the transportation time. Since for the objected type of cargo time is not an important factor, this advantage is of minor importance. Besides rail also road transport is a less favourable option, mostly because of the high transporting costs and harmful emissions.

Secondly it will not be taken into account who the investors are for each cost item. It is not clear if the government will be fully financing the river interventions, or that private investors will invest in this infrastructure. There are for example some railway projects that are financed purely by private investors [22]. Because the financial constructions are unknown, the best overall cost-benefit result will be studied. In this, waterway interventions, terminal capacity and operating and maintenance costs are taken into account.

Due to these assumptions the class I type vessel has become the reference scenario to which all the costs and benefits will be related.

11.4.1 Costs method

To calculate the costs of the required river interventions the D-RATIN tool has been used in combination with literature. Firstly, literature has been studied to obtain information about the costs of interventions in the river bed. Three types of costs, dredging, signalling and riverbank strengthening, have been studied for the river construction costs. Signalling and riverbank strengthening's costs have been derived from the Arcadis report. Estimating the unit costs for dredging appeared to depend on a set of factors. The price is for example highly influenced by the distance from the river to the storage location. The unit costs given by literature ranged from 3 euros [23] up to almost 17 euros [24]per cubic meter. The report "Watervast" [25] provides more insight in the costs of dredging. With this document the dredging costs have been set to 15 euros per cubic meter. This price holds true for a transport distance of 60km for the dredged soil. To translate these costs from a Dutch market to a Brazilian market the Big Mac index and the Currency rate have been applied. The total costs of the river interventions, for each scenario, are then calculated with help of the D-RATIN tool, for the smaller vessel classes. ArcMap has been used for the larger vessel classes, because of the illogical routes generated for these classes. The D-RATIN tool directly calculates the required dredging volume and the related costs. The cost calculations with ArcMap have been done by generating a map that contains the dredging depth. These depths are then multiplied by the cell area. Subsequently all the volumes per cell have been summed up.

The yearly maintenance costs, are estimated to be 1,5% of the initial intervention costs. This percentage is given by PIANC [26]. Subsequently to determine the costs over 30 years, the projected lifetime of a waterway, inflation and discount rates for the investment have been taken into account. Firstly, the operating and maintenance costs have been corrected by 4,5% each year. This inflation has been predicted by the International Monetary Fund [27]. Then the net present value of the total maintenance and operating costs has been calculated. To do so the current interest rate, 14,5 % [28], of the Central Bank has been used.

To facilitate the cargo transport not only the waterway needs to be prepared, also the capacity of the ports that tranships the cargo from the inland vessels to, probably, sea ships needs to be upgraded. Arcadis does provide some cost estimates for these terminal expansions that have been taken over directly. The costs of the terminal expansions are assumed to depend on the amount of shipped cargo and not on the amount of ships that needs to be handled. Therefore, the costs regarding the port expansion are assumed to be constant for each alternative.

11.4.2 Cost results river and port construction

Figure 11.25 shows all the calculated construction costs necessary to prepare this river for inland navigation. The shown numbers and their proportions indicate that the chosen river might not be representative for an average situation. Remarkable are the river intervention costs that are not in the same order of magnitude with respect to the port improvement costs. The Arcadis study shows that for each of the other rivers the river intervention costs are in the same order of magnitude, or even higher, as the port upgrading. That this river’s costs differ that much is not illogical because only 46 km of the Tocantins River need to be prepared for navigation; the remaining 400 kilometres are already navigable. Another striking finding is that the costs relative to the reference scenario, vessel class I, are relatively low, this is due to the fact that only the river intervention costs have been assumed to be vessel type dependent. Since all costs are relative to the reference scenario, all the port construction costs drop out.

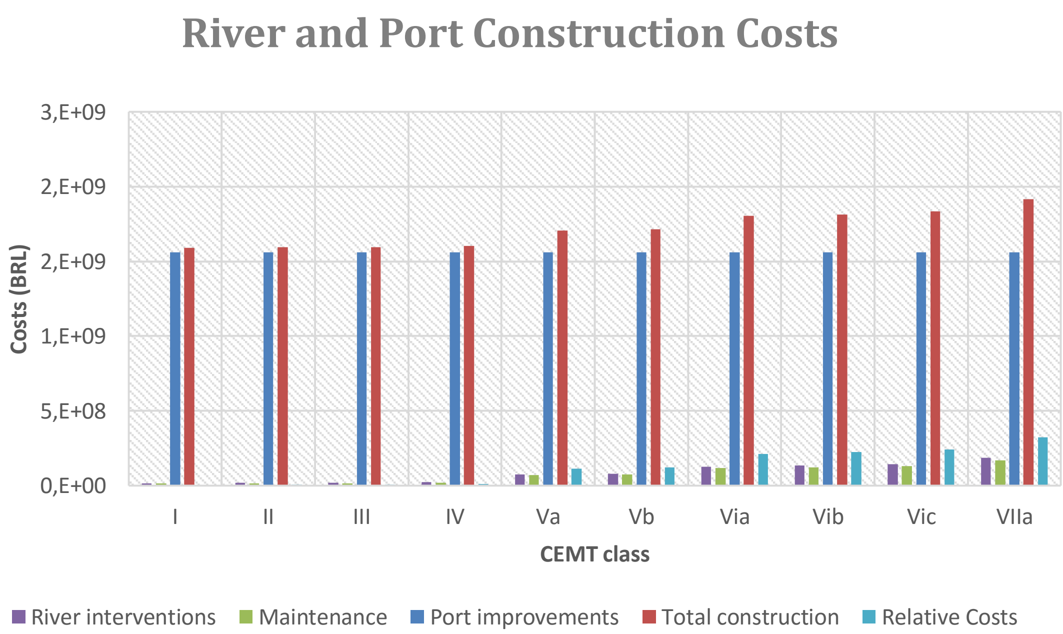

Figure 11.25: Costs

Type of intervention	Costs	unit
Riverbank strengthening	BRL 210,00	BRL/meter
Signalling	BRL 120,00	BRL/meter
Dredging	BRL 52,00	BRL/m^2

Table 11.3: River intervention unit costs

11.4.3 Benefits operating costs - method

The construction of a new waterway influences many aspects. Employment, global warming, economic activity, harbours, maintenance and operating costs are all affected by the waterway. Some of these effects can be quantified relatively easy, for example the operating costs; others require more work, for example the economic spin off. Because of the limited time and knowledge available only the operating costs will be quantified and used for the cost-benefit analyses. These operating costs exclude the costs of transhipment, since these costs are related to the amount off cargo which is constant [PIANC] for all the alternatives. Besides the operating costs of the ships also the benefits in maintenance and operating costs of the infrastructure are calculated. In this research it became clear that these costs decrease when the construction costs increase. Therefore, are these cost reductions considered to be benefits.

PIANC's report "Economic aspects of inland waterways" [26] provides an indication of the operating costs related to vessel size. They state that for small vessels and for large vessels the operating costs range respectively between 0,04-0,03 € /ton-km and between 0,023-0,015 € /ton-km. In this research the CEMT classes I - IV are considered to be small vessels and the Va - VIIa classes are considered to be large vessels. To be able to assign a specific operating cost per vessel class it has been assumed that the operating costs are directly related to the cargo capacity. Another option to calculate the specific operating costs was to relate them to the amount of push boats required per class. This method is based on the assumption that the operation costs are mainly determined by the push boat. For most of the costs this is actually the case. Fuel, maintenance, staff, emissions, they are all influenced mostly by the push boat. Both methods have been calculated, in the end the capacity driven method has been chosen. This method corresponds best with the economies of scale. Also does this method rely on fewer unsure assumptions than the push boat driven method.

Nonetheless these costs might represent an American policy, they still are not applicable for Brazil, because they account for Dutch prices. To convert the Dutch costs to Brazilian costs, the Big Mac index has been used. Even though this index started off as an unofficial index, it is considered as a proper index nowadays [29]. This index states that in order to convert European costs to Brazilian costs, the costs need to be multiplied by a factor of 0,84. Finally the currency has been converted from Euros to Brazilian Reals. This has been done by using the current currency rate, 1 euro relates to 3,99 BRL [30]. After all the above mentioned steps, the operating and maintenance costs per year have been calculated.

Subsequently the transportation costs of the predicted 32,5 million tonnes of cargo have been calculated over the distance from Marabá to the seaport, 450 kilometres. These costs were then multiplied by the lifetime of the project, 30 years [31], taking the inflation into account. This inflation has been set to 4,5 % per year, predicted by the International Monetary Fund [inflation]. The total cost of transporting the predicted amount of cargo for 30 years has then been discounted to its net present value, taking into account the Central Bank's current interest rate of 14,25% [28]. Finally, the benefits of each alternative have been obtained by calculating the transport costs, difference between the alternatives and the reference scenario, over 30 years.

11.4.4 Benefits operation costs - results

The calculated operating costs for each vessel class, in euros, are presented in Figure 11.26. The gradient of these costs does look plausible. Figure 11.28 shows the estimate of the operating costs with respect to the cargo capacity. The trend line shape corresponds with the economies of scale theory presented in Figure 11.29 [32].

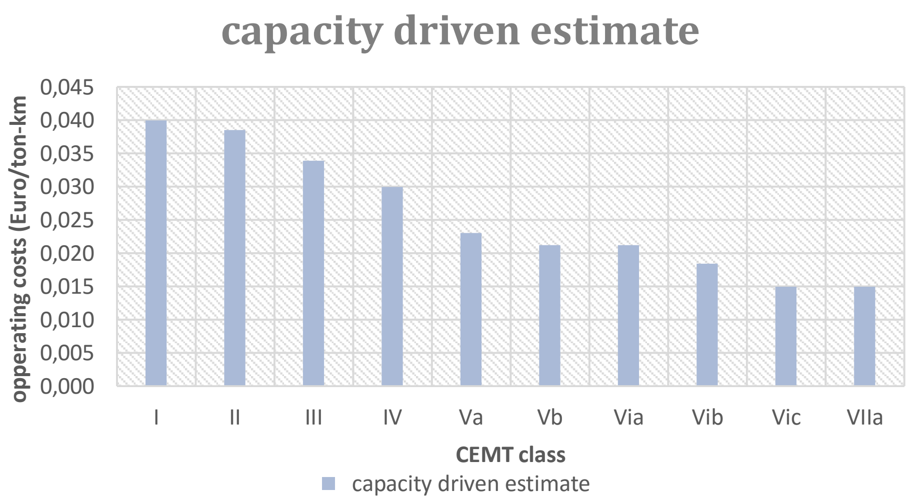

Figure 11.26: operating cost estimate per CEMT class

The calculated transportation costs and benefits for each vessel class are shown in Figure 11.27. The benefits deviate between 0,8 and 14,26 billion BRL. These numbers are remarkably high. Nevertheless, this is no more than logically since each year, 30 years long, there is a demand of almost 18 billion ton-km.

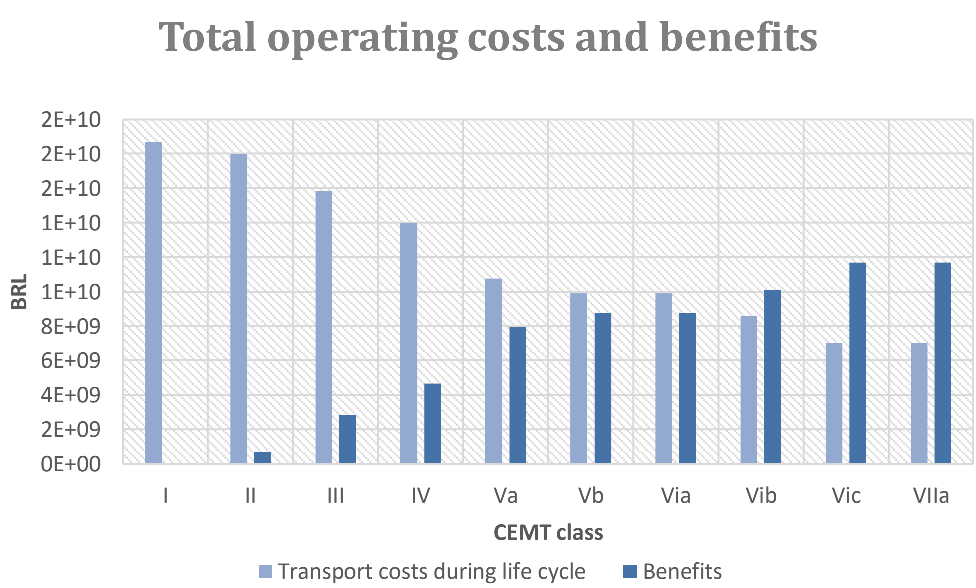

Figure 11.27: total operating costs and benefits per CEMT class

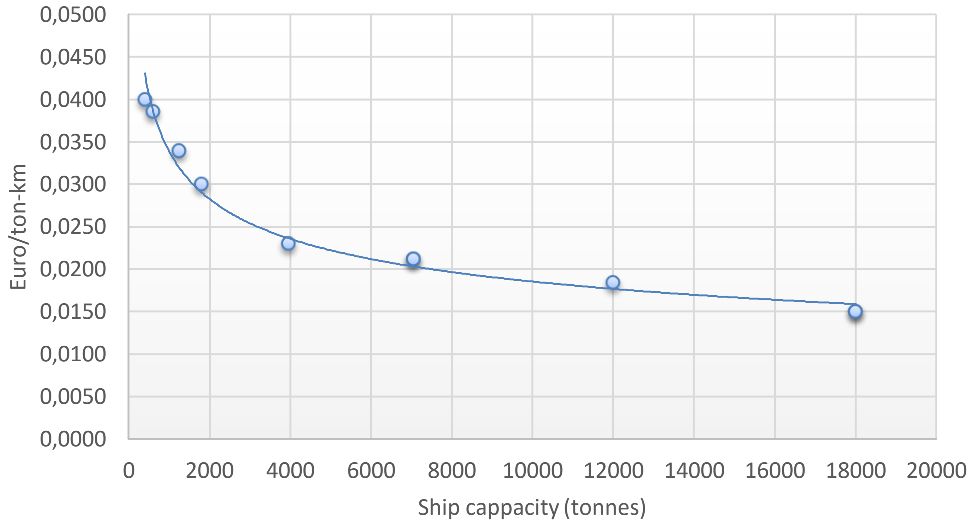

Figure 11.28: vessel capacity vs. operating costs

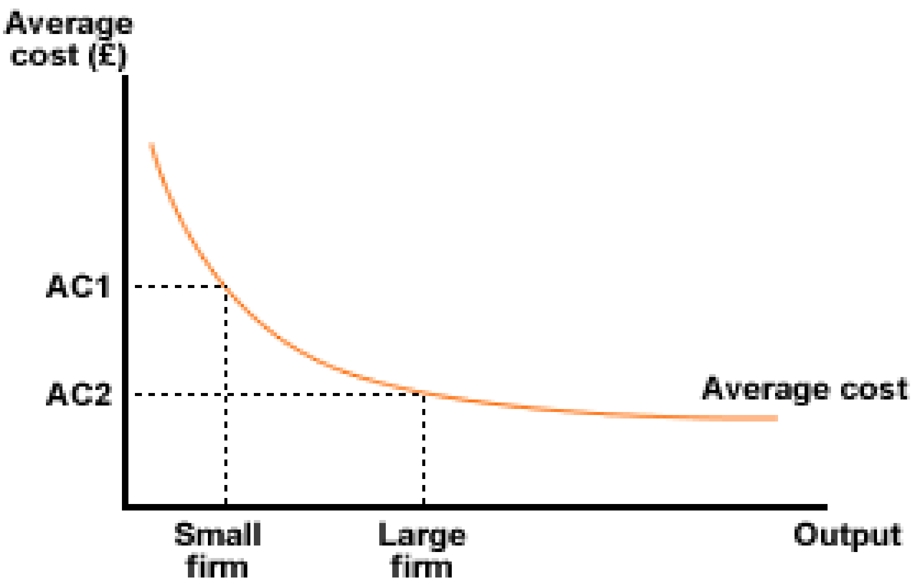

Figure 11.29: economies of scale

11.5 Result interpretation

11.5.1 Sensitivity analyses

Model section	Parameter	Reference value	boundary values	Relative input deviation	Costs	Deviation absolute	Deviation relative
Grid changes	distance	150	100	-33%	BRL 29.024.012,00	BRL 5.292.130,00	22%
			200	33%	BRL 22.818.132,00	BRL (913.750,00)	-4%
	Width	10	8	-20%	BRL 23.391.448,00	BRL (340.434,00)	-1%
			12	20%	BRL 26.502.820,00	BRL 2.770.938,00	12%
Bed level changes	chezy coefficient	40	55	38%	BRL 38.050.590,00	BRL 14.318.708,00	60%
	grain size	4,0E-05	2,2E-05	-45%	BRL 16.054.776,80	BRL (7.677.105,20)	-32%
			8,00E-05	100%	BRL 42.817.911,00	BRL 19.086.029,00	80%
	downstream waterlevel	78	77	-1%	BRL 23.482.114,00	BRL (249.768,00)	-1%
			79	1%	BRL 24.036.615,00	BRL 304.733,00	1%
	nr cells for bank (l,r)	1,2	0,1	-100%	BRL 28.965.249,00	BRL 5.233.367,00	22%
			2,3	100%	BRL 20.040.669,00	BRL (3.691.213,00)	-16%
	smootihing window	20	15	-25%	BRL 28.783.305,00	BRL 5.051.423,00	21%
			25	25%	BRL 21.359.088,00	BRL (2.372.794,00)	-10%
water level changes	Waterlevel downstream	71,2	72,2	1%	BRL 18.227.135,00	BRL (5.504.747,00)	-23%
			70,2	-1%	BRL 29.707.548,00	BRL 5.975.666,00	25%

Table 11.4: Sensitivity analyses

Parameter	Deviation
Chézy friction coefficient	14%
Longitudinal river slop	1%
Grain size	9%
Related coefficient	56%
Bankfull discharge	2%

Table 11.5: Quantified parameter uncertainty

11.5.2 Effects of the added sandbars

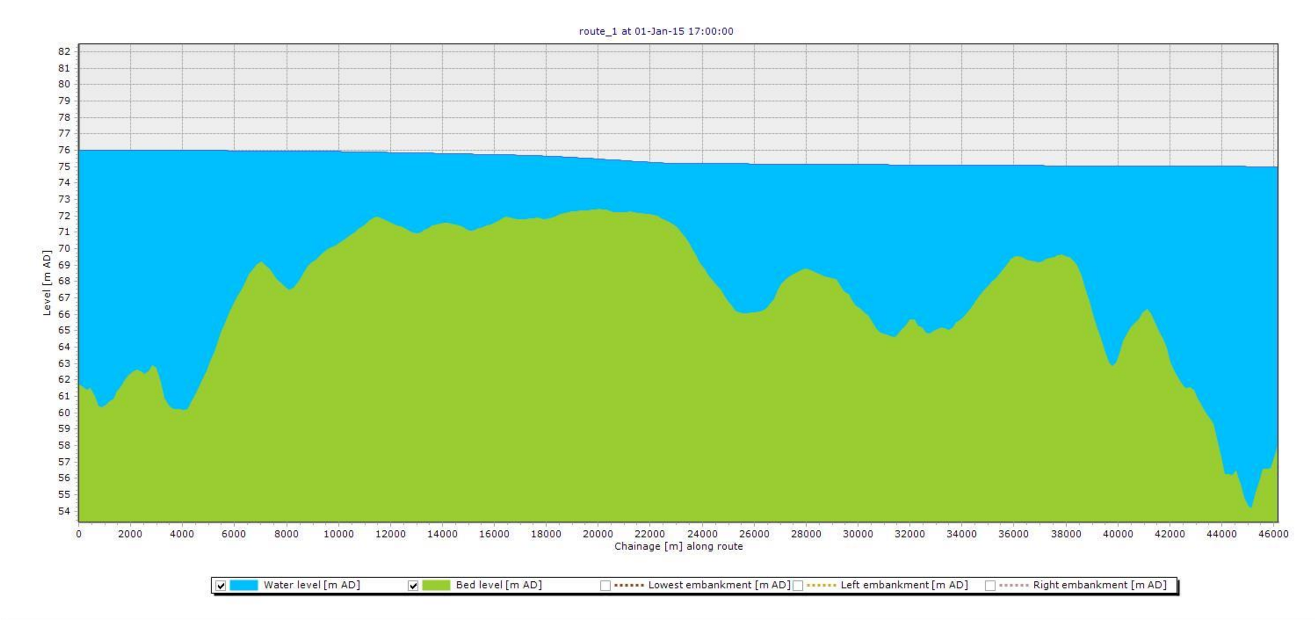

Figure 11.32: Water level along river excluding sandbars corresponding to 2500 m³/s discharge

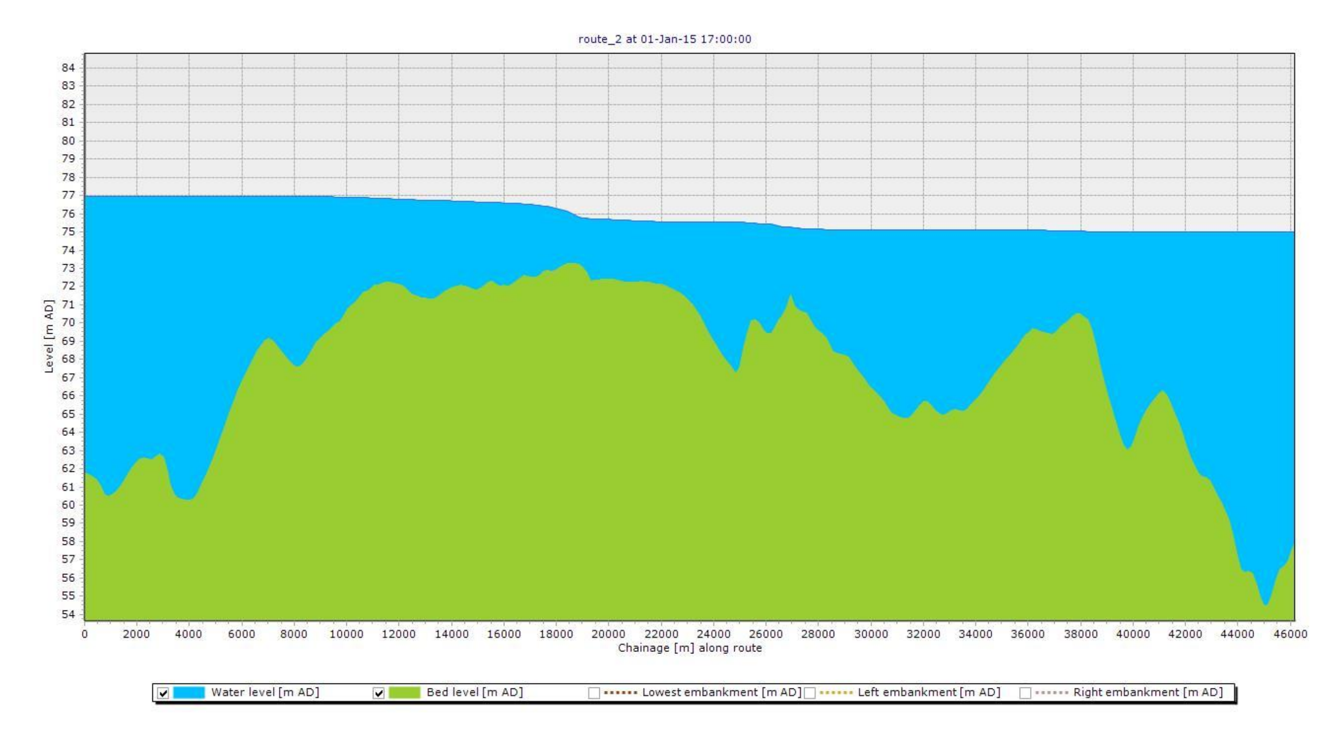

Figure 11.31: Water level along river including sandbars corresponding to 2500 m³/s discharge

Figure 11.30: Cross section profile changes

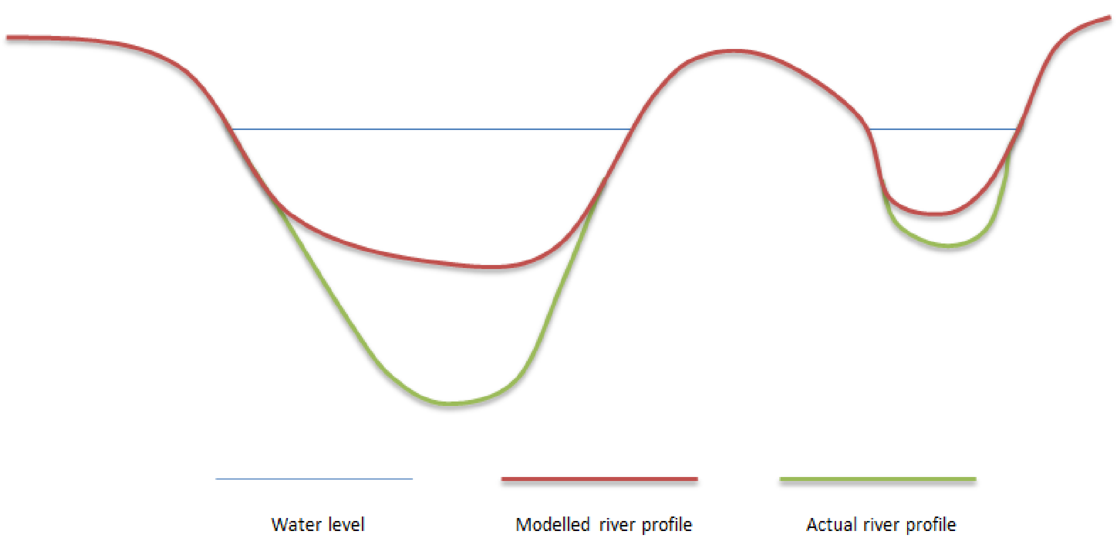

Figure 11.33: Schematization of river cross-section with sandbar, modelled and actual profile

Parameter	reference scenario	Sandbar sensitivity	Treshold sesitivity	Power sensitivity	Anistropy sensitivity
sandbar height points	84 m	83 m	84 m	84 m	84 m
Distance treshold	300 m	300 m	200 m	300 m	300 m
interpolation power	2	2	2	3	2
anistropy	3	3	3	3	4
output costs	BRL 189.287.926	BRL 192.175.297	BRL 194.532.219	BRL 189.413.140	BRL 189.289.904
Deviation	0%	1,525%	2,771%	0,066%	0,001%

Table 11.6: Cost sensitivity to sandbar parameters

11.5.3 Accuracy of the used theories

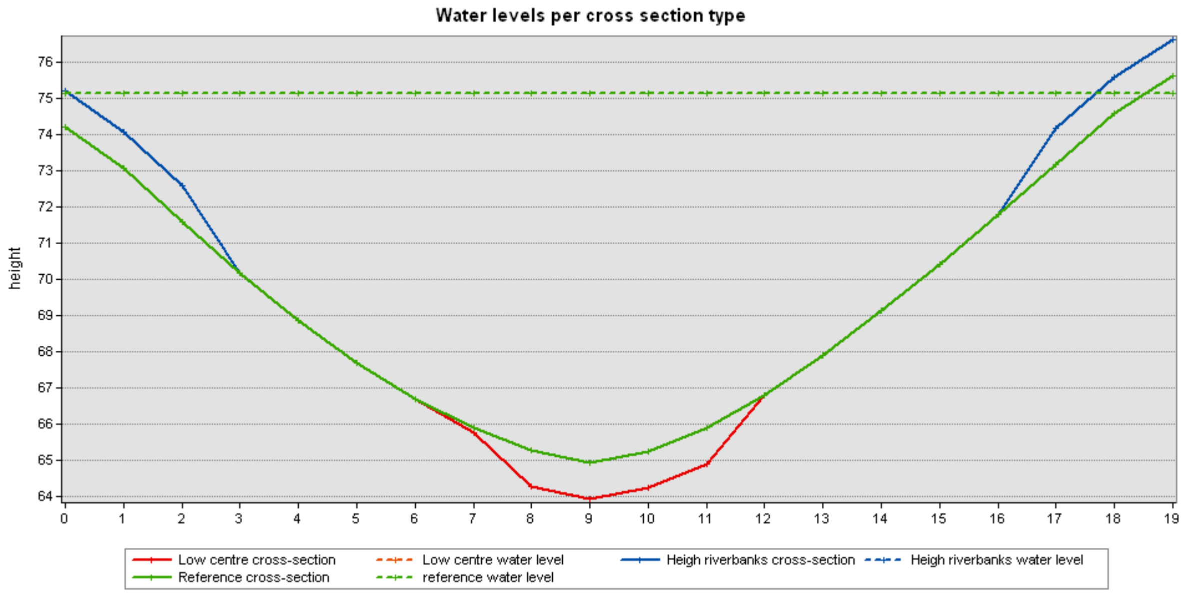

Figure 11.34: Bed level changes cross-sectional view

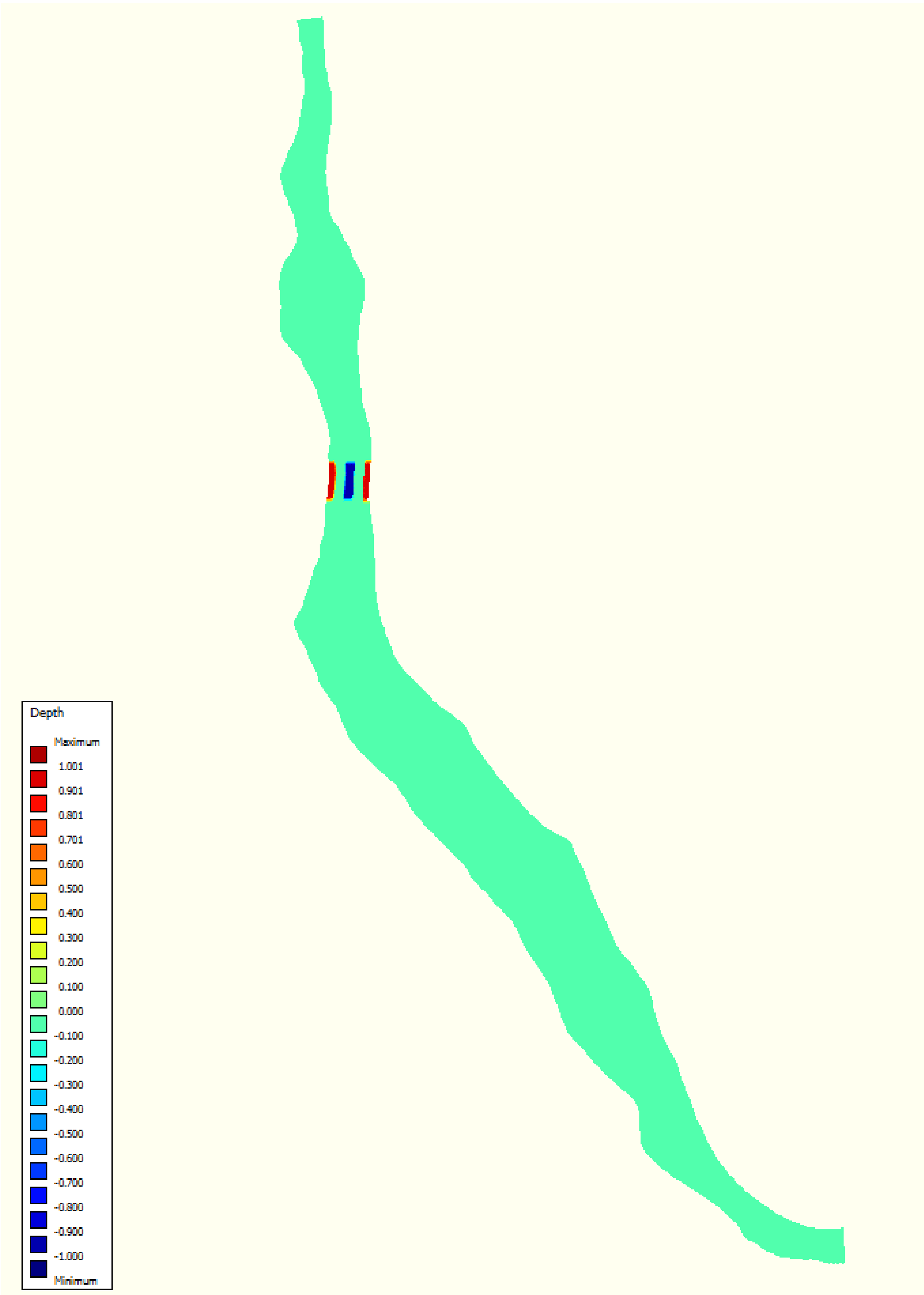

Figure 11.35: Both bed level changes

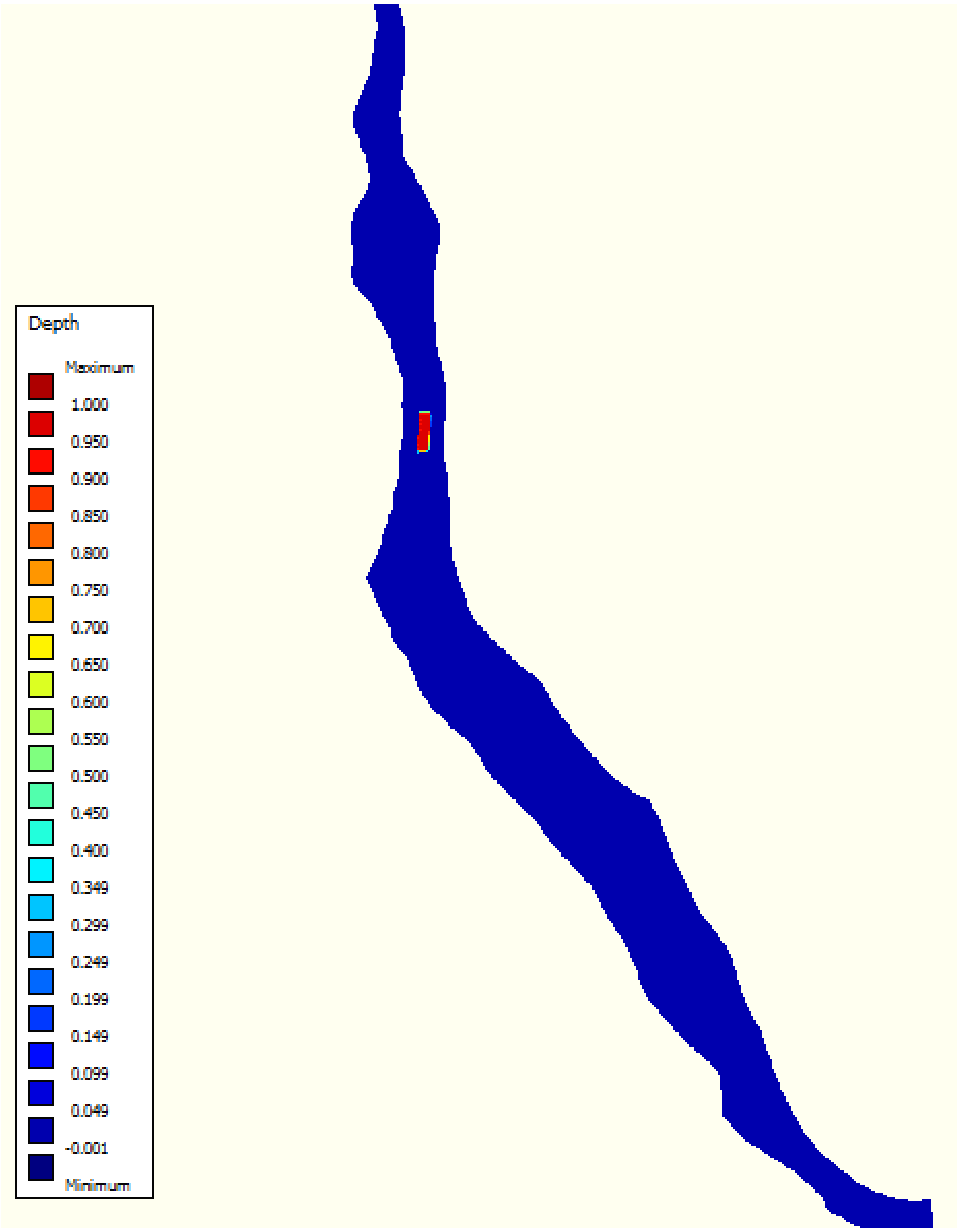

Figure 11.36: Centre bed level changes

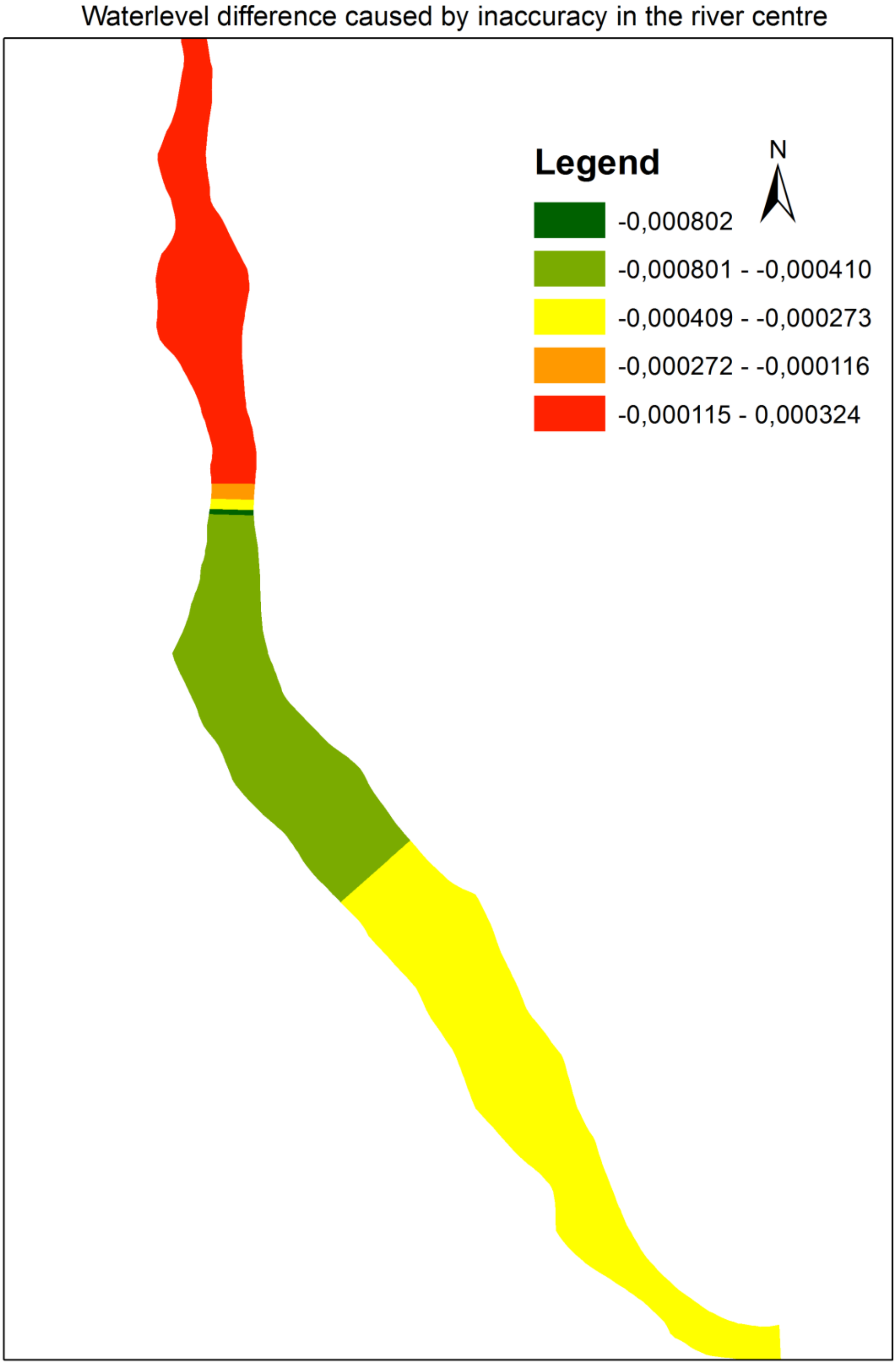

Figure 11.37: Water level difference caused by centre bed level changes

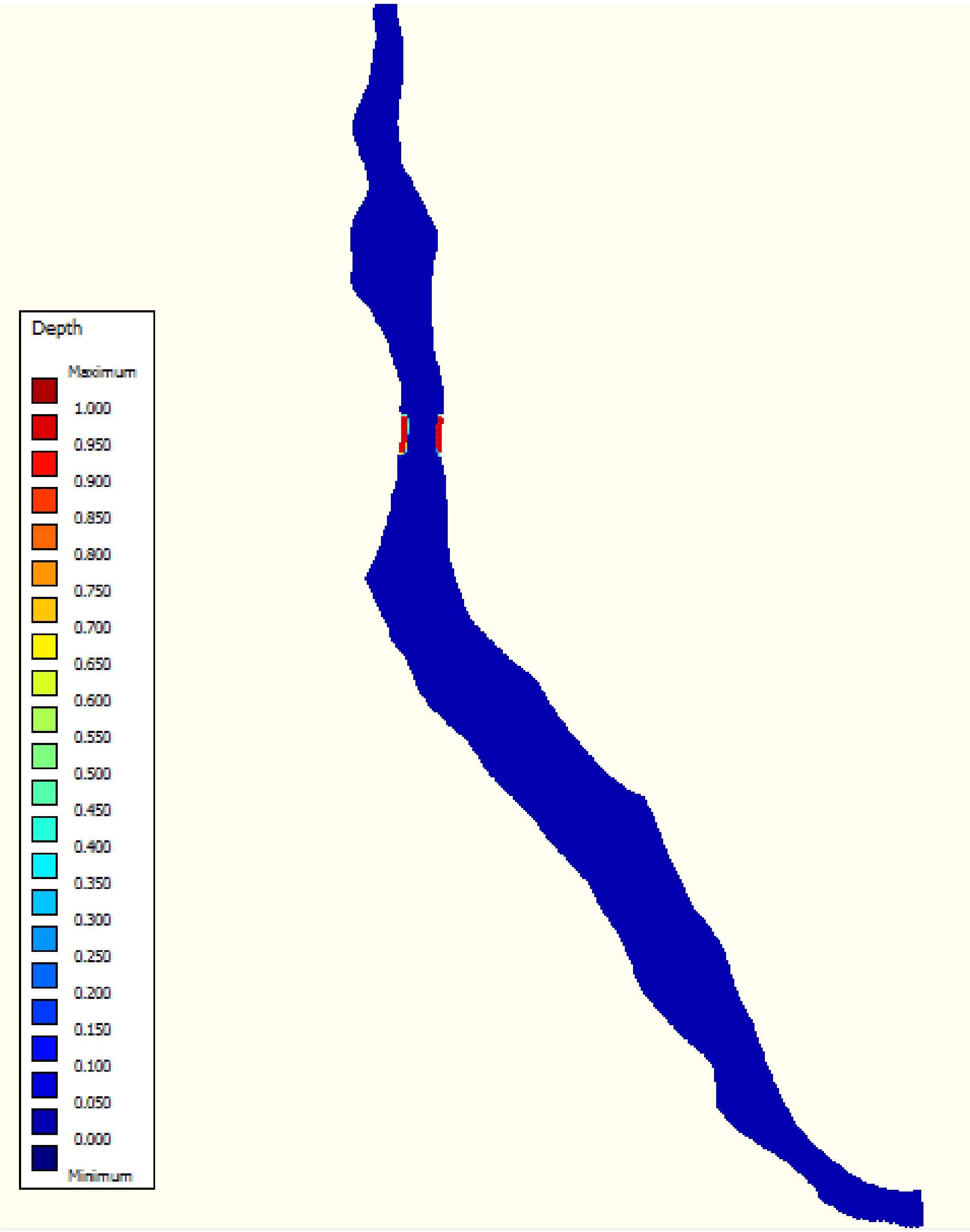

Figure 11.38: Riverbank bed level changes

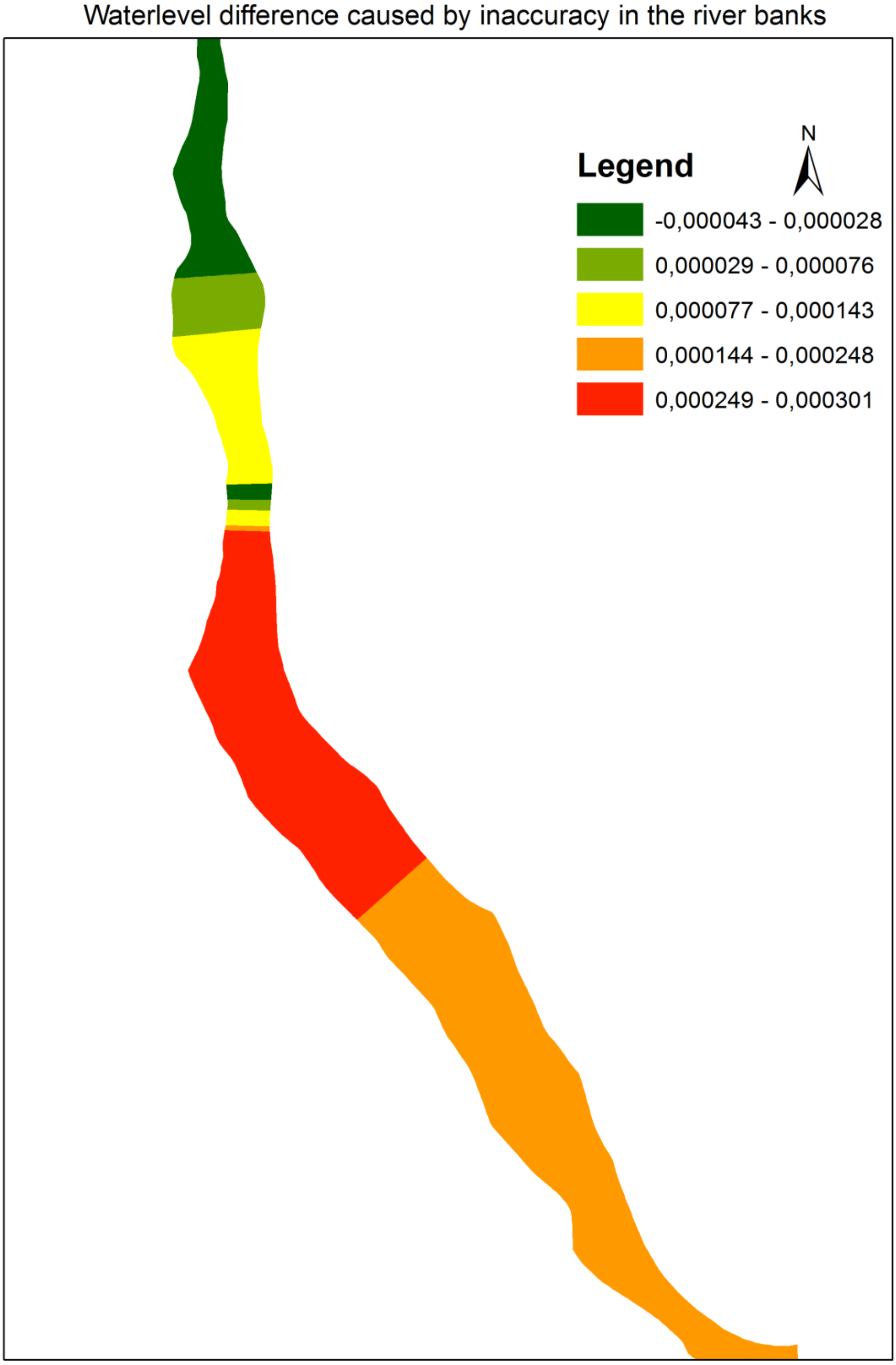

Figure 11.39: Water level changes due to riverbank bed level changes

11.5.4 Validation

Figure 11.40: indication of deepest water path

11.5.5 Measurement importance

To obtain a better understanding in the important locations for measurement, a map has been constructed in ArcMap. This map calculates a score of importance for each location of the river. This score is based on three factors. Firstly, for each point its water depth relative to the maximum water depth in the same cross section has been scored. This has been done because a relatively large water-depth has a bigger influence on the water-level than a relatively low water-depth. This has been schematized in Figure 11.41: schematization of the interesting bathymetry heights. The score has been assigned according to equation 1.1:

$$Score_{depth,\inf luenc} = \frac{Waterdepth}{Waterdepth_{\max CrossSection}} * 10 \tag{1.7}$$

The second score checks whether the location is a possible or certain bottleneck location. If so a possible location will score a 10, since for this point the measurement must determine whether it indeed is a location and what the dredge depth is. A certain location receives a score of 5, since it is only needs to improve the depth for the cost calculation.

$$\begin{aligned}
&If \rightarrow location = certain_location\\
&\text{Score} = 5\\
&\text{ElseIf} \rightarrow location = possible_location\\
&\text{Score} = 10\\
&\text{Else}\\
&\text{Score} = 0
\end{aligned} \tag{1.8}$$

Subsequently the average of these scores has been calculated. These scores are presented in Figure 11.15 , 10.17, 10.19, 10.21 and 10.22.

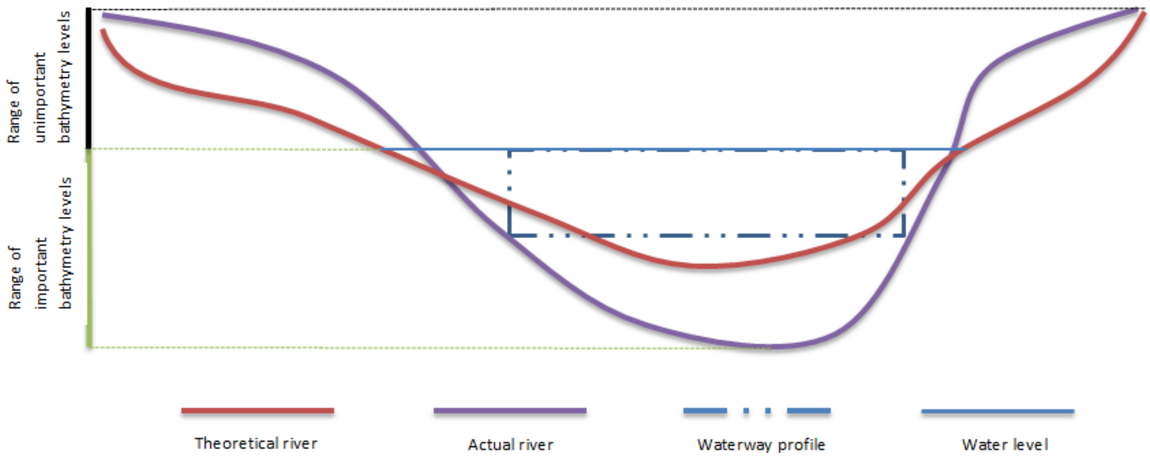

Figure 11.41: schematization of the interesting bathymetry heights

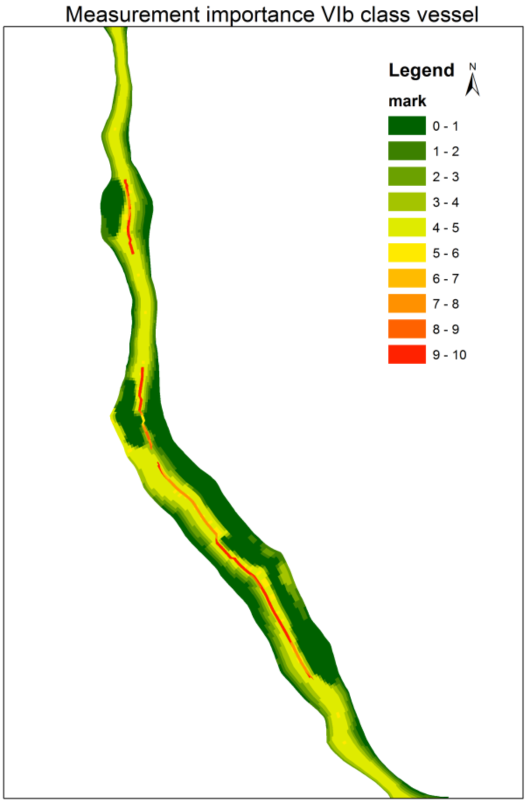

Figure 11.45: Measurement importance map Va+ class vessel

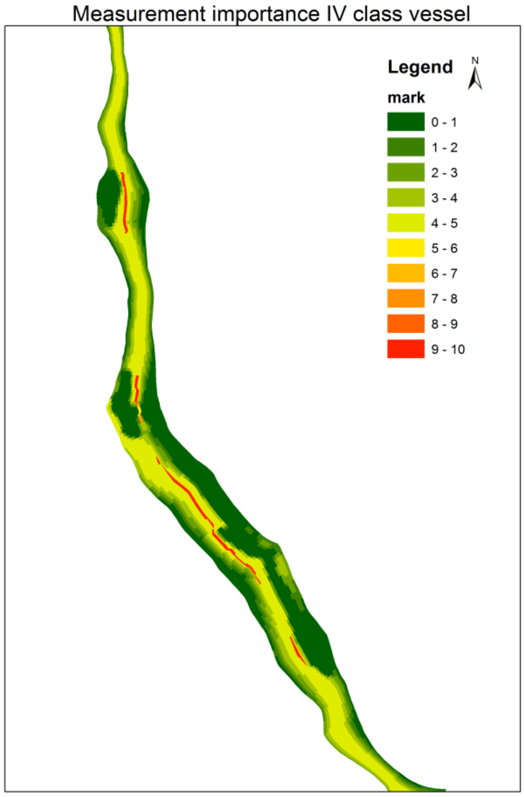

Figure 11.42: Measurement importance map IV class vessel

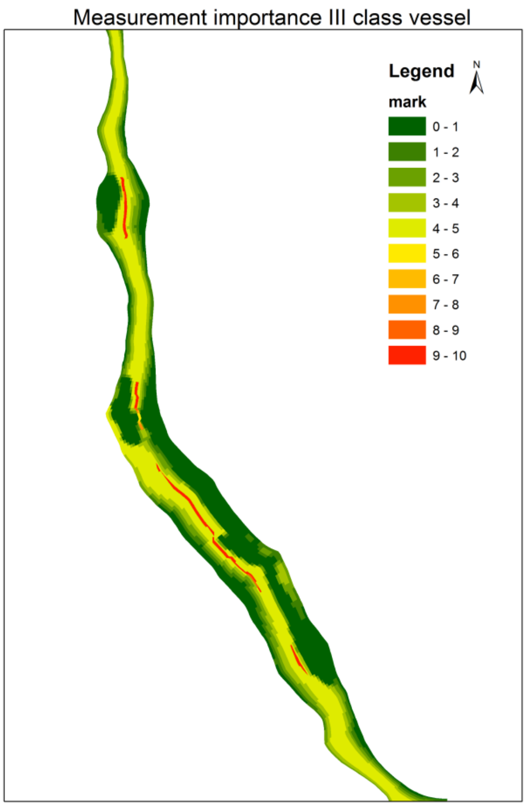

Figure 11.44: Measurement importance map III class vessel

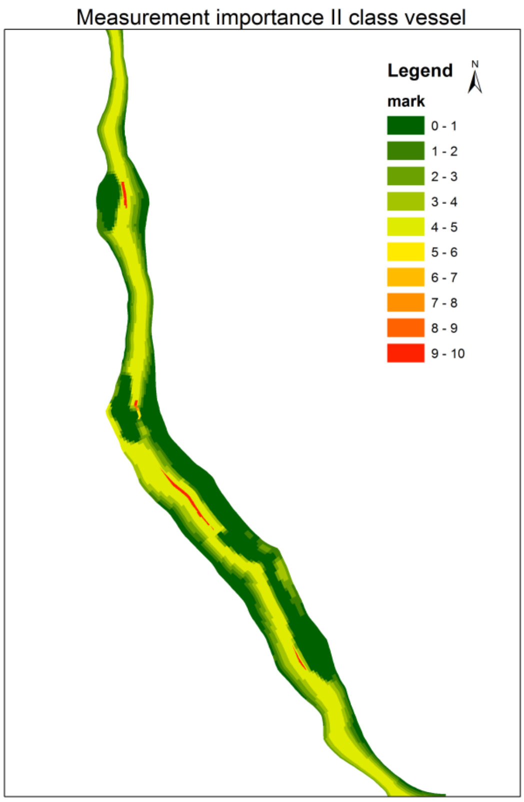

Figure 11.43: Measurement importance map II class vessel

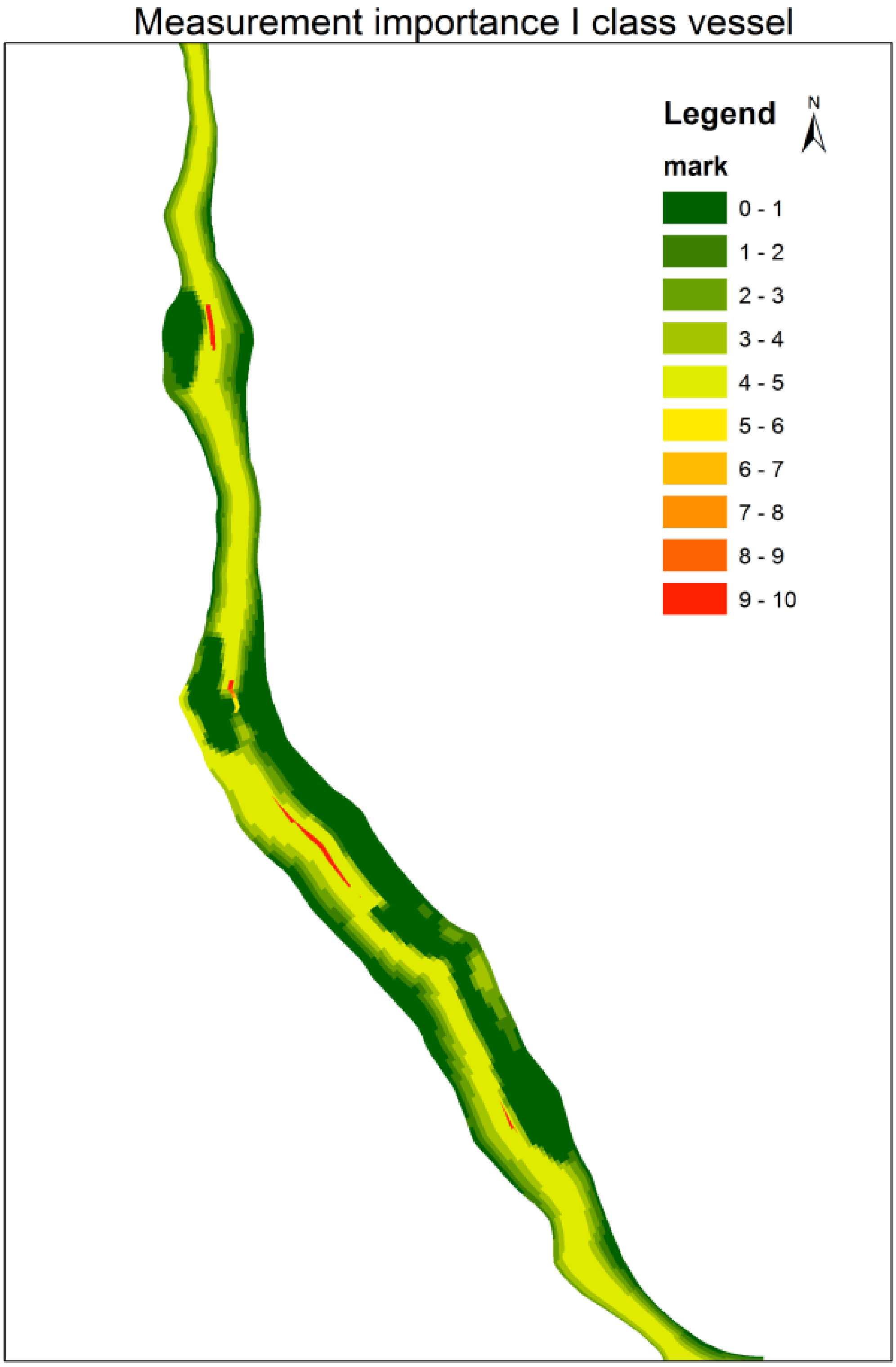

Figure 11.46: Measurement importance map I class vessel

11.6 Discussion

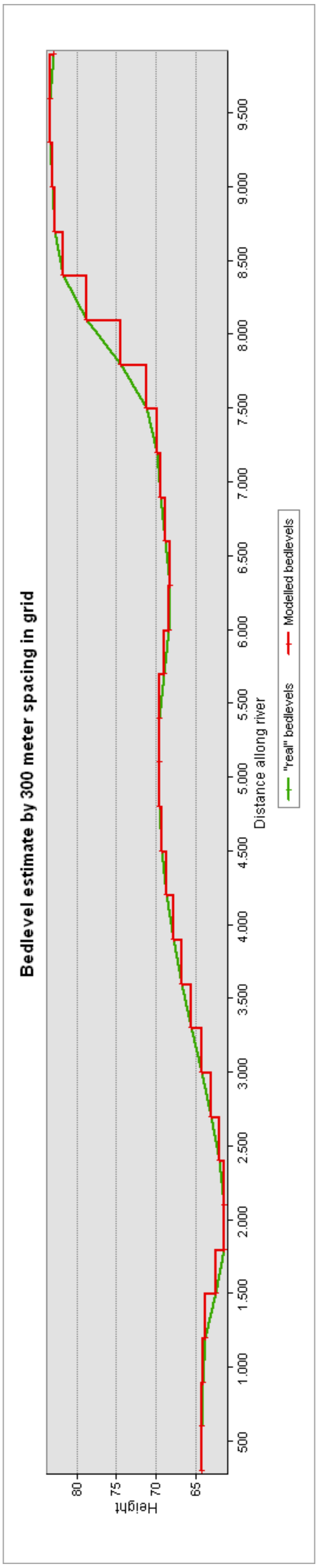

Figure 11.47: Grid dependency