Undesirable sedimentation in the Magdalena River around the city of Barrancabermeja

The quest for an efficient solution

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Cover picture: Yondó Bridge, taken during the field trip (11^{th} of December, 2017)

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Preface

This is the final report of our multidisciplinary project, executed as a part of the Master's degree in Civil Engineering at the Delft University of Technology. The project took place in Bogotá in collaboration with the Pontifical Xavierian University.

During eight weeks an extensive study has been performed to investigate the situation of the Magdalena River around the city of Barrancabermeja. The dynamic behaviour of this river causes many problems regarding the navigability of the river. Especially because of the construction of a bridge across the river in 2005, near Barrancabermeja, the problems regarding the navigability increased significantly. This project gave us the opportunity to implement our theoretical knowledge obtained during our years at the university in Delft and to learn about working in different circumstances than the Netherlands.

We would not have been able to accomplish this result without the help of our supervisors. Therefore we would like to thank Andrés Vargas-Luna, our supervisor from the Pontifical Xavierian University, who was always there to discuss our difficulties and to come up with new ideas. In additional, we would like to thank Jorge Alberto Escobar Vargas, for his help and advice during the first two weeks of our project and for his presence during the field trip. Also we would like to thank our supervisors from the Netherlands, Erik Mosselman, who always gave technical advice when needed, and Jan van Overeem. Last, but not least, we would like to thank David Enrique Trujillo Osorio, a Civil Engineering student at the Pontifical Xavierian University. Without David we would not have been able to do our fieldwork and to convert all the results into usable data.

Enjoy reading our report.

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Team members of Project Magdalena, from left to right: Daphne van der Bilt, Sebastiaan van Wierst, Jenske Kroes, Sjoerd Paulissen

Summary

The reach of the Magdalena River around the city of Barrancabermeja experiences a large issue concerning its navigability. The purpose of this study is to investigate possible causes of this poor navigability and to come up with a proper solution for the improvement of the situation. Three hypotheses concerning the cause of the sedimentation of the thalweg, which is the origin of the poor navigability, are proposed: the natural behaviour of the Magdalena River, the presence of one or multiple sand bars and the scour holes that form around the piers of the Yondó Bridge.

Firstly, a preliminary study, that consists of a stakeholder and a transport analysis, is performed. From the stakeholder analysis follows that the Ministry of Transport, Cormagdalena, Ecopetrol and ANLA can be identified as the four main stakeholders. These four parties represent the most important interests of all stakeholders, such as, the navigability of the Magdalena River, environmental issues, and development in and around the river basin and the transportation over land in Colombia. Furthermore, from the transport analysis can be concluded that the infrastructural accessibility of the main cities along the Magdalena River is another important aspect that should be improved.

The bar mode analysis shows that, for the examined river section, the river contains one alternate bar over the years. Satellite pictures prove that the sand bar on the left side of the river started to disappear after the construction of the bridge, and shifted to the right bank of the river, where the thalweg was located originally. It is plausible that the construction of the bridge has induced changes in flow conditions in such way that the original alternate bar started to erode and eventually totally disappeared. Therefore, it is highly possible that the construction of the bridge forms the main reason for the shift of the thalweg.

The scour holes around the piers of the Yondó Bridge that were approximated by the method of Melville and Coleman (2000) have the following dimensions: the depth ranges from 2.5 to 7.5 m and the width from 18.5 to 36.0 m. These scour holes are incorporated in the Delft3D-model to assess their influence by adapting the initial bed elevation profile. This bed elevation profile and the other settings in the Delft3D-model are based and calibrated on measurements obtained during the field trip to Barrancabermeja. From the model simulation it turns out that the flow around the scour holes does not increase or decrease uniformly, but the presence of the holes does result in more erosion in the vicinity of the bridge.

Six possible river training measures for solving the sedimentation problems and improving the navigability around Barrancabermeja have been analysed. It turns out that out that groynes and guide bunds are the most suitable alternatives, next to the current dredging activities, for the situation in Barrancabermeja. Groynes are transverse dams that extend from the river bank into the river itself and thereby reduce the conveying cross section of the river. This results in higher flow velocities accompanied by less sedimentation in the thalweg. Guide bunds have the same effects but the orientation of the design differs from groynes as they are placed parallel to the river banks.

The three possible solutions (null-solution and two alternatives) were graded on three categories of criteria in a Multi-Criteria Analysis: hydraulic and morphological conditions, spatial and natural integration and implementation and maintenance. Based on these criteria, the guide bunds appeared to be the most suitable solution. The structure was implemented in the Delft3D-model and some additional simulations proved that the effect of this structure on the hydro and morphodynamic conditions in the river is twofold.

First, the guide bunds improve the distribution of the flow over the cross section of the river. More flow is forced trough the right side and indeed the flow velocities turn out to be higher at that location. Moreover, the flow velocities on the left side decrease, as expected. However, the structure has an opposing effect on the cumulative erosion and sedimentation. More sedimentation takes place at the right side of the channel, whereas the left side of the channel gets deeper.

It can be concluded that the best way to improve the situation in Barrancabermeja, is the construction of a guide bund structure in the vicinity of the Yondó Bridge. This structure will force more of the flow into the right part of the channel and therefore, it reduces the amount of sedimentation on this side. As a result,

the dredging activities that are currently executed can be terminated. However, more detailed (physical) model tests should be performed to gain better insight in the effect of the guide bunds on the hydro and morphodynamic conditions in the Magdalena River around Barrancabermeja.

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Nomenclature

α	calibration coefficient for σ
β	Reduced latitude
β_c	Part of the shear stress due to secondary flow represented in the momentum equation
Δ	Relative sediment density under water
μ	Mean
ϕ	Latitude
ϕ_{min}	Minimum latitude
ψ	Longitude
ψ_{min}	Minimum longitude
ρ_{sediment}	Sediment density
σ	Standard deviation
σ_g	Geometric standard deviation of the particle size distribution
θ	Flow angle of attack
A	Cross-sectional area
a	Equatorial radius
B	River width
b	Degree of non-linearity
b_{e}	Equivalent pier width
b_{fp}	Width of the foundation pile
b_{mp}	Width of the main pillar
b_{pc}	Width of the pile cap
b_{p}	Adapted frontal width of the pillar
b_{rec}	Breadth of the rectangular pier
C	Chézy coefficient
$c_{\text{sediment,boundary}}$	Sediment concentration at the boundaries
d	Degrees
d_{16}	Grain size, 16th percentile
d_{50}	Median grain size
d_{84}	Grain size, 84th percentile
d_{90}	Maximum grain size
d_{s}	Depth of scour hole
F_{x}	Cumulative distribution function
f_{x}	Probability density function

g	Gravitational constant
h	Water level
h_0	Water depth at bank full conditions
h_{max}	Maximum water level
h_{mean}	Mean water level
h_{min}	Minimum water level
i	Longitudinal river gradient
K_{d}	Sediment size factor
K_{I}	Flow intensity factor
K_{s}	Foundation shape factor
k_{s}	Equivalent bed roughness for Colebrook-White equation
K_{t}	Time factor
K_{yb}	Depth-size factor
K_{θ}	Foundation alignment factor
l_{rec}	Length of the rectangular pier
M	Number of bars in a cross section
m	Minutes
Q	Discharge
Q_{bf}	Bank full discharge
Q_{max}	Maximum discharge
Q_{mean}	Mean discharge
Q_{min}	Minimum discharge
Q_{S}	Sediment discharge
q_{S}	Sediment discharge per running meter
S	Sediment transport
s	Seconds
s_{bed}	Distance to the river bed
S_{fp}	Longitudinal centre-to-centre distance between the foundation piles
S_{max}	Maximum sediment transport
S_{mean}	Mean sediment transport
S_{total}	Total sediment transport
t	Travelled time of the sound wave
u	Calibration coefficient for μ
$u_{*\mathrm{c}}$	Critical shear velocity
V	Flow velocity
V_{a}	Boundary velocity between clear-water and live-bed conditions
V_{c}	Critical flow velocity
v_{sound}	Speed of sound in water

Y	Difference between the river bed and the top of the pile cap
y	Water depth outside the scour zone

1 Introduction

1.1. Stimulus

In 2005, a new bridge over the Magdalena River, known as the *Puente Guillermo Gaviria* or just the *Yondó Bridge*, was built near the city of Barrancabermeja, Colombia. Since the construction of this bridge, the behaviour of the river around Barrancabermeja has undergone several unplanned changes. The most obvious of these is the migration of the thalweg from the right to the left side of the stream at the place of the bridge. This shift, that significantly reduced the depth at the right side of the river, put the navigability of the Magdalena River at stake. Although the newly formed thalweg at the left side of the stream was sufficiently deep for navigation, ships were hindered by the bridge piers, which are located much closer to each other here than they are on the right side of the river, were the navigation channel used to be located. (plaatje situatie, evt van gesprek met Eduardo).

Due to the economical importance of a navigable Magdalena River, the channel should be accessible to shipping at all times. Therefore, the Colombian authorities maintain the depth of the navigation channel by intensive dredging. However proved to be an effective measure, its considerable costs are burdening authorities and dredging is therefore on the long term not a desirable solution.

But this is not the only area of concern. Colombian authorities' plans to improve national transportation include several new bridges crossing the Magdalena River. The most well-advanced plans concern a new bridge near Puerto Berrío, located about 100 kilometres upstream from Barrancabermeja. The authorities are using the same design for this bridge as used for the Yondó Bridge. Considering the dynamical character of the Magdalena River near Puerto Berrío, and the still unknown origin of the problems around the similar bridge in Barrancabermeja, this might not be a wise decision.

1.2. Magdalena River

The Yondó Bridge is an example of a recent improvement in the nations infrastructure. By investing a lot of money in roads, Colombia wants to make different parts of the country more accessible. For a long time, due to the inhospitable interior of the country, large-scale transportation by road was not an option in large parts of Colombia. This caused river transport to be the only way to move significant amounts of cargo around within the Colombia.

Colombia possesses a very wide variety of rivers. Braided, anabranching, meandering and straight rivers are all present in the country. One of Colombia's largest rivers is the Magdalena, which has a length of more than 1500 kilometres and can discharge over 7000 cubic metres of water per second. It is also in economical terms the most important river of Colombia. Current economical activities around the river, however, also have a big drawback. Urban, agricultural, industrial and mining related waste input begins to take its toll on the river. Especially the overexploitation of open pit gold and coal mines, often close to the river, have deteriorated the river's water quality (Restrepo and Kjerfve, 2004).

Next to its transportation capacities, the Magdalena River provides its host with another important resource. The power generated by the Magdalena hydropower plants makes up more than 40 percent of the nations total electricity production (International Hydropower Association, 2016). However very valuable to the country, there are some major drawbacks to this development. Large dams have been constructed in the upstream reach of the river to store the water. These dams and their corresponding reservoirs have vastly changed the character of the river. Braided parts of the river have become meandering and whole ecosystems have diminished.

Although the Magdalena River has brought many benefits to the Colombian people over the years, it has also been the origin of a lot of misery in the form of large floods. These are often caused by *La Niña*, the meteorological phenomenon causing wet periods in the Southern American continent. Next to its direct impact, large floods also create large alterations to the rivers path, forcing the displacement of many people.

But not only large scale floods are the cause of river alterations in Colombia. On a local scale, erosion and sedimentation constantly shift the path of the river. Dealing with these phenomena has often turned out to be problematic in Colombia. Oftentimes, engineers have assumed that rivers will just stay in the place they are. A very simple example is shown in Figure 1.1. With the right knowledge, an engineer would probably have concluded that a bank protection would be necessary. These kind of mistakes are unfortunately not uncommon in Colombia.

Figure 1.1: Rivers do not always stay in the place they are in Colombia. Picture taken in Boyacá (Consejo Profesional de Geologia, 2015).

This, however, is not the only origin of suboptimal project execution in Colombia. Sometimes, the undesirable consequences are or should be known, but still do not stop the project from being proceeded. Incentives of third parties often play a role in this type of projects. For example, the negative consequences of the previously discussed dams being built should have been known, but the political advantages of constructing the dam just outweigh the social and environmental concerns. In this example, the decision was a well-considered one, but this is not always the case in Colombia. There are also examples of projects in which government officials made a decision on whether a project was launched based on external interests, ignoring potential problems.

1.3. Decision-making issues in a bigger picture

The fact that decision-making around large projects in Colombia does not always go in the way it should, might not be a complete surprise when someone takes the dynamic history of the country into account.

Since the Spanish arrived on the Colombian shores in 1500, the country has never really come back to rest again. First, it were the Spanish conquistadores who brutally forced their traditions on the indigenous people of pre-colonial Colombia. Besides, they were forced to work as slaves to develop the newly conquered lands. They were used for example to build one of the first, and probably the most remarkable man-made river intervention in the history of Colombia. In 1650, the more than 115 kilometre long *Canal del Dique* was constructed to connect the port city of Cartagena with the Colombian inland and shorten the way from the Caribbean to the Magdalena River. Many natives and slaves died during the construction of the channel, which was completely built by hand and finished after only six months of work.

But it was not only Spanish cruelty that spread agitation around indigenous communities. Over time, European diseases turned out to be even more deadly to the Colombian natives. Diseases like smallpox, influenza and typhus, were unconsciously introduced to the new world by European settlers and their slaves, and ended up killing about 95 percent of the pre-Colombian Native American population (Diamond, 1997).

After three centuries of Spanish rule, several armed conflicts led to the independent *Gran Colombia* in 1819. This newly formed country was led by national hero and formal head of the revolutionaries Simón Bolívar. Its territory consisted at that time out of the current countries of Colombia, Panama, Ecuador and Venezuela. The newly formed country would not last a long time=. Only a decade after Gran Colombia had been granted independence from the Spanish, Venezuela and Ecuador separated themselves.

After several internal conflicts and name changes, the Republic of Colombia was formed in 1886. The republic only accommodated two political parties: the liberals and the conservatives. This would later prove to be not a stable situation. Divisions between the only two parties led to one of the most bloody civil wars, called the Thousand Days' War, which lasted from 1899 to 1902. The instability following this clash gave the USA the opportunity to successfully support Panama's independence, turning Panama de facto into a vassal state of the USA. This development enabled the USA to construct the Panama channel.

Also during the following decades, a lot of unrest was present within the republic. The agitation came to a height in 1948, when Jorge Eliécer Gaitán, the subversive presidential candidate of the liberal party, was gunned down in the centre of Bogotá. His murder ignited a widespread anarchy within the country. This turmoil, known as *La Violencia*, costed the lives of about 200.000 Colombians in the years to follow (Roldan, 2002). It also set out the conditions of the establishment of guerilla groups like FARC and the National Liberation Army (ELN), who filled in the void on the left side of the political spectrum.

In the second half of the twentieth century, left-wing guerillas, right-wing paramilitaries and narcotraffickers combated the government for power within the country, causing restless times again. Though since the nineties, situations are gradually getting better and militant groups are slowly demobilizing. Nowadays, although there are still some conflictual areas within the country, the position of the average Colombian has vastly improved compared to the previous decades. Colombia is even one of the fastest growing tourist destinations in the world (FAR International, 2017).

This is a comforting feeling, but the fact the political situation is settling down does not mean that all problems are solved. Still, the effects of the large period of turmoil are very well present. As explained before, questionable decision-making, caused by government officials not following experts consultation due to secondary interests, is still a large problem in the field of river engineering in Colombia.

The planned bridge near Puerto Berrío has everything in it to become an example of such a project. At the moment, all signs point to a decision-making process where not all available information has been taken into account. The probability of similar problems occurring as have been witnessed after the construction of the Yondó bridge, is substantial.

1.4. Yondó Bridge

Barrancabermeja, also known as the oil capital of Colombia (OECD, 2014), is located on the banks of the Magdalena River (see Figure 1.2) and is an important economical hub for the country. A large part of the countries oil production is refined and transshipped here. For a long time, only the eastern bank of the Magdalena River was used for large-scale economical activities. During this period of time, the western bank was only accessible by a ferry.

Figure 1.2: The Magdalena River and its drainage basin. Also the location of Barrancabermeja, the city in which the Yondó Bridge is situated, is shown. Adapted from Wikimedia Commons (2010).

Around the turn of the century, plans for implementing the left bank of the river in the economical zone of the city became concrete. Eventually, a tender put out by the Colombian Ministry of Transport was won by the *Desarrollo de Vías* consortium in 2001. After the construction of the bridge finished in 2005, the western bank became more attractive for economical activities and the petrochemical industry quickly developed the lands. Nowadays, the bridge is of vital interest for the petrochemical industry around Barrancabermeja (García, 2007).

The second incentive for the construction of the bridge was a general improvement to the accessibility, national integration and interconnection of different parts of the country. Prior to the construction of the Yondó Bridge, no bridges crossing the Magdalena within a proximity of 80 kilometres to Barrancabermeja existed. It was planned that the construction of a bridge in Barrancabermeja would improve the connection between Venezuela and the eastern part of Colombia, and the pacific ocean (García, 2007). However, twelve years after the completion of the bridge, the infrastructure behind the bridge still has not been further developed. There are still virtually no roads that connect the bridge with the Western Colombian hinterland, which makes the bridge useless in this perspective.

The Desarrollo de Vías consortium considered three major first designs during the development of the bridge:

1. **Option 1:** Cable-stayed bridge with a concrete box girder functioning as bridge deck;

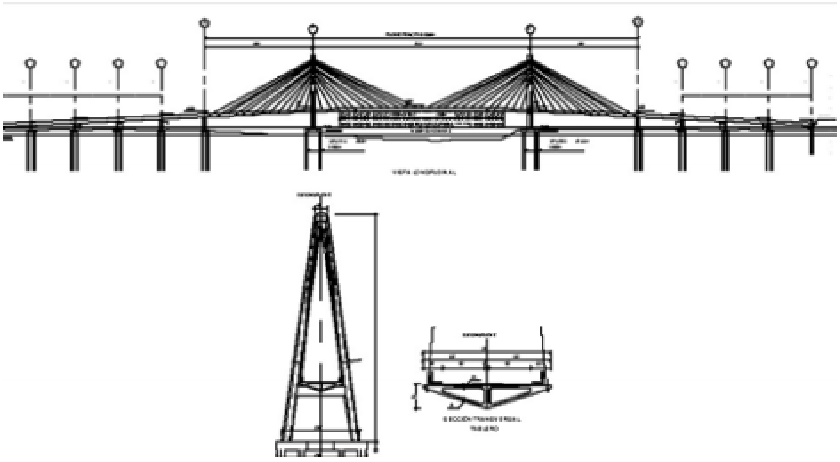


Figure 1.3: Design option 1 considered by Desarollo de Vías (García, 2007)

2. **Option 2:** Cantilever bridge made out of metal box girders;
3. **Option 3:** Cantilever bridge made out of concrete box. girders.

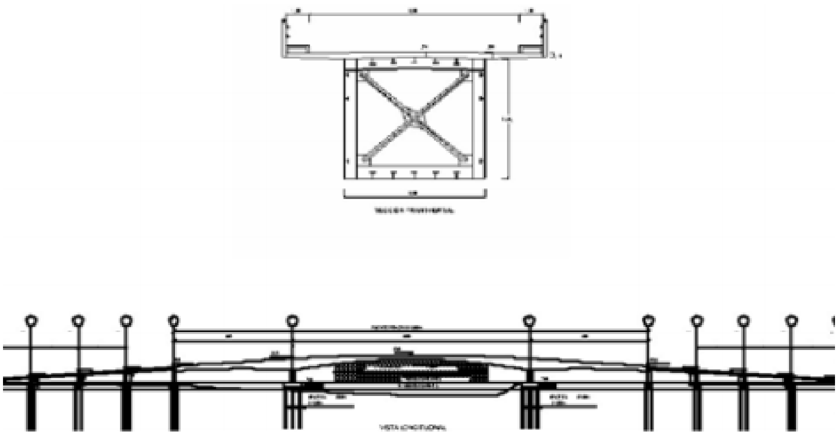


Figure 1.4: Design options 2 & 3 considered by Desarollo de Vías (García, 2007)

A preliminary cost estimation based on these three options was executed. The three designs that were compared turned out to be about equally expensive. Also availability of resources and opportunities to create employment in Colombia during the construction of the bridge were taken into account. With this kept in mind, there has been chosen for the option that uses concrete box girders in a cantilever bridge. In January 2014, the construction of the bridge was started by the installation of the foundation piles. After about 22 months of construction, the bridge was taken into service in November of 2005. The final costs of the project came out on a total of 33.730 million COP, the equivalent of about 12 million Euro at the time of completion (García, 2007).

Cormagdalena, the governmental body responsible for navigation over the Magdalena River, makes sure that the Magdalena River is always navigable for barges despite the hydraulic issues explained before. Dredging is used to achieve this. Because of legislation, the dredged material needs to be dumped just upstream of the bridge. This is not ideal since it amplifies the sedimentation underneath the bridge. ALthough dredging is an effective solution, is not a very efficient one. Therefore, this study focusses on finding a better, more efficient solution to the sedimentation issues.

1.5. Research scope

This study is limited to the part of the river around Barrancabermeja that is directly influenced by, or influences, the situation around the Yondó Bridge. Although the new bridge in Puerto Berrío is briefly discussed in this report, because of its ties with the Yondó Bridge, it is not part of the study itself. It is, however, a very interesting case that is definitely worth looking into in the future. Besides, this study is limited to only the hydraulic and morphodynamic issues around the bridge. This contains everything that relates to the interaction between river flow, sediment and bridge piers. Structural issues concerning the bridge will not be studied.

1.6. Problem definition and objective

At the moment, the causes of the sedimentation problems are unknown. This lack of knowledge has blocked the path to the development of alternatives to the currently used dredging solution. This solution is undesirable on the long term because it is expansive and unsustainable.

The main objective of this study is to provide a solid alternative to the currently used dredging solution. This alternative solution should efficiently improve the current situation. To be able to achieve this, firstly, the causes of the sedimentation problems need to be identified. With this information, possible solutions to the sedimentation problems can be mapped and applied to the current situation.

1.7. Research questions

The study consists of several subquestions, supporting the main question. The main question is defined as follows:

What can be done to improve the efficiency of the approach that is used to deal with the sedimentation problems around the Yondó Bridge?

Subquestions

- What is the current state of Magdalena River around Barrancabermeja and what are stakeholders' interests?
- What caused the shift of the thalweg from the right to the left side of the river after the construction of the Yondó Bridge?
  - What would be the morphological behaviour of the Magdalena River in case the Yondó Bridge would not have been built?
  - What is the influence of local sand bars on the morphological behaviour of the Magdalena River?
  - What is the influence of scour holes around around bridge piers on the morphological behaviour of the Magdalena River?
- Which changes can be made to the current situation in order to deal with the sedimentation problems around the Yondó Bridge?
- How does the selected measure influence the morphological behaviour of the Magdalena River?

1.8. Approach

The approach that is used to tackle these research questions can be subdivided into a couple of different techniques that are made use of. Firstly, a bar mode analysis is used to find the influence of locally present sand bars on the river. Secondly, the river is submitted to numerical simulations using Delft3D software. To learn more about the influence of the bridge on the river, the simulations are executed both with and without the bridge taken into account, and the results are compared.

Afterwards, common river training measures are mapped and applied to the situation in Barrancabermeja. The best fitting alternatives are worked out into more detail and compared using a Multi-Criteria Analysis. Using this analysis, the most appropriate solution can be selected. Lastly, the influence on the river of the preferred measure is evaluated using a numerical simulation.

1.9. Reading guide

This report consists of four parts, namely the preliminary study, the scour assessment, the solutions, and the conclusions and recommendations. Every part is divided in several chapters, as can be seen in Figure 1.5. The sections below describe briefly the content of every part.

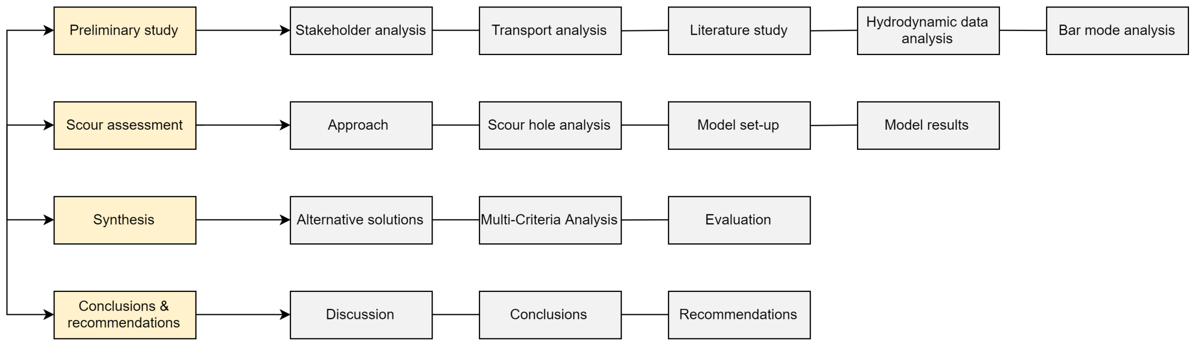


Figure 1.5: Reading guide for the report

Preliminary study

In the preliminary study all information needed for a thorough analysis of the situation in Barrancabermeja is gathered. These analyses are mainly done based on internet research or conversations with related parties.

Scour assessment

In this part, with help of a model in Delft3D, the influence of scour around the piers of the Yondó brigde is assessed.

Synthesis

This part provides more insight in possible measures for the sedimentation problems. A Multi-Criteria Analysis is performed in order to objectively judge the solutions, and the solution with the highest final score is eventually modelled in Delft3D to assess its influence on the river behaviour.

Conclusions & recommendations

As the title of this part says, this part contains the concluding chapters of the study. Starting with a discussion about the results and used methods, it is followed by the conclusions and. Finally, a couple of suggested recommendations are listed regarding future research into the topic of sedimentation, scour holes and numerical simulations.

I

Preliminary study

In the preliminary study all information needed for a thorough analysis of the situation in Barrancabermeja is gathered. Firstly, general knowledge is gained in a stakeholder- and transport analysis. This is followed by a short study of relevant literature to obtain more insight in general river behaviour. Subsequently an analysis of the available hydrodynamic data is performed and finally, a bar mode analysis is executed.

2

Stakeholder analysis

In this chapter all stakeholders associated with the project are considered and analysed. The analysis consist of the steps as depicted in Figure 2.1.

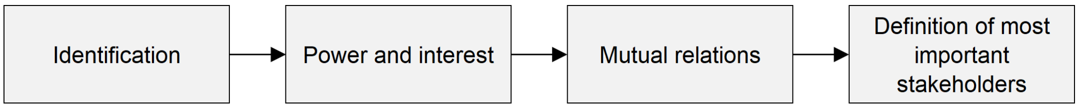


Figure 2.1: Structure of the stakeholder analysis

Firstly, all stakeholders are identified after which their involvement is explained in terms of their power and interest, and the realisation of a power-interest grid. Subsequently the relations between the different stakeholders are explained before the conclusion gives the most important stakeholders.

Stakeholders who benefit from or are disadvantaged by the existence of the Yondó Bridge are considered to lie beyond the scope, as the existence of the bridge is one of the starting points of this research.

2.1. Identification

In this section all the stakeholders associated with the project are described. A distinction is made between public and private actors.

2.1.1. Public actors

Ministry of Transport

The Colombian Ministry of Transport is responsible for the formulation and adaptation of the political plans, programs, projects and economical regulation of the transport and infrastructures in highway, maritime, fluvial, rail and air modes. In their opinion, building bridges over the Magdalena River is essential for the improvement of the national transportation capabilities over land. Besides transportation over land, also the river navigability belongs to the Ministry's objectives.

Invías

Invías (Instituto Nacional de Vías) is the executive organ of the Ministry of Transport and is responsible for the implementation of policies, strategies, plans and programs related to the infrastructure of Colombia, such as highways and waterways. Invías is, together with the Ministry of Transport, the initiator of the plans for the bridges and they are also responsible during the construction period.

Cormagdalena

Cormagdalena is a public Colombian authority active in the surroundings of the entire basin of the Magdalena River. They have the following objectives: the recuperation of the river navigability, harbour activities, land adaptation and energy generation around the river. Besides, they also aim for the sustainable management and protection of the environment in the same area, for example, by preservation and use of ichthyological resources and renewable natural resources.

CAS

CAS stands for Corporación Autonoma Regional de Santander, the Autonomous Regional Corporation of Santander. In general, the function of an autonomous regional corporation in Colombia is to take care of the protection of natural resources in the region. They authorize, amongst others, licenses and environmental permits for projects regarding infrastructures (Ministerio de Ambiente y Desarrollo Sostenible, 1993).

When a corporation contains municipalities located on the riverside of the Magdalena River, it has to execute their tasks in cooperation with Cormagdalena in order to guarantee the adequate use and preservation of the environment, fish resources and other renewable resources in the Magdalena Basin (Ministerio de Ambiente y Desarrollo Sostenible, 1993). For the CAS, this is clearly the case, since the city of Barrancabermeja is located at the riverside of the Magdalena River.

ANLA

ANLA (Autoridad Nacional de Licencias Ambientales) is a governmental organ focussing on projects and activities from other entities concerning the environment. ANLA provides licenses to these entities as a permission for their acitivities, in order to maintain the sustainable development of Colombia (ANLA, 2014).

2.1.2. Public-private actors

Ecopetrol

Ecopetrol is the first petroleum company in Colombia and it has a big oil refinery located in Barrancabermeja. With an initial production capacity of 1,500 barrels per day (238,481 litres) and an area of 254 hectares, it is the biggest oil refinery of Colombia and it belongs to the top four biggest refineries of South America. Approximately 75% of the gasoline, fuel oil, diesels and other fuels that Colombia requires are generated in this refinery (Ecopetrol, 2014).

Initiated as a public company, in 2007 Ecopetrol issued an initial public offering on the Colombian Stock Exchange (BVC) and became a public-private company. At the moment 88% of Ecopetrol's shares are appropriated by the state and the rest is in hands of private investors.

2.1.3. Private actors

Contractors

Desarollo de Vías (Development of the roads) is the name of the consortium of two companies that designed and built the bridge in Barrancabermeja, commissioned by Invías. The two companies involved in the consortium are Intersa S. A. (75%) and DIN LTDA (25%).

For the remaining steps of the stakeholder analysis, Desrollo de Vías is considered to be part of the *contractors* since other contractors might be involved, for example, for maintenance or improvements of the bridge.

Impala

Impala is a big port located north of Barrancabermeja where cargo ships can load an unload. Impala is a very important terminal, because it facilitates the handling of the inland cargo to the hinterland of Colombia.

During a conversation with Luis Francisco Dulcey from Cormagdalena it became clear that Impala also has it's own fleet and approximately 80% of their cargo consist of petroleum based products originating from Ecopetrol.

Shipping companies

There are a lot of activte shipping companies in Colombia, for example the Federación Nacional de Navieros (Fedenavi). This is a group consisting of 6 shipping companies that operate in total approximately 260 ships and carries out more than 500 shipments per year on the Magdalena River (Mouthón, 2017) and (FullAvante, 2017). Besides Fedenavi there are plenty of other shipping companies using the Magdalena River for transporting their cargo.

Dredging companies
In order to maintain the Magdalena River navigable, dredging activities are necessary. At the moment, Panamerican Dredging & Engineering is responsible for the dredging of the Magdalena river (Mouthón, 2017). Panamerican Dredging & Engineering is considered under *dredging companies* because in the future another company can take over the dredging activities, but the interest of these type of companies will not change.

NGO's
Several NGO's are active in the Magdalena Basin. Colombia has the second largest biodiversity of the world and with 1826 bird species they have the biggest bird diversity of all the countries in the world (Butler, 2016). Around Barrancabermeja NGO's could be active especially because of the dredging around the bridge, which might influence the biodiversity.

Some of the active NGO´s are:

- The Nature Conservancy
  TNC is an NGO active all over the world. In Colombia they aim amongst others for the protection of freshwater ecosystems.
- Conservación Internacional
  This NGO has as main goal to move entire societies towards a healthier and more sustainable way of living. They believe that scientific knowledge of the ecosystems and biodiversity is required to realise actual sustainable development.
- Fundación Humedales
  Fundación Humedales is an NGO active in Colombia. One of the projects of Fundación Humedales is called *Proyecto Bagre Rayado*. The goal of this project is the protection of the catfish in the Magdalena Basin.
- Fundación Guayacanal
  The main goal of Fundación Guayacanal is to promote an applied ecology and proactive environmental management in Colombia. They try to obtain this by research, consultancy, development and dissemination in ecological restoration, land planning, urban ecology and eco-urbanism. Regarding the Magdalena River, they assisted with the development of the Ecological Restoration Protocol for Middle Magdalena Wetlands (FAO Colombia, 2015).
- Fundación Natura
  This foundation is dedicated to the conservation, use and management of biodiversity to generate social, economic and environmental benefits within the framework of sustainable human development. They have several projects dealing with the Magdalena River with respect to it's biodiversity.

Local residents
Barrancabermeja has around 190,000 inhabitants and Yondó, the village at the other side of the river, has around 18,600 inhabitants (DANE, 2005). A lot of the inhabitants work in the fishery, for whom it is important to have sufficient fish and fish species in the Magdalena River around Barrancabermeja.

2.2. Involvement of stakeholders

This section discusses the interests and power of the different stakeholders. A power-interest grid is created, based on the interest and power. This grid can be used as a guideline for the management of the different stakeholders.

2.2.1. Description of interests

Ministry of Transport
The Ministry of Transport works on large scale plans and therefore they do not have a strong interest in one specific, smaller project, such as, the construction of the Yondó bridge. However, they have a lot of power, as they have a couple of authorities working for them and executing their plans. One of this authorities is, for example, Invías.

Invías

As Invías supervises the project around the bridge in Barrancabermeja they have a lot of power in the design and building processes. Their interest is also significant, as they are executing and leading the project. Invías's reputation might be damaged in case problems occur during the construction, which results in a high interest as well.

Cormagdalena

One of the main goals of Cormagdalena is the navigability of the Magdalena river, and therefore their interest is very large. As a part of the navigability management, Cormagdalena organises the maintenance dredging activities and pays the executing companies for their work. They do not provide the entire budget for the dredging, but they can be considered as a powerful decision maker.

CAS

The Corporación Autonoma de Santander has a specific interest in the project, since they, together with Cormagdalena, have to take care of the preservation of the environment and fish resources in the Magdalena River and the surrounding area. In some cases they have control over the activities of Cormagdalena, since the CAS provides the permits for certain activities. For example, in May 2016, they granted Cormagdalena and the Port Society of Barrancabermeja to execute some kind of port activities which positively influence the navigability of the Magdalena River (Ministerio de Ambiente y Desarrollo Sostenible, 2016).

ANLA

The interest of ANLA in this specific project is small as ANLA is working on a much larger scale. Despite their small interest, their power is certainly present, as the activities of the CAS and Cormagdalena depend on permits of ANLA.

In general two ways of dredging can be defined:

- Gathering the sand from the river bed and relocate it on another position in the river
- Gathering the sand from the river bed and discharge it on the land next to the river

The first method is called maintenance dredging of the river and Cormagdalena has the power to perform this type of dredging at any time. For the second option Cormagdalena needs an environmental license from the Corporación Autonoma Regional (CAS), that on their turn needs permission from ANLA. If ANLA does not provide this permit, the dredging activities cannot be executed.

Ecopetrol

Ecopetrol has a very large interest in the navigability, as they produce a large amount of oil, which need to be transported in barrels. The majority of these barrels are transported over the Magdalena River. Recently, in the summer of 2017, Ecopetrol created budget for Cormagdalena in order to execute dredging activities in the Magdalena River around Barrancabermeja (Ministerio de Transporte, 2017). By proving the money they gave themselves a significant amount of power.

Impala

The core business of Impala depends completely on shipping, and therefore the maintenance of the navigability of the river is extremely important. If there would be no shipments, they would be out of business. Impala has its own fleet of ships, transporting cargo from Ecopetrol, which strengthens their interest. In November 2016 Impala obtained a place in the Board of Directors of Cormagdalena as representative of the shipping associations (Suárez Salazar, 2016). This position provides them with additional power to stand up for both their own interest and the interest of the other shipping companies. Furthermore, according to Luis Francisco Dulcey from Cormagdalena, Impala created budget for dredging activities as well.

Shipping companies

For the shipping companies it is essential that the river remains navigable as their business purely consist of shipping. Although their interest is very high, their power is almost zero. One of the few things they can do is protest or inform higher entities that measures must be taken. In February 2017, for example, they handed in a petition asking for an enhanced navigability (FullAvante, 2017). However, the government decides whether or not changes in the navigability will take place.

Contractors
In general, the main goal of contractors is earning money, which is possible in every type of project. However, they have to be assigned to the project by Invías so their own power is very low.

Dredging companies
The principal objective of dredging companies, such as Panamerican Dredging & Engineering, is earning money as well. However, their work is more specific so their interest for this specific project is more significant than the interest general contractors, mentioned above. Just as the contractors, the dredging companies are also assigned to the project by Invías, resulting in a low power position.

NGO's
A meeting has been arranged with Hector Angarita from the Nature Conservancy. From this conversation it became clear that the Nature Conservancy is aiming for a maximum protection of the freshwater ecosystems in the Magdalena River. They also try to influence (local) authorities in the process of strategic decision making. Their influence in a single project, such as the construction of the bridge in Barrancabermeja, is not noteworthy, as they focus on the Magdalena Basin as a whole. Their power is very small, because they can not take action immediately. One thing they can actually do is trying to create awareness about the ecosystem by the decision making authorities and hope that they will adjust their strategic decisions.

Local residents
For the local residents it is important that they can safely work and live in the surroundings of the Magdalena River. In order to understand the interest of the local residents several interviews have been conducted of which a detailed report can be found in Appendix A. In general, their living conditions are not influenced by the construction of the bridge. Only the residents living very close to the river suffer from flooding more often. Furthermore, from the interviews it became clear that their working conditions are also not affected by the problems around the Yondo bridge. Sedimentation might negatively influence the fish migration which influences the fishing opportunities for the fishermen, but so far, this effect is not noticeable, according to the fishermen.

The power of the local residents is almost zero. Protest against the dredging activities seems the only real action that they could take, but the local residents do not seem to have any plans to do this in the near future.

2.2.2. Power-interest grid
In order to understand the relative importance of all the stakeholders, it is very useful to position them within a power-interest grid. This means that each stakeholder is plotted in a graph where interest is defined on the x-axis and power on the y-axis. Stakeholders with a lot of power and a high interest are plotted in the top right corner, whereas a stakeholder with a small amount of power and interest is plotted in the bottom left corner. In Figure 2.2 the power-interest grid for the stakeholders of the situation in Barrancabermeja is given. By analysing this grid, the different types of stakeholders can be identified and managed.

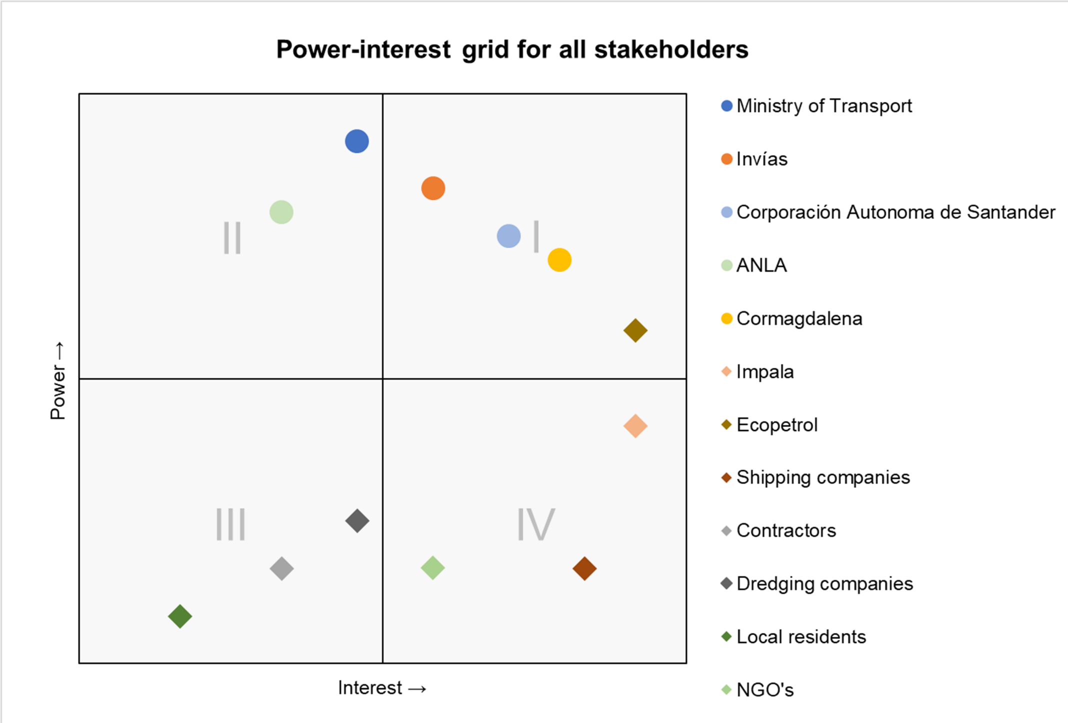


Figure 2.2: Power-interest grid for the different stakeholders

The figure can be subdivided into four quadrants, that corresponds to a different way of dealing with the stakeholders. The meaning of the four different quadrants with the corresponding stakeholders is as follows:

I Manage closely
This category represents the most important stakeholders, as they have both high power and interest. They must be fully engaged and kept satisfied during the entire project, since they can make important decisions.

- Invías
- Cormagdalena
- Ecopetrol
- CAS

II Keep satisfied
These stakeholders do not have a high interest in the project, so as long as they are satisfied they will not cause any problems.

- Ministery of Transport
- ANLA

III Monitor
These stakeholders have the lowest interest and power. They should be monitored and kept informed, but with minimum effort.

- Dredging companies
- Local residents
- Contractors

IV Keep informed
These stakeholders have a high interest but do not have a lot of power. Therefore it is important to keep

them informed and make sure to no unexpected issues arise. They can also be helpful for the project by providing details, as they are probably willing to put in some additional effort.

- Impala
- NGO's
- Shipping companies

2.3. Relation between the stakeholders

In order be able to identify the main stakeholders, it is important to understand the relationship between the different stakeholders. In Figure 2.3 these relations are visualised.

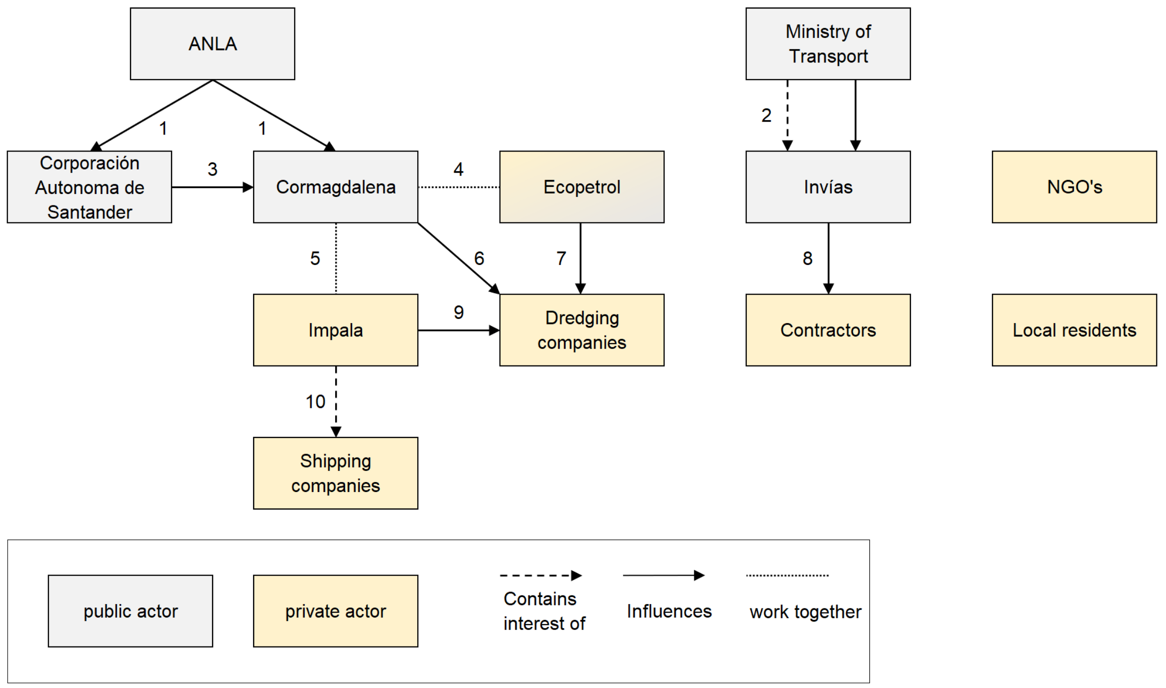


Figure 2.3: Visualisation of stakeholder relations

The numbers in the schedule have the following meaning:

1. ANLA provides licenses to both the CAS and Cormagdalena concerning actions that potentially affect the environment, such as dredging activities;
2. The Ministry of Transport controls the actions and objectives of Invías;
3. In case Cormagdalena wants to perform an action that affects the area next to the Magdalena River, the CAS or any other corresponding Corporación Autonoma Regional needs to provide a permit;
4. Ecopetrol creates budget for Cormagdalena in order to enhance the dredging activities around Barrancabermeja;
5. Impala is part of the board of Directors of Cormagdalena as a representative of the shipping associations. Also they provide Cormagdalena with money for the dredging activities around Barrancabermeja;
6. Cormagdalena decide which company will be responsible for the dredging activities and pays this company as well;

7. Ecopetrol contributes to the payment of the dredging companies for their work around Barrancabermeja;
8. Invías decides which contractors will be assigned to the project;
9. Impala contributes to the payment of the dredging companies for their work around Barrancabermeja;
10. Impala represents the shipping companies in the Board of Directors of Cormagdalena.

2.4. Main stakeholders

From the sections above can be concluded that the actions of certain stakeholders are depending on actions of other stakeholders. Based on the power-interest grid and the relations between the stakeholders, the following main stakeholders can be identified:

- **Ministry of Transport**
  The first main stakeholder is the Ministry of Transport. Although they are situated in the second quarter of the power-interest grid, they have a lot of power and influence in other stakeholders (Invías, contractors). By considering the Ministry of Transport as a main stakeholder, the interest of Invías is also covered.
- **Cormagdalena**
  The second main stakeholder is Cormagdalena as they aim to keep the river navigable, which is very important for a couple of other stakeholders, such as, Impala and the shipping companies.
- **Ecopetrol**
  Ecopetrol can be considered as a main stakeholder, because they provide money for the dredging activities in the Magdalena River.
- **ANLA**
  Although ANLA is focused on environmental issues more than on navigability problems, they are an important stakeholder to deal with. The execution of the dredging activities mainly depends on the permits provided by this institution.

3
Transport analysis

Without any interventions the Magdalena River would not be very well navigable and the bridge near Barrancabermeja is one of the causes for the needed interventions. The question rises how this poor navigability is related to the transport in Colombia. Therefore, this chapter analyses the importance of the navigability of the Magdalena river with respect to the broader view of transport in Colombia.

Figure 3.1 shows the structure of the analysis. It starts with an analysis of the the distribution of cargo transport over the different transport modes, followed by the rivers over which cargo transport takes place. Finally, the cargo transport over the Magalena River is evaluated.

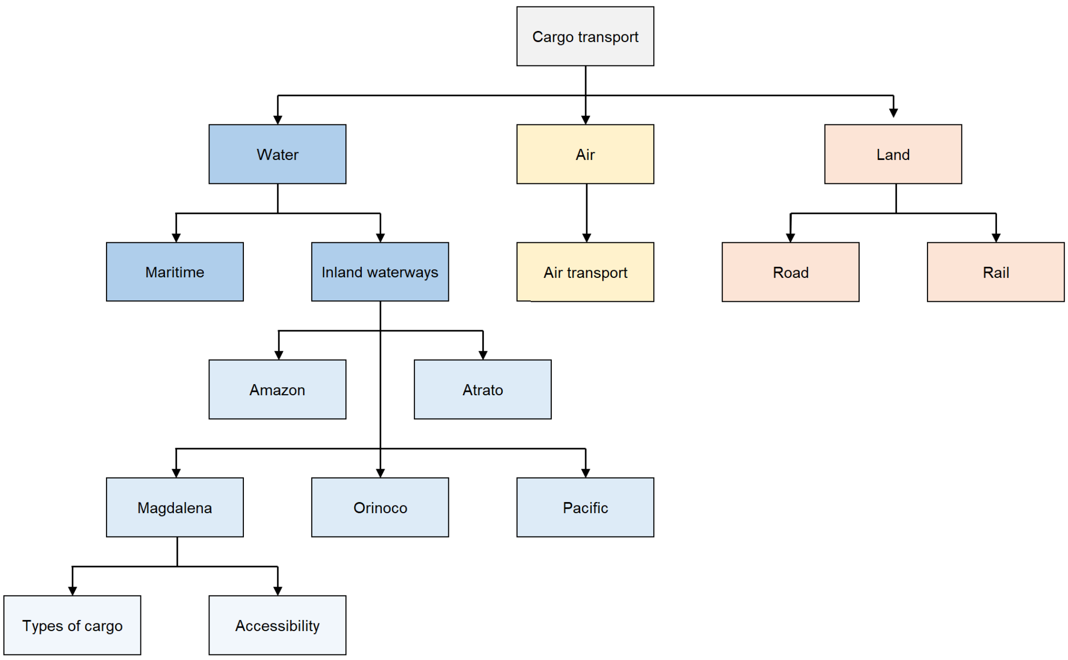


Figure 3.1: Scheme of transport analysis in Colombia

3.1. National cargo transport

Import and export mainly takes place via maritime transport and the percentage of import and export transported over inland waterway transport is almost zero, as can be seen in Figures 3.2a and 3.2b. Therefore only the national cargo transport data are considered in order to analyse the cargo transport of Colombia.

(a) Import (b) Export

Figure 3.2: Percentages of used transport modes for import and export of Colombia in 2011 (Zárate Farias and Sierra Reyes, 2012)

The high percentage of maritime transport might be due to the fact that import and export is considered until the cargo is being transferred to a new transport mode within the country. This will probably take place at the main ports of the coast, for example in Barranquilla, or at an airport. From here the cargo will be transported over land or rivers, but this is considered as national cargo transport. However, this is an assumption as it is not explained in the document from which the majority of data comes (Rojas Giraldo et al., 2017).

3.1.1. Use of different modes of transport

In Colombia different modes of transport are used for the inland cargo. These are as follows:

1. Road
2. Railway
3. Inland waterway
4. Air
5. Maritime

Figure 3.3 depicts the development of the transported amounts of inland cargo over the different transport modes from 2002 in Colombia. In Table B.1 all the exact numbers can be found on which the graphs are based.

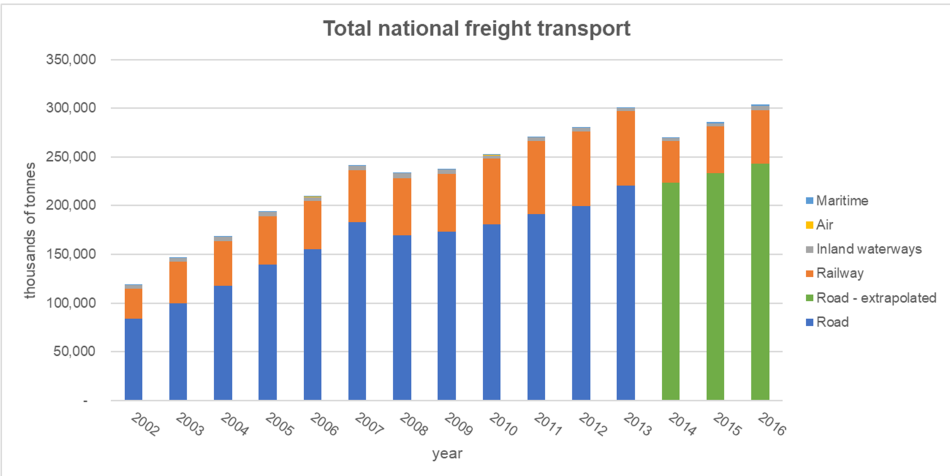
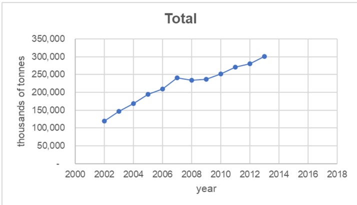


Figure 3.3: Overview of the development of cargo transport for different transport modes, based on Rojas Giraldo et al. (2017)

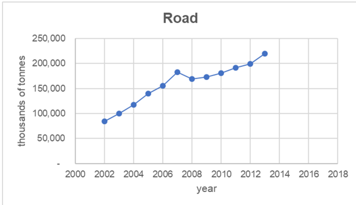
The road transport of the last three years, 2014, 2015 and 2016, is extrapolated based on the years 2008 to 2013.

At the moment of writing these numbers are not known, and as from 2008 to 2013 the grow looks stable, it has been chosen to extrapolate the numbers for the years of 2014, 2015 and 2016.

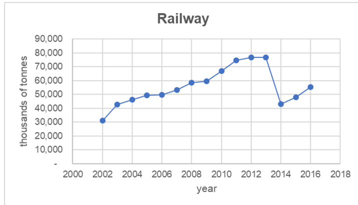
It is very clear that the maritime, air and inland waterway transport are very small compared to road transport. In Figures 3.4a to 3.4f, separate graphs are shown for the development of cargo transport over the different transport modes because this not every different transport mode is clearly visible in the graph shown in Figure 3.3.



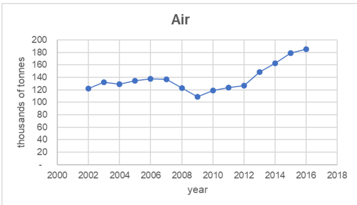
(a) Total transport



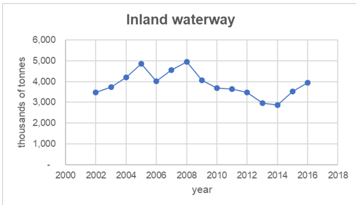
(b) Road transport



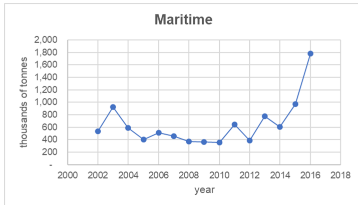
(c) Railway transport



(d) Air transport



(e) Inland waterway transport



(f) Maritime transport

Figure 3.4: Development of cargo transport over different transport modes, based on Rojas Giraldo et al. (2017)

Striking is the fact that the road transport is growing at the same rate as the total transport. In 2005, both the total transport and the road transport have peaked in the amount of tonnes transported. Furthermore, the air transport seems to have a steady growth as well, although the maritime and inland waterways transport have very unpredictable amounts of cargo. The railway transport has a stable growth until 2013, but has a big decline in 2014. The reason for this decline is unfortunately not known.

In order to make a better comparison between the development of the different transport modes, their average growth per year is calculated as can be seen in Table 3.1. For road transport data from 2002 till 2013 is used, as the three most recent years are determined by extrapolating values of previous years. This makes the average growth calculation as follows:

$$\frac{\text{amount cargo}(2013) - \text{amount cargo}(2002)}{2013 - 2002}$$

To be able to compare the growth for the different transport modes, the average growth per year is divided by the initial amount of cargo in 2002. For maritime transport data from the years 2002-2015 are used. The year of 2016 shows a big peak that might not be constantly continuing. For railway, inland waterway and air transport all the known data are used, so 2002 - 2016.

Table 3.1: Average growth rates of different transport modes

	Road	**Railway**	**Inland waterways**	**Air**	**Maritime**	**Total**
Average growth per year [thousands of tonnes]	12,390.00	1,732.93	32.71	4.50	33.62	16,526.91
Average growth per year / first year cargo [-]	0.15	0.06	0.01	0.04	0.06	0.14

Table 3.1 makes clear that the land transport grows at the biggest rate, both in absolute and relative terms. The inland waterway growth is far behind the other transport modes. It must be denoted that with this type of calculation a linear growth is assumed which is not the case, but it gives an indication and it enables a comparison of the growth rates of the different transport modes.

3.1.2. Types of cargo

According to Clavijo et al. (2014) the type of cargo transported over roads in 2013 consist mainly of four sectors, namely:

- Industry (±46%)
- Agro-industry and agricultural sector (together ±44%)
- Minery (±9%)

The railway transport focuses mainly on one type of cargo, namely coal. This is because the railways do not grant access to the principal production zones of goods in order to transport other types of cargo (Clavijo et al., 2014).

In fluvial transport the main products transported are petroleum based products, probably because in both Barrancabermeja and Santa Marta two big refineries are located. For them it is efficient to transport their products over the rivers.

3.1.3. Conclusion

From the preceding analysis it becomes clear that the cargo transport over roads is mostly used and has the biggest growth rates of all different transport modes. The development of the inland waterway transport has a different behaviour than the development of the total cargo transport. Where the total cargo transport has been growing for most of the years observed, the inland waterway transport has a very unstable development and is even declining between 2008 and 2014. One of the possible causes for this phenomena might be the poor navigability of the Colombian rivers, which is investigated in the next paragraph.

3.2. Fluvial transport in Colombia

As depicted in Figure 3.3, the fluvial cargo transport in Colombia makes up only a small fraction of the total cargo transport. This might have several causes, of which one is a poor river navigability. In this paragraph the fluvial transport in Colombia is analysed some more in depth, focussing on the navigability of the rivers.

3.2.1. Basins in Colombia

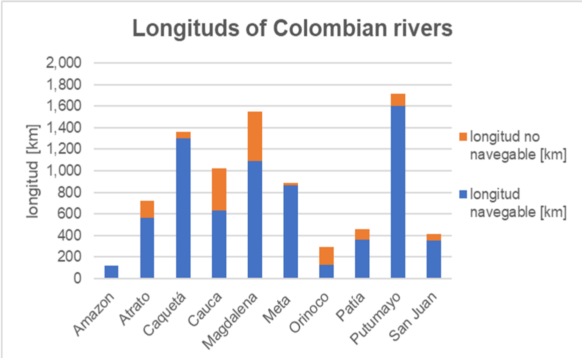
In total Colombia contains 24,725 kilometres of rivers of which 18,825 kilometres are navigable (Rojas Giraldo et al., 2017). The waterways of Colombia can be subdivided into five basins of which four have a main river. These basins are:

- Amazon
- Atrato
- Magdalena
- Orinoco
- Pacific

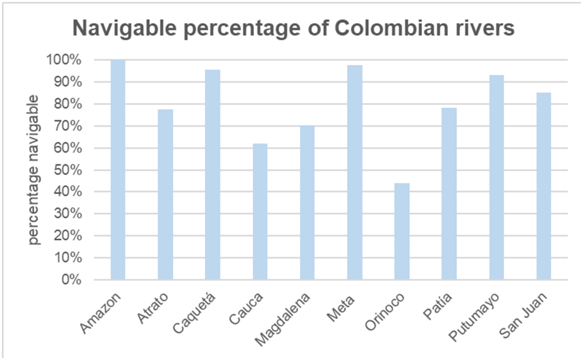
The division of the country into the basins can be seen in Figure 3.5.

Figure 3.5: Overview of the rivers with their basins (in Spanish: *cuencas*) in Colombia (Schilperoort et al., 2015)

In the next paragraphs some more information about the different basins is given. All the detailed numbers of the rivers without direct reference have as reference chapter T20 of the statistical report of the Ministry of Transports, (Rojas Giraldo et al., 2017). Figures 3.6a and 3.6b depict an overview of the lengths of the most important rivers in Colombia together with the navigable percentages.



(a) Lengths of Colombia's most important rivers



(b) Percentages of navigable river parts in Colombia

Figure 3.6: Overview of the navigability of Colombia's most important rivers (Rojas Giraldo et al., 2017)

Amazon

With a length of approximately 6,992 kilometres and a basin area of 7,000,000 km^2, the Amazon one of the biggest rivers in the world. A part of this enormous river covers 341,994 km^2 in the southern part of Colombia (Instituto Sinchi, 2016). The length of the Amazon which flows trough Colombia is 116 kilometres and is fully navigable. Three bigger branches of the Amazon are Putumayo, Caquetá and Patía. Besides, there are plenty of small rivers covering a total length of 3,502 kilometres merging with the Amazon.

Atrato

The Atrato River is located in the North-West of Colombia and its basin borders Panama. With a total length of 720 kilometres, of which 560 kilometres are navigable, it is the third most navigable river of Colombia after the Magdalena River and the Cauca River (Ospina Zapata, 2014). The Atrato River is well connected to both the Atlantic and the Pacific ocean, but still it is not used a lot for cargo transport. The basin of the Atrato River is very rich in gold, wood and also it is a very fertile region. The main port of the river is located in Quibdó.

Magdalena

The Magdalena River is the most important river to Colombia with regards to the transport opportunities. With a total length of 1,550 kilometres it is also the longest river. At the moment 1,092 kilometres are navigable. Figure 3.5 shows that some bigger cities are located close to the Magdalena River, namely Bogotá, Bucaramanga, Barranquilla and Cartagena.

The biggest side-branch of the Magdalena River is called the Cauca River, with a length of 1,024 kilometres and a navigable length of 634 kilometres. Important cities along this river are Medellín and Cali.

The basin of the Magdalena River is the fifth largest of South-America. More information over the Magdalena River and it's transport properties can be found in Section 3.3.

Orinoco

The main part of the 2140 kilometres long Orinoco river flows through Venezuela and also the delta of this river can be found in the neighbour of Colombia. A 290 kilometre stretch of the river functions as a border between Venezuela and Colombia. The river in general is well navigable, thanks to the high discharge of 33,000 cubic metres per second. However, the navigable part in Colombia is small. The main branch of the Orinoco River in Colombia is the Meta River, the most important river in Colombia after the Magdalena River and Cauca River. The Meta River has a length of 885 kilometres which is almost fully navigable.

Pacific coast

The basin at the Pacific coast of Colombia consist of multiple smaller rivers having their deltas in the Pacific ocean. The San Juan river is the most important of these (Schilperoort et al., 2015). It has a length of more or less 410 kilometres and the navigable part has a length of 350 kilometres.

3.2.2. Conclusion

Figure 3.5 shows that primarily along the Magdalena River and the Cauca River, the biggest branch of the Magdalena River, important cities are established. However, Figure 3.6 shows that these two rivers, together accounting for 10% of the total length of the rivers in Colombia, in percentage have the poorest navigability except the Orinoco river. This is probably a large bottleneck in the development of transport over inland waterways. In the next paragraph the navigability of the Magdalena River is analysed in some more depth.

3.3. Transport over the Magdalena River

In 2016 around 3,938,000 of tonnes of cargo have been transported over the inland waterways, while Gleave (2002) found that the capacity of the inland waterway transport of Colombia is around 500 million tonnes of cargo a year. This is almost 130 times more than it was in 2016. Apparently, there is a lot of room for an increase in river cargo transport. In this section, the transport over the Magdalena River is analysed more in detail. First the development of the cargo transport is analysed, after which the accessibility to the river of the larger cities is investigated.

3.3.1. Cargo transport

As already mentioned, the Magdalena River is Colombia's most important river with respect to cargo transport. Looking to the past 14 years (2002-2016), the percentage of cargo transport over the Magdalena River of the total inland waterway cargo transport varied between 40% and 66%. Compared to the total amount of cargo, the amount transported over the Magalena River varies between 0.46% (2013) and 1.79%(2002) (see Table B.3). Striking is the fact that this percentage, the amount of cargo transported over the Magdalena River compared to the total cargo transport, is highest in the first year of the known data and lowest in the last year. This corresponds to the fact that the growth of cargo transport over the inland waterways is lower than the growth of the total cargo transport (Table 3.1).

The fluctuation of cargo transport over the Magdalena River and over the inland waterways in total can be seen in Figure 3.7. Figure 3.8 depicts the development of the different kind of cargo that is transported over the Magdalena River.In Table B.2 the detailed numbers of different types of cargo can be found on which the graphs are based.

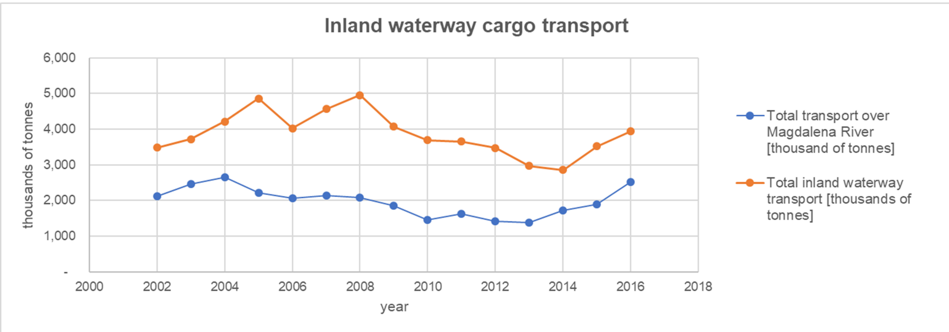


Figure 3.7: Overview of national cargo transport over both the Magdalena River and the total inland waterways, based on Rojas Giraldo et al. (2017) and Felfe Montalvo (2013)

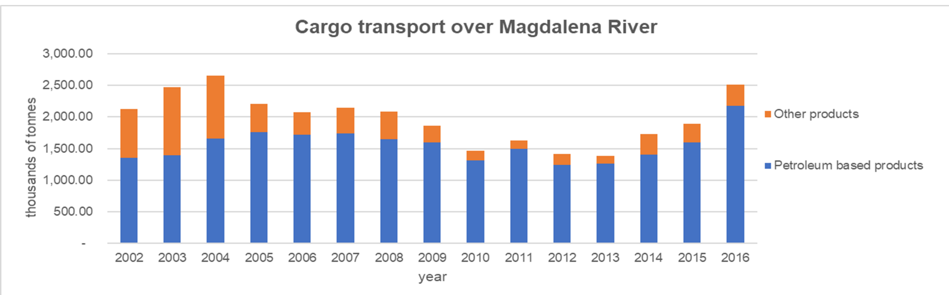


Figure 3.8: Types of cargo transport over Magdalena River, based on Rojas Giraldo et al. (2017) and Felfe Montalvo (2013)

As can be seen, the main part of the cargo contains petroleum based products and the amount of other products has declined a lot between 2002 and 2011. The petroleum based products are mainly transported between Barrancabermeja and Cartagena (where a refinery plant is located) or between Barrancabermeja and the maritime ports (Felfe Montalvo, 2013).

From 2013 on the cargo transport over the Magdalena River is growing, especially the petroleum based products. This might correspond with a better navigability but more likely also with a growth in the amount of produced petroleum products in the oil refinery of Ecopetrol in Barrancabermeja. However, this is an assumption as no data is obtained.

Till August 2017 the cargo transport over the Magdalena River increased a lot compared to 2016. From January until the end of August an increase of about 630,000 tonnes has been registered compared to 2016, which means an increase of approximately 43% of cargo transport (Dinero, 2017).

3.3.2. Accessibility of the Magdalena River

An important aspect for cargo transport over rivers is the accessibility of the river. As already mentioned, some important cities of Colombia are located close to the Magdalena River (Bogotá, Cartagena, Bucaramanga, Barranquila). Also the cities of Cali and Medellín are not very far from the Magdalena River, namely approximately 250 and 200 kilometres. In total 90% of the national cargo transport has as destination one of the cities of Bogotá, Cali or Medellin (Clavijo et al., 2014) and therefore it is important that the road connections between the ports on the river and these cities are good enough for transporting cargo.

Figure 3.9 shows a map in which the main ports of Colombia are pointed out.

Figure 3.9: Overview of the main ports of Colombia (Redacción Elheraldo.co, 2016)

The ports of Figure 3.9 along the Magdalena River are:

- El Banco
- Gamarra
- Barrancabermeja
- Puerto Berrío
- Puerto Salgar

From the delta to Puerto Salgar the Magdalena River is (because of interventions such as dredging) navigable, so it should be possible to reach ports listed above from Barranquilla over the Magdalena River. Measuring approximately 1090 kilometres from Barranquilla (the navigable length of the Magdalena River according to Rojas Giraldo et al. (2017)) leads to Girardot, another city and port upstream of Puerto Salgar. Not much information is available about this port and therefore, for the cities closer to Girardot, both the distances to Girardot and Puerto Salgar have been measured. All distances and travel times have been estimated using google maps.

As mentioned in Section 3.2.1, the cities of Medellín and Cali are close to the Cauca river. However, as the Cauca River has a navigable length of 634 kilometres, one cannot reach Cali as it is too far upstream. Close to Medellín the Cauca river should be navigable, but no big ports are known around Medellín. In order to execute cargo shipments a port is needed, and therefore for both Medellín and Cali the accessibility to a port along the Magdalena River is measured as well.

Table 3.2: Overview of distances and travel times of the most important cities of Colombia to a port on the Magdalena River

From city	To port	Distance [km]	Travel time by car [hours]	Average speed [km/h]
Bucaramanga	Barrancabermeja	125	02:33	49.0
Medellín	Puerto Berrío	183	03:29	50.1
Medellín	Barrancabermeja	314	06:17	50.0
Bogotá	Puerto Salgar	185	03:41	50.2
Bogotá	Girardot	137	02:40	51.4
Cali	Girardot	325	06:20	51.3
Cali	Puerto Salgar	426	08:15	51.6

As can be seen in Table 3.2 the distances of the cities to the ports on the river vary between 120 and 430 kilometres and the average speed is about 50 kilometres per hour for every section. Especially Cali is located far away from the ports, but the distances of Bucaramanga, Medellín and Bogotá are acceptable. However, the travel times are very long, which indicates a poor road connection. There are many mountains in Colombia which definitely delay the travel time but besides this the roads are often not in a very good condition.

Furthermore it must be noted that, because of the bridge in Barrancabermeja, a new road could be constructed from Barrancabermeja to Medellín. During the interviews held with the citizens of Barrancabermeja (see Appendix A) some of them mentioned this road. If this road would be built, the distance from Barrancabermeja to Medellín will be approximately 220 kilometres, depending on the exact location. With an average speed of 50 kilometres per hour, but with a newly built road this speed might be higher, this gives a travel time of 4:24 hours, 1:30 hours less than it currently takes.

From this paragraph one can conclude that for fully taking the advantage of the Magdalena River in terms of cargo transport, not only the river navigability needs to be improved but also the connections between the river and the cities. Without a good connection, the inland waterway transport will probably not grow to it's maximum.

3.4. Conclusion

As this chapter shows, the cargo transport in Colombia is growing almost every year. The majority of this growth can be observed in the growth of cargo transport over roads. The amount of cargo transport over the inland waterways is at the moment very small, and the growth rate is very low compared to the growth rate of the total cargo transport. The fact that the growth rate of the cargo transport over the inland waterways, and in particular over the Magdalena River, is so small, can have multiple causes. These are amongst others a poor navigability and a poor accessibility of the most important cities of Colombia to the ports along the Magdalena River. Is has been investigated by Gleave (2002) that the capacity of the inland waterways of Colombia is approximately 130 times larger than it is at the moment. In order to be able to make use of this capacity, it is important to take into account both the navigability of the river and the access of the cities in order to increase the cargo transport over the Magdalena River.

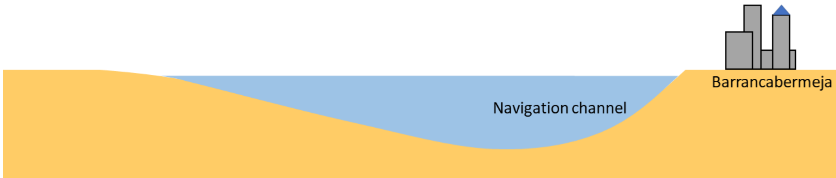
4

Literature study

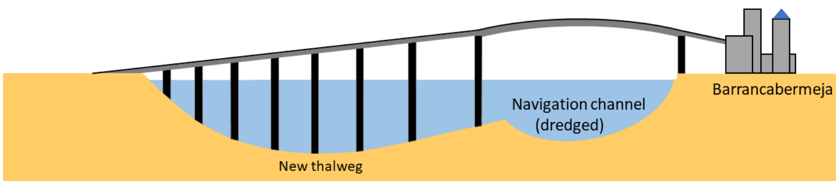
This chapter contains a short overview of the available literature, which is relevant for the situation in Barrancabermeja, introduced in Section 4.1. Section 4.2 contains a description of the natural behaviour of rivers, whereas Section 4.3 discusses the influence of hydraulic structures on the dynamics of a river.

4.1. Introduction

Before the construction of the Yondó bridge in 2005, the thalweg and the navigation channel were located on the right side of the Magdalena river, next to the city of Barrancabermeja (see Figure 4.1a). During the development of the bridge, the designers took into account the navigability of the right side of the channel, considering this reach was preferred for navigation purposes. This implied that the bridge was designed with smaller gaps between the pillars at the left side than at the right side. The largest span of the concrete cantilever bridge is located above the navigation channel, to create the largest clearance for the vessels. However, the response of the river differed from the expected behaviour. After the construction of the bridge, the thalweg shifted to the left side of the river, where most bridge pillars are located. Also, the deck has already descended to ground level. In order to maintain the river navigable, authorities are now forced to dredge the right side of the river to retain a minimum depth. In this way, the navigation channel is sustained under the highest part of the bridge. Figure 4.1b, below, shows the situation of the changed river.



(a) Situation before the bridge was built (< 2005)



(b) Situation after the bridge was built (> 2005)

Figure 4.1: Overview of the situation in Barrancabermeja before and after the bridge was built in 2005

Since the undesirable and unexpected change of the river took place, some parties have been trying to find an explanation for the unforeseen effect. After speaking with these parties, two main reasons are given for the unfavourable change of the river:

1. The Magdalena River is an anabranching river and will change its shape and location over time. This is a natural process which is not easy to predict.
2. The pillars of the Yondó bridge have affected the hydraulic en morphodynamic characteristics of the river, changing its behaviour.

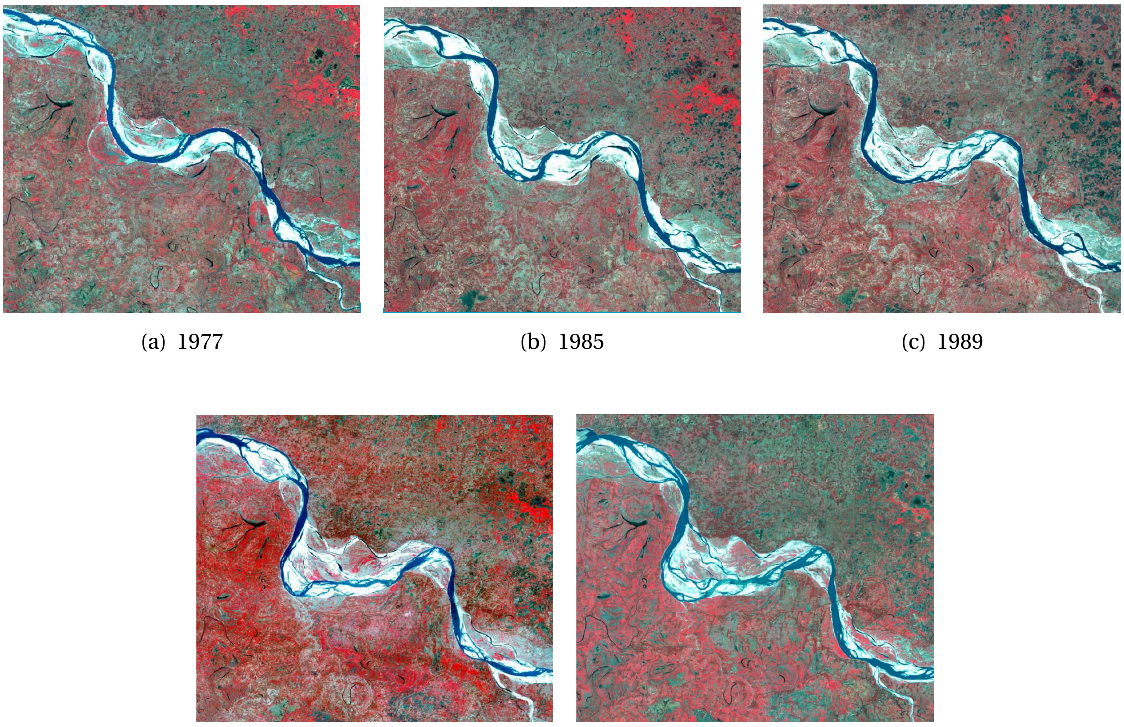
These two hypothesized reasons are discussed in the sections below.

4.2. Natural river behaviour

In this section, the natural behaviour of rivers is assessed. At first, the general characteristics, that are relevant for the situation in Barrancabermeja, are listed and after that these characteristics are linked to the Magdalena River.

4.2.1. General characteristics

Rivers are present all over the world, on every continent and in every country. All these rivers have different characteristics, such as the dimensions, discharge and sediment concentration, but one thing they all have in common: their primary function is the conveyance of water and sediment (Jansen, 1994). The river brings these substances from higher-located areas, such as mountains, to lower-lying places and eventually the river will debouch into another river, lake or sea. Due to rain, wind and other effects of Mother Nature, the shape of the river is subdue to short-term and long-term spatial changes, see Figures 4.2a to 4.2e. These figures illustrate the spatial development of a part of the Ganges River in India. The main observations are the changes in width and the relocation of the bends in the river. These phenomena will be described in more detail below.



(a) 1977 (b) 1985 (c) 1989

(d) 1995 (e) 1999

Figure 4.2: Short-term and long-term spatial changes in a part of the Ganges River in India, close to the border of Bangladesh in 1977, 1985, 1989, 1995 and 1999 (Mosselman, 2016)

Nowadays, satellite images are found to be a very handy tool for river engineers to analyse these changes. The main goal of river engineers is trying to deal with the changes and make quantitative predictions of expected developments (Jansen, 1994). This is important since a lot of people live close to rivers, a part of the transport of goods takes place via the main rivers, and bridges and other structures have to be placed in the surrounding areas of the rivers. However, as amongst others Mother Nature is involved, these changes are hard to predict. Moreover, one spatial change at a specific location will result in another spatial change at a location further up or downstream. This makes the analysis of these changes even more complex. As Mosselman (2016) once stated: "The river changes faster than we can model." Figure 4.3 gives an overview of the most well-known causes that influence the shape of a river. The specific processes in bends and around bifurcations are not included in this analysis, since only the general behaviour of the whole river is assessed.

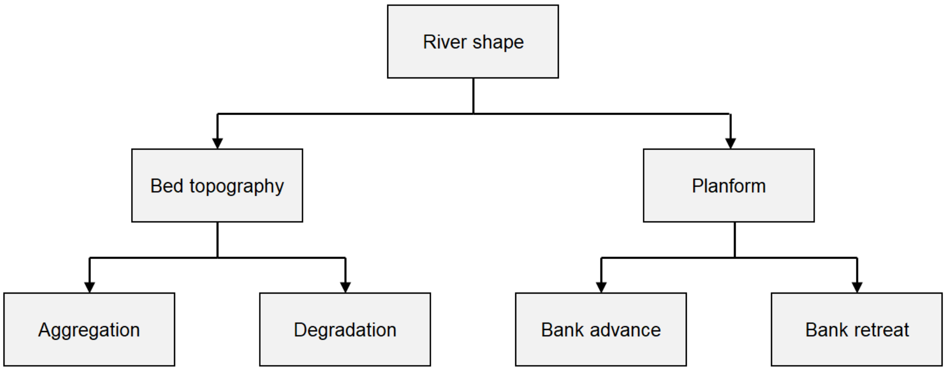


Figure 4.3: Overview of the causes that result in a change of the shape of a river, adapted from Blom (2016)

In Figure 4.3 it can be seen that a change in bed topography or in the planform can lead to a different river shape. Those modifications take place when either the bed or the bank of the river is altered over time. Aggradation or degradation mainly takes place as the width of a reach in the river is adapted by humans or by nature. An example of a natural widening of a river is bank retreat (erosion) due to groundwater outflow or toe erosion. This shows that both parts of the diagram in Figure 4.3 are connected, since a change in the planform of the river results in a change in bed topography and vice versa. Other examples of bank retreat and advance are amongst others, the direct entrainment of sediment, deforestation, fluvial deposition and the trapping of fine material by vegetation (Mosselman, 1995). The large-scale features that can be observed in the river are meandering, channel migration and the short-cuts. The formation of an oxbow lake is an example of a feature that contains all these three processes (see Figures 4.4a to 4.4d).

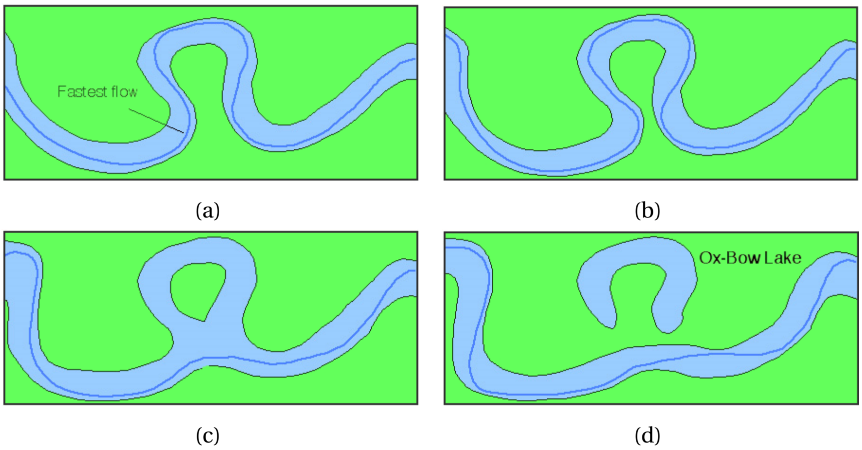
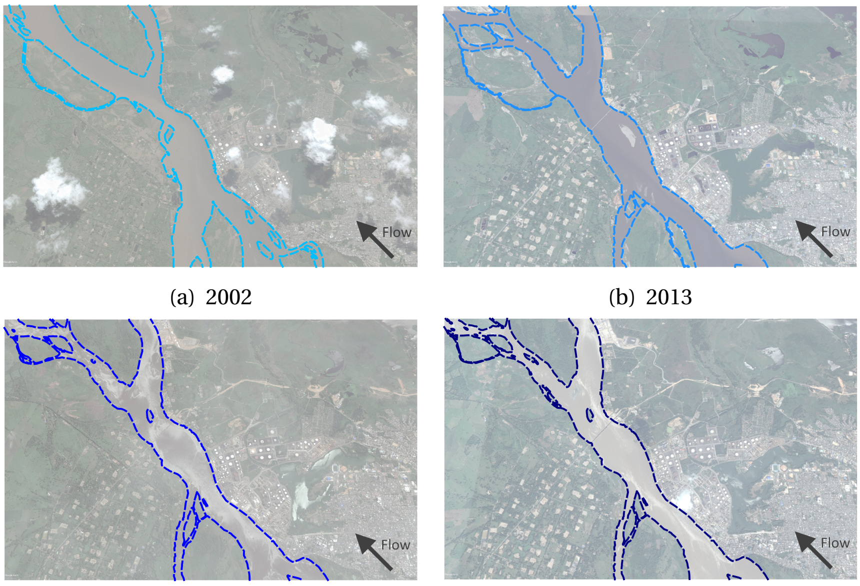


Figure 4.4: Development of an oxbow lake in a river, adapted from Benson (2017). (a) The river follows the fastest flow route indicated by the blue line. (b) The necks becomes more narrow due to erosion. (c) The neck disappears and the river connects with the more downstream part. (d) The bend is cut off and a more straight course remains.

Over the years, river engineers found ways to keep the river at its current or desired position. This is called ‘river training’ and refers to the structural measures which are taken to improve the river and its bends (Shrestha et al., 2012). The following river training works are the most common: embankments, spurs and (im)permeable groynes, bed pitching and dredging (te Slaa, 2004). A disadvantage of these measures is the effect on the upstream and downstream part of the adapted river reach. For example, at the first part of the straight river branch in Figure 4.4d embankments are placed. This part will not be able to meander, since the river banks are kept at the same location by the embankments. However, at the transition and downstream of these embankments the banks will still be under attack of the water that flows through the river. This will probably result in more bank erosion. Once you started with river training, you are obliged to continue (Mosselman, 2016).

4.2.2. Characteristics of the Magdalena River

As the Magdelena River is the largest river in Colombia, it might be expected that all the spatial changes described above will be present in this river as well. For this project the area of focus is the part of the Magdalena River around Barrancabermeja, as the bridge, which resulted in sedimentation problems, was built there in 2005. The spatial development of this river breach is depicted in Figures 4.5a to 4.5d and 4.6. Figure 4.5 shows four separated shapes of the river in the years 2002, 2013, 2016 and 2017, whereas Figure 4.6 shows all these patterns on top of each other.



(a) 2002 (b) 2013

(c) 2016 (d) 2017

Figure 4.5: Spatial changes in the Magdalena River around the city of Barrancabermeja in 2002, 2013, 2016 and 2017, adapted from Google Earth (2017). The black arrow indicates the flow direction of the river.

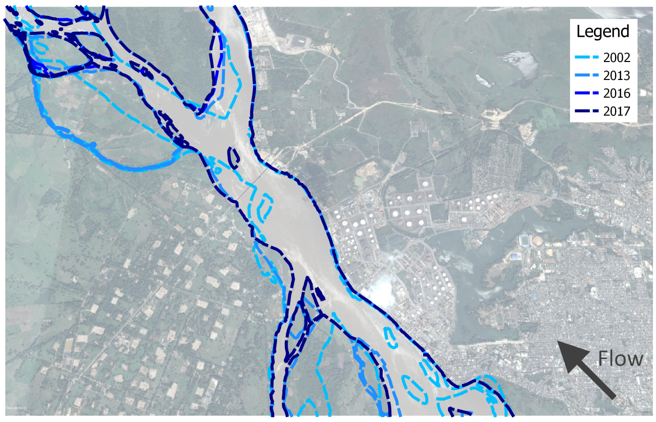


Figure 4.6: Overview of the development of the shape of the river around the city of Barrancabermeja for all four years depicted in Figure 4.5, adapted from Google Earth (2017). The black arrow indicates the flow direction of the river.

The figures above demonstrate that spatial changes are present in this part of the Magdalena River. The most apparent changes are the width variation in the middle part of the reach and a decrease of the flow in the left downstream branch. These changes are probably due to the construction of the bridge in 2005. Another interesting aspect that is pointed out by Figure 4.6 are the stable banks at the east side of the river. According to Eduardo Bravo, consultant at Universidad Nacional in Bogota, hard river training measures are taken at this location to keep the banks stable, which prevents buildings in the city of Barrancabermeja from collapsing.

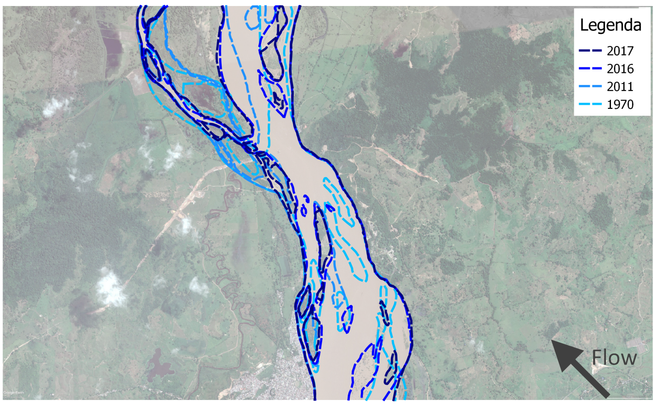


Figure 4.7: Overview of the development of the shape of the river around the city of Puerto Berrío for a time range of 15 years, adapted from Google Earth (2017). The black arrow indicates the flow direction of the river

.

In Figure 4.7 above, an overview of the spatial changes of the Magdalena River around Puerto Berrío are displayed. It can be seen that over the years a lot of spatial changes have occurred. This indicates that an undisturbed part of the river, where no hydraulic structures are present, is also significantly active.

4.3. Influences of hydraulic structures

The construction of bridges across a river or channel can have a varying level of impact on river hydrodynamics and sedimentation processes. The reach of this impact is normally limited to several channel widths upstream and downstream of the bridge, and depends on the steepness of the river. The steeper the river, the smaller the distance from the bridge that is effected by the construction (US Bureau of Reclamation, 2006).

No articles have been found about similar situations where, since the construction of a bridge, the navigation channel started to get effected by sedimentation. Therefore, other studies are used as reference to indicate the influence of a construction of a bridge on the behaviour of a river. Two articles are used to state the influence of bridges on rivers and one article to state the influence of scour on macroscale river morphology.

4.3.1. The effect of bridge structures on rivers

According to Suvendu (2013) bridges can increase stream flow velocity, shear stress, turbulence of flow, bed degradation and aggradation, development of deep scours, channel braiding and downstream bank erosion. In the study of Suvendu (2013), the effect of a road bridge over the Kunur River on the river morphology is monitored from 2003 until 2011. The length of this bridge is 87 meters and it has ten pillars, which are horizontally interconnected on the river bed with a concrete layer. During the research the cross sectional channel dimensions were measured at four sites, two in the upstream reach (50 meters and 10 meters from the bridge) and two in the downstream reach with the same distances from the bridge. Over an area of 1 kilometre upstream and 1 kilometre downstream of the bridge motion was measured. In Figure 4.8, below, the shift of the river is shown.

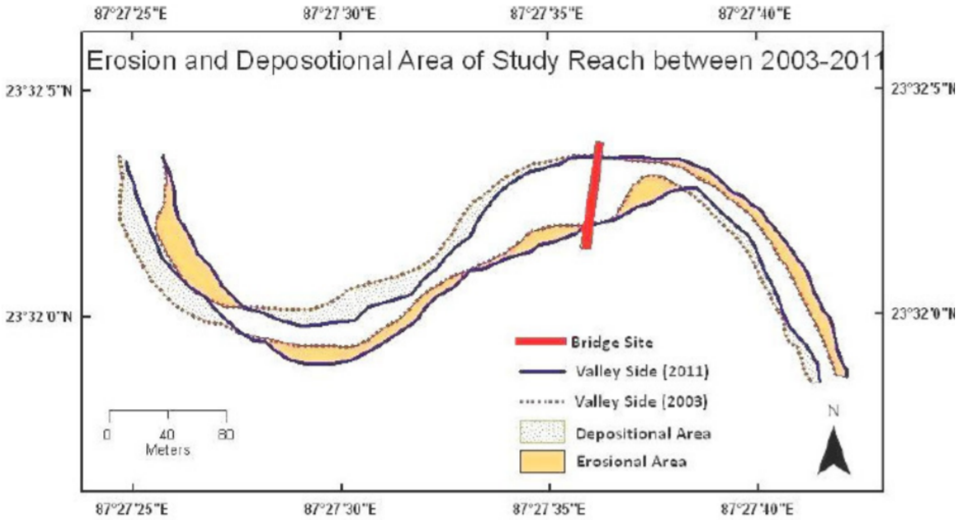


Figure 4.8: The shift of the river during the examined time frame, with the erosion and accretion areas included (Suvendu, 2013)

In the discussion of this paper, it is stated that alluvial channels are unstable. Therefore, during the development of a hydraulic structure like a bridge, knowledge about the shifting tendency of the river, local geology, channel degradation and aggregation rates should be taken into consideration. The study has demonstrated the needs of understanding the fluvial dynamics of a waterway, whenever realising a river crossing that has interference with the river. The usability of this paper is however mediocre, due to the fact that no information is provided about the rivers behaviour from the time before the research and before the construction of the bridge.

In a case study by Biswas (2010) the influence of the bridge pillars of the Kazir Bazar bridge is investigated. In this paper 2D numerical models are used for an area of 12.5 km upstream and 12.5 km downstream of the bridge (25 km model area in total), to observe the rivers response due to the presence of the bridge, and for different flood conditions. Subsequently the outcome was analysed by assessing the hydrodynamic and morphodynamic characteristics of the Surma River.

The thalweg was located along the left bank of the river, at the initial stage of the simulation (prior to the monsoon). Undergoing the monsoon flood conditions, the thalweg shifted from the left river bank to the right bank, resulting in a decrease of the shallower area near the right bank directly upstream of the bridge (see Figure 4.9). This simulation was also done for extreme flood conditions. Both flood events resulted in similar sedimentation and erosion patterns, only with different quantities. The situation in this study is not exactly the same as the situation in Barrancabermeja, but it shows the impact of a bridge construction on the river morphology. In Figure 4.9 the changes of the river bed of the Surma River are depicted. in the subfigures, the effect of the bridge on the bed topography is displayed for different moments in time.

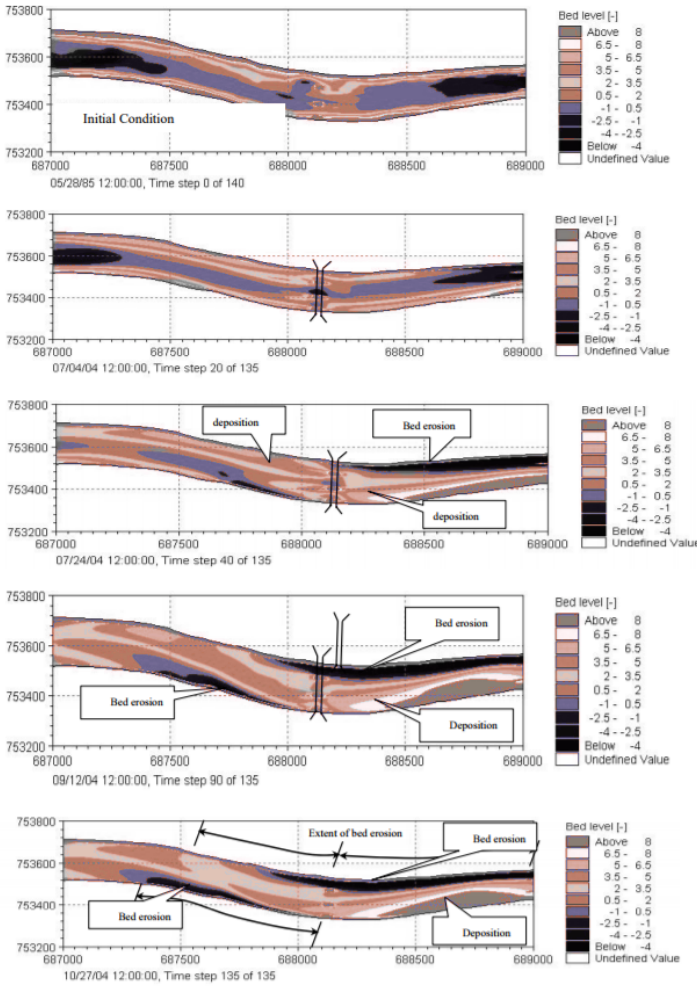


Figure 4.9: Bed level contour for extreme (100 year return period) flood event at different stage of monsoon, adapted from Biswas (2010)

4.3.2. The effect of scour on rivers

A well known problem of bridges is the potential risk of instability due to scour formation. Hydraulic structures in flowing water bodies will cause turbulence around themselves, which leads to the formation of scour holes. At the time of the bridge construction, contraction scour can occur due to the accelerations of the water as it flows through an opening that is narrower than the channel. This results in higher stream velocities, which induces the removal of material from the bed and banks. In both upstream and downstream direction, degradation scour will occur over large areas from the bridge. Degradation scour is the erosion of the of bed material induced by man-made structures, that effects a larger reach of the river on which the structure is located. Over a long period of time, this can result in the lowering of the bed level (Landers, 1992).

Mosselman and Sloff (2002) conducted a study about the effect of scour holes on macroscale river morphology. In the paper it was stated that field observations and laboratory experiments suggested that local scour affects the morphology of a river on a large scale. The effect of local scour holes are proven by reproducing them, using numerical experiments with Delft3D.

According to Mosselman and Sloff (2002) local scour holes can affect the macroscale river morphology in numerous ways, such as channel attraction, channel narrowing and downstream superimposition of forced bars. They also state that this implies the need of feedback from near-field models to far-field models in scour studies for the design of structures on alluvial rivers. In the conclusion of the paper it is recommended that river engineers should be aware of this, when designing river works. In Figure 4.10 below, the changed river bed is shown after two years of scouring.

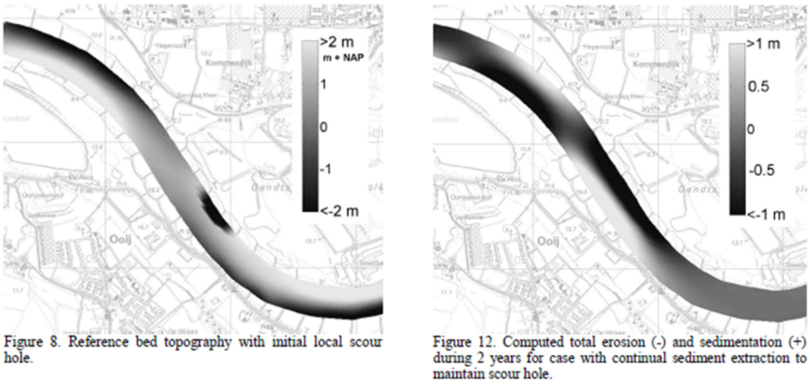


Figure 4.10: Changed river morphology (Mosselman and Sloff, 2002). The left figure shows the situation before the effect of scour, the right pictures shows the effect of the scour hole after a period of two years.

4.4. Conclusion

As concluded before from Figure 4.6, the Magdalena river clearly is a spatially active river. However, both in stable and unstable rivers, human interferences, such as hydraulic structures, may cause changes in the flow conditions of a river. This can result in a different spatial pattern on local scale or for the entire river. In case of the Yondó Bridge, it is very likely that the construction of the bridge is related to the spatial changes of the river and the shifting of the thalweg. This hypothesis will be assessed in the next part of this report. The main challenge for engineers is to understand both the structural and the hydraulic aspects of a river. Such an approach will usually prove to be more efficient than constantly trying to maintain the system against the natural behaviour.

5

Hydrodynamic data analysis

This chapter gives a description of the processing of the hydrodynamic data of the Magdalena River obtained from IDEAM (2017) and the data measured during the field trip of this project. Detailed information about the field trip can be found in Appendix C. In the first section, the source and the type of data are discussed, whereas in Sections 5.2 and 5.3, the results and the conclusions of the processing are presented.

5.1. Sources

The Instituto de Hydrologia, Meteorologia y Estudios Ambientales, in short IDEAM, has different types of measuring stations in the Magdalena River. Part of the stations measure the discharge [m^3/s] or the water level [cm], whereas other stations measure the sediment transport [kton/day]. An overview of the locations of the stations in the reach from Puerto Berrío to Badillo is given in Figure 5.1 and the characteristics of these stations are summarised in Table 5.1.

The margin of error, mentioned in the table, is based on the amount of days that a measurement is missing during the entire measuring period. For some stations, such as Penas Blancas, this margin of error is significant: 28%. However, the data measured by IDEAM (2017) is the only available data, so it will be used, but with care. Most of the stations were installed between 1970 and 1980, but the measurement station in Puerto Berrío was installed already in 1936. Therefore, it can be assumed that the data from this station represents the overall flow situation in the Magdalena River considerably well.

Figure 5.1: Overview of the locations of the measuring stations in the Magdalena River. The white arrow indicates the flow direction in the river reach from Puerto Berrío to Badillo, which has overall a length of 210 km.

Table 5.1: Overview of the location, elevation, measured variables and the margin of error of the measuring station in the Magdalena River, adapted from IDEAM (2017). It should be noted that the percentages that represent the margin of error are indications and no exact values.

Name	Department	Latitude	Longitude	Elevation [m.s.n.m]	Variables	Margin of error
Puerto Berrío	Antioquia	6°29’00.00 N	74°24’00.00 W	111	Q, h, S	10 %
Penas Blancas	Antioquia	6°95’47.22 N	73°95’08.33 W	80	Q, h, S	28 %
Barrancabermeja	Santander	7°06’02.78 N	73°87’61.11 W	76	Q, h	6 %
Puerto Wilches	Santander	7°34’41.67 N	73°90’50.00 W	65	h	16 %
Sitio Nuevo R-11	Santander	7°78’33.33 N	73°80’08.33 W	56	Q, h, S	12 %
Badillo	Santander	7°97’50.00 N	73°85’69.44 W	53	h	27 %

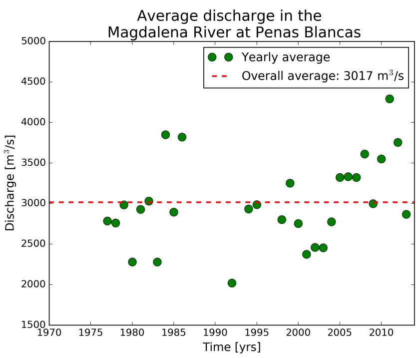
The second source that provided hydrodynamic data of the area of interest, is the measuring equipment used during the fieldwork in Barrancabermeja. As mentioned before, a detailed description of this field trip can be found in Appendix C. The discharge, water level and flow velocity were measured during two entire days. It is hard to compare the measurements of this field trip to the data provided by IDEAM, since the data of IDEAM is based on long-term measurements. Therefore, the measurements of the field trip will be used to check whether the order of magnitude coincides with the range of the hydrological institute.

5.2. Results of processed data

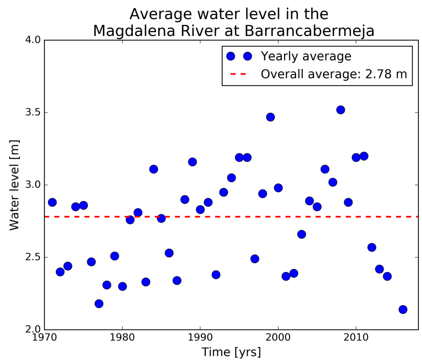
This section gives an overview of the results of the processed data. Firstly, the long-term data of IDEAM is summarised and after that the measurements of the field trip are presented.

5.2.1. IDEAM

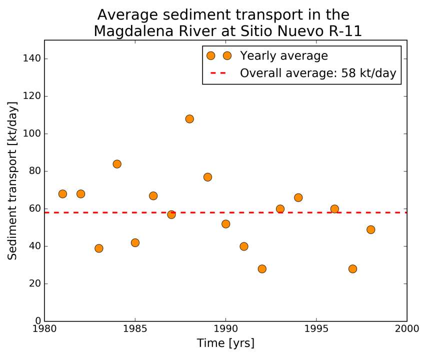
For all three measured variables, the data is averaged and plotted versus the time. This is depicted in Figures 5.2a to 5.2c. Appendix D contains the graphs with the results of all the measuring stations. Also, the overall average of the year averages is taken and indicated by the red-dotted line in the graphs. A complete overview of these overall averages is given in Table 5.2.



(a) Discharge



(b) Water level



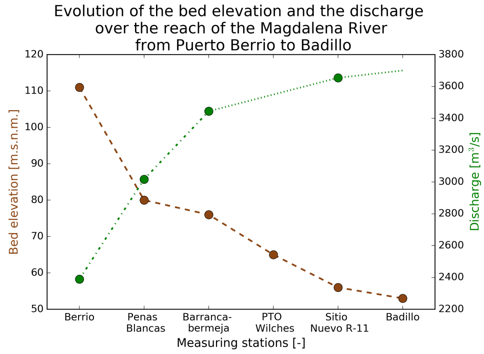
(c) Sediment transport

Figure 5.2: Graphs that represent the three types of hydrodynamic data of IDEAM (2017). The red-dotted line indicates the average value of the entire measuring period.

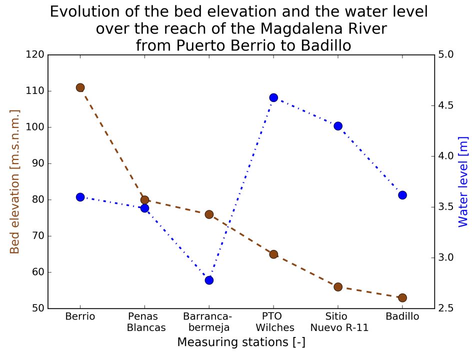
Table 5.2: Processed results of the available hydrodynamic data of the six measuring stations in the Magdalena River in the river reach from Puerto Berrío to Badillo. A hyphen indicates that no data is available for the variable at that specific location. The maximum is the absolute maximum value and the minimum is the average minimum value.

	Variables								
	Discharge $[m^3/s]$			Water level [m]			Sediment transport [kton/day] and [kton/year]		
Name	Q_{mean}	Q_{max}	Q_{min}	h_{mean}	h_{max}	h_{min}	S_{mean}	S_{max}	S_{total}
Puerto Berrío	2,389	5,557	987	3.60	5.38	2.38	138	805	50,244
Penas Blancas	3,017	5,403	1,368	3.49	5.10	2.09	120	391	34,167
Barrancabermeja	3,444	6,278	1,278	2.78	4.66	1.11	-	-	-
Puerto Wilches	-	-		4.58	6.17	3.08	-	-	-
Sitio Nuevo R-11	3,654	6,064	1,575	4.30	5.85	2.54	58	157	19,901
Badillo	-	-		3.62	5.06	1.99	-	-	-

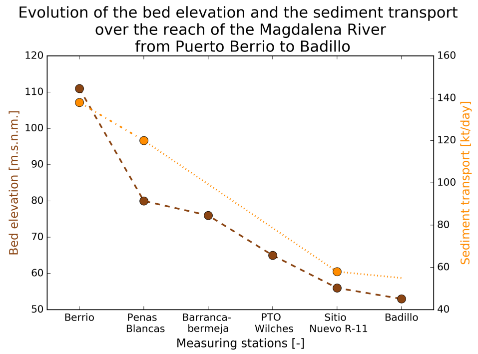
In order to visualise the values summarised in Table 5.2, the three graphs in Figures 5.3a to 5.3c are created. These images show the evolution of the bed level versus the discharge, the water level and the sediment transport, respectively. For the water level, every station measures a value, whereas for the sediment transport only three stations obtain values. Therefore, a distinction is made between an actual relation (dots and hyphens) and an assumed relation (dots only).



(a) Discharge



(b) Water level

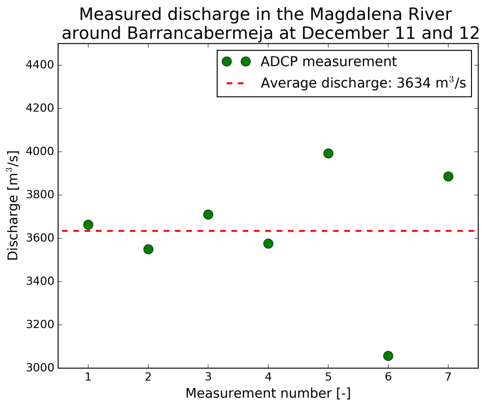


(c) Sediment transport

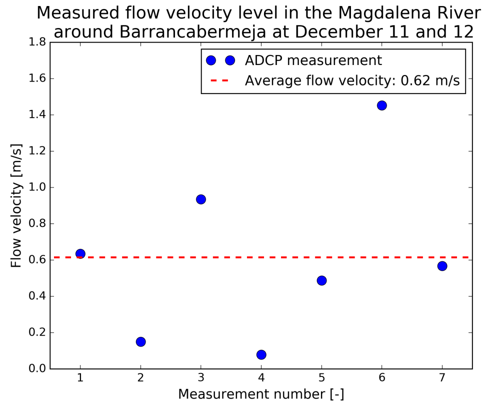
Figure 5.3: Graphs that show the relation between the bed elevation of the measuring stations and the discharge (a), the water level (b) and the sediment transport (c). A line with dots and hyphens indicates an actual relation, whereas a line consisting of dots only, represents an assumed relation. It should be noted that the distance between in the measuring stations is not taken into account in these graphs.

5.2.2. Field trip in Barrancabermeja

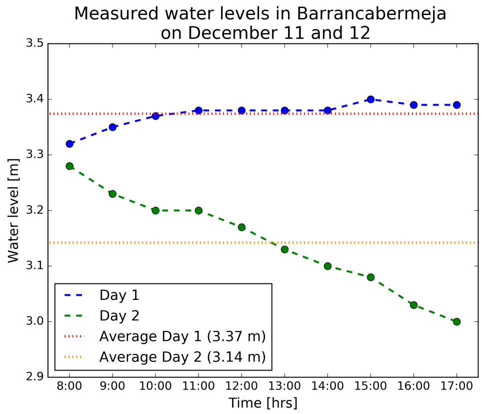
The discharge, water level and flow velocity measured on December 11 and 12 (2017) are plotted in Figures 5.4a to 5.4c. Appendix E describes the conversion steps that are taken to make the data suitable for analysis. The spread in measurements is significant, especially the variation in water level between the first and the second day is remarkable. This could be explained by the weather, as this was very different on the first and second measuring day. The average discharge measured by the ADCP in Barrancabermeja is 3,634 m^3/s and this value is 3,444 m^3/s according to the measurements by IDEAM. These numbers are almost similar, meaning that the flow situation in the Magdalena River did not change remarkably compared to the year 2014 (the most recent year in the measurements of IDEAM (2017)).



(a) Discharge



(b) Flow velocity



(c) Water level

Figure 5.4: Graphs that represent the three types of hydrodynamic data measured during the field trip. The red-dotted line indicates the average value of the two day period.

5.3. Conclusions

Ayala et al. (2007) analysed the morphological effects and the sediment relations of the construction of the bridge in Barrancabermeja. This article uses discharge values from the measuring station in Maldonado, located between Barrancabermeja and Puerto Wilches (latitude: 7°12'17.00 N and longitude: 73°55'36.00 W). These values, see below, are in the same order of magnitude as the values presented in Section 5.2.

- Average discharge: 2,626 m^3/s
- Maximum discharge: 6,860 m^3/s
- Minimum discharge: 485 m^3/s

Figure 5.2 indicates a lot of dispersion in the measured discharge, water level and sediment transport values. This could be caused by an error in the measurement equipment or by yearly climate variations, such as El Niño. Despite this scatter, it is assumed that the average value, indicated by the red dotted line, represents the discharge and the water level in the area well enough for this stage of the research. However, at Puerto Berrío a decreasing trend in sediment transport is observed since 1990. This should be kept in mind in case sediment transport is incorporated in the analysis.

Therefore, the numbers in Table 5.2 are used in the empirical analysis, performed to approximate the dimensions of the scour holes in the Magdalena River and in the Delft3D-model of the river reach. Both parts will be described later in this report, see Chapters 8 and 9.

6
Bar mode analysis

The bar mode might be a possible explanation of the transition of the thalweg in the Magdalena River after the construction of the Yondó Bridge. It indicates the number of sand bars that should be present in a river. River widening may lead to the formation of alternate bars, whereas river narrowing might result in disappearance of the bars. According to Crosato and Mosselman (2009), these bars also affect the size of the cross section of the navigation channel. Therefore, it is important to conduct the bar mode analysis for the Magdalena River, as it could prove a relation between the construction of the bridge and the shift of the location of the thalweg.

6.1. Theory and method

In order to calculate the number of bars with the bar mode the formula of Crosato and Mosselman (2009) is used:

$$M^2 = 0.17 \cdot g \cdot \frac{(b-3)}{\sqrt{\Delta \cdot d_{50}}} \frac{B^3 \cdot i}{C \cdot Q_{\mathrm{bf}}} \tag{6.1}$$

In which:				
	M	=	number of bars in a cross section	[-]
	g	=	gravitational acceleration constant	[m^2/s]
	b	=	degree of non-linearity	[-]
	Δ	=	relative sediment density under water	[-]
	d_{50}	=	median sediment grain size	[m]
	B	=	river width	[m]
	i	=	longitudinal river gradient	[-]
	C	=	Chézy coefficient	[m$^{\frac{1}{2}}$/s]
	Q_{bf}	=	bank-full discharge	[m^3/s]

The method uses the river width-to-depth ratio, longitudinal slope, bed roughness and sediment characteristics at bank-full conditions to estimate the number of steady bars that form in the cross section of a river. This will be done for the years 1981, 1998, 2002, 2013 and 2017, as high quality aerial photographs and satellite pictures are available for these years. The years cover a total period of 36 years, which is quite a significant time. The sections below describe how the necessary data of the Magdalena River is obtained from different sources.

6.1.1. Necessary river data

For the years 1981 and 1998, the width of the river is obtained by analysing aerial photographs from Bravo (2017) that were digitalised in AutoCAD. This program is able to combine the right coordinate system with the aerial picture, resulting in the right scale of the photo. Based on that scale, the width of the river is computed. For the other three years, the satellite images of Google Earth (2017) are used to obtain the width of the cross section.

The longitudinal river gradient is calculated based on the measurements of the water level during the fieldwork in Barrancabermeja, see Appendix F. This value, for the year 2017, is equal to $3.37 \cdot 10^{-4}$ and is assigned to all five years, as no data of the other years is available.

According to Oliveros-Acosta et al. (2015), the median sediment diameter (d_{50}) in this part of the river is 350 μm. In the ideal situation, this sediment size was calculated from the two sediment samples taken during the field trip to Barrancabermeja. However, the results of the sieve analyses were too inaccurate to calculate representative values for the median sediment diameter, see Appendix G.

In order to determine the Chézy value, Equations (6.2) to (6.5) were used. Equation (6.3) is substituted in Equation (6.2), resulting in Equation (6.5), which has one unknown parameter: h_0. This parameter is computed with a solve function in Python and subsequently this value is substituted in Equation (6.3).

$$Q = A \cdot C\sqrt{h_0 \cdot i} \tag{6.2}$$

$$C = 18 \cdot \log\left(\frac{12 \cdot h_0}{k_s}\right) \tag{6.3}$$

$$k_s = x \cdot D_{50}, \text{ with x between 3 and 4} \tag{6.4}$$

$$Q = B \cdot h_0 \cdot 18 \log\left(\frac{12 \cdot h_0}{k_s}\right)\sqrt{h_0 \cdot i} \tag{6.5}$$

In which:	Q	=	discharge	[m^3/s]
	A	=	cross-sectional area	[m^2]
	h_0	=	water depth at bank full conditions	[m]
	k_s	=	equivalent bed roughness for Colebrook-White equation	[m]

Unfortunately, this method results in a Chézy value of 80 $m^{\frac{1}{2}}/s$, which is too high for a river section like the one in Barrancabermeja. This could be due to inaccurate values of k_s and h_0. Therefore, another method for the determination of the Chézy value is used.

The other method is based on the cross-sectional area that was measured during the field trip. This area is divided by the width resulting in a value for h_0. By substituting this value in Equation (6.2), a new Chézy value of 38.6 $m^{\frac{1}{2}}/s$ is obtained. This value is more realistic, as bottom dunes could make the river bottom rough. This Chézy value is used for all five years, just as for the river slope, due to insufficient data for the 1981, 1998, 2002 and 2013. However, this simplification is appropriate as the Chézy value of a river remains in general constant over a long-term period.

The degree of non-linearity (b) indicates the dependence of the sediment transport on the flow velocity. According to Engelund and Hansen (1967) this value should be equal to five, whereas Crosato and Mosselman (2009) state that this value should be lower, due to the bank-full conditions of a river. For this reason, the bar mode is both computed with a degree of non-linearity of four and five.

As the calculation of the bank-full discharge is extensive, the entire next section is dedicated to this topic.

6.1.2. Bank-full discharge

In Equation (6.1) the bank-full discharge (Q_{bf}) is one of the input parameters. This value is the flow discharge at the moment that the river is just about to spill onto its floodplains, see Figure 6.1. It is also an important parameter for the estimation of channel geometry.

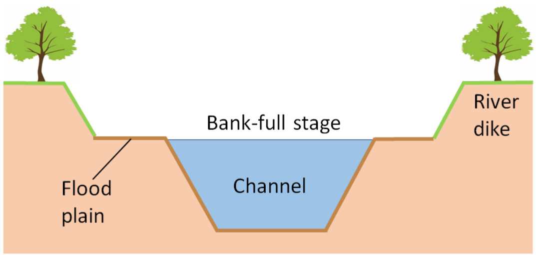


Figure 6.1: Situation bank full discharge

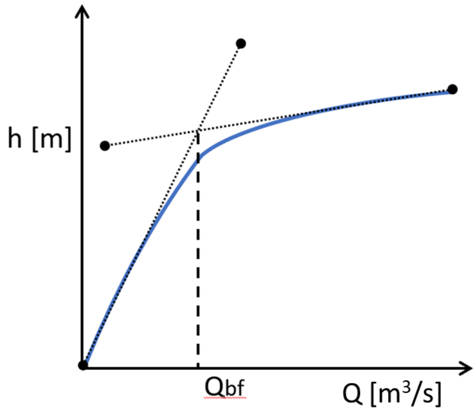


Figure 6.2: Relation between the discharge and the water level, also called a Q,h-curve. The bend in the graph shows the bank-full discharge (Q_{bf}).

There are several methods to estimate the bank-full discharge. One method is to use actual measurements of the river discharge. However, as the bank-full discharge does not occur frequently, this method is considered impractical. The second method is based on the water level-discharge curve, see Figure 6.2. In order to gain a reliable value the curve should consist of data that was taken nearby the area of interest. This method is also not suitable for Barrancabermeja as no long-term data of the water level and discharge is available of the corresponding years.

Luckily, Williams (1978) suggests a method for the estimation of the bank-full discharge, that is not directly dependent on water level measurements. Williams states that the bank-full discharge has the same value as the peak flood discharge with a return period of two years. It must be denoted that this method is calibrated for gravel-rivers and not for sand-rivers such as the Magdalena River. However, given the available data, this method is the most suitable. Below, a description of the determination of the peak flood discharge with a return period of two years in the Magdalena River is given.

The discharge and water level data from 2007 to 2013 is obtained from the measurement stations in Barrancabermeja and Peñas Blancas, that is located approximately eight kilometres upstream of Barrancabermeja. As no large branches discharge water in the section between those two measurement stations, the data from Peñas Blancas are assumed to be representative for Barrancabermeja as well. The daily water levels are plotted against the daily discharge in order to obtain a trend line for the relation between both variables. This trend line is used to calculate the daily discharges for the years 2014 until 2017. From the daily discharges, the maximum discharges are retrieved.

By creating a histogram of the maximum discharges and fitting a distribution through this data, a discharge value with a certain return period can be obtained. For the available data, the Gumbel distribution, see Equations (6.6) to (6.9), turns out to be the best fitting distribution. This is visually indicated in Figure 6.3.

$$F_{\mathrm{x}}(x) = \exp[-e^{-\alpha(x-u)}] \tag{6.6}$$

$$f_{\mathrm{x}}(x) = \alpha \cdot \exp\left[-\alpha(x-u) - e^{-\alpha(x-u)}\right] \tag{6.7}$$

$$u = \mu - \frac{0.5772}{\alpha} \tag{6.8}$$

$$\alpha = \frac{\pi}{\sigma\sqrt{6}} \tag{6.9}$$

In which:	F_{x}	=	cumulative distribution function	[-]
	f_{x}	=	probability density function	[-]
	μ	=	mean	[-]

σ	=	standard deviation	[-]
u	=	calibration coefficient for μ	[-]
α	=	calibration coefficient σ	[-]

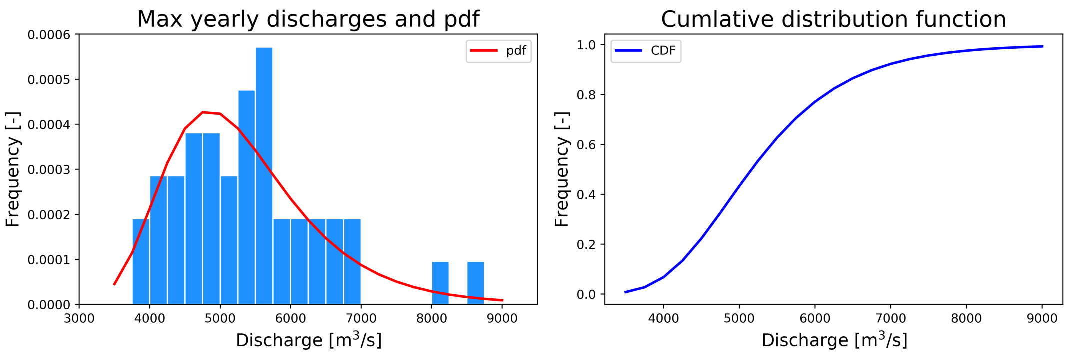


Figure 6.3: Left: Histogram of the yearly maximum discharges in Penas Blancas (near Barrancabermeja), with the corresponding pdf. Right: corresponding cumulative distribution function.

For a return period of two years, the probability of exceedance will be equal to 0.5, as $p = P(x \geq x_{2\text{ years}}) = 0.5$. This value can be used to determine the final bank-full discharges per year. Table 6.1 provides an overview of the final values that are used for the bar mode computations.

Table 6.1: Overview of the bank-full discharges for the years 1981, 1998, 2002, 2013 and 2017

Year	1981	1998	2002	2013	2017
Q_{bf} [m^3/s]	5844.8	5245.3	5103.9	5244.9	5162.3

6.2. Bar mode computations

In this section, the bar mode computations are made for each year separately. The outcomes are also compared to the aerial photographs of that year. In the end, the results of all five years are analysed.

6.2.1. Situation in 1981

In Figure 6.4 below, the position of the Magdalena River around Barrancabermeja in 1981 is depicted. A sand bar can be distinguished at the left side of the river, opposite of the city of Barrancabermeja.

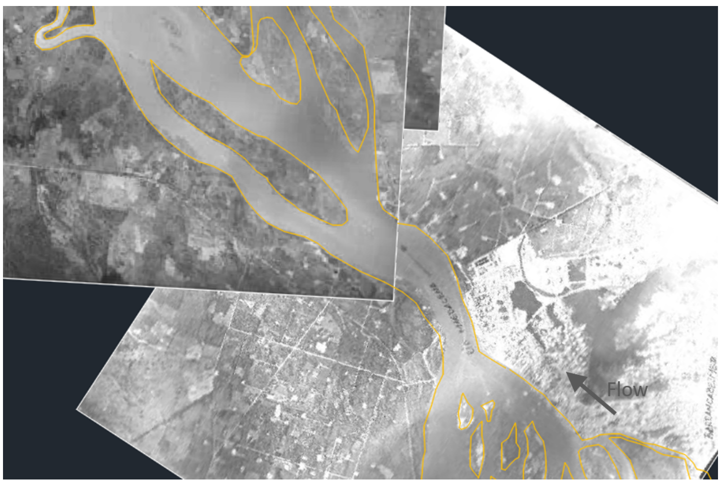


Figure 6.4: Aerial photograph of the position of the Magdalena River around Barrancabermeja in 1981, adapted from (Bravo, 2017)

Table 6.2 summarises the input for the bar mode computations. In Table 6.3, that shows the outcomes of the calculations, it can be observed that for both values of the non-linearity (b=4 and b=5), the M-value lies within a range of 0.5 to 1.5. According to Crosato (2015), alternate bars will be present for this M-values and therefore the visual observation is in correspondence with the outcome of the computations.

Table 6.2: Input parameters for the bar mode computations for the year 1981

Year	i [-]	Q_{bf} [m^3/s]	B [m]	h_0 [m]	d_{50} [μm]	Chézy [$m^{1/2}/s$]	B/h_0 [-]	Observed Bar Mode
1981	$3.37 \cdot 10^{-4}$	5844.8	588	3.9	350	38.6	151	1

Table 6.3: Computed and observed bar mode as well as planform styles for the year 1981

Year	computed M b=4	computed M b=5	Observed Bar Mode	Predicted barform	Observed planform
1981	0.82	1.15	1	alternate bars	alternate bars

6.2.2. Situation in 1998

In Figure 6.5 below, the position of the Magdalena River around Barrancabermeja in 1998 is depicted. In comparison with the situation in 1981, the sand bar is more dominant, but still located at the left side of the river. The thalweg is located on the other side of the river.

Figure 6.5: Aerial photograph of the position of the Magdalena River around Barrancabermeja in 1998, adapted from (Bravo, 2017)

As can be seen in Table 6.5, the M-value for a value of b=4 is still within in the range of 0.5 to 1.5 (Table 6.4 provides the input parameters for the computations). However, for a value of b=5, the M-value is slightly larger than 1.5. This can be explained by the overestimating behaviour of the model when the width to depth ratio is above 100. In that case, the computed bar mode value is higher than the actual value. Therefore, the outcomes of the model are still in correspondence with the visual observations for the given river conditions.

Table 6.4: Input parameters for the bar mode computations for the year 1998

Year	i [-]	Q_{bf} [m^3/s]	B [m]	h_0 [m]	d_{50} [μm]	Chézy [$m^{1/2}/s$]	B/h_0 [-]	Observed Bar Mode
1998	$3.37 \cdot 10^{-4}$	5245.3	711	3.9	305	38.6	182.3	1

Table 6.5: Computed and observed bar mode as well as planform styles for 1998

Year	computed M b=4	computed M b=5	Observed Bar Mode	Predicted planform	Observed planform
1998	1.15	1.62	1	alternate bars	alternate bars

6.2.3. Situation in 2002

In Figure 6.6 below, the position of the Magdalena River around Barrancabermeja in 2002 is depicted. The situation is still the same as in 1998. However, the sand bank is hardly visible, due to the high water level in the river at the moment that the satellite image was taken.

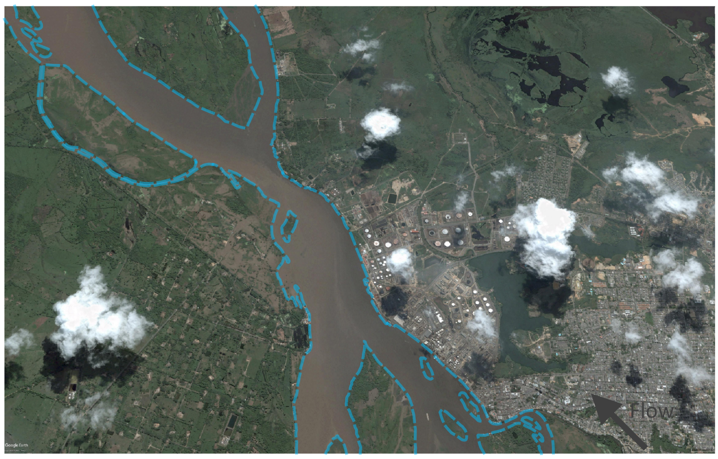


Figure 6.6: Satellite picture of the position of the Magdalena River around Barrancabermeja in 2002, adapted from (Google Earth, 2017)

Just as in 1981, the computed M-values for b=4 and b=5 both lie within the range of 0.5 to 1.5, and therefore validate the presence of one bar in this river section. The input and output values can be found in Tables 6.6 and 6.7.

Table 6.6: Input parameters for the bar mode computations for the year 2002

Year	i [-]	Q_{bf} [m^3/s]	B [m]	h_0 [m]	d_{50} [μm]	Chézy [$m^{1/2}/s$]	B/h_0 [-]	Observed Bar Mode
2002	$3.37 \cdot 10^{-4}$	5103.9	600	3.9	350	38.6	153.8	1

Table 6.7: Computed and observed bar mode as well as planform styles for 2002

Year	computed M b=4	computed M b=5	Observed Bar Mode	Predicted planform	Observed planform
2002	0.9	1.27	1	alternate bars	alternate bars

6.2.4. Situation in 2013

In Figure 6.7 below, the position of the Magdalena River around Barrancabermeja in 2013 is depicted. A sand bar can be observed at the right side of the channel, in front of the city and the refineries of Ecopatrol. In the middle of the sand bar an artificial island of dredged material is present. This material originates from the former thalweg on the right side of the channel, that is currently dredged by local authorities. The shift of the alternate bar from the left to the right side of the channel is interesting, as the bar was considered stable over the period from 1981 to 2002.

Figure 6.7: Satellite picture of the position of the Magdalena River around Barrancabermeja in 2013, adapted from (Google Earth, 2017)

The outcomes of the bar mode computations for the year of 2013 (see Tables 6.8 and 6.9), are similar to the results of 1998. For a value of b=4 the M-value lies within the range of 0.5 to 1.5, whereas for b=5, the value lies outside this range. However, the results are still considered to represent the actual situation in the river. The only difference is the location of the bar.

Table 6.8: Input parameters for the bar mode computations for the year 2013

Year	i [-]	Q_{bf} [m^3/s]	B [m]	h_0 [m]	d_{50} [μm]	Chézy [$m^{1/2}/s$]	B/h_0 [-]	Observed Bar Mode
2013	$3.37 \cdot 10^{-4}$	5244.9	722	3.9	350	38.6	185.1	1

Table 6.9: Computed and observed bar mode as well as planform styles for 2013

Year	computed M b=4	computed M b=5	Observed Bar Mode	Predicted planform	Observed planform
2013	1.17	1.66	1	alternate bars	alternate bars

6.2.5. Situation in 2017

In Figure 6.7 below, the position of the Magdalena River around Barrancabermeja in 2017 is depicted. The sand bank is still located on the right side of the channel. Although it is hardly visible in this picture, the bar was visually observed during the field trip to Barrancabermeja.

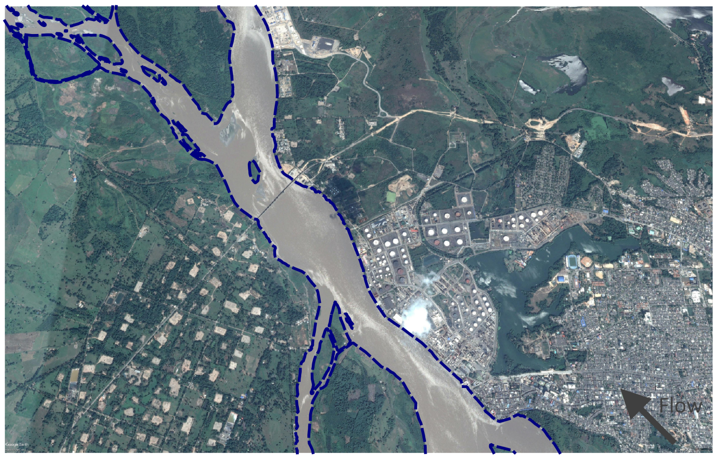


Figure 6.8: Satellite picture of the position of the Magdalena River around Barrancabermeja in 2017, adapted from (Google Earth, 2017)

The outcomes of the bar mode computations (see Tables 6.10 and 6.11) are similar to the results of the previous year and could also be explained by the same phenomenon. The bar is still located at the right side of the river, probably indicating a stable position of the bar.

Table 6.10: Input parameters for the bar mode computations for the year 2017

Year	i [-]	Q_{bf} [m^3/s]	B [m]	h_0 [m]	d_{50} [μm]	Chézy [$m^{1/2}/s$]	B/h_0 [-]	Observed Bar Mode
2017	$3.37 \cdot 10^{-4}$	5162.3	696	3.9	350	38.6	178.5	1

Table 6.11: Computed and observed bar mode as well as planform styles for 2017

Year	computed M b=4	computed M b=5	Observed Bar Mode	Predicted planform	Observed planform
2017	1.12	1.58	1	alternate bars	alternate bars

6.3. Conclusion

The results from the bar mode analysis show that for the examined river section, and given the local river conditions, the river contains one alternate bar over the years. Although the river conditions changed slightly between the examined years, the bar mode value always lies within a range that corresponds to one alternate bar.

Due to the fact that the bar has shifted from the left to the right bank of the channel between 2002 and 2013, satellite pictures are used to monitor this process and to detect in which year the changes started to appear. The latter is interesting, because the construction of the bridge took place within this timespan.

In Figures 6.9a to 6.9h, the spatial changes of the Magdalena River around Barrancabermeja are displayed with satellite pictures from Google Earth (2017) for the years 2005 to 2012. Between 2007 and 2009 the changing behaviour of the bar is clearly noticeable. In 2008 the alternate bar at the left side of the river already decreased in size for more than 60% and in the satellite picture of 2009 the bar on the left river bank completely disappeared and is now located at the right bank of the river, the only other possible position. This is due to the fact that under the given circumstances, the river will maintain the alternate bar, as central bars are not able to form. Central bars require an M-value of at least two.

It can also be noticed that the sand bar in the picture of 2007 is larger in size than the sand bar in the picture of 2006, although in those years the construction of the bridge was already complete. This can be explained by the fact that the water level of the river was rather low at the moment the picture was taken. In the satellite picture of 2012 the artificial island of dredged material can be observed. All the dredged material from the thalweg is being dumped just upstream of the dredging area, because it is not allowed to take sediment out of the river system.

In short, the satellite pictures in Figures 6.9a to 6.9h prove that the sand bar on the left side of the river started to disappear after the construction of the bridge, and shifted to the right bank of the river, where originally the thalweg was located. It is plausible that the construction of the bridge has induced changes in flow conditions in such way that the original alternate bar started to erode and eventually totally disappeared. The creation of the alternate bar on the right side of the river that followed, is the reason of sedimentation in this part. Therefore, it is highly possible that the construction of the bridge forms the main reason of the shift of the thalweg.

How the bridge has exactly influenced the flow patterns river will be investigated in Part 2 of this report. One possibility is that scour around the bridge piers attracts the flow in such way, that it induced the erosion of the alternate bar.

(a) 2005 (b) 2006

(c) 2007 (d) 2008

(e) 2009 (f) 2010

(g) 2011 (h) 2012

Figure 6.9: Spatial changes in the Magdalena River around the city of Barrancabermeja from 2005 to 2012, showing the shift of the alternate bar, adapted from Google Earth (2017).

II

Scour assessment

The influence of scour around the piers of the Yondó brigde is assessed in this part. First, an approximation of the dimensions of the scour holes is made based on the method of Melville and Coleman (2000). After that, these dimensions are incorporated in a Delft3D-model that represents the hydrodynamic and morphodynamic situation in the river reach around Barrancabermeja.

7 Approach for bridge scour assessment

To be able to comprehend the influence of bridge pier scour holes on the river on a macro-scale, a strategy as explained by (Mosselman and Sloff, 2002) is used. Mosselman and Sloff argues that a transition of the thalweg can be initiated by scour around bridge piers. The hypothesis is that a new path with less resistance is created around the bridge piers, which influences the dynamics of the river on a larger scale, see Figure 7.1. In this situation, scour holes around bridge piers grow when more of the flow is attracted. Because of this increasing flow, additional erosion between the scour holes takes place and results eventually in a fully developed wide channel around and in between the bridge piers. As a result of the extra flow surface, flow velocities decrease in the original channel and accretion occurs. In the end, without any dredging, the original channel on the right side of the river will disappear.

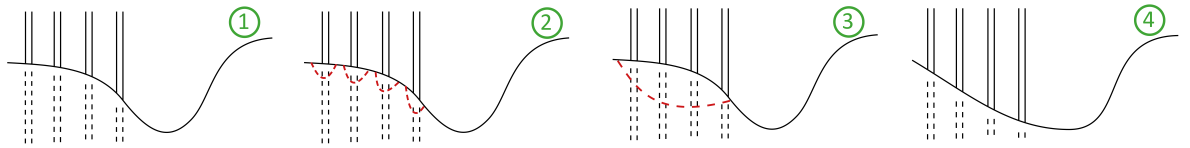


Figure 7.1: Four steps that depict the hypothesis of the creation of a new path around the bridge piers in the Magdalena River

There is no easy way to evaluate if and how this process takes place around the Yondó bridge in Barrancabermeja. Nevertheless, Delft3D software can be used to make a model of the river and its evaluation over time. However, Delft3D is not able to cope with the specific processes regarding the emergence and evaluation of scour holes. It analyses the river developments on a full-river scale. Scour holes, on the other hand, develop on a much smaller order of magnitude. But despite this discrepancy, there is a way to implement scour around bridge piers in Delft3D.

Mosselman and Sloff (2002) propose a two-step approach, where a near-field and a far-field model can be distinguished. These two models interact with each other as depicted in Figure 7.2 and it work as follows: first, the dimensions of the scour holes around the bridge piers are estimated by the method of Melville and Coleman (2000) (near-field model), that will be described in more detail in Chapter 8. After that, these dimensions can be incorporated in the Delft3D-model (far-field model), representing the current situation in the river. In the ideal situation, a bed profile indicating the status of the river before and after the construction of the bridge should be used for this analysis. Unfortunately, only a post-construction river bed profile is available, which results in a slightly different outcome, as the effect of the scour holes on the null situation (without the Yondó Bridge) cannot be evaluated.

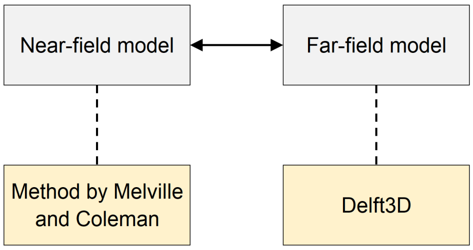


Figure 7.2: Connection between the near-field and the far-field model

By performing simulations with and without the scour holes around the bridge piers implemented in the model, the net effect of these holes can be assessed. This is done for both the average flow velocities in the river reach, predominantly around the bridge, and the cumulative sediment transport in the area. These features provide a good indication of the hydrodynamic and morphodynamic conditions in the river and for that reason they are suitable for this analysis.

The different aspects of the near-field and far-field model are described in the upcoming chapters. Figure 7.3 gives an overview of the way how these chapters are structured. The first chapter provides an extensive description of the estimation of the dimensions of the scour holes by the method of Melville and Coleman (2000). After that, the specific details of the set-up of the Delft3D-model are presented and the last chapter elaborates on the model simulations, the corresponding results and conclusions that can be drawn from the simulations.

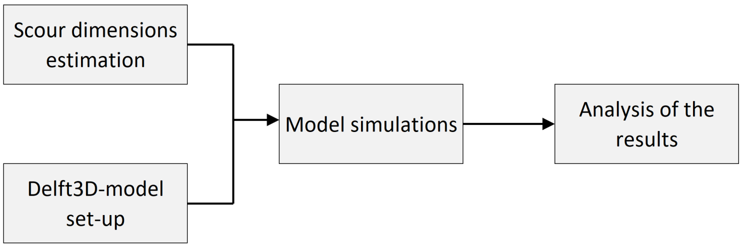


Figure 7.3: Structure of the chapters that are part of the scour assessment

8
Scour holes around bridge piers

8.1. Approach

Different strategies can be used to gain insight in a scour development process. The easiest and most reliable way to do this is by measuring scour dimensions continuously after the placement of the bridge piers. But since the piers have already been placed and these measurements have not been carried out in 2004, a different approach is necessary.

Next to executing straightforward measurements, scour dimensions can also be derived from general data on the Magdalena River. But this is not a straightforward task, as scour around a bridge pier is a very complex process to understand. Although a lot of research has been conducted into the field of scour, it is still not very well-understood by experts. Nonetheless, three main approaches that can be used to estimate scour development exist:

- Using numerical models;
- Using physical models;
- Using empirical relations.

Contrary to the field of large-scale river dynamics, in which the use of numerical models is widely spread, numerical modelling is still hard to apply in practice for estimating scour development. Therefore, in large-scale projects in which scour plays a role, physical models are used to obtain information about the relevant scour processes. For smaller or more budget constrained projects, a physical model is often not an option. Empirical relations provide in this case the ability to learn more about the scour processes that are likely to occur. Since during this project the time and resources to draw up a physical model are not available, empirical relations have to be used to gain more knowledge about the scour taking place around piers of the Yondó Bridge.

The required information that needs to follow from this empirical approach is used as an input to the Delft3D model. With information on the river, the sediment and the piers, the required scour dimensions can be estimated. Normative scour dimensions are determined and used in the Delft3D model. In the following sections, the scour process is explained and the method that is used to determine the scour dimensions is introduced and clarified. Subsequently, the relevant input data for this method are provided and the corresponding scour hole dimensions are presented.

8.2. The scour process

The development of a scour hole around a bridge pier is a complicated process that is influenced by countless factors. Immediately after a pier is placed on a river bed, the scour process starts and the holes develop rapidly. In most cases, scour has to be controlled because of foundation undermining risks. When the sediment that supports a structure's foundation is washed away, there is nothing left to support the structure. Therefore, scour mitigation is often applied.

Scour development is mainly driven by three processes: down flow as a result of flow deceleration in front of the pier, a horseshoe vortex in the scour hole and wake vortices behind the pier. The first two are mainly responsible for the depth of the hole.

8.3. Method to determine scour dimensions

The situation around the Yondó Bridge is an example of a reasonably complicated case in the field of scour development. Various factors such as varying water levels, exposed pier foundations and non-uniform pier shapes, shown in Figure 8.1, significantly complicate the situation. Therefore, no off-the-shelf, directly applicable relation to this problem is available. To include all the important factors in the estimation, one of the more elaborate relations should be used. The methods that are used to estimate the scour hole dimensions are introduced and described in Appendix H.

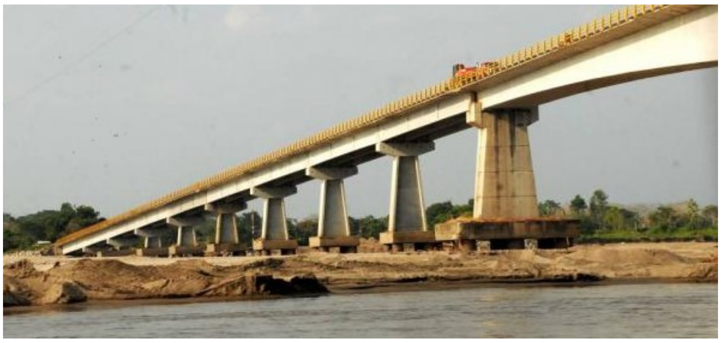


Figure 8.1: Yondó Bridge during low discharge (Suárez Salazar, 2015)

8.4. Determination of scour dimensions

In this section, the method described Appendix H will be applied on the piers of the Yondó Bridge. Since all piers deal with different dimensions and river flow characteristics, the scour dimensions have to be determined for each pier individual. To make the method explained in Appendix H easily applicable to several conditions, a spreadsheet has been composed in which the variables that determine the scour dimensions can be filled in. The output of the spreadsheet is the depth and the width of a scour hole under input conditions. The input of the spreadsheet consists of the following variables:

- Water depth;
- Flow angle of attack;
- Flow velocity;
- Pier dimensions.

8.4.1. Water depth

The water depth is an important variable in the development of scour holes. It influences the scour depth in case of wide or intermediate wide bridge piers. As explained in Section H.2.3, the scour depth around narrow piers does not depend on water depth, but rather just on bridge pier width. However, in each possible case, a larger water depth is always normative. Scour holes develop very quickly, so high water levels registered in the recent past can correspond with the current scour depth. However, if floods do not occur for a while, the depth of the scour hole will reduce again over time.

To find the normative water depth, two datasets are used. First, historical water levels in Barrancabermeja measured by IDEAM, the Colombian Institute of Hydrology, Meteorology and Environmental Studies and second, the current bed elevation around the bridge that has been measured during the field trip. The normative water depths can be derived when the data from both measurements are combined. The considerations about what data to use from which datasets are explained below.

IDEAM water level measurements

The IDEAM data provide hourly water level measurements in Barrancabermeja from 2007 to 2017 (IDEAM, 2017). These data are shown in Figure 8.2. From the data, a water level that relates as best as possible to the normative scour size can be derived. There has been chosen to use the weighted average value of the dataset as the normative water level. This choice has been made because this is the water level that results in a scour depth that is most representative as an input to the Delft3D model. When there would have been chosen for the peak water level from the previous year, or from the whole dataset, the maximum scour depth that has occurred during this period would be found. However, as explained before, scour holes will fill up again due to sediment transport and return to equilibrium conditions over time after a flood has ended. Therefore, there has been decided to use the weighted average water level. This water level is a good representation of the dataset and will result in an 'average' scour depth, which is desirable as an input for the Delft3D model. To determine the weighted average water level, the water levels from the dataset are subdivided into 20 smaller sets of water levels. The values are ranked by magnitude and sorted into 20 sets. The first set for example contains the 5% lowest water levels. With the median values of these 20 sets, the weighted average water level can be determined. The normative water level that is found is equal to 2.87 meters.

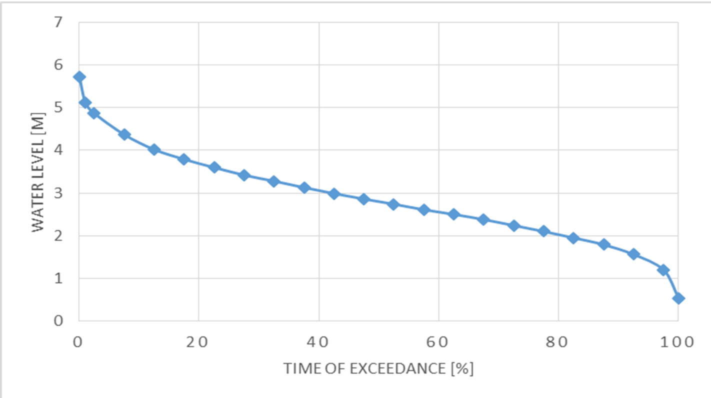


Figure 8.2: Water levels in Barrancabermeja from 2007 to 2017, adapted from IDEAM (2017)

Field trip bed elevation measurements

During the field trip to Barrancabermeja, a large amount of measurements have been taken. Only a small part of these measurements can be used to determine the flow depth of the river around the bridge. In Figure 8.3, the cross sections that have been measured around the bridge are shown.

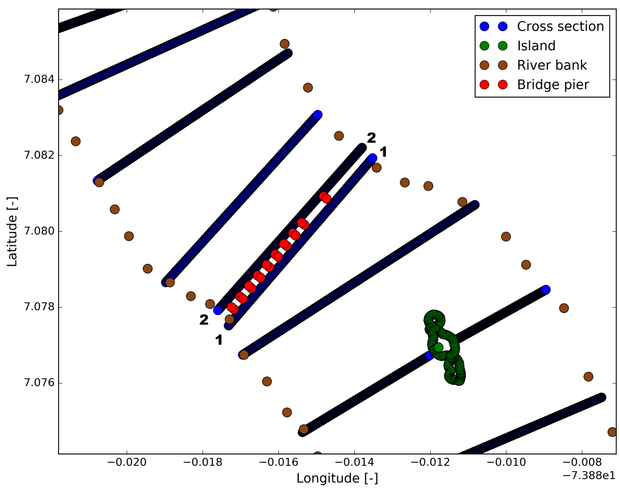
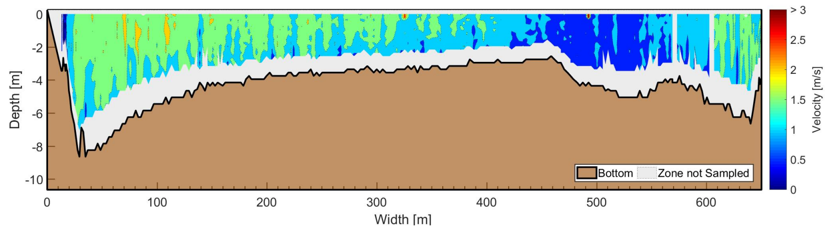
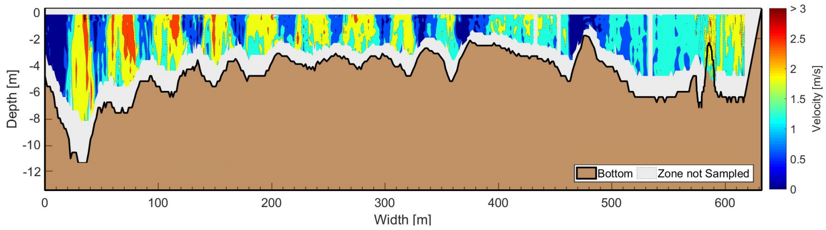


Figure 8.3: Overview of the measured points around the bridge

The two cross sections that have been measured at about the right location are marked with 1 and 2. The order of magnitude of the width of the scour hole is in the range of several tens of meters. Cross sections 1 and 2 are both measured within this distance from the bridge piers. Therefore, the scour holes around the bridge piers should be visible on the measurements. This is not desirable because the required water depth is the water depth without scour hole influence. Despite its vicinity to the bridge piers, the measurements do not show scour influence in cross section 1 (Figures 8.4a and 8.4b). Therefore, these measurements can be used to determine the scour depth. At the time of the measurements, the water level in de Magdalena River in Barrancabermeja was 3.20 meter (IDEAM, 2017).



(a)

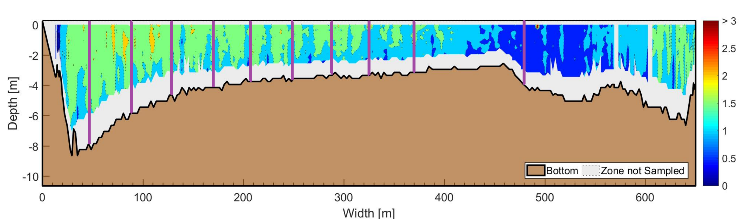


(b)

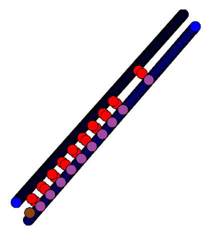
Figure 8.4: Depth and velocity measurement just upstream (a) and just downstream (b) the bridge

Normative flow depth determination

The locations on cross section 1 that correspond with the locations of the bridge piers are derived from Figure 8.3. In Figures 8.5a and 8.5b, the locations in the cross section 1 corresponding to the locations of the piles are shown. From this figure, the depth of the water around the bridge during the measurement can be determined. The values found are shown in Table 8.1. With both the normative water level and the depth for a certain water level being known, the normative water depth per pier can be found. The normative water depths per pier are also presented in Table 8.1.



(a)



(b)

Figure 8.5: (a): Representative cross section of the river with with in purple the location of the piers. (b): Real location of the piers (in red) compared to the assumed location of the piers in the cross section (purple).

Table 8.1: Normative water depth for each bridge pier. The piers are numbered in consecutive order, starting with the pier closest to the Yondó bank. The naming of the piers is further explained in Appendix I.

Normative water level	2.87	[m]
Water level during measurement	3.20	[m]
Correction to measurement	-0.33	[m]
Pier number	**Measured depth [m]**	**Normative depth [m]**
Pier 1	7.70	7.37
Pier 2	5.74	5.41
Pier 3	4.49	4.16
Pier 4	3.96	3.63
Pier 5	3.62	3.29
Pier 6	3.50	3.17
Pier 7	3.14	2.81
Pier 8	3.17	2.84
Pier 9	2.98	2.65
Pier 10	3.72	3.39

8.4.2. Flow angle of attack

The flow angle of attack is determined from a Delft3D run described in Section 9.4. In this run, sediment and bridge piers are not yet taken into consideration. Therefore, it provides a set of vectors that indicate flow directions in the river. Since the required angle of attack is not influenced by the bridge piles, the angles that the Delft3D run provides can be used as an input here. The flow directions in relation to the Yondó Bridge are shown in Figure 8.6. In Table 8.2, these values are presented.

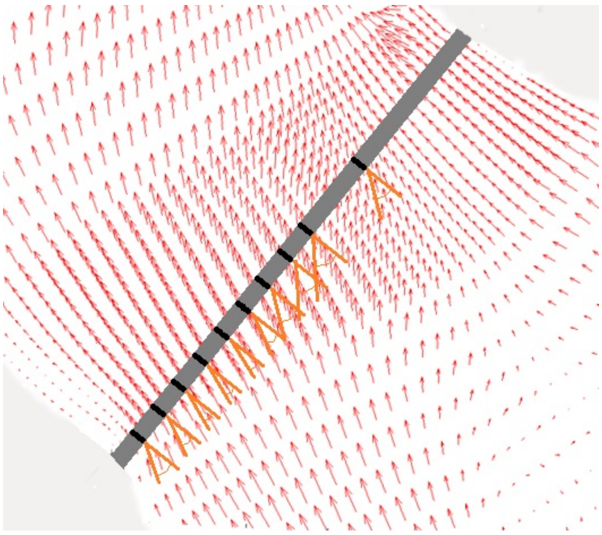


Figure 8.6: Flow directions around the Yondó Bridge are shown with the red errors. The grey beam represents the brigde, with the piers shown in black. The angle of attack per pier is presented in orange.

Table 8.2: Flow angle of attack per pier. The piers are numbered in consecutive order, starting from the Yondó side (bottom left in Figure 8.6).

Pier number	**Angle of attack** [°]
Pier 1	32
Pier 2	27
Pier 3	22
Pier 4	20
Pier 5	20
Pier 6	28
Pier 7	38
Pier 8	47
Pier 9	50
Pier 10	37

8.4.3. Flow velocity

The desired flow velocity is the one at the location of the bridge piers in case of normative water depth, without influence of the piers themselves. This can be found from two available data sources. First, the velocity over the cross section is extracted from Figure 8.5. Second, these velocities are converted to the flow velocities that occur under normative water level conditions.

The flow velocities that have been measured, and are shown in Figure 8.5, need to be converted to a workable value. This is achieved by averaging the flow velocities of the vertical columns that represent the locations of the bridge piers. The flow velocities found are presented in Table 8.4.

The values in the table correspond to the water level at the time of the measurements, not to the normative water level. A correction is be made using the discharges that correspond to the water level during the measurements and the normative water level. The method introduced in Section 6.1.2 is used for this. The water levels with their corresponding discharges are presented in Table 8.3.

Table 8.3: Water levels and discharges during normative and measuring conditions

	Water level [m]	**Discharge** [m^3/s]
During measurment	3.20	3599
Normative	2.87	3229

Because of the steep bank slopes, there can be assumed that the width of the river does not change in case of varying discharges in the river. Because of this, the ratio between discharge during the measurement and the normative discharge can be used as a correction factor for the average flow velocities at the location of the piers. This results in the normative flow velocities, which are presented in Table 8.4.

Table 8.4: Equivalent measured average flow velocities and the normative flow velocities, found by applying a correction factor for a different water level during normative conditions, compared to the water level at the time of the measurements.

Pier number	**Measured flow velocity [m/s]**	**Normative flow velocity [m/s]**
Pier 1	1.74	1.56
Pier 2	1.63	1.46
Pier 3	1.59	1.43
Pier 4	1.67	1.50
Pier 5	1.61	1.44
Pier 6	1.40	1.26
Pier 7	1.48	1.33
Pier 8	1.66	1.49
Pier 9	1.59	1.43
Pier 10	0.98	0.88

8.4.4. Pier dimensions

The determination of the bridge pier dimensions is explained in Appendix I. A table that shows these dimensions can be found at the end of the appendix. From the appendix can be extracted as well that the bottom of the pile cap of pier 1 is located at an elevation of 0.5 meter, which is on - 2.37 meters compared to the normative water level. The bottom of the pile cap of pier 2 to 10 is located at 3.0 meters, + 0.13 meter compared to normative water level.

8.4.5. Scour depth per pile

With all the input data for the model present, the spreadsheet (introduced at the beginning of this section) that runs the model is used to obtain the estimated scour dimensions. The normative values of the water depth, the flow angle of attack and the flow velocity per pier are summarized in Table 8.5. When the values form this table together with the pier dimensions, and the pile cap elevation described in the previous section are filled in into the spreadsheet, the scour dimensions shown in Table 8.6 are obtained. These dimensions will be incorporated in the Delft3D model, which will be described in Chapter 9.

There is one complicating factor. Because of the large distance between the bottom of the pile cap and the river bed at pier 1, the exception for case IV piers in which Equation (H.2) is not valid applies (see Section H.2.1). Therefore, engineering judgement is required to find the equivalent pier width. The exposed foundation pile length is 5.00 metres and the exposed pile cap height is 2.37 metres. The average estimate of the equivalent pier width of three future engineers yields a value 2.75 metres. Because of the same reasons, also the method that is used to determine the equivalent pier length in Section H.2.2 is not valid. There has been decided to reduce the conservative value of K_ϑ = 1.51 to a more realistic K_ϑ = 1.25.

Table 8.5: Water depth, angle of attack and flow velocity that is used as input for the scour dimension calculation method described in Appendix H

Pier number	Depth [m]	Angle of attack [°]	Flow velocity [m/s]
Pier 1	7.37	32	1.56
Pier 2	5.41	27	1.46
Pier 3	4.16	22	1.43
Pier 4	3.63	20	1.50
Pier 5	3.29	20	1.44
Pier 6	3.17	28	1.26
Pier 7	2.81	38	1.33
Pier 8	2.84	47	1.49
Pier 9	2.65	50	1.43
Pier 10	3.39	37	0.88

Table 8.6: Scour dimensions that follow from the input data given in Table 8.5. Also the scour case is corresponding scour case is shown.

Pier number	Depth [m]	Width [m]	Case
Pier 1	8.25	35.75	IV
Pier 2	4.47	19.10	V
Pier 3	4.39	18.77	V
Pier 4	4.36	18.64	V
Pier 5	4.36	18.64	V
Pier 6	4.49	19.16	V
Pier 7	4.66	19.82	V
Pier 8	4.80	20.41	V
Pier 9	7.76	33.05	V
Pier 10	7.74	32.95	V

8.5. Scour risks

Next to the possible influence of scour holes on marco-scale river dynamics, scour can cause problems to the structure of the bridge itself as well. A well known consequence of bridge scour is bridge piers being undermined. which is one of the most common causes of bridge failure. This is not a risk for the Yondó Bridge. According to Eduardo Bravo, advisor at the National University of Colombia and concerned with the course of events around the Yondó Bridge, the foundation piles are long enough to guarantee sufficient vertical support of the bridge in every possible situation. But this comprises only the risk of a loss of vertical support. But there are more risks that can endanger the bridge over time. One of these is seismic hazard. Seismic risk in different parts of Colombia is shown in Figure 8.7. The effects of earthquakes combined with scour might not have been fully covered during the design of the bridge.

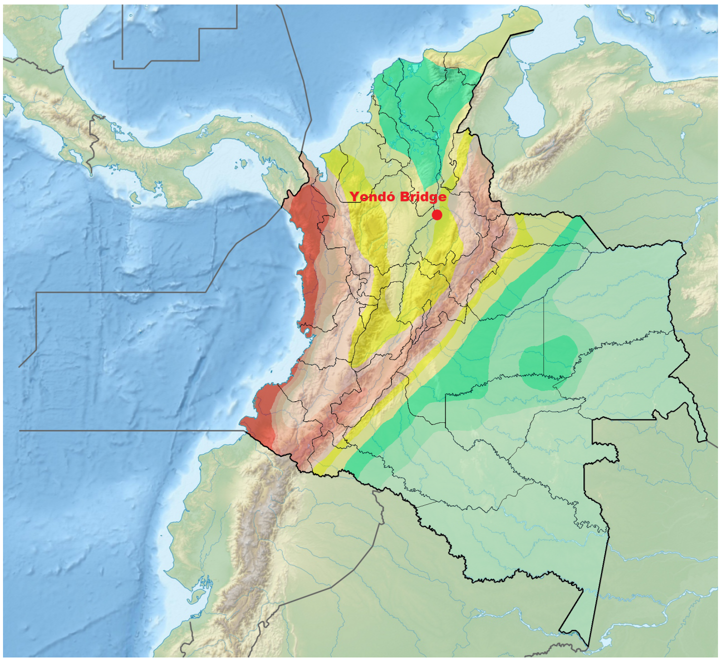


Figure 8.7: Map that shows seismic risks in different parts of Colombia (Ingeominas, 2011). From very high risk (dark red) to low risk (light green).

Earthquakes should always be taken into account when a structure is designed for a region with significant seismic activity. There can be assumed that this has been the case for the Yondó Bridge. However, the situation has significantly changed over the years. Right after the construction of the bridge, the pile cap was located right on the bottom of the river bed. This changed over the years when the pile cap became undermined up to the current situation in which multiple meters of foundation pile are exposed. With Section H.2 can be found that the exposed foundation pile length can even grow to largely over 15 meters due to extreme scour in case of flood conditions. Although this is not a problem in vertically supporting the bridge, it can be very risky when dealing with horizontal loads. The bridge's foundation piles are way less resistant against horizontal loading than the main pillars. Right after completion of the bridge this was not a problem because the foundation piles were horizontally supported by a soil layer. But this support has eroded away, leaving the bridge vulnerable to earthquakes.

With the available information, it is not possible to verify if the risks accompanying the current situation have been taken into account during the design of the bridge. However, there are indications that this is not the case. It is not a commonly desired situation that the foundation piles of the bridge are exposed in the way they are right now. This points to a situation wherein the current state was not taken into account at all. In addition, Edgar Eduardo Muñoz, professor in structural scour at the Pontifical Xavierian University, has expressed his concerns about the current situation. So in the end, there are sufficient reasons to look further into the situation and check whether the expressed concerns are valid.

9 Delft3D-model set-up

This chapter provides a detailed description of the model set-up of the Delft3D-model that is used to assess the influence of the bridge piers on the amount of scour in the river reach around Barrancabermeja. The model is calibrated based on the measurements of the discharge and the water level around the Yondó Bridge obtained during the field trip to Barrancabermeja. This was done by adjusting the Chézy value until the slope of the water level coincided with the measured river slope: $3.37 \cdot 10^{-4}$. Appendix F describes how this value for the slope is determined.

In this chapter, all relevant aspects of the model, necessary for the simulations of the scour holes, are discussed. Section 9.1 presents the grid and the depth profile of the model, whereas Section 9.2 discusses the initial and boundary conditions. The last two sections, Sections 9.3 and 9.4, provide an overview of the monitoring points in the model and the settings of the remaining parameters.

9.1. Grid and depth

The measurements of the bed elevation of the river, obtained in Barrancabermeja during the fieldwork, are used to generate the grid for the model. An extensive description of this generation process can be found in Appendix J and the final product is depicted in Figure 9.1. The grid has 42 cells in M-direction (x-direction) and 61 cells in N-direction (y-direction). The red colours on the side indicate the river banks, the blue part on the top right represents the thalweg and the red spot in the bottom right part shows the island consisting of dredged sand.

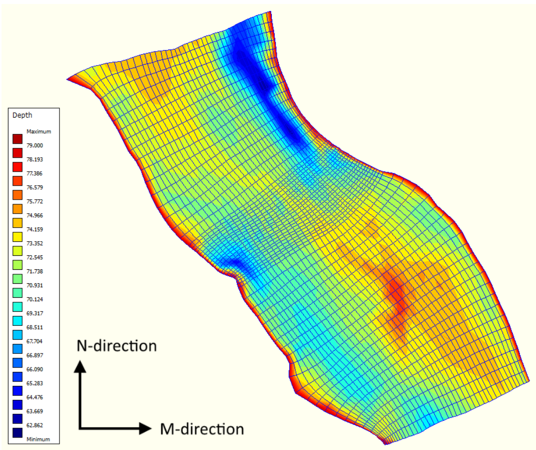


Figure 9.1: Final grid and depth profile that are used during the simulations in Delft3D. The values of the depth have a unit of m above MSL.

The values indicating the bed elevation are multiplied by minus one as Delft3D assigns negative values to the bed elevation and positive values to the water level, see Figure 9.2.

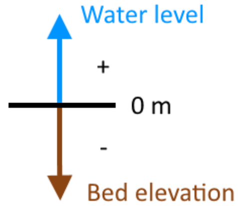
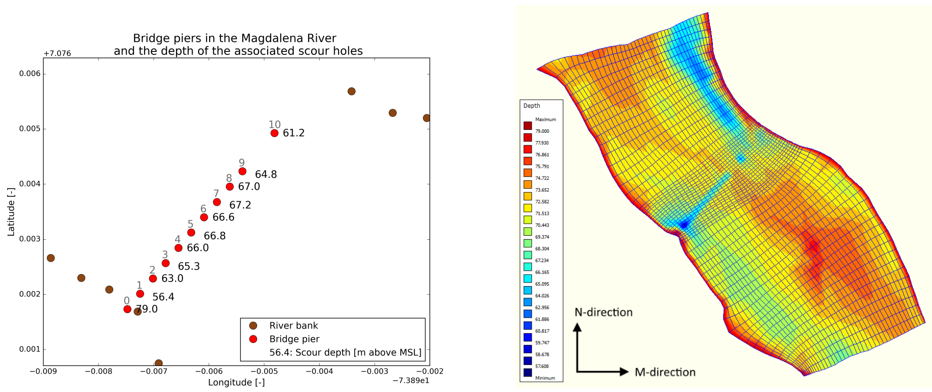


Figure 9.2: Reference frame for the water level and the bed elevation in Delft3D

The scour holes around the bridge piers are included in the Delft3D-model by adapting the river bed profile. These adaptations are based on the estimation of the scour depth around the piers in Chapter 8. The final dimensions of these scour holes can be found in Table 8.6 in Section 8.4.5. Figure 9.3a depicts the location of the bridge piers in the river and the corresponding elevation of the river bed. These points were added to the original bed elevation points and interpolated over the grid cells. This results in the depth profile in Figure 9.3b. The difference with the original profile is the deeper area around the bridge that corresponds to the emerged scour holes, indicated by the blue line.



(a) Bridge piers and associated scour depth (b) Depth profile including scour holes

Figure 9.3: An overview of the bridge piers in the Magdalena River and their associated scour depth (left) and the grid and depth profile including the scour depths (right), both in m above MSL. An overview of the location of the piers can be found in Figure I.1.

9.2. Initial and boundary conditions

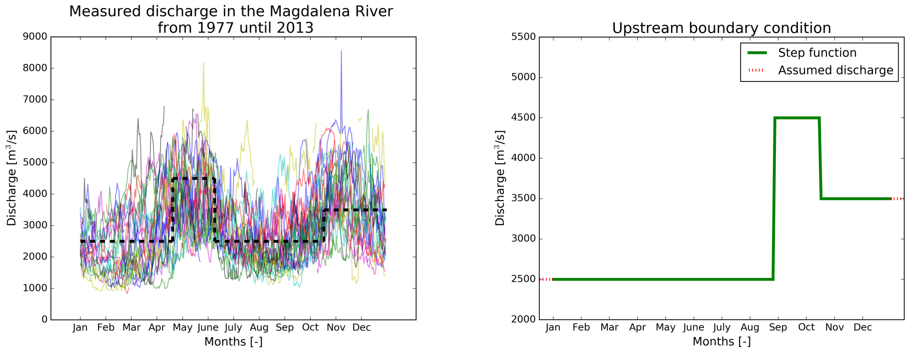
As mentioned before, the model is calibrated on the water level and discharge measurements obtained during the field trip. However, it turned out that the altitude, which determines the water level, was not measured and should be corrected to coincide with the reference level at the office of Cormagdalena. Appendix F contains a comprehensive description of the steps that are taken to correct the water levels. These corrected water levels determine amongst others the initial conditions and a boundary conditions of the model, see below.

Initial conditions

The initial water level is set to the value of the downstream boundary condition and the initial sediment concentration is set to a value of 0 kg/m^3. The initial setting of the secondary flow is also equal to zero, as it is not expected to be present from the beginning. Secondary flow adds the influence of helical flow to the momentum transport (Deltares, 2014). The parameter β_c is used to indicate which percentage of the helical flow is added to the momentum equation. This value is set to 0.5, which is the default value.

Boundary conditions

In general, the boundary conditions of a river consist of a discharge definition upstream and a fixed water level downstream, see the dark blue lines in Figure 9.7. This water level varies with the upstream discharge as prescribed by the dynamics of a river. For the upstream boundary condition, an average is taken from the discharge of the years 1977 until 2013, see Figure 9.4a. The black dotted line, representing the governing discharge over those years, is transformed into a step function that can be imported in Delft3D, see Figure 9.4b. The two time periods with a low discharge (January to May and June to November in Figure 9.4a) are merged to one large period in this boundary condition. In the model the steps between the discharges have a slight gradient to prevent the model from exploding.



(a) Governing discharge

(b) Upstream boundary condition

Figure 9.4: Plot of the discharge in the Magdalena River over the years, indicating the governing discharge (left) and the discharge representing the upstream boundary condition (right)

Based on the upstream discharges, the downstream water level can be determined with the Q,h-relation defined in Section 6.1.2, see Equation (9.1). The measured discharge and reference water level are used to define the water levels for the governing discharges. An overview of these water levels can be found in Table 9.1. These water levels function as a downstream boundary of the Delft3D-model. A visual overview of these levels is depicted in Figure 9.5. In this image, the small gradients of the step function can be identified. These gradients are necessary as Delft3D cannot handle pure step functions (Deltares, 2014).

$$h = \frac{Q - 11.437}{1121.1} \tag{9.1}$$

Table 9.1: Summary of the discharges and the corresponding water levels in the Magdalena River around Barrancabermeja. The numbers in the first line of the table are measured during the field trip.

Discharge [m^3/s]	**Water level [m]**	**Water level [m above MSL]**
3030	2.69	75.065
2500 (low)	2.81	74.595
3500 (medium)	3.70	75.485
4500 (high)	4.59	76.375

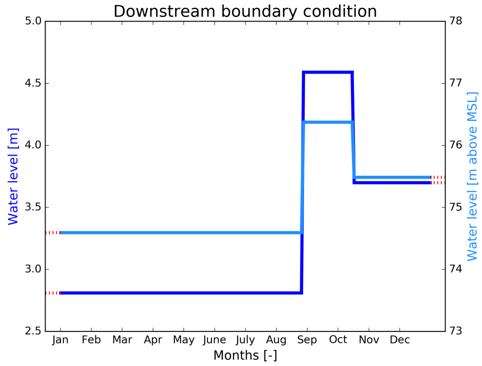


Figure 9.5: Plot of the downstream boundary condition of the model, both in m and m above MSL

For the sake of completeness, the sediment concentration at the upstream and downstream boundary ($c_{\text{sediment,boundary}}$) is defined based on Equations 9.2, 9.3 and 9.4. For every discharge and corresponding flow velocity, a concentration is computed with the following input parameters: the density of the sediment is 1600 kg/m^3 and the width of the river is equal to 700 m. The other parameters were already defined in Chapter 6.

$$c_{\text{sediment,boundary}} = \frac{Q_s \cdot \rho_{\text{sediment}}}{Q} \tag{9.2}$$

$$Q_s = q_s \cdot B \tag{9.3}$$

$$q_s = \frac{1}{12 \cdot C^3 \cdot \Delta^2 \cdot d_{50} \cdot \sqrt{g}} \cdot u^5 \tag{9.4}$$

In which:

	$c_{\text{sediment,boundary}}$	=	sediment concentration at the boundaries	[-]
	Q_s	=	sediment discharge	[m^3/s]
	q_s	=	sediment discharge per running meter	[m^3/s/m]
	ρ_{sediment}	=	sediment density	[kg/m^3]
	B	=	width of the river	[m]

The calculations result in three values for the sediment concentration at the boundary, see Table 9.2. These values differ in order of magnitude due to the fact that the velocity to the power of 5 is present in Equation (9.4). Figure 9.6 depicts the step function that is implemented into Delft3D.

Table 9.2: Sediment concentration at the upstream and downstream boundary condition for the three discharges

Discharge [m^3/s]	**Flow velocity [m/s]**	**Sediment concentration [kg/m^3]**
2500 (low)	1.07	0.41
3500 (medium)	1.50	1.58
4500 (high)	1.93	4.34

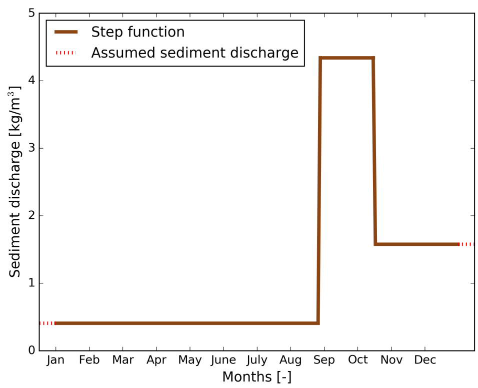


Figure 9.6: Plot of the sediment concentration in the upstream and downstream boundary condition in the Delft3D-model

9.3. Monitoring points

In Delft3D, the user can define observation points and cross sections that can be used to analyse the output of the simulation. In this case the observation points are located around the bridge, in the refined area of the grid, see Figure 9.7. This figure also indicates the cross sections in the refined area and over the entire river reach (light blue lines).

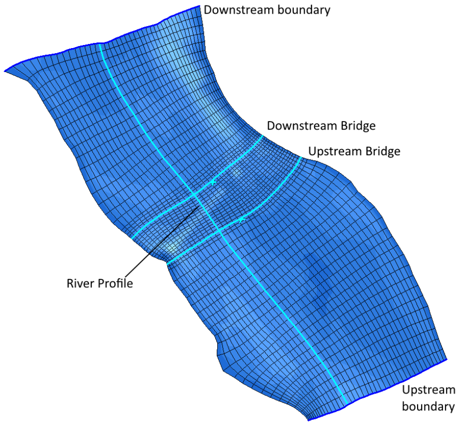


Figure 9.7: Overview of the boundaries, cross sections and observation points in the Delft3D-model

9.4. Other parameter settings

Table 9.3, below, contains the other relevant parameters defined in the Delft3D-model.

Table 9.3: Summary of the relevant parameters defined in the Delft3D-model

Parameter	**Value or method**	**Unit**	**Comment**
Latitude	7.0	°	Google Earth (2017)
Number of layers	1	[-]	default
Orientation	0	°	default
Time step	0.1	min	
Gravity	9.81	m/s^2	default
Water density	1000	kg/m^2	default
Roughness	35	$m^{1/2}/s$	Chézy (uniform), calibrated
Horizontal eddy viscosity	1	m^2/s	default
Horzontal eddy diffusivity	10	m^2/s	default
Specific density	2650	kg/m^3	default
Dry bed density	1600	kg/m^3	default
Median sediment diameter	350	µm	see Appendix G
Sediment transport formula	Engelund and Hansen (1967)		Calibrated transport coefficient
Bed-slope effects	Koch and Flokstra (1980)		Default coefficients
Morphological scale factor	1	[-]	
Initial sediment layer thickness	10	m	
Spin-up interval	720	min	default

Simulation overview

The settings of the Delft3D-model as described above are used to perform nine simulations, see Table 9.4. A distinction can be made between the short simulations and the longer simulations (1 month versus 1 year). The main goal of these shorter simulations is to investigate the effect of the scour holes on the depth averaged velocity in the model, whereas the longer simulations are used to assess the influence on the total sediment transport. The results of these simulations are discussed in Chapter 10.

Table 9.4: Overview of the performed simulations with the Delft3D-model

Run	Scour holes	Discharge	Sediment transport	Hydraulic structures	Simulation time
1	no	low	no	no	1 month
2	no	medium	no	no	1 month
3	no	high	no	no	1 month
4	yes	low	no	no	1 month
5	yes	medium	no	no	1 month
6	yes	high	no	no	1 month
7	yes	high	no	yes	1 month
8	no	Hydrograph, Figure 9.4b	yes	no	1 year
9	yes	Hydrograph, Figure 9.4b	yes	no	1 year
10	yes	Hydrograph, Figure 9.4b	yes	yes	1 year

10

Delft3D-model results

This chapter contains the results of the model simulations in Delft3D, listed in Table 9.4 in Chapter 9. Sections 10.1 and 10.2 present plots of the depth averaged flow velocity and the cumulative erosion and sedimentation in the area around the bridge near Barrancabermeja. In the last section, Section 10.3, conclusions are drawn from these plots and the overall influence of the scour holes around the piers of the Yondó Bridge on the flow conditions in the Magdalena River is assessed.

The plots in Sections 10.1 and 10.2 are created by exporting the data of the simulations in Delft3D in the Tekal-format, which is certain type of text file, into Python. This program is able to depict the data from Delft3D with a higher resolution and more functionalities than the Quickplot-module of Delft3D. However, slight inaccuracies occur in the upper right part of the plot of the river, see Figure 10.1. These inaccuracies (encircled by the dotted red line) are caused by the method that Python uses to interpolate the different points. These inaccuracies are considered to be very small and therefore they do not influence the quality of the model results.

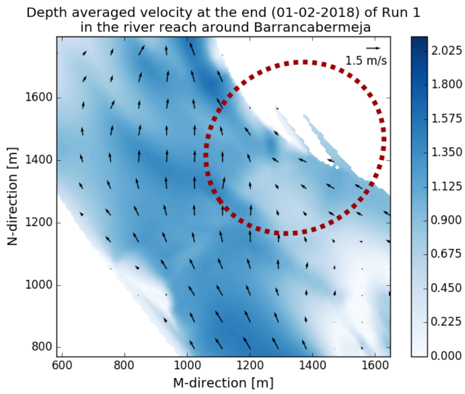


Figure 10.1: Plot that represents the inaccuracies in Python in the interpolation of the data from Delft3D, encircled by the red dotted line

10.1. Depth averaged velocity

In order to assess the depth averaged velocity in the river reach around the Yondó Bridge, six simulations are performed with Delft3D. The specific settings of these simulations can be found in Chapter 9. Figure 10.2 depicts the results of Run 6 and in Appendix K the results of the other simulations can be found.

In general, higher velocities are present upstream of the bridge on the left side of the island, where a deeper part is located. Also in the top left part of the plot, higher velocities are identified. This is the area where the dredging activities take place. The pattern of velocity arrows bends around the island and comes together just before the bridge. Downstream of the bridge, the major part of the velocity vectors remains in line with the orientation of the river.

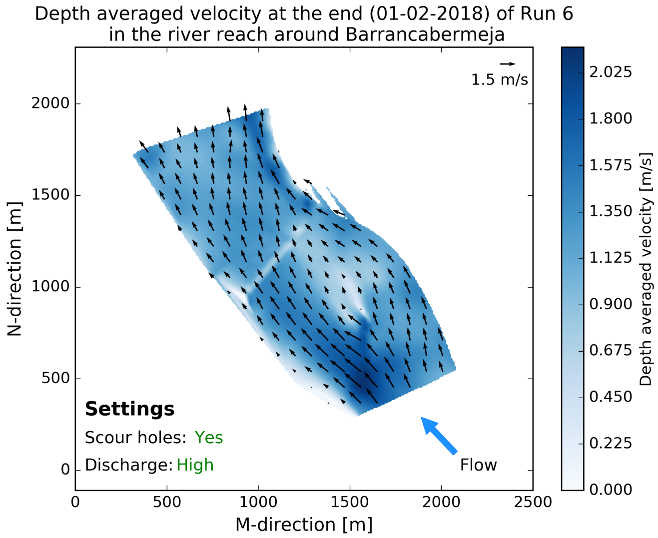


Figure 10.2: Plot of the depth averaged velocity [m/s] in the river reach around the Yondó Bridge (white line in the middle) after Run 6. The blue arrow indicates the flow direction and the black arrow on the top right represents the reference velocity.

Based on a quantitative analysis of the magnitude of seven velocity vectors over the cross section in the vicinity of the bridge, it is possible to assess the changes in behaviour of the depth averaged velocity vectors. The vectors that are analysed are marked in Figure 10.3 by seven coloured dots. Table 10.1 provides an overview of the velocities at the location of these vectors and Figure 10.4 shows a visual interpretation of these values.

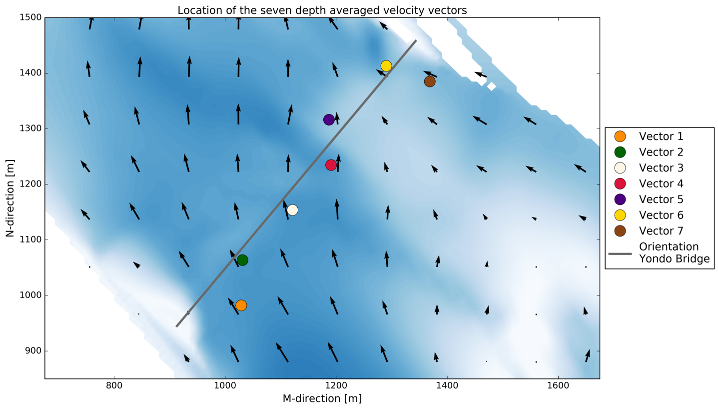


Figure 10.3: Overview of the area around the Yondó Bridge including seven coloured dots indicating the velocity vectors that are quantitatively analysed

Table 10.1: Overview of the magnitudes of the velocity [m/s] of the seven vectors indicated in Figure 10.3, listed for Run 1-6. The grey coloured cells indicate interesting values.

	Velocity [m/s]						
Run	**Vector 1**	**Vector 2**	**Vector 3**	**Vector 4**	**Vector 5**	**Vector 6**	**Vector 7**
1 (low Q, no scour)	1.25	1.21	1.27	1.16	0.78	0.87	0.95
2 (medium Q, no scour)	1.32	1.27	1.26	1.04	0.82	1.10	1.21
3 (high Q, no scour)	1.37	1.35	1.34	1.03	0.87	1.24	1.36
4 (low Q, with scour)	1.32	0.75	0.86	0.97	0.69	0.84	0.91
5 (medium Q, with scour)	1.39	0.79	0.86	0.81	0.74	1.06	1.18
6 (high Q, with scour)	1.43	0.85	0.91	0.79	0.76	1.21	1.33

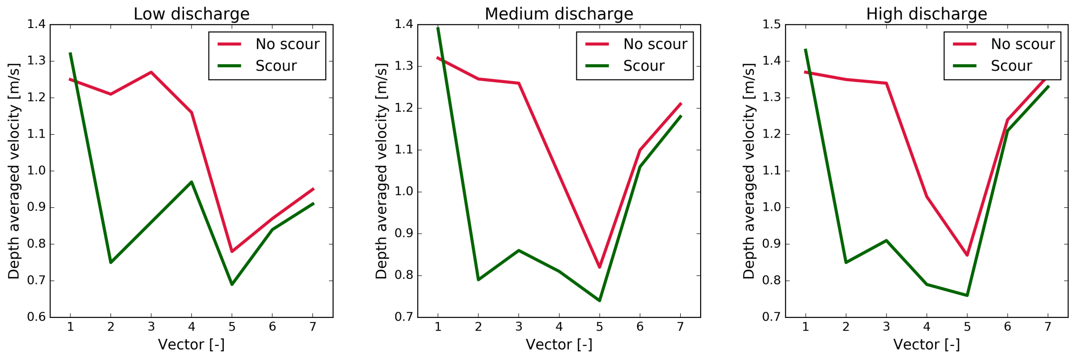


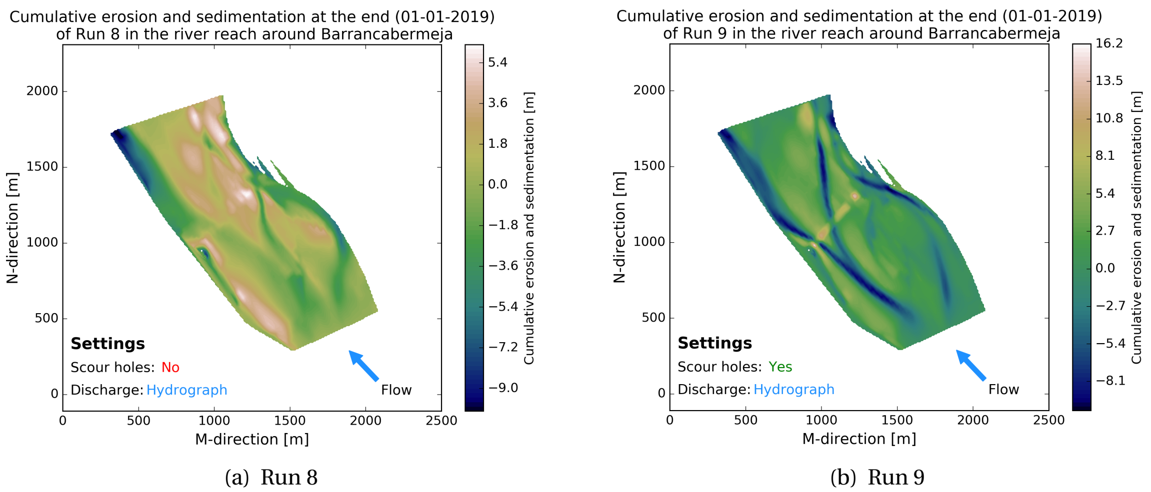
Figure 10.4: Three plots of the depth averaged velocity per vector for the three different types of discharges: low (left), medium (middle) and high (right)

In the table, two columns, containing interesting values, are coloured in dark and light grey. The differences and meaning of these values are discussed below. In the other five columns a regular pattern of the velocities can be observed. This pattern is similar for all vectors in those columns (Vector 1, 2 and 5 to 7): the depth averaged velocity increases as the discharge increases both for a situation with and without the incorporation of the scour holes. In general, the differences per vector are quite small, in the order of magnitude of 0.01 - 0.08 m/s. Except for the two vectors at the river bank on the right side (Vector 6 and 7), where the differences are one order of magnitude larger: 0.14 - 0.27 m/s.

On the contrary, the differences per vector in depth averaged flow velocity for Vector 3 and 4 are completely arbitrary in relation with the varying discharge. For example, at the location of Vector 4, a low discharge results in the highest depth averaged velocity for a situation with and without scour holes. These unexpected patterns could be dedicated to the irregular initial elevation of the river bed, as the bed is composed based on a handful of measurements obtained during the field trip to Barrancabermeja. In Section 10.3 a final conclusion regarding the depth averaged solution is presented.

10.2. Cumulative sediment transport

For the longer simulations of one year, that include the morphodynamics of the river, the cumulative erosion and sedimentation is analysed. These phenomena are depicted in Figure 10.5, and the most interesting patterns are described below. The plots in Figure 10.5 are based on the initial and final values of elevation of the river bed in the Magdalena River. Figures that illustrate these two moments in time can be found in Appendix K.



(a) Run 8

(b) Run 9

Figure 10.5: Plot of the cumulative erosion (negative) and sedimentation (positive) in the river reach around the Yondó Bridge for Run 8 (left) and Run 9 (right)

The plot of the cumulative sediment transport after Run 8 represents the natural response of the system, as no scour holes or structures are involved, see Figure 10.5a. The maximum sedimentation is approximately 5.5 m and the maximum erosion is equal to 9 m. This extreme erosion takes place at the top left part of the river reach around the river bank. The bank erosion mechanism that is by default incorporated in the model is very simplistic and works to a certain extent. It is also sensitive for the grid resolution (Deltares, 2014). Therefore, it is highly possible that this erosion is caused by local inaccuracies in Delft3D. For this reason, it is assumed that this erosive area does not spoil the general pattern of the results.

In Figure 10.5b, the morphodynamic situation after a one year simulation including scour holes is depicted. This plot shows significant differences when compared to Figure 10.5a. The three major differences are listed below:

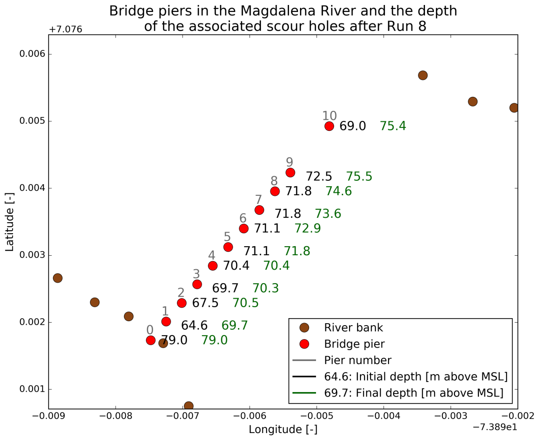
- The order of magnitude of the sedimentation that takes place differs significantly: approximately 16 m versus 5.5 m.
- The scour holes, implemented in the model by adapting the initial value of the bed elevation, are filled during the model simulation. This is indicated in Figure 10.5b by the sand brown dots in the area of the bridge.
- Three deeply eroded 'lines' occur over the river reach, two on the left side and one on the right side. These lines are represented by the blue colours in Figure 10.5b.

These phenomena are dedicated to the difference in initial bed elevation profile, but do not correspond to the expected morphodynamic patterns in the river. This is explained more extensively in Section 10.3.

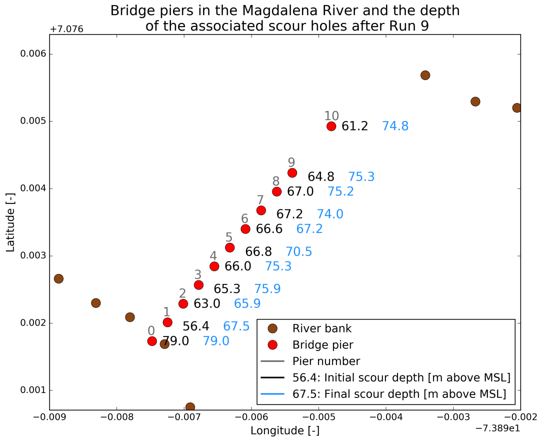
10.3. Conclusion

Purely based on the results of the Delft3D-model simulations, a few conclusions regarding the effect of scour holes on the hydro and morphodynamics can be drawn. Firstly, the amount of flow that is attracted by the bridge piers does not increase or decrease uniformly for a situation with and without scour holes, as indicated in Table 10.1. It was expected that the presence of a scour hole would result in more flow and therefore more erosion, but based on the performed simulations this hypothesis cannot be approved or rejected. More (detailed) simulations of the flow conditions around a scour hole are necessary, see Chapter 16. Because of the limited amount of time, these simulations could not be executed during this research project.

The plots of the cumulative sediment transport and the initial and final bed elevation can be used to generate values for the (scour) depth at the end of the simulations. These values are incorporated in the figures that were presented before in Chapter 9, see Figure 10.6. In general, sedimentation takes places around all bridge piers. However, when Run 9 (with scour holes) is compared to Run 8 (the natural situation) this pattern is different. The values of this comparison are presented in Table 10.2 and it can be observed that around six of the eleven piers erosion takes place, whereas around four piers sedimentation occurs. Therefore, the hypothesis that the presence of a scour hole results in more erosion can be approved. However, more morphodynamic simulations should be performed to obtain quantitative proof for this hypothesis.



(a) Run 8



(b) Run 9

Figure 10.6: Initial and final (scour) depth [m] around the piers of the Yondó Bridge after Run 8 (left) and Run 9 (right). These plots are based on numbers in Table K.1 in Appendix K. An overview of the location of the piers can be found in Figure I.1.

Table 10.2: Absolute and percent differences in bed level between the beginning and the end of Run 9 relative to Run 10. The last column indicates whether increased (+) or decreased (-) sedimentation takes place. The numbers in this table are based on the values of the bed elevation per run, presented in Appendix K.

	Run 9 with respect to Run 8		
Pier number	Absolute difference [m]	Percentage [%]	Increased or decreased sedimentation [+ or -]
0	0.0	0.0	x
1	2.2	3.2	-
2	4.6	6.5	-
3	5.6	8.0	+
4	4.9	7.0	+
5	1.3	1.8	-
6	5.7	7.8	-
7	0.4	0.5	+
8	0.6	0.8	+
9	0.2	0.3	-
10	0.6	0.8	-

III

Synthesis

This part provides more insight in possible measures for the sedimentation problems. Firstly, general types of solutions for river training are listed after which the most suitable options are chosen and worked out in more detail. A Multi-Criteria Analysis is performed in order to objectively judge the solutions, and the solution with the highest final score is eventually modelled in Delft3D to assess its influence on the river behaviour.

11

Alternative solutions

In this chapter, different solutions to the sedimentation problem around Barrancabermeja are introduced and analysed. This process is subdivided into two main steps. Firstly, possible river training measures are introduced. For each alternative, there is shortly evaluated whether the solution would work for the situation in Barrancabermeja, see Section Section 11.1. In case a measure is rated as a viable solution, the measure is analysed into more depth in Section 11.2. The expected effects of each viable measure is discussed and compared to the characteristics of the current situation (null-solution). At the end of this chapter, the costs of the possible solutions are discussed.

11.1. River training measures

In this section, possible river training measures are introduced. There is also evaluated whether or not a measure is applicable to the situation in Barrancabermeja. The following measures are examined:

- Dredging;
- Riparian zone;
- Non-erodible layers;
- Submerged vanes;
- Groynes;
- Longitudinal dams;
- Guide bunds.

Dredging

Dredging is the activity in which sediments or rocks are excavated from the bottom of a water body. Dredging is applied for a large variety of purposes all over the world. The most common types of dredging are capital dredging, maintenance dredging and dredging in order to obtain granular material. Capital dredging is carried out to create water bodies, such as waterways or ports. Also the deepening of existing waterways in order to enable larger vessels to pass falls under capital dredging. Maintenance dredging on the other hand, is a routine activity that is executed continuously in order to maintain the navigability of a waterway. It is usually applied in waterways exposed to heavy sedimentation. In case of a land reclamation or a beach nourishment, dredging can be used as a source of material.

Currently, maintenance dredging takes place in the Magdalena River around Barrancabermeja. This is an effective solution that keeps the river navigable, but there are also some serious disadvantages associated with this method. One of the biggest disadvantages is that dredging is not a durable solution, and is therefore very costly over a longer period. The advantages and disadvantages of dredging as a solution to the sedimentation problem in Barrancaberemeja are discussed in Section 11.2.1.

Riparian zone

A riparian zone is an area covered with vegetation that forms the transition zone between land and river. Riparian zones often develop naturally, but also planted riparian zones exist. Because rivers often contain lots of nutrients, riparian lands are very fertile. This causes plants in this area to grow fast and close to each other. This makes that riparian zones come with some advantages. One of these, and in this case the most relevant one, is the fact that the vegetation in the riparian zone improves resistance against erosion. Riparian zones can also play an interesting role in the preservation of biodiversity. As riparian zones form the interface between land and river, they also connect terrestrial and aquatic ecosystems (Oates, 2000). A riparian zone on itself is not able solve the sedimentation problem around Barrancabermeja, but when combined with other measures, riparian zones can be of added value.

Non-erodible layers

In order to prevent bottom erosion in a river, a non-erodible layer can be constructed on the river bed. Non-erodible layers can be applied in the form of concrete mattresses. Such mattresses consist of concrete blocks that are connected by cables (Figure 11.1). Because of its flexibility, the mattress is able to adjust itself to the contours of its supporting soil layer (Crow and Hansen, 1983).

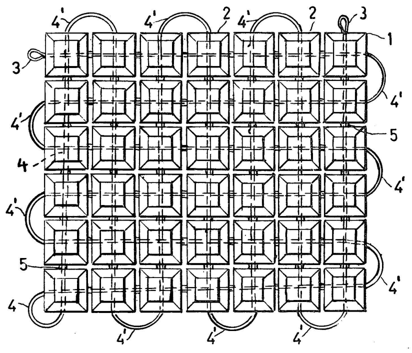


Figure 11.1: Lay-out of a non-erodible layer that consists of concrete blocks, which are connected by a continuous wire (Crow and Hansen, 1983).

Non-erodible layers are usually applied in a river bend. In this case, the placement of a non-erodible layer prevents sediment transport initiated by the spiral flow from the outer to the inner part of the river bend (Figure 11.2). This results in a deeper inner river bend. In Barrancabermeja, the situation is slightly different. The bar analysis presented in Chapter 6 shows that the Magdalena River around Barrancabermeja will always house at least one alternate bar. This bar is currently situated at the right side of the river. If the bar would be artificially moved to the left side of the river, and kept there using a non-erodible layer, the sedimentation issues would probably be solved. However, this would be an enormous and very costly operation. Not only because the mattresses have to be installed, but also because the whole bed topography needs to be artificially changed. Besides, also the flow conditions in the Magdalena impede such a solution. Therefore, non-erodible layers are not a viable solution to the problems observed in Barrancabermeja.

Figure 11.2: Drawing of a cross-sectional river section with a non-erodible layer (Mosselman, 2016)

Submerged vanes

The application of submerged vanes is an easy to apply and cost-effective way to modify the flow pattern in a river. The usage of submerged vanes is a relatively new development within the field of river engineering. A submerged vane is basically a thin vertical plate that is placed on the river bed. It is placed under an angle with the main flow, which directly influences the flow close to the bottom. A schematisation of submerged vanes in a river is shown in Figure 11.3.

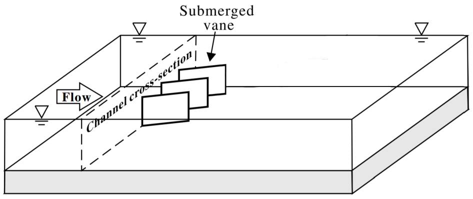


Figure 11.3: Simplified schematisation of submerged vanes on the bottom of a river, adapted from (Ouyang and Lu, 2016)

Vanes do not only affect the flow because of its blockage and roughness, but they also redirect the flow close to the bottom. This causes a secondary circular flow in the river, a mechanism that is similar to the secondary flow in a river bend. This process influences the bed load transfer in a river. The generation of this circular flow is tricky in dynamic rivers, since the flow needs to make an angle of 15 to 20 degrees with the vanes. According to E. Mosselman, because of the dynamic character of the Magdalena River, an angle of attack of 15 to 20 degrees cannot be maintained. The dynamic character of the river also causes the bed level elevation to change over time. This can result in the vanes being undermined or covered in sediment, which makes the vanes ineffective. Because of these two reasons, submerged vanes are not a serious alternative for solving the sedimentation issues around the Yondó Bridge.

Groynes

Groynes are transverse dams that extend from a river bank into a river. An example of groynes applied in practice is shown in Figure 11.4. Groynes protect a river bank against erosion by keeping the main flow at a safe distance from the bank. Between the parallel orientated groynes, low velocity areas are present. These low velocities result in sedimentation. In the part of the river where no groynes are located, increased flow velocities can be observed. The reason for this is the decrease in cross-sectional area, which contracts the flow. The increase in flow velocity deepens the part of the river without groynes (King, 2009), which is favourable to the navigability of a river.

This is exactly what is required to solve the sedimentation problems in Barrancabermeja. The effectiveness of groynes have been proven before in situations with similar problems. Therefore, groynes could be a useful solution. The effects of groynes applied to the situation in Barrancabermeja are studied and explained in Section 11.2.2.

Figure 11.4: Groynes applied in the Rhine near Mainz, Germany (King, 2009)

Longitudinal dams

Longitudinal dams are, like groynes, earthen structures in a river that are placed to influence flow conditions in a river in a favourable way. Longitudinal dams are located parallel to the river flow. This divides the river in a main channel and a bank channel. An example is shown in Figure 11.5. Longitudinal dams keep the main channel of a river in place. An additional advantage of longitudinal dams compared to groynes is the minimal hinder that the flow encounters during high discharge conditions. Due to their parallel orientation, longitudinal dams only marginally reduce the effective cross-sectional area of the river, compared to a significant section of the river that is 'closed off' when groynes are used. This results in lower water levels during floods (Rijkswaterstaat, 2013). Another advantage of longitudinal dams is that they are easy adjustable. This makes a correction to the situation in case of undesirable morphodynamic effects possible (Huthoff, 2011).

Longitudinal dams are a relatively new river training measure. A longitudinal dam is constructed in 2016 in the Waal River in the Netherlands in as a part of a pilot project. The effects of the this dam are still being monitored closely, and therefore, the precise effects of a longitudinal dam are still unknown. A river training measure that is similar to a longitudinal dam, but fits better into the situation in Barrancabermeja, is a guide bund. The application and effects of this measure are explained in the next paragraph.

Figure 11.5: Longitudinal dams in the river Waal in the Netherlands (Rijkswaterstaat, 2015)

Guide bunds

Guide bunds, also known as guide banks, are local longitudinal embankments in a river that are used to guide flow through a certain part of the cross-section. Guide bunds are orientated roughly parallel to the river flow. By choosing their location and orientation, the part of the total discharge that is directed through the selected cross-section can be determined. The heads of the guide bunds play an important role in this determination. Their size and orientation regulates the amount of water that flows through the guide bunds. The idea is that the amount of water through the guide bunds increases after their implementation. Because of this increase, flow velocities increase as well, which results in a deepening of the channel. This is exactly what is required to solve the sedimentation problems beneath the main span of the Yondó Bridge. The effects of guide bunds being applied to the situation in Barrancabermeja are explained in Section 11.2.3. A simplified drawing of a set of guide bunds is shown in Figure 11.6, which also indicates the different parts of the structure, such as the shank and the head.

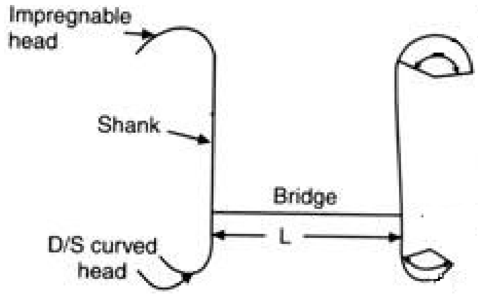


Figure 11.6: Simplified example of a set of guide bunds. Adapted from Sen (2017).

11.2. Possible solutions

In the previous section, several possible river training measures have been introduced. Their effectiveness when applied tot the situation in Barrancabermeja has been shortly evaluated as well. This has yielded two possible alternatives to the current dredging solution (null-solution): the construction of groynes and the construction of guide bunds. This section explains how these solutions can be applied to the situation in Barrancabermeja and what the consequences of this implementation would be. In Figure 11.7, an overview of the subjects that are discussed is shown. The costs of the possible solutions are compared in Section 11.3.

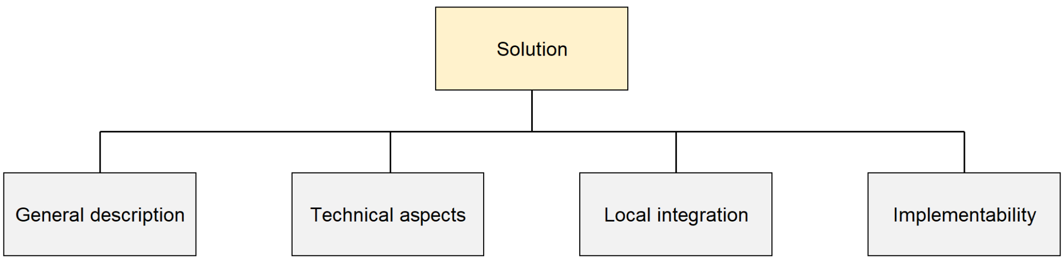


Figure 11.7: Overview of discussed subjects in description of alternatives

11.2.1. Null-solution

The idea of a null-solution is that a situation is analysed in which no changes to the current state are made. At the moment, dredging is used to keep the Magdalena River navigable around Barrancabermeja. According to permits that are provided by ANLA and CAS (see Section 2.2.1), dredged sediment has to be returned to the river at a location upstream of the Bridge. This prevents the river from being disrupted, but it also restricts the durability of the dredging solution.

Since dredging does not take away the origin of the problem, but repairs the consequences instead, dredging is never a durable solution. This is worsened by the dumping policy explained in the previous paragraph. Since the dredged material has to be dumped right upstream of the bridge again, it can quickly return to its previous place, where it needs to be removed again.

11.2.2. Groynes

As explained in Section 11.1, groynes can be used to deepen certain parts of a river. The part of the river that needs to be deepened in the situation in Barrancabermeja is located close to the right bank. The bar mode analysis presented in Chapter 6 has provided strong arguments for the theory that sedimentation underneath the Yondó Bridge is caused by a shift of the alternate bar from the right to the left side of the river. Groynes can be used to reverse this shift.

Groynes can contribute to this change in two ways: by blocking the current thalweg at the left side of the river and by trapping sediment between the groynes. An approach that uses groynes on only one side should be sufficient to deal with the existing problems. The left bank is in this case the most attractive place for groynes. In the first place because this section of the river is not used for shipping, and in the second place because the current thalweg can be blocked by groynes on the left side of the river. As groynes increase flow velocities, the right bank should be protected.

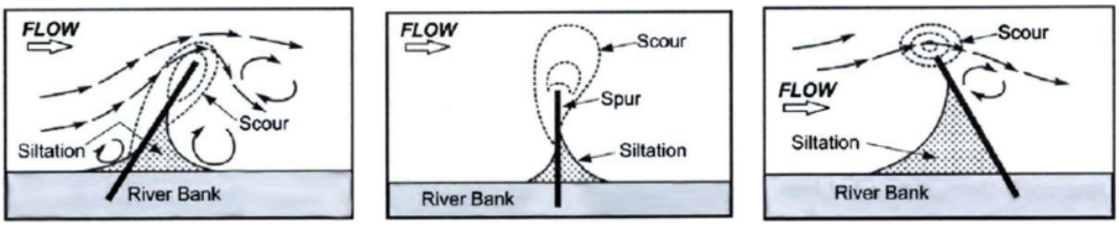
There are three different types of groynes that can be used:

- Attracting groynes;
- Deflecting groynes;
- Repelling groynes.

The first type of groyne, the **attracting groyne**, points downstream into the river. This has as main characteristic that the current is attracted to the bank. Sedimentation can mainly be expected in the area behind the groyne. The sizes of the scour holes that form around the heads of the groynes are limited (King, 2009). A schematisation of an attracting groyne is shown in Figure 11.8a.

Deflecting groynes are located perpendicular to the main river flow and tend to keep the flow away from the bank without changing its direction. Sedimentation occurs on both sides of the deflecting groynes and scour hole dimensions around the heads of the groynes are moderate (King, 2009). An impression of a deflecting groyne is shown in Figure 11.8b.

The **repelling groynes**, that point upstream into the river, deflects currents from the bank. Strong currents can occur around the heads of repelling groynes, resulting in large scour holes. In order to resist these currents, the heads of the groynes need to be reinforced with material that can resist larger flow velocities. A relatively calm area is created upstream of the groyne, in which suspended sediment load is being deposited (King, 2009). This can be observed in Figure 11.8c.



(a) Attracting groyne (b) Deflecting groyne (c) Repelling groyne

Figure 11.8: Three types of groynes, according to their function, adapted from Kashyap (2010)

After comparing the advantages and disadvantages of the different groyne types, there can be concluded that deflecting groynes suit the situation in Barrancabermeja the best. Deflecting groynes block the part of the river that needs to be blocked, trap sediment and the accompanying scour holes are manageable in size. Attracting groynes concentrate the flow to a part of the river in which it is not desired. Repelling groynes, on the other hand, come with large scour holes. This is troublesome because the river should be as shallow as possible in the parts close to the left bank of the river. Therefore, there has been chosen for the balanced option using deflecting groynes. In Figure 11.9, a possible design is presented. This drawing only shows a conceptual design and is therefore not to scale. More research is needed to find an optimised design.

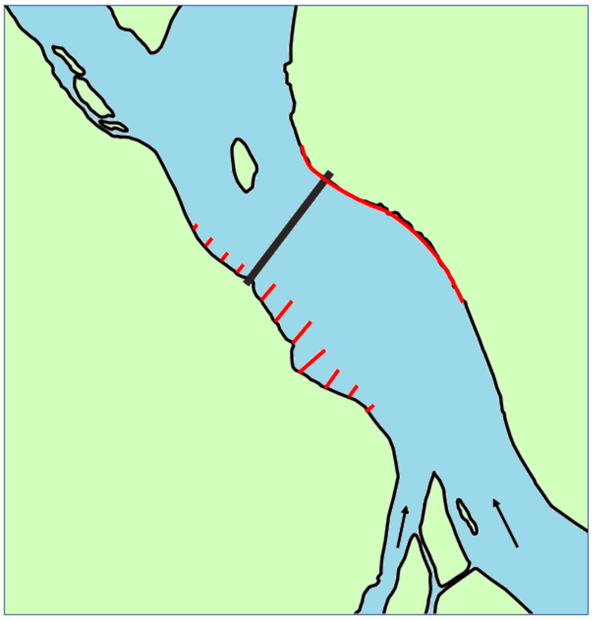


Figure 11.9: Conceptual design of a solution using groynes (not to scale)

Technical aspects
Groynes are, if designed well, an effective measure to maintain minimum required water depths. This minimum depth should be in place at all time. Groynes are situated on the side of the river, outside of the navigation channel, and therefore do not hinder shipping. Scour around groyne heads will be kept acceptable by the design of the groynes that is used. The groynes will significantly influence the river characteristics both upstream and downstream of the area where they are placed. Besides, groynes have a negative influence in flood risk. Since they block a considerable part of the cross-section, higher water levels can be expected in the river.

Local integration
Groynes can be integrated quite well into in the existing situation. No surrounding lands have to be permanently used for this solution. However, there might be hinder in the surrounding areas during the construction works, mainly because of temporary storage of construction material and equipment. Groynes can also not be considered to be a well-looking solution because of its unnatural appearance. Local navigation and activities of fishermen should not be hindered be groynes. Groynes do also not negatively influence the biodiversity in the region.

Implementability
In Section 11.3, the costs of the different alternatives are estimated and compared. Because of the scale of the operation, realisation time of this measure can expected to be long and costs can expected to be high. The active currents and the large amounts of required construction materials severely complicate the building process, which increases the chances on a delay. During the construction of the groynes, hindrance to shipping can be expected. Using groynes is, compared to dredging, a sustainable solution. Negative effects almost solely occur during the construction of the groynes. Therefore, in the end, groynes will end up being the more sustainable solution of the two.

11.2.3. Guide bunds
The usage of guide bunds can be, as explained in Section 11.1, an effective river training measure. It guides an increased part of the discharge through a selected part of the river, which increases flow velocity between the bunds, and subsequently, it increases the water depth as well.

Because the navigation channel is located close to the river bank, only one guide bund is required to contract the flow in the desired section. The other boundary of the contracted area is provided by the river bank. A guide bund has the structural properties of a groyne. The core is made out of locally available material. It should be noted that this material needs to have certain characteristics. Granular material has to be of a minimum size to not be flushed away with the flow in the Magdalena River during construction. Therefore, rubble stone is often used. The outer layer of the guide bund should be able to resist erosion in all types of conditions that can occur in the Magdalena River. This can be achieved by using sufficiently large rocks or a combination of rocks and geotextiles. There should also be looked into the river bank's erosion resistance. The adjusted flow regime should not damage the bank protection. If the river bank is not strong enough, adjustments should be made. A concept of a solution that uses guide bunds is shown in Figure 11.10.

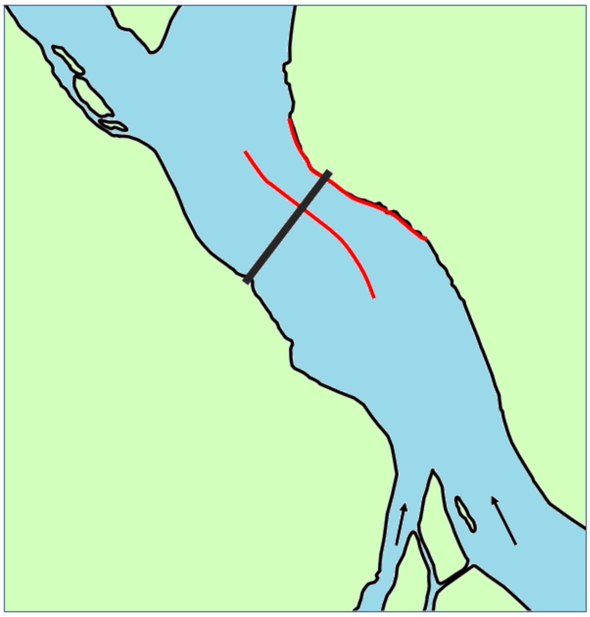


Figure 11.10: Conceptual design of a solution using guide bunds (not to scale)

The desired flow contraction is determined by the orientation and size of the head of the guide bund. The main shank of the guide bund is constructed parallel to the river bank. The head, on the other hand, bends slightly towards the outside. This creates a narrower cross-sectional surface area near the shank of the bund than near its head. Therefore, the water that enters the contracted section, is sped up to higher velocities between the shank and the river bank. At the other part of the cross-section, the flow is slowed down instead because of a wider surface area. The slope of the head of the guide bund (1:5 to 1:10) should be significantly smaller than the slope of its shank (1:2 to 1:3) (CIRIA et al., 2007). The reason for this is the sensitivity to scour. Scour around the head is largely reduced in case of a gentler slope. For the shank, this does not play a role since the flow is parallel to it.

The concept of guide bunds can also be applied in a more extreme variant by closing off the entire non-contraction part of the river. Even though this is very efficient in retaining the depth of the navigation channel, this would result in a unsafe situation in case of high discharges and floods. This applies to a lesser extend to the ordinary guide bunds described before. Consequently, guide bunds should be designed with care to be sure that the measure does not increase flood risks to an unacceptable level.

Technical aspects

Guide bunds are, as explained, a good measure to improve the navigability of the river section by influencing the equilibrium situation in a desirable way. Unwanted erosion and sedimentation will not be problematic any more. Guide bunds will, when finished, not be of any hindrance to shipping. They also fit well in the existing river because they do not influence the river characteristics outside the area of interest in a significant way. They do, however, slightly reduce the cross-sectional surface of the river, which increases flood risk a bit. But this is just a small increase.

Local integration
Guide bunds can be integrated well in the existing situation. Apart from the construction phase, little hindrance to people of Barrancabermeja is caused. Also the environmental aspects are not compromised.

Implementability
The magnitude of the costs associated with guide bunds is a disadvantage. In the first place, a large initial investment is required. Guide bunds are, however, when well-designed, a durable solution that can last for many decades. However, a serious investment for the monitoring and maintenance of the guide bunds is needed (CIRIA et al., 2007). In Section 11.3, the costs of the different solutions are estimated and compared. The construction of guide bunds requires a large and complicated operation. Guide bunds are large structures that cannot easily be built somewhere, especially not in a river with significant flow velocities like the Magdalena River. Because the guide bund is planned in the middle of the river, the structure has to be built from vessels, which significantly complicates the construction process.

11.3. Cost comparison of possible solutions

The total costs of a measure consist of initial costs, operational costs and maintenance costs. The dredging solution comes only with operational costs. Therefore, in case of a short term solution, dredging will be the most economic option. However, according to professor Vargas Luna from the Pontifical Xavierian University in Bogotá, the large costs of dredging outweigh the high initial costs that are associated with groynes or guide bunds over a longer period of time. Therefore, on the long term, groynes and guide bunds will be the favourable option.

The total costs of the these two measures consist of initial costs and maintenance costs. Both expenses can be related to the size of the structure. It is hard to make a representative cost estimate. Therefore, there has been decided to compare the costs of groynes and guide bunds solely by comparing the amount of resources required. This can be done because the structures are similar to each other, and similar construction methods are used. Although still a rough estimate, it will expose large differences in costs, which makes it possible to compare the two measures.

To calculate the volume of building material required, a rough design of the cross-section of both a groyne and a guide bund is needed. It is assumed that both structures have the same cross-sectional design. This assumption is safe because both structures have to deal with the same conditions in the Magdalena River. The design that is used is presented in Figure 11.11. For this design, a water depth of 10 metres is used, as this is the largest water depth measured around Barrancabermeja. To be able to withstand erosion and scour, the structure continues until 5 metres below the river bed. The structure arises 3 metres above mean water level and a slope of 1:2 is used to limit the structure's width.

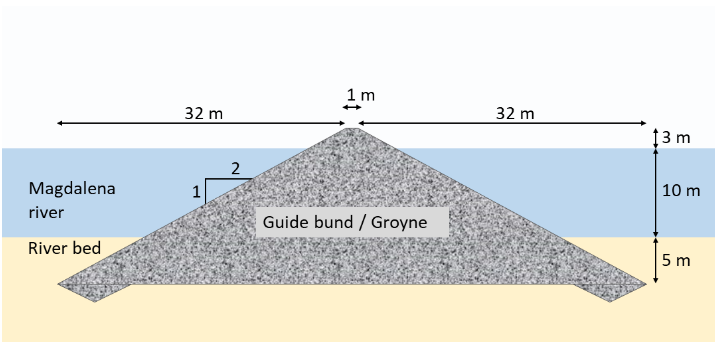


Figure 11.11: Assumed cross-sectional design of a groyne/guide bund

These cross-sectional dimensions lead to a volume of 342 cubic metres per running metre. The estimated total length of the groynes is 1650 metres compared to about 920 metres associated with the guide bunds. In Table 11.1, the estimated amount of construction material for both solutions is presented.

Table 11.1: Overview of the required material for the construction of groynes and guide bunds

Measure	**Total required length [m]**	**Required material per unit length [m^3/m]**	**Total required material [m^3]**
Groynes	1650	342	564,300
Guide bunds	920	342	314,640

From this rough estimation follows that the solution using groynes requires almost 1.8 times the amount of construction materials that is required for the solution that uses guide bunds. As the costs in this estimation completely rely on building material quantities, it can be concluded that the solution that uses groynes is almost 1.8 times as costly as the solution that uses guide bunds. Therefore, guide bunds will be the favourable measure when looking at costs, followed by groynes and dredging. Costs are however only a limited part of the criteria on which the decision for a measure is based. In the next chapter, also the other criteria are compared.

12

Multi-Criteria Analysis

Chapter 11 describes potential solutions for the sedimentation problems around the city of Barrancabermeja and in this chapter a Multi-Criteria Analysis (MCA) is performed. An MCA helps to identify preferences and make a rational choice between alternative solutions, especially for more complicated decisions an MCA is a method for accomplishing a well-structured decision making process (Mendoza et al., 1999).

The MCA is subdivided into multiple steps, as can be seen in Figure 12.1. Firstly, an objective tree is created to gather insight in the desired objectives of the solution. From this objective tree, several criteria are generated. A weight between 1 and 10 is assigned to these criteria, which defines their importance. The more important the criterion, the higher the weight given to this criterion. The criteria are divided into three categories, that represent an overall percentage which they contribute to the final score. Standardised weights are now calculated for every criterion, which sum up to a total of 100%. Subsequently, for every alternative, a score between 1 and 5 is assigned to the criteria. The more positive the effect of the solution regarding the concerning criterion is, the higher the allocated score. Finally, for every design alternative, the scores are multiplied with the standardised weight of the corresponding criteria. Summing up all the scores per design alternative results in a final score between 1 and 5, and, the higher the score, the better the alternative. The alternative with the highest score appears to be the best alternative based on the MCA.

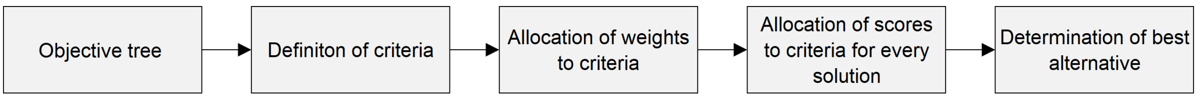


Figure 12.1: Structure of the different steps of the Multi-Criteria Analysis

During the MCA it is important to take into account the stakeholders identified in Chapter 2. For example, negatively affecting the interest of important stakeholders, such as Cormagdalena and Ecopetrol, is considered a disadvantage. A higher weight should be assigned to criteria in the interest of these stakeholders. Therefore, the definition of the criteria sometimes contain references to involved stakeholders.

12.1. Objective tree

In order to define the criteria, used to assess the effectiveness of the possible solutions, an objective tree is created. Using an objective tree is a method that assists in making an overview of the main and sub goals of the ideal solution. The tree is made up of multiple levels and the highest (also called first) level represents the main objective of the proposed solutions (Enserink et al., 2010). For the situation in Barrancabermeja this main goal is defined as follows:

Better navigability of the Magdalena River around the city of Barrancabermeja

This goal is divided in lower-level objectives in such a way that, if all these intermediate objectives are met, the main goal is also achieved. These lower-level goals are subdivided once more into multiple goals, from which the final criteria, used in the MCA, are defined. Figure 12.2 depicts the objective tree for the sedimentation problems in Barrancabermeja, a larger version of this tree is depicted in Figure L.1 in Appendix L. The red boxes in this diagram represent the final goals from which the criteria are defined, these are described subsequently.

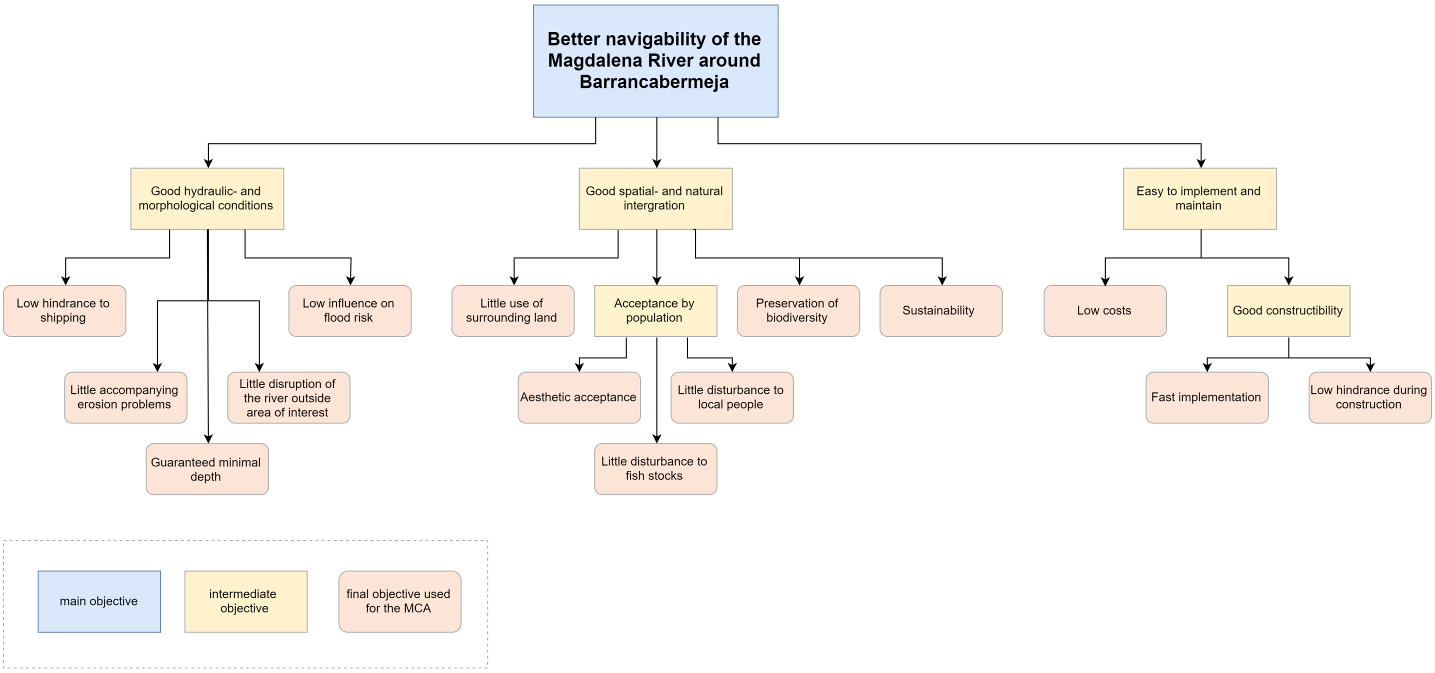


Figure 12.2: Objective tree that provides an overview of the main and sub goals of the solution and the criteria used in the MCA

12.2. Definition of the MCA criteria

12.2.1. Hydraulic and morphological conditions

The main goal of the proposed solutions is to guarantee the navigability of the Magdalena River around the city of Barrancabermeja. Therefore, the hydraulic and morphological conditions and consequences of the proposed solutions are very important. Also, many important stakeholders, such as Cormagdalena, Ecopetrol, Impala and the shipping companies, have a high interest in these conditions. Therefore, the criteria in this category contribute in total for 50% to the final score.

Hindrance to shipping

The demand for a solution for the sedimentation problems around the Yondó Bridge is high. The sedimentation is undesirable since it causes hindrance to the shipping at the Magdalena River. If one measure takes away the sedimentation issues, but another form of nuisance occurs in its place, this measure is not the ideal solution. The hindrance for the ships should be reduced as much as possible. As this contributes significantly to the main purpose of the solutions, a high weight is assigned to this criterion.

Accompanying erosion problems

A measure should not endanger other structures or decrease their functionality. This can happen, for example, due to macro-scale erosion or local scour around the abutments or piers of the Yondó Bridge. Changes in the hydraulic situation in the river are allowed, as long as they do not influence other relevant aspects in a negative way. For situations that cause these unfavourable changes, additional measures should be taken to deal with them. These additional measures cost money, but these costs are relatively small compared to the costs of the construction of the bridge and the dredging activities. Therefore, a low weight is awarded to this criterion.

Guaranteed minimum depth

An important goal is to find a solution that ensures a minimum retained depth. In principle, all alternatives meet this requirement. However, anything strange or unexpected could happen in a river. In such a case, it might be possibe that the minimum depth cannot be guaranteed any more. The risk of occurrence of this situation represents this criterion and gets a high weight as it is one of the main goals of the proposed solutions.

Disruption of the river outside area of interest

A solution should fit well into the entire Magdalena River. This means that an intervention should not influence the characteristics of the river outside of the immediate vicinity of the bridge in a negative way. For Cormagdalena this is an important criterion, as they are responsible for the entire Magdalena Basin. However, the criteria relating the navigability around the city of Barrancabermeja are considered more important for this project. Therefore, this criterion gets a lower weight than the criteria directly related to the navigability.

Influence on flood risk

Flood risk is an important criterion on which it is very hard to compromise. Floods can have large economical and human consequences, and therefore only a slight increase of this risk, as a result of an intervention, can already make a large difference. Therefore, a very high weight is allocated to this criterion.

12.2.2. Spatial and natural integration

Spatial integration represents, amongst others, the use of surrounding land and the acceptance by the local population, for example, by the aesthetics of a solution. One can consider sustainabiliy and fish conservation under natural integration. Several stakeholders have an interest in this type of criteria. Clearly, the citizens of Barrancabermeja belong to this group but also Cormagdalena, as they are responsible for both the navigability and the conservation of the biodiversity of the Magdalena River. In total this category of criteria contributes for 25% to the final score.

Use of surrounding land

A proposed solution is more valuable if less land around the river sides is occupied. The use of this land can have several negative consequences, for example, in case of building on the flood plaines, the discharge capacity of the river will decrease. Also, original users of the land might have to move their activities. However, a medium weight is assigned to this criterion, as for example the preservation of the biodiversity is considered to be more important than the occupancy of land at the river sides.

In case a solution requires land on the right side of the river, where the city of Barrancabermeja and Ecopetrol are located, these stakeholders are negatively influenced. This must be taken into consideration when allocating scores to the solutions.

Acceptance by population

The citizens of Barrancabermeja are an important stakeholder regarding this objective, as the population should approve the solution. Three aspects are defined which contribute to the total acceptance of the population:

- **Aesthetic acceptance**
  The proposed solution should fit in the landscape of Barrancabermeja.
- **Disturbance to local people**
  The proposed solution should not disturb the daily activities of the local people, for example, by noise or traffic hinder.
- **Disturbance to fish stocks**
  As many of the locals around the city of Barrancabermeja work in the fishery, it is important that the proposed solution does not significantly affect the number of fishes and the amount of species. This would have a big impact on the local citizens in terms of their economic welfare.

A low weight is assigned to the first aspect, as for example use of surrounded land is considered to be more important. Furthermore, in the stakeholder analysis, executed in Chapter 2, the interest of the local residents is considered to be low, as until now they do not directly suffer from the sedimentation problems around Barrancabermeja. It is undesirable that this interest would change and therefore, the second and third criterion get a higher weight, as these aspects have a direct negative influence on the living conditions of the citizens of Barrancabermeja.

Preservation of biodiversity
As Colombia has a high biodiversity, it is preferred that the proposed solution maintains this biodiversity. By achieving this goal also the requirements of the NGO's and, partially, of Cormagdalena are fulfilled. If a solution negatively influences the biodiversity in a significant way, probably ANLA will intervene and the solution will be rejected. Therefore, a high weight is assigned to this criterion.

Sustainability
Nowadays, sustainability is always considered as an important aspect in construction projects. Although the requirements for sustainable development are less strict in Colombia then, for example, in Europe, it should still be taken into account. Moreover, ANLA can intervene in case the influence of a measure on the sustainability is too large. Therefore, a high weight is allocated to this criterion, but as the number of criteria in this category (spatial and natural integration) is significant, the relative contribution of this weight is small.

12.2.3. Implementation and maintenance
This category represents the way of dealing with the costs, the construction and the maintenance. Only three criteria are defined and they contribute in total 25% to the final score.

Costs
Costs are a very important aspect of the project. The costs can be divided into tree types of costs, namely: initial, operation and maintenance costs. The total costs must be as low as possible and for now the type of costs is not considered relevant. Therefore, a high weight is allocated to the total costs of a possible solution.

Constructibility
The constructibility is also an important aspect of the solution. It is assumed that all of the proposed solutions are possible to construct, but a distinction is made in the time needed for the implementation and the hindrance during the construction.

- **Implementation time**
  The problem around Barrancabermeja is very actual. Therefore, a solution which can be implemented quickly is preferred above solutions which take much time to implement. This criterion does not have a very high weight, because the costs of the solution are considered to be more important.
- **Low hindrance during construction**
  The solution should not only provide a favourable situation for shipping when it is implemented. During construction, ships also have to be able to pass the area of interest in an acceptable way. Much hindrance during this period will result in a low grading.

12.3. Weight factors of criteria
Table 12.1 gives an overview of all the criteria accompanied by the weights assigned to these criteria. The higher the weight, the more important the criteria is and the more it contributes to the final score of the proposed solutions.

Table 12.1: Weights of criteria that are used in the Multi-Criteria Analysis. The three bold numbers indicate the weight of the criteria categories, whereas the other numbers represent the weights of the final criteria.

Criterion	**Weight category**	**Weight [1-10]**	**Standardised weight [%]**
Hydraulic and morphological conditions	**0.5**		
Hindrance to shipping		8	10.00
Accompanying erosion problems		5	6.25
Guaranteed minimal depth		10	12.50
Disruption of the river outside area of interest		7	8.75
Influence on flood risk		10	12.50
Spatial and natural integration	**0.25**		
Use of surrounding land		4	2.63
Aesthetic acceptance		2	1.32
Disturbance to local people		7	4.61
Disturbance to fish stocks		7	4.61
Preservation of biodiversity		9	5.92
Sustainability		9	5.92
Implementation and maintenance	**0.25**		
Costs		8	15.38
Implementation time		2	3.85
Hindrance during construction		3	5.77
Total weight			100.00

12.4. Allocation of scores

This section provides an overview of the allocation of the scores to all the alternative solutions. Section L.2 contains a comprehensive description of the reasoning behind these scores for each design alternative. Table 12.2 shows the scores for every design alternative per criteria and the final standardised score, adapted according to Table 12.1.

Table 12.2: Overview of the final scores per design alternative resulting from the MCA

Criterion	Weight category	Weight [1-10]	Standardised weight [%]	Null solution	Groynes	Guide bunds
Hydraulic and morphological conditions	0.5					
Hindrance to shipping		8	10.00	2	5	5
Accompanying erosion problems		5	6.25	5	4	4
Guaranteed minimal depth		10	12.50	5	5	5
Disruption of the river outside area of interest		7	8.75	5	3	4
Influence on flood risk		10	12.50	5	2	4
Spatial and natural integration	0.25					
Use of flood plains		4	2.63	5	5	5
Aesthetic acceptance		2	1.32	2	3	4
Disturbance to local people		7	4.61	4	5	4
Disturbance to fish stocks		7	4.61	1	5	4
Preservation of biodiversity		9	5.92	2	4	4
Sustainability		9	5.92	1	3	4
Implementation and maintainenance	0.25					
Costs		8	15.38	2	3	4
Implementation time		2	3.85	5	2	2
Hindrance during construction		3	5.77	5	2	1
			Final standardised score	**3.55**	**3.59**	**4.00**

Figure 12.3 shows the contribution of each category of criteria to the final score of an alternative. Overall, the guide bunds appear to represent the most complete solution, which is mainly caused by the high scores on the hydraulic and morphological conditions. Also for the criteria relating to the implementation and maintenance of the solution, the guide bunds score better than the other two alternatives, but these scores contribute less to the final score. For the criteria regarding spatial and natural integration, the groynes have the highest score. This is caused by the fact that the disturbance to the local population is considered lower for groynes than for guide bunds.

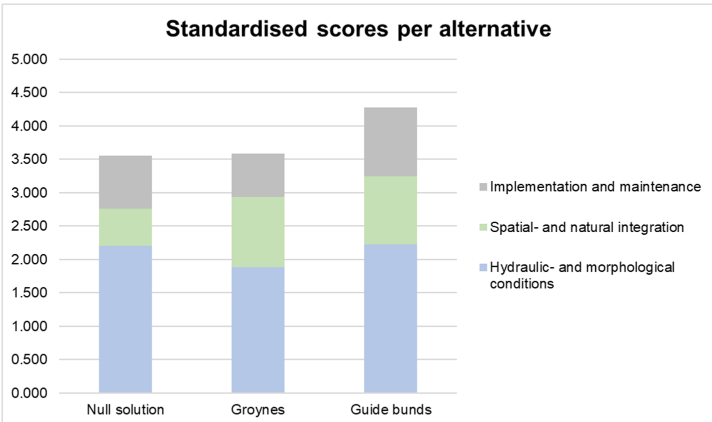


Figure 12.3: Standardised scores of the design alternatives

12.5. Results

The MCA shows that guide bunds are the best solution. This section analyses the scores of the guide bunds in relation to the other alternatives. Figures 12.4 and 12.5 show the distribution of the scores assigned to the guide bunds solution. Figure 12.4 shows the absolute scores in a range between 1 and 5 per criterion. The missing credits are represented by the red parts of the columns. Figure 12.5 shows the standardised scores according to Table 12.1. The maximum score varies per criteria, due to the different weights. Again, the red parts of the columns indicate unassigned scores.

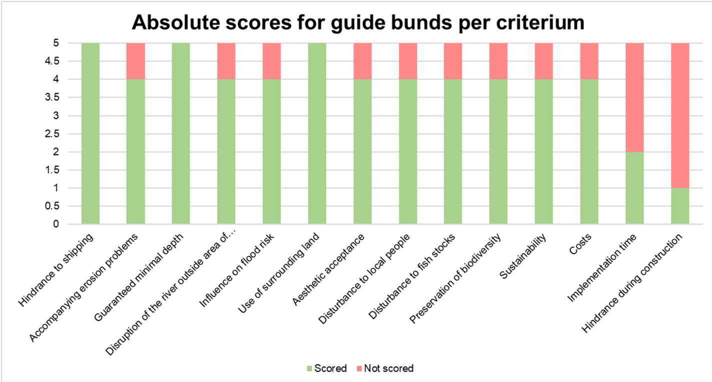


Figure 12.4: Absolute scores for the guide bunds. The green colums show the scores, the red colums show the missing credits based on the fact that the maximum score per criteria is 5.

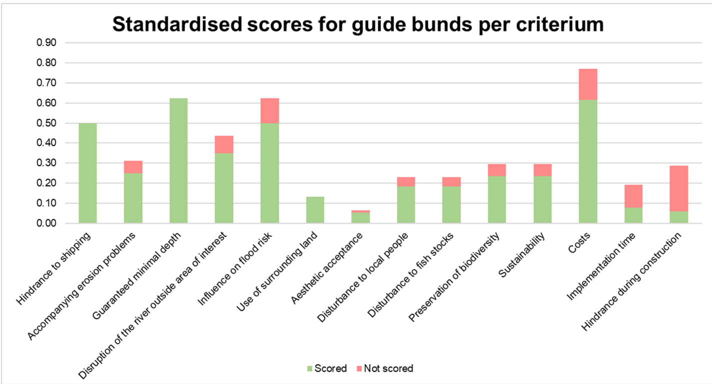


Figure 12.5: Standardised scores for the guide bunds. The green colums show the scores, the red colums show the missing credits.

The figures indicate that almost all points are allocated for the criteria regarding hydraulic and morphological conditions and the costs, whereas it obtains low scores for the implementation and the hindrance during construction. However, the guide bunds are still considered to be the best solution for the sedimentation problems around the Yondó Bridge. Therefore, in Chapter 13 the effect of the guide bunds on the hydrodynamic and morphodynamic conditions in the Magdalena River is analysed by means of a Delft3D-model.

13

Evaluation of the guide bunds

This chapter contains an evaluation of the final solution for the sedimentation problems in the river reach around the city of Barrancabermeja: guide bunds, see Section 12.5. This evaluation consists of a couple of model simulations in Delft3D in which the guide bunds structure is incorporated in the grid and bed elevation profile. The results of these simulations are compared to the results of the simulations without the guide bunds, presented in Chapter 10. Section 13.1 explains how the guide bunds are implemented in the Delft3D-model. Sections 13.2 and 13.3 contain the results and the conclusions that can be drawn from this results.

13.1. Implementation in Delft3D

In general, Delft3D is not the most suitable program to assess the impact of an hydraulic structure on the hydro and morphodynamic conditions in a river. Though, the structure will be implemented in the best possible way in the Delft3D-grid. There are two available options for this implementation: a combination of thin dams and dry points or an adaptation of the elevation of the river bed.

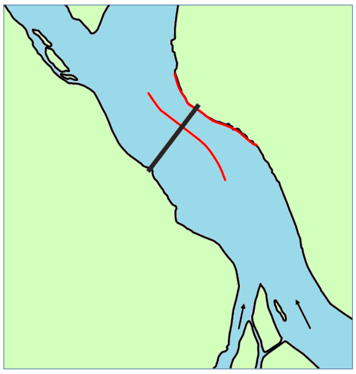
Thin dams and dry points are both features of Delft3D which can be used to influence the status of a grid cell. A dry point is a grid cell centred around a water level point that is permanently dry during a computation, independent of the water depth in the model. A thin dam is a very small object defined at a velocity point, which prevents water to flow between the adjacent cells. However, the volume of the model and the total wet surface remain the same. More detailed information about dry points and thin dams can be found in the Delft3D-FLOW User Manual (Deltares, 2014).

The advantages and disadvantages of both options are summarised in Table 13.1. The options are assessed on the correct representation of the geometry of the structure and the local flow effects that occur around the structure. It is interesting to see that both options have opposing (dis)advantages. The thin dams and dry points represent the geometry well, whereas an adaptation of the elevation of the bed results in a better simulation of the local flow effects. In the end, it is chosen to implement the guide bunds by means of thin dams and dry points as in this stage of the research a correct representation of the geometry of the structure is considered to be more important.

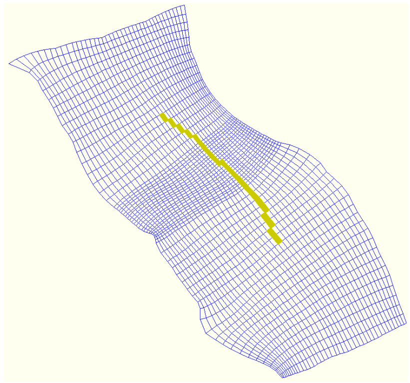
Table 13.1: Overview of the advantages (+) and the disadvantages (-) of the available options for the representation of the guide bunds in Delft3D

Option	**Geometry**	**Local effects**
Thin dams & dry points	++	-
Adaptation bed elevation	-	+

The design of the guide bunds in the Magdalena River is depicted in Figure 13.1a. The shape is a fluent line over a part of the river reach, which is not possible to simulate in Delft3D due to the composition of the grid. Therefore, it is chosen to create a cascading pattern that has a width of one grid cell, see Figure 13.1b. The second part of the design, at the right side of the river, is not added to the Delft3D-grid for two reasons. Firstly, that part of the structure is located at the bank and in Delft3D the banks are naturally stable, so they actually resemble this part of the structure automatically. The second reason is the occurrence of additional local flow effects at the river bank in case, which is undesirable. Figures 13.2a and 13.2b depict the grid and bed elevation profile including the guide bunds structure, that will be used to perform two additional simulations. The specifications of these runs (Run 7 and Run 10) can be found in Table 9.4 in Chapter 9.

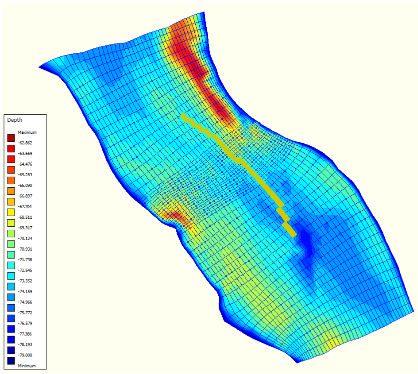


(a) Design of the guide bunds

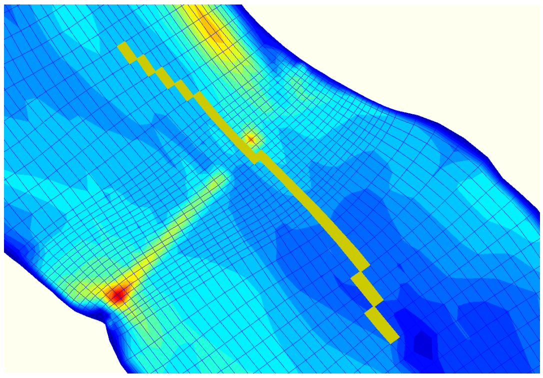


(b) Guide bunds in the grid

Figure 13.1: Figures that depict the design of the guide bunds around the bridge in the Magdalena River (left) and the guide bunds in the Delft3D-grid (right). The yellow boxes and stripes represent the dry points and thin dams.



(a) Overview

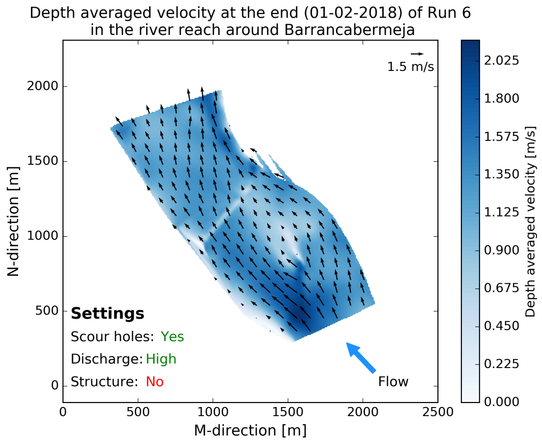


(b) Zoom

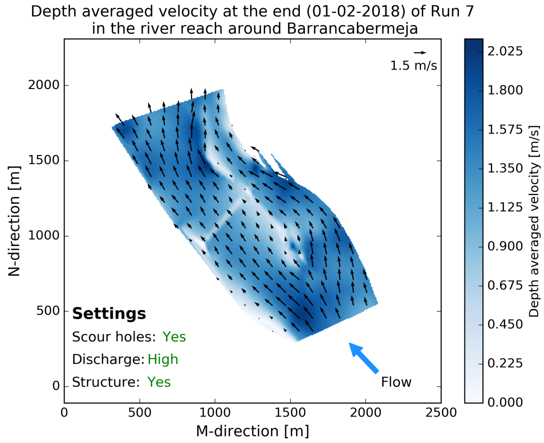
Figure 13.2: Images from the bed elevation profile of the river reach in Delft3D containing the guide bunds. A total overview is depicted on the left and a zoom of the structure on the right.

13.2. Results of additional simulations

The results of the additional simulations are presented in the same way as is done in Chapter 10. First, the depth averaged velocity is analysed and subsequently the amount of cumulative sediment transport is examined. In Figure 13.3 the depth averaged velocity pattern over the river reach is depicted for a simulation with the following conditions: a high discharge and scour holes included but with and without the guide bunds structure. It can be visually observed that the structure forces more of the flow through the right side of the channel. This is quantitatively supported by analysing the same seven velocity vectors as in Chapter 10. The numbers are summarised in Table 13.2 and indeed the velocities on the left side of the river decrease (light grey colours), whereas the velocities on the right side increase (dark grey colours). This is also visible in Figure 13.4 where the black dot indicates the transition point.



(a) Run 6



(b) Run 7

Figure 13.3: Plot of the depth averaged velocity [m/s] in the river reach around the Yondó Bridge after Run 6 (left) and Run 7 (right). The blue arrow indicates the flow direction and the black arrow on the top right represents the reference velocity.

Table 13.2: Overview of the magnitudes of the velocity [m/s] of the seven vectors indicated in Figure 10.3, listed for Run 6 and 7. The grey colours indicate interesting values.

	Velocity [m/s]						
Run	**Vector 1**	**Vector 2**	**Vector 3**	**Vector 4**	**Vector 5**	**Vector 6**	**Vector 7**
6 (without structure)	1.43	0.85	0.91	0.79	0.76	1.21	1.33
7 (with structure)	1.29	0.75	0.75	0.63	0.31	1.49	1.70

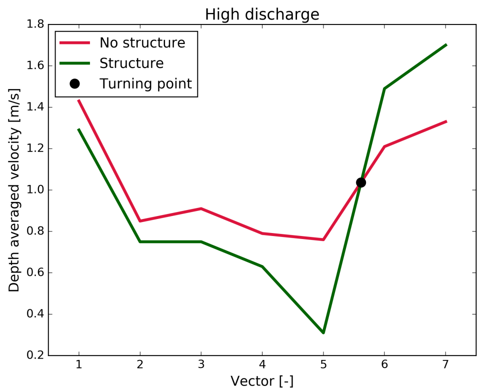
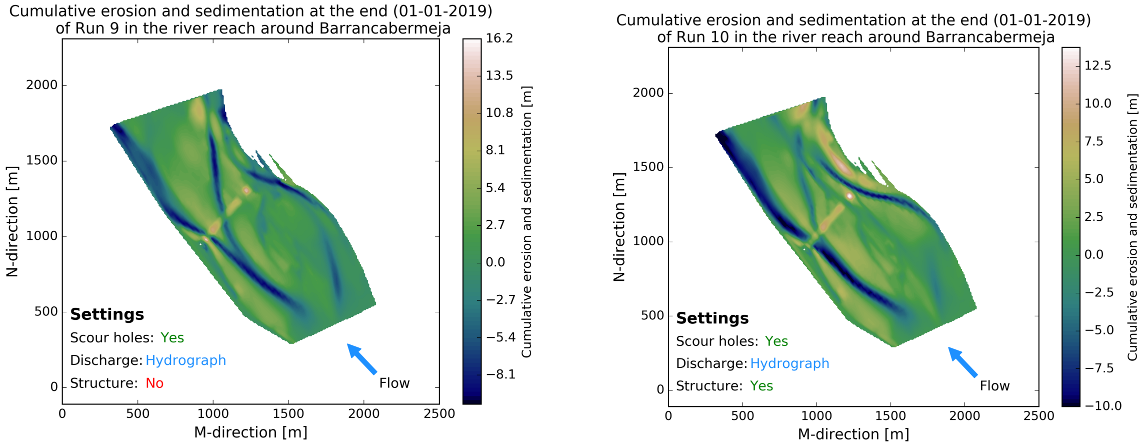


Figure 13.4: Plot of the depth averaged velocity per vector for Run 6 and 7. The black dot indicates the turning point of the velocities.

The final elevations of the river bed profile after a one year simulation are illustrated in Figure 13.5 for both a situation with and without the structure. The differences between the two plots are clearly noticeable. The outer left eroded ‘line’ gets deeper as the guide bunds are present, whereas the area on the right side of the image gets more shallow. Approximately twelve meter of sediment is deposited at that location during one year, which is an extremely large amount. This is highly undesirable, as the right part of the channel is supposed to become deeper. This will be discussed more extensively in Section 10.3. In both cases, the existing scour holes are filled during the simulation, indicated by the sand brown dots in the area of the bridge in Figure 13.5.



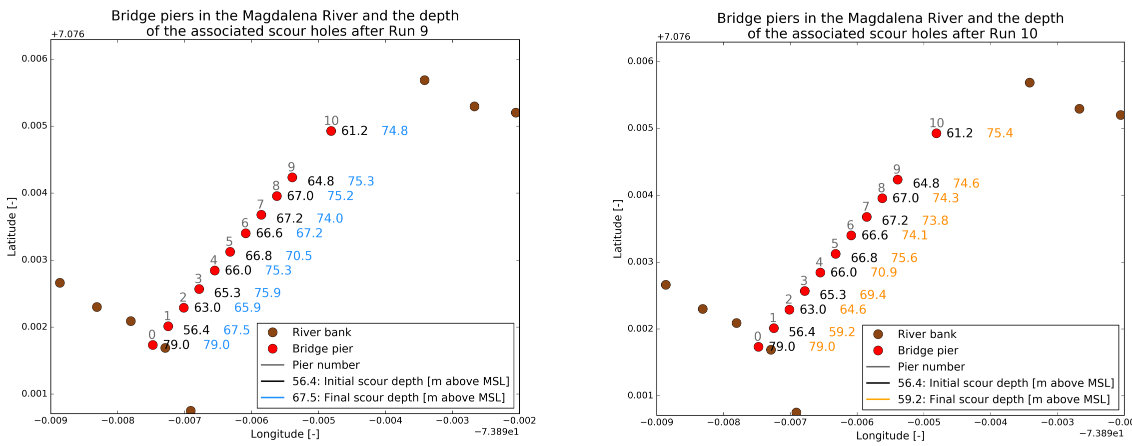
(a) Run 9 (b) Run 10

Figure 13.5: Plot of the cumulative erosion (negative) and sedimentation (positive) in the river reach around the Yondó Bridge for Run 8 (left) and Run 9 (right)

13.3. Conclusion

From the analysis of the depth averaged flow velocity can be concluded that the guide bunds function well. It was expected that this structure would force more of the flow through the right side of the river reach and less through the left side. This hypothesis is supported by the results of the additional simulations. However, as mentioned before, Delft3D is not created to purely test the effects of hydraulic structures on the flow conditions in a river. Therefore, more (detailed) simulations and physical models should prove that this is indeed the case.

Just as in Chapter 10, an overview of the initial and final scour depths around the bridge piers is made, see Figures 13.6a and 13.6b. Based on the plots of the cumulative sediment transport, presented in the previous section, sedimentation takes place around all bridge piers. However, when the simulation with the guide bunds structure (Run 10) is compared to the simulation without the structure (Run 9) some interesting differences appear. The numbers of this comparison are presented in Table 13.3, below.



(a) Run 9 (b) Run 10

Figure 13.6: Initial and final scour depth [m] around the piers of the Yondó Bridge after Run 9 (left) and Run 10 (right). These plots are based on numbers in Table K.1 in Appendix K. An overview of the location of the piers can be found in Figure I.1.

From the table it can be concluded that at the left side of the channel (Pier 1 to 9) predominantly erosion takes place, whereas at the right side of the channel (Pier 10) half a meter of sedimentation occurs. Based on these numbers, it seems that the guide bunds structure strengthens the existing sedimentation problems. The effect is opposite to the expected pattern that would occur in case the structure is installed. Therefore, two possible next steps could be taken in order to check whether or not the guide bunds can still be considered the best solution: revision of the design of the guide bunds or additional (physical) model tests based on more reliable data. This will be discussed further in Chapters 14 and 16.

Table 13.3: Absolute and percent differences in bed level between the beginning and the end of Run 10 relative to Run 9. The last column indicates whether increased (+) or decreased (-) sedimentation takes place. The numbers in this table are based on the values of the bed elevation per run, presented in Appendix K.

	Run 10 with respect to Run 9		
Pier number	Absolute difference [m]	Percentage [%]	Erosion or sedimentation [ERO or SED]
0	0.0	0.0	x
1	8.3	12.3	-
2	1.3	2.0	-
3	6.5	8.6	-
4	4.4	5.8	-
5	5.1	7.2	+
6	6.9	10.3	+
7	0.2	0.3	-
8	0.9	1.2	-
9	0.7	0.9	-
10	0.6	0.8	+

IV

Discussion, conclusion and recommendations

In the final part of this report, a discussion about the obtained results is provided, followed by the conclusions. Finally, a couple of suggested recommendations are listed regarding future research into the topic of sedimentation, scour holes and numerical simulations.

14

Discussion

In this chapter, the reliability of this study is evaluated. The discussion is subdivided into three sections, each representing a part of this study. In each section, the limitations of this part of the study and the interpretation of its results are discussed.

- Bar mode analysis
- Delft3D-model simulations
- Multi-Criteria Analysis

Bar mode analysis

According to Crosato and Mosselman (2009), the bar mode analysis gives good results for width-to-depth ratios up to 100. Width-to-depth ratios larger than 100 result in an overestimation of the number of bars. The river section of interest has a width-to-depth ratio of around 200, so the bar analysis slightly overestimates the number of bars. Due to the fact that the bar mode value is still below 2, it is safe to state that the value found corresponds to the number of alternate bars.

Incomplete and missing input data are the main limitation of the bar mode analysis. To be able to execute the bar mode analysis despite these shortcomings, assumptions and extrapolations had to be made:

- In an ideal situation, the Chézy value used in the bar mode analysis is calculated with data measured during bank-full conditions. Unfortunately, these data are not available for the situation in Barrancabermeja. Therefore, data obtained during the field trip to Barrancabermeja were used instead. During this trip. bank-full conditions were not present. Therefore, the Chézy value determined will slightly deviate from the Chézy value that would have been found in case bank-full conditions would have been used.
- To calculate the bank-full discharge, information on the yearly maximum discharges is required. This information is derived from the daily discharges. During the period from 2014 to 2017, daily discharges were not measured, however, the daily water levels have been measured during this period. By combining information on the known daily discharges from the period before 2014 with data on water levels during this period, a trend line can be used to estimate daily discharges from 2014 to 2017. The correlation coefficient of this trend line is 0.89, which results in a coefficient of determination of 0.8. This results in a 20% chance of the determined discharge is not corresponding to the real value.

Based on this, there can be concluded that the determined number of bars is based on some uncertainties and therefore should be handled with care. Despite these uncertainties, the results of the bar mode analysis match the number of bars observed in the years 1981, 1998, 2002, 2013 and 2017. Therefore, the results are reliable enough to be used to explain the observed shift of the thalweg. Although the shift of the thalweg started after the construction of the bridge, it does not necessarily mean that the bridge is the direct and only cause of the shift.

Delft3D-model simulation

The ten different flow situations that are simulated in the Delft3D model software generated plenty results, which are used to assess the influence of the scour holes on the hydrodynamic and morphodynamic conditions in the Magdalena River, see Chapter 10. The amount and type of results meet the expectations that were made beforehand. It was perfectly possible to analyse the patterns of the depth averaged velocity and the cumulative erosion and sedimentation. However, two main aspects differed from an 'ordinary' model set-up, which decreases the validity and usefulness of the results. These aspects are explained below.

- The first aspect regards the input data used for the model. The initial bed elevation profile used in the model is based on measurements obtained during the field trip to Barrancabermeja in December 2017. At that moment, scour holes were already present in the river reach. The initial bed elevation profile is influenced by these holes, and therefore, the actual influence of the scour holes cannot be assessed precisely.

  This is also the reason that the scour hole dimensions cannot be derived from the measurements. Data on scour holes are required for the simulation in which scour holes are taken into account. The scour hole dimensions have eventually been determined with the use of the empirical relation provided by Melville and Coleman. The accuracy of the scour hole dimension estimates using this method is compromised by the uncertainty of input values and the shortcomings of the method itself.

- The second aspect is about the calibration of the model. This is done, based on two days of water level measurements in the river reach around the Yondó Bridge. Ideally, the calibration is based on, for example, a year of measurements. However, this data was not available at the preferred location. It might be possible that the inclusion of water levels of more seasons or months would results in a different Chézy value.

Based on the two points mentioned above, the results of the Delft3D simulations can be considered useless when one wants to assess the effect of scour holes specifically. However, the goal of this research was to get a first impression of the phenomena that are present in the nearby area of the Yondó Bridge and that influence the morphodynamic situation in the river. The results do actually serve this purpose perfectly fine, but one should be careful with the interpretation and use of the results for design decisions or other conclusions regarding the amount of scour, for example.

The same holds for the additional simulations, performed in Chapter 13. These simulations are based on similar input as the original simulations, but now the guide bund structure is incorporated as well. This structure is implemented by adding dry points and thin dams to the grid. These Delft3D-features are not able to represent the actual geometry of the guide bund for 100%. Therefore, some additional uncertainty is added to the model and the results will also contain that uncertainty. The bottom line of this section is that the model results generated by Delft3D should be handled with care.

Multi-criteria analysis

Due to restrictions in time, resources and specific available knowledge, there is left room to improve the way in which the possible solutions are compared to each other. In the first place, an improvement in the selection criteria that are used to grade the alternatives can be made. Not just on which criteria the alternatives are tested, but also the weighting of these criteria, which relates to their importance, can be improved. Also to the way in which scores are awarded to each alternative is room for improvement. For some specific criteria, the solutions are only being graded using engineering judgement from master students. Although this is enough to compare the alternatives in a qualitative way, it is of course not an optimal situation.

15
Conclusions

This chapter describes the conclusions of this study. These conclusions are based on the evaluation of the research questions posed in Chapter 1. First, the subquestions are evaluated and after that the main question is answered.

- *What is the current state of Magdalena River around Barrancabermeja and what are stakeholders' interests?*

  Nowadays, the cargo transport over roads, railways and through the air in Colombia is growing very fast every year. However, for the cargo transport over inland waterways this is not the case, even though there is room for a 130 times multiplication of the current amount of transport. It is hypothesised that due to the poor accessibility and poor navigability of the main rivers, this growth cannot be realised. The phenomena, mentioned above, also occur in the Magdalena River around Barrancabermeja. Currently the navigability of this river reach is guaranteed by maintenance dredging of the thalweg, since heavy sedimentation threatens the passage of (large) ships.

  Based on the generation of a power-interest grid and the identification of the relations between the different stakeholders, four important stakeholders can be identified: the Ministry of Transport, Cormagdalena, ANLA and Ecopetrol. These four parties represent (in)directly all the identified stakeholders and do all have their own interest regarding the sedimentation problems around the Yondó Bridge. The Ministry of Transport wants to improve the transport capabilities over land, whereas Cormagdalena wants to maintain the navigability of the Magdalena River at all time. Besides, ANLA is involved with the sustainable development of Colombia and Ecopetrol has as main concern the production and transport of generated gasoline and oils. All these parties interact with each other to make sure that their own interest is fulfilled.

- *What caused the shift of the thalweg from the right to the left side of the river after the construction of the Yondó Bridge?*

  This question is subdivided into three questions as the shift is probably caused by a combination of multiple phenomena and due to a lack of data it was not possible to assess this as a whole.

  – *What would be the morphological behaviour of the Magdalena River in case the Yondó Bridge would not have been built?*

    If the Yondó Bridge would not have been constructed in Barrancabermeja, the river would be subdue to natural spatial changes, such as, changes in width and a relocation of the bends. This behaviour is indeed observed on satellite pictures of the Magdalena River in the period of 1970-2002, before the construction of the bridge. Also, multiple small sub-channels within the river appear and disappear, but the main shape of the river keeps in position. This is mainly due to the hard river training measures at the right side of the river, at the location of the city of Barrancabermeja. In general, the natural changes of a river remain unpredictable.

  – *What is the influence of local sand bars on the morphological behaviour of the Magdalena River?*

The results from the bar mode analysis show that for the examined river section, and given the local river conditions, the river contains one alternate bar over the years. Although the river conditions changed slightly between the examined years, the bar mode value always lies within a range that corresponds to one alternate bar.

The satellite pictures prove that the sand bar on the left side of the river started to disappear after the construction of the bridge, and shifted to the right bank of the river, where originally the thalweg was located. It is plausible that the construction of the bridge has induced changes in flow conditions in such way that the original alternate bar started to erode and eventually totally disappeared. The creation of the alternate bar on the right side of the river that followed, is the reason of sedimentation in this part. Therefore, it is highly possible that the construction of the bridge forms the main reason of the shift of the thalweg.

- *What is the influence of scour holes around around bridge piers on the morphological behaviour of the Magdalena River?*

  The scour holes around the piers of the Yondó Bridge that were approximated by the method of Melville and Coleman (2000) have the following dimensions: the depth ranges from 2.5 to 7.5 m and the width from 18.5 to 36.0 m. These scour holes are incorporated in the Delft3D-model to assess their influence by adapting the initial bed elevation profile. It turns out that the flow around the scour holes does not increase or decrease uniformly, but the presence of the holes does result in more erosion in the vicinity of the bridge.

- *Which changes can be made to the current situation in order to deal with the sedimentation problems around the Yondó Bridge?*

  The sedimentation problems around the Yondó Bridge can be solved by applying river training to the reach around the location of the bridge. After analysing six river training measures (riparian zone, non-erodible layers, submerged vanes, groynes, longitudinal dams and guide bunds) it turns out that groynes and guide bunds are the most suitable alternative, besides the current dredging activities, for the situation in Barrancabermeja.

  Groynes are transverse dams that extend from the river bank into the river itself and thereby reduce the conveying cross section of the river. This results in higher flow velocities accompanied by less sedimentation in the thalweg. Guide bunds have the same effects but the orientation of the design differs from groynes as they are placed parallel to the river banks.

- *How do the selected measures influence the morphological behaviour of the Magdalena River?*

  The three possible solutions (null-solution and two alternatives) were graded on three categories of criteria in a Multi-Criteria Analysis: hydraulic and morphological conditions, spatial and natural integration and implementation and maintenance. Based on these criteria, the guide bunds appeared to be the most suitable solution. The structure was implemented in the Delft3D-model and some additional simulations proved that the effect of this structure on the hydro and morphodynamic conditions in the river is twofold.

  First, the guide bunds improve the distribution of the flow over the cross section of the river. More flow is forced trough the right side and indeed the flow velocities turn out to be higher at that location. Moreover, the flow velocities on the left side decrease, as expected. However, the structure has an opposing effect on the cumulative erosion and sedimentation. More sedimentation takes place at the right side of the channel, whereas the left side of the channel gets deeper.

What can be done to improve the efficiency of the approach that is used to deal with the sedimentation problems around the Yondó Bridge?

Based on the answers on the subquestions of this research, it can be concluded that the best way to improve the situation in Barrancabermeja, is the construction of a guide bund structure in the vicinity of the Yondó Bridge. This structure will force more of the flow into the right part of the channel and therefore the amount of sedimentation on this side is reduced. As a result, the dredging activities that are currently executed could be terminated. However, as mentioned before in Chapter 14, more detailed (physical) model tests should be performed to gain better insight in the effect of the guide bunds on the hydro and morphodynamic conditions in the Magdalena River around Barrancabermeja.

16

Recommendations

The recommendations that are made in this chapter differ in nature to each other. Therefore, they have been subdivided into four categories: recommendations of topics of future research projects, recommendations for projects concerning bridges, recommendations related to river simulating and practical recommendations.

Topics of future research projects

Development of the guide bund solution in Barrancabermeja

This report shows that the implementation of guide bunds in the the Magdalena River in Barrancabermeja would be an efficient way to improve the situation. However, the implementation of guide bunds has only been studied at a conceptual level. Therefore, more research into a favourable design of the guide bunds, and their effects on the morphological situation is required. In the case of a positive outcome, steps should be made to implement the solution in practice.

Situation Puerto Berrío

When looking at the sedimentation problems occurring around the bridge, one might conclude that the design of the Yondó Bridge was not ideal in the first place. The same design is being used at the moment for a new bridge in Puerto Berrío. It is hard to say if the issues observed in Barrancabermeja are also going to be present in Puerto Berrío as well, but the conditions are strikingly similar to the conditions in Barrancabermeja, so a similar response is likely to occur. which greatly increases the probability of similar problems occurring. Therefore, the design of the bridge should be re-evaluated in two ways. Firstly, the design of the bridge itself should be improved, and secondly, the design of the bridge should be adjusted to the situation in Puerto Berrío.

Seismic risks

As has been explained in Section 8.5, the possibility exists that the Yondó Bridge in its current state is not sufficiently resistant against earthquakes. It would be very helpful and interesting to evaluate this in a future study, and look for measures in case the situation does not fulfil the requirements.

Recommendations to for projects concerning bridges

Include hydraulic effects into a bridge design

In case a new bridge is developed, it is important to include the dynamics of the river in the design process. Also the influences of the newly designed bridge on the river should also be evaluated. Besides, the effects of the new bridge on the locally present sand bars should be investigated in more detail. Considering these factors will significantly reduce the probability of sedimentation or erosion related problems occurring.

River simulation related recommendations

Data availability

Experience shows that the availability of data is a key factor in the success of a study. In countries like the Netherlands, this is often not a problem, but in a country like Colombia, the process of data gathering can be a project on its own. Therefore, make sure that data sources are reliable and secure in case a study is started that depends on external data sources. To this study, data on bed topography before, during and just after the construction of the bridge would have made a large difference.

River simulation method including scour
In this study, Delft3D software has been used to simulate river development. This turned out to be non-ideal, since Delft3D has not been designed to take into account local scour. Scour holes had to be integrated in the model in a very forced way. So in the future, if a river needs to be analysed taking into account local scour, the use of more detailed software that can handle scour, for example OpenFOAM, is recommended. However, this software is more advanced and therefore less easy to use than Delft3D.

Practical recommendations

Sieve analysis improvement
One of the biggest disappointments during this study was the analysis of a sediment sample taken during the field trip to Barrancabermeja. The sieve test that has been used to analyse the sediment sample turned out to be useless. The reason for this was a clumsy selection of sieve sizes. The difference between sizes of the used sieves were way to large. In the end, only two sieves retained a significant amount of sediment, which is way too small. Because of the unavailability of the laboratory in the following weeks, the sediment sample could not be tested again, which made the sediment sample useless. So in case a sieve analysis is used, there should be made sure that correctly sized sieves are used.

Method to accurately measure boat to bank distances
During the field trip in Barrancabermeja, distances from the boat to the bank of the river at the time the measurement of a cross-section started, were manually measured. A little device was used to measure these distances, but the device was neither accurate nor fast. In the end, these distances had to be estimated by the passengers of the boat. So in case of similar measurements, the availability of a functional method to measure distances to the bank is important as this improves the reliability of the measurements.

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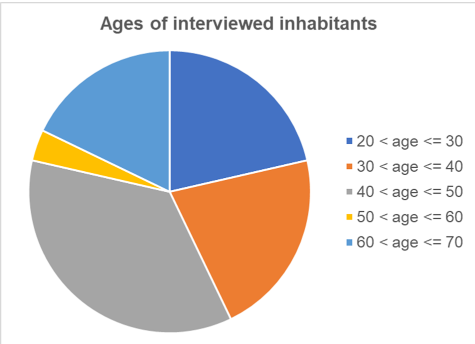
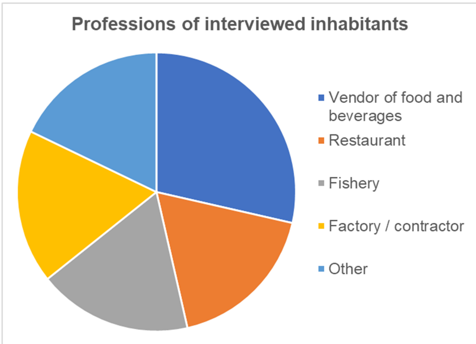
Appendices

A
Interviews with the inhabitants of Barrancabermeja

During the field trip to Barrancabermeja several interviews have been conducted with the inhabitants of this city (see Figure A.3). The purpose of these interviews was to understand the position of the citizens in relation to the Magdalena River in general and the occurring problems around around Barrancabermeja. In total 28 conversations have been held covering a broad range of ages and professions. In Figures A.1a and A.1b the distributions of the ages and professions of the interviewed citizens are depicted. During the 28 conversations a lot of corresponding things came up and therefore it has been decided not to conduct any more interviews.



(a) Age distribution



(b) Professions

Figure A.1: Statistical data of interviewed inhabitants of Barrancabermeja

The citizens were asked for their opinion about the existence and influence of the bridge in general and their opinion about the river dynamics and the dredging processes. The essence of these questions was to check whether or not the mentioned subjects changed anything in their living conditions, as this indicates their interest in the whole project.

The first clear conclusion is that a lot of citizens do not have a clear opinion about the whole situation, as can be seen in Figure A.2. Mostly because they do not know about the occurring problems and apparently have no interest in it.

"I am too old for this, I do not think about these things"
– 70 year old vendor from Barrancabermeja

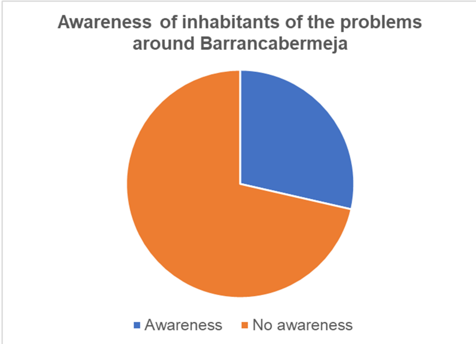


Figure A.2: Division of interviewed citizens who are and are not aware of the problems of the Magdalena River around Barrancabermeja

Taking into consideration the professions of the interviewed citizens, no clear division can be made regarding the awareness with the situation of people in certain professions. The expectation was that inhabitants working in the fishery would have more problems with the dredging than other inhabitants, as some people in general claim that local dredging negatively influences the amount of fishes. However, they did not mention the effect of dredging on the amount of fishes at all, besides one fisherman:

"Dredging is good for the fishery because it gives a bigger river depth and therefore more fishes"
– 50 year old fisherman from Barrancabermeja

As there is no direct relationship between a local bigger depth and the amount of fishes, this shows the fisherman's ignorance about this subject. Allegedly, the interest of the fishermen is not that great. The citizens who do have an opinion about the situation are more talking about the situation in general than about the impact of the situation on their living conditions. In general their displeasure about the dredging comes up, for example, because the dredging is already going on for such a long time and they do not see any improvements. Also some of the citizens mentioned a road from Barrancabermeja to Medellín which, according to them, should have been built, but which is not there.

"The sand of the river is eternal, it is important to dredge but in this way nothing will change"
– 50 year old motorboat driver, living since one year in Barrancabermeja

Furthermore, when asking the citizens specifically for the impact of the situation on their living conditions, they could not give an clear answer.

(a) Interviewing a local transporter of tiles

(b) Interviewing a retired teacher

Figure A.3: Interviewing the citizens of Barrancabermeja

The general conclusion from the conducted interviews is that the citizens of Barrancabermeja almost do not suffer from the situation of the Magdalena River around their city. Many of the citizens do not even know about the problem, and if they are aware of the problem, they often do not have an opinion. In case they have an opinion, this is more about the general process of how the dredging is going and how the government is organising everything but not about the effects on their living conditions. Therefore the interest of the inhabitants of Barrancabermeja is set to be very low in the stakeholder analysis (Chapter 2) of this study.

B

Details of cargo transportation

This appendix shows the tables used for generating the graphs of the transport analysis described in Chapter 3.

B.1. National cargo transport in Colombia

Table B.1: Cargo transport over different modes of transport (Rojas Giraldo et al., 2017), in thousands of tonnes de cargo

Year	Land	Land - extrapolated	Railway	River	Air	Maritime	Total
2002	84,019		31,032	3,480	122	532	119,185
2003	99,782		42,781	3,725	132	928	147,348
2004	117,597		46,182	4,211	129	588	168,707
2005	139,646		49,227	4,863	135	400	194,271
2006	155,196		49,708	4,025	138	509	209,576
2007	183,126		53,204	4,563	137	454	241,484
2008	169,714		58,472	4,953	123	372	233,634
2009	173,558		59,398	4,070	109	364	237,499
2010	181,021		67,025	3,691	119	353	252,209
2011	191,701		74,554	3,650	124	646	270,675
2012	199,369		76,800	3,474	127	388	280,158
2013	220,309		76,781	2,968	149	774	300,981
2014		223,387	42,907	2,858	163	601	269,916
2015		233,133	47,935	3,524	179	969	285,740
2016		242,878	55,293	3,938	185	1,786	304,080

B.2. National cargo transport over Magdalena River

Table B.2: Division of cargo transport over the Magdalena River (Rojas Giraldo et al., 2017) in tonnes de cargo

	2006	**2007**	**2008**	**2009**	**2010**	**2011**	**2012**	**2013**	**2014**	**2015**	**2016**
Petroleum based products											
Asphalt	0	348,056	0	0	0	0	0	0	0	0	0
Diesel	45,775	3,463	40,376	0	0	0	0	15	0	0	0
Diesel - motors	215,731	106,930	233,330	237,896	255,605	36,873	28,563	17,281	124,101	6,592	7,377
Fuel oil	973,286	233,330	914,622	888,317	791,418	1,340,355	1,108,059	1,209,925	1,267,148	1,241,081	1,320,000
Gases	1,902	914,622	4,095	17,484	10,655	17,199	14,868	7,705	1,746	0	0
Gasoline	51,781	4,095	81,270	35,634	28,289	24,401	25,162	1,585	2,475	6,506	6,194
Lubricants	160	40,376	3,236	2	1	924	0	0	0	0	1
Naphtha	225,566	81,270	174,296	297,908	108,854	11,662	6,825	0	0	224,761	739,806
Thinners	57,222	0	3,463	0	3,387	0	339	0	0	5,991	0
Others	151,663	3,236	190,928	116,884	113,177	65,382	60,398	21,156	4,775	113,325	105,804
Subtotal	1,723,086	1,735,378	1,645,616	1,594,125	1,311,386	1,496,796	1,244,214	1,257,667	1,400,245	1,598,256	2,179,182
Other products											
Agricultural	10,330	2,444	4,069	3,018	7,865	1,002	5,538	7,141	19,177	21,300	13,638
Cement	58,751	41,786	15,858	12,186	5,199	7,872	6,478	1,951	21,030	10,307	35,905
Construction	53	9	133	95	154	6	16	10	61	8,151	2,985
Drinks	1,731	29,011	1,974	1,015	406	364	288	314	222	313	46
Fertilizers	20,801	31,849	20,313	4,678	3,953	11,050	4,014	147	7385	7618	10051
Fish	7	13	1,447	1,001	0	0	2	0	2	0	0
Groceries	4,477	13,192	6,095	2,203	3,297	2,624	1,168	942	5271	8422	9,347
Iron and steel	0	5	990	14,713	12,613	0	2,718	14,852	45,753	61,894	60,026
Machinery	92,940	141,326	160,131	75,328	34,088	26,275	68,880	56,812	139,797	102,437	60,618
Manufactures	1,432	3,154	6,732	7,269	11,763	1,657	62	15,771	420	121	66
Metalworking	0	411	8,082	2,258	3,405	15,822	7,875	2,166	10,984	128	137
Mineral carbon	29	11,848	60,075	39,171	880	0	2,050	2,930	3,800	6,152	10,001
Minerals	15,337	2,101	59,103	41,172	2,400	2,459	0	0	0	393	25,744
Woods	26,592	14,443	6,937	11,962	2,448	244	38	25	232	132	110
Others (including paper and packaging)	119,580	123,127	84,124	50,761	62,315	65,098	74,893	23,464	72,492	64,843	106,909
Subtotal	352,060	414,719	436,063	266,830	150,786	134,473	174,020	126,525	326,626	292,211	335,583
Total	**2,075,146**	**2,150,097**	**2,081,679**	**1,860,955**	**1,462,172**	**1,631,269**	**1,418,234**	**1,384,192**	**1,726,871**	**1,890,467**	**2,514,765**

Table B.3: Cargo transport over Magdalena River compared to total inland waterway and total national cargo transport

Year	**2002**	**2003**	**2004**	**2005**	**2006**	**2007**	**2008**	**2009**	**2010**	**2011**	**2012**	**2013**
Total inland waterway transport [thousands of tonnes]	3,480	3,725	4,211	4,863	4,025	4,563	4,953	4,070	3,691	3,650	3,474	2,968
Total transport over Magdalena River [thousands of tonnes]	2,131	2,472	2,653	2,210	2,075	2,150	2,091	1,861	1,462	1,631	1,418	1,384
Total cargo [thousands of tonnes]	119,185	147,348	168,707	194,271	209,576	241,484	233,634	237,499	252,209	270,675	280,158	300,981
% transport over Magdalena	61.25	66.36	63.00	45.45	51.56	47.12	42.21	45.72	39.61	44.69	40.82	46.64
% of total cargo	1.79%	1.68%	1.57%	1.14%	0.99%	0.89%	0.89%	0.78%	0.58%	0.60%	0.51%	0.46%

C

Fieldwork in Barrancabermeja

This appendix provides an overview of the fieldwork that took place during the project. The goal of the fieldwork was to gather the missing information needed for the Delft3D-model and the empirical scour analysis. From December 10 until December 13, measurements have been taken in the Magdalena River around the city of Barrancabermeja. Section C.1 provides more information about this location. The measurements were taken from a boat and different types of equipment were used, which will be described in Section C.2. Section C.3, the last section, summarises the most important conclusions of the fieldwork.

During the fieldwork, the local population of Barrancabermeja was interviewed to gather more insight in their opinion on the situation around the bridge. The results of these interviews are described in Chapter 2 and Appendix A.

C.1. Measurement area

Figure C.1 shows a visual overview of the most important aspects of the measurement area. The GPS reference points needed to be installed before the measurements could start. Finding these reference points appeared to be a significant challenge, since some of the existing points were covered by asphalt or vegetation. Luckily, two suitable options were found on the first day, when the measurement area was investigated. A measuring stick for the water levels is present at the river side across the office of Cormagdalena. A vendor of orange juice, whose stall is located next to this measuring stick, recorded the water level during the measuring days every hour (see Figure C.2).

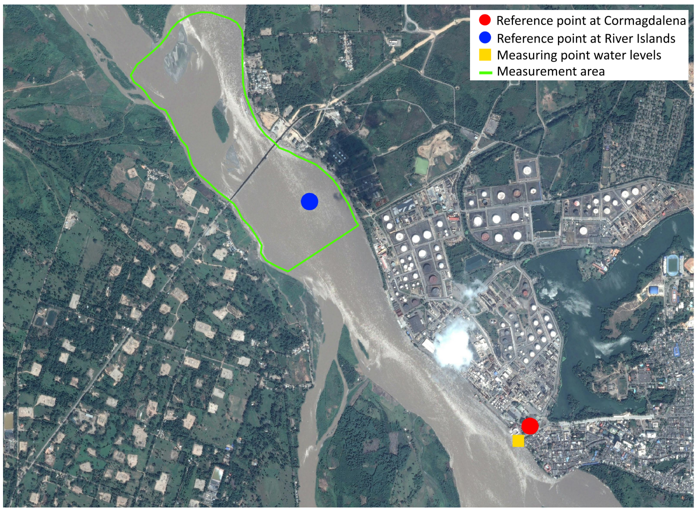


Figure C.1: Visual overview of the measurement area in Barrancabermeja by the green, dotted line. The GPS reference points used during the measurements are indicated by the red circle (Cormagdalena, existing) and the blue circle (the River Island, self-created). The yellow square represents the point where the water levels were measured during the fieldwork.

Figure C.2: The measuring stick attached to the river side in Barrancabermeja, used to measure the water levels in the Magdalena River.

C.2. Measurement methods

In this section, the measurement methods used during the fieldwork are described. Subsequently, the working of the ADCP, the echo sounder, the RTK and GPS and the Van Veen Grab Sampler is explained.

ADCP

An Acoustic Doppler Current Profiler (ADCP) is used to measure the velocity of the water in the entire water column. It measures the water currents with sound waves called the Doppler effect, defined as follows: a sound wave has a higher frequency, when it moves to you than when it moves away from you (Ocean Instruments, 2017). This is, for example, the case when an ambulance fastly passes by on the way to an accident.

The ADCP transmits sound with a constant frequency into the water of the river. Humans cannot hear this sound, because the frequency is very high. The sound wave reflects back to the measuring instrument as it reaches the water particles. The frequency of the returning sound wave is slightly higher, due to the Doppler effect mentioned above. Based on the difference in frequency between the outgoing and incoming wave, the instrument computes how fast the particle and the surrounding water moves (Ocean Instruments, 2017). This happens continuously as the equipment moves through the water, mounted on a boat. An example of the construction of the ADCP on a boat is illustrated by Figure C.3. During the field trip nobody took a representative picture of the ADCP, therefore a picture from earlier fieldwork is taken.

Echo sounder

The echo sounder is used to measure the location of the river bed. Just as the ADCP, the echo sounder is also based on the principle of transmitting and receiving sound. It is also kept 30 centimetres under the water surface and connected to the same structure as the ADCP. The echo sounder determines the distance to the bed according to the following formula (Ocean Instruments, 2017):

$$\mathrm{s}_{\mathrm{bed}} = \frac{t}{2} \cdot v_{\mathrm{sound}} \tag{C.1}$$

Where:	s_{bed}	=	distance to the river bed	[m]
	t	=	travelled time of the sound wave	[s]
	v_{sound}	=	speed of sound in water	[m/s]

Figure C.3: A construction to stabilise the ADCP at the right side of the boat. During the field trip, the ADCP was shifted slightly to the right so the echo sounder fitted next to it.

RTK and GPS

The ADCP and the echo sounder do not have a properly functioning Global Positioning System (GPS). Therefore both instruments were coupled to the Real-Time Kinematic (RTK) equipment, which can determine the geographical position very precisely. It is based on the general GPS system, consisting of 24 satellites, flying in six different orbits around planet Earth. They work 24 hours a day and the position of an object or a person is based on the distance between the satellite and the object or person, indicated by the time that it takes for a radio wave to cover the distance (NovAtel, 2017).

An RTK system consists of a fixed point, called the base station, and a moving point, known as the rover. The position of the base station is known, as it is located at a predefined GPS location. Figure C.4 illustrates the relation between the different parts of the RTK system. The connection between the base and the rover may not be lost during the measurements as the base station is the reference point. Figures C.5 and C.5a depict the instruments that were used during the field trip.

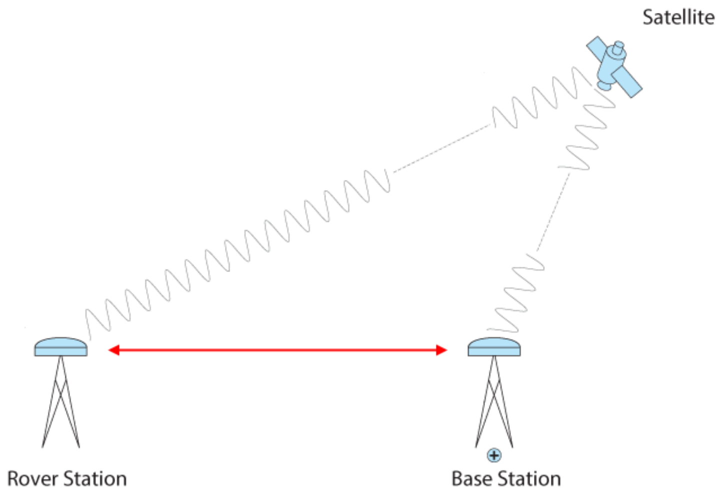


Figure C.4: Visualisation of the working of RTK measurement equipment, adapted from NovAtel (2017)

(a) Base

(b) Rover

Figure C.5: Photos of the setup of the base (left) and the rover (right) station during the fieldwork

As a backup and double check for the RTK, a small GPS measuring instrument was used to record the latitude and longitude of the measured sections by hand. Garmin's GPSmap 60CSx, see Figure C.6, fits this purpose as it stores specific points defined by the user. The person who was responsible for this job had to specify the beginning and the end of a section at the exact same time as the operator of the ADCP started or ended a measurement. In this way, the highest possible human accuracy is achieved.

Figure C.6: GPS measurement equipment to record the latitude and longitude by hand (Garmin, 2017)

Van Veen Grab Sampler

In order to get more insight in the sediment types and grain sizes in the reach of the Magdalena River around Barrancabermeja, two sediment samples were taken. This was done by using a Van Veen Grab Sampler, see Figure C.7, which automatically closes its jaws as soon as it feels the bottom or the bed. On the island in the middle of the river, consisting of the dredged sand from the bottom, the samples were taken. The location was chosen close to the base of the RTK as depicted in Figure C.5a. The sediment samples were analysed in the lab at the Javeriana University, the results of this analysis can be found in Appendix G.

Figure C.7: Example of a Van Veen Grab Sampler (Hydro-Bios, 2017)

C.3. Conclusions

The fieldwork was very useful for two reasons. Firstly, we measured amongst others the water depths, the discharge, the flow velocity and the sediment characteristics, which could be used in different parts of the project. Moreover, the practical skills that are needed to operate the measuring equipment is a really good addition to the predominantly theoretical skill set of a student at the Delft University of Technology. Also, during the fieldwork a lot of minor and major problems occurred, such as the absence of a GPS reference point or a measured water level that is higher than the ground level at the river side. Those problems have to be solved on the spot by being smart and creative and this really shows that retrieving data from the field is not as easy as it seems. For Dutch students, who always have access to enough and reliable data, this is a convenient revelation for the future. Figures C.8a to C.8d show an impression of the fieldwork.

(a)

(b)

(c)

(d)

Figure C.8: An impression of the fieldwork by four photos taken by the project group: (a) Puente Yondo, (b) Installing the base at the island, (c) Sjoerd with the RTK-base, and (d) Bas working on the boat.

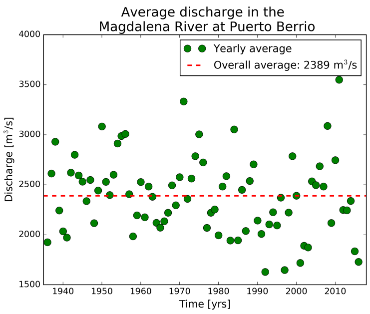
D

Results hydrodynamic data processing

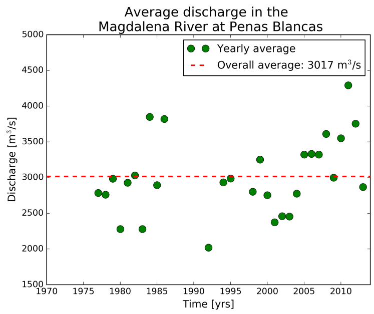
This appendix contains all results of the hydrodynamic data processing, executed in Chapter 5. Section D.1 contains the graphs of the discharge, whereas Sections D.2 and D.3 present the results for the water level and the sediment transport.

D.1. Discharge

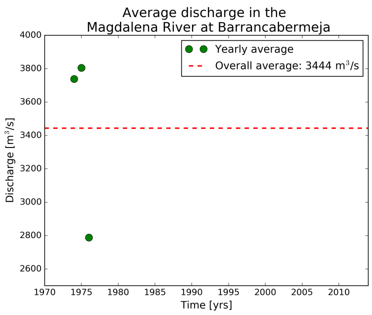
Mean



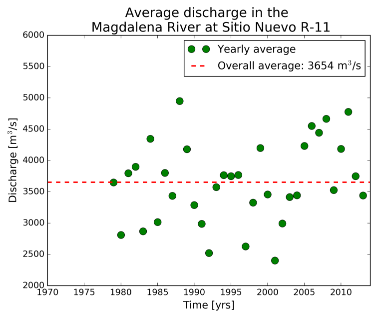
(a) Puerto Berrio



(b) Penas Blancas



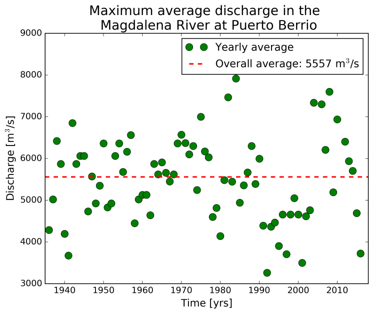
(c) Barrancabermeja



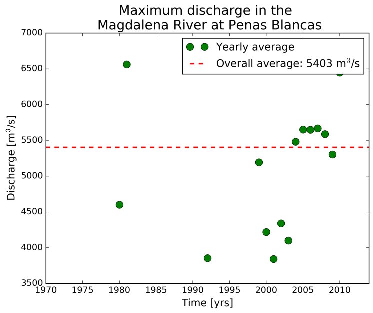
(d) Sitio Nuevo R-11

Figure D.1: Graphs that represent the average discharge in the Magdalena River at four measuring stations. The red-dotted line indicates the average value of the entire measuring period.

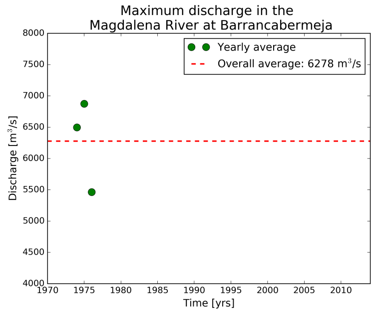
Maximum



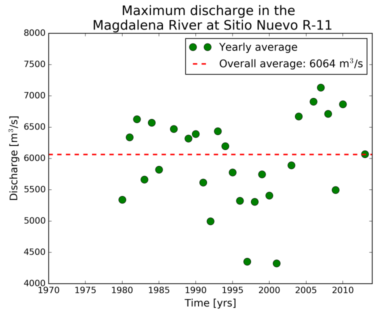
(a) Puerto Berrio



(b) Penas Blancas



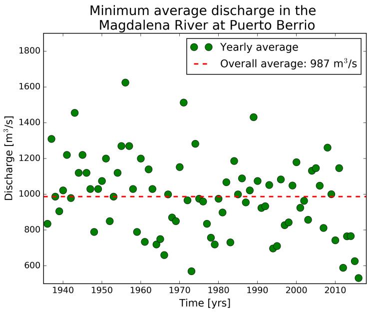
(c) Barrancabermeja



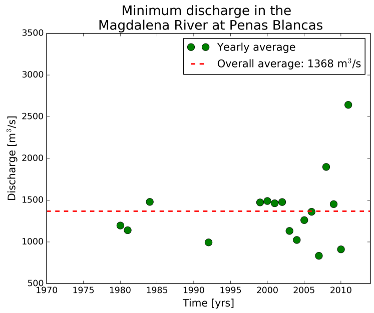
(d) Sitio Nuevo R-11

Figure D.2: Graphs that represent the maximum discharge in the Magdalena River at four measuring stations. The red-dotted line indicates the average value of the entire measuring period.

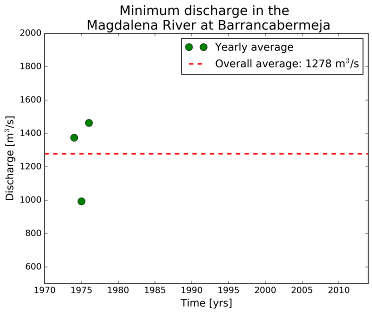
Minimum



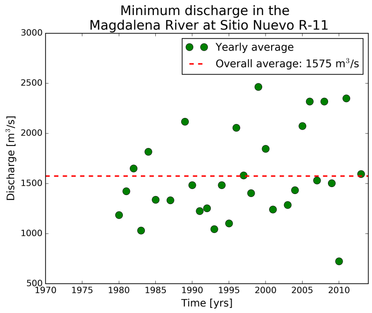
(a) Puerto Berrio



(b) Penas Blancas



(c) Barrancabermeja

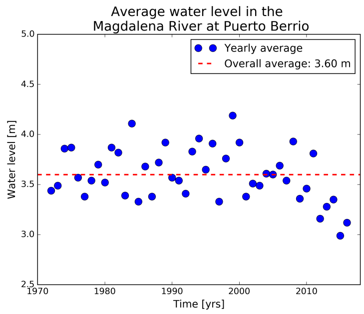


(d) Sitio Nuevo R-11

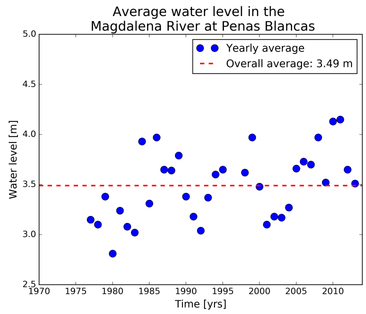
Figure D.3: Graphs that represent the minimum discharge in the Magdalena River at four measuring stations. The red-dotted line indicates the average value of the entire measuring period.

D.2. Water level

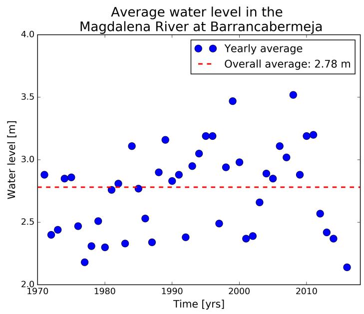
Mean



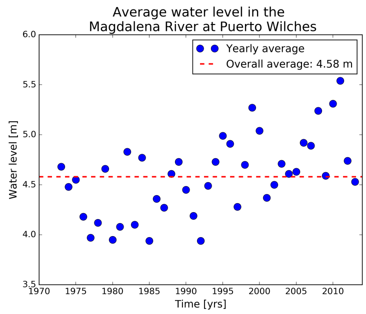
(a) Puerto Berrio



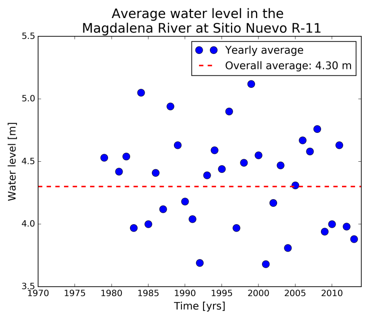
(b) Penas Blancas



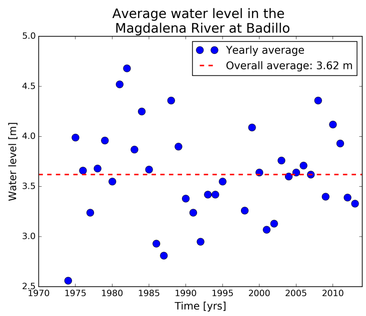
(c) Barrancabermeja



(d) Puerto Wilches



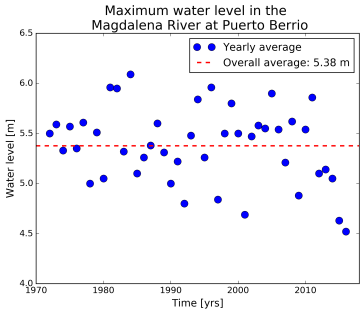
(e) Sitio Nuevo R-11



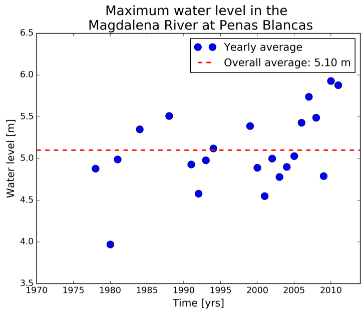
(f) Badillo

Figure D.4: Graphs that represent the average water level in the Magdalena River at six measuring stations. The red-dotted line indicates the average value of the entire measuring period.

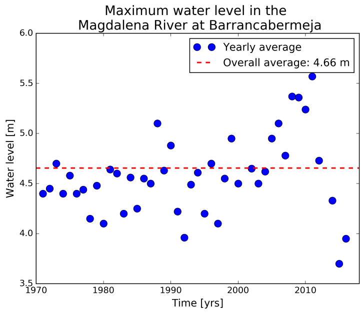
Maximum



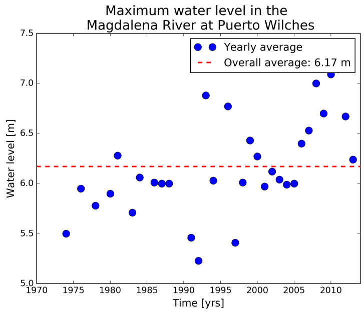
(a) Puerto Berrio



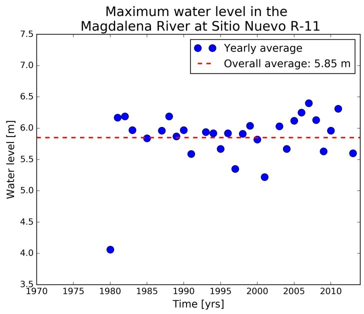
(b) Penas Blancas



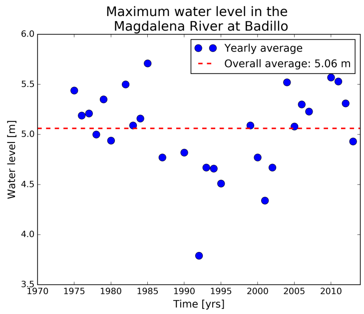
(c) Barrancabermeja



(d) Puerto Wilches



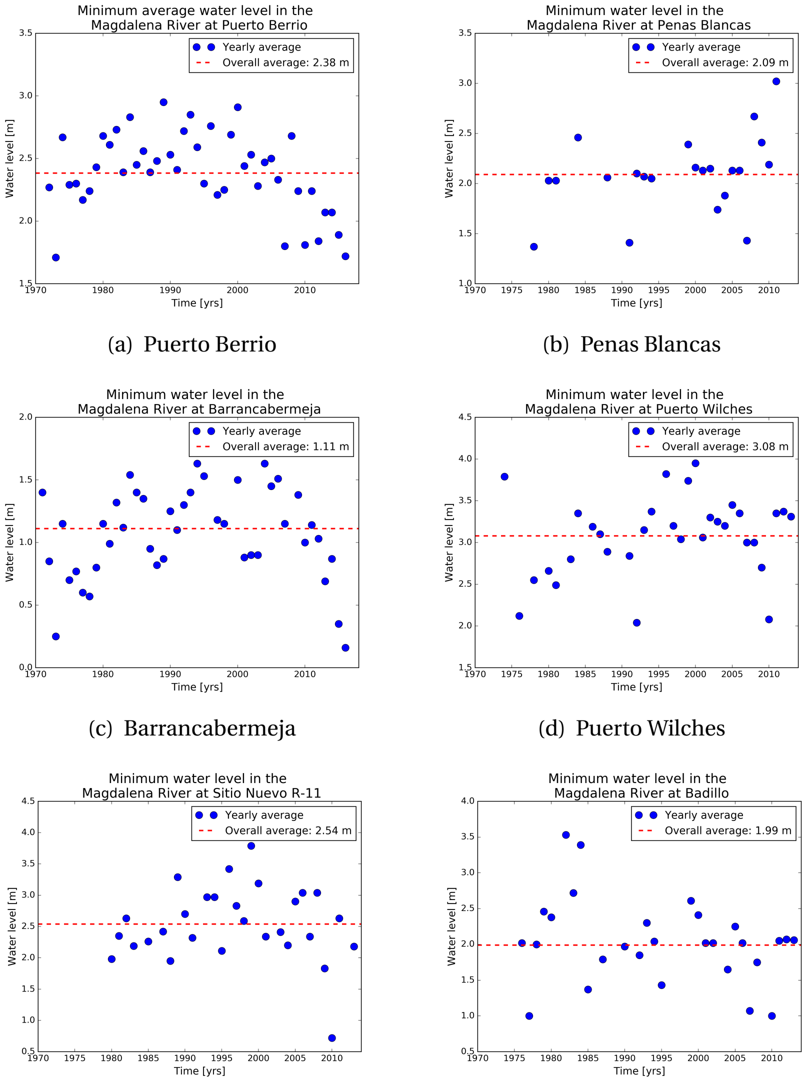
(e) Sitio Nuevo R-11



(f) Badillo

Figure D.5: Graphs that represent the maximum water level in the Magdalena River at six measuring stations. The red-dotted line indicates the average value of the entire measuring period.

Minimum



(a) Puerto Berrio

(b) Penas Blancas

(c) Barrancabermeja

(d) Puerto Wilches

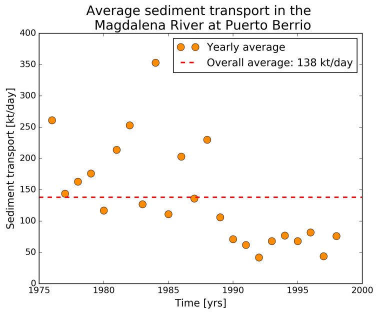
(e) Sitio Nuevo R-11

(f) Badillo

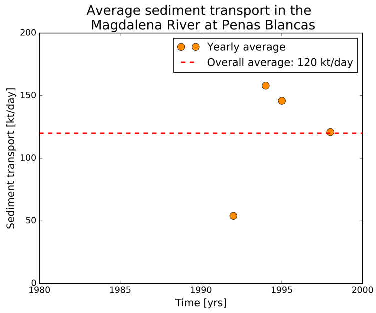
Figure D.6: Graphs that represent the minimum water level in the Magdalena River at six measuring stations. The red-dotted line indicates the average value of the entire measuring period.

D.3. Sediment transport

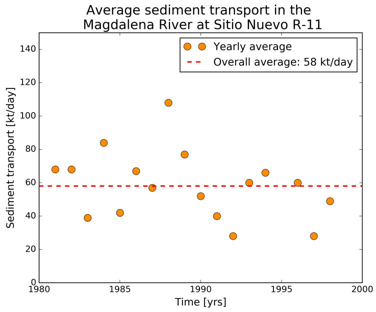
Mean



(a) Puerto Berrio



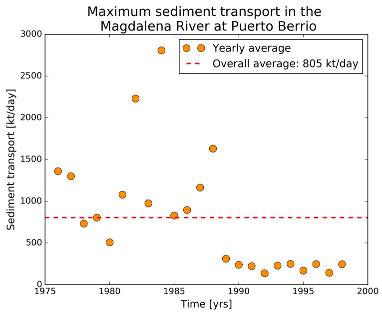
(b) Penas Blancas



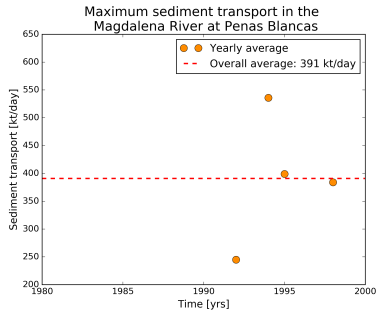
(c) Sitio Nuevo R-11

Figure D.7: Graphs that represent the average sediment transport in the Magdalena River at three measuring stations. The red-dotted line indicates the average value of the entire measuring period.

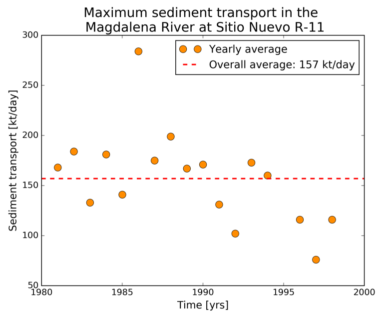
Maximum



(a) Puerto Berrio



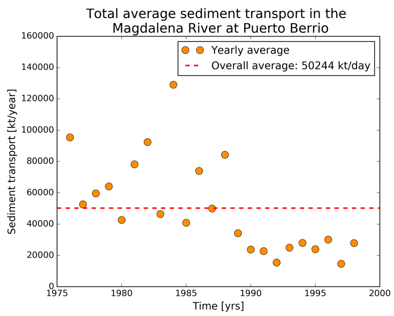
(b) Penas Blancas



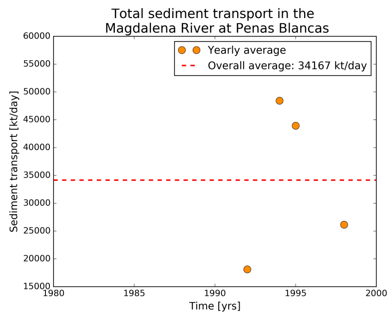
(c) Sitio Nuevo R-11

Figure D.8: Graphs that represent the maximum sediment transport in the Magdalena River at three measuring stations. The red-dotted line indicates the average value of the entire measuring period.

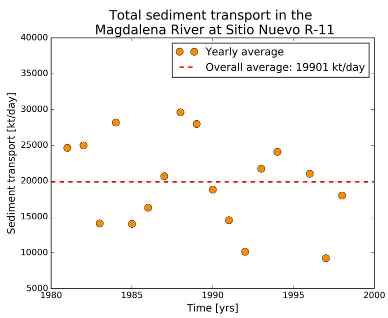
Total



(a) Puerto Berrio



(b) Penas Blancas



(c) Sitio Nuevo R-11

Figure D.9: Graphs that represent the total sediment transport in the Magdalena River at three measuring stations. The red-dotted line indicates the average value of the entire measuring period.

E

Field measurement conversion

This appendix describes the conversion of the data measured during the fieldwork in Barrancabermeja. During the trip, data was measured with an ADCP and an echo sounder. A more detailed description of this equipment can be found in Appendix C. The ADCP and the echo sounder store the measurements in a format that is not directly suitable for an analysis. In order to be able to analyse and use the data, a couple of conversion steps are conducted. A summary of these steps can be found in Figure E.1 and below the steps are shortly described.

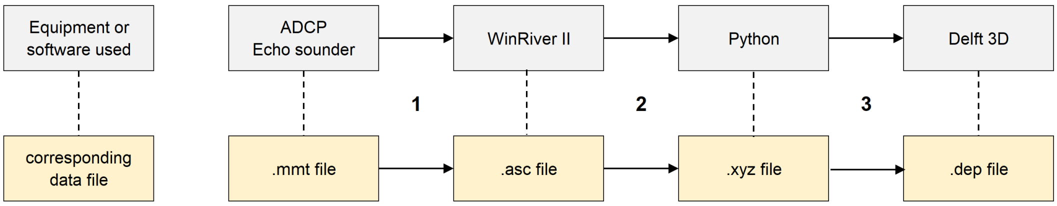


Figure E.1: Visual overview of the conversion steps taken in order to make the data suitable for analysis

- **Step 1:** The output files of the ADCP and the echo sounder have a .mmt format. These files can be viewed in a program such as WinRiver II, which displays amongst others, the measured profile, see Figure E.2. The program also provides an overview of the statistics of the measurements. The user can decide into which format the data is processed. In this case, the ASC output is chosen to be the most suitable.

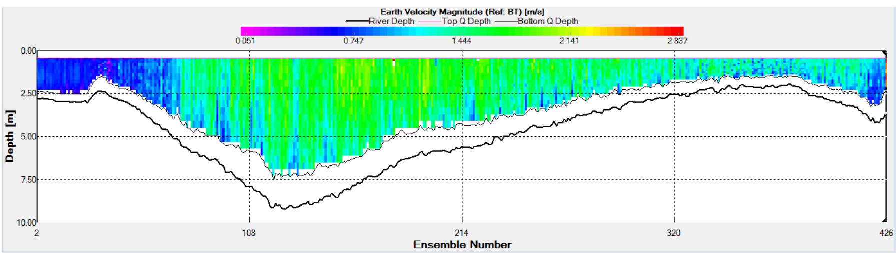


Figure E.2: A screenshot of WinRiver that shows the profile of a cross section in the Magdalena River, measured during the fieldwork

- **Step 2:** Figure E.3 shows one section of a WinRiver II-output file, which is a text file that can be imported in Python. The red triangle indicates the depths measured by the beams of the echo sounder that are used in the analysis.

Example ASCII-Out File

```
This is WinRiver II comment line #1
This is WinRiver II comment line #2
    20     16     20     14      1      0      3
17 8 20 6 26 49 99     2      1    4.000   -2.390  228.770   28.190
-74.62    59.64     4.76     3.25     2.62     0.00     0.00     0.00     2.78     2.83     2.69     2.93
0.00         0.00         0.00         0.00         0.00
30000.0000000 30000.0000000 -32768   -32768         0.0
-0.0          -0.0          -0.0          0.0          7.0          0.0          5.0  0.45   2.20
14 cm BT dB 0.42  0.066
  0.45     69.38    320.15  -44.5   53.3    2.4    3.7   84.8   86.9   81.4   83.1  100 2147483647
  0.55     74.90    318.25  -49.9   55.9    1.8    2.6   85.3   86.5   81.5   83.2  100 2147483647
  0.65     72.60    319.50  -47.2   55.2    1.7    3.0   89.5   87.0   82.3   84.9  100 2147483647
  0.80     73.21    317.69  -49.3   54.1    1.7   -0.4   91.2   89.5   87.0   88.7  100 2147483647
  1.00     74.82    314.21  -53.6   52.2    2.3   -2.1   90.0   89.1   82.8   87.4  100 2147483647
  1.20     81.03    314.04  -58.3   56.3    3.3    0.9   86.6   88.7   84.5   87.1  100 2147483647
  1.40     82.22    316.71  -56.4   59.8    5.0    1.4   87.5   87.5   82.0   84.5  100 2147483647
  1.60     78.80    317.24  -53.5   57.9    7.2   -0.6   87.1   86.7   80.8   84.6  100 2147483647
  1.80     71.72    317.52  -48.4   52.9    6.3   -2.6   86.6   86.2   80.7   85.0  100 2147483647
  2.00     69.02    314.53  -49.2   48.4    5.8   -5.3   87.6   87.2   82.5   83.8  100 2147483647
  2.20     64.34    318.38  -42.7   48.1    5.2   -3.0   86.7   88.0   83.3   84.6  100 2147483647
  2.40    -32768    -32768 -32768 -32768 -32768 -32768    255    255    255    255    0 2147483647
  2.60    -32768    -32768 -32768 -32768 -32768 -32768    255    255    255    255    0 2147483647
  2.80    -32768    -32768 -32768 -32768 -32768 -32768    255    255    255    255    0 2147483647
```

Figure E.3: One section of a WinRiver II-output file. The red rectangle shows the depths, measured by the beams of the echo sounder. The meaning of all numbers in this image can be found in the User Manual of WinRiver II by Teledyne (2008).

- **Step 3:** The xyz.files that are created by Python are used for the grid generation in Delft3D. The process of grid generation is described in Appendix J.

F

Water level correction

This appendix describes how the altitudes, measured by the ADCP during the fieldwork in Barrancabermeja, are checked and corrected. These altitudes are related to the water levels in the river and as they appeared to be incorrect, they should be corrected in order to coincide with the reference water level at Cormagdalena.

At the riverside just outside the office of Cormagdalena, a ruler indicating the water level in the river reach, is located. At the second day of the field trip, the coordinates and altitude of this point were measured, see the third column of Table F.1. Since these exact coordinates are known, the ruler can be used as a checkpoint for the altitude of the water levels, measured in the downstream part of the river.

As can be seen in the second and third column of Table F.1, the altitudes of the two cross sections are higher than the one measured at Cormagdalena (80.96 and 77.72 m above MSL versus 77.1 m above MSL). This is impossible as the cross sections are located more downstream, and therefore closer to the sea, than the office of Cormagdalena. This means that the water levels measured by the ADCP should be shifted to the correct level of the ruler. The correction factor for the altitude of the water levels is computed using the latitude, longitude and altitude of the most upstream and downstream measured cross section.

Table F.1: Overview of the latitude, longitude and altitude of the two cross sections ('CS1' and 'CS13') and the office of Cormagdalena ('CM'). Those points are also indicated in Figure F.1.

	'CS13'	**'CS1'**	**'CM'**
Latitude [°]	7.0756	7.0734	7.0333
Longitude [°]	-73.8902	-73.8866	-73.5242
Altitude [m above MSL]	80.96	77.72	77.10

The position of these cross sections relative to Cormagdalena are depicted in Figure F.1. The distance between 'CS13' and 'CS1' can be used to determine the slope of the river, which is equal to $3.37 \cdot 10^{-4}$. After that, this slope can be used to calculate the water level at Cormagdalena based on the measurements. As expected, this water level turns out to be 2.26 m too high. This means that 2.26 m is subtracted from all the measured altitudes of the water levels.

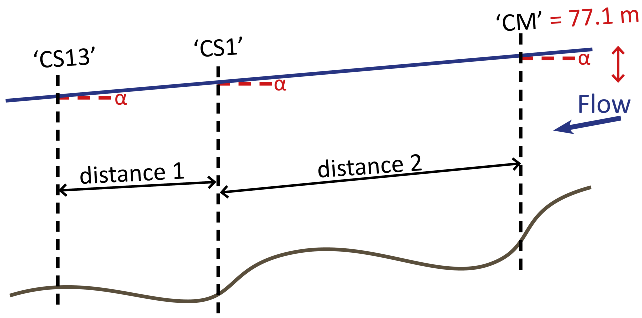


Figure F.1: Profile of the Magdalena River indicating the ruler at Cormagdalena ('CM') and two measured cross sections ('CS1' and 'CS13'). The slope is constant over the entire river reach and the flow goes from right to left.

G

Sediment

In order to analyse and predict the dynamics of the Magdalena River, information about the type of sediment is required. Especially the median size of the bed material (d_{50}), the maximum grain size (d_{90}) and the geometric standard deviation of the particle size distribution (σ_g) is needed. This information is used as an input for the bar mode analysis presented in Chapter 6 and to both the estimation of the scour hole dimensions in Chapter 8 and the generation of the Delft3D-model in Chapter 9.

The sediment information is derived from a sieve analysis executed by a laboratory technician at the Pontifical Xavierian University in Bogotá. The sediment samples that are examined have been collected from an artificial sand bank close to the Yondó Bridge. This sand bank is created by a dredging company, by dumping the sand that is removed from the river bed just upstream of the bridge. The sediment samples can therefore be considered to be representative for the river bed load.

Usually, a sieve test is conducted by a machine, but due to unclear reasons, the analysis was preformed manually by a laboratory technician (see Figure G.1). Two samples were sieved, of which the total amount of sediment was weighted before the process. Afterwards, the retained sediment per sieve was weighted. In total, six sieves were used for the test. The results of the tests are presented in Tables G.1 and G.2.

Figure G.1: Sediment analysis conducted manually by a laboratory technician from the Xavierian University

Table G.1: Sieving results of sediment sample 1

Sieve type	Sieve size [µm]	Residue weight [g]	Cumulative retained weight [g]	Cumulative passed weight [g]	Percentage cumulative [%]
3/8	9500	0.00	0.00	1451.58	100.00
4	4750	1.45	1.45	1450.13	99.90
10	2000	3.12	4.57	1447.01	99.69
40	425	645.25	649.82	801.76	55.23
100	150	779.30	1429.12	22.46	1.55
200	75	21.47	1450.59	0.99	0.07
Residue	-	0.99	1451.58	0	0.00
	Total weight [g]	1451.58			

Table G.2: Sieving results of sediment sample 2

Sieve type	Sieve size [µm]	Residue weight [g]	Cumulative retained weight [g]	Cumulative passed weight [g]	Percentage cumulative [%]
3/8	9500	3.51	3.51	1694.86	99.79
4	4750	17.06	20.57	1677.80	98.79
10	2000	43.75	64.32	1634.05	96.21
40	425	1091.69	1156.01	542.36	31.93
100	150	532.53	1688.54	9.83	0.58
200	75	9.48	1698.02	0.35	0.02
Residue		0.35	1698.37	0.00	0.00
	Total weight [g]	1698.37			

From these sieving results a plot of the cumulative sediment size distribution can be made, see Figure G.2.

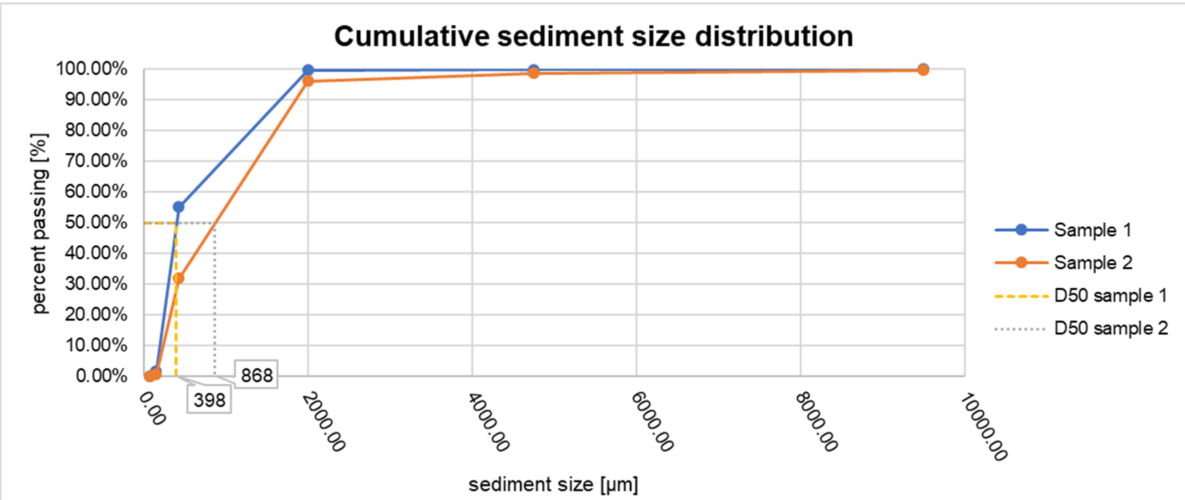


Figure G.2: Visualisation of sediment size distribution from samples 1 en 2

From each sample, the median size of the bed material (d_{50}), the maximum grain size (d_{90} can be used) and the geometric standard deviation of the particle size distribution (σ_g) is required. The σ_g can be determined using Equation (G.1), which represents the average of the difference between d_{50} and d_{16}, and d_{50} and d_{84}.

$$\sigma_g = 0.5 \cdot \left(\frac{d_{84}}{d_{50}} + \frac{d_{50}}{d_{16}} \right) \tag{G.1}$$

Unfortunately, it was not possible to execute a more elaborate sediment test in the laboratory. As can be inferred from the data in Tables G.1 and G.2, only one of the six sieves used matched with the sample. Therefore, it is really hard to determine the required data from the sieve test. It would be beneficial to test the sample again using additional sieves with diameters in the range of 150 μm to 2000 μm, in particular sieves with a diameter close to 450 μm.

From sample 1, a somewhat reasonable estimate of the nominal diameter of the soil can be made. From Table G.1 can be inferred that $d_{55.24}$ = 425 μm, in which is 55.24 is close to 50. Interpolation between $d_{1.55}$ = 150 μm and $d_{55.24}$ results in d_{50} = 398 μm. Applying the same strategy to the information gathered from the second sediment sample (Table G.2), a value of d_{50} = 868 μm is found. It might be clear that these results, when properly determined, cannot possibly result from samples taken from the same location. The method produces unreliable results that cannot be used. Also on the uniformity of the soil cannot be judged because of the lack of intermediate points, making it impossible to say anything about d_{16}, d_{50}, d_{84}, d_{90} and σ_g.

Since the method described before does not provide usefull data when executed in this way, an other source of data needs to be used. During a previous study on the Magdalena River near Barrancabermeja by (Oliveros-Acosta et al., 2015), a sediment study has been executed as well. During this study, d_{50} = 350 μm has been found. This result is in the same order of magnitude as the d_{50} = 398 μm found for the first sample. Because of its superior trustworthiness, the sediment size of (Oliveros-Acosta et al., 2015) will be used.

During this study, only the nominal diameter has been determined. This provides no information on the uniformity of the sediment. Therefore, assumptions based on observations and Tables G.1 and G.2 are required. The fact that Tables G.1 and G.2 show such large differences in residue in the sieves with sizes 150 μm and 425 μm, while both samples should be similar, indicates that a large part of the sediment is about 425 μm, which makes a uniform gradation likely. Own observations confirm there has probably to be dealt with uniform sediment (σ_g<1.3).

Also the maximum sediment diameter, often given by d_{90}, requires assumptions for its determination. In Table G.1 and Table G.2 it can be seen that a small but non-zero portion of the sediment is larger than 2000 μm. Therefore, d_{90} is assumed to be equal to 2000 μm. All the values decided on in this section on are summarized once more in Table G.3.

Table G.3: Sediment information

d_{50}	350 μm
d_{90}	2000 μm
σ_g	<1.3

H

Method to determine scour dimensions

The methods that are used to estimate the relevant scour hole dimensions are introduced and described in this appendix. Firstly, the selection of the scour depth determination method is described, followed by an explanation of the chosen method. Thereafter, the scour hole width determination method is introduced and in the last section the influence of abutments is discussed.

H.1. Scour depth relation selection

Because of the large amount of research carried out on scour holes, a lot of literature about this topic has been produced. Since the Second World War, numerous empirical relations, growing increasingly advanced over the years, have followed from these studies. All relations, however, are still based on a ratio between the (effective) pier width and the water depth, also known as the flow-field scale (Ettema et al., 2011). For each relation, this ratio differs as different other factors are taken into account. The most simple one just focusses on a circular pier in a flow field. More advanced relations take about a dozen other factors into consideration.

An evaluation of the available scour depth determination methods by Ettema et al. (2011) finds the methods presented by Melville and Coleman (2000), Richardson and Davis (2001) and Sheppard and Miller (2006) to be the leading ones. Melville's method is the only one of the three that is directly designed to make estimates of scour depths. The other two methods are designed to learn more about the influence of different parameters on scour. Furthermore, the method from Melville and Coleman is extensively used. Because of its availability and effectiveness, there has been chosen to use Melville and Coleman 's method to determine the scour depths around the piers of the Yondó Bridge.

H.2. Scour depth determination method

The approach suggested by Melville and Coleman (2000) takes a broad range of variables that influence scour depth into account. The majority of these variables are accommodated within Equation (H.1), the main relation of the method, by empirical factors (K's).

$$d_s = K_{yb} \cdot K_I \cdot K_d \cdot K_s \cdot K_\theta \cdot K_t \tag{H.1}$$

Where:	d_s	=	depth of the scour hole	[m]
	K_{yb}	=	depth-size factor	[m]
	K_{I}	=	flow intensity factor	[-]
	K_{d}	=	sediment size factor	[-]
	K_{s}	=	foundation shape factor	[-]
	K_θ	=	foundation alignment factor	[-]
	K_{t}	=	time factor	[-]

Every K can be determined by a different empirical relation suggested by Melville and Coleman. The origin and the application on the situation in Barrancabermeja of each factor is discussed in the following sections.

(Melville and Coleman, 2000) suggest to start with the determination of the equivalent pier widths in case of a non-uniform pier. Since this is the case for the Yondó Bridge, the foundation shape factor will be treated first.

H.2.1. Foundation Shape Factor, K_s, and Equivalent Pier Width, b_e

The foundation shape factor is one of the most complex and uncertain parameters in the model. As can be seen in Figure H.1, the scour process around the piers went through several stages with each a different pier geometry to reach its current state. Five cases can be distinguished:

- **Case I:** the top of the pile cap remains below the base of the scour hole, the flow is only influenced by the main pillar;
- **Case II:** the top of the pile cap is exposed by the scour hole;
- **Case III:** the top of the pile cap lays above the bed level around the pier;
- **Case IV:** the top of the pile cap lays above the water level;
- **Case V:** the bottom of the pile cap lays above the water level.

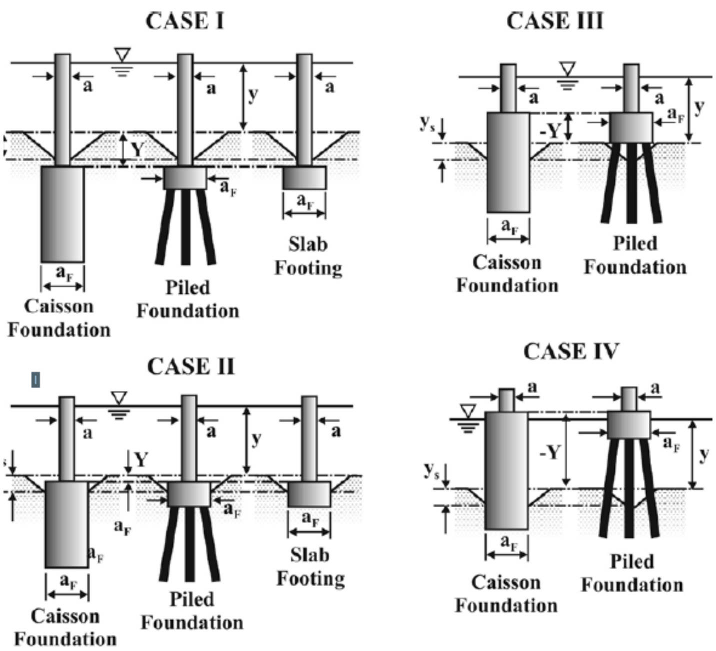


Figure H.1: Scour cases for non-uniform pier shapes. Case V, in which the pile cap is fully above the water surface, is not depicted (Melville and Coleman, 2000).

As mentioned before, the piers of the Yondó Bridge went through different stages before reaching their current state. These different set-ups each have their own effect. For **Case I**, the pile cap does not affect the scour depth because it is still buried below bed level. Local scour can be estimated using the dimensions of the main pillar. The pillar is tapered upwards, slightly reducing scour depth. Chiew (1984) has found a relation to take this into account for uniform piers. For an upwards-tapering pier, a value of K_s = 0.76 is given, corresponding to an angle of α= 22.5°. Interpolation between K_s = 1.0 and and K_s = 0.76 with the actual pillar provides a correction factor for tapering. A correction factor needs also to be taken into account for the angular shape of the pillar.

When the flow extracts more sediment from the hole and it grows deeper, the elevation of bottom of the scour hole matches the elevation of the top of the pile cap on a certain point (**Case II**). This causes an erosion reduction due to an interception of the down flow by the concrete pile cap. This stays the case up to a point in which the sides of the pile cap become exposed, increasing effective width of the pier and therefore increasing scour depths. The influence of the complicated form of the structure on the scour depth can be taken into account by adapting the pier diameter to an equivalent pier diameter, using Equation (H.2) given by Melville and Raudkivi (1996).

$$b_e = b_{mp}\left(\frac{y+Y}{y+b_{pc}}\right) + b_{pc}\left(\frac{b_{pc}-Y}{b_{pc}+y}\right) \tag{H.2}$$

Where:	b_e	=	diameter of a circular pier resulting in an equivalent scour depth	[m]
	b_{mp}	=	width of the main pillar	[m]
	y	=	water depth outside the scour zone	[m]
	Y	=	difference between the river bed and the top of the pile cap	[m]
	b_{pc}	=	width of the pile cap	[m]

By using this relation, both the influence of the pile cap and the main pillar are taken into account. The equation is only valid if the distance from the top of the pile cap to the bottom of the river is smaller than the width of the pile cap. If this is not the case, the second term of the equation gets negative, resulting in a physically incorrect equation. If this is the case, the equivalent pier width has to be determined using engineering judgement.

When the bottom level lowers even more, the pile cap will become undermined, reaching **Case III**. A more complex situation with exposed foundation piles is created. Whether an increase or a decrease of the scour depth will occur depends on the dimensions of the foundation piles, pile cap and main pillar. This holds true for Case IV and Case V as well. Equation (H.2) provides an estimation of the scour depth for Case III and can be used for this situation as well. The method does not take into account the flow underneath the pile cap, but assumes the pile cap to reach to the bottom instead. Since the latter would cause more scour than the real situation, using Equation (H.2) yields a conservative (too deep) estimate. In case the pile cap is located just above the river bed, one can get away with this simplification, but when the distance between the bottom of the pile cap and the river bed increases, the method gets increasingly inaccurate. So if this is the case, and the real scour depth is relevant instead of a conservative estimate, Equation (H.2) cannot be used. There has been decided to deviate from Melville and Coleman's method, and determine the equivalent pier using engineering judgement instead for this case.

A similar but simpler method is applicable for **Case IV**. The pile cap diameter can be simply used as the equivalent pier diameter. This results, because of the same reasons as observed for Case III, in a conservative estimate as well. Again, if there is a lot of space between the bottom of the pile cap and the river bed, this method is not applicable for finding the real scour dimensions. Like for case III, also for Case IV there has been decided to cast aside Melville and Coleman's method and use engineering judgement to determine the equivalent pier width.

In case the pile cap is situated above the water level (**Case V**), a scour depth prediction given by Hannah (1978) can be used. This method combines the shape factor with the alignment factor (K_ϑ), which is further discussed in the next section. The angle of attack on the piers, the number of foundation pile rows and the distance between the foundation piles play a role in estimating scour depths. For the piers in Barrancabermeja, there has to be dealt with multiple rows of foundation piles. The longitudinal centre-to-centre distance between the piles (S_p) is used. Table H.1 can be used to find K_sK_ϑ. Also for three rows of foundation piles, the values of a double row are used.

Table H.1: K_sK_ϑ for piers in Case V (Hannah, 1978)

Type	$\mathbf{S_{fp}/b_{fp}}$	$\mathbf{K_sK_\vartheta}$	
		ϑ**<5°**	ϑ**=5°→45°**
Double row	2	1.50	1.80
	4	1.35	1.50

Only a for a very small and a large angle of attack (ϑ), values are provided by the table. An abrupt and dramatic increase from an angle smaller than 5° to an angle larger than 5° can be observed. It is not very likely that the depth of the scour hole can increase by 10 to 20 percent given an increase in the angle of attack of just one percent. Therefore, there is assumed that the Table H.1 implies that the maximum value occurs for an angle of 45°. The angle of attack at the the Yondó Bridge piers is in the majority of the situations between 5°and 45°. Interpolation is used to find the values corresponding to the angle of attack. Also for the ratio between foundation pile distance and pile diameter should be interpolated. By putting this (S_{fp}/b_{fp}) on one axis, and the angle of attack (ϑ) on the other axis, the corresponding value of $K_s K_\vartheta$ can be found.

H.2.2. Foundation Alignment Factor, K_ϑ

One of the most important parameters that influences scour depth is the width of the pier. In the previous section, we have modified this width for several cases to be able to find an equivalent scour depth. This method can be also be used to adapt the model to non-aligned flows. For example, if a rectangular pier is attacked by a flow under an angle of 20 degrees, the effective frontal width of the pillar is significantly larger than in case the pillar is perfectly aligned width the flow direction. Laursen and Toch (1956) have published a chart (Figure H.2) showing values for the correction factor for K_ϑ. This chart is nowadays still normative.

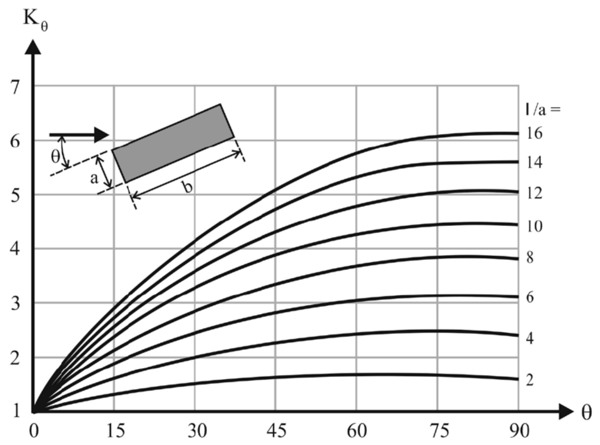


Figure H.2: Flow Alignment Factor for different angles (Laursen and Toch, 1956)

The values in the chart can be approximated by the following equation:

$$K_\theta = \left(\frac{b_p}{b_{\text{rec}}}\right)^{0.65} = \left(\frac{l_{\text{rec}}}{b_{\text{rec}}}\sin\theta + \cos\theta\right)^{0.65} \tag{H.3}$$

Where:	b_p	=	adapted frontal width of the pillar	[m]
	l_{rec}	=	length of the rectangular pier	[m]
	b_{rec}	=	breadth of the rectangular pier	[m]
	θ	=	flow angle of attack	[°]

For the cases II and III, introduced in Section H.2.1, the equivalent width b_e is used as the width to determine the foundation alignment factor. But not only for the pier width do the differences between the dimensions of the foundation piles, the pile cap and the pillar complicate the situation. Also for the length of the pile, Equation (H.2) should be considered. Since the physical basis of the equation is the same for determining the equivalent width as for determining the equivalent length, there is assumed that this relation can be used for the pier lengths as well. The relation is again only used for Case II and Case III. In Case I, the pillar length at pile cap level is used and in Case IV, the length of the pile cap represents the equivalent length. Also here, in case the pile cap is located far from the river bed, the approach explained here for Case III and Case IV is too conservative and therefore not valid. Engineering judgement should be used to make a reasonable correction to the value that is found for K_ϑ. In this way, also the influence of the foundation piles on the foundation alignment factor, and not that only the influence of the pile cap, is taken into account.

H.2.3. Depth - Size Factor, K_{yb}

The depth - size factor represents the effects of shallowness in the scour depth prediction. The width of the pier compared to the depth of the river determines the strength of the scour driving processes described in Section 8.2. The influence of the pier width compared to the water depth can be demonstrated by two extreme examples. For example, in case the pier is very wide compared to the water depth, the pier width has no influence on scour depths around the pier. Consider an island, that can essentially be seen as a very wide pier. Clearly, in this case the width of the island does not influence the scour depth around the shores of the island. The other extreme is a very narrow pier in a very deep river. The water depth does not influence the depth of the scour hole.

Piers can be subdivided into three categories: narrow, intermediate and wide piers. The conditions and corresponding relations for K_{yb} are shown in Equations (H.4a) to (H.4c).

$$K_{yb} = 2.4 b_e \qquad \frac{b_e}{y} < 0.7 \tag{H.4a}$$

$$K_{yb} = 2\sqrt{y b_e} \qquad 0.7 < \frac{b_e}{y} < 5 \tag{H.4b}$$

$$K_{yb} = 4.5 y \qquad \frac{b_e}{y} > 5 \tag{H.4c}$$

Where: b_e = equivalent pier width [m]

Since the equivalent pier width is the width of a circular pier with the same characteristics as the pier dealt with, and the formula is developed for circular piers, the equivalent pier width should be used. K_{yb} also introduces the dimension [m] to the main scour depth formula, and provides a starting position of a scour depth estimate. The other factors correct this by taking complicating elements into account.

H.2.4. Flow Intensity Factor, K_I

A distinction between two types of scour can be made: scour under clear-water conditions and scour under live-bed conditions. During clear-water conditions, there is no sediment supply from upstream and the only sediment in the water is introduced by scour. In this case, the critical velocity of the sediment, known as the velocity that is required to pick up sediment from the bottom, is larger than the flow velocity in the stream. So except for sediment unloosed by scour, no sediment is transported by a stream. On the other hand, if the stream already transports sediment before it reaches the scour hole, we speak of live-bed conditions. In case of live-bed conditions, the flow velocity exceeds the critical velocity. This means that a stream itself is able to transport sediment by its regular flow.

The intensity of a flow is given by the ratio between the flow velocity and the critical flow velocity (V/V_c). Larger flow intensities are generally associated with a larger scour depths. There is, however, a complicating factor. The homogeneity of the sediment plays in important role in the determination of the flow intensity. If sediment is uniform (σ_g <1.3), the known relation V/V_c can be used to determine the flow intensity. If sediment is non-uniform (σ_g >1.3), armour layers that reduce scour depth are formed in the scour hole. In this case, an extra variable V_a that represents the boundary velocity between clear-water and live-bed conditions is introduced for non-uniform sediments.

Since sediment in the Magdalena River near Barrancabermeja is uniform, as explained in Appendix G, the latter does not have to be taken into account. Also d_{50} = 350 μm and d_{90} = 2000 μm follow from this appendix. With this information, the flow intensity can be determined.

$$\text{Flow intensity} = \frac{V}{V_c} \tag{H.5}$$

Where: V = flow velocity [m/s]
V_c = critical flow velocity [m/s]

With Equations (H.6a) and (H.6b), a set of relations provided by Melville and Coleman based on the Shields equation, the critical flow velocity can be found.

$$u_{*c} = 0.0115 + 0.0125\, d_{50}{}^{1.4} \qquad 0.1\text{mm} < d_{50} < 1\text{mm} \tag{H.6a}$$

$$V_c = u_{*c} \cdot 5.75\, log\left(5.53 \frac{y}{d_{50}}\right) \tag{H.6b}$$

Where:	u_{*c}	=	critical shear velocity	[m/s]
	d_{50}	=	median grain size of sediment	[mm]

Flow velocities in the Magdalena River are mostly in the range of 1.0 to 1.5 m/s. This results in a flow intensity of 10 to 15. From experimental data for uniform sediment presented by Melville and Coleman, shown in Figure H.3, can be concluded that K_I in case of the Magdalena River near Barrancabermeja is 1.0.

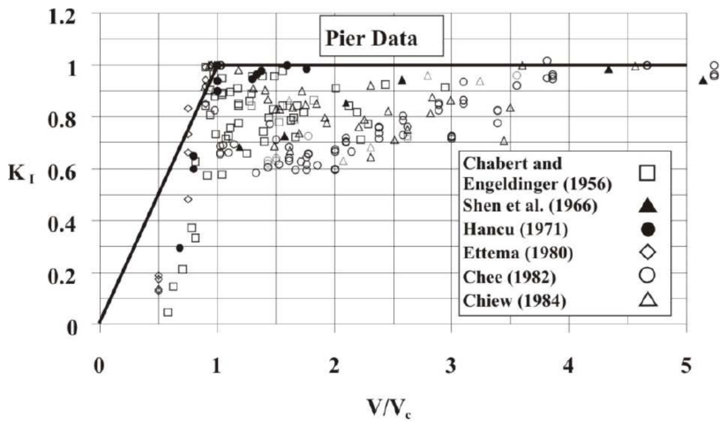


Figure H.3: Flow Intensity Factor for uniform sediments (Melville and Coleman, 2000)

H.2.5. Sediment Size Factor, K_d

If the sediment particles located around a bridge pier have a relatively large size compared to the width of the pier, the energy of the down flow is party dissipated by the porous bed. This makes erosion at the sides of the pier the main operating scour mechanism, which reduces the maximum scour depth. From the data shown in Figure H.4, it can be inferred that in case of uniform sediment and a pier wider than 100 times the nominal sediment diameter, this effect does not play a role, resulting in K_d = 1.0. This applies for the situation concerning the Yondó Bridge.

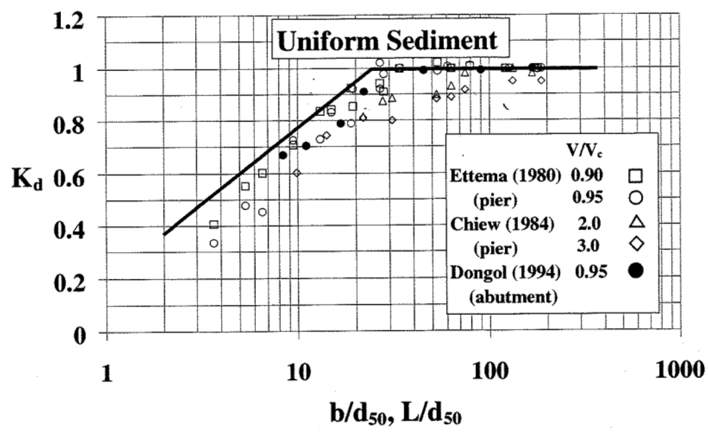


Figure H.4: Sediment Size Factor for uniform sediments (Melville and Coleman, 2000)

H.2.6. Time Factor, K_t

Scour holes develop rapidly in the live-bed conditions. These conditions are experienced in the Magdalena River near Barrancabermeja, as explained Section H.2.4. Therefore, in case of these live-bed conditions, K_t = 1 can be assumed.

H.2.7. Effects of debris

Debris accumulation behind a bridge pier can severely increase the effective width of a pier, and thus the scour dimensions. Debris are likely to be transported by rivers during floods. So during these conditions, extra scour might be expected. Based on observations done during the field trip described in Appendix C, there can be concluded that the Yondó Bridge is in risk of enlarged scour holes due to debris. In Figure H.5, a picture taken of the bridge during this field trip is shown.

Figure H.5: Debris stuck behind the most south western bridge pier of the Yondó Bridge (Pier 1, Appendix I)

However, due to the large pile cap that is submerged during normative circumstances, debris do not significantly contribute to scour depth. Therefore, there has been decided to disregard debris in order to not unnecessarily complicate the scour dimension determination method.

H.3. Scour width determination method

Not just the depth of the scour hole is of importance in a situation wherein the influence of bridge scour on the dynamics of a river is studied. Its complete dimensions should be taken into account. Therefore also the horizontal dimensions of the scour holes have to be estimated. This is a hard task since there has not been done a lot of research on widths of scour holes. So a nice off-the-shelf relation with as input the characteristics of the river around the bridge pier is not available. The present-day leading approach originates from a a study from Richardson and Abed (1999). Richardson and Abed present the following relation for the scour width:

$$W = d_s(K + \cot\phi) \tag{H.7}$$

Where:	W	=	top width of the scour hole	[m]
	K	=	bottom width of the scour hole	[m]
	ϕ	=	sediment angle of repose	[°]

This approach is not applicable to the the Yondó bridge piers. In the first place because the bottom width of the scour hole is not known, and in the second place because the slope angle can not be determined in an accurate way. Richardson and Abed also provide a relation for practical applications, which is derived from generally occurring situations. This relation assumes a distance of two times the depth of the scour hole between the side of the pile and the top of the scour hole, which is shown in Figure H.6.

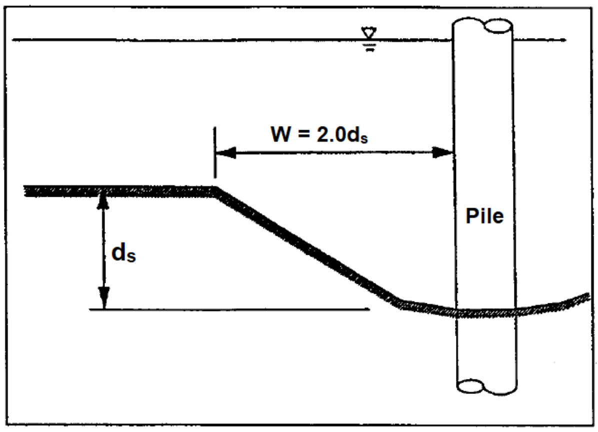


Figure H.6: Estimated scour width (Richardson and Abed, 1999)

The limitations induced by the numerical method used to predict river development make the inaccuracy of the scour width estimation acceptable. In the this method, in the scour hole is assumed to be cubic formed. This already severely limits the accuracy of the input. So because of this limitation, it is not of vital importance to precisely estimate the scour width. The scour dimensions will be generalised in the numerical model anyway.

H.4. Abutment scour

The abutments at the sides of the river reach out only a couple of meters into the river, which is only a very small fraction of the river width. The bridge piers are located too far away from the sides to have its scour be influenced by the abutments. The influence of flow contraction due to abutments on scour at bridge piers will therefore be ignored. The scour at the abutment itself will also be too small to have a meaningful influence on the macro-scale situation.

I Bridge pier dimensions

The bridge pier dimensions are required in order to estimate scour hole dimensions. Despite several attempts at Invías, the executive body of the Colombian ministry of transport and main initiator of the bridge, and at Cormagdalena, the governmental body responsible for amongst others the navigability of the Magdalena River, it turned out to be not possible to obtain the blueprints of the Yondó Brigde. Instead of the blueprints, a slide show that contains some screen shots of the blueprints was made available (Cormagdalena, 2014). Because the screen shots are to scale, and several dimensions are given in the screen shots, useful information can be derived from these pictures. Unfortunately, not every single relevant pier is described. From the presentation and from pictures of the bridge, the dimensions of the bridge piers can be estimated. Although not a very accurate approach, this is the only way to obtain the bridge pier dimensions.

The bridge is supported by a total of 17 piers. From these 17 piers, the outer left and 6 most right ones are not of interest because they are not subjected to local scour. The relevant bridge piers have been given numbers, which are presented in Figure I.1.

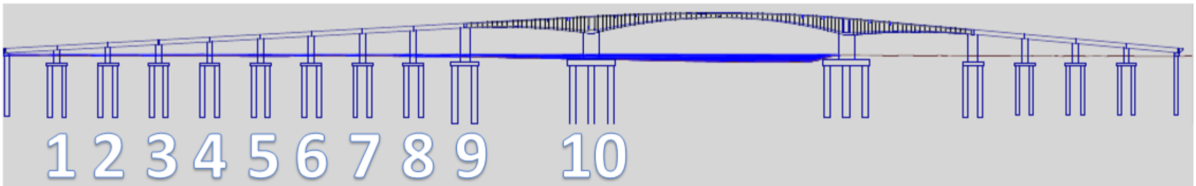


Figure I.1: Schematisation of the Yondó Bridge. Numbers have been allocated to the relevant piers. (Cormagdalena, 2014)

All bridge piers consist of the same elements: a main pillar, a pile cape and several foundation piles. A picture of the bridge piers is shown in Figure I.2, and the composition of a pier is shown in Figure I.3.

Figure I.2: Picture of the piers of the Yondó Bridge

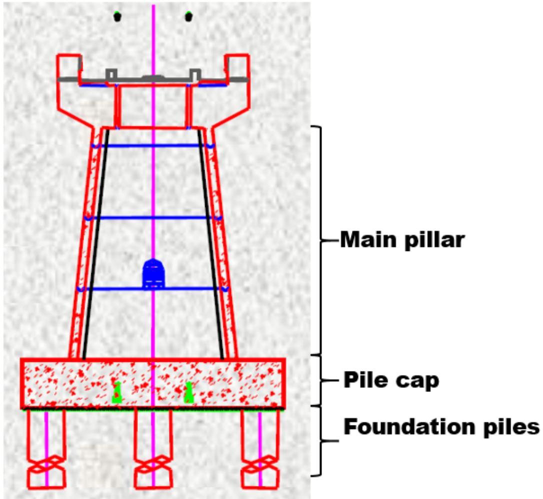


Figure I.3: Composition of a pier of the Yondó Bridge (Cormagdalena, 2014)

Table I.1 gives an overview of the different types of piers. The piers have been divided into three main groups. The piers categorised in group A are similar to each other in dimensions. They have the same pile foundations, similar main pile caps and similar main pillars. But, some important differences can be noticed. Pier 1, 2 and 8 have aberrant pile caps and the piers listed in category B and C are significantly larger than the previously mentioned piers. The dimensions of each pier are provided in Table I.2. Besides, the elevation of the pile cap of pier 1 is different compared to the elevation of the other pile caps. For pier 2 to 10, the bottom of the pile cap is located at 3.00 metres. This is determined by comparing water levels from IDEAM (2017) to pictures taken during the field trip. The bottom of the pile cap of pier 1 is located 2.5 metres lower.

Table I.1: Pile categorisation

Category	**Particularity**	**Pile number**
A	-	3 - 7
A1	Pile cap is located at a lower elevation	1
A2	Longer pile cap in both upstream and downstream direction	2
A3	Longer pile cap in downstream direction	8
B	-	9
C	-	10

Table I.2: Overview of the relevant pier dimensions

Pier 1		
Foundation piles		
Width	1.20	[m]
Centre to centre distance	3.55	[m]
Pile cap		
Width	5.15	[m]
Length	10.00	[m]
Height	1.25	[m]
Pillar		
Width (base)	1.45	[m]
Length	2.40	[m]
Tapering	6.00	[°]

Pier 2		
Foundation piles		
Width	1.20	[m]
Centre to centre distance	3.55	[m]
Pile cap		
Width	5.15	[m]
Length	10.00	[m]
Height	1.25	[m]
Pillar		
Width (base)	1.45	[m]
Length	2.40	[m]
Tapering	6.00	[°]

Pier 3		
Foundation piles		
Width	1.20	[m]
Centre to centre distance	3.55	[m]
Pile cap		
Width	5.15	[m]
Length	5.15	[m]
Height	1.25	[m]
Pillar		
Width (base)	1.45	[m]
Length	2.40	[m]
Tapering	6.00	[°]

Pier 4		
Foundation piles		
Width	1.20	[m]
Centre to centre distance	3.55	[m]
Pile cap		
Width	5.15	[m]
Length	5.15	[m]
Height	1.25	[m]
Pillar		
Width (base)	1.45	[m]
Length	2.40	[m]
Tapering	6.00	[°]

Pier 5		
Foundation piles		
Width	1.20	[m]
Centre to centre distance	3.55	[m]
Pile cap		
Width	5.15	[m]
Length	5.15	[m]
Height	1.25	[m]
Pillar		
Width (base)	1.45	[m]
Length	2.40	[m]
Tapering	6.00	[°]

Pier 6		
Foundation piles		
Width	1.20	[m]
Centre to centre distance	3.55	[m]
Pile cap		
Width	5.15	[m]
Length	5.15	[m]
Height	1.25	[m]
Pillar		
Width (base)	1.45	[m]
Length	2.40	[m]
Tapering	6.00	[°]

Pier 7		
Foundation piles		
Width	1.20	[m]
Centre to centre distance	3.55	[m]
Pile cap		
Width	5.15	[m]
Length	5.15	[m]
Height	1.25	[m]
Pillar		
Width (base)	1.45	[m]
Length	2.40	[m]
Tapering	6.00	[°]

Pier 8		
Foundation piles		
Width	1.20	[m]
Centre to centre distance	3.55	[m]
Pile cap		
Width	5.15	[m]
Length	8.00	[m]
Height	1.25	[m]
Pillar		
Width (base)	1.45	[m]
Length	2.40	[m]
Tapering	6.00	[°]

Pier 9		
Foundation piles		
Width	2.00	[m]
Centre to centre distance	5.90	[m]
Pile cap		
Width	8.70	[m]
Length	14.60	[m]
Height	2.00	[m]
Pillar		
Width (base)	2.95	[m]
Length	7.55	[m]
Tapering	6.00	[°]

Pier 10		
Foundation piles		
Width	2.00	[m]
Centre to centre distance	5.90	[m]
Pile cap 1		
Width	14.60	[m]
Length	29.10	[m]
Height	2.80	[m]
Pile cap 2		
Width	14.60	[m]
Length	14.60	[m]
Height	1.00	[m]
Pillar		
Width (base)	5.25	[m]
Length	10.35	[m]
Tapering	6.00	[°]

J

Grid generation

This appendix provides an overview of the grid generation process for the simulations in Delft3D. After a few weeks of research it turned out that it was impossible to get access to a useful bathymetry of the reach of the Magdalena River around the Yondó Bridge, both from before and after the construction. Therefore, the measurements of the river bed, obtained during the fieldwork in Barrancabermeja, are used to create a bed elevation profile of the river reach. Below the different steps are discussed.

Combining RTK and ADCP data

The RTK was used to measure the latitude and longitude of the cross sections with an interval time of ten seconds. The ADCP continuously provided values of the depth of the river over the measured cross sections, but was not able to measure correct values of the latitude en longitude. For a detailed description of the working of the equipment, see Appendix C. The data from both instruments have to be combined in order to obtain an x, y and z-value at all locations. As the RTK gives less values than the ADCP, interpolation between the data points of the RTK is necessary. This is realised based on the sketch in Figure J.1 and the following assumption: the path of the boat between the first and the last RTK point is straight. This means that (small) deviations of the boat are not taken into account.

The length of the path is computed based on Pythagoras and the depth points of the ADCP are linearly divided over this distance. In order to determine the correct bed elevation at all these points, the average water level over the cross section is calculated and the depth, measured by the ADCP, is subtracted. As the average water level has a standard deviation of 0.05 m over a cross section, which is 0.05% of the total value of the water level. Since this percentage is very low, this assumption is considered valid.

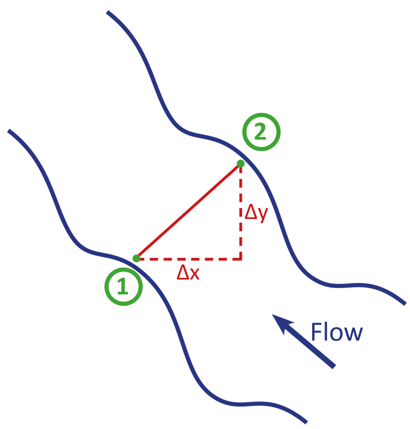


Figure J.1: Assumed path of the boat over a cross section, based on the first and the last RTK point. The distance is calculated based on Pythagoras.

River banks

The RTK and the ADCP are not able to measure the profiles of the river banks. Therefore, these values were extracted from Google Earth (2017). This program allows the user to click a pattern on the map and save the latitude and longitude values, see Figure J.2. It was chosen to set the elevation of the river banks on a constant value of 79 m, which is based on the elevation of the office of Cormagdalena, located close to the river side.

Figure J.2: Pattern of the river banks of the Magdalena River in Google Earth (2017)

Latitude and longitude format

The RTK uses a slightly different format for the latitude and longitude than Google Earth (2017). This results in significant differences when comparing both formats. Therefore, the RTK values, provided in degrees, minutes and seconds, were transformed as follows:

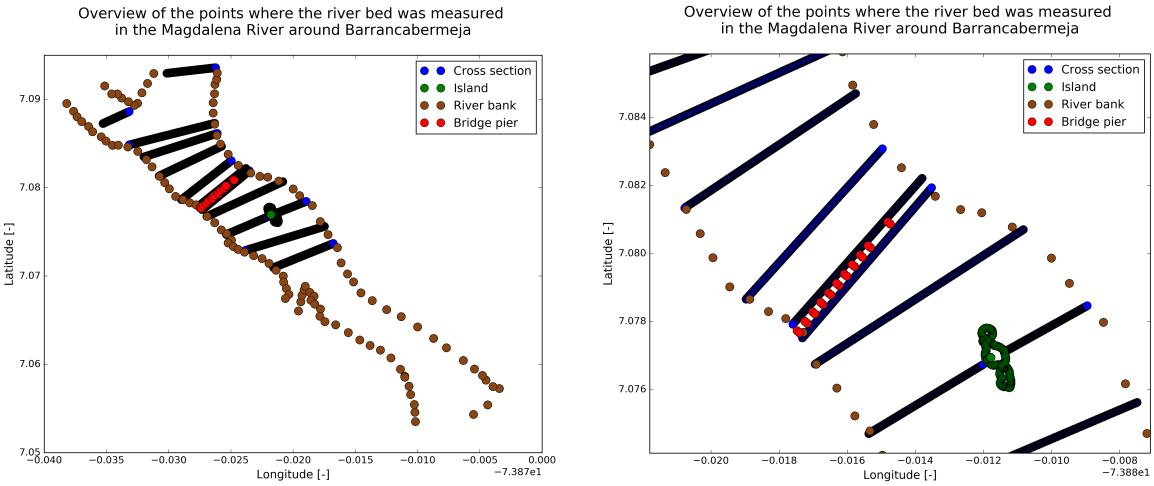
$$\text{Latitude} = d + m \cdot \frac{1}{60} + s \cdot \frac{1}{60} \cdot \frac{1}{60} \tag{J.1}$$

$$\text{Longitude} = -(d + m \cdot \frac{1}{60} + s \cdot \frac{1}{60} \cdot \frac{1}{60}) \tag{J.2}$$

Where:	d	=	degrees	[°]
	m	=	minutes	[min]
	s	=	seconds	[s]

Overview of the points

As the formats of the latitude and longitude are now similar, the points of the RTK and the river banks are plotted in the same figure. The result is displayed in Figures J.3a and J.3b, which show the entire river reach on the left and a zoom of the area around the bridge on the right.



(a) Entire river reach

(b) Area around the bridge

Figure J.3: Overview of the measured points and the points from Google Earth (2017) representing the cross sections of the river, the bridge, the island en the bridge

Conversion of the points to metres

The grid generation module of Delft3D is based on distances in metres, which means that the points should be converted from latitude and longitude values to x and y values. Rosenberg (2017) describes a method to realise this conversion grounded on the varying distance between latitudes and longitudes over planet Earth, see Equations J.3, J.4 and J.5.

$$\beta = \operatorname{atan}\left(\frac{b}{a}\cdot\tan(\phi_{\min})\right) \tag{J.3}$$

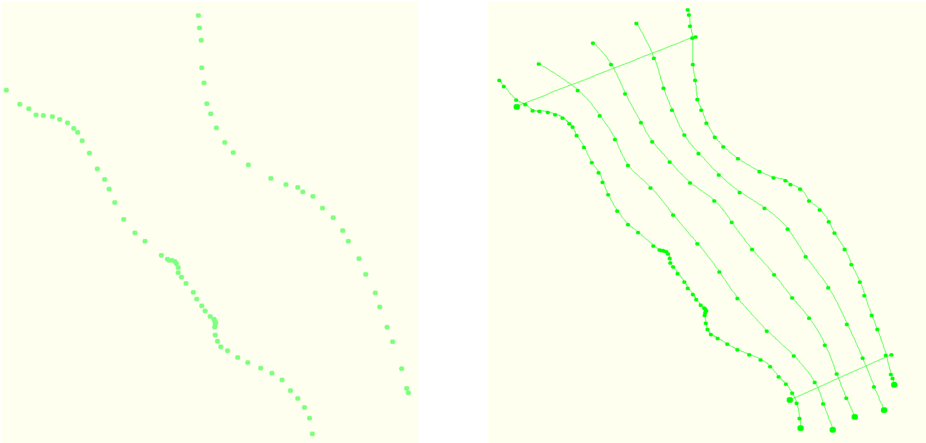
$$x = (\psi - \psi_{\min})\cdot\left(a\cdot\frac{\pi}{180}\cdot\cos(\beta)\right) \tag{J.4}$$

$$y = (\phi - \phi_{\min})\cdot(111,132.954 - 559.822\cdot\cos(2\phi_{\min}) + 1.175\cdot\cos(4\phi) \tag{J.5}$$

Where:	β	=	reduced latitude	[°]
	a	=	equatorial radius	[m]
	$\frac{b}{a}$	=	ratio between the radius at the pole and the equatorial radius	[-]
	ϕ	=	latitude	[°]
	$\phi_{\min}$	=	minimum latitude	[°]
	ψ	=	longitude	[°]
	$\psi_{\min}$	=	minimum longitude	[°]

Delft3D interpolation

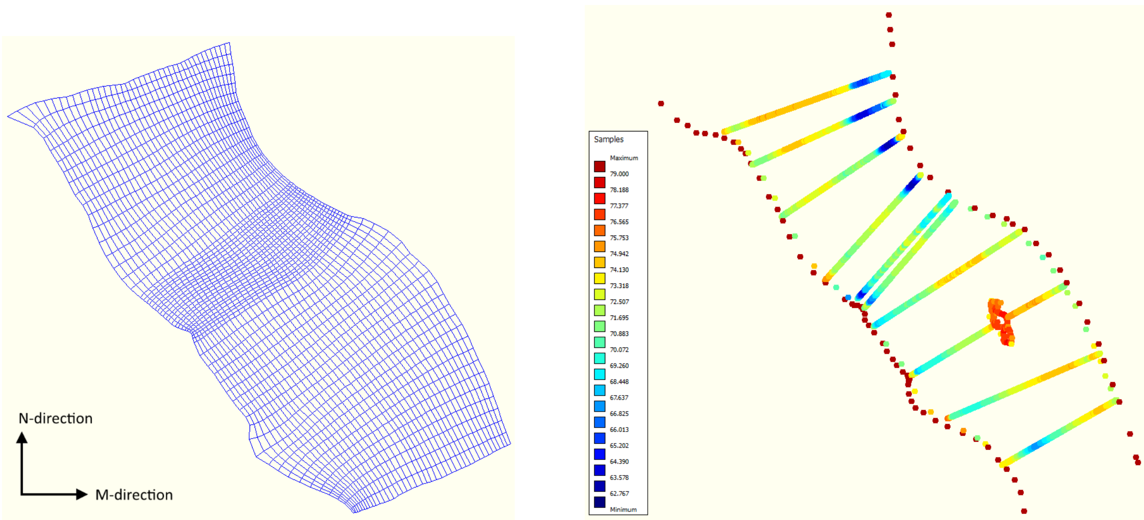
The text files, containing the x, y and z values of the cross sections and the river banks, can be imported in the grid generation module of Delft3D. This module is called Quickin and can be used to create customised grids and depth files. First, the river banks are imported and curved lines are clicked within the area of the banks to create a curved grid, see Figures J.4a and J.4b. A curved grid is more suitable than a rectangular grid in this situation, as the curved lines can follow the river banks. Moreover, implementing boundary conditions is easier on a straight line at the outer sides of the grid than on a cascading line, that would be present in a rectangular grid.



(a) River banks (b) Additional points

Figure J.4: Delft3D Quickin module containing the points of the river banks and the additional points, needed to generate a curved linear grid

Delft3D can create a grid from the curved lines, resulting in the shape depicted in Figure J.5a. The area of the grid around the location of the bridge is refined, as these cells should be able to mimic the scour holes around the piers. The last step is to combine the empty grid with the measured (depth) points of the cross sections indicated in Figure J.5b. As the bed elevation around the river side is not known over the entire reach, a few additional points are added between the different cross sections. By triangular interpolation between all these points and the grid cells, the final version of the grid is created, see Figure J.6. This grid will be used during the simulations in Delft3D.



(a) Empty grid (b) River banks and cross sections

Figure J.5: The empty curved grid that is combined to the measured points of the cross sections and the river banks

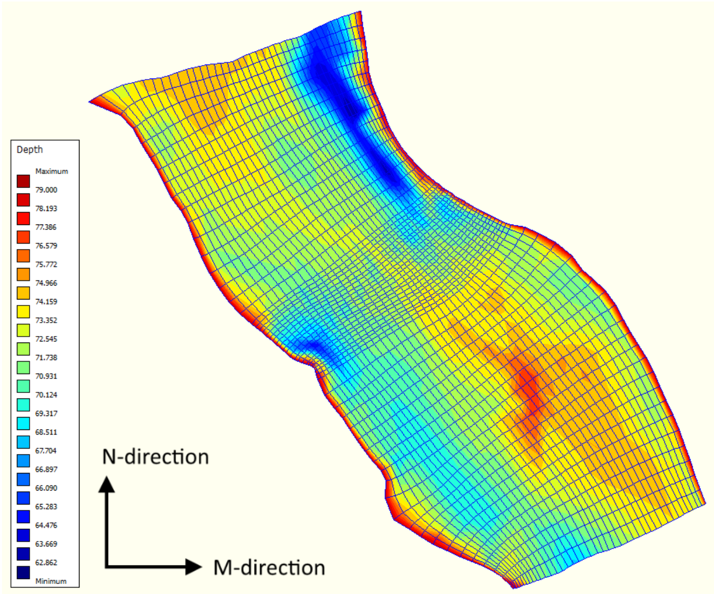


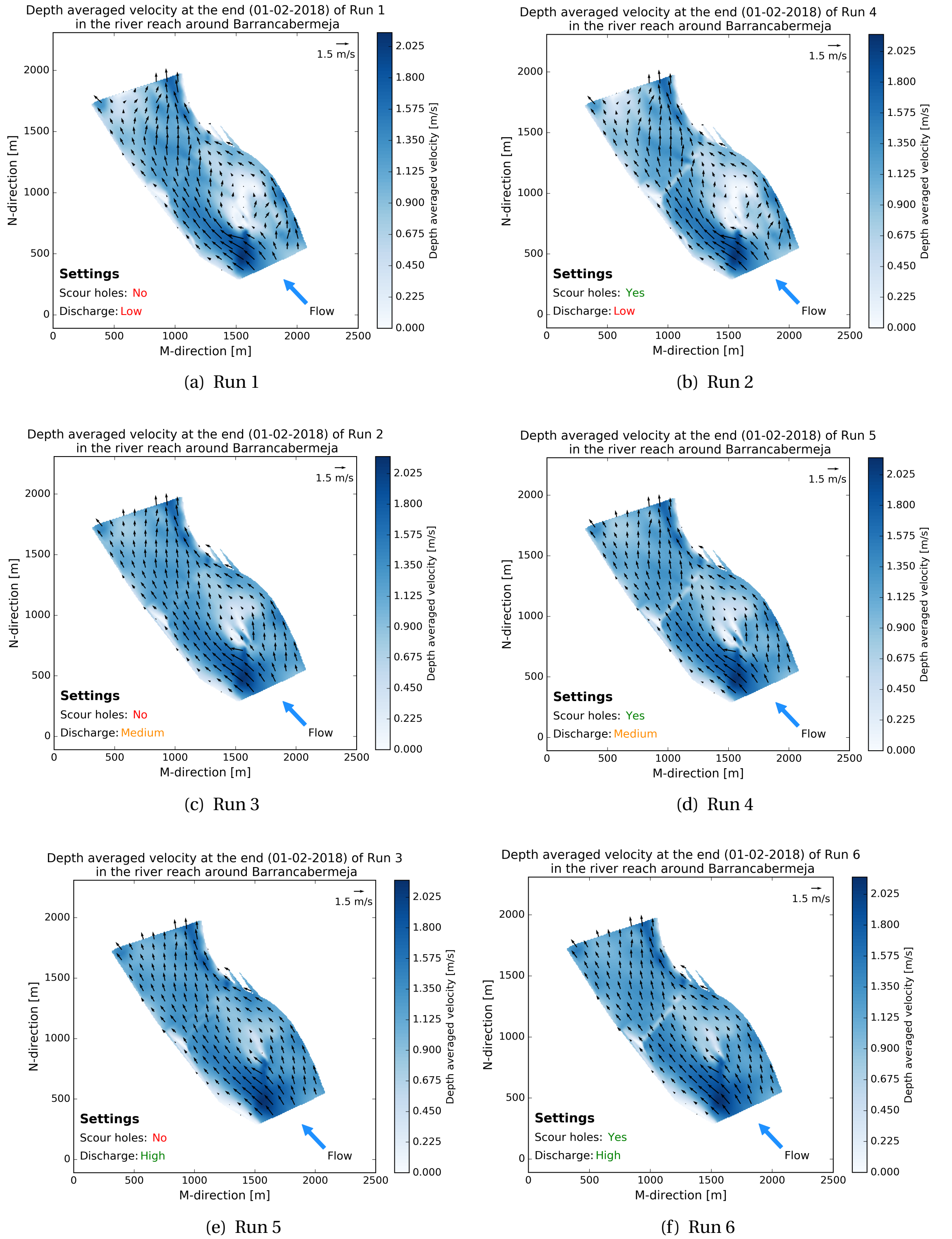
Figure J.6: Final grid that are used during the simulations in Delft3D

K

Additional model results

This appendix contains all the results of the Delft3D-model simulations that are not presented in Chapter 10. Figure K.1 depicts the depth averaged velocities over the river reach, whereas Figures K.2 to K.4 show the elevation of the bed at the start and the end of a simulation. At the end, a table containing all the (scour) depths around the bridge before and after the simulations in Delft3D is presented, see Table K.1. The difference between the beginning and the end of a simulation are analysed and summarised per run in Tables K.2, K.3 and K.4.

Plots

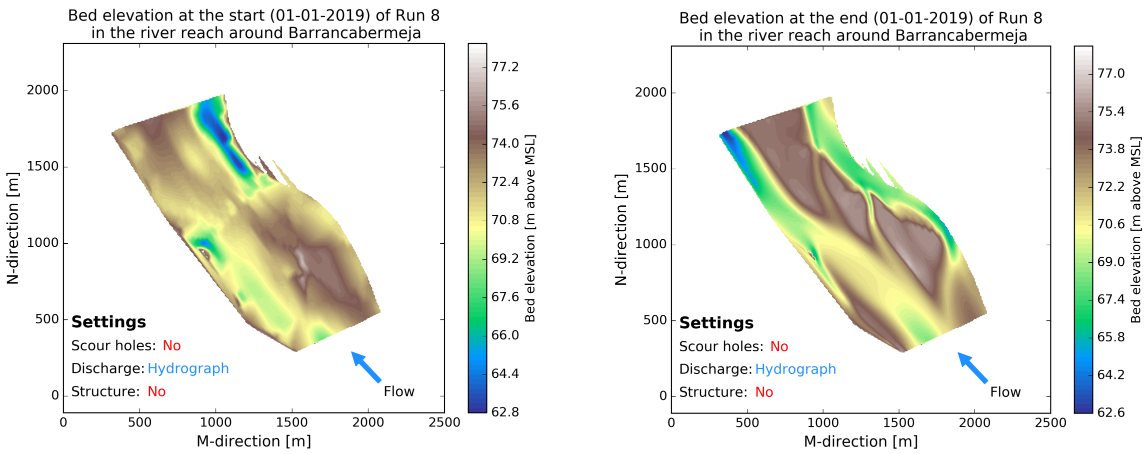


(a) Run 1 (b) Run 2

(c) Run 3 (d) Run 4

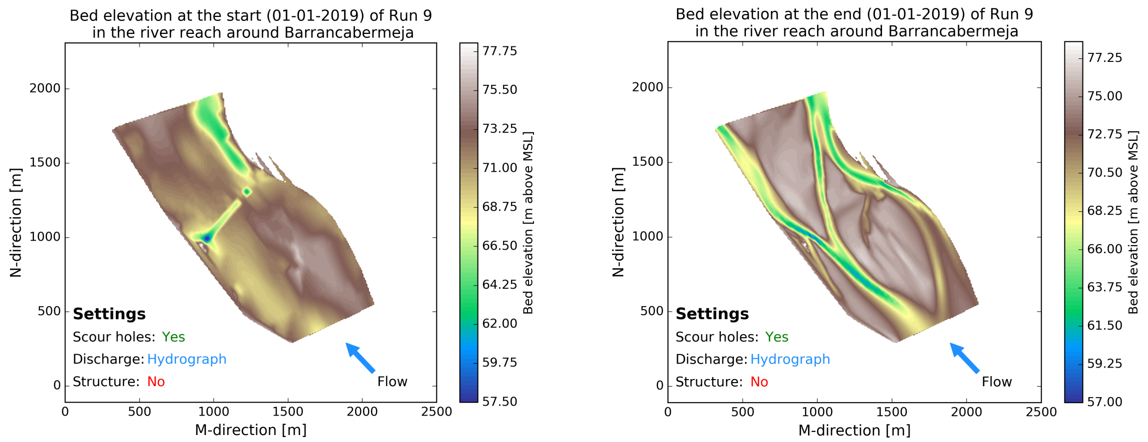
(e) Run 5 (f) Run 6

Figure K.1: Plots of the depth averaged velocity of the hydrodynamic simulations (Run 1-6) in the river reach around the Yondó Bridge. The blue arrow indicates the flow direction and the black arrow on the top right represents the reference velocity.



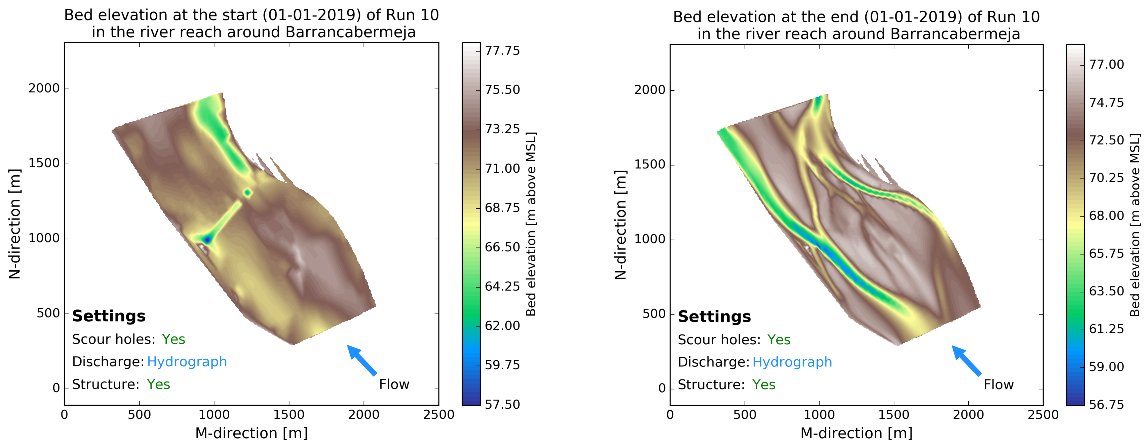
(a) Start (b) End

Figure K.2: Elevation of the river bed at the start and the end of Run 8 (without scour, a discharge hydrograph and no structure)



(a) Start (b) End

Figure K.3: Elevation of the river bed at the start and the end of Run 9 (with scour, a discharge hydrograph and no structure)



(a) Start (b) End

Figure K.4: Elevation of the river bed at the start and the end of Run 10 (with scour, a discharge hydrograph and a structure)

Tables

Table K.1: Overview of the (scour) depths around the bridge before and after the simulations in Delft3D

	Depth [m above MSL]				
Pier number	**Initial depth**	**Initial scour depth**	**Final depth**	**Final scour depth without a structure**	**Final scour depth with a structure**
0	79.0	79.0	79.0	79.0	79.0
1	64.6	56.4	69.7	67.5	59.2
2	67.5	63.0	70.5	65.9	64.6
3	69.7	65.3	70.3	75.9	69.4
4	70.4	66.0	70.4	75.3	70.9
5	71.1	66.8	71.8	70.5	75.6
6	71.1	66.6	72.9	67.2	74.1
7	71.8	67.2	73.6	74.0	73.8
8	71.8	67.0	74.6	75.2	74.3
9	72.5	64.8	75.5	75.3	74.6
10	75.4	74.8	75.4	74.8	75.4

Table K.2: Absolute and percent differences in bed level between the beginning and the end of Run 8. The last column indicates whether erosion or sedimentation takes place.

	Run 8		
Pier number	Difference [m]	Percentage [%]	Erosion or sedimentation [ERO or SED]
0	0.0	0.0	-
1	5.1	7.9	SED
2	3.0	4.4	SED
3	0.6	0.9	SED
4	0.0	0.0	-
5	0.7	1.0	SED
6	1.8	2.5	SED
7	1.8	2.5	SED
8	2.8	3.9	SED
9	3.0	4.1	SED
10	0.0	0.0	-

Table K.3: Absolute and percent differences in bed level between the beginning and the end of Run 9. The last column indicates whether erosion or sedimentation takes place.

	Run 9		
Pier number	Difference [m]	Percentage [%]	Erosion or sedimentation [ERO or SED]
0	0.0	0.0	-
1	11.1	19.7	SED
2	2.9	4.6	SED
3	10.6	16.2	SED
4	9.3	14.1	SED
5	3.7	5.5	SED
6	0.6	0.9	SED
7	6.8	10.1	SED
8	8.2	12.2	SED
9	10.5	16.2	SED
10	0.0	0.0	-

Table K.4: Absolute and percent differences in bed level between the beginning and the end of Run 10. The last column indicates whether erosion or sedimentation takes place.

	Run 10		
Pier number	Difference [m]	Percentage [%]	Erosion or sedimentation [ERO or SED]
0	0.0	0.0	-
1	2.8	5.0	SED
2	1.6	2.5	SED
3	4.1	6.3	SED
4	4.9	7.4	SED
5	8.8	13.2	SED
6	7.5	11.3	SED
7	6.6	9.8	SED
8	7.3	10.9	SED
9	9.8	15.1	SED
10	0.6	0.8	-

L

Details of the Multi-Criteria Analysis

In Chapter 12 the details of a Multi-Criteria Analysis that assesses the effectiveness of the possible solutions of the sedimentation problems are described. Some parts of the analysis are described briefly and this appendix contains a more extensive elaboration of these parts.

L.1. Objective tree

Figure L.1 depicts a larger version of the objective tree. In Sections 12.1 and 12.2 the characteristics of this tree are explained.

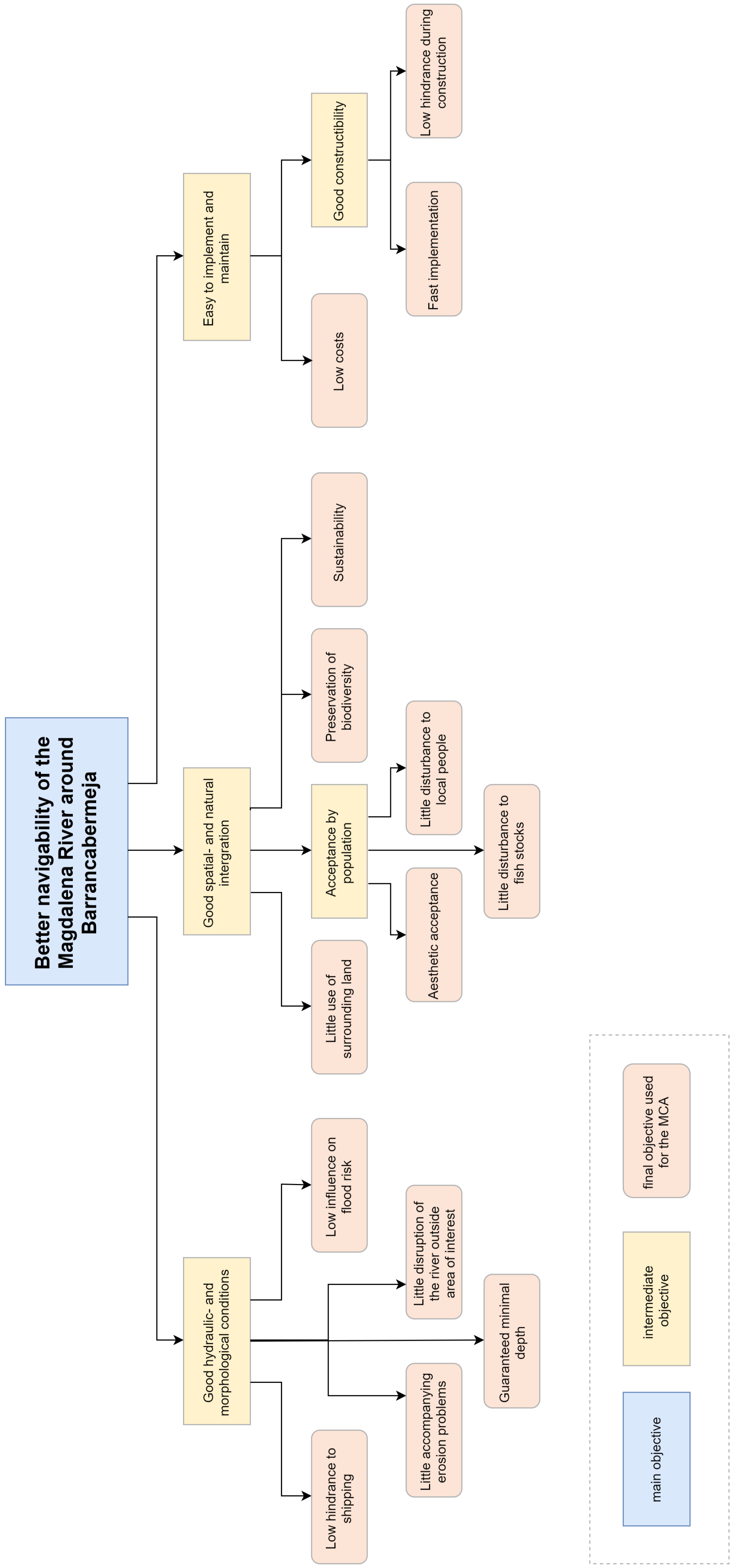


Figure L.1: Objective tree that provides an overview of the main and sub goals of the solution and the criteria used in the MCA

L.2. Allocation of scores

This section shows in detail the allocation of the scores to the alternative solutions. These scores are used in the Multi-Criteria Analysis, see Section 12.4. The final scores are calculated by multiplying the scores of all the criteria with the standardised weights for these criteria, indicated in Table 12.1.

L.2.1. Null solution

Table L.1: Allocation of scores to the null solution

Criteria	Consideration	Score	Standardised score
Hydraulic and morphological conditions			
Hindrance to shipping	Because the dredging occurs on constant basis, there will be a constant hindrance to shipping.	2	0.20
Accompanying erosion problems	No accompanying erosion problems.	5	0.31
Guaranteed minimal depth	Sedimentation is not prevented, but sediment is being removed continuously. Therefore, the required depth is always present.	5	0.63
Disruption of the river outside area of interest	The dredged sediment is given back to the river again upstream of the bridge. Therefore, since nothing changes, the solution fits in the natural behavior of the river.	5	0.44
Influence on flood risk	Dredging does not influence flood risk.	5	0.63
Spatial and natural integration			
Use of surrounding land	No land acquisition is needed, floodplanes remain unoccupied.	5	0.13
Aesthetic acceptance	Dedging vessels do not contribute to a nice view on the river. As dredging has to occur on a constant base, the dredges will be almost always there.	2	0.03
Disturbance to local people	Dredging hinders local shipping and fishery. Dredging vessels and floating pipeline can be an obstacle. Further nuicance is negligible. Therefore, the disturbance level is medium.	4	0.18
Disturbance to fish stocks	Dredging is in principle not a fish-friendly activity.	1	0.05
Preservation of biodiversity	Continuous dredging is an attack on local biodiversity. However, when only executed in a small stretch around Barrancabermeja, it does not influence the preservation of biodiversity in the whole river.	2	0.12
Sustainability	Dredging has to go on for years. During all this time, pollutive diesel consuming dreding vessels are active. Therefore, dredging cannot be seen as a sustainable solution.	1	0.06
Implementation and maintenance			
Costs	Since dredging has to be repeated continuously, it has high operational costs and it is a very non-durable solution. Although the initial costs are almost zero, it is a more costly measure than groynes and guide bunds are.	2	0.31
Implementation time	Dredging can happen on every moment and has a direct impact, which makes it a very effective solution.	5	0.19
Hindrance during construction	During normal conditions dredging is easy to execute.	5	0.29
		Final standardised score	**3.55**

L.2.2. Groynes

Table L.2: Allocation of scores to solution involving groynes

Criterion	Consideration	Score	Standardised score
Hydraulic and morphological conditions			
Hindrance to shipping	Since groynes are not located in the navigation channel, they do not hinder shipping.	5	0.50
Accompanying erosion problems	Scour around the heads of the groynes occurs. The groynes, however, should be designed to deal with these scour holes. Therefore, no large accompanying problems are expected.	4	0.25
Guaranteed minimal depth	The intervention is designed to meet the requirements in every situation. The requried depth is guaranteed.	5	0.63
Disruption of the river outside area of interest	The river will be distrubed both upsteam and downstream of the bridge. To know what the response is going to look like, more research into this topic is required.	3	0.26
Influence on flood risk	Groynes disturb the free flow, lowering the discharge capacity of the river. This leads to higher water levels, which increases flood risk.	2	0.25
Spatial and natural integration			
Use of surrounding land	Groynes are built between the banks of the river. The floodplanes stay unoccupied.	5	0.13
Aesthetic acceptance	Groynes are artificial structures that can be seen as a disturbance to the natural situation, which is regarded to be nonideal.	3	0.04
Disturbance to local people	Groynes will not be of any disturbance to the local people.	5	0.23
Disturbance to fish stocks	After construction of the groynes is finished, fish stocks will not affected by groynes.	5	0.23
Preservation of biodiversity	Groynes will not have a significant effect on biodiversity.	4	0.24
Sustainability	Groynes require only a one time building process compared to the continuous maintenance that can be observed in case of the dredging solution. It requires more material than the solution that uses guide bunds and is therefore less attractive.	3	0.18
Implementation and maintenance			
Costs	For the construction of the groynes a huge amount of construction materials is needed. Furthermore, the complicated river characteristics lead to a complex construction environment. Therefore, the initial costs of the groynes are very high.	3	0.46
Implementation time	Due to the large scale of the project, its realisation time will be long. An unpredictable river and the large volumes of the building materials increase the possibility of delay.	2	0.08
Hindrance during construction	During construction, there will be nuisance to surrounding areas due to traffic and temporary storage of building materials. Hinder can be minimised by the use of pontoons and vessels.	2	0.12
		Final standardised score	**3.59**

L.2.3. Guide bunds

Table L.3: Allocation of scores to the guide bunds

Criterion	Consideration	Score	Standardised score
Hydraulic and morphological conditions			
Hindrance to shipping	No direct hindrance to cargo transport. Small shipping can be slightly affected because of decreased accessibility due to the longitudinal orientation of the guide bund.	5	0.50
Accompanying erosion problems	Erosion around the heads of the guide bund occurs. This is minimized due to its streamlined shape. Therefore, erosion induced by the guide bund will not be disturbing.	4	0.25
Guaranteed minimal depth	The intervention is designed to meet the requirements in every situation. A certain depth is one of these requirements. The requried depth is therefore guaranteed.	5	0.63
Disruption of the river outside area of interest	The guide bund influences the flow characeristics around the bridge. This slight change causes a disturbance in the river upstream and downstream of the bridge. The disturbance will probably not have negative consequences.	4	0.35
Influence on flood risk	The guide bund located in the centre of the river causes a decrease in cross sectional area of the river, which increases water levels in case of high discharges. The differences are small, resulting in little effect to flood risk.	4	0.50
Spatial and natural integration			
Use of surrounding land	No land acquisition is needed. Flood plains stays undisturbed.	5	0.13
Aesthetic acceptance	Guide bunds are large structures that disturb the natural situation. A guide bund is, however, not an unnaturally looking structure. Therefore, the negative impact is low.	4	0.05
Disturbance to local people	The longitudinal dam will slightly hinder the water taxi, but besides that, the locals will not be disturbed by this solution.	4	0.18
Disturbance to fish stocks	After construction of the guide bund is finished, fish stocks will not affected by guide bunds.	4	0.18
Preservation of biodiversity	After the guide bund is constructed, biodiversity will not be influenced by the guide bund.	4	0.24
Sustainability	Guide bunds are constructed during one large project, and not during a continuous maintenance cycle, which is the case for the dredging solution. Therefore, the environment is harmed only a signle time. This solution also requires less building material than the solution that uses groynes.	4	0.24
Implementation and maintenance			
Costs	Constructing guide bunds in the centre of the river is a very expensive operation. Also maintenance can be costly. Nevertheless, due to the smaller scale of the structure, the costs will be smaller compared to the groynes.	4	0.62
Implementation time	The construction of the guide bund is a vast project, that requires a long preparatory. Also its building time will be long. An unpredictable river and the large volumes of the building materials increase the possibility of delay.	2	0.08
Hindrance during construction	Building guide bunds in the centre of a river is a huge project that causes a lot of hindrance to shipping. Traffic increase and temporary storage of construction materials can cause nuisance to people living in the surrounding area.	1	0.06
		Final standardised score	**4.00**