Delft University of Technology

Multidisciplinary project, Sogamoso river

Hydraulic behaviour of the Sogamoso river and Ciénaga El Llanito by a modified flow regime

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Abstract

The hydraulic behaviour of ciénagas and their surroundings is essential to understand the impact of adjustments in catchment area of associated rivers. Ciénagas inhabit different species of birds, small mammals, frogs, reptiles, insects and fish. Vegetation around the ciénaga functions as a natural filtering of the water by storing and releasing the water. The water resource is important for the environment, as well as the inhabitants around the ciénagas.

The behaviour of the system of ciénagas and their surroundings is complicated and disruptions may lead to major consequences in the hydro- and morphodynamics in that area. These consequences have major influence on the environmental and socio-political aspects of such areas. At the moment limited studies focussed on the hydraulic behaviour of the ciénagas. This report will focus on one particular catchment area, namely the Sogamoso catchment area.

In the Sogamoso catchment area the Ciénaga El Llanito is located just before the confluence between the Magdalena river and Sogamoso river. In 2014 a hydroelectric power plant, called Hidrosogamoso, was built in the Sogamoso river, which disturbed the natural flow in the Sogamoso river. There has been a decrease of fish population by 70 %. This report describes the influence of a modified flow regime on the Ciénaga El Llanito and the Sogamoso river, regarding the hydraulics and socio-political context.

In the report the influence of the Hidrosogamoso on the hydraulic regime downstream of the dam is defined first. With statistical analyses the characteristics of the new regime are addressed. After the construction of the Hidrosogamoso the average discharge decreased by almost 40 %. Furthermore there are less daily averaged discharge fluctuations, but if a fluctuation occurs it will be more extreme. The last major modification of the flow regime is that discharge fluctuations have become more rapid. These fluctuations are on a shorter time-scale than before, which will

cause certain flood waves in the river.

The stakeholders involved are analysed to understand the socio-political context of the area. First the stakeholders are identified and there interests are assessed. Subsequently their power and interests are elaborated and the two main relations between them are determined. Firstly, Isagen (owner of the Hidrosogamoso) has to meet certain requirements and regulations to avoid environmental damage as much as possible to retain an environmental license for operation of the Hidrosogamoso. This license is provided by the ministry of Environment and Sustainable Development. The second relation, regarding social and economical development initiated by the ministry of Agriculture and Rural Development, states that Isagen should work together with ASOPESAMM to think of solutions to improve the social and economical development of the Ciénaga El Llanito. The interest of Isagen is mainly economical and ASOPESAMM is mostly interested in job opportunities. Together with their interaction in the current situation with the ministries, the Ciénaga El Llanito might be undervalued regarding environmental aspects.

The hydraulic regime upstream in the Sogamoso river has been modified. To understand the behaviour further downstream, the propagation of flood waves downstream of the Hidrosogamoso are investigated. By means of a one-dimensional SOBEK model, the fluctuations at the Hidrosogamoso are modelled and the deformation of the flood waves. In general an increase of the discharge is observed, caused by the tributaries. Also the flood wave shows diffusion of the hydrograph.

The hydrograph 7 kilometres upstream of the connection channel between the Ciénaga El Llanito and Sogamoso river is used to assess the influence of the modified flow regime on the Ciénaga El Llanito. This hydrograph is obtained from the SOBEK model. The response of this modified flow regime is assessed by using a two-dimensional hydrodynamic model, which is set-up in Delft3D. Different aspects of the modified flow regime are examined: 1) extreme discharges , 2) discharge fluctuations and 3) influence of the Magdalena river.

The modified flow regime led to minimum and maximum water depths in the Ciénaga El Llanito of respectively 1.10 m and 1.22 m, given a representative discharge coming from the caño San Silvestre. The discharge fluctuations at the Hidrosogamoso influence the hydrodynamics in Ciénaga El Llanito on a much larger time-scale. The time to adjust to fluctuations of Ciénaga El Llanito is much larger compared to Sogamoso river. With respect to the flow direction the model showed that for all upstream fluctuations, the flow direction in caño San Silvestre is towards the Sogamoso river. Backwater curves influence the water level in Ciénaga El Llanito when extreme water levels are present in the Magdalena river. For both the backwater curves and fluctuating discharges upstream, an increase of extreme water levels and discharges result in relatively larger impacts on the water levels in Ciénaga El Llanito compared to an equal increase of average values.

In addition to the hydrodynamics, also a qualitative morphodynamic analysis in the Ciénaga El Llanito and Sogamoso river is performed. To investigate the adjustments in the area, we used analytical relations. The part of the Sogamoso river where it is connected with the caño San Silvestre experience an initial response of eroding, due to the average decrease of water level in the Sogamoso river. This decrease in water level affects the hydro- and morphodynamics in the caño San Silvestre. It is expected that the initial response of caño San Silvestre is an eroding process, starting at the connection between the Sogamoso river and caño San Silvestre. This eroding of the bed will proceed upstream along caño San Silvestre on the long term. Since the ciénaga El Lanito is connected via caño San Silvestre the water level is expected to decrease in the ciénaga as well on the long term.

All these changes led to the intention to build hydraulic structures to control the water level in the Ciénaga El Llanito. These structures are assessed qualitatively and it is expected that the construction of the hydraulic structures will result in a higher water level and depth in Ciénaga El Llanito on the short term. On the long term, morphodynamic processes might influence the system such that an import of sediment causes the water depths to decrease. However the hydraulic structures should be implemented in the current existing hydrodynamic model of the area to give a decisive conclusion. Due to time constraints this has not been executed in this project.

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Chapter 1

Introduction

1.1 Context

1.1.1 Area of Interest

The Sogamoso Hydroelectric Power plant, also known as the Hidrosogamoso, is located in the Department of Santander (Colombia), on the Eastern Mountain Range of the Andes. It has been constructed in a canyon where the Sogamoso river passes the Serrania La Paz to flow into the Magdalena river. The Sogamoso river is one of the largest tributaries from the Magdalena river and contributes as a major sediment source for the Magdalena river. The confluence of the Magdalena river and the Sogamoso river is 15 kilometres north of Barrancabermeja, see figure 1.1.

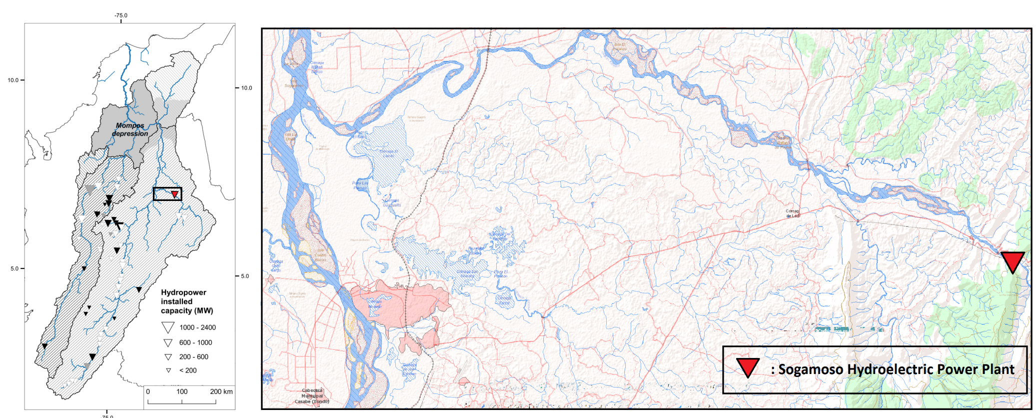


Figure 1.1: Downstream catchment basin Sogamoso river

Before the construction of the Hidrosogamoso, the discharge in the Sogamoso river fluctuated during the year, because of the rainy and dry seasons in the Andean area. This three-months cycle is broadly visible in the discharge graph of the Sogamoso river (see figure 1.2). The data used in the graph are obtained from IDEAM (Institute of Hydrology, Meteorology and Environmental Studies of Colombia).

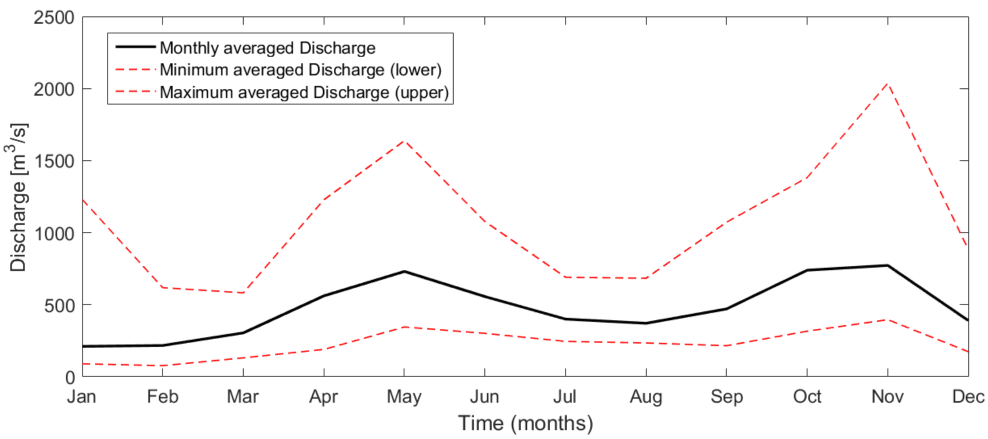


Figure 1.2: Discharges during the year

Since the construction of the Hidrosogamoso the natural flow in the Sogamoso river is blocked. The flow downstream of the Hidrosogamoso depends on the amount of energy that will be generated.

In the downstream area of the Sogamoso river, from the Hidrosogamoso until it flows in the Magdalena river, the Ciénaga El Llanito is located. Ciénaga is the Spanish word for swamp or wetland. Generally ciénagas are flat shallow areas of water filled during high water levels or floods in the river(s) nearby. It inhabits different species of birds, small mammals, frogs, reptiles, insects and fish. Vegetation around the ciénaga functions as a natural filtering of the water by storing and releasing the water. Ciénagas are complex dynamic systems depending on relations between the components described above. Fishing, hunting and agriculture are professions often aspired by inhabitants around the ciénagas.

The Ciénaga El Llanito has a surface of about 1250 hectares and is connected to the Sogamoso river by means of the caño San Silvestre. The bifurcation of the Sogamoso river and the caño San Silvestre is just 4 kilometres upstream from the confluence of the Sogamoso river and the Magdalena river (figure 1.3).

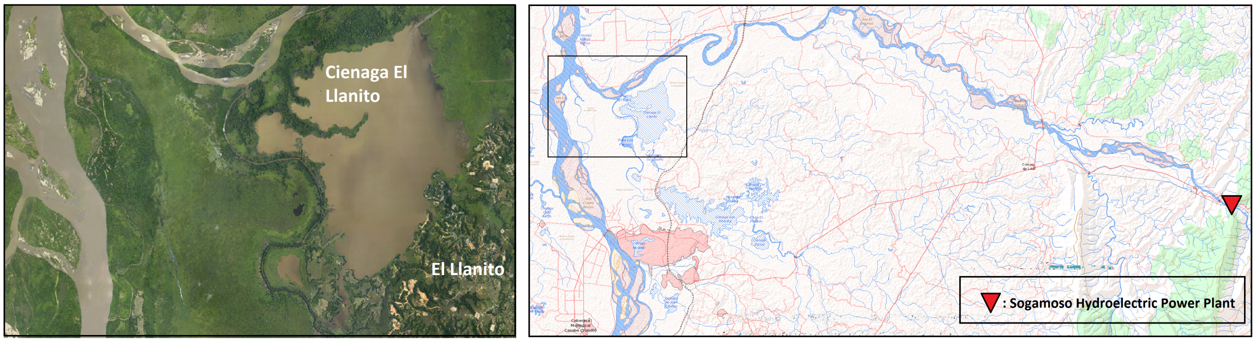


Figure 1.3: Location of ciénaga El Llanito

At the south-east side of the ciénaga the village El Llanito is located which has approximately 2.500 inhabitants. A large part of the inhabitants of the villages are fishermen. Furthermore several farmers are active in and around the village.

Relative to the Sogamoso river the caños are small channels, which connect the Sogamoso river with Ciénaga El Llanito. The main caño is San Silvestre. This caño is connected with three smaller caños to the ciénaga El Llanito. One more caño at the east side of the ciénaga El Llanito, caño La Roja, supplies an additional amount of water to the ciénaga. At the south another ciénaga is located, ciénaga San Silvestre (not visible in figure 1.4), which is connected to the ciénaga El Llanito by caño San Silvestre.

Before 1970 one more natural caño existed, namely caño El Llanito. Around 1970 caño El Llanito was disconnected from ciénaga El Llanito for petroleum activities. Afterwards two artificial caños were made by fishermen of the area, to improve the connection with the Sogamoso river. In figure 1.4 all the current active caños are displayed.

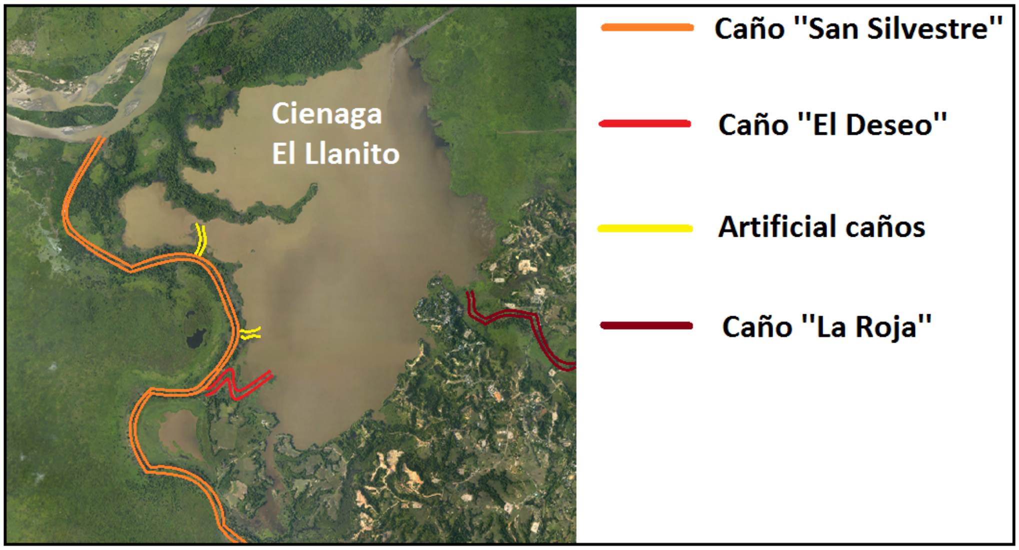


Figure 1.4: Overview of caños of ciénaga El Llanito

The Hidrosogamoso is located 75 km upstream from the confluence with the Magdalena River (see figure 1.1) and 62 km downstream of the confluence of the Suarez and Chicamocha river. The power plant takes advantage of the river flow by building a dam on the riverbed, which forms a reservoir. This reservoir is used to create a large water level difference that is needed to have sufficient flow velocity in the "water fall", where the turbines are located. It is the fourth largest hydroelectric power plant in Colombia and will provide the country with around 8.3 % of the energy consumed by Colombians each year. In table 1.1 some key facts are presented and in the intermezzo below a small summary of the construction milestones can be found.

Information Hidrosogamoso	
Height	190 m
Width (at the crest)	355 m
Reservoir Volume	4.8 million m^3
Installed capacity (electricity)	820 MW

Table 1.1: Key facts Hidrosogamoso

Intermezzo: Summary of the construction milestones

The first studies of this project were provided in 1960, after which the technical feasibility and environmental studies were carried out from 1973 till 1998. In 2007-2008 ISAGEN acquired all project studies and in 2009 they began constructing the general construction work. On the 7th of June 2014 the Reservoir began filling and was up to the required level in October. On the 20th of December was the official startup of the Hidrosogamoso commercial operations with an installed capacity of 820 MW.

There are three possibilities to let water pass the Hidrosogamoso.

1. **Outlet Channel Turbines**: These are the main water passages, where stored water in the reservoir can be withdrawn to the generating equipment. There are three conduits, that distribute the water to the three groups of turbines and generators housed in the underground powerhouse. After the water is used to generate energy, it enters the downstream catchment basin of the Sogamoso river.

   Each of the vertical turbines has a maximum discharge of 210 m^3/s. The energy market in Colombia uses the one-day ahead market, where the seller of energy (Isagen) needs to provide the pre-arranged volume of energy. The amount of water that passes the turbines depends on the energy demand at that moment.

2. **Bypass System**: This structure is constructed to guarantees proper environmental flow downstream during construction (fill up process of the reservoir) and operation. If the power plant is unable to generate power the bypass system guarantee proper flow downstream in compliance with the Projects Environmental License.

   The bypass system consists of a pipe with a length of 605 metre and a diameter of 7.8 metre. There is an adjustable radial gate with a maximum discharge capacity of 486 m^3/s. At the moment the bypass system is not used, however ISAGEN has proposed to use the bypass system in order to regulate the flow regime, including the sediment transport. However the National Authority of Environmental Licenses (ANLA) has not give permission yet, because the influence of this sediment supply on the Sogamoso river and Magdalena river is unclear.

3. **Spillway**: This concrete passageway has the purpose to evacuate excess water when the reservoir's storage capacity is exceeded. The greatest possible water discharges of the Sogamoso river are used as design values, however due to uncertainties a spillway is still necessary. The spillway will not be used during normal operations, but only in case of extreme events.

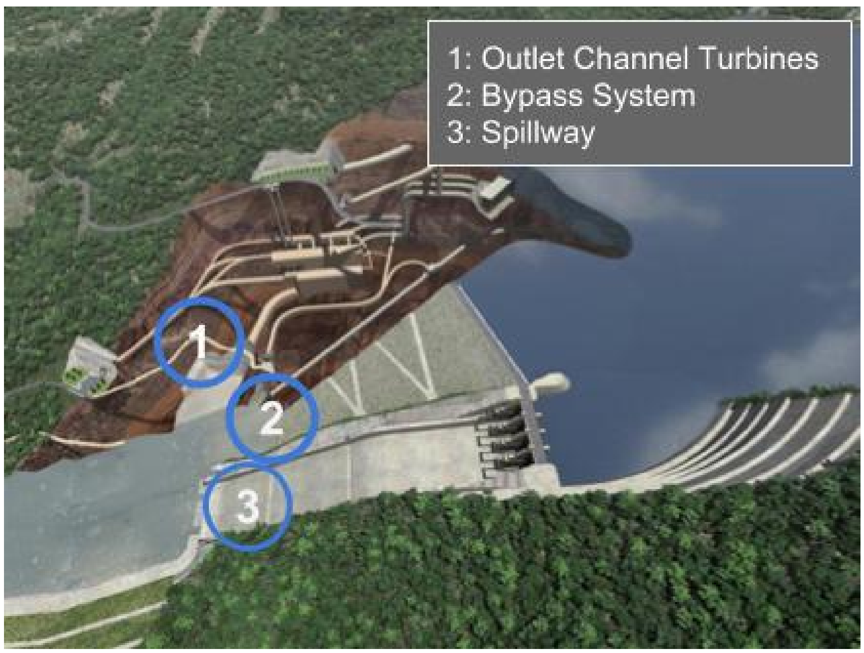


Figure 1.5: Overview elements Hidrosogamoso

Minimum environmental flow: According to the environmental license of the Sogamoso Hydroelectric project, ISAGEN is obliged to a minimum discharge of 80 m^3/s passing the Hidrosogamoso, which is known as the Minimum environmental flow.

Due to the interruption of the natural flow, to which ecosystems are adapted to, the fish population decreased significantly in the downstream area. It is expected that the new flow regime will lead to morphological changes, namely degradation of the Sogamoso riverbed. This change will occur during the upcoming 50 years causing a decrease in the water level of Ciénaga El Llanito. According to the fisherman, the Ciénaga El Llanito is sedimentating at the moment and this all affects the ecosystem around the Sogamoso river.

ISAGEN, owner of the Hidrosogamoso, is obliged to monitor and mitigate the impacts of the Dam (formulated in the Environmental management plan) in order to retain the Environmental License to operate the Hidrosogamoso. One of the monitoring projects is about the protection of fish and fishing resources in the Sogamoso river and this has the goal to maintain the reproduction dynamics of migratory fish species and the hydraulic conditions. A proposed solution for the decreased fish population is to maintain a regular discharge through the Ciénaga El Llanito, to simulate the historical average flows. According to the fishermen association sufficient water levels are needed for the reproductive stage of the migratory fish species in the Ciénaga. They have planned and already partly build several structures to control the hydraulics in the Ciénaga El Llanito and the caños.

However, these structures are not examined by hydraulic models, but are mainly based on experiences of the fishermen. The impact on the complete hydraulic system of the Ciénaga and caños is not known. At the moment there is limited information about the hydraulic behaviour of the ciénagas and the operation of the structures may influence the ecosystem enormous.

1.2 Research scope and objective

1.2.1 Research Scope

Until the present situation no hydraulic or morphological researches have been executed with respect to the ciénaga El Llanito and the river Sogamoso. To start this process the hydraulic interaction of the ciénaga El Llanito with its surroundings is the first step in understanding the system of the ciénaga El Llanito.

In the relevance tree of figure 1.6, the research scope is divided in three parts: Impact, downstream area and modified flow regime. Within the three main parts several sub-parts are determined. The blue colour indicates that it is relevant to our research and is part of our research, pink means that it is relevant but that this research will not consider that sub-part in depth. The light-blue colour of the morphological impact indicates that it is not elaborated on in detail but considered qualitative as an begin for further research.

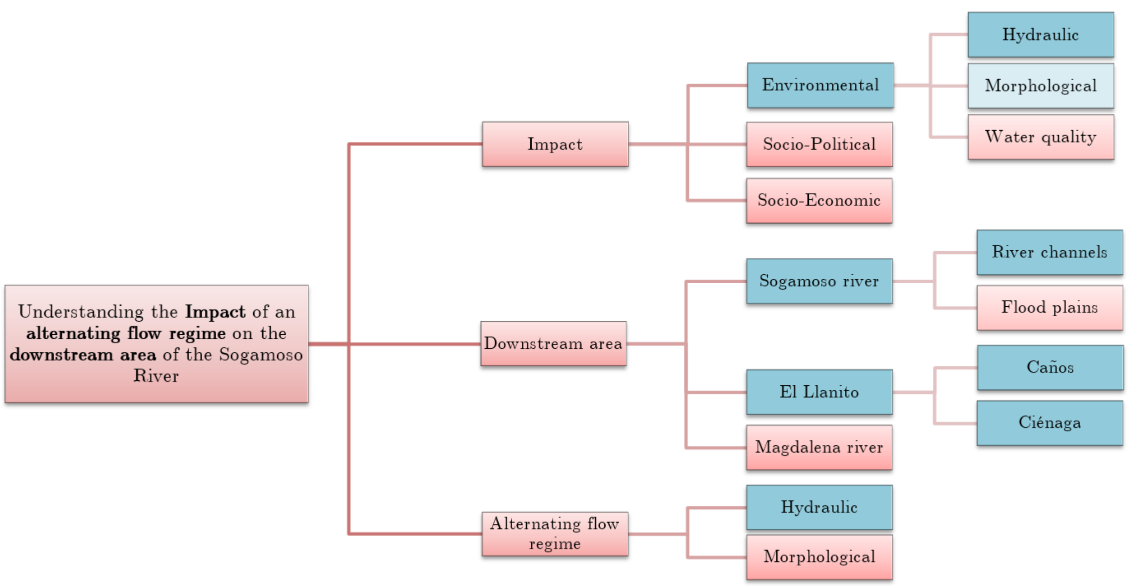


Figure 1.6: Relevance tree of the project

1.2.2 Objective

After mapping the organizational structure of our project and the feasibility and relevance of the different sub-parts, the objective is formulated.

Objective

Understanding the influence of a **modified flow regime** on Ciénaga El Llanito and the Sogamoso River, regarding the **hydraulics** and **socio-political context**

The impact of modified flows on the environment is a very complex topic, where the conditions of a environment are difficult to define. Part of the environment are the hydrodynamics and morphodynamics in the system. Therefore, our research project focussed on the hydraulic interaction.

The change in the flow regime of the Sogamoso river is the construction of the Hidrosogamoso. This influence the hydro- and morphodynamics in the Magdalena river, Sogamoso river and Ciénaga El Llanito. The changes in the flow regime are examined and are used to assess the changes in the hydraulic interaction between Ciénaga El Llanito and the Sogamoso river.

The socio-political context is part of the objective to have a multidisciplinary understanding of the system.

1.3 Research questions

The research questions are questions which are answered to accomplish the objective of the project. The terminology used in the research questions and approach is displayed in figure 1.7.

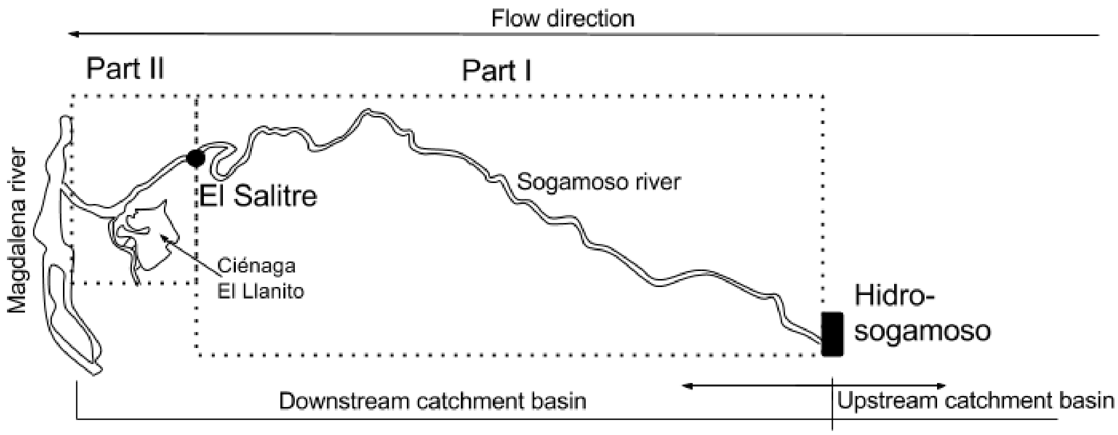


Figure 1.7: Overview terminology

The research questions regarding the modified flow (red), socio-political context (green) and hydraulics (blue) are:

Modified flow regime

- How did the construction of the Hidrosogamoso influence the flow regime downstream?

Socio-political context

- What are the interests and positions of the stakeholders involved?

Hydraulics

- How do flood waves downstream of the Hidrosogamoso propagate to the area of the Ciénaga El Llanito?
- How is the hydraulic behaviour in the Caño San Silvestre and Ciénaga El Llanito influenced by the modified flow regime?
- Which processes contribute to the morphological response of the Sogamoso river, caño San Silvestre and Ciénaga El Llanito?
- What is the influence of the proposed hydraulic structures on the Ciénaga El Llanito?

1.4 Approach

This section gives an overview of the report structure, and with that a short overview of the approach used to answer the research questions. The report is divided into chapters. Each chapter consists of sections of which some are subdivided into subsections.

The next chapter, Chapter 2, presents the answer to the question how the construction of the Hidrosogamoso influence the flow regime downstream. To answer this question, analysis of datasets are used which provide statistical analysis of water levels and discharge data. Also the stage-discharge relationship is analysed to get insight in the flow properties of the Sogamoso river.

After the analysis of the hydraulic changes, the interests and positions of the stakeholders involved are analysed in chapter 3. This is done to understand the socio-political situation in the area of interest.

To find out how flood waves propagate from the Hidrosogamoso to the area of the Ciénaga El Llanito, a SOBEK 2.13 model is used. Chapter 4 describes the set up, as well as the results of a one-dimensional hydraulic model that simulates the flood waves in part 1 of our area of interst (see figure 1.7). This gives insights in the change of the hydrograph shape, which is important for the hydraulic behaviour at ciénaga El Llanito and its surroundings.

Chapter 5 elaborates on the hydraulic behaviour in the Caños and ciénaga El Llanito, part 2 of our area of interest. A two-dimensional hydraulic model in Delft3D is used to simulate the ciénaga El Llanito and its surroundings. The hydrograph of flood waves in the Sogamoso river, simulated by SOBEK 2.13, will be used as input for the two-dimensional hydraulic model. Multiple scenarios of the modified flow regime in the Sogamoso river are simulated, after which the hydraulic interaction with the ciénaga is assessed.

The morphodynamics of part one and two together are discussed qualitively in chapter 6, to understand the basics of the morphological processes in the system. Subsequently chapter 7 presents an analysis of the proposed hydraulic structures. The impact of the hydraulic structures is assessed with the knowledge of the previous chapters.

The conclusions of all preceding chapters are summarised in Chapter 8 and also includes several recommendations for further research or development on this topic.

Chapter 2

Hydraulic changes downstream of the Hidrosogamoso

2.1 Introduction

In this part an analysis is performed of the hydraulic changes of the Sogamoso river downstream of the Hidrosogamoso. The situation before and after the construction of the dam will be analysed for two locations along the Sogamoso river. The following research question about the modified flow is answered:
"How did the construction of the Hidrosogamoso influence the flow regime downstream?"
For the influence of the Hidrosogamoso on the modified flow further downstream in the direction of the Magdalena river, the tributaries also need to be considered. The flow regime of the tributaries entering the Sogamoso river in the reach after Hidrosogamoso are not affected by man made structures and still have a natural flow. This analysis is necessary for the further research questions about the propagation of the modified flow along the Sogamoso river in the next chapter of the report.

2.2 Methods

2.2.1 Data collection

There are limited data available in our area of interest. IDEAM had in the past two measuring stations in the Sogamoso river, namely PTE La Paz Automatico and PTE

Sogamoso (see figure 2.1). These stations give the daily averaged discharge and the daily averaged water levels.

Figure 2.1: Overview measuring stations downstream catchment basin

La Paz: This is the station just 0.8 kilometres after the Hidrosogamoso. IDEAM has got data from this station for the years 1972 until 2009. In this time-series there are still a lot of samples missing where no data are available for certain days or weeks. The time-series of this data is over such a long period, that these missing data will not significantly influence our analyses.

With the samples from 1972 until 2009 the discharges and water depths can be analysed before the construction of the Hidrosogamoso. To know the influence of the Hidrosogamoso on the flow regime of the Sogamoso river, samples from after December 2014 need to be obtained. ISAGEN provided data from December 2014 until September 2016, which contains a time-series of hourly averaged discharges and water levels.

PTE Sogamoso: This station is located 55 kilometres downstream of the Hidrosogamoso. For this station daily averaged discharges and water depths for the years 1992 until 2014 and 2015 until July 2016 are available. Again samples are missing, but the influence on the data analysis is minor.

Summarizing, the following data is used for the two different situations and for the two different locations:

	Before Hidrosogamoso	After Hidrosogamoso
La Paz	Jan 1972 - Dec 2009	Dec 2014 - Sep 2016
Puente Sogamoso	Aug 1992 - Dec 2009	Jan 2015 - Jul 2016

Table 2.1: Used time-series for the situation before and after the construction of the Hidrosogamoso

2.2.2 Statistical analysis

To analyse the modified flow regime and determine the characteristic differences between before and after the construction of the Hidrosogamoso a probabilistic approach is used. A certain event, like amount of discharge in a river, may take particular values with positive probability. The function describing this probability is called the probability density functions. This function is denoted as follows:

$$f_X(x) = P(X = x) \tag{2.1}$$

The probability density function has many properties, but the two most important ones are

$$0 \leq f_X(x) \leq 1 \tag{2.2}$$

$$\sum_{x \in X} f_X(x) = 1 \tag{2.3}$$

In most of the cases engineers wants to know the probability that an certain event will occur. To determine the probability that X lies between two possible outcomes the probability density function can be used

$$P(x_1 \leq X \leq x_2) = \sum_{x \in \{x_1 \leq X \leq x_2\}} f_X(x) \tag{2.4}$$

or

$$P(x_1 \leq X \leq x_2) = \int_a^b f_X(x)dx \tag{2.5}$$

The graphical representation of a probability density function gives values or outcomes on the x axis, and probabilities on the y axis. See figure 2.2 for an example.

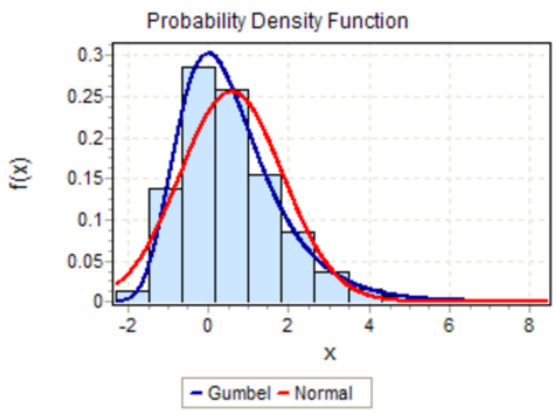


Figure 2.2: Example of a Probability histogram

Figure 2.2 shows the theoretical PDF of the fitted distribution (in this case Gumbel and Normal distribution) and the one of the sample data, which is a histogram of the empirical probability density function. To obtain a histogram of the empirical probability density function first the number of bins and width need to be determined.

$$k = \left\lceil \frac{\max x - \min x}{h} \right\rceil \tag{2.6}$$

where k is the number of bins and h is the width of that bin. After that the probability of that certain bin (in this case the bin has boundaries at x_1 and x_2) can be calculated:

$$P_n(x_1 \leq X \leq x_2) = \frac{x_1 \leq \text{number of elements in the sample} \leq x_2}{n} \tag{2.7}$$

2.3 Results

Figure 2.4 and 2.3 show the daily discharges during a year before and after the construction of the Hidrosogamoso for the two different stations La Paz and Puente Sogamoso. In figure 2.3 the influence of the Hidrosogamoso is the most clearly visible. The magnitude of fluctuations of the discharges in 2015-2016 differs from the situations before. Also the maximum discharge is limited by 630 m^3/s, because of the maximum operational discharge from the turbines. Figure 2.4 shows that there are higher discharges, caused by the tributaries, and the high fluctuations have decreased.

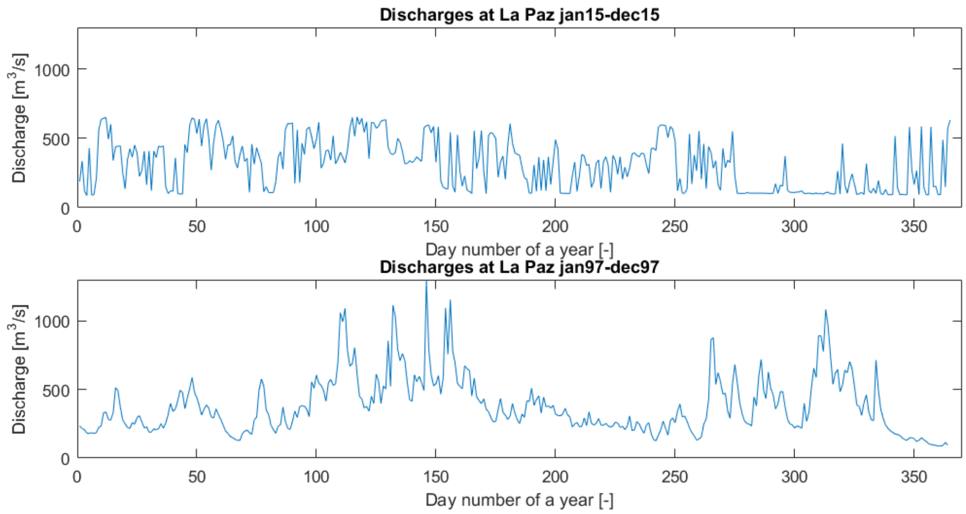


Figure 2.3: Daily averaged discharges La Paz during a period of one year (excluded non-measuring days)

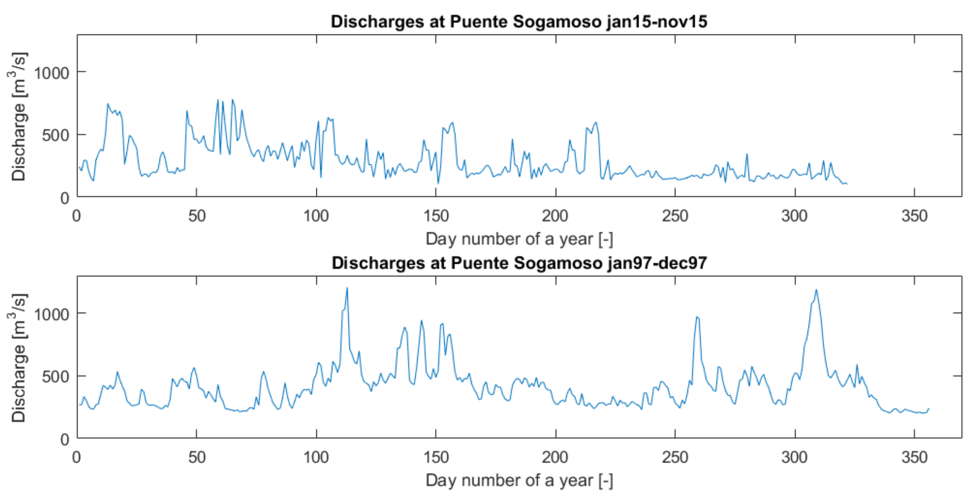


Figure 2.4: Daily averaged discharges Puente Sogamoso during a period of one year (excluded non-measuring days)

This chapter will start with the stage-discharge relations to obtain insights in the river properties, like stability and streamflow in the river. Next the modified flow will be discussed and some remarks and conclusions will be made.

2.3.1 Stage-discharge relations Sogamoso river

A stage-discharge relation is often used to create an impression of the river properties at a certain location, like presence of floodplains, dynamics of the river and present of down- and upstream influences. The stage-discharge relation represents the relationship between the discharge and the water level. The relationship is analysed using a scatterplot, where different discharges and there corresponding water levels at a certain location during a certain time period (for e.g. several years) are displayed. In this case daily averaged discharges and water levels are used.

If a curve can be fitted through the scatter-plot, without outliers, it can be said that the hydraulic condition of the river is in permanent control. It means that the stage-discharge relation does not change in time and the channel is stable. However it also occurs that the data is not aligned, which represents changes in time and is referred to shifting control. This could provide information about the morphological developments in the river.

The shape of the curve also tells something about the river. If significant increases in discharge are required for only moderate increases in water level, it can be concluded that the channel is influenced by flood plains. The water can be stored in those areas, and this influences the channel-conveyance capacity.

Puente Sogamoso

In figure 2.5 the stage-discharge relation at location Puente Sogamoso is shown. In the lower part of the plot, it can be clearly seen that the channel is not stable, because there are multiple aligned samples. It is also visible that floodplains are present, because of the declining growth in water level with increasing discharges in the first stage of the stage-discharge relation.

In the upper part of the plot a cloud of samples can be seen, which are really outliers from the stage-discharge relation. These deviating samples can have several causes. But in this case it is suspected that there are effects from backwater curves. Backwater effects occur when disturbances tend to propagate upstream (for the case of sub-critical flow). Puente Sogamoso is located 20 kilometres upstream of the confluence between the Sogamoso river and the Magdalena river. At the point of the confluence, there needs to be a continuous water level. High water levels in the Magdalena river, combined with relatively low water levels in the Sogamoso river will cause these backwater curves. The deviating samples are analysed and the samples are consecutive during certain months, namely November, December and January. In general November and December are rainy months and January is the driest month of the year. Other possibilities for the deviating samples are seasonal changes in vegetation, adjustments in the reference of the measuring equipment, other errors in measurements or hysteresis.

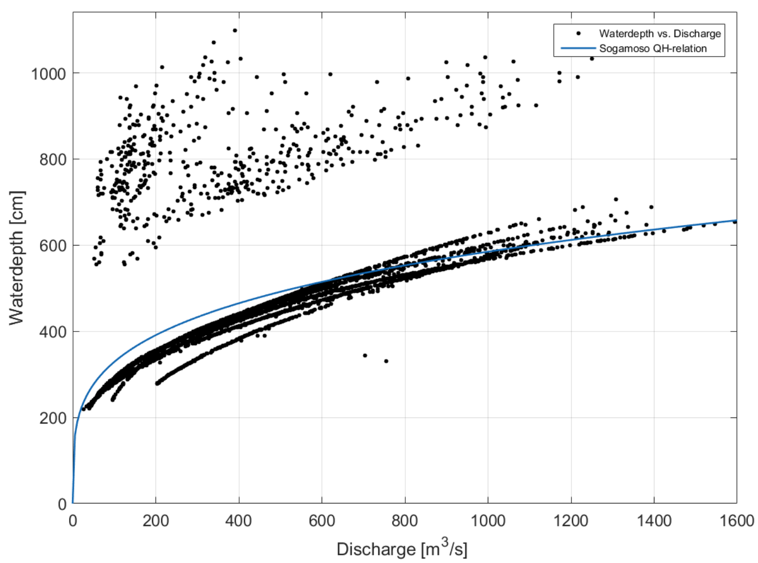


Figure 2.5: Discharges and water levels Puente Sogamoso 1993-2009

Hysteresis is a phenomenon, where the discharge will be larger during rising water levels than the discharge will be for the same water level during falling water levels. This is because of the fact that the discharge depends on the spatial gradient ($\partial h/\partial s$) of the flow. During fast rising stages the water surface slope is significantly steeper than for steady flow conditions, resulting in greater discharge than indicated by the stationary flow conditions. This phenomena is most common in flat sloped rivers and rapid water level changes. Whether this occurs, can be determined by the formula Jones [Handerson, 1966].

$$Q = Q_e * \sqrt{1 + \frac{1}{i_b c}\frac{\partial h}{\partial t}} \quad (2.8)$$

where i_b is the bed slope, c the propagation speed of a high-water wave and $\partial h/\partial t$ the change in water level in time.

The stage-discharge relation for the years 2015-2016, after construction of the Hidrosogamoso, is shown in figure 2.6. It needs to be noticed that the time series is much shorter than the previous one. It can be seen that the channel is stable during the previous one and a half year. Deviating points are noticed again and could be explained by the hysteresis effect, backwater curves or errors in measurements.

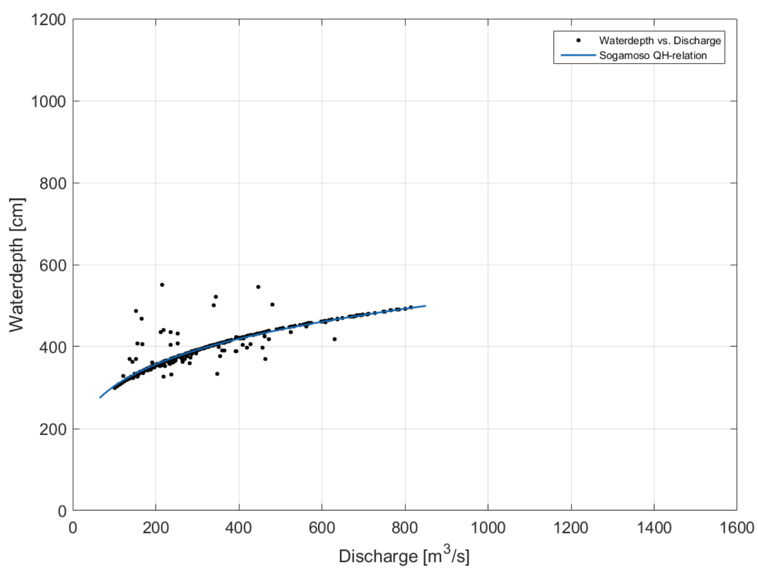


Figure 2.6: Discharges and water levels Puente Sogamoso 2015-2016

La Paz

Figure 2.7 shows the discharge-stage relation at the point La Paz before the construction of the Hidrosogamoso. It can be seen that the channel at this point was unstable with a lot of influences, whereby the flow deviates a lot from the steady state.These deviating points can be seen in the figure and the interpretation of which is uncertain. An analysis is performed where the samples which deviate more than 100 % from the fitted curve were further investigated. It can be seen that there are a lot of consecutive samples, whereby the average length of the series is approximately 5 days and mostly occur in January (65%) and the remaining deviations mainly in Februari (12%) and December (12%). A valid conclusion is hard to draw. The confluence with the Magdalena river is located 75 kilometres further downstream. However tributaries are closer located, but have much smaller discharges and less influence on backwater curves in the Sogamoso river. Seasonal changes in vegetation could be a possibility or potential changes in the gauge.

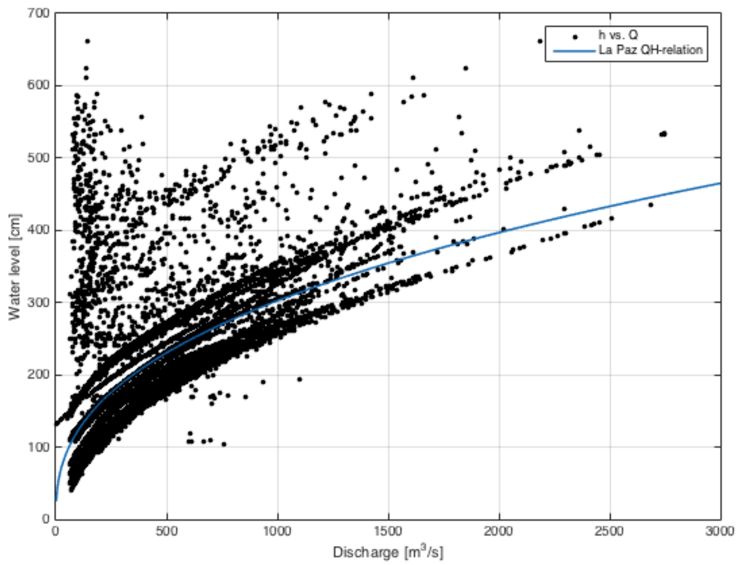


Figure 2.7: Discharges and water levels La Paz 1972-2009

The previous graph showed the deviations of a time-series of 37 years, but now we zoom in on the deviating samples from 2008. It can be seen that there are three series with consecutive samples, which occur in January, November and December (see figure 2.8). This corresponds approximately with the months from the longer time-series analyses. The deviating points do not lie close to the normal flow condition. The graph suggests that downstream water levels are influencing the upstream water level. A possibility is that the tributaries of the Sogamoso river may have influence. The largest tributaries are located 18 kilometres downstream the Hidrosogamoso. There is no data of those tributaries and valid conclusions can not be made at this point.

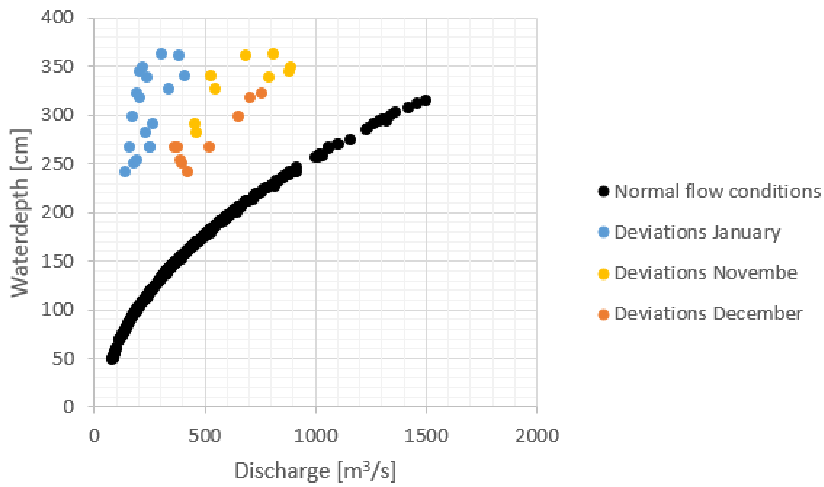


Figure 2.8: Deviating samples of data from the year 2008

After the construction of the Hidrosogamoso the discharge-stage relationship has changed. Figure 2.9 shows the changes of the stage-discharge relation between 2008 and 2015-2016. The deviating points mentioned before are not longer present after the construction of the Hidrosogamoso, which implies a permanent controlled condition. The disappearing of those deviations also suggests that these deviations came from upstream, because the Hidrosogamoso may block those influences. The aligned samples also show that the channel is stable and does not change in time. This could by explained by the fact that there are mainly rocks just after the dam, which was confirmed by visual inspection of the river during our field trip(large rocks along the banks of the river).

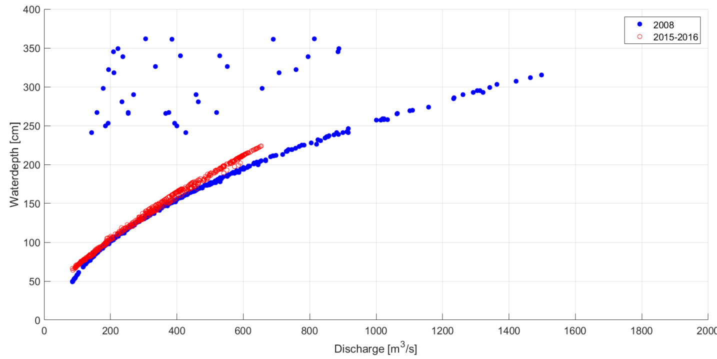


Figure 2.9: Stage-discharge relation before and after the construction of the Hidrosogamoso

2.3.2 Modified Flow regime

Figure 2.10 shows an hourly time-serie of the discharge at La Paz. It can be clearly seen that the discharges have different stages, which are caused by the turbines of the Hidrosogamoso (each with a discharge of 210 m^3/s) and the minimum environmental flow of 80 m^3/s. The fluctuations of the discharge are really abruptly, where switches of discharges of 200 m^3/s in just one hour may occur.

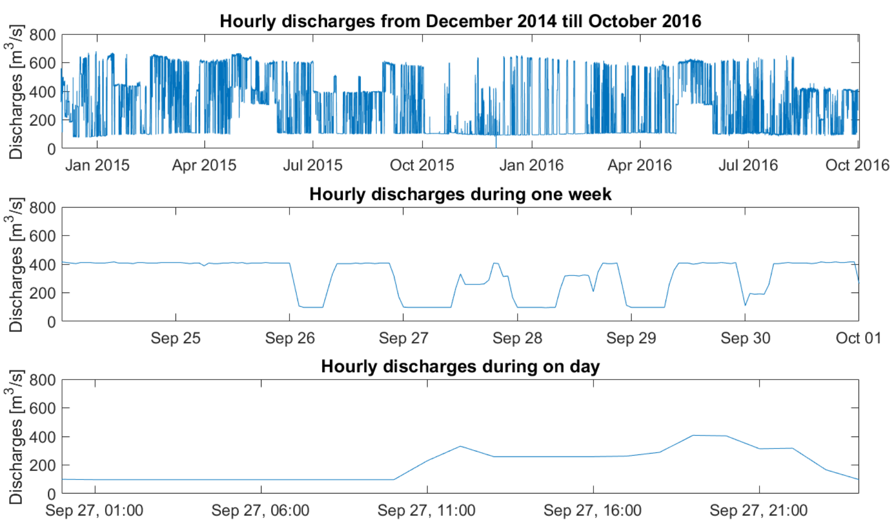


Figure 2.10: Discharge time-serie at La Paz

In this section the modified flow regime downstream of Hidrosogamoso will be analysed, which will be done with probability density functions. Two different values will be examined, namely the amount of discharges and fluctuations of the discharges in time. To compare the situation before and after the construction of the Hidrosogamoso the analysis are mainly performed with daily averaged discharge, because of the available data before 2009.

Amount of discharge

Figure 2.11 shows that the range between which the discharges occur became smaller after the construction of the Hidrosogamoso. Occurrences of the extreme discharges (lower and higher) have become less after the construction of the Hidrosogamoso. The expected daily averaged discharge changed from circa 480 m^3/s to 300 m^3/s and the discharge range with the largest probability changes from 240-280 m^3/s to 80-120 m^3/s.

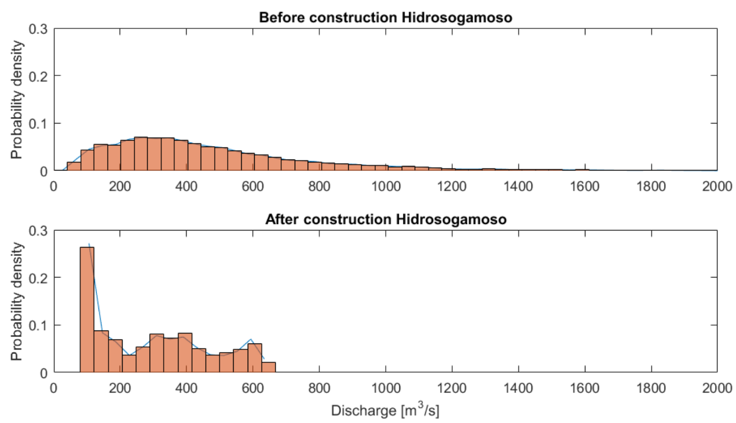


Figure 2.11: Probability density function of the daily averaged discharges of La Paz for the situation before and after

Now Puente Sogamoso will be considered which will differ from La Paz, because of the tributaries along the Sogamoso river. It can be seen that the discharge with the largest probability shifted to a higher value.

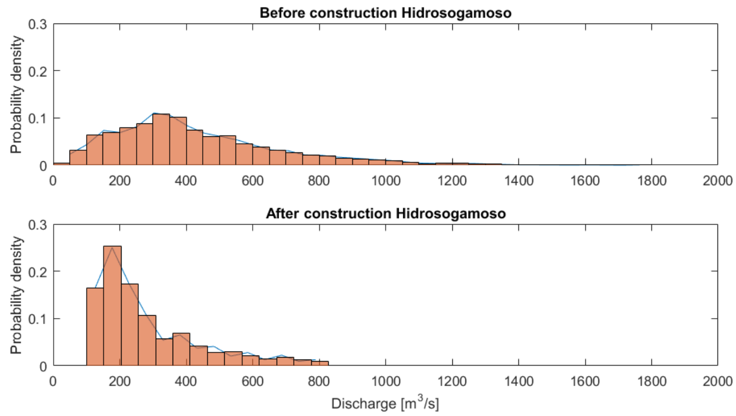


Figure 2.12: Daily changes in discharges

	Before Hidrosogamoso	After Hidrosogamoso
La Paz	479 m^3/s	296 m^3/s
Puente Sogamoso	430 m^3/s	280 m^3/s

Table 2.2: Expected discharges before and after the construction of the Hidrosogamoso

Intermezzo: Reliability of Puente Sogamoso and La Paz data

In table 2.2 the averaged discharges are shown, where it can be seen that the average discharge is higher at La Paz before and after the construction of the Hidrosogamoso than of Puente Sogamoso. A volume balance analysis also shows that there is water flowing away between La Paz and Puente Sogamoso. With additional tributaries along this traject, this is impossible. The explanation may be that the measuring stations are incorrect. It could be due to the lack of calibration of Puente Sogamoso, that the discharges are incorrect. The data at La Paz is considered as correct and most of the analysis further on will be executed with those data.

If we now look more in detail to the discharges at La Paz and consider the occurrence of hourly discharges after the construction of the Hidrosogamoso, it can be noticed again that there is a very large possibility of a discharge between 80-120 just like the daily averaged discharges(see figure 2.13). But now the different stages become more clear, were it can be seen that the Hidrosogamoso will mainly have a discharge of around 100, 400 and 600 m^3/s.

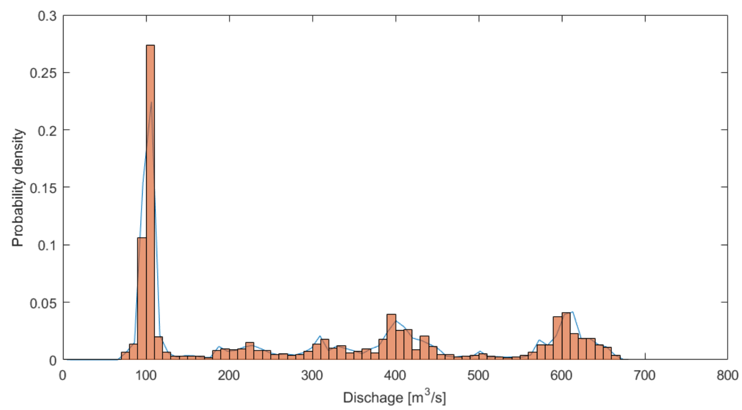


Figure 2.13: Probability density function of the hourly discharges of La Paz for the situation after the construction of Hidrosogamoso

Discharge fluctuations

So far only the amount of discharge and the probability of occurrence have been analysed. Typical effects of the operation of the Hidrosogamoso are sudden flow changes due to the operation of the turbines. There are only daily averaged discharges available before the construction, so first these will be compared.

Figure 2.14 shows the result of the daily fluctuations at La Paz. It can be seen that there are in general less daily averaged fluctuations. However if there are fluctuations nowadays, this daily fluctuation will be larger compared with the situations before the Hidrosogamoso. The figure shows that there is a longer tail, with more peaks.

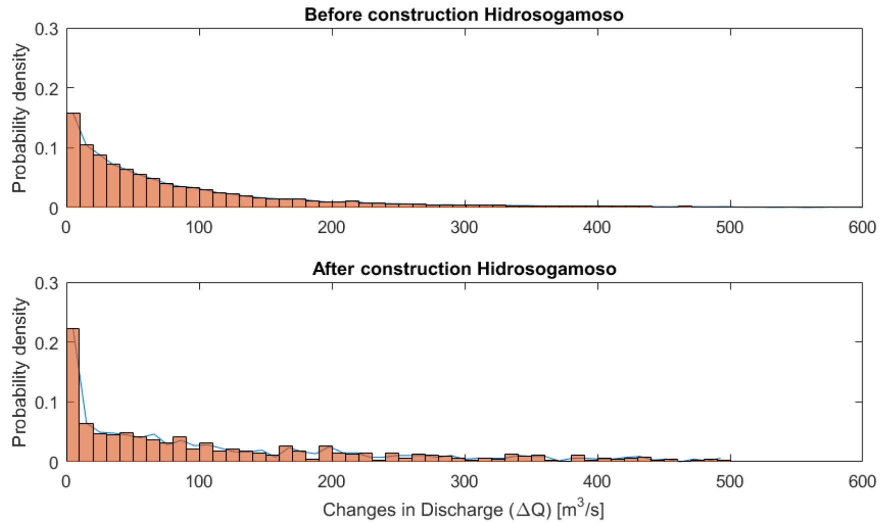


Figure 2.14: Fluctuations of the daily discharges at La Paz

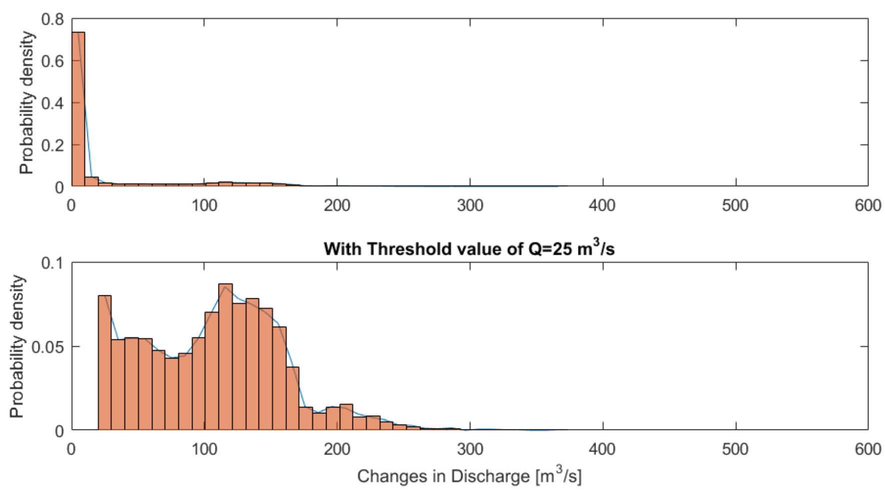


Figure 2.15: Fluctuations of the hourly discharges at La Paz

In figure 2.15 the hourly fluctuations are shown. There is a possibility of 78% that the hourly discharge fluctuations lie between 0 and 20 m^3/s. If we look at the probabilities of discharge fluctuations, the following can be summarized:

ΔQ [m^3/s]	P (Discharge >ΔQ)
50	0.1799
100	0.1261
200	0.0107

Table 2.3: Probabilities greater than a certain discharge fluctuation

So we can see that there is every day a probability of 12.61 % that there will be a discharge fluctuation of 100 m^3/s or more. Or it can be said that every 3 months there is a discharge fluctuations of 200 m^3/s between two consecutive hours.

2.3.3 Hydraulic impact of the confluence between the Sogamoso river and Magdalena river

In this subsection the possible influence of the Magdalena river on the Sogamoso river is focussed on. The Sogamoso river is a tributary of the Magdalena river and the confluence of these rivers allows hydrodynamic interaction. In the case of one-dimensional hydraulic models, confluences are relatively simple with respect to the dynamics in rivers. Two branches convert to one branch, so there are no problems with the distribution of discharge of water and sediment. In comparison with bifurcations, local geometry around the confluence does not matter to the division of discharges and those can just be added up to each other.

At the point of confluence, the equilibrium depth according to the properties and discharge of the joint rivers is valid. This is not the equilibrium depth of each of the two branches upstream and will induce a disturbance, which propagates upstream in each of the two branches. The discharges in both branches, because of the varying precipitation during the year, often induces those backwater curves because of the associated different equilibrium depths.

For known river properties there is an equilibrium water depth (h_e) that can be derived from the Chézy equation:

$$h_e = \sqrt[3]{\frac{Q^2}{C^2 i_b B^2}} \tag{2.9}$$

where Q is the discharge in the river, B is the width, i_b the bed slope and C the Chézy coefficient.

The effect of backwater curves is only mentioned a certain distance from the confluence. The effect slowly fades out and can be described by the Bélanger equation:

$$\frac{\partial h}{\partial x} = i_b \frac{h^3 - h_e^3}{h^3 - h_c^3} \tag{2.10}$$

where $\partial h/\partial x$ the spatial water depth gradient, h the actual water depth and h_g the critical water depth. The order of magnitude of the influence of those backwater curves is 1 till 100 kilometres.

Changes in backwater curves

After the construction of the Hidrosogamoso the averaged discharge decreased from 479 to 296 m^3/s at La Paz, noted as Q2 in figure 2.16. The water level at the confluence is determined as the combined discharge at the locations of the joint rivers. The averaged discharges will lead to a decrease of the equilibrium water level in the Sogamoso river by a factor 0.73, according to equation 2.9 (assumed that Chezy, bed slope and width of the river remains constant). However the reduction in discharge in the Sogamoso river will not lead to the same decrease of discharge in the joint part, because of the Magdalena river that has a significantly higher discharge than the Sogamoso river.

$$Q1 > Q2_{old} > Q2_{new} : \quad \frac{Q2_{new}}{Q2_{old}} < \frac{Q1 + Q2_{new}}{Q1 + Q2_{old}} \tag{2.11}$$

Therefore there will be a backwater curve and the Sogamoso river needs to adjust to the new equilibrium state in the downstream area, given a water level in the Magdalena river. This will fade out of the system during the years, because of morphological changes.

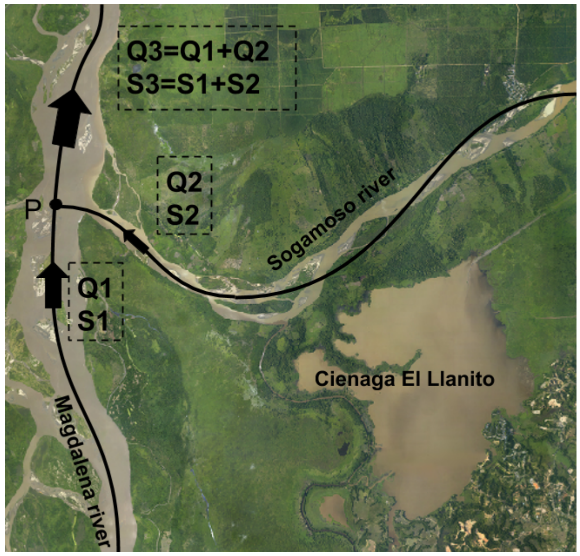


Figure 2.16: Overview confluence Sogamoso river and Magdalena river

We have seen that there are more fluctuations in the Sogamoso river after the construction of the Hidrosogamso. Given a certain water level in the Magdalena river, this will also lead to more backwater curves. The influence of those backwater curves will be analysed in the part about the hydrodynamics in the Ciénaga El Llanito in chapter 5.

2.4 Discussion

The performed analyses are based on uniform data, whereby trends are not considered. This can mainly have influences on the analysis performed at La Paz for the years 2014 until 2016. It could be that during the first months, the Hidrosogamoso was not on full operation capacity. To some extent, the historical data from La Paz says something about the future discharges. However it still depends on the energy market of Colombia.

Also the reliability of the measurements at Puente Sogamoso is doubtful. A rough volume balance analysis (inflow = outflow) showed that water flows out of the section between La Paz and Puente Sogamoso, which is remarkable with tributaries entering the river. Therefore conclusions about any analysis in which this data is used, are unreliable.

The analysis suggests that backwater curves occur, which will influence the system. Later on, the influence will be considered and examined with a numerical model for the last seven kilometres of the Sogamoso river. However the performed analysis could be extended with historical data of the Magdalena river to see if there is a correlation between high water levels in the Magdalena river and deviations in the Sogamoso river.

2.5 Conclusion

From the stage-discharge relations, it can be concluded that the Sogamoso river is very dynamic. The channels at puente Sogamoso and La Paz changed in the past years. Nothing can be said about the dynamics of the river after the construction of the Hidrosogamoso, because of the relatively short period in which the river should adapt to the flow.

The situation before and after the construction of the Hidrosogamoso is analysed, where the modified flow at the beginning of the downstream catchment basin (at La Paz) is characterized as follows:

	Before	After
Mean Discharge [m^3/s]	479	296
Discharge range [m^3/s]	6 - 4142	86 - 654

Table 2.4: Overview changes flow regime

In general the amount of daily averaged discharge fluctuations is decreased. However, at the same time the occurrence of extreme daily averaged discharge fluctuations is increased. This means that there are less fluctuations, but if there is a fluctuation it will be extremer. The different discharge stages are after the construction of the Hidrosogamoso clearly visible, which are generated by the turbines. The fluctuations between these stages are on shorter time-scales than before.

The characteristics above have also additional side effects on the flow in the downstream catchment area. The short time-scales of those fluctuations create a hysteresis in the river and will lead to unsteady flows.

Chapter 3

Stakeholder analysis

3.1 Introduction

In this chapter the following research question is answered: 'What are the interests and positions of the stakeholders involved?'

In general the stakeholder analysis is a tool for supporting management processes. It should provide a framework, which helps the understanding of a system, by identifying the key actors and their interests in that particular system. The aim of a stakeholder analysis is to develop a strategic view of the human and institutional landscape, the relationships between the different stakeholders and the issues they care about most [Rosso et al., 2013].

Building large-scale water (infra)structures has proven to have a huge social and environmental impact, whereby burdens and benefits are unevenly distributed among different social groups, regions and scales [Bibiana Duarte-Abadía, Rutgerd Boelens and Roa-Avendaño
This analysis will focus on the downstream area of the Hidrosogamoso. The stakeholders analysis is carried out in the following steps:

- Indentification and assessment of interests of the relevant stakeholders
- Overview of their power and interests
- Relations between the stakeholders
- Discussion and conclusion

The first three steps are treated in the section methods the discussion and conclusion are both seperate sections.

3.2 Methods

3.2.1 Identification and assessment of interests

Below the relevant stakeholders are identified. Their interests are assessed by either the conversations held with them during the fieldwork or by consulting their websites.

Public actors

Ministry of Environment and Sustainable Development: The national executive ministry has the task to direct and coordinate the planning processes and the implementation of environmental activities to ensure the sustainable development of the country. The following agencies are associated to this ministry:

ANLA Also known as the National Authority of Environmental Licenses. This agency focusses on projects, works or activities which need an environmental license. They monitor if the environmental processes comply with environmental regulations, to contribute to sustainable development of the country [ANLA, 2016].

CAS Is the Autonomous Regional Corporation of Santander whose objective is the implementation of policies, plans, programs and projects on natural resources in the department Santander. This authority is also responsible for the monitoring of the implementation of the Environmental Plan of Isagen [CAS, 2016].

Cormagdalena Is the public authority that focusses on managing the navigation and harbour activities, managing sustainable use and preservation of the environment (e.g. fish resources), management and the protection of the environment of the Magdalena river system, including its surrounding environments like ciénagas.

CIRMAG Is part of Cormagdalena and focuses on the scientific study of thethehehth rivers. Complex systems of interactions between water, society and the natural environment are part of their researches.

Ministry of Agriculture and Rural Development Directs, coordinates and evaluates policies related to rural, farming, fishing and forestry development in Colombia [Minagricultura, 2016]. The following agencies are associated to this ministry:

AUNAP Is the National Authority for Aquaculture and Fisheries. They are responsible for fisheries policy and aquaculture in Colombian territory. They monitor and control the fishing activities and aquaculture in Colombia [AUNAP, 2016].

UMATA Is the Municipal Units for Agricultural Technical Aid, which provides technical assistance to small farmers (450.000 farmers) on a full range of issues [UMATA, 2016]. ‘

INCODER Is the Colombian Institute for Rural Development. Their mission is to run rural development policies. In coordination with communities, public and private institutions related to agriculture, forestry and fisheries sector, facilitating access of rural people to productive and social factors, to help improve their quality of life and the socio-economic development of the country [INCODER, 2016].

Municipality of Barrancabermeja The local government coordinates, directs, and controls the adequate administrative action to develop the mission of the municipality of Barrancabermeja.

Private actors

Isagen The third-biggest electricity generator in Colombia. Until January 2016 the government had a 57.6% stake in this company. In a bid to diversify and attract foreign investments in the electricity market, the government has sold her stake to Brookfield Asset Management Inc. The goal of Isagen is to develop projects for the generation, production and sale of electric energy, in order to meet its clients energy needs and create business value. The mission of the company's management is aligned with the highest ethical standards, maintains high corporate and social responsibility, uses good economic judgement and focuses on great customer service.[Isagen, 2016]

ASOPESAMM Association of Artisanal Fishermen and Farmers of the Middle Magdalena Basin, is formed by 35 associations in 16 municipalities. Their mission is to work for the well-being of artisanal fishermen, farmers and their families in a healthy environment, focusing on building policies and initiatives promoting social and economic development [ASOPESAMM, 2016].

APALL Is the Association of Fishermen and Aquaculture Producers of ciénaga El Llanito. Their main focus is to conserve job oppertunities to provide food and economical opportunities for the local residents of the villages around Cìenaga El Llanito. Furthermore they are interested in the conservation and restoration of the Ciénaga systems, preserving and sustaining the ichthyological (also called fish science) wealth, the wetlands and the biodiversity that exists there.

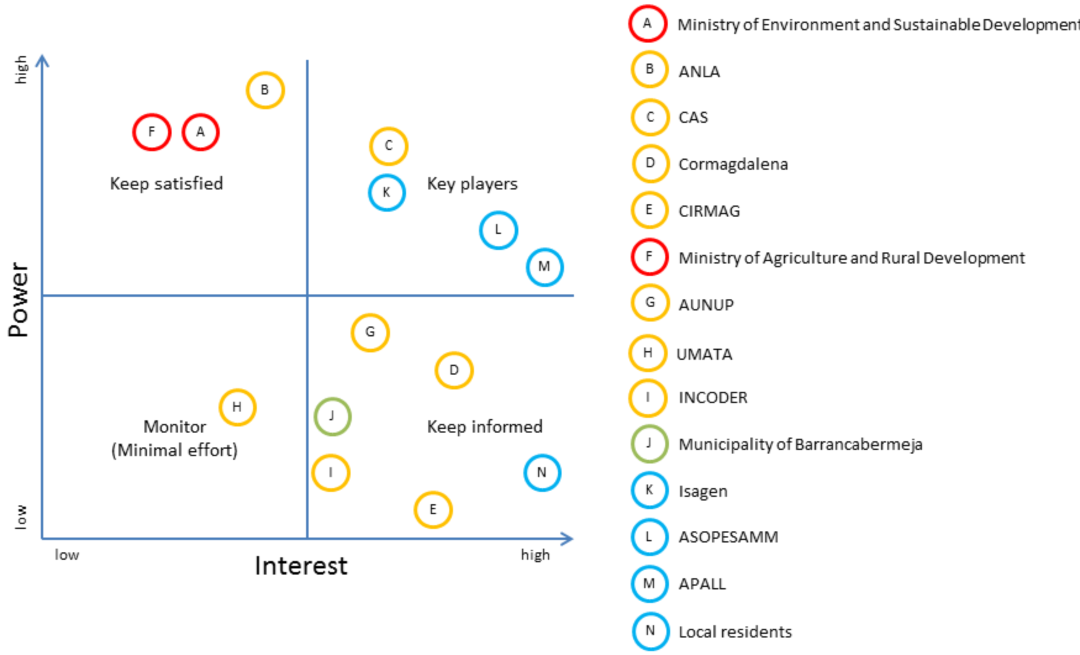


Figure 3.1: Power-interest diagram

Local residents The local residents that live around the Ciénaga El Llanito are influenced by the modified flow mainly with respect to work availability. Due to the reduction of the fish population, there is less work available. Since almost all the residents of the villages around ciénaga El Llanito are fishermen, their main interest is to obtain a solution for the fish problem in ciénaga via the fishermen organisations to obtain job oppertunities.

3.2.2 Overview power and interests

In figure 3.1 the power-interest diagram is given. The actors power and interest are elaborated below.

Ministry of Environment and Sustainable Development
The interest of the ministry is more focussed on larger political scale, therefore the specific interest for a single project like this is small. However the ministry has a lot of power because they are responsible for the related agencies which execute their interests on smaller political scale. The ministry is involved in the planning and

implementation process, which makes their interest in this project slightly higher compared with the Ministry of Agriculture and Rural Development. The interest of this ministry is focussed more on policies.

ANLA
The operation of Hidrosogamoso is not possible without a environmental license. ANLA is the agency providing environmental licenses, therefore their power is very large. However their interest is moderate as long as the rules are followed.

CAS
Since this is a very large project influencing the natural resources in the Santander Department their interest is large. They are responsible for the monitoring of the implementation of the Environmental Plan of Isagen such that their power is large too.

Cormagdalena
Cormagdalena is interested in this project because the navigability at the confluence with the Magdalena river is negatively influenced due to the Hidrosogamoso. Their power is limited because they have not a direct connection with Isagen true which they can influence there operations and by that the influence of the Hidrosogamoso on the area of interest.

CIRMAG
As a research institute of Cormagdalena they are dependent on which projects are assigned to them, such that their power is limited. Since this research about the area around the ciénaga is initiated by CIRMAG their interest is significant.

Ministry of Agriculture and Rural Development
This ministry is responsible for the coordination and evaluation of policies on larger political scale, their interest are represented by the relevant agencies. Via this agencies their power is large, however their interest is smaller compared to the Ministry of Environment and Sustainable Development, because they are less involved in projects as such but more in policies which influence projects.

AUNAP
Since the fish population is largely decreased they are interested in this project. As a national authority they have a certain political power, however they are not involved enough in this project to be considered as key players.

UMATA
For some farmers technical assistance can be useful since the conditions of the Ciénaga have changed. Because this stakeholder is not directly involved with this project but more with the consequences their power and interest is limited.

INCODER
This institute is mostly interested in policies regarding rural development. Those policies influence this project but are not neccesarly part of it. The power is therefore small. The stakeholder is moderatly interested to whether the policy are effective and succesfull regarding this project.

Municipality of Barrancabermeja
The municipality of Barrancabermeja is in general not related to the project of the Hidrosogamoso, they have no direct way by legislation to influence Isagen with their operations. Therefore they have limited power, however since Ciénagas El Llanito is located near the city of Barrancebermeja their interest is more than average.

Isagen
Isagen is one of the main actors because they are the owners of Hidrosogamoso. Their interest is therefore also large, however their main focus is an economical interest by the production of electricity. As long as their license is valid they are satisfied, to keep their license it is necessary to be in close contact with the parties negatively influenced and come up with new solutions to compensate.

ASOPESAMM
Because they represent the local fisherman and farmers their interest is very large. In the environmental plan of Isagen it is stated that Isagen has to work together with this party, which provides the ASOPESAMM with power.

APALL
This is the part of the ASOPESAMM that specializes on the Cìenaga El Llanito, such that their interest is bigger but their power slightly smaller.

Local residents
The interest of the local residents around the Cìenaga El Llanito is very high because they are directly influenced by the building of Hidrosogamoso. Their power is small as resident but respresented by the fishermen organisations.

3.2.3 Relation between stakeholders

All the separate stakeholders presented in the previous section can be reduced to four main actors in which all the interests are presented. The ministries are responsible for their obligations and via their agencies they execute this obligations. The ministries contain therefore the interests of their agencies and provide the two main actors in the public sector. Within the private actors the fishermen organisations represent the local residents, which form one of the main actors, and Isagen is the second main private actor. In figure 3.2 the relation between the four main actors are given. The two main relations are:

Environmental requirements
The ministry of Environment and Sustainable Development and its associated agencies provide the operator of the Hidrosogamoso, Isagen, with requirements and regulations to avoid environmental damage as much as possible. Isagen has great interest to meet this demands because of the required environmental license to operate the Hidrosogamoso.

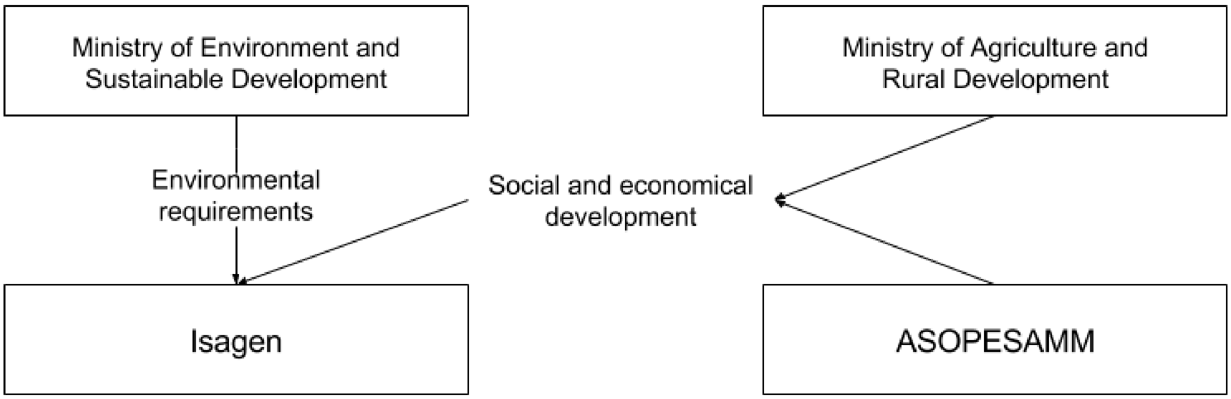


Figure 3.2: Relation between stakeholders

Social and economical development
The fish population in the Sogamoso river and Ciénaga El Llanito provides the inhabitants of the downstream part of the Hidrosogamoso food and work. The ASOPESAMM represent these people and together with Isagen, who is obliged by the Ministry of Agriculture and Rural Development, they think of new alternatives to improve the social and economical development of this downstream area.

3.3 Results

In the current situation two main relations are decisive between the ministeries, Isagen and AOPESAMM to understand the decision making about the Ciènaga El Llanito. Within this relation Isagen cooperates with ASOPESAMM to design solutions for the problems around the Ciènaga El Llanito. They are obliged to do this based on policies made by the Ministry of agriculture and rural development. Furthermore Isagen executes the obliged regulations of the Ministry of Environment and Sustainable Development.

The result of this situation is that Isagen has provided solutions upon which the fishermen agree. The fishermen mainly are accepting the solutions according to their main interest, which is job oppertunity. Whether the Ministry of Environment and Sustainable Development provide Isagen with a license for operation is partly based on the fact Isagen gratify the demands of the fishermen.

The ASOPESAMM made a plan to create a fish-farm of the Ciènaga El Llanito. This will provide alternative jobs for the local people. Isagen has agreed to this plan and has started building some of the hydraulic structures. This might be a good solution for the rural development, however these hydraulic structures will influence the natural resources of the Ciènaga El Llanito, and subsequently the environmental development. No detailed studies are performed about the influence of these hydraulic structures on the future behaviour of the ciènaga.

3.4 Discussion

The environment of the Ciénaga El Llanito is the main subject regarding this project. When judging the results and conclusion about the stakeholders analyse regarding this project a remark should be made about the perception of the environment. In Colombia the perception of the environment along stakeholders such as ASOPESAMM and ISAGEN is different compared to the general perception considered in the Netherlands. The environment is seen more as a resource to provide work, food and energy. Environmental aspects are seen more as an obligation demanded by ministries.

Apart from the perception of the environment, some uncertainties arose during the conversations with the actors.

From the conversation with the ASOPESAMM it became clear that they have political interests, if they succeed their power will significantly increase. How this will influence the developments in the area is also uncertain.

Cormagdalena recently received a new director, which has led to changes in the organization structure. The future involvement of Cormagdalena is therefore uncertain.

3.5 Conclusions

The stakeholders involved can be reduced to four main stakeholders in which the interest of all the smaller stakeholders are represented. The four main stakeholders are:

1. Ministry of Environment and Sustainable Development
2. Ministry of Agriculture and Rural Development
3. Isagen
4. ASOPESAMM

The main interest of the ministries are the sustainable development of Colombia and policies regarding rural development. Isagen mainly has an economical interest, but to continue their operation of the Hidrosogamoso, the demands of the ministries has to be obliged. Resulting in the cooperation with the last main stakeholder, the fishermen organisation ASOPESAMM, which is mainly considered about job opportunities in the new situation of the Ciénaga El Lanito.

In the co-operation between Isagen and ASOPESAMM, Isagen provide solutions for the current situation in the Ciénaga El Lanito. A remark about the solutions for the current situation is that they are not confirmed by any research and mainly based on the experience of the fishermen organisation. As long as Isagen co-operates and provide the solution according to the demands of the ASOPESAMM the ministries are satisfied.

In the current structure of stakeholders, power and interests the future of the Ciénaga El Lanito as a wetland is uncertain. If stakeholders with large power maintain their view on the Ciénaga as a resource, environmental aspect might be undervalued.

Chapter 4

One-dimensional hydraulic modelling of flood wave propagation

4.1 Introduction

In this chapter the following research question is answered: 'How do flood waves downstream of the Hidrosogamoso propagate to the area of the Ciénaga El Llanito?'

Flood waves are in essence humps of water travelling downstream. These humps are temporary increases and decreases of discharge and water level in a river. The most common cause is a temporarily enlarged run-off in catchment basins due to heavy rainfall, however the discharge fluctuations at the Hidrosogamoso cause also such flood waves. These flood waves will deform as they propagate, where internal dynamics of the flood wave cause it to flatten and to elongate. As a result, the variations in flow rate and water level in the lower reaches differ from upstream. Therefore it is interesting to know the propagation from the Hidrosogamoso till the Delft3D model boundary. We are interested in the characteristics of the flow regime at the boundary of the Delft3D model, where the Delft3D model is used to investigate the hydraulic behaviour between the Sogamoso river and Ciénaga El Llanito. The propagation of the flood wave in the basin is simulated by means of a 1D Sobek model.
In section 2 the model area, set-up and settings are discussed. Furthermore the used relevant data and related assumptions are elaborated. In section 3, 4 and 5 the results are given, discussed and concluded.

4.2 Methods

4.2.1 Model area

The model area is chosen such that the scarce collected data is within the model area. This information is obtained from a research about monitoring the morphologic changes and the degradation of the Sogamoso river bed and contains cross-sections, bed slope and data about water depths [Isagen, 2015a]. The data is known in several measuring stations along the Sogamoso river. This research has been performed by a team from Universidad de Antioquia, that did measurements in December 2014 and August 2015. The upstream boundary of the Delft3D model, discussed in chapter 5, is within the model area. This is done, to impose the obtained flow characteristic from the SOBEK model on the upstream boundary of the Delft3D model. The upstream boundary of the SOBEK model is located at measuring station S2 (puente La Paz), 800 meter downstream of the Hidrosogamoso. The area of interest of our model ranges from S2 to S8, which is shown in figure 4.1 included the intermediate measuring stations. In the remaining of this chapter the report about the Sogamoso river bed will be referenced as the morphological report.

Figure 4.1: Location of stations downstream of the Hidrosogamoso

4.2.2 Model set-up

Longitudinal profile

Specifications about the location and elevation of the measuring stations are given in table 4.1. Figure 4.2 shows the longitudinal profile of the Sogamoso river downstream of the Hidrosogamoso. It can be seen that the bed slope is significantly steeper in the upper part of the river, in comparison with the lower part. Between Puente Sogamoso and the bifurcation of Sogamoso river and the caño San Silvester is the mildest slope. This longitudinal profile is used in the set-up of the SOBEK model.

ID	Station	Elevation level 2015
S2	Puente La Paz (0.8km from the Hidrosogamoso)	166,45
S3	10 km from the Hidrosogamoso	152,29
S4	17 km from the Hidrosogamoso, before tributary Rio Sucio	133,90
S5	30 km from the Hidrosogamoso, between tributaries La Payoa and La Raya	100,92
S6	43 km from the Hidrosogamoso, before the tributary La Seca	85,81
S7	Puente Sogamoso (55 km after the Hidrosogamoso)	75,46
S8	70 km from the Hidrosogamoso, before the bifurcation of Sogamoso river and caño San Silvestre	72,71
S9	Before the confluence of the rio Magdalena (75 km after the Hidrosogamoso	67,53

Table 4.1: Specifications stations along Sogamoso river downstream of Hidrosogamoso

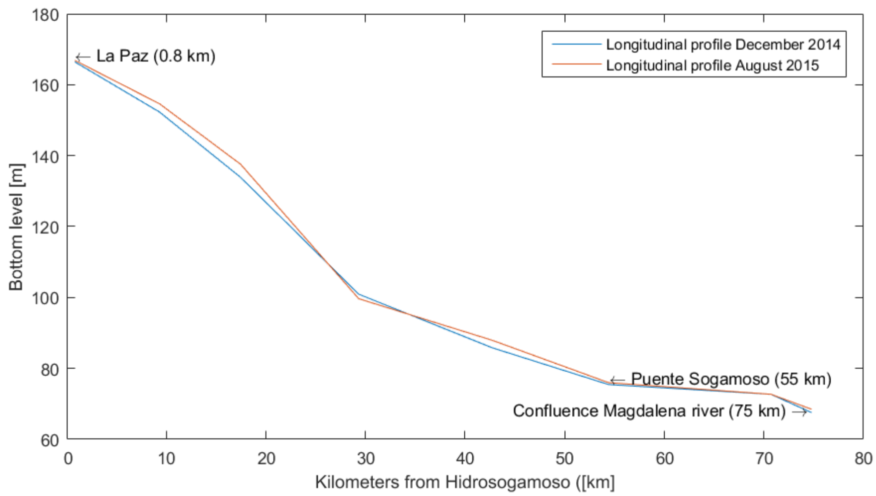


Figure 4.2: Longitudinal profile Sogamoso river

Cross-sections

In the SOBEK model seven cross sections are implemented, which are obtained from the morphological report. SOBEK interpolates those cross-section in order to receive the cross-section in the reaches between. An example of a cross sections digitalized from the morphological report is shown in figure 4.3.

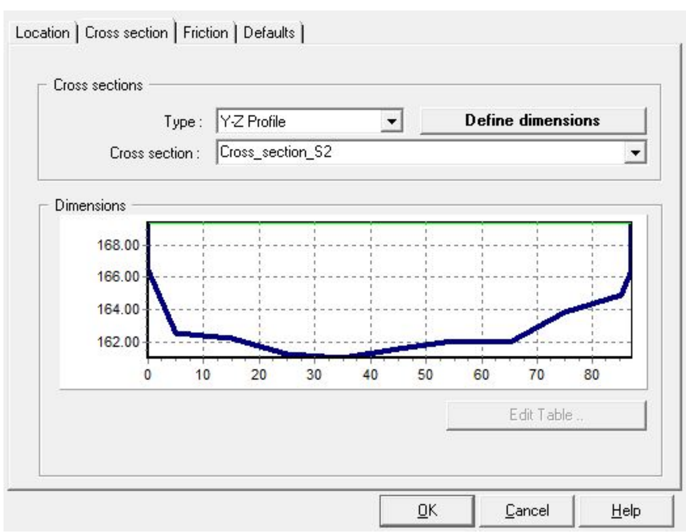


Figure 4.3: Example of a YZ table cross-section in SOBEK

In addition the embankments of the cross sections are heightened three meters. This is done because fieldtrip observations and interviews showed that the cross sections never flood in the present situation. Therefore lateral flow over the embankments is excluded in the model.

4.2.3 Model settings

Tributaries

In appendix F, several sub-catchment basins are shown in the downstream catchment basin. The run-off of those sub-catchment basin will be added to the Sogamoso river in the form of tributaries. With Google Earth the locations are determined and via lateral flow points the tributaries are implemented in the 1D SOBEK model. In figure 4.4 an overview of the tributaries is given.

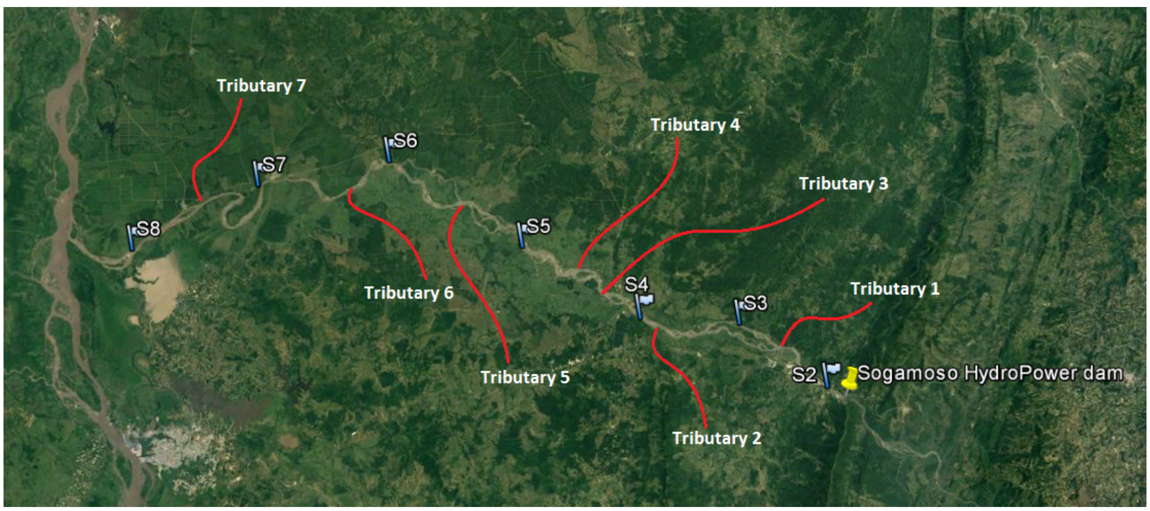


Figure 4.4: Overview tributaries Sogamoso river

Boundaries

In the 1D SOBEK model an up- and downstream boundary is imposed. The upstream boundary is chosen as a discharge time-serie to simulate the operation of the Hidrosogamoso. A constant water level is chosen for the downstream boundary condition. It is placed 20 kilometres downstream of the measuring point S8, so the influence of the boundary is not noticed in our model area.

Δx and Δt

The smallest river reach in the model is 8 km, in such a reach the model interpolates two cross sections known at each side of the reach. To get an accurate model a space step of 100 m is chosen. This space step combined with an estimated maximum velocity of 2 m/s, will provide our time step by the restriction that the Courant number needs to be less than or equal to 1. The time step calculated is 30 seconds.

Simulation time

With respect to the simulation time 1,5 day is needed for a steady state at the maximum discharge of 630 m^3/s at the upstream boundary, given an initial water level of zero. Therefore after every discharge fluctuation in the upstream boundary, according to the imposed discharge time-serie, the model runs 1,5 day to be sure the steady state is achieved.

4.2.4 Model runs

Regarding the tributaries and the boundary condition upstream several model runs are determined. First the discharges by tributaries are discussed for which a method is used which approaches the discharges of a catchment area. Subsequently the final discharge time-serie for the upstream boundary is mentioned.

Tributaries

The discharge of a catchment area depends on multiple factors, like rainfall surface cover and topography. One of the simplest methods to approach the discharge from a catchment basin is the rational equation method. The application of this method is based on simple formula that relates runoff-producing potential of the watershed, the average intensity of rainfall for a particular length of time and the drainage area:

$$Q = CiA \tag{4.1}$$

where Q is the discharge [m^3/s], C is the runoff coefficient [-], i is the rainfall intensity [m/s] and A is the drainage area [m^2]. However, in our project area insufficient data is available to use this method. Therefore there is made use of ratio's of the sub-catchment area's downstream of the Hidrosogamoso and the upstream catchment basin. The discharges measured at La Paz are related to the upstream catchment basin, of which also the drainage area is known. With the assumption that the runoff coefficient and the rain intensities are equal, the discharges from the tributaries could be determined given their drainage area's.

In figure 4.5 the upstream area is shown together with the drainage basin of a tributary illustratively, the values of the area's are not correct. The area upstream of the dam is 20.000 km^2 and the area of the tributary is 200 km^2. Now the ratio 200/20000 determines that 10 % of the amount of discharge that come from the upstream catchment basin, should occur in that particular tributary.

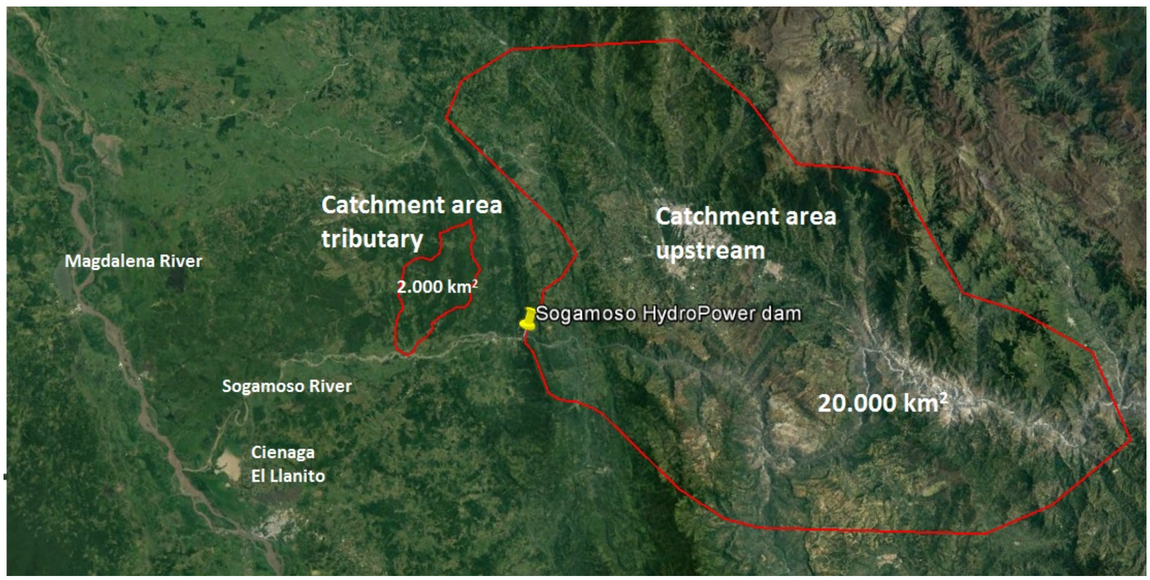


Figure 4.5: Example catchment area's

However the rainfall intensity could differ heavily in both catchments basins, because clouds are naturally formed in the foothills of mountain ranges and there is often more precipitation.

Rain intensity

There is made use of the data from the morphological report, to approach the differences in rain intensity in both catchment basins. In the morphological report values for the discharge at the eight points in the model are given at two moments in time, so the discharges coming from the sub-catchment basins can be calculated. With the assumption that this discharge is representative during a mean amount of rainfall for that certain month, we can estimate the ratio of the two rain intensities in the down- and upstream catchment basins by using equation 4.1.

Discharges tributaries in the downstream catchment basin
In appendix F, the characteristic values (minimum, maximum and mean) for the discharges of the upstream catchment basin before the construction of the hidrosogamoso are determined, were there was made distinction between rainy and dry season. With the rational equation method, the characteristic discharges for the whole downstream catchment basin can be determined, additionally the total average is added for rainy and dry season together:

	Total discharges tributaries (m^3/s)		
Season	Max	Min	Mean
Rainy season	181.41	46.19	91.56
Dry season	91.21	27.36	48.44
Average			70

Table 4.2: Total discharges tributaries

Which has the following distribution along the Sogamoso river:

Tributary	1	2	3	4	5	6	7
Percentage of discharge upstream	5%	23%	18.7%	11.3%	17%	14%	11%

Table 4.3: Distribution discharges along tributaries

Upstream boundary condition

To determine the influence of the changes in discharges on the downstream part of the Sogamoso river, a block scheme is used as upstream boundary. The discharges vary between 100, 420 and 630 m^3/s, which represent the possible capacities of the hidrosogamoso, and include increasing and decreasing situations (see previous part for probabilities of occurrence of different discharges just downstream of the Hidrosogamoso). It is assumed that the changes in discharges during the dam operation are instantaneously. In figure 4.6 the time-serie of the upstream boundary is shown. For all the models with different scenarios for the tributaries, this boundary is used as upstream boundary.

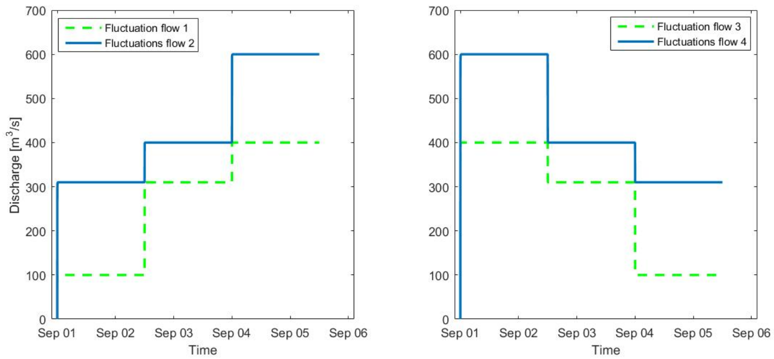


Figure 4.6: Distribution discharge upstream boundary condition

4.2.5 Sensitivity analysis

The last parameter for the model, which is not treated yet, is the roughness. Data from the morphological report is used to verify our model, however the water depths and velocities deviated to much along the Sogamoso river in order to choose one representative roughness value for reality. There was insufficient data, like inadequate bed profile along the river, too few measure-points and only observations for two moments in time. In the real situation difference in roughness between segments are present, where there are much larger grain sizes upstream near the Hidrosogamoso.

A sensitivity analysis is carried out to examine the influence of the roughness on our model. With the knowledge about the influence of roughness on our model, there can still made conclusions about the propagation of the flood wave.

A separate model is made, where the roughness is varied. The Manning's coefficient is used to impose roughness, where three different coefficient are used to simulate our model: 0.025,0.045 and 0.065. These values are based on reference tables from Manning's value for main channels and the typical value for simulations in the Magdalena river.

For the sensitivity analysis there is imposed a constant discharge for the upstream boundary and for the downstream boundary there is chosen for a constant water level. Again this boundary is 20 kilometres downstream of measuring station S8 to prevent any influences of this boundary.

4.3 Results

The results of the sensitivity analysis are presented in the next sub-section, before the results of the model runs. This is done because the results of the sensitivity analysis are used for the model runs.

4.3.1 Results of sensitivity analysis

The results for the different manning coefficients at one location along the Sogamoso river are shown in figure 4.7. The red arrows show the most important results, where it can be seen that an increasing Manning's coefficient (results to larger roughnesses in the river) cause higher water levels. For the propagation speed of the flood wave, a higher Manning's coefficient means a lower propagation speed and therefore it takes longer before the flood wave is noticed further downstream. At the end of the model, at S8, a range of about 1.5 m and 10 hours for the water depth and the delay time is observed for the results.

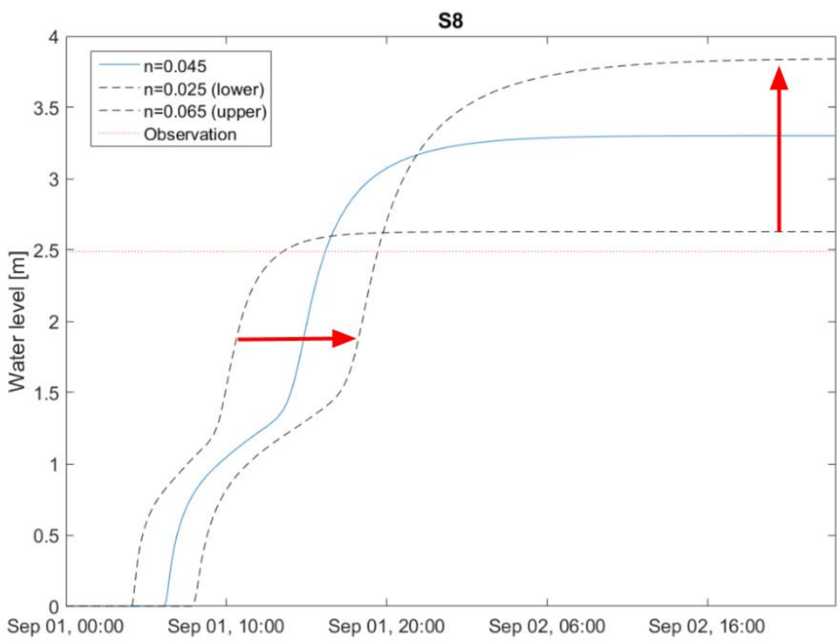


Figure 4.7: Water level different roughness

In addition to the influence of the roughness on water depth and time for the flood wave to arrive at measuring station S8 the influence on the deformation of the flood wave is assessed. This is done, because this is an important phenomena regarding the research questions. The discharge variations in time are representative for the modified flow, and therefore important to the hydraulic interaction between the Sogamoso river and the caños and Ciénaga El Llanito.

In figure 4.8 the results of the discharge variations in time at measuring station S8 are shown. To exclude the influence of the roughness on the propagation time of the flood wave, the lines are shifted.

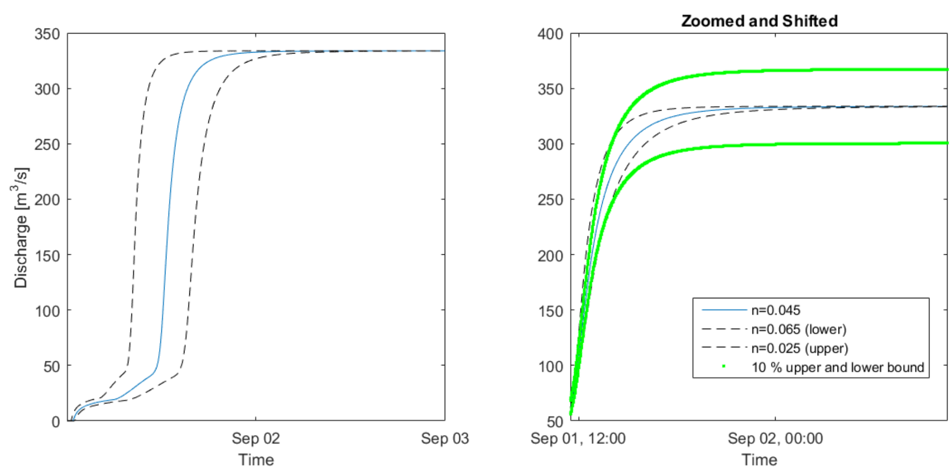


Figure 4.8: Discharge with different roughnesses

With the shifted lines the conclusion is made that there is a small influence in the deformation of the flood waves at the downstream part of the model. With a higher Manning's coefficient the diffusion of the flood wave is larger, however these deviations are small and lie in the range of 10 %.

4.3.2 Results of model runs

The model run with mean tributary discharges and a discharge fluctuation from 400, 310 and 100 m^3/s is used to show the result regarding the 1D SOBEK model. The results of the sensitivity analysis showed that the influence of the roughness on the water depth and propagation of the flood wave is significantly. Therefore the results regarding the research questions are given with respect to the discharge and the

water depth and velocities are not considered. On basis of experience at CIRMAG the value mostly used for the Manning's coefficient in the Sogamoso river is 0.045. Therefore this value is used in all the model runs described in this sub-section.
Three points at the beginning (La Paz), the middle(S5) and at the boundary of the Delft3D model are shown in figure 4.9 to elaborate on the change of the discharge pulse along the Sogamoso river.

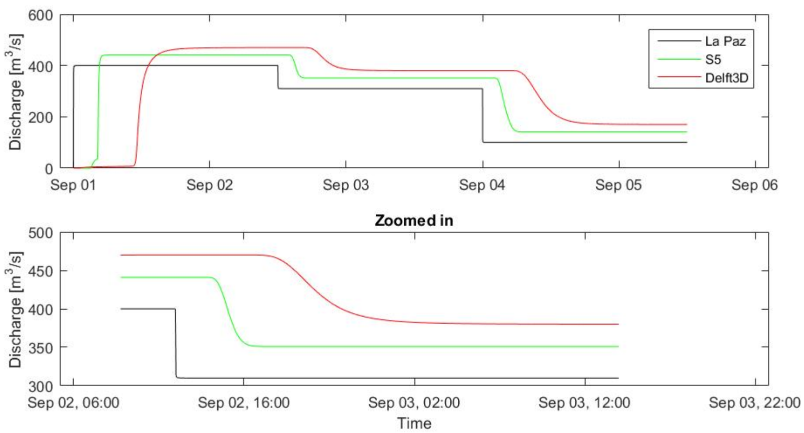


Figure 4.9: Discharge distribution

Towards the end of the model the influence of the tributaries is noticed by the rising of the amount of discharge. Furthermore the front and back of the discharge block scheme diffuses towards the end of the model. This processes are observed for all the possible changes in upstream boundary discharge condition
The processes causing the change of the discharge pulse are important for the boundary that is chosen in Delft3D. In figure 4.10 the different capacities and the resulting flow characteristics at the Delft3D model are given. These results are implemented as upstream boundary for the Delft3D model.

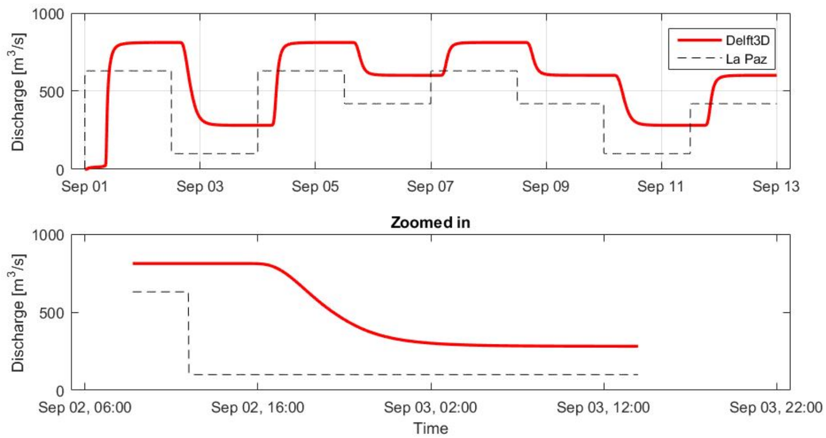


Figure 4.10: Flow characteristics Delft3D boundary

4.4 Discussion

The model area is chosen until measuring point S8, without the connection to the caños and the confluence with the Magdalena river. However if the water level in the Magdalena is high compared to the water level in the Sogamoso river a backwater curve may have influence on the model area and thereby on the boundary condition for the Delft3D model. This fact is not included in our model by choosing a constant water level 20 km downstream of measuring point S8.

The friction is taken constant for the whole Sogamoso river, which will differ per river segment in reality. Also the inadequate longitudinal profile can lead to errors in the deformation of the flood wave.

In the chapter "Analysis of the Hydraulic changes downstream of the Hidrosogamoso" the hysteresis effect is described. This could influence the consistency of the data which is used to verify the model. We are not able to peruse this effect without more data about longitudinal profile and water level information during longer periods. However it was concluded from the Q-h curve that the hysteresis effect was not present at measuring station La Paz, but it is not possible to verify the model their without information about the roughness at that part of the river. The roughness will differ definitely with the rest of the Sogamoso river.

4.5 Conclusion

With the 1D Sobek model the boundary condition of the Delft3D model is determined and displayed in the results. Thereby the characteristics of the flow regime are described at the Delft3D model, in general an increase of the discharge is observed by the tributaries and a diffused flood wave is obtained at the boundary condition. Regarding the depth characteristics at the boundary condition the model was not sufficient because the model could not be verified with respect to the roughness and the roughness has a significant influence on the value of the depth downstream according to the sensitivity analysis.

With respect to the way the flood wave propagates from the Hidrosogamoso until the Delft3D model a distinction is made between the time and the diffusion of the discharge. From the results it can be concluded that all the upstream boundary conditions diffused towards the end of the model which affect the boundary at the Delft3D model. With respect to the time propagation the model had the same short comings as for the depth. The roughness has a significant influence on this parameter, and the roughness could not be checked with the current data. The range for the time of propagation untill the Delft3D model was 10 hours. The total time for the discharge distribution to arrive at the Delft3D model is approximatly 0,5 to 1 day, therefore a difference of 10 hours is too large to draw conclusions.

More information is needed about the coarse of the bed together with data including a long time series along the Sogamoso river. In this way the hysteresis effect can be indicated and the roughness can be verified for the model.

Chapter 5

Two-dimensional hydraulic modelling of the Ciénaga El Llanito and its surroundings

5.1 Introduction

In this chapter the hydraulic influence of the alternating flow regime in the caños and Ciénaga is discussed. Varying upstream conditions, using the results of the Sobek upstream model, were inputted as an upstream boundary condition. The influence has been assessed by using a Delft3D flow model. The settings and set-up of the model will be discussed first. Later on, the influence of the Magdalena river is elaborated. The Hydrodynamics chapter has shown that there is sometimes a backwater curve in Sogamoso river, coming from the Magdalena river. With a constant upper boundary conditions, different water levels are compared at the downstream boundary condition to measure the influence. At the end of this chapter, the results, discussion and conclusion are given.

5.2 Methods

5.2.1 Model Area

In figure 5.1 an overview is given of the Model Area. Artificial caño 1 and 2 are man made caños, caño San Silvestre is connected to Ciénaga San Silvestre, located 3 kilometers southwards Ciénaga El Llanito. The Magdalena river is following from south to north and the hydrodam is located 70 kilometers stream upwards. The blue cross sections in figure 5.1 are the three boundary conditions of the model. The downstream boundary is chosen to be in the small downstream part of the Sogamoso river. The upstream boundary condition is the Sogamoso river is upstream the new artificial caño and at the location where measurements are made with the ADCP. The upstream boundary at the Caño Silvestre is also at the same location as the ADCP.

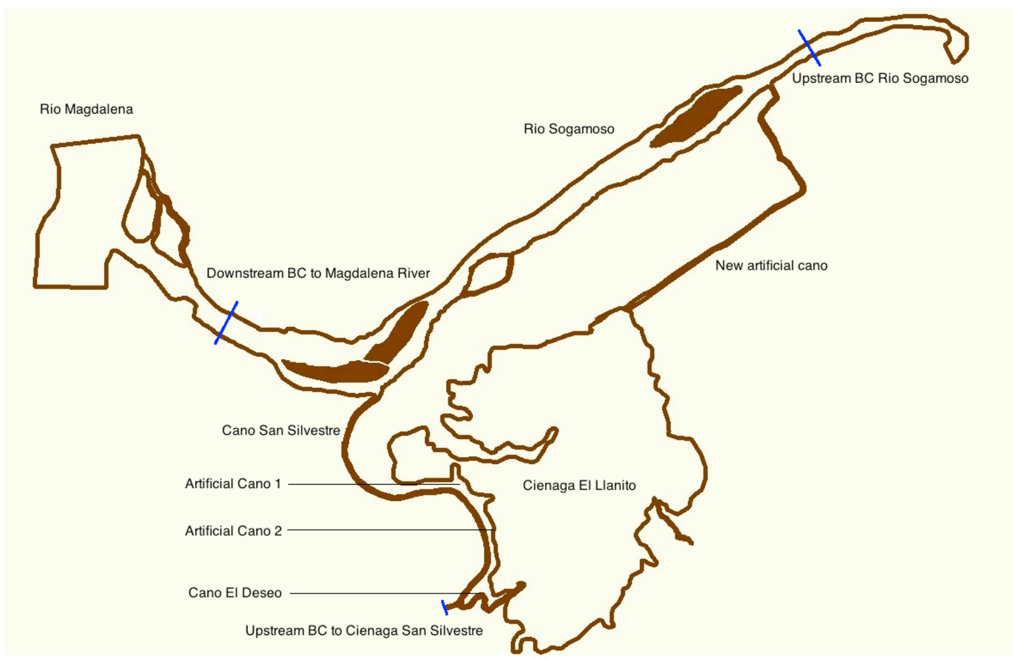


Figure 5.1: Overview Model Area

5.2.2 Model Set-up

Landboundary file

During the fieldwork trip, several high quality satellite images were obtained. These maps are inputed as layers in Google Earth, with these 2016 images, it was possible to draw polygons in Google Earth. These polygons represent the landboundaries. By converting these polygons to the right coordinate system and creating an .lbd file, the landboundaries in figure 5.1 were obtained. These landboundaries are used as a guideline for the water surface in the depth file.

Grid File

The first step in the model set-up in Delft3D is the construction of a grid. A grid contains cells, where every corner of a cell includes a depth. It is important that the total model area contains cells and that the area of interest is refined enough. The caño Silvestre and the atificial caños will need to be at least three cells wide. The Sogamoso river and the Ciénaga El Llanito can have coarse grids. In the Appendix is elaborated about the independent test between a grid and a more refined grid. Also the results are compared between a rectangular grid and a curvelinear grid. After these tests, the final grid can be seen in figure 5.2. By drawing curved splines, a curved grid was created. By refining and local refining, this was the result. The grid has 479 cells in the M-direction and 395 cells in the N direction. After the cell size in the grid is sufficient more grid tests have been done. The grid must fulfil the following criteria:

- it must fit as closely as possible to the land-water boundaries of the area to be modelled
- it must be orthogonal, i.e. the grid lines must intersect perpendicularly
- the grid spacing must vary smoothly over the computational region
- the aspect ratio, measured by the ratio of grid cell dimensions in M and N

Table 5.1: Requirements Grid

Test	Requirements area of interest	Requirements outside area of interest
Orthogonality	<0.04	0.05 - 0.1
Smoothness	<1.1	<1.6
Aspect ratio	0.5 -2	<6

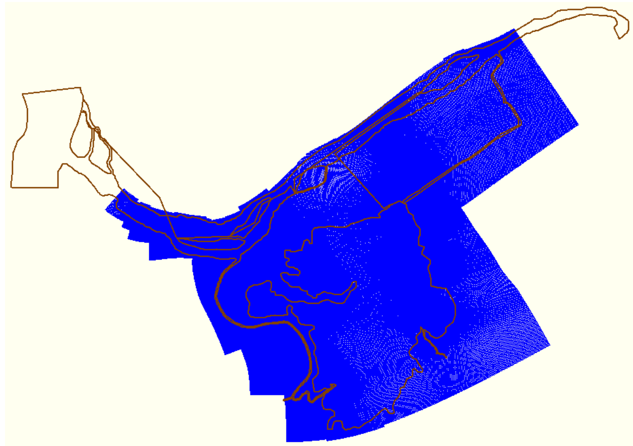


Figure 5.2: Final Curved Grid

Depth file

The depth file consists out of the water depth, profile of the banks and the slope of the river. The final depth file is shown in figure 5.3. The depth file was created by adding two layers, one layer consists of the depth values and the other layer shows the slope of the river, this last layer is called the reference map. By using the reference map as an initial water level, the spin-up time in the model is decreased. This is an advantage because a small spin-up time ensures that the required simulation time is lower. A figure of the reference map can be found in the Appendix.

Table 5.2: Creating Depth file

Location	Method of creating depth file
Sogamoso river	Adjusted reference with elevation points from DEM file and depth from echosounder
Caño San Silvestre	Adjusted reference with elevation points from DEM file and depth from echosounder
Ciénaga El Llanito	DEM file for the floodplains, manually decreased the Ciénaga by 1-2 meter

The difference between the DEM (Digital Elevation Map, see Appendix) and the actual land surface is a lot. For the Sogamoso river the DEM file shows clearly the slope of the river. The caño San Silvestre is not visible on the DEM. The

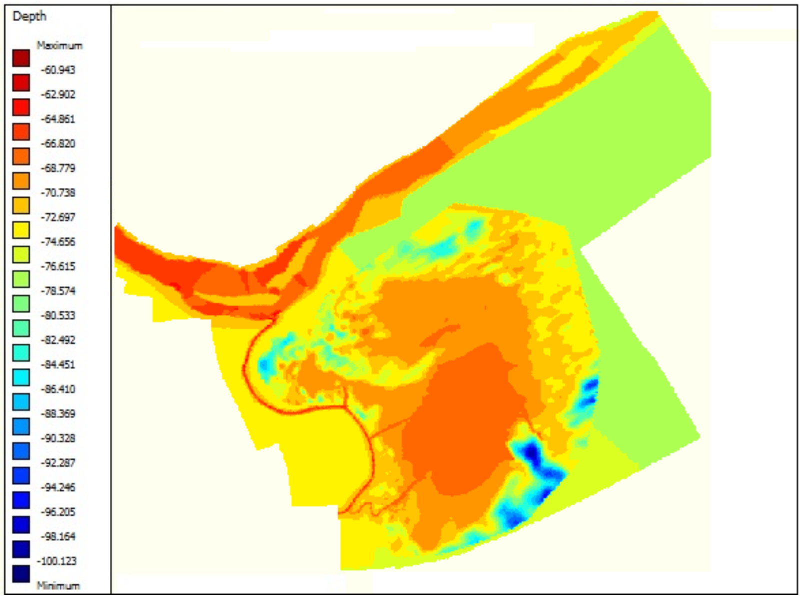


Figure 5.3: Depth file Delft3D

Ciénaga and its flood plains are clearly visible. Therefore the DEM is used for the Ciénaga and the Sogamoso river. The banks along the caños and the Sogamoso river are elevated by 2 meters, so it is assumed that there will be no floods along these streams. The floodplains around the Ciénaga are obtained from the DEM because there will be floods around the Ciénaga and these are clearly visible on the DEM. It is assumed that there is no water level slope in the Ciénaga and measurements from the echosounder showed depths varying between 1 and 2 meter. These depths are manually added to the depth obtained form the DEM.
The orange reference poles, which are showed in the appendix, are not used as reference points, because the reference height of these poles were not obtained. More information about the depth file, references and elevation can be found in the Appendix.

Initial water level

For the initial condition, an initial condition file is used. This file contains the water levels at the starting time of the model. This map is constructed using the reference map.

5.2.3 Model Settings

Boundary conditions

As showed in the model area section, the Delft3D model has three boundary conditions. At the upstream boundaries discharge time series are inserted. At the downstream part a Neumann boundary condition is applied such that the gradient of the water level can be set to a fixed value. This value is set tot zero such that there is no influence of backwater curves on an upstream alternating flow regime. The upstream boundary condition at the Sogamoso river is chosen such that the, still to be constructed, new artificial caño is within the model area and the S-curve of the Sogamoso river is outside the model area. This reduced the complexity of the model. The downstream boundary condition of the Sogamoso river is chosen such that the Magdalena river and the Sogamoso river bifurcation is excluded of the model area. For the caño San Silvestre the incoming boundary condition is located 200 meters southward of the bifurcation with the caño El Deseo, see figure 5.1. In table 5.3 the measured values during the fieldwork with the ADCP are shown, these values are initially inserted as the boundary conditions. During the verification of the model a fixed water level at the downstream boundary of the Sogamoso river is used, such that the influence of the backwater curve that was present during the measurements is taken into account. In 5.3.5 the quantities of the boundaries conditions used for the results are elaborated.

Table 5.3: Imposed boundary conditions

Location	Boundary condition
Sogamoso upstream b.c.	Q=320 m^3/s (East to West)
Sogamoso downstream b.c.	h=69 m
caño San Silvestre upstream b.c.	Q=-40 m^3/s (South to North)

Simulations time and time step

The starting time of the model is set to 01 01 2016 00 00 00. Every time the grid is refined the time step must be decreased such that the courant numbers are within an acceptable range. For the final grid, the time step is set to 0.05 minutes, which equals 3 seconds. For larger time steps the CFL conditions exceeds the limit of 10 such that the model will not run or show unreliable values. Different simulation times are used. For the verification of the model a steady discharge was assumed. First a simulation time of 15 hours was used to see the behavior of the model in time.

During the verification process smaller simulation times of 4 hours were used to see the influence of the changes made. Finally after the final changes a simulation time of 15 hours was performed to see the behavior in time again. For the results of a smooth varying discharge, longer simulation times were needed. The continuous discharge time series was plotted with a simulation time of 38 hours. For the influence of the steady discharges a simulation time of 15 hours was used again.

Dry points

In Delft3D several dry points were added around the first artificial caño to create a width of the caño consisting out of 1 cell. After refining the grid it would be possible to change the elevation of the banks to create the correct width of the caño. However to stay consistent with the different grid files it is chosen to add in the refined grid dry points at these locations as well.

Monitoring locations

To analyze the output of the Delft3D model several observation points and cross sections are made. In figure 5.4 an overview of these monitoring locations is given. In the observation points it is possible to see the water level changes over time. From the cross sections the instantaneous discharge can be obtained.

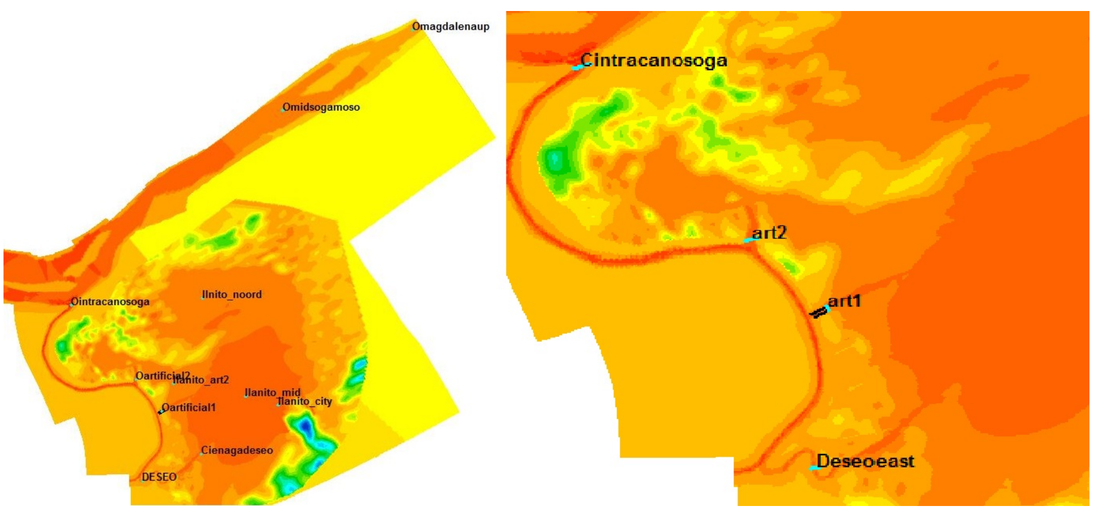


Figure 5.4: Left: location of observation points, right: location of cross sections.

Friction coefficient

The friction coefficient is inversely proportional to the equilibrium depth, if the equilibrium depth is known, the friction coefficient can be adjusted such that the model gives the same equilibrium depth. However during the measurements taken it is unknown, and very unlikely, that a steady state situation occurred. From the sediment samples taken during the fieldwork it is possible to conclude that the friction is small at the Ciénaga, large at the upstream part of the caño San Silvestre and decreasing towards the downstream part. The same occurs in the Sogamoso river, upstream larger friction and decreasing towards the downstream part. See also the sediment and morphodynamic chapters.
Except the knowledge of relative magnitude differs, nothing can be said about the actual value of the coefficient. This is a very complex part and mostly solved by an iterative process, however to be able to do this iterative process a reference value is needed which is not available for this model. Therefore the default value of Delft3D for the Chezy value is applied, this equals 65 $m^{0.5}/s$. In this model except the influence of the friction another big unknown is present. This is the reference level of the earth. In this model its chosen to first try to adapt the reference level such that the model results are of the same order of magnitude as the measured values.

5.3 Model verification

For the verification of the model first the model area and measurements are given. Next the method for verifying the model with the measurements is highlighted. Whereafter the method to verify the model results is explained. Finally the required data is listed to further verify the model.

5.3.1 Overview model area

In figure 5.5 a detailed overview of the interaction between the Ciénaga El Llanito, caño San Silvestre and the Sogamoso river is given. The arrows represent the flow direction and relative size measured during the fieldwork with the ADCP. In table 5.4 the magnitudes are given.

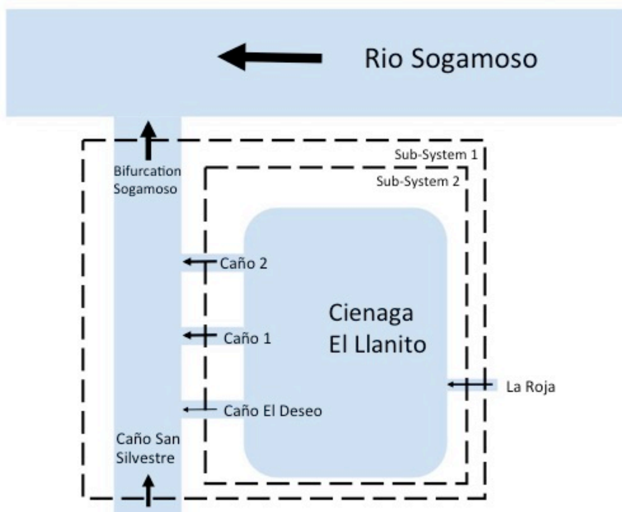


Figure 5.5: Overview abstract model area

Table 5.4: Overview measured data

Location	Velocity [m/s]	Discharge [m^3/s]
Bifurcation Sogamoso	0.47	64.8
Artificial Caño 2	0.29	8.6
Artificial Caño 1	0.27	10.6
Caño El Deseo	0.01	0.74
Caño San Silveste	0.5	40

5.3.2 Model verification using the measurements

When the model needs to be verified with the measured discharges the following problems occur:

- The measurements with the ADCP in the Sogamoso river and the Ciénaga are done on different days, however on both days the discharge at the bifurcation of the caño San Silvestre with the Sogamoso river were measured. On the second day the measurements from table 5.4 were performed, during this day the discharge at the bifurcation of the caño San Silvestre and the Sogamoso river was 5 m^3/s lower, or relatively 9%. This difference was not taken into account in the model.

- The discharges at the boundary conditions were not measured for a longer period of time, but are representing a discharge at a certain moment in time. If these discharges are applied to the model boundaries, a certain time is needed to adjust from the initial conditions. Therefore there are two possibilities for the measured discharges in sub-system 1 of figure 5.5 to coincide with the modeled discharges at these locations:

  - The measurements coincide with the model results during the spin-up time. During the spin-up time the model is dependent on the imposed initial conditions such that the model results are unreliable.
  - The measurements coincide with the steady state solution of the model. This would be a very large assumption that is not realistic because the discharge of the dam fluctuates a lot during the day, so the probability of a steady state is low.

- There is no data of the reference level of the Ciénaga and the caño San Silvestre.

Despite these problems it is still possible to say something about the order of magnitude of the hydraulic behavior between the Sogamoso river and the Ciénaga. This can be shown from figure 5.6. In this figure the discharges are plotted for the three connecting caños and the bifurcation between the Sogamoso river and the caño San Silvestre. If these discharges are compared to the measured values it can be observed that the individual magnitude of the three connecting caños are not close to the measured values. The flow direction in El Deseo is also wrong, but the sum of the three connecting caños corresponds to the measured value and a total discharge of 60 m^3/s in the caño San Silvestre is entering the Sogamoso river.

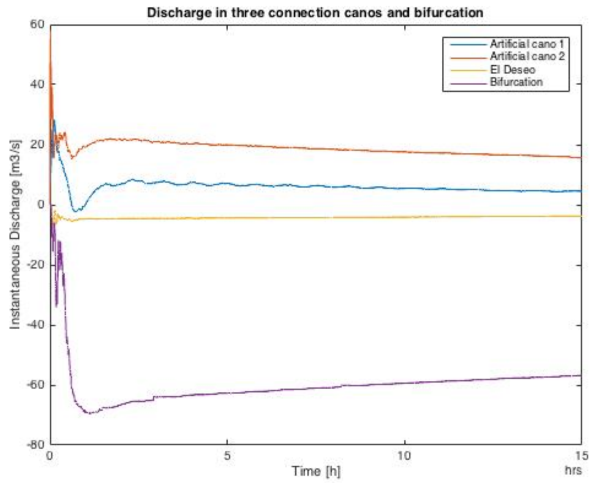


Figure 5.6: Discharges in three connection caños and bifurcation

However from figure 5.7 it can be observed that the model is still in its spin-up time, therefore it is doubtful if the model is representing the correct interaction between the Sogamoso river and the Ciénaga

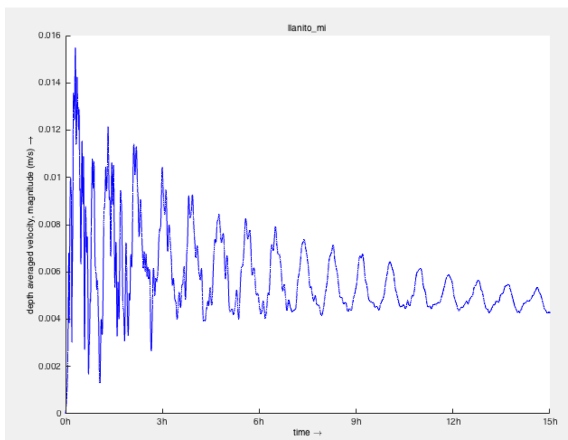


Figure 5.7: Depth average velocity in middle of Ciénaga

5.3.3 Verification of model results

Despite that it is impossible to verify the model, different flow scenarios that are characteristic for the upstream boundary condition in the Sogamoso river are inserted in the model and the results can be considered as useful when the following condition is reached.

The effect of the initial conditions has to be completely disappeared. The spin-up time is the time it takes for the solution, for the water level for example, to reach a steady state. This means that the effect of the initial condition is completely removed and a horizontal water level should be present. Three observation points are analysed, one in the Sogamoso river, the second one in the caño San Silvestre and the third one in the El Llanito.

The Ciénaga El Llanito is a large basin downstream the Sogamoso river, therefore the Ciénaga needs to most time to adapt to an upstream boundary condition. When the discharge out or in the Ciénaga reaches zero and the water level is constant, the total model is in steady state.

The boundary condition at caño San Silvestre is constant. To know whether the discharge in the Ciénaga reaches zero, the discharge at the bifurcation between caño San Silvestre and Sogamoso river can be compared with the input discharge at the boundary condition. When the discharge at the bifurcation is the same as the boundary condition (53 m^3/s) there is no in or outflow in the Ciénaga.

In figure 5.8 the steady state determination is shown. The discharge at boundary condition caño San Silvestre is subtracted from the discharge at the bifurcation. The range of the steady state is determined as 1% of the initial discharge. After 50 hours this 1% boundary is crossed. Therefore 80 hours computational time was used for constant discharges to reach a steady state. The steady state in the Sogamoso river is already reached within 2 hours.

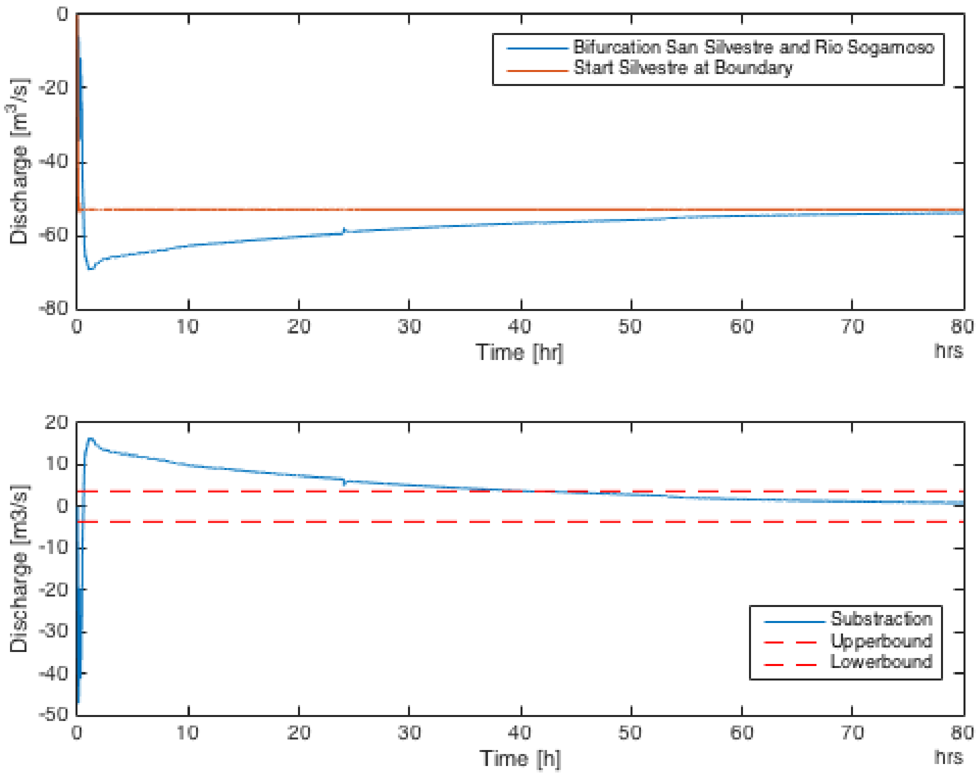


Figure 5.8: Steady state determination El Llanito

5.3.4 Required data for verification

The model would be able to be verified if the following data would be available:

1. Continuous discharge at the upper boundary condition such that the model can be modeled until its past its spin-up time.

2. Continuous discharge at the El Deseo, Artificial 1 and 2.

3. Reference levels of the Ciénaga, Caño San Silvestre and the connecting caños

If this data is available than the first discharge measured upstream should be modeled until a steady state has occurred. Next the continuous discharge is applied to the model and the model is fine-tuned until the discharges at the caños are equal to the one measured.

With this model the assumption is made that the discharge of the San Silvestre stays constant over time, this discharge only depends on the amount of rainfall. Another assumption is that the water level at the Magdalena river stays constant during the day of measurements.

5.3.5 Flow scenarios

In figure 4.10 the results of the SOBEK model are shown. The black dashed line represents the flow at the La Paz station, located 800 meter downstream of the HidroSogamoso. The red line represents the flow at the upstream boundary condition of the Delft3D model, which is the result of the SOBEK model.
As mentioned in the Hydrodynamics chapter, the HidroSogamoso changed the averaged flow and the fluctuations in the discharge distribution. To model these changes, different types of runs are determined. The boundary condition in caño to San Silvestre is 53 m^3/s for all models to neglect the influence of caño to San Silvestre on the model. This value differs from the measured and used value of 40 m^3/s in the previous model. Based on the rational equation method of the catchment areas, the value of 53 m^3/s is determined and is more general compared to a single measurement in time.

Constant flow

The extreme conditions after the construction of the HidroSogamoso are modelled using a constant boundary condition. During minimum flow conditions of the HidroSogamoso, the discharge is 80 m^3/s, by adding the mean discharge of the tributaries, the upper boundary will have a flow of 150 m^3/s. The maximum outflow of the Hidrosogamoso is 630 m^3/s, again by adding the mean discharge of the tributaries, a total discharge of 700 m^3/s is modelled. By modeling these different events and analyzing the water levels, discharge and flow directions it is possible to start understanding the effect of the alternating flow regime.

Fluctuations

In figure 5.9 the four different fluctuations are shown. These fluctuations were based on the probability density function in the section Hydrological part 1. The most common discharges together with the most common fluctuations form the four fluctuations series. Two positive and two negative fluctuations are modelled. To compare the results in Delft3D, both time series were given the same length.
The input at La Paz was a block diagram, at the upper boundary these 'corners' were already smoothed out. To understand the effects of the fluctuations, this smoothing will be analysed. Comparing this delay of the system, characteristic locations were compared such as the Sogamoso river, caño San Silvestre and Ciénaga El Llanito.

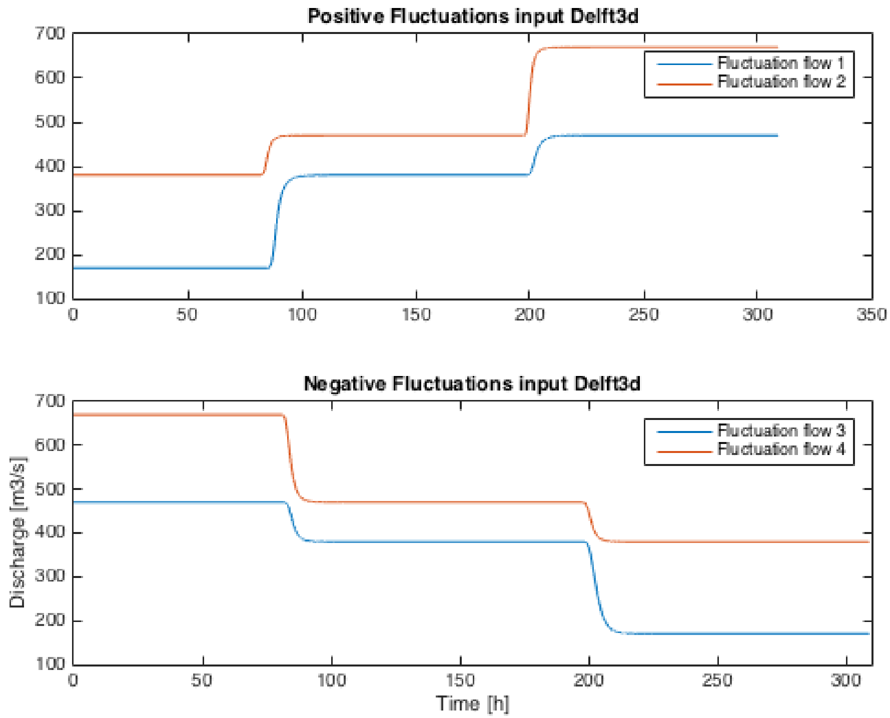


Figure 5.9: Positive and negative fluctuations used as an input at the upper boundary condition

Backwater curve

The water level at the Magdalena river can lead to a backwater curve in the Sogamoso river. Before the construction of the HidroSogamoso large floodings occurred during the high peak flow of the Sogamoso river and a high water level at the Magdalena river. After the construction of the HidroSogamoso the high peak flow is reduced but the high water levels in the Magdalena river can still occur. To model the influence of the backwater curve on the water level of the Ciénaga it is chosen to model four fixed water levels in one time series. Each rise of water level in the Magdalena river was modelled with steps of 50 cm, to a total of 1.5 m.

For each scenario the influence on the water level at the bifurcation of the Sogamoso river with the caño San Silvestre and the centre of the Ciénaga is compared. A total of 1.5 m is assumed because this is the height of the banks at the downstream part of the Sogamoso river and it is assumed that these banks are not flooded anymore after the construction of the HidroSogamoso. This height of the bank and the fact that the Sogamoso river is not flooding anymore is observed during the Fieldwork. This assumption is made because there is no data of the Magdalena river water levels. The initial water level, 67.5, is based on a model run with the same discharge. With a Neumann boundary condition, it appeared that the steady state water level at the downstream boundary condition is 67.5 m. See for the complete input the figure below.

Finally the location of the Magdalena river is not located at the downstream boundary of the Sogamoso river but in reality 1500 meters more downstream. Therefore an increase in water level at the downstream boundary condition will lead to an even higher water level at the Magdalena river.

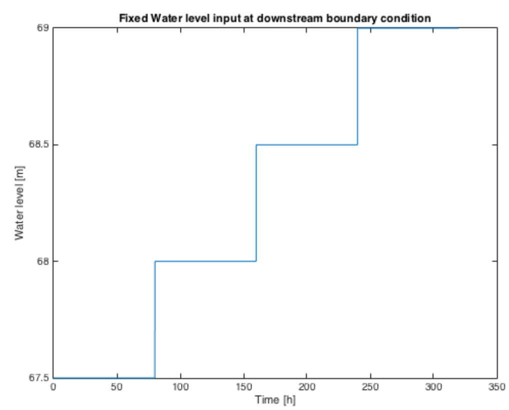


Figure 5.10: Input water level at downstream boundary condition

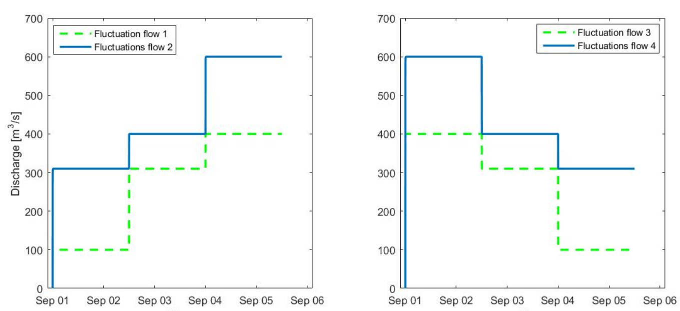


Figure 5.11: Flow characteristics La Paz

Run Model	Situation	Discharge [m^3/s]	Water level Magdalena BC [m]	Simulation time [h]
1 Constant flow	Average flow before the dam + Mean discharge tributaries	549	Nuemann - Free water surface	120
2 Constant flow	Average flow after the dam + Mean discharge tributaries	366	Nuemann - Free water surface	120
3 Constant flow	Min. environmental flow Hidrosogamoso+ Mean triburaties	150	Nuemann - Free water surface	120
4 Constant flow	Max. flow Hidrosogamoso + Mean triburaties	700	Nuemann - Free water surface	120
5 Fluctuation flow	Characteristic fluctuation 1	170-380-470	Nuemann - Free water surface	309
6 Fluctuation flow	Characteristic fluctuation 2	380-470-670	Nuemann - Free water surface	309
7 Fluctuation flow	Characteristic fluctuation 3	470-380-170	Nuemann - Free water surface	309
8 Fluctuation flow	Characteristic fluctuation 4	670-470-380	Nuemann - Free water surface	309
9 Constant flow, varying water level	Backwater curve	366	Fixed time series 67.5-68-68.5-69	80-80-80-80

Figure 5.12: Model Scenarios

5.3.6 Methodology analyzing results

In this section is described how the results are analyzed. With the results of Delft3D the following research question will be answered: 'How is the hydraulic behaviour in the caño San Silvestre and Ciénaga El Llanito influenced by the modified flow regime?' With the modified flow regime two influences are meant. The first influence is of the output from the SOBEK model. This model provided characteristic flows for the upstream Sogamoso boundary condition. The second influence is caused by a backwater curve from the Magdalena river.

The method for the characteristic flow of the upstream Sogamoso boundary condition will be given in section 5.3.6 and section 5.3.6. The method to determine the influence of the backwater curve will be provided in section 5.3.6.

Averaged flow

Each constant flow, which is used as an upper boundary condition, will eventually reach a steady state in the total model area. The further away from this system, the longer it takes to reach this steady state. For all the averaged flows, described in 5.3.5, the steady state is known. For all the inputs at the boundary condition, a discharge of 70 m^3/s is taken for the mean flow of the tributaries.
The minimum and maximum water level in the Ciénaga were modelled using the extreme conditions as an input at the boundary condition. It can be stated that the water level in the Ciénaga is between these two outer boundaries. Assuming that caño San Silvestre always has the averaged discharge and no external water is added to the system, such as precipitation.

Fluctuating discharges

Based on the research of the hydraulic changes chapter, a probability density function showed the most common discharges and fluctuations at the upper boundary condition. To understand the time that it takes for the system, especially Ciénaga El Llanito, to adjust to the upper boundary conditions, two following fluctuations were compared from and to a steady state.
Take figure 5.9 for example, where the red discharge time series (flow1) starts at 380. Then the following change in discharge can be modelled if the system is in steady state. Only when the the starting discharge is in steady state, the initial water level will not influence the model anymore. Then the discharge is increased to 470, modelled till the new discharge is in a steady state. If again the steady state is

reached, the last discharge of 670 is used as an input. By using two fluctuations, the time that the systems needs to adapt is modelled without the influence of the initial water level. Besides the delay, it is also possible to know all the steady state water levels for the different discharges upstream.
The influence of these characteristic discharges is determined if the minimum/maximum water levels in the Ciénaga El Llanito are known and the time different sections of the downstream system need to adjust from one flow condition to another.

Backwater curve

To understand how the hydraulic behaviour in the caños and Ciénaga El llanito is influenced by varying discharges in the Magdalena river it is necessary to analyse the backwater curve. The total discharge of the Magdalena river is much larger than the discharge of the Sogamoso river. Therefore the water level at the Magdalena river can have a significant influence on the modeled area. To understand this influences, the effects of the backwater curve are analyzed in the Sogamoso river, caño San Silvestre and Ciénaga El Llanito. By looking to the water levels it is possible to see how the backwater curve propagates into the system. Is the backwater curve only effecting the Sogamoso river or is there also an influence on the Ciénaga El Llanito? In chapter Hydrodynamics a Q-H curve is plotted at puente Sogamoso. It is already concluded that there only occurs a M1 backwater curve, therefore only higher water levels than the steady state conditions will be inserted in the model. For the initial water level at the downstream boundary condition the steady state water level will be used for 366 m^3/s. While raising this water level every 80 hours with 50 cm and wait till the system reaches the new state state, the effect can be visualized.

5.4 Results

By analysing the Delft3D output the following research question will be answered: 'How is the hydraulic behaviour in the caño San Silvestre and Ciénaga El Llanito influenced by the modified flow regime?'

To understand the hydrodynamics, several output locations are defined in the Delft3D model. An overview of all output locations is given in figure 5.13. The behaviour of the Ciénaga El Llanito is analysed by observing the observation point 'Llanito mid'. In the caño San Silvestre the cross section 'caño first' and 'caño four' are analysed. The cross section at the bifurcation gave almost the same results as 'caño first'. It should be taken into account that 'caño four' is influenced by the individual behaviour of the three connecting caños, which is not accurate. However the cross section gives information about the impact in the system by a change of the upstream flow. It is interesting to see how far upstream these changes have an impact on the caño San Silvestre.

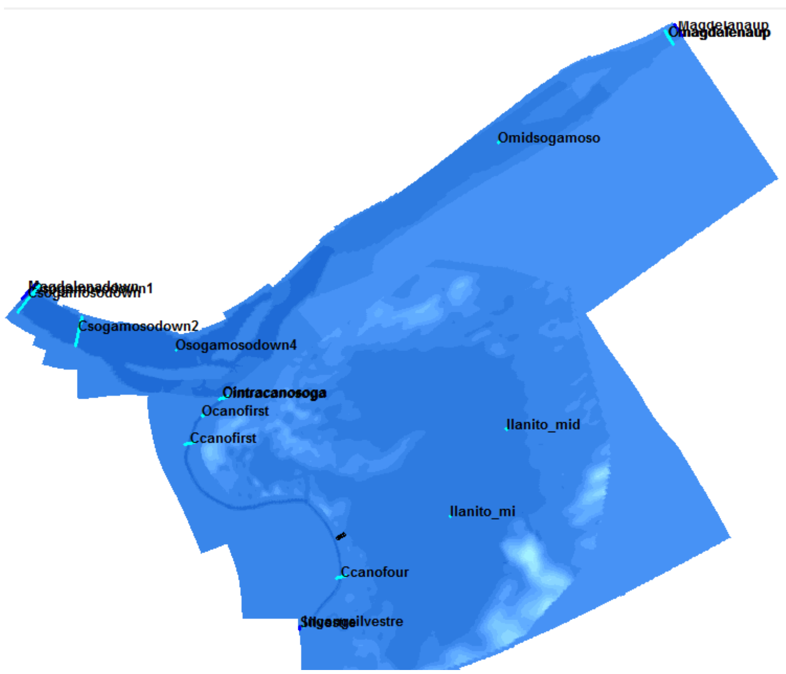


Figure 5.13: Overview of the output locations

5.4.1 Average flow and fluctuating discharges

Limits of water level in Ciénaga El Llanito

First the constant discharge,s imposed at the upstream Sogamoso boundary, are analysed. In figure 5.14 the maximum and minimum water levels in the Ciénaga are given. It is important that the system reaches the steady state. As mentioned earlier in the report, it will take a long time until the water level changes in time are exactly zero. However, its assumed that the steady state for a constant discharge is reached after 80 hours, see section 5.3.3 and figure 5.8.

Considering only the influence of the upstream boundary condition, it can be concluded that the Ciénaga El Llanito will have a minimum water level of 69.67 m with a corresponding constant discharge of 150 m^3/s upstream. The bottom level at the location of the observation point 'Llanito mid' is at 68.57 m, such that the minimum water depth equals 1.10 m. For the maximum water level a discharge of 700 m^3/s is used. This results in a water level of 69.79 m, which equals a maximum water depth of 1.22 m. From figure 5.14 it can also be observed that the discharge increase from 150 to 366, a total of 216 m^3/s, is resulting in a relative small increase of the water level in the Ciénaga El Llanito if compared to the increase of 549 to 670, total of 151 m^3/s. Such that it can be concluded that extreme discharges have a larger impact on the water level of Ciénaga El Llanito.

As noted in section 5.3.5 the model assumes a constant discharge entering the caño San Silvestre upstream and a constant discharge of the tributaries located upstream in the Sogamoso river. The flow direction in the caño San Silvestre is always towards the Sogamoso river. Furthermore, precipitation, a possible backwater curve from the Magdalena river and the small precipitation caño La Roja are neglected.

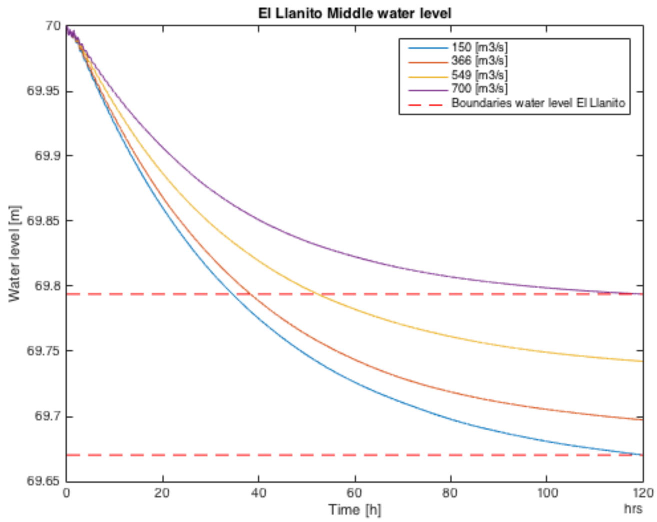


Figure 5.14: Boundaries water level El Llanito

Hydrodynamic influence of fluctuating upstream discharges in the caño San Silvestre

To understand the impact of an upstream discharge fluctuation, two different output locations in caño San Silvestre are compared. Two increasing fluctuating discharges (170-380-470 & 380-470-670) are used as an input of the upstream boundary condition. In figure 5.15 the discharges at 'caño first' and 'caño four' are plotted. It can be observed that the first fluctuations are useless because the system has not reached a steady state after approximately 90 hours. Therefore only the second fluctuations are considered, so the fluctuation from 380 m^3/s to 470 m^3/s and 470 m^3/s to 670 m^3/s.

From figure 5.15 it can be concluded that the impact at 'caño first' is significant larger compared with 'caño four'. It can also be seen that larger fluctuations have a relatively bigger impact on the system. A fluctuation of 200 m^3/s (470-670) has a relative larger influence than a fluctuation of 90 m^3/s (380-470) at 'caño first'.

Till now only increasing discharge fluctuations are considered. If decreasing discharge fluctuations at the upstream Sogamoso boundary would be plotted, the discharge in the caño San Silvestre would increase over time. This means a larger discharge from the caño San Silvestre into the Sogamoso river.

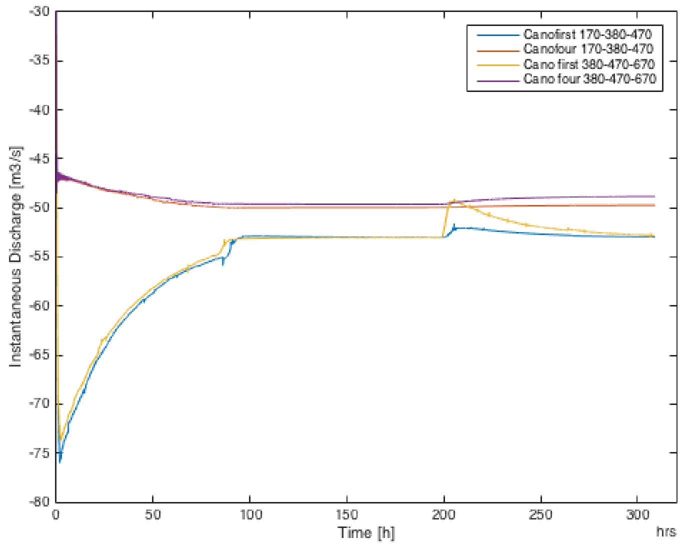


Figure 5.15: Influence fluctuating discharge on caño San Silvestre

Hydrodynamic influence of fluctuating upstream discharges on Sogamoso river and Ciénaga El Llanito

The time that is needed to reach the steady state at a certain location in the system differs, this time is expressed as the adjustment time. By comparing the Sogamoso river and the Ciénaga El Llanito for different fluctuating upstream discharges, this effect can be shown. The discharges at the upstream boundary condition of the Sogamoso river are obtained from the SOBEK model, see chapter 4. The influence at the downstream boundary of the Sogamoso river can be visualized by subtracting the upstream Sogamoso boundary condition and the upstream San Silvestre boundary condition. A steady state situation will show a discharge of zero m^3/s. The influence at the Ciénaga El Llanito can be visualized by taking the discharge of 'caño first' and subtracting the upstream San Silvestre boundary condition. Here a zero discharge will mean that no water is entering or leaving the Ciénaga El Llanito.

First the magnitude of a fluctuation is analysed. In figure 5.16 a fluctuating discharge of 170-380-470 is entering the system at the upstream boundary condition of the Sogamoso river. In the top figure the discharge is plotted of Sogamoso up- and downstream and 'caño first'. In the bottom figure a close-up of the second fluctuation, from 380 to 470 m^3/s, is given. Here the subtraction as explained above are plotted such that a zero discharge means a steady state flow. Note that the first fluctuation (around 90 hours) is not considered since a steady state is not reached. From figure 5.16 it can be concluded that a fluctuation at the upstream boundary of the Sogamoso river of 90 m^3/s (from 380 to 470) is transformed in the system to a fluctuation with a magnitude of almost 35 m^3/s at the downstream boundary of the Sogamoso river. The magnitude of the fluctuation in the Ciénaga El Llanito is very small (1 m^3/s).

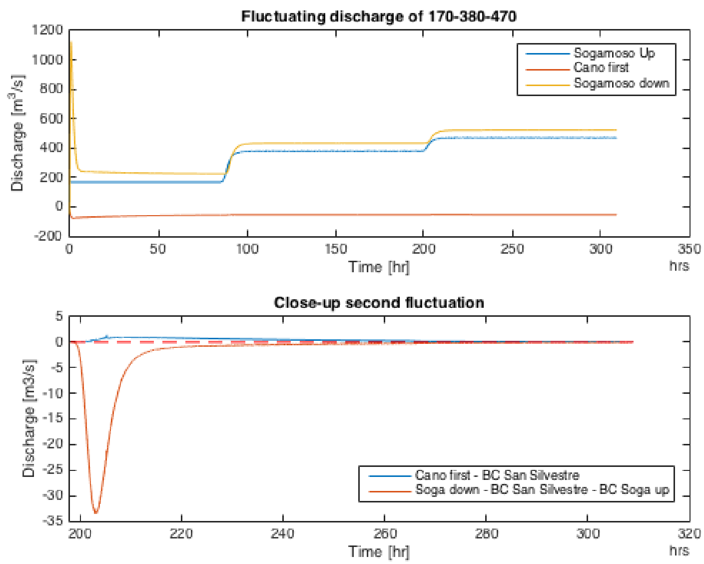


Figure 5.16: Difference in fluctuation magnitude between Sogamoso up- downstream and Ciẽnaga El Llanito

Next the adjustment time of respectively the Ciénaga El Llanito and Sogamoso river will be treated for four different fluctuating discharges. In figure 5.17 the adjustment time for the Ciénaga El Llanito is visualized. Again, after subtracting the upstream discharge boundary condition of San Silvestre (53 m^3/s) from the measured discharge at output location 'caño first' the adjustment time is clearly visualized. With a zero discharge representing a steady state flow. If the discharge in the Sogamoso river is reducing, for example 470 m^3/s to 380 m^3/s, the discharge of caño San Silvestre into the Sogamoso river will increase. This is represented with a negative discharge since a negative discharge means a flow from the caño San Silvestre into the Sogamoso river. Further it can be observed that all fluctuations are not zero after 120 hours.

However the discharge fluctuation 380-470 is the closest to the steady state situation. The discharge fluctuation 470-670 is the farthest away of the steady state situation. The adjustment times are summarized in table 5.5.

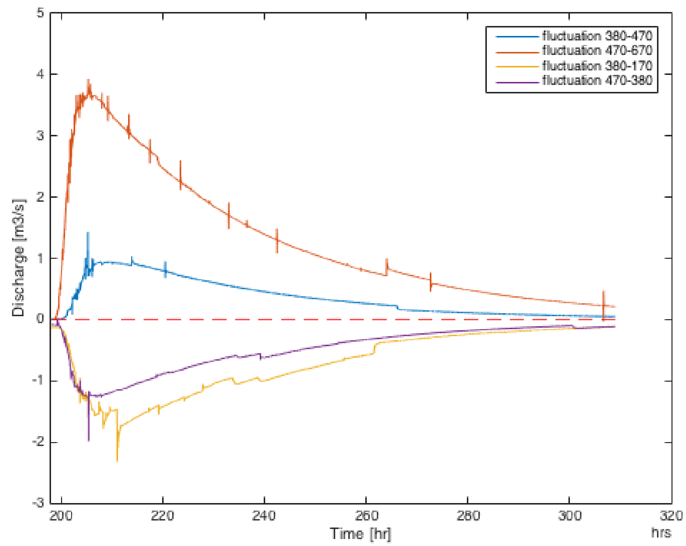


Figure 5.17: Effect upstream fluctuations on adjustment time Ciénaga El Llanito

In figure 5.18 the adjustment times of the downstream boundary of the Sogamoso river are plotted. From this figure it can be observed that the steady state is reached much faster than for the Ciénaga El Llanito. Again the largest deviation occurs for the fluctuation 470-670 and the smallest for 380-470.

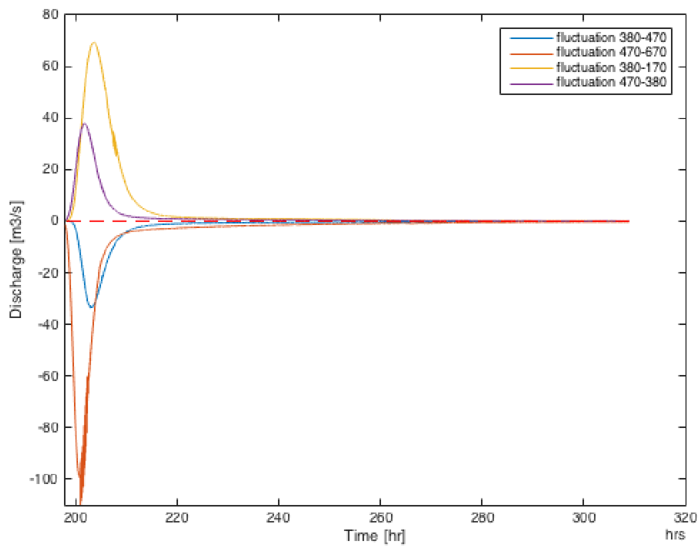


Figure 5.18: Effect upstream fluctuations on adjustment time Sogamoso Down

The approximated times that are needed to reach the new steady state for each fluctuation are summarised in table 5.5. From this table it can be concluded that the Ciénaga El Llanito needs much more time to adjust than the Sogamoso river.

Table 5.5: Approximated adjustment times of Sogamoso river and Ciénaga El Llanito for 4 different fluctuations

	Fluc. 380-470	Fluc. 470-670	Fluc. 380-170	Fluc. 470-380
Sogamoso upstr.	12 hours	10 hours	13 hours	9 hours
Sogamoso downstr.	30 hours	50 hours	25 hours	20 hours
Ciénaga El Llanito	=110 hours	>>110 hours	>110 hours	>110 hours

5.4.2 Influence of a backwater curve

The steady state waterlevel at the downstream Sogamoso boundary is 67.49 m for a constant upstream Sogamoso boundary of 366 m^3/s, see figure 5.19. To analyse the influence of the backwater curve, the upstream Sogamoso boundary is set to a constant discharge of 366 m^3/s. The upstream boundary condition of caño San Silvestre is 53 m^3/s. The waterlevel of the downstream Sogamoso boundary starts with the steady state value of 67.5 m and is after 80 hours increased to 68 m. At t=160 hours the waterlevel is increased to 68.5 m, and finally the water level is set to 69 m from t= 240 hours until t=320 hours. Such that three artificial backwater curves are created.

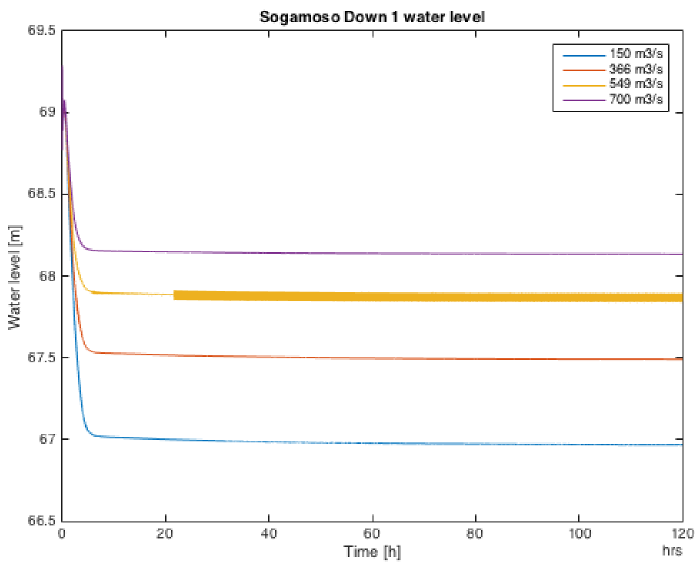


Figure 5.19: Steady state water levels at Sogamoso Down

In figure 5.20 the water levels are plotted for different observation points. The following conclusions can be made from figure 5.20:

The effect of the backwater curve does not reach the observation point 'mid Sogamoso', purple line. This location is more influenced by the upstream Sogamoso boundary condition.

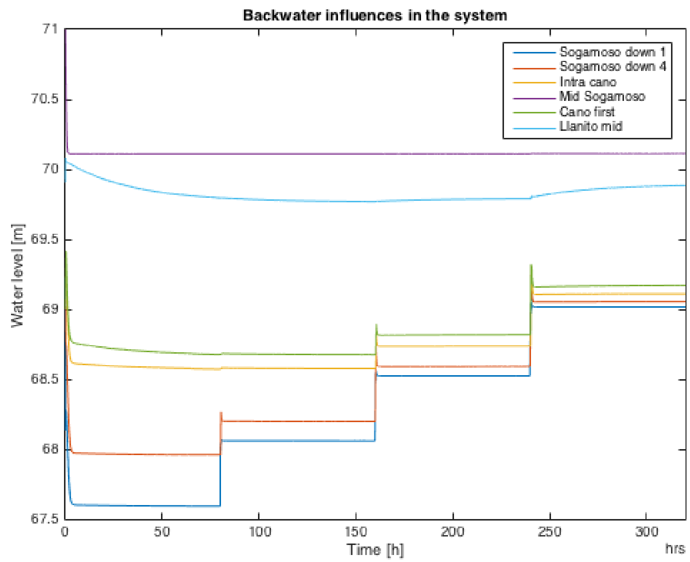


Figure 5.20: Backwater influence in the system

The first 150 hours are needed to reach the steady state of the Ciénaga. The steady state water level of the Ciénaga corresponding to a constant discharge of 366 m^3 is 69.7 m. The rising of the water level downstream from 68 m to 68.5 m has little to no influence on the water level of the Ciénaga. Only the rising of 68.5 m to 69 m is resulting in an increase of the water level of the Ciénaga with approximately 10 cm. To illustrate what happens with a water level of 69 m at Sogamoso down: the steady state water level at Sogamoso down with a discharge of 700 m^3/s is 68.13 m, see figure 5.19. So the related discharge to a water level of 69 m is between 1100-1300 m^3/s.

Furthermore it can be observed that the first increase, from 67.5 m to 68 m, is only influencing the observation points 'Sogamoso down 1 & 4'. The other locations are located to far away. The water level of the Ciénaga is changing but this is because it has not reached its steady state and not due to the influence of the backwater curve.

The red line, 'Sogamoso down 4' increases every step with a larger value. Such that this location is more vulnerable to extreme water levels of the downstream Sogamoso boundary.

The yellow and green line, ‘Intra cano’ and ‘cano first’ are both not influenced by the first increase of 67.5 m to 68 m. However they are influenced by the next increase, from 68 m to 68.5 m and even more influenced by the last increase to 69 m. Again this shows that extreme water levels downstream of the Sogamoso river have a relative larger influence on the system.

The dark blue line shows the water level in the observation point close to the downstream Sogamoso boundary. In this observation point the water level is already slightly lower than at the boundary condition. When the boundary condition increases with 50 cm the water level in this point immediately follows the boundary condition.

5.5 Discussion

In this section a brief discussion is held about the uncertainties of the Delft3D model.

5.5.1 Discussion related to to set-up

- The initial condition file and the total depth file depends on the natural slope of the earth in the model. The slope of the Sogamoso river is based on the DEM map and the slope of the rest of the model is assumed horizontal and changed during the adjustment of the depth file, see Appendix. However if these values of the slope of the earth are correct is impossible to verify with the available data.

5.5.2 Discussions related to the settings

- The measured discharge with the ADCP depends on how close the boat went to the banks of the river, therefore the imposed discharges for the verification have a different measurement error compared to each other.
- How large is the influence of the assumption of an uniform Chezy value. Does it mostly influence the absolute results and in a less amount the relative results of the different flow regimes?

5.5.3 Discussions related to the verification

- It is assumed that with this model it is possible to say something about the hydraulic behavior but the model can not be verified properly, so what is the error of the model compared to the reality?

5.5.4 Discussions related to the flow regime

- The steady state situation is assumed to occur, however the modeled area is highly dynamic with a very large volume of water in the Ciénaga that makes it very unlikely that it ever would be in equilibrium.
- The imposed discharge at the San Silvestre boundary condition is based on an analysis of the average amount of rain and the area of the Ciénaga San Silvestre. This amount of discharge is set as a constant value entering the modeled area. Is this a realistic value?

5.5.5 Discussions related to the results

- For the maximum and minimum water levels of Ciénaga El Llanito only the upstream Sogamoso boundary is considered. The actual water level boundaries can be much higher if precipitation and backwater curve effects are taken into account. To which boundaries this will lead is not possible to say, however it is possible to say that the backwater curves have a large influence on the water level of the Ciénaga El Llanito
- The cross section 'caño four' is located between the caño El Deseo and artificial 1. Since the individual flow of these connecting caños are not accurate it is discussable how that influences the flow at 'caño four'. The expected behaviour of the flow is confirmed, the model shows a significant decrease at 'caño four', however where the exact location is where the influence can be neglected is not possible to say.
- The exact response time is not determined, only a approximation is given. From the figures it is clearly visible that the Sogamoso down is faster adjusted to the new flow conditions than the Ciénaga El Llanito, which is the main conclusion. - The adaptation length of a backwater curve is dependend among others on the roughness coefficient which is assumed to be an uniform value for the entire model, see section 5.2.3. If the friction coefficient is determined more accurate the solution will become more valueble.

5.6 Conclusion

The Delft3D model is created with the objective to give an answer on the following research question: 'How is the hydraulic behaviour in the caño San Silvestre and Ciénaga El Llanito influenced by the modified flow regime?' The conclusions based on the Delft3D model are summarised below.

The hydrodynamic behaviour of the Ciénaga El Llanito is influenced by the modified flow regime as follows:
The minimum and maximum water levels are obtained assuming a constant upstream Sogamoso boundary, a constant discharge at the caño San Silvestre and no influence of the Magdalena river at the downstream Sogamoso boundary. In reality the upstream discharges will fluctuate to much to reach a steady state anywhere in the system. However for a steady state situation this resulted in a min-max water level of respectively 69.67-69.79 m. If the bottom depth is subtracted this results in 1.10-1.22 m of water depth. It is also observed that a discharge increase from 549 to 670 (total difference of 151 m^3/s) is leading to almost a twice as large increase of water level in the Ciénaga El Llanito than the discharge increase from 150 to 366 (total difference of 216 m^3/s). Therefore it can be concluded that extreme discharges have a relative larger effect on the water level of Ciénaga El Llanito.

The hydrodynamic behaviour of the caño San Silvestre is influenced by the modified flow regime as follows:
The fluctuations of the upstream Sogamoso boundary enter the caño San Silvestre at the bifurcation, a little further in the caño San Silvestre cross section 'caño first' is located, whereafter the artificial caño 1 and 2 are flowing in the caño San Silvestre whereafter the final crosssection 'caño four' is located. 'Caño four' is located close to the boundary San Silvestre where a constant discharge of 53 m^3/s is entering the system. In the caño San Silvestre the flow is always directed from the San Silvestre boundary towards the Sogamoso river. Therefore high water levels in the Sogamoso river will result in a lower discharge of the caño San Silvestre in the Sogamoso river and vice versa a low water level in the Sogamoso river results in a higher discharge of the caño San Silvestre in the Sogamoso river. From the Delft3D model it can be concluded that the influence, as expected, is much larger at the cross section 'caño first' and almost neglectable at the cross section 'caño four'. In the caño San Silvestre its again observed that a extreme discharge at the Sogamoso river influenced relatively larger the discharge of the caño San Silvestre. Which in its turn is logical because if the water levels in the Ciénaga El Llanito increase less water should flow

from the caño San Silvestre in the Sogamoso river.

The hydrodynamic influence on the Sogamoso river compared to the Ciénaga El Llanito is as follows:
First the magnitude difference between the Ciénaga El Llanito and the Sogamoso river are observed. This showed that a fluctuation of 90 m^3/s at the upstream part of the Sogamoso river is spread out to a fluctuation of 35 m^3/s at the downstream part of the Sogamoso river and to a fluctuation of 1 m^3/s in Ciénaga El Llanito. Next the time needed to adjust, after a change of the upstream Sogamoso boundary, is considered. It can be concluded that the Ciénaga El Llanito needs much more time than the Sogamoso river. The fluctuation from 470 m^3/s to 670 m^3/s has the largest influence and thus needs the most time to reach its new steady state.

The influence of a backwater curve is:
The three artificial backwater curves, showed in figure 5.20, are not influencing the observation point 'Sogamoso mid'. The Ciénaga El Llanito is only influenced by a backwater curve corresponding with a water level of 69 m, this results in a significant increase of the water level. Furthermore it can be concluded that the increase of water level from 68 m to 68.5 m and 69 m are influencing the largest area with the largest influence for the 69 m water level.

Chapter 6

Qualitative analyses of the morphological response of Ciénaga El Llanito and its surroundings

6.1 Introduction

In this chapter a qualitative analysis is given regarding the morphodynamics of part one and two of the area of interest. With this analysis the following research question is answered: 'Which processes contribute to the morphological response of the Sogamoso river, caño San Silvestre and Ciénaga El Llanito?' For more information about sediment in the area of interest see appendix B. In the next section the relevant theory is explained together with the parameters which are involved in the theory. Based on this influenced parameters the results are given for the Sogamoso river, caño San Silvestre and ciénaga El Llanito. Finally the discussion and conclusion regarding the results are presented.

6.2 Methods

6.2.1 Theory

The theory discussed in this chapter is related to 1-D Morphodynamic changes with respect to the bed topography of non-cohesive sediments which are present in the area of interest. The bed topography includes aggredation and degradation, an overview of all elements in river morphodynamics is given in figure 6.1. Processes in lateral direction such as bends and small scale changes in bed elevation are not includes in this theory. However during the field trip it is turned out that the planform is experiencing bank advancement, which has to be kept in mind when judging the data with respect to the theory. Before the theory about the river response firstly the influence of hydrodynamics on morphodynamics is considered.

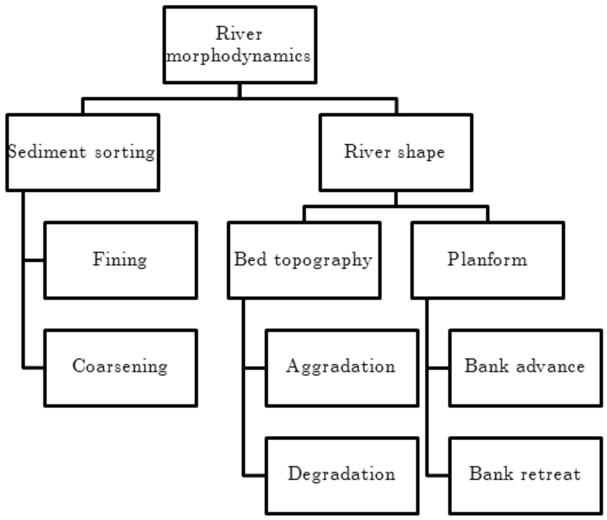


Figure 6.1: Overview components morphodynamics

Influence hydrodynamics on morphodynamics

The influence of the hydrodynamics on the morphodynamics is considered regarding non-cohesive sediment. The transport of non-cohesive sediment can be understood by the following action-reaction example. If a certain flow is present in a river, this flow will change the transport of bed material such that certain bed forms are created. These bed forms will change the bed friction which in it's turn will influence the water motion and sediment transport. After which the whole process starts again.
An important dimensionless parameter describing the sediment transport is the Shields stress. Shields (1936) related the flow force against the gravity force. He found experimentally that a minimum stress is required to move a particle, this is called the critical Shields stress. If the stress exerted by the water motion on the bed is below this critical shields stress no bed transport is present and vice versa.

The transport of sediment in a water column can be divided in two types:

Bed load
These are non-cohesive sediments that are rolling, sliding and saltating over the river bed. The force acting on the sediment particles is large enough to set a particle in movement but to small to keep the particle in suspension. Many empirically sediment transport relations exist. However there are large variations between the results of each formula, factors of 10 or higher between different transport relations are not uncommon. Therefore calibration of the used transport formula is an essential part when describing or modelling the bed load transport.
Suspended load
Suspended load can be divided into wash load, this sediment enters the area of interest already in suspension and consists of such a fine material that it barely settles on the river bed, and bed material load that becomes into suspension. The different particle motions that can influence the suspended load are shown in figure 6.2.

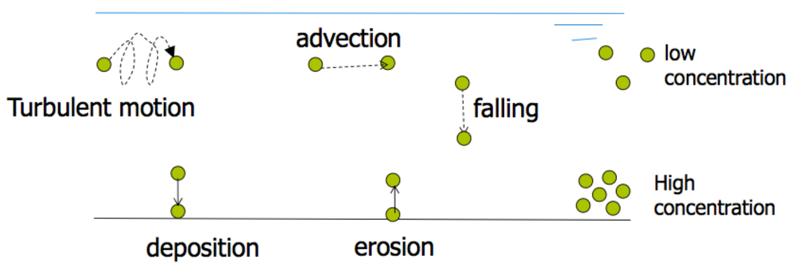


Figure 6.2: Particle motion for suspended sediment

An equilibrium situation is present when the amount of erosion equals the amount of deposition and when the amount of sediment particles settling on the bed due to the falling velocity equals the amount of sediment particles lifted from the bed by turbulent forces. From the balance between the falling force and the turbulent force a concentration profile over the depth can be derived, this is called the Rouse profile. Using this Rouse profile, the depth averaged velocity, depth and the sediment concentration near the bed, it's possible to get a formulation about the depth averaged sediment load, see equation 6.1.

$$\underbrace{h\frac{\delta \overline{c}}{\delta t}}_{storage} + \underbrace{\alpha \overline{U} h \frac{\delta \overline{c}}{\delta x}}_{advection} + \underbrace{\frac{\delta}{\delta x} h \epsilon_H \frac{\delta \overline{c}}{\delta x}}_{diffusion} = E - D \qquad (6.1)$$

River response

Initial river response The initial river response of a river reach after an adjustment in the river system is done by a mass conservation equation. When assuming that the interchange of suspended sediment is equally divided along the river, the control volume of this mass conservation is as shown in figure 6.3. In which $s(x)$ is the sediment load upstream of the control volume and $s(x + \Delta x)$ is the sediment load downstream of the control volume. z_b represents the bed elevation.

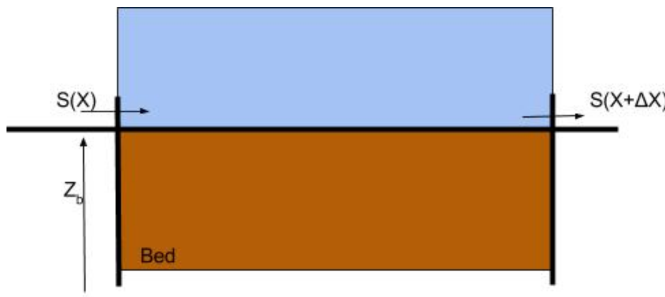


Figure 6.3: Mass conservation volume

Deriving the conservation of sediment mass in this volume the final equation that is used to look at the initial response of a river reach is the formula of Exner:

$$C_b \cdot \frac{\delta z_b}{\delta t} = -\frac{\delta s}{\delta x} \qquad \text{Formula of Exner} \quad (6.2)$$

where:

C_b = sediment concentration within the bed [-]
z_b = mean elevation of bed surface [m]
s = volume of transported sediment per unit width and time [$\frac{m^2}{s}$]

When looking at a river this means that if the downstream sediment load is larger compared to the upstream sediment load, the river bed will erode. The opposite is also true, when the downstream sediment load is smaller compared to upstream the bed will experience sedimentation. In the initial response the bed level is not adjusted to the new situation. This means that the bed level is not adapted yet but the process is illustrated what will happen in time.

Equilibrium river profile The equilibrium profile of a river means that the river has adjust to an equilibrium with respect to mass and momentum conservation, it is referred to as the morphodynamic steady state of the river. The river had time to adjust to the deviating situation, this means that the bed level has adjusted such that the velocity can transport all the sediment that is coming into the control volume upstream towards the downstream direction. No time derivations along the river are present in conservation of sediment mass, water mass and stream wise momentum. This results in a constant velocity, discharge and thereby depth. When rewriting these equations an equation is found for equilibrium velocity, depth and bed slope.

$$u_e = (\frac{S}{B \cdot m})^{1/n} \qquad \text{equilibrium velocity} \tag{6.3}$$

$$d_e = \frac{Q}{B^{1-1/n}} \cdot (\frac{m}{S})^{1/n} \qquad \text{equilibrium depth} \tag{6.4}$$

$$i_{be} = \frac{c_f \cdot B^{1-3/n}}{g \cdot Q} \cdot (\frac{S}{m})^{3/n} \qquad \text{equilibrium bed slope} \tag{6.5}$$

where:

S = volume of transported sediment per unit time [$\frac{m^3}{s}$]
B = river width [m]
m = Engelund-Hansen transport equation coefficient [-]
n = Engelund-Hansen transport equation coefficient [-]
Q = water discharge [$\frac{m^3}{s}$]
c_f = friction coefficient [-]
g = gravitational acceleration [$\frac{m}{s^2}$]

When looking at the formula of Exner the spatial gradient of the sediment load is zero, this means that the bed will not experience eroding or sedimentation. However the sediment load is not necessarily zero. The equilibrium flow velocity is not depending on the flow discharge because the river has adjust such that the river can transport all the sediment.With a constant discharge the water level is parallel to the bed level and there will be no backwater curve in the system. The controlling variables in the steady-state situation are water discharge, sediment load and sediment characteristics.

Non-steady discharge equilibrium In many river systems the discharge is not constant along the year. The previous equations for the morphodynamic steady state with a constant discharge are not valid in that situation. When looking at the situation with varying discharge the water level, active river, sediment load and friction coefficient are varying in time as well. Dealing with this situation the assumption is made that the time scale of changes in river slope are much larger compared with the time-scale of change in flow rate. Because of this assumption the historic data of the water discharge can be used to approach a constant discharge and calculate the steady state situation. To calculate the expected value for the water discharge and sediment transport rate the discharge is described as a probability density function based on historical data (figure 6.4).

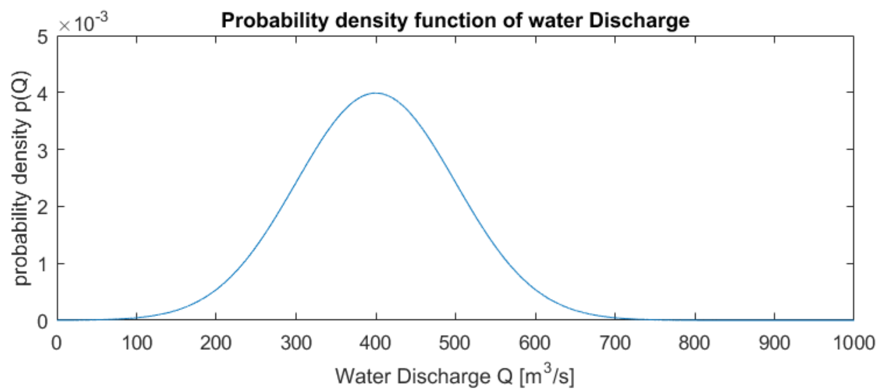


Figure 6.4: Probability density function water discharge

The formulas for this expected values in the steady sate situation are given in 6.7 and 6.8.

$$\int_0^\infty p(Q)dQ = 1 \qquad \text{definition of PDF} \tag{6.6}$$

$$E(Q) = \int_0^\infty Qp(Q)dQ \tag{6.7}$$

$$E(S) = \int_0^\infty S(Q)p(Q)dQ \tag{6.8}$$

$$V = T \cdot E(S) \qquad \text{Annual sediment transport volume} \quad (6.9)$$

When for this equations the annual sediment volume and the discharge distribution is known, the equilibrium slope can be computed by eliminating flow depth from the sediment transport equation. To do this the Engelund-Hanssen tranport formula and normal flow are assumed. The final equations for velocity, depth and river slope in the morphodynamic steady state with varying discharge are given in 6.10,6.11 and 6.12.

$$u_e(t) = (\frac{Q(t)}{Q_{dom}})^{1/3} \cdot (\frac{E(S)}{Bm})^{1/n} \tag{6.10}$$

$$d_e(t) = (\frac{Q_{dom}^{1/3} Q(t)^{2/3}}{B^{1-\frac{1}{n}}}) \cdot (\frac{m}{E(S)})^{1/n} \tag{6.11}$$

$$i_{be} = (\frac{c_f B^{1-\frac{3}{n}}}{g Q_{dom}}) \cdot (\frac{E(S)}{m})^{\frac{3}{n}} \tag{6.12}$$

With Q_{dom} given by,

$$Q_{dom} = \left[\int_0^\infty Q^n p(Q) dQ \right]^{3/n} \tag{6.13}$$

where:

S = volume of transported sediment per unit time [$\frac{m^3}{s}$]
B = river width [m]
m = Engelund-Hansen transport equation coefficient [-]
n = Engelund-Hansen transport equation coefficient [-]
Q = water discharge [$\frac{m^3}{s}$]
c_f = friction coefficient [-]
g = gravitational acceleration [$\frac{m}{s^2}$]

In order to get to the final equations for the morphodynamic steady state with varying water discharge the assumption is made that normal flow is occurring. Because of this fact the equations are only valid upstream from the backwater curves causing by the varying water discharges.

6.2.2 Influence parameters

In this section the parameters regarding the theory are discussed.

Initial response The initial response of a river is done by the mass balance formula of Exner as explained in the theory. For this mass balance the sediment load S(x) along the river is the parameter discussed.
Morphological steady state For the morphological steady state situation the parameters $E(Q)$, B, $E(S)$,D_{50} and C_f determine the qualitavely analysis.
In figure 37 the measuring stations are given where parameters are known at a moment in December 2014 and Augustus 2015. With respect to the discharge of the Sogamoso river an expected value of before and after the dam is used to say something about the morphological equilibrium, the values are determined and explained in chapter four. The Sogamoso river contains measuring station S2 until S9, the caño San Silvestre contains measuring station S17. In ciénaga El Llanito no measuring station and thereby data is available. If a parameter showed the same trend for the whole Sogamoso river only three values at the beginning in the middle and at the end are given. The sediment loads are given in every station for the results regarding the initial state of the river. The tables with values are given in the Appendix

6.3 Results

The Sogamoso river and caño San Silvestre are discussed with respect to the initial response after the building of Hydro Sogamoso. Furthermore a estimation is made regarding the influence of the relevant parameters on the new equilibrium state. The theory of river reaches is not applicable on ciénaga El Lanito. Regarding the ciénaga a general description of observed processes is given.

6.3.1 Sogamoso river

With respect to the initial response of the Sogamoso river the changes of $S(X)$ between the measuring stations are the same in 2014 and 2015. Therefore a degradation between stations S2 and S3 is expected, between S3 and S5 erosion, between S5 and S7 degradation and between S7 and S9 erosion.

Regarding the long term equilibrium the expected discharge is decreased after the construction of Hidrosogamoso. For the new equilibrium situation this change means a lower equilibrium depth d_e and a higher equilibrium slope i_{be}.
Over the whole Sogamoso river an increase in the width is observed. Regarding this parameter a smaller equilibrium velocity U_e and depth d_e is expected and a higher equilibrium slope i_{be}.
For all the measuring stations the sediment load was higher in 2015 compared to 2014. However this was only at one moment in time. Taking into account that the discharge in 2015 was high compared to 2014, this would be likely the cause of the difference in sediment load. Furthermore it is expected that after the construction of the Hidrosogamoso the sediment load decreases on average since the sediment is blocked by the dam. At last the observations during the field trip showed controversially a lot of deforestation which would contribute to a higher suspended sediment load. The data, the expected behaviour after building a dam and the observations are not showing a corresponding trend. The deforestation will lead to a large amount of suspended sediment transport. This suspended sediment transport will contribute on a shorter time-scale to the response of the system, compared with the bed load transport considered in the Exner equation and long-term response of the river.
The influence of the median grain size is represented in the parameter m in the equations of the morphological steady state with the relation $m \sim 1/D_{50}$. At measuring station 2 an decrease of the median grain size is observed, station 4 stayed the same and at the rest of the measuring stations the median grain size increased. For the largest part of the river the increase in median grain size will results in a higher equilibrium velocity U_e and bed slope i_{be} whereas the equilibrium depth d_e would increase on the long term.
The last parameter regarding the long term response of a river, the roughness c_f, is not treated because no data is available regarding the parameter.

6.3.2 Caño San Silvestre

In the caño San Silvestre only measuring station S17 is located. Based on two moments in time at one location nothing can be said about the initial situation and the new equilibrium state. However something can be said in this situation by considering the interaction with the Sogamoso river. In the Sogamoso river after the construction of the Hidrosogamoso the expected discharge is decreased. Taking this as assumption into account, the situation for the initial response is shown in figure 6.5

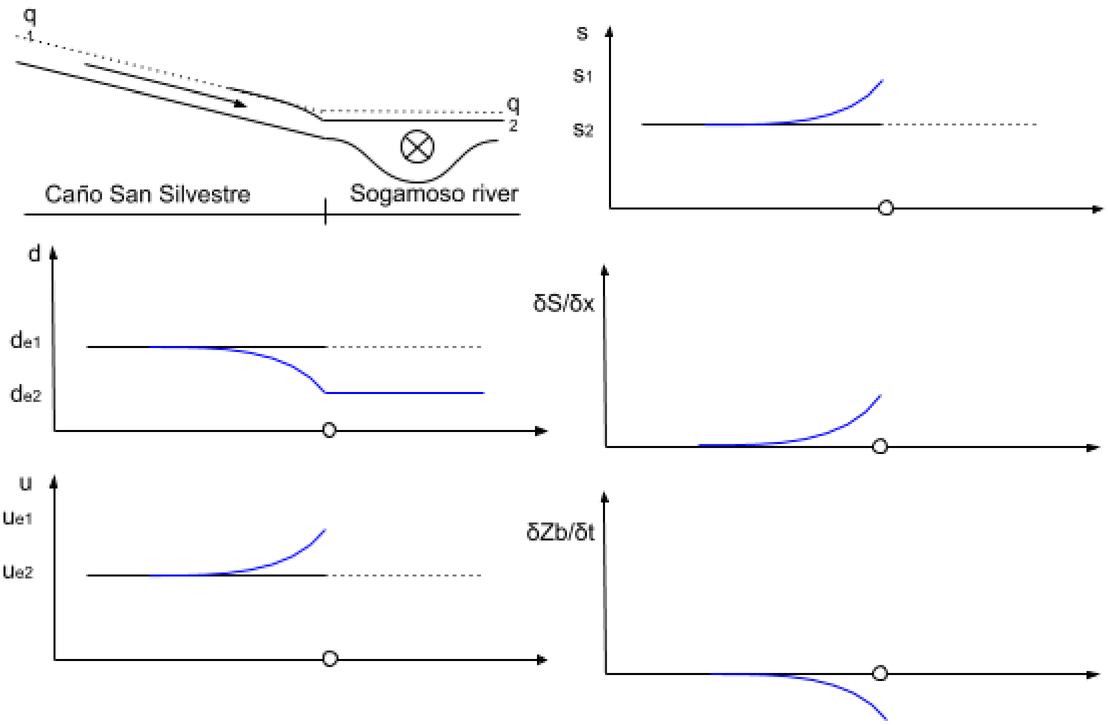


Figure 6.5: Morphodynamic initial response caño San Silvestre

Assuming the same cross section before and after the construction of the Hidrosogamoso the water level decreases with a decreased discharge in the Sogamoso river. Furthermore the upstream discharge in the caño San Silvestre stays is assumed constant. Therefore a M2 backwater curve results in an increasing velocity towards the downstream part of the caño San Silvestre. With this increasing velocity also the sediment load increases. According to Exner erosion will occur in this initial situation at the downstream part of the caño San Silvestre.

On the long term the new morphodynamic steady state is adapted to. The same water depth in the caño San Silvestre is present only the bed level is eroded over the water depth difference of the Sogamoso river before and after the construction of the Hidrosogamoso. This new situation in shown in figure 6.6

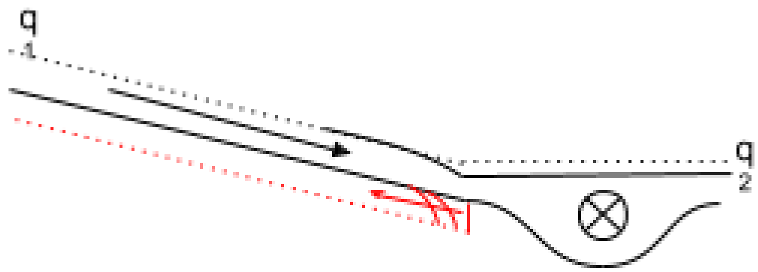


Figure 6.6: Morphodynamic steady state caño San Silvestre

6.3.3 Ciénaga El Llanito

In figure 6.7 an overview is given of the situation for the ciénaga El Llanito. The boundary condition upstream of the caño San Silvestre is assumed unchanged after the construction of the Hidrosogamoso. The bed level in the caño San Silvestre will decrease on the long term due to the decreasing expected discharge in the Sogamoso river after the construction of the Hidrosogamoso. Therefore the water level in the ciénaga becomes lower when this system adopts to its surroundings.

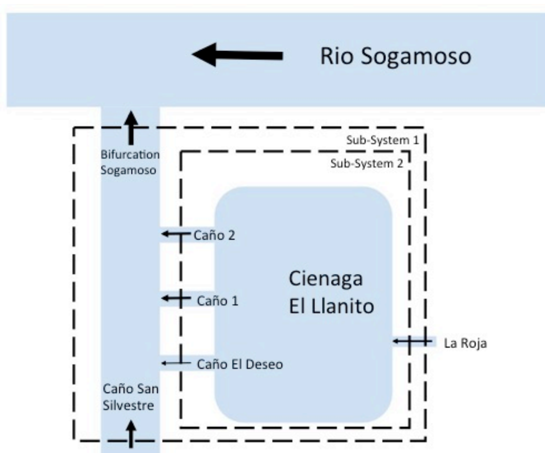


Figure 6.7: Overview connections ciénaga El Llanito

6.4 Discussion

In the initial response mass balance it is assumed that along the river the interchange of sediment is equal, therefore the assumption for the Exner formula could be made. In reality there might be parts of the river where there is more interchange between the water column and bed.

The long term steady state of the Sogamoso river is discussed for each parameter assuming that the other parameters stay constant. In reality multiple parameters may change at the same time and the ratios between the relevant parameters determine the steady state situation. Moreover the initial response of caño San Silvestre is made under the assumption all the relevant parameters stay the same in the caño, in reality there also might be changes within the caño San Silvestre. For these reasons this qualitatively morphodynamics chapter presented results for the caño San Silvestre and the ciénaga El Llanito which are not decisive but function as a first indication of the way the systems might behave and react on the changes observed.

6.5 Conclusion

Along the first part of the Sogamoso river three parts with successive sedimentation, erosion and sedimentation are distinguished in the initial response. For the long term behaviour the parameters are discussed, morphological models are needed to determine the decisive result regarding the morphodynamic steady state of the river as a whole. The sediment transport consists of bed load transport and suspended transport, since both transports act on different time-scales this is an important consideration when making the morphological models

The part of the Sogamoso river where the connection is with the caño San Silvestre experience an initial response of eroding due to the average decrease of water level in the Sogamoso river. Additionally the parameters on which the equilibrium depth d_e depends indicated an decrease of the equilibrium depth d_e on the long term at this location. Based on this results the initial and long term response of caño San Silvestre is determined. For the initial response an eroding process is expected starting at the connection between the Sogamoso river and caño San Silvestre. This eroding of the bed proceed upstream along caño San Silvestre on the long term. Since the ciénaga El Lanito is connected via caño San Silvestre the water level is expected to decrease in the ciénaga as well on the long term.

Chapter 7

Assessing the proposed hydraulic structures

7.1 Introduction

According to the ISAGEN report [Isagen, 2015b] new ideas have been developed to solve the problems at the ciénaga El Llanito. These ideas consists of the construction of new hydraulic structures around the ciénaga El Llanito. These hydraulic structures will be elaborated in this section. The goal of those structures is to obtain a minimum water depth in the Ciénaga El Llanito. The hydraulic structures are designed by ISAGEN in cooperation with the fishing community ASOPESAMM. With a minimum water depth in the ciénaga El Llanito, the fishing community expects to have a higher fish population in the ciénaga. Unfortunately, this result is not confirmed by any investigation.

The influence of the hydraulic structures on the Ciénaga El Llanito is very interesting for ISAGEN and ASOPESAMM. They try to control and stabilize the water depths in the ciénaga El Llanito, but no studies have been performed if these hydraulic structures will result in larger water depths and in the end a higher fish population. In this chapter there is made a first move to the understand the influences of these structures on the hydraulics in the Ciénaga El Llanito.

Intermezzo: Water levels and water depth

In this chapter both water levels and water depths will be mentioned. To make sure the difference between those two concepts is clear, the definitions will be given:
A **water level** is the elevation of the free surface of a river, lake or reservoir relative to a specified datum. A **water depth** is the distance between the bed and the free surface at a specific location.

7.1.1 Overview proposed hydraulic structures

In figure 7.1 the locations of the hydraulic structures are shown (black circles are the locations where the construction of structures is planned/executed). In this subsection all the hydraulic structures will be elaborated shortly.

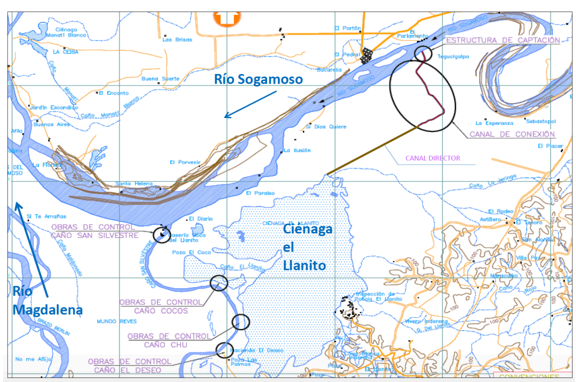


Figure 7.1: New hydraulic structures in the surroundings of the ciénaga El Llanito

Hydraulic structure at new artificial caño
To add more water in Ciénaga El Llanito, a new artificial caño has been realised in 2015 at the North-east side of Ciénaga El Llanito. This hydraulic structure has 9 different doors, which can result in a total discharge of 30 m^3/s, if all the doors are open. At this moment, November 2016, it is still unknown who is going to control this structure. It is planned that at the beginning of 2017, this hydraulic structure will start to operate. The caño that connects the Sogamoso river and the Ciénaga El Llanito has a total length of 4600 m, a base width of 16 metre and an the height

of the banks are on averaged 2.8 metre from the bed.

The purpose of this structure, according to intervies with ASOPESAMM during the field-trip, is to generate a second connection between the Sogamoso river and Ciénaga El Llanito. They expect to "flush out" the Ciénaga El Llanito, which have to reduce the sediment in the ciénaga. By controlling the doors, they expect to manage the water levels in the ciénaga by open and close the doors at the right time, depending on the water levels in the Sogamoso river.

(a) New structure (b) New artificial caño (c) Top view

Figure 7.2: New hydraulic structure at Sogamoso river

Hydraulic structure at bifurcation caño San Silvestre and Sogamoso river

A new hydraulic structure is designed near the bifurcation between caño San Silvestre and the Sogamoso river. The main purpose of this structure is to reduce the flow from San Silvestre to the Sogamoso river during low water levels in the Sogamoso river. During high water levels in the Sogamoso river the structure will not significantly influence the water level in the caño San Silvestre, because the water is able to flow over the structure. With the reduction in outgoing discharge, the goal is to have a higher water level in the caño San Silvestre and subsequently the Ciénaga El Llanito during low water in the Sogamoso river.

The sketch shown in figure 7.4 gives a visualization of the water levels in the caño San Silvestre during high and low water levels in the Sogamoso river.

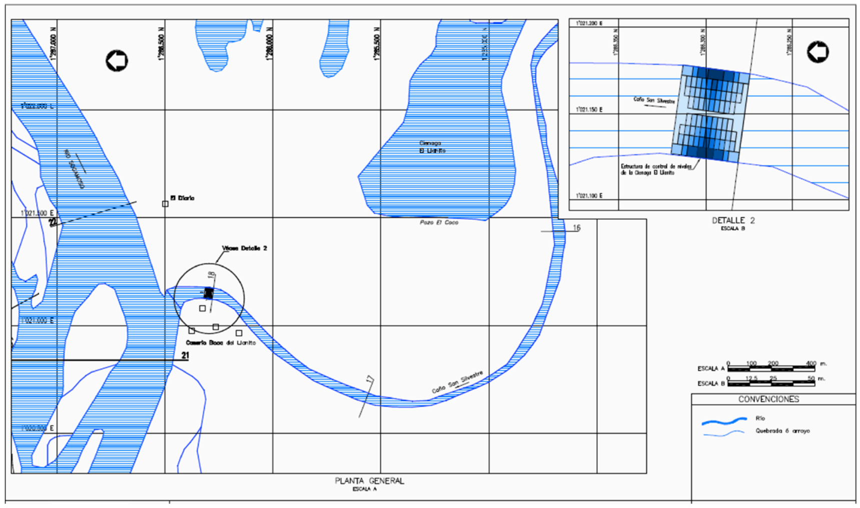
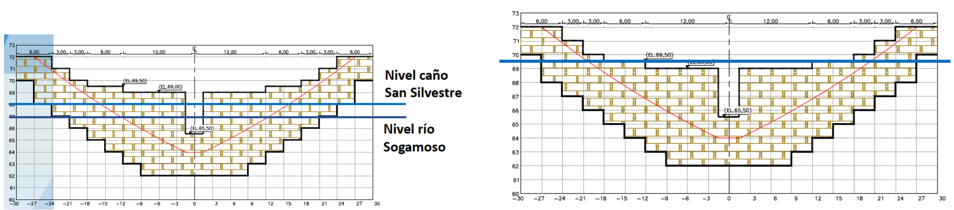


Figure 7.3: Top view of hydraulic structure at bifurcation Sogamoso river and caño San Silvestre



(a) Low water Sogamoso river

(b) High water Sogamoso river

Figure 7.4: Effect of hydraulic structure at bifurcatoin

Hydraulic structure at caño El Deseo

To contain a certain water level in the ciénaga El Llanito a structure has been built in caño El Deseo. This structure is shown in figure 7.5. It contains a 2 meter high wall with a small gap near the left bank. This small gap has been created to give the fishes an easy access from the ciénaga to the Sogamoso river. The importance of this fish cycle is elaborated in the appendix.

The goal of this structure is to reduce the conveyance cross-section in order to maintain a minimum water level in the ciénaga El Llanito. The new artifical caño can be used to obtain enough water inflow.

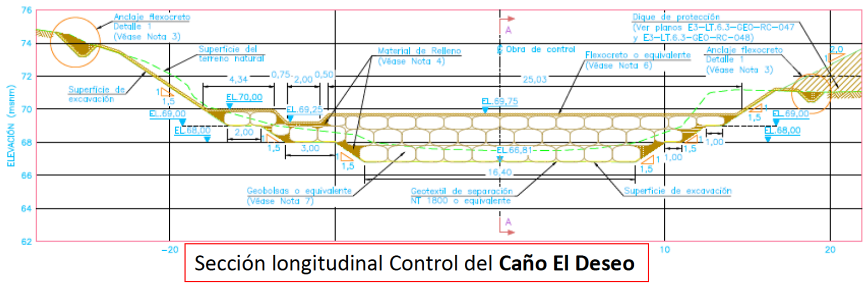


Figure 7.5: Hydraulic structure in caño El Deseo

Hydraulic structure at caños Chu and Cocus

Caños Chu and Cocus, mentioned as artificial Caño 1 and 2 in this report, were created by the fisherman years ago. Again for the purpose to contain a minimum water level in the ciénaga, these two caños are planned to be closed. After that, Caño El Deseo will be the only direct connection between the caño San Silvester and Ciénaga El Llanito.

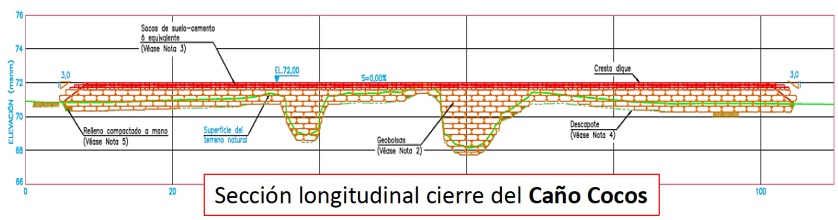


Figure 7.6: Closing artificial caño 2 (Cocos)

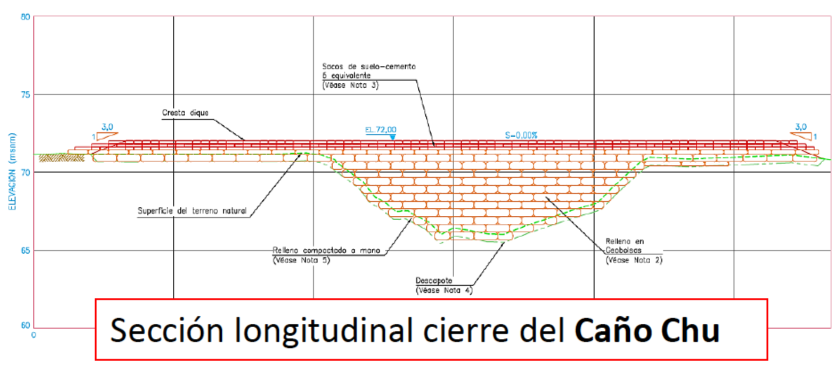


Figure 7.7: Closing artificial caño 1 (Chu)

7.2 Methods

The construction of the proposed hydraulic structures have great influences on sub-system 1, defined in figure 7.8. Flow channels are blocked and a new one is created, so the connection between the Sogamoso river and Ciénaga El Llanito is completely changed. One of the unchanged hydraulic aspects in sub-system 1 is the discharge entering the Caño San Silvestre coming from Ciénaga San Silvestre and the discharge entering the Ciénaga El Llanito from Caño La Roja.

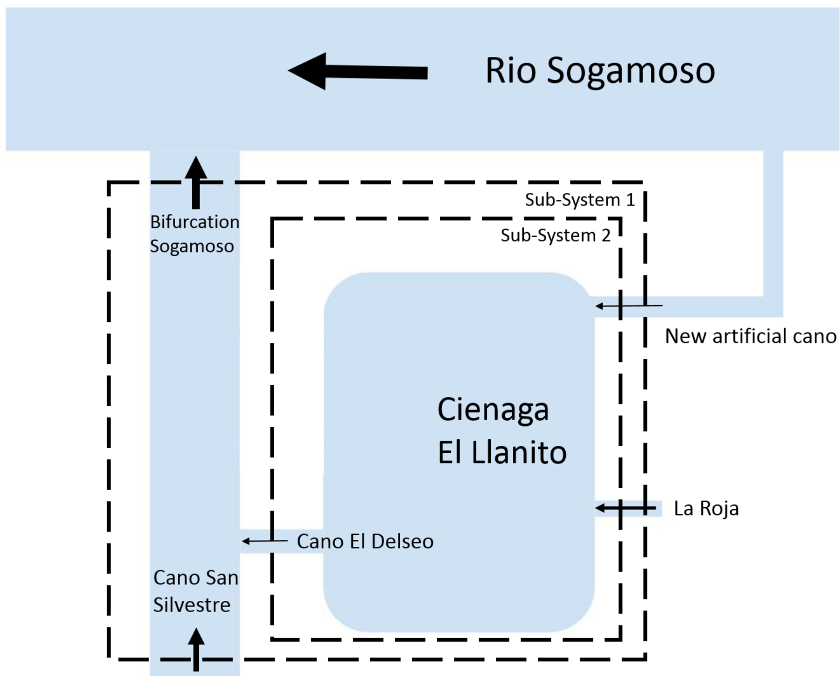


Figure 7.8: Overview of flows in the Ciénaga El Llanito and surroundings after construction proposed hydraulic structures

The system will be heavily disturbed if the proposed hydraulic structures will be constructed. Both hydrodynamics and morphodynamics in the Ciénaga El Llanito and and the Caño San Silvestre will be affected. To identify this effect the hydrodynamic model, described in the chapter 5, should be set-up with the prescribed hydraulic structures. However, time constrains limited the working hours and an additional model with the proposed hydraulic structures was not possible to set up.

The influence of all hydraulic structures together is too complex to assess without a hydraulic model. As a first step in understanding the influence of the hydraulic structures on the Ciénaga El Llanito, the general influence of each hydraulic structures on the hydrodynamics and morphodynamics in sub-system 1 have been elaborated in the next section . In the end, the goal of those structures, to obtain a constant minimum water level in the Ciénaga El Llanito, is tried to assess.

7.3 Results

In general the water level changes in the Ciénaga El Llanito depends on the in- and outflow:

$$\frac{dh_B}{dt} = \frac{Q_{in} - Q_{out}}{A_B} \tag{7.1}$$

where h_B is the water level in a basin, Q_{in} is the inflow of a basin, Q_{out} is the outflow and A_B is the surface area of the basin, which also depends on the water level in the basin. Precipitation plays also a role, but this will be neglected in this case.

The in and outflows depend mainly on the water level differences between the Ciénaga El Llanito and its surroundings, according to the gravitational forcing term in the momentum equation. In the next subsection we will assess the in- and outflows with respect to water levels in the Ciénaga El Llanito and surroundings.

7.3.1 Current situation

In the current situation the Ciénaga El Llanito is connected to the Caño San Silvester by means of three other caños. The water level differences between the Caño San Silvester and the Ciénaga El Llanito determine the in- or outflow in the Ciénaga. The water level in the Caño San Silvester is mainly determined by two factors, namely the discharge coming from Ciénaga San Silvestre and the water level in the Sogamoso river. The first factor is not changed after the construction of the Hidrosogamoso, however the water levels in the Sogamoso river are on average lowered after the construction of the Hidrosogamoso. The consequence is a backwater curve, described in chapter 6, which will lower the water levels in the caño San Silvestre on the short- and long-term. These lower water levels will cause in general lower water levels in the Ciénaga. ISAGEN and ASOPESAMM try to avoid this decrease in water level.

7.3.2 Influence proposed hydraulic structures

Hydraulic structures in and connected to the caño San Silvestre

The Hydraulic structure at the bifurcation between the caño San Silvestre and Sogamoso river has the purpose to reduce the flow from caño San Silvestre to the Sogamoso river, to maintain a higher water level during low water level in the Sogamoso river. The conveyance cross section differs with different water levels, this creates a delay in the decrease of the water level in caño San Silvestre during a low water level in the Sogamoso river. The conveyance cross section is smaller during low water levels (see figure 7.4) The structure also affects the water levels in the caño San Silvestre further upstream and will probably lead to higher water levels at caño El Deseo, assuming that the influence of the backwater curve is large enough.

At caño El Deseo there is also planned a hydraulic structure, which also has the purpose to reduce the flow leaving the Ciénaga El Llanito. It is the same concept as the structure at the bifurcation between the caño San Silvestre and Sogamoso river.

The closure of the two artificial caños lead to a longer connection channel between the Ciénaga El Llanito and Sogamoso river. At the same time the conveying cross section between the Ciénaga El Llanito and caño San Silvester is decreased. This will also lead to a slower response of water level changes in the Ciénaga El Llanito, compared with the current situation.
Summurazing the hydraulic structures at the east side of the Ciénaga El Llanito will contribute to higher water levels in the Ciénaga El Llanito. It is expected that the hydraulic structure at the bifurcation between the caño San Silvestre and Sogamoso river will block the sediment and sedimentation will take place in the the caño San Silvestre. However this sedimentation will not influence the increased water levels in the caño San Silvestre, but the water depths. It is hard to say the morphological influence of those structures in the Ciénaga El Llanito.

New artificial caño

The construction of a new artificial caño well lead to a new connection between the Ciénaga El Llanito and Sogamoso river. The length of the channel, 4600 m, will lead to a delay of the arrival of a flood wave in the Ciénaga El Llanito. It is unknown how this structure precisely will be controlled during different water levels, but in general the idea is that the doors are open during high water levels in the Sogamoso river, which will generate an inflow in the Ciénaga El Llanito. During low water levels in the Sogamoso river the doors are closed and there will not be an outflow.

7.4 Discussion

It is very hard to say how the hydrodynamic and morphodynamic behaviour in the Ciénaga will be influenced by those hydraulic structures without a hydraulic model. The bed level of the new artificial caño is unknown, as well as the bed slope. There is missing to much data to give a qualitatively answer to the research question: What is the influence of the proposed hydraulic structures on the Ciénaga El Llanito?

By controlling the doors at new artificial caño, the water levels in the Ciénaga may be increased. However, the morpholigical response of the Ciénaga on those structures is hard to say. It could be that the Ciénaga will import more suspended sediment by means of the new artificial caño, which will settle in the Ciénaga. This will lead to sedimentation in the Ciénaga and in the end lower water depths. Than the goal of enlarge the water depth will fail.

The openings in the hydraulic structure at caño El Deseo and at the bifurcation of the Sogamoso river and caño San Silvestre are, as explained in the results, meant to reduce the outflow during low water levels of the surroundings and maintain water levels in caño San Silvestre and the Ciénaga El Llanito. However the influence on the fish migration during the low water levels is unknown, based on experience it is assumed that the openings are sufficient for this purpose.

7.5 Conclusion

Overall all the hydraulic structures together will probably lead to higher water levels in the Ciénaga El Llanito. The outflow is delayed because the structures influence the conveyance cross-section in such a way that water will be stored longer in the Ciénaga El Llanito. Based on experience of the fishermen it is assumed that the higher water level will lead to larger fish population in the the Ciénaga El Llanito. However, it is hard to say how the system will morphological react. This can have a large influence on the actual obtained water depths by the structures on the long term. Furthermore it is unknown how fish migration will be influenced by the hydraulic structures during low water in the surroundings of the system.

Chapter 8

Conclusions and recommendations

8.1 Conclusion

The objective of this project is:

Objective

Understanding the influence of a **modified flow regime** on Ciénaga El Llanito and the Sogamoso River, regarding the **hydraulics** and **socio-political context**

Below the conclusions are given regarding the objective and corresponding research questions of the project.

The modified flow downstream of the Hidrosogamoso is characterized by two aspects after the construction of the dam. Less and on shorter time-scales fluctuations occur, but if there is a fluctuations it will be more extreme. The stages of fluctuation are determined by the operating turbines of the Hidrosogamoso. Furthermore the average discharge is decreased with almost 40 %.

The modified flow results in flood waves downstream of the Hidrosogamoso. The way flood waves propagate downstream from the Hidrosogamoso to the area of the Ciénaga El Llanito is adressed by means of a 1D-Sobek model and it determined the characteristics of the flow regime at the boundary of the Delft3D model. A sensitivty analysis showed that the influence of the roughness is significant regarding the time the flood waves propagate to the area of Ciénaga El Llanito and for the depth of the flood waves at the boundary of the Delft3D model. With the current lack of data regarding the roughness the flood wave characteristics are therefore described regarding the diffusion and discharges of flood waves. In general an increased discharge caused by the tributaries along the Sogamoso river and a diffused flood wave are observed at the boundary condition of the Delft3D model.

Implemtening this boundary in the Delft3D model, the upstream fluctuating discharge has lead to a minimum and maximum water depth in the Ciénaga El Llanito of respectively 1.10 m and 1.22 m. Fluctuations at the upstream boundary of the Sogamoso river showed that the influence regarding the discharge are significatly smaller in Ciénaga El Llanito compared with the downstream part of the Sogamoso river. The time to adjust to a fluctuations of Ciénaga El Llanito is much larger compared to Sogamoso river. With respect to the flow direction the model showed that for all upstream fluctuations, the flow direction in caño San Silvestre is towards the Sogamoso river.

Backwater curves influence the water level in Ciénaga El Llanito when extreme water levels are present at the downstream boundary of the Sogamoso river of 69 m. This influence is not present at the upstream part of the Delft3D model. For both the backwater curves and fluctuating discharges upstream, an increase of extreme water levels and discharges result relatively in larger impacts on the water levels in Ciénaga El Llanito compared to an equal increase of average values.

In addition to the hydrodynamic models, a qualitative morphodynamic analysis is performed to give a first indication of the processes that contribute to the morphological response of the Sogamoso river, caño San Silvestre and the Ciénaga El Llanito. Along the Sogamoso river three parts with successive sedimentation, erosion and sedimentation are distinguished in the initial response. The parameters on which the long term response depend are adresses, however for the long term response of the Sogamoso river as a whole, a morphodynamic model is needed.

At the connection of the Sogamoso river and caño San Silvestre, initially and on the long term the results indicated that the water level decreases. Based on this result the initial response of caño San Silvestre is expected to be erosion at the connection between the Sogamoso river and the caño. On the long term this erosion will proceed upstream along the caño San Silvestre. Since the Ciénaga El Llanito is connected to caño San Silvestre the water level in the Ciénaga is expected to decrease on the long term.

The last part of the hydraulics adressed the hydraulic structures in and around Ciénaga El Llanito, which are partly build and party still have to be constructed. Initially it is expected that the hydraulic structures result in a higher water level and depth in Ciénaga El Llanito on the short term. On the long term, morphodynamic processes might influence the system such that an import of sediment causes the water depths to decrease. However the hydraulic structures should be implemented in the current existing hydrodynamic model of the area to give a decisive conclusion. Due to time constraints this is not executed in this project.

A stakeholder analysis is performed to understand the influence of the modified flow regime on the area of interest regarding the socio-political context. The four main stakeholders in which all interests of the remaining stakeholders are represented

- Ministry of Environment and Sustainable Development (ESD)
- Ministry of Agriculture and Rural Development (ARD)
- Isagen
- ASOPESAMM

are connected by two main relations. Firstly, Isagen has to meet certain requirements and regulations to avoid environmental damage as much as possible to retain an environmental license for operation of the Hidrosogamoso. This license is provided by the ministry of ESD. The second relation regarding social and economical development initiated by the ministry of ARD states that Isagen should work together with ASOPESAMM to think of solutions to improve the social and economical development of the Ciénaga El Llanito. The interest of Isagen is mainly economical and ASOPESAMM is mostly interested in job opportunities. Together with their interaction in the current situation with the ministries, the Ciénaga El Llanito might be undervalued regarding environmental aspects. Ciénaga El Llanito is seen more as a resource for food and work, the long term effects are less considered. The future of Ciénaga El Llanito as a wetland is therefore uncertain.

8.2 Recommendations

For the recommendations a distinction is made between data, further research and direct proceedings. This is done to emphasise the meaning of the recommendations. The data recommendations adres the additional data which is required to improve the current hydrodynamic model of Sobek and Delft3D. The further research recommandations show the sequal researches to have a better understanding of the area of interest and the subject of this project. The direct proceeding recommendations function as framework for CIRMAG to have an idea of relevant actions which can be executed on the short term.

8.2.1 Data

With respect to the 1-D Sobek model additional data is needed of the tributaries and for the roughness validation. Measuring stations can be realised to obtain the discharges and water levels in the tributaries along the Sogamoso river. However this is a costly solution, hydrological models can be a more economical solution to obtain the data. For the validation regarding the roughness of the model, data is required of the water levels along the Sogamoso river of a longer periode of time.

For the 2-D Delft3D model data is required to validate the model. Furthermore a reference level is missing to connect the model to a reference datum. The data required for the validation of the model has to be over a longer periods of time, in the order of years. Together with measurements in Ciénaga El Llanito, the connecting caños and the Sogamoso river, it is possible to validate the model with respect to hydrodynamics.

8.2.2 Further research

Further research on the influence of the fluctuating discharges during the year from the Ciénaga San Silvestre is recommended to understand the hydraulic behaviour of the Ciénaga El Llanito and its surrounding. In our two-dimensional model the discharge entering the caño San Silvester upstream is an average discharge estimated with the rational method equation. First of all the reliability of this method, given the lack of data, is doubtful. Secondly, the flow from the Ciénaga San Silvester depends on the natural flow cycle of water. It fluctuates during the different seasons in the year and the hydraulics in the Ciénaga El Llanito can not be defined with a constant discharge from the Ciénaga San Silvester.

For the Delft3D model it is recommended to look when the flow direction in caño San Silvestre is changing direction, thus towards Ciénaga El Llanito. So what should the boundary conditions in the Sogamoso river and caño San Silvestre be to reach this situation. And more importantly, are these realistic boundary conditions? For example it is concluded from this report that both a high discharge at the upstream Sogamoso boundary and a high water level at the downstream Sogamoso boundary individually result in a significant increase of the water level of Ciénaga El Llanito. But if these two situations occur simultaneously, does that result in a relative higher rising of the water level Ciénaga El Llanito?

In this research the morphological processes in the Ciénaga El Llanito and Sogamoso river are qualitatively examined. To obtain more insights in the morphological processes in these areas, further investigation is necessary. Mixing of the suspended sediment in confluences and bifurcations are not considered. Suspended sediment is able to settle in the Ciénaga El Llanito and therefore the processes related to suspended sediment.

Another remarkable note is the morphological influences of the modified flow regime on the Magdalena river. The sogamoso river is the largest tributary of the Magdalena river and act as the main sediment contributor. In order to achieve the goal of Cormagdalena (described in chapter 3), a study focusing on the morphological influences of the Sogamoso river on the Magdalena river is necessary.

For a thorough understanding of the influence of the hydraulic structures on the Ciénaga El Lanito the structures should be implemented in the Delft3D model. This is not achieved, because of time constrains.

8.2.3 Direct proceeding

The gauging station PTE Sogamoso does not give reliable discharges and water levels. It is recommended to investigate the measurements at this station, where new calibration is very likely necessary. In this report, PTE Sogamoso is considered as unreliable and the discharges from the tributaries between the Hidrosogamoso and PTE Sogamoso are used to obtain an estimate of the hydrograph just upstream of the Ciénaga El Llanito.

Currently reference poles are missing to connect obtained data to a reference data. To connect the existing models to a reference datum it is recommended to install reference poles along the Sogamoso river, Ciénaga El Llanito and the connecting caños.

For now, we would also recommend to postpone the further construction of the hydraulic structures. The influence of those structures unknown and can affect the system of the Ciénaga El Llanito and its surroundings significantly. It may lead to sedimentation of the Ciénaga El Llanito and turn back to the original morphological state of the ciénaga would be difficult.

Appendix A

General information about Colombia

Appendix A.1. Geography

The Republic of Colombia is located in the North of South America and is often called the gateway to Latin America countries, because of the connection with Panama in the Northwest of the country (see figure A.1). Further it is bordered by Venezuela (east), Brazil (east), Ecuador (south) and Peru (south). The total area is 1,140,000 km^2, including the islands San Andrés and Providencia.

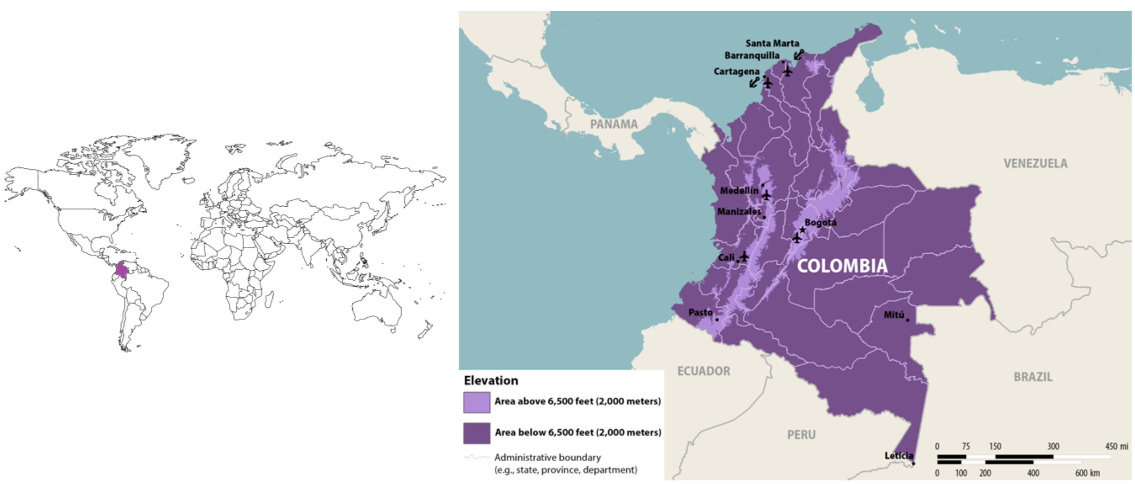


Figure A.1: Topographical map of Colombia

The Andes Mountains (highlands along the western edge of South America) divide into three roughly parallel ranges in Colombia (called *cordilleras*): Occidental (West), Central and Oriental (East) Cordilleras. Those mountain ranges are separated by two valleys, Cauca River Valley and Magdalena River Valley. The two rivers in these valleys are very important for Colombia because of the biology, transport and electric power purposes. Both rivers drain into the Caribbean sea, where the main ports of Colombia are located.

Country Snapshot

Country Snapshot	
Population	48,23 Million
Density	43,47 inhab/km^2
Nominal GDP (US$)	$ 292.08 billion
GDP Per capita	$ 6059.75
Major Cities	Bogota (capital), Medellin, Cali
Official Language	Spanish
Currency	Colombian Peso (COP)

Table A.1: Snapshot Colombia [Group, 2016]

Appendix A.2. Climate

Colombia's climatic variations are determined by altitude. The different seasons are characterized by periods of lesser or greater rainfall, with little or no temperature change. The country may be divided vertically into four regions.

- From sea level to roughly 1,100 m there is a tropical zone, where the mean annual temperature is 20 °C to 27 °C. At sea level, temperatures have a mean maximum of 38 °C and a minimum of 18 °C
- Between 1,100 m and 2,000 m is the temperate zone, where the average year-round temperature is about 18 °C.
- Between 2,000 m and 3,000 m is the cold country, with temperatures averaging a little over 13 °C.
- Above the 3,000 m level the temperature varies from 13 °C to -17 °C, according to altitude.

Rainfall is heaviest on the west coast and in the Andean area. A distinguish can be made between rainy and dry seasons, or "winter" and "summer", which generally alternate with a three-month cycles. Precipitation occurs most heavily and consistently during the periods of April to June and October to December (see figure A.5 for Bogota). Northern areas have only one long rainy season, from May through October. The annual average rainfall is 107 cm.

El Nino and La Nina

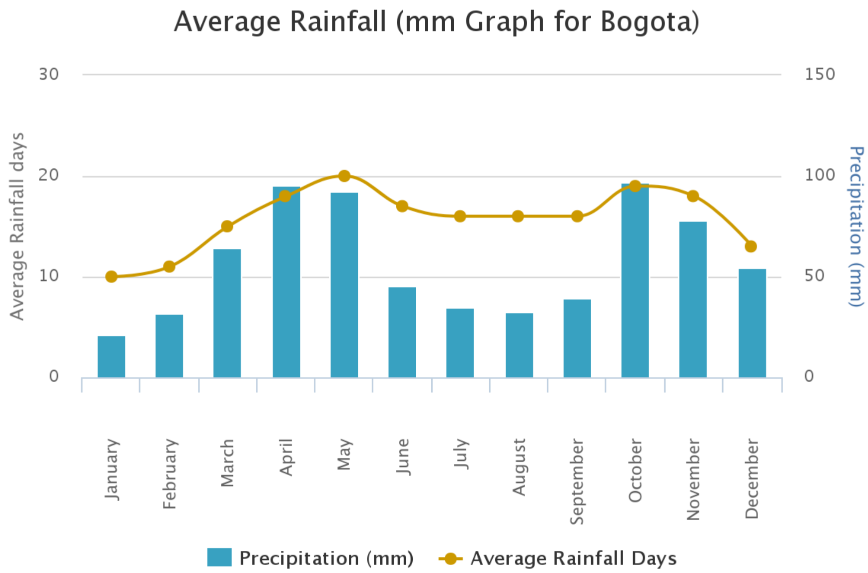


Figure A.2: Average Precipitation for Bogota

Apart from the subdivision of the climate by altitude in Colombia the El Nino and El Nina are two phenomena which are very important for the climate in Colombia.

Intermezzo: El Nino and La Nina

El Nino and La Nina are processes occurring and influencing the global climate system. They contain the deviation in surface temperature of the east-central Equatorial Pacific and the temperature of the surrounding atmosphere. El Nino and La Nina are occurring in a cycle and are the opposite phase of the cycle known as the El-Nino-Southern Oscillation (ENSO).

El Nino is referred to as the warm period of the ENSO because the trade winds blowing from east to west reduce in strength and warm water piles up against south America. Whereas La Nina is often referred to as the cold period of the ENSO because due to stronger trade winds large parts of the pacific ocean are covered with cold water (Figure A.3).

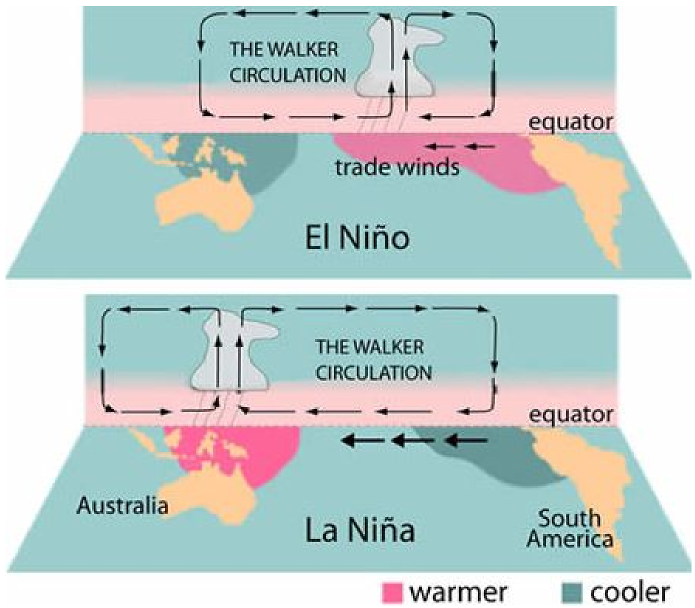


Figure A.3: Overview processes El Nino and La Nina

The length of an event is usually between 9 and 12 months, however rarely they might last for years. The return period of El Nino or El Nina is not regular but is between 2 and 7 years and El Nino occurs more often. In figure A.4 the past El Ninos and La ninas are shown.

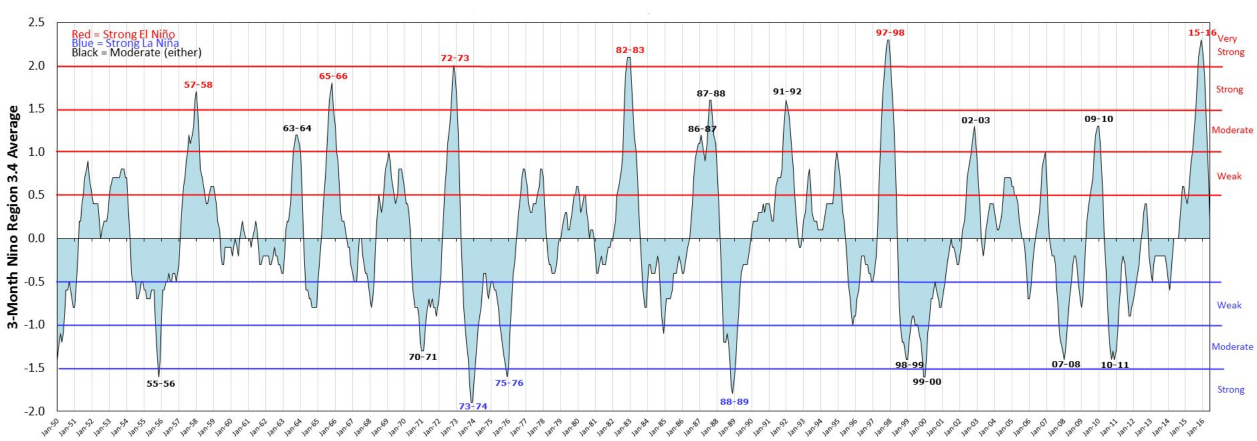


Figure A.4: Historical data about the magnitude of ENSO

El Nino and La Nina have a global impact on seasonal precipitation and temperature structures. In South America El Nino is often related to drought periods and La Nina to periods with large amounts of precipitation.

The last El Nino in Colombia affected 5.5 million people by dry conditions or drought until May 2016. Agricultural production, rural employment, household income and food access experienced significant impact negatively influencing vulnerable populations. Apart from that water quality and quantity affected rural areas. The Magdalena River also experienced a decrease in water level [UMAIC and OCHA, 2016].

The last El Nina in 2010 and 2011 affected 4 million Colombians causing an economic loss of approximately US $7.8 billion. This lost was related to devastation of infrastructure, flooding of agricultural land and subsidies paid by the government [Hoyos et al., 2013].

Appendix A.3. Government and Economy

The Republic of Colombia, named after the explorer Christopther Columbus, is independent since 20 July 1810. The current president is Juan Manual Santos (since 7 august 2010) who just started his second 4-year term.

Colombia depends heavily on energy and mining exports and is the world's fourth largest coal exporter and Latin America's fourth largest oil producer. Declining oil prices have resulted in a drop in government revenues. In 2014, Colombia passed a tax reform bill to offset the lost revenue from the global drop in oil prices.

Appendix A.4. Electricity network

Colombia has an energy market with an independent system operator. Within the energy market, power generation companies, like hydroelectric powerplants, buy and sell energy within a regulatory framework of the market. This framework is established by the Energy and Gas Regulatory Commission (CREG) [Bachra et al., 2015].

The Colombian electricity sector uses the so-called one-day-ahead market. Contracts are made between seller and buyer for the delivery of power the following day. A buyer, typically a utility, needs to assess how much energy (volume) it will need to meet demand the following day, and how much it is willing to pay for this volume, hour by hour. The seller, for example the owner of a hydroelectric power plant, needs to decide how much he can deliver and at what price, hour by hour. 4:00 pm is the deadline for submitting bids for power which will be delivered the following day. The market determines prices. The next day, power contracts are physically delivered, meaning that the power is provided to the buyer, hour for hour according to the contracts agreed.

Hydroelectric power accounts for 67% of the total consumption in Colombia, despite the problems associated with this source of energy such as protests at construction sites and a risk of guerrilla attacks. A main advantage of Hydropower is the ability to manage the power network by quickly responding to the peak demands on a day[Opperman et al., 2014].

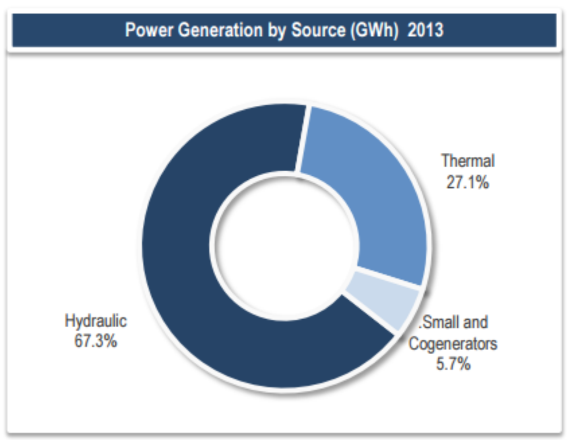


Figure A.5: Distribution of power generation in Colombia

Appendix B

Environmental analyses

Appendix B.1. Fish

B.1.1 Introduction

The fishing activity in the ciénaga El Llanito is reduced by 70 percent; over 20 tons will no longer be sold, this affects 1200 fishers [Bibiana Duarte-Abadía, Rutgerd Boelens and Roa-Aven
The men in El Llanito are depended of this fishing activity, since all the men become fisherman's. In this chapter information will be given about the important fishes in this area, the way the fish cycle interacts with water levels and river discharges. The fisherman also have to the deal with the regulations and prohibition about fishing in the area, which makes the people's food security uncertain. ISAGEN is aware of this problem and started a discussion with the fisherman community Asopesamm. Together they came up with the plan to build an artifical cano and a summer dike in cano El Deseo.

B.1.2 Support of ISAGEN

The ISAGEN report [Isagen, 2015c] states that the goal of stocking 20 million was met with 19 million in the lower Sogamoso and 1 million in the reservoir. During the first two years of the power plant, ISAGEN will stock another 10 million additional fish downstream from the site. They supported families who use the Sogamoso River for fishing by providing educational programs like fish-farming and raising broiler chickens. The goal is to support the 1430 families downstream of the dam by setting up 200 production units.
Besides the social help that ISAGEN offers they are going to build a new artifical cano, that can add more water from the Rio Sogamoso into the ciénaga El Llanito.

This new cano has 9 gates which can release a maximum discharge of 30 m^3/s. The two earlier build artificial cano's are planed to be closed, where a summer dike is going to be build in 2017. With these changes ISAGEN and Asopesamm wants to control the water level in the ciénaga El LLanito. Where the goal is to have a minimum water level of 2 meter in the ciénaga. At this moment it is uncertain which party is going to control the new cano.

B.1.3 5 important fish species in Rio Sogamoso

In the report of Anglica Ramirez and M.Sc Gabriel Pinilla, from the National University of Colombia in 2012, the five important fish species in the Rio Sogamoso were investigated. For each specimen the length, weight, the gonadal status, the coefficient of vacuity and the importance of each food category is defined.
In table B.1 there is an overview of the important fish species of the Rio Sogamoso. The measurement locations of the report can be found in figure B.1. For the rest of this report, the focus will be lied on the Bocachio fish. This fish is as mentioned earlier, sensitive for changes in the environment and it is a fish that is important for the fisherman.

Fish Specie	Information
Bocachico (Prochilodus Magdalenae)	Greatest abundance in the river during dry season and the beginning of spawning was recorded in December. Its vacuity coefficient was high and its diet was based on organic matter.
Pimelodus Blochii	Greatest catches in December; diet was based on insects and fish.
P.grosskopfii	Greatest catches in December; diet was based on insects and fish.
Loricariids Chaetostoma	In the middle and upper reaches of the river. The reduction of Rio Sogamoso flow may decrease their habitats and limit the connection to the tributaries trough which they migrate
Sturisoma aureum	In the middle and the upper reaches of the river

Table B.1: Overview of 5 most relative fish spieces in the Rio Sogamoso

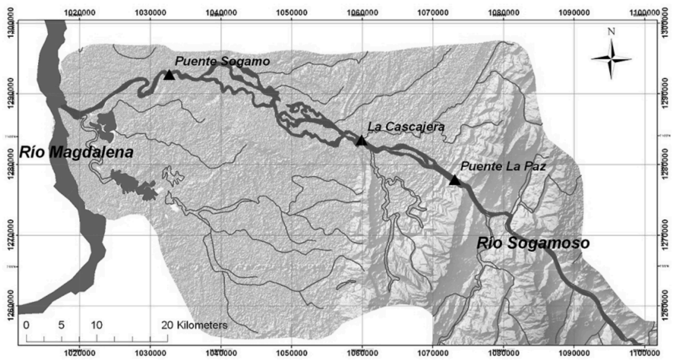


Figure B.1: Location of measurements in Rio Sogamoso

B.1.4 Correlation between rainfall, water level and Ichthyoplankton

Most tropical rivers subject to a single-yearly flooding, migratory fish usually spawn in the onset of the flooding and larvae drift to their nursery habitats. The reproduction of migratory fish species are influenced by the water level and the nursery areas in floodplain lakes [L. F. Jimenez-Segura J. Palacio, 2010]. The important fish species like the Pseudoplatystoma magdaleniatum and the Prochilodus Magdalenae (Bocachico) spawn twice a year in the main channel and its larvae input into the floodplain lakes are not always associated with flooding. Spawning in the main channel and larvae inputs into the floodplain lakes suggest that the habitat used by the migratory fishes may be consistent with some hypotheses on habitats used by these fishes.

Tropical floodplain rivers which are subject to a single annual flood pulse, migratory fishes normally reproduce during flooding in the main river channel. These floodplains can provide sheltering and food. There are a lot of rivers with an annual flood pulse but the Magdalena River is one of the rare rivers with an two-yearly flooding. The Cienagas around the Magdalena River are used as a floodplain for the larvea. The fish migrate in the main river, reproduce in the flooding season and their larvae drift to the floodplain lakes for feeding and growing.

In figure B.2 you can see two low water periods, one from December-March and July-September. During December and March there is no local rainfall, so the lakes water level is low and the first river floods can easily reach the lakes. During the other low water period, there is local rainfall, so the water level of the lakes is high and the water discharge to the Magdalena river increases. The Magdalena Rivier is also flooding, however the input to the floodplain lakes is minimal due the high

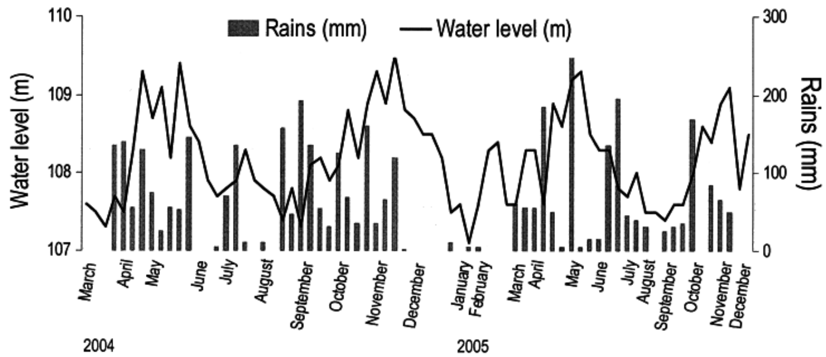


Figure B.2: Weekly rainfall and Magdalena River water level at the Puerto Berrio during 2004 and 2005 [L. F. Jimenez-Segura J. Palacio, 2010]

water level of the lakes. In figure B.3 the two cycles are defined, which show four hydro-periods of river water level (rising, high, lowering and low). It is interesting to compare these hydro-periods with the behaviour of fishes.

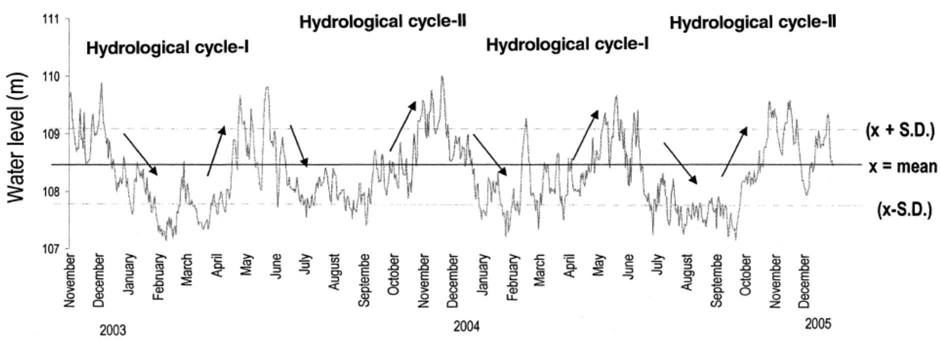


Figure B.3: Hydrological cycles and periods of sampling in Magdalena River. Blak arrows shows the transition periods (rising and lowering water level) to high or low waters [L. F. Jimenez-Segura J. Palacio, 2010]

Ichthyoplankton are eggs and larvea of fish. They are usually found in the sunlit zone of the water column. The Ichthyoplankton is planktonic, meaning it cannot swim effectively under their own power, but it is mostly drifted by currents. The eggs phase is the first stage and the larvae has multiple stages were in the last stage the larvae can swim better. For the Bocachico fish, the egg phase is around 15 hours and the larve phase is around 28 days. During the low periods of the Magdalena river, the migration of the fish starts, were it ends around the start of the rising phase. The rising phase of Magdalena therefore goes together with the density of the Ichthyoplankton. In figure B.4 the density of the plankton can be found. It can be seen that during the rising phases of the Magdalena river, the Ichthyoplankton density has high values. The trend of figure B.4 can be assumed to be the same as for the Rio Sogamoso.

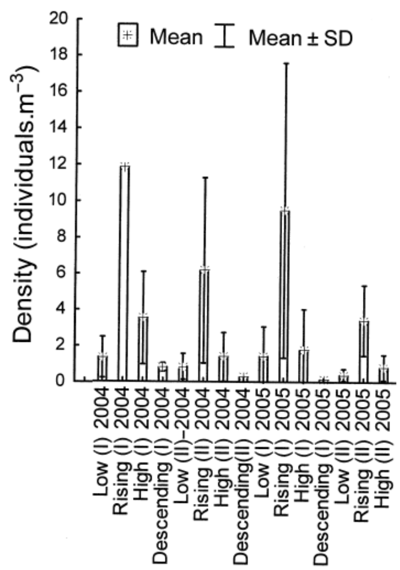


Figure B.4: Ichthyoplankton density ($ind * m^{-3}$) in the Magdalena River during hydro-periods in 2004 and 2005 [L. F. Jimenez-Segura J. Palacio, 2010]

B.1.5 Behaviour of Ciénagas

To know more about the behaviour between the ciénaga El Llanito and the Rio Sogamoso, another report from 2004 about the Ayapel ciénaga and the San Jorge river [?] is used. The correlation between weight and length of fishes can show information about the fish species in the area where they live. The Ayapel is a 45 km^2 swamp. This swamp has also a two-annual flood pulse, where the results of the report show that there is a significant difference in fish sizes between the hydrological periods. With this report as a background, we assume that the correlation between the rising water period in the river and the high amount of Ichthyoplankton are the same for the ciénaga El Llanito and the Rio Sogamoso.

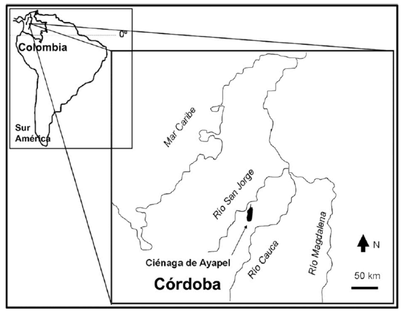


Figure B.5: The Ayapel ciénaga and the San Jorge river [?]

B.1.6 Fish Cycle

To explain the phases of the fish cycles, the information of the previous section is used. Adult fishes that are ready to expand migrate around January and February. During the rising of the water level in the water level, this migration takes place. The level of Ichthyoplankton (eggs and larvea) rises in the river. When the water level in the river is high, the Ichthyoplankton floats to the floodplains and the side canals of the river. Via these two routes they float into the ciénaga. In the ciénaga it developes from a larva to a fish, it takes around 28 days for the Bocachico fish. When the fishes are still not fully developed, they leave the ciénaga to the river. This happens when the water level in the river is low again. Therefore it is important that there is a connection between the ciénaga and the river during the low water phase of the river. Blocking the canal from the ciénaga to the river has a significant effect on the cycles. The young fishes, which are not interesting to catch, will not reach the river and will not migrate. The planed summer dike which is going to be build in the cano El Deseo still gives the fish an opportunity to go from the ciénaga to the river. With the summer dike the outflow from the ciénaga to the Rio Sogamoso is reduced during low water level in the river. With the new artificial cano it is possible to maintain an higher water level.

B.1.7 Interview local fisherman El Llanito

According to a 40 year experienced fisherman in El Llanito, a low water level in the ciénaga makes it easy to catch fish. During high water levels in the ciénaga, the fish are going to find shelter in the banks, where it is much harder to catch. He is unsure whether the new artificial cano is going to help him to catch more fish. 'The cano will increase the water level in the El LLanito and there will be a higher minimum

but it will be harder to catch the fish', according to the fisherman. The idea of the cano and the summer dike is founded by the fisherman community and unfortunately this idea is not tested by an model. With this report a start is made to understand the influences of the cano and the dike, which also can be used to know when it is better to open or close the cano.
However, the conclusion whether the new cano is going to increase the population of fish is still unknown. Therefore a different study is necessary, where this report can support the hydraulic part of that study.

Appendix B.2. Floods

"An overflow of a large amount of water beyond its normal limits, especially over what is normally dry land" [press, 2016] states the definition of a flood. Floods may occur in coastal areas, along river-systems or in urban areas and are often related to catastrophic event. Apart from a threat, floods can also be a resource for ecological systems. Flooding of low lying areas provide the dynamic balance for flora and fauna in many parts of the world. If one focuses on rivers floods, they are responsible for the connectivity of rivers with their surrounding area. The connection between the river main channel, floodplain and groundwater give rise to different floodplain habitats in space and time, leading to high biodiversity [Bunn and Arthington, 2002]

B.2.1 River-floodplain system

The river-floodplain system of the Sogamoso river contains the main river and the surrounding floodplains. Within this system one can distinguish the cienega as a seperate element, providing a fishing area for the people living in the surrounding villages. In a river-floodplain system the principal process that is responsible for the origin and keeping them alive is the fact that there is a dynamic interaction between water and land in lateral direction [Bayley, 1995]. In river systems this interaction is caused by flooding of the river. In several studies the flood pulse concept (FPC) is used to describe the effect on the flora and fauna in river-floodplain systems.

Flood pulse concept

The flood pulse concept stresses that the flood pulse is the most important driving force responsible for the existence, productivity and interactions for flora and fauna in large River-floodplain systems. The flood pulse is the annual pulsing of the river system causing the lateral exchange of water between the main channel and the floodplains. The flow regime of the annual pulsing depends on the hydrological climate causing the discharge regimes in rivers.

Intermezzo: Floodplain

Areas that are periodically inundated by the lateral overflow of rivers or lakes, and/or by direct precipation or groundwater; the resulting physicochemical environment causes the biota to respond by morphological, anatomical, physiological, phenological, and/or ethological adaptions, and produce characteristic communicty structures

Often the floodplains are also referred to as aquatic/ terrestrial transition zone (ATTZ) because the floodplain shifts between the aquatic and terrestrial environments. In the proceeding however the River-floodplain system is distinguish with the main channel en the floodplains. The main channel and floodplains can vary over both space and time in a system under the influence of different hydrologic conditions.
The life cycles of flora and fauna within the floodplains depends on the timing of the flood pulse in terms of the annual timing, duration, and the rate of rise and fall (Junk1989).

B.2.2 Flow regimes

Recognized by many ecologists is the influence of flow regimes on river-floodplain systems. Since the floods are gone and the flow is regulated by the dam the natural flow is altered Four principles can be distinguished to show the influence of flow regime on aquatic biodiversity. In figure B.6 an overview of the four principles is given.

"principle 1: Flow Is a Major Determinant of Physical Habitat in Streams, Which in Turn Is a Major Determinant of Biotic Composition" [Bunn and Arthington, 200
The interaction of the flow regime and the local geology determines mainly the shape and size of the river channels,the floodplains and the stabillity of those. These characteristics on their turn can be related to organisms ranging from algae and aquatic plants to invertebrates and fish [Bunn and Arthington, 2002].
Examples of flow characteristic influencing the downstream part of dams including: high peaks causing to large shear resistance for organism, long time of base flow

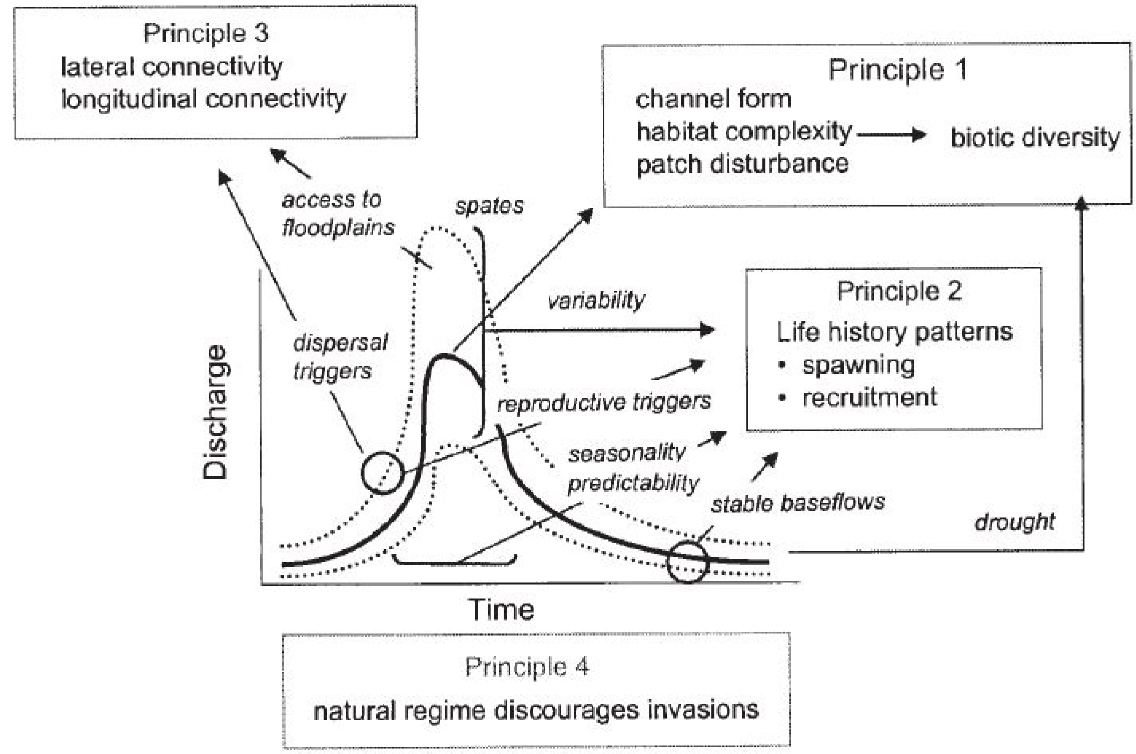


Figure B.6: Aquatic biodiversity and natural flow regimes

and rapid changes in flow. In general flow, temperature, sediment transport and vegetation dynamices are the characteristics influenced regarding principle 1.

"principle 2: Aquatic Species Have Evolved Life History Strategies Primarily in Direct Response to the Natural Flow Regimes" [Bunn and Arthington, 2002]

Aquatic plants, fish species and other aquatic biota in area with highly variating flow regimes have adapt there life cycle on it. Apart from hydraulically dependence on the regime, temperature is also a important parameter in this story. Often the flow regime is related to a certain temperature regime. When the flow regime is artificial this is often together with a shift in the thermal regime. Since biota uses this thermal regime to determine there life cycle this can be highly influenced.

"principle 3:Maintenance of Natural Patterns of Longitudinal and Lateral Connectivity Is Essential to the Viability of Populations of Many Riverine

Species" [Bunn and Arthington, 2002]
In river-floodplain system building of dams and their associated regulated flow regimes usually reduces the longitudinal and laatteral connectivity. Typically hydraulical characteristics with dams are: dampended peaks, reduced frequency of peaks, dry floodplains. This can cause lower bio-diversity in the longterm.

"principle 4:The Invasion and Success of Exotic and Introduced Species in Rivers Is Facilitated by the Alteration of Flow Regimes" [Bunn and Arthington, 2002]
This principle states that other species who are in their native environment are used to the new flow regime can servive in the new situation and can replace the native species adaptod to the old regime.

B.2.3 Agriculture/land use

Floods have a influences on the agriculture/land use of the people living around the Sogamoso river. Area's who are regular flooded will not be used by people to live on. Furthermore will areas that are often flooded cause groundwater flows which are positive for agriculture. Since the floods in the Sogamoso river are dissapeared these two aspects are negatively influenced.
People tend to illegally start to live in the areas which were usually flood. This because they need the river and since the water level is constant low they moved towards the river.

B.2.4 Fish

Fish species living in the main channel use the temperate floodplains for recruitment, spawning and food. They developed a life history pattern depending on the alternating flow pattern of the river [Bunn and Arthington, 2002]. During the rising period of the floods the spawning of many fish species takes place. In this period they feed and seek shelter in the temporary floodplains. When the floods reduced and the water level drops the fishes return to the main channel, tributaries or in remaining parts of the floodplain [Junk, 1989]. In the river-floodplain system of the river Sogamoso the cienga El Llanito may be one of this permanent remaining floodplains. In B.1 the life of fish in rivers and cienegas is discussed in more detail.

B.2.5 Flow regime before/after Dam

Since the dam is build in the Sogamoso river the floods are not anymore naturally occurring in the river. This fact has influence on the floodplains along the river of the Sogamoso river and the Cienega El Llannito. before the dam was build the floods were occurring mainly during the two rainy seasons. Now this floods are not there anymore. The flora and fauna of the downstream part of the dam may be negatively influenced in an ecological perspective. Apart from this hydraulically influence the building of the dam and the absence of the floods have influence on the morphological character of the river.

B.2.6 Restoration river-floodplain system

According to [Stanford et al., 1996] the general consequences of an artificial flow regime is a dis-continuum of environmental conditions and the disconnection of the elements of the river-floodplain system. The components becomes spatially the same because of the limited pulse regulated by the dam operation.
Parameters including in this process influencing each other are displayed in figure B.7.

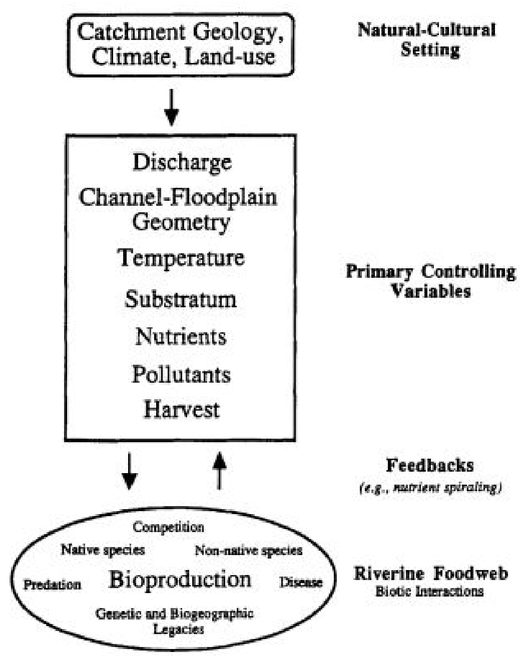


Figure B.7: Primary controlling variables and biophysical interactions of river ecosystems

The restoration regarding the FPC is based on reintroducing the flood pulse. The success of this reintroduction is based on the reconstruction of the flood pulse with respect to duration, timing, diversity of flood processes and unpredictability [Tockner et al., 2000]. To do this all the processes regarding to the parameters which influence each other have to be understood.

B.2.7 Conclusion

Floods are of significant value for river-flood plain systems such as the downstream part of the Sogamoso river. None of these systems are the same and are complex systems with many parameters interacting with each other. The flood pulse concept described a way of looking at this systems and stresses out several framework to restore river-flood plain systems by restoring the flood pulse.

Appendix B.3. Sediment

B.3.1 Sogamoso basin

Many studies have been performed for the Magdalena basin. In figure B.8 the total Magdalena basin is shown. Each circle with a number represents a sub basin. The Sogamoso river flows with a single meandering channel into the Magdalena river and adds a quarter of the total flow of the Magdalena river. The Sogamoso river and its connection with the magdalena river is given in a close-up. The Sogamoso river originates from three sub basins, indicated with numbers 27, 28 and 29 which respectively represents the Suárez basin, Fonce basin and the Sogamoso basin. The Sogamoso river is of great importance for the Magdalena river as it is the largest supplier of sediment into the Magdalena river. At the confluence of the two rivers a large divagation zone is present which leads, together with the large sediment load, to sedimentation. [Yossef, 2014] This large sediment load in the Sogamoso river is mainly present due to an increase in mining & deforestation activities together with a large natural run off and peak water discharges.

Mining and deforestation

Mining is a main export product in Colombia. Colombia has the largest coal reserve in Latin America and is producing the most of the worlds emeralds. In the Sogamoso catchment a large increase in mining activities of marble and emerald is present at the year 1990. Together with an increase in deforestation due to population growth and urbanization this has led to a highly erodible area, stated by IDEAM, of 86% of the Sogamoso riverbanks. This is also observed during our field trip, the banks of the Sogamoso river are mostly vertical walls of 1-1.5 m high composed of very fine material, see figure B.9. In figure B.10 the cumulative monthly averaged sediment loads in the Sogamoso river, normalized with the long term cumulative averaged sediment loads, are given. A decrease in the sediment flux means that the monthly sediment load is smaller than the long term monthly averaged sediment load. After the 1990 the sediment flux steadily increases, which means that the monthly

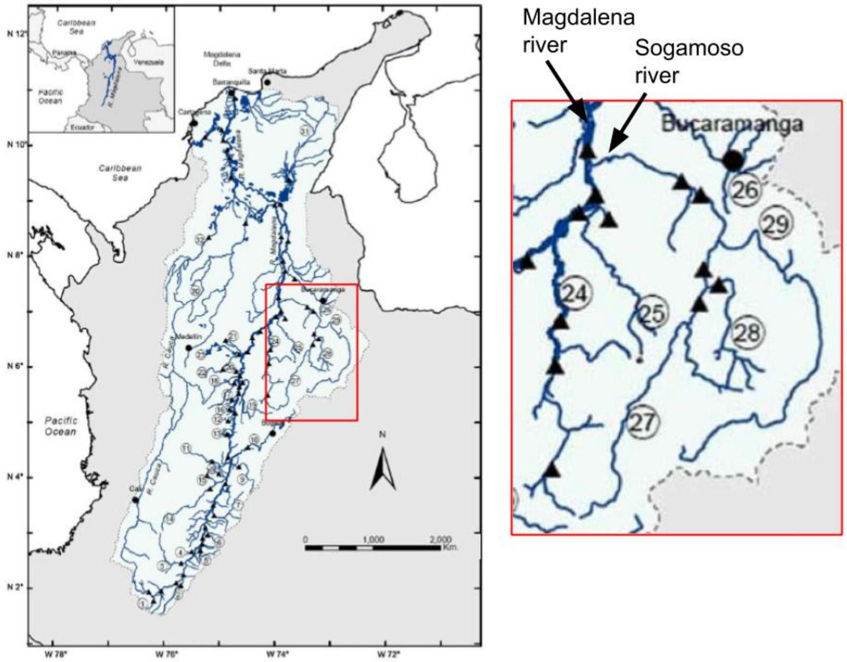


Figure B.8: Magdalena basin - Close-up Sogamoso river

averaged sediment load is larger than the long term monthly averaged sediment load. [Kettner et al., 2010].

Figure B.9: Highly erodible bank observed during field trip

B.3.2 Importance of sediment in the Sogamoso river

Amount and type of sediment

The amount and type of sediment in a river is of great importance for the behaviour

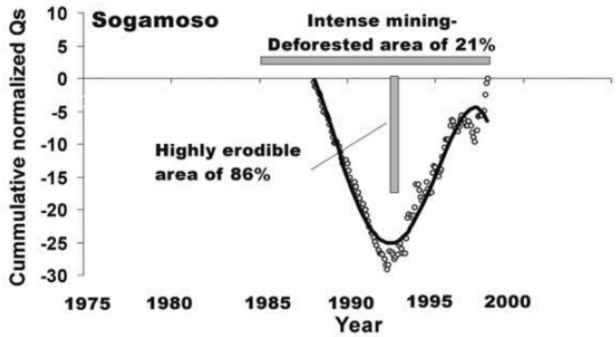


Figure B.10: Cumulative normalized sediment load in the period 1975-2000

of the river. If there is to less sediment in a river it can start eroding the bottom or the banks of the river. Erosion of the bottom can lead to a change of the navigation channel. Erosion of the banks leads to a loss of area that can be used for agriculture, housing or farming.
If there is to much sediment in a river this sediment will settle at the border or the bottom of the river. Sediment deposits on the bottom can be negatively for the navigability in the river. In the Sogamoso river many fisherman fish during the night because of the lower water level that makes it easier to fish, it regularly happens a fisherman crashes into such a new island and gets injured. On the other hand these islands can be good for ecological purposes because of birds nesting there.

If a river consists of fine or rough material is depended on the availability of the sediment type and the velocity in that part of the river. Rough sediment is heavier and thus falls with relative larger velocities on the bottom. Whereas fine sediment is very light and thus needs very calm water to be able to settle on the bottom. Fine sediment mostly consists of organic material, which has cohesive forces holding the soil together. Rough sediment like sand or gravel consists of particles that are held together by it's internal friction. When during a flood fine sediment is deposited somewhere and this sediment becomes dry during low water, it will take a long time before all the water has escaped the sediment. Because this water stays in the open spaces of the sediment no plants are able to grow on it. Therefore during a next flood the sediment can easily be picked up and transported somewhere else. This is different for coarser sediments, the water can easily exit after the water level has decreased such that plants can start growing on the deposited sediments which will lead to a stronger cohesion of the soil. Therefore its possible that during a next flood the deposited sediment will stay on its place and new sediment is added, such that islands can be created.

Dynamic behaviour of the river
Water is flowing the path of the least resistance. Because of this property the location of a river changes a lot over time. Small changes can occur due to a local structure or object in the river. Large changes can occur for example due to changes in sediment load, type of sediment or water discharge. Because the characteristics of a river, with little or large influence, are almost always changing faster than the time the river needs to adjust, a natural river is continuing changing its course.

B.3.3 Soil type

Based on soil map
The type of soil present in the Sogamoso river, ciénaga Llanito and it's connecting caños differs a lot. In figure B.11 a map of the different soil types in the area of interest is given, based on a global soil map of Colombia. [Arcgis, 2016]
RVAa stands for: sandy loam, silt loam, silty clay
RVCa stands for: silty clay loam, silt loam, silty, clay loam
From figure B.11 it can be observed that the water is flowing at the area containing the RVAa soil. In figure B.12 the percentage of sand, silt and clay can be found for every soil type. This shows that the Sogamoso river and the caño San Silvestre are flowing at the area containing more sand. The ciénaga El Llanito is located at a swampy area.
Based on measurement Isagen
Isagen has measured the median grain size (D50), which is the grain diameter for which half the sediment is larger and the other half smaller, in several sections for the years 2014 (December) and 2015 (August) [Isagen, 2015a]. In figure B.13 the locations of the measurements are shown. Location 1 is at Puente Sogamoso, location 2 is in the Sogamoso river, location 3 is located at the bifurcation of the caño San Silvestre with the Sogamoso river and the location 4 is located near the confluence with the Magdalena river.

Based on own measurement
During the field trip sediment samples were taken, see Appendix B. In total three sediment samples were analyzed, one in the ciénaga, one at the bifurcation of the caño San Silvestre with the Sogamoso river and one at Puente Sogamoso. The results are obtained by using a Malvern Mastersizer 3000E, see figure B.15.

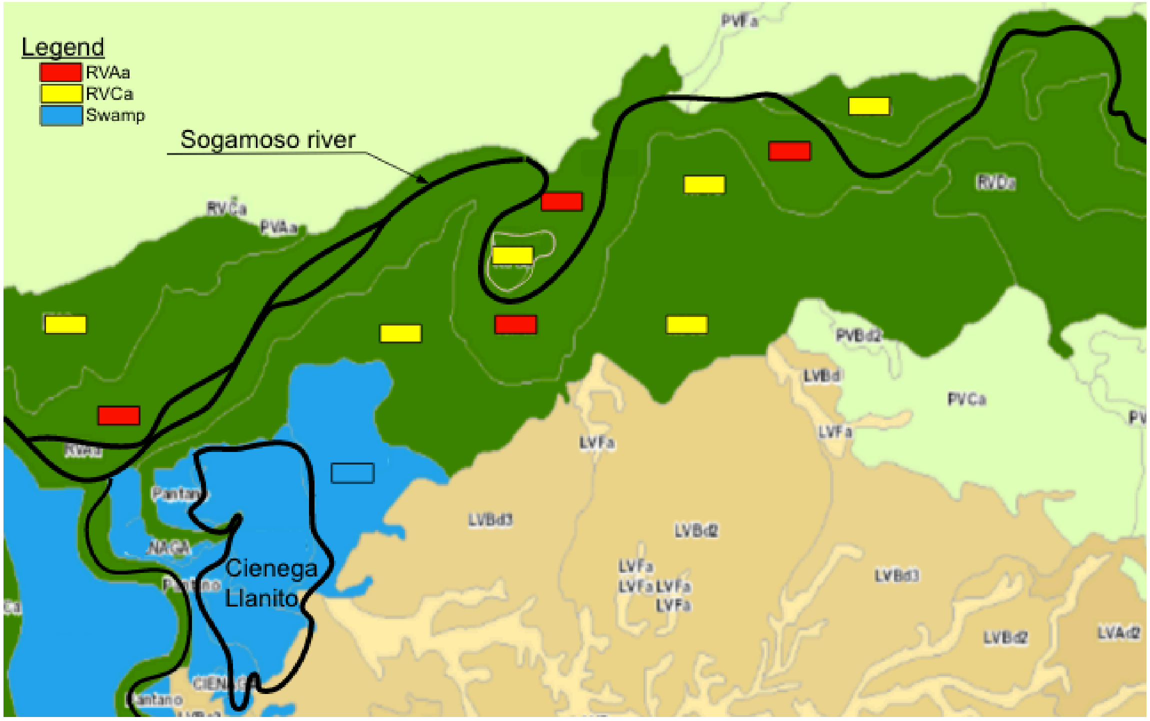


Figure B.11: Soil map

It can be observed that the grain size in Puente Sogamoso has increased a lot from 0.18 mm in 2014 to 0.6 mm in 2016. In the downstream part of the Sogamoso river the grain size is increasing. At the bifurcation the grain size decreased between 2014 and 2015 but increased in 2016.

B.3.4 Sediment loads

In figure B.16 the annually averaged sediment load in 10^3 tons/day are given of the entire flow of the Sogamoso river into the Magdalena river for the years 1989-1998 [Restrepo, 2005]. As explained in the previous section the influence of the mining and deforestation is clearly visible after the year 1992.
Isagen has measured in December 2014 and August 2015 the total sediment load of the locations given in figure B.13. These sediment loads are obtained using the sediment transport model of Toffaletti.

Figure B.12: percentage of sand, clay and silt

Figure B.13: Measurement points Isagen

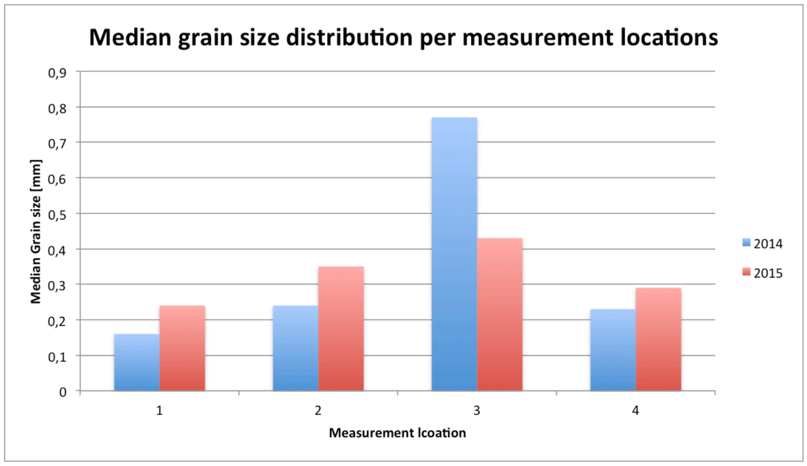


Figure B.14: median grain size distribution per location

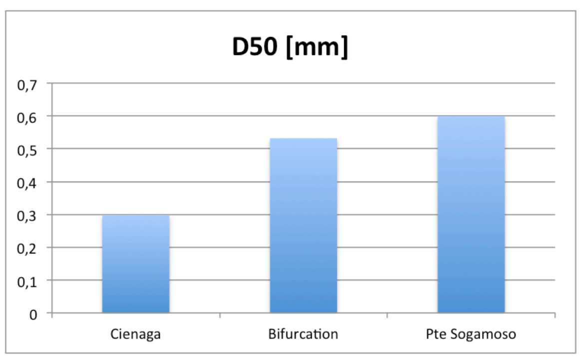


Figure B.15: D50 of sediment samples

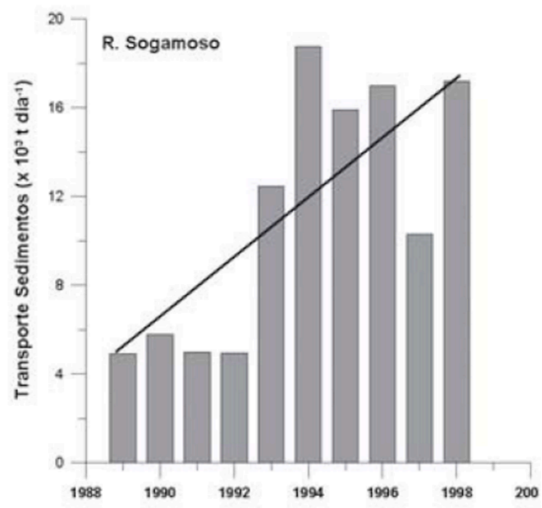


Figure B.16: Annually averaged sediment transport of Sogamoso river

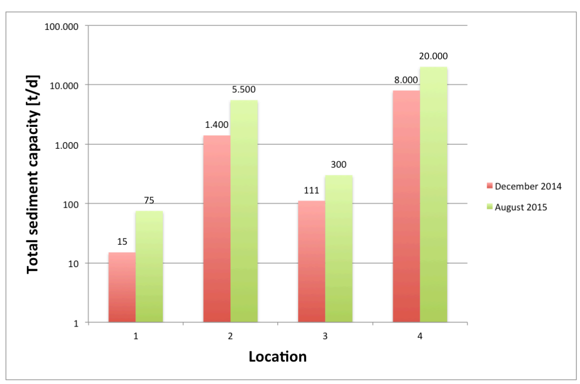


Figure B.17: Sediment load [t/d] per location

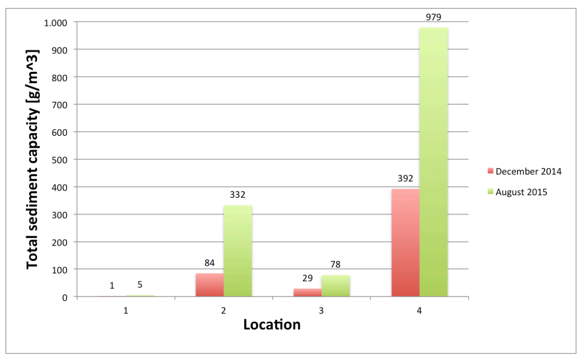


Figure B.18: Sediment load [g/m^3] per location

Appendix C

Fieldwork

Appendix C.1. Introduction

To model the area of interest new data was required on specific locations as the caños for example. In the 3th week of September several measurements were made in the Rio Sogamoso, Ciénaga El Llanito and different caños. In this chapter is described which and what measurements are made and which information is used for the model. Besides the measurements during the fieldwork also interviews were held with the fisherman, the fish community, Cormagdalena and ISAGEN. These interviews gave a good insight about the different interests of these actors.

Appendix C.2. Overview measurements locations

In figure C.1 and figure C.2 an overview is given of the locations of measurements. The measurements were made in two different boats during the three consecutive days. At the reference points the water level is measured, so the measured water depth can be referenced to XYZ coordinates.

C.2.1 Measurement methods

C.2.2 ADCP

An Acoustic Doppler Current Profiler (ADCP) is used to measure how fast the water is moving across an entire water column. The ADCP measures water currents with sound, using the principle of sound waves, which is called the Doppler effect. A classic example of this effect is when a car passes by with a characteristic building

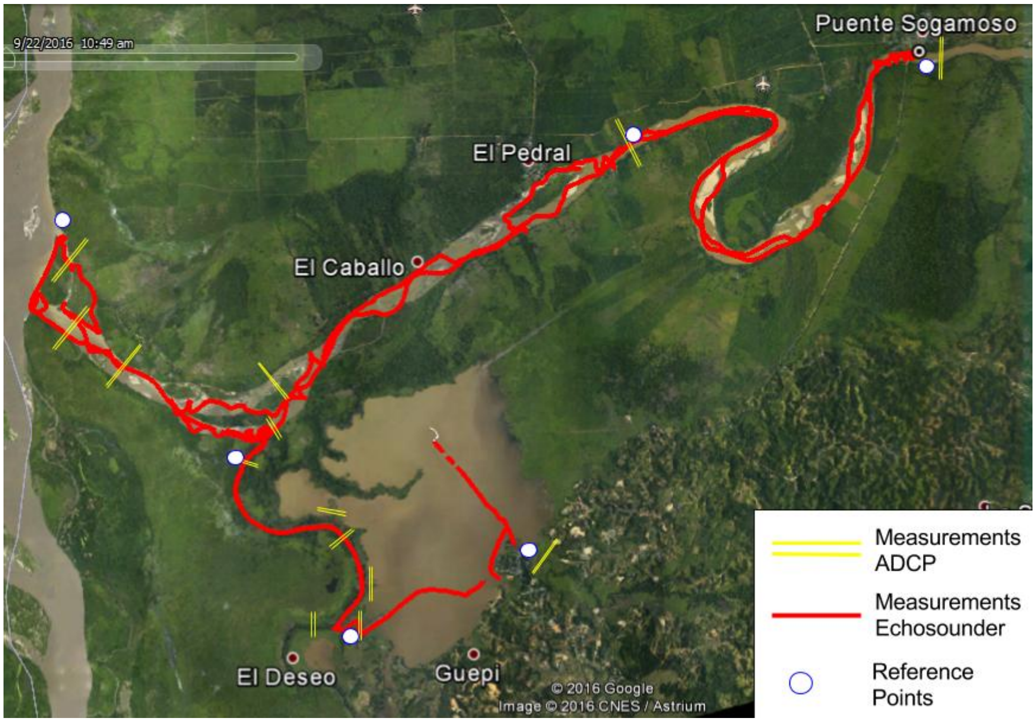


Figure C.1: Location of measurements in area of interest

of sound that fades when the car passes. By transmitting 'pings' of sound at a constant frequency into the water, as the sounds waves travel, they ricochet off particles suspended in the moving water. These sound waves are bounced back from the particle and the frequency is slightly lowered when it returns to the ADCP. The difference in frequency between the waves that the ADCP sends out and the received waves called the Doppler shift. The ADCP uses this shift to calculate how fast the particle and the water around it are moving. With time it takes for the waves to bounce back and the earlier mentioned Doppler shift, the ADCP can measure current speeds at different depth with each series of pings.
The have a clear result from the ADCP it is necessary that during the measurements the device is under water and that there is not to much turbulence at the downside of the device. To accomplish these requirements a construction is needed, with a curved board at the front of the device. The device worked properly because it reduced the turbulence and the results were clear, see figure C.3. For each correct measurement an minimum of 4 trips (left bank to right bank, etc) is necessary, if the standard deviation is less than 5% no additional trip is needed.

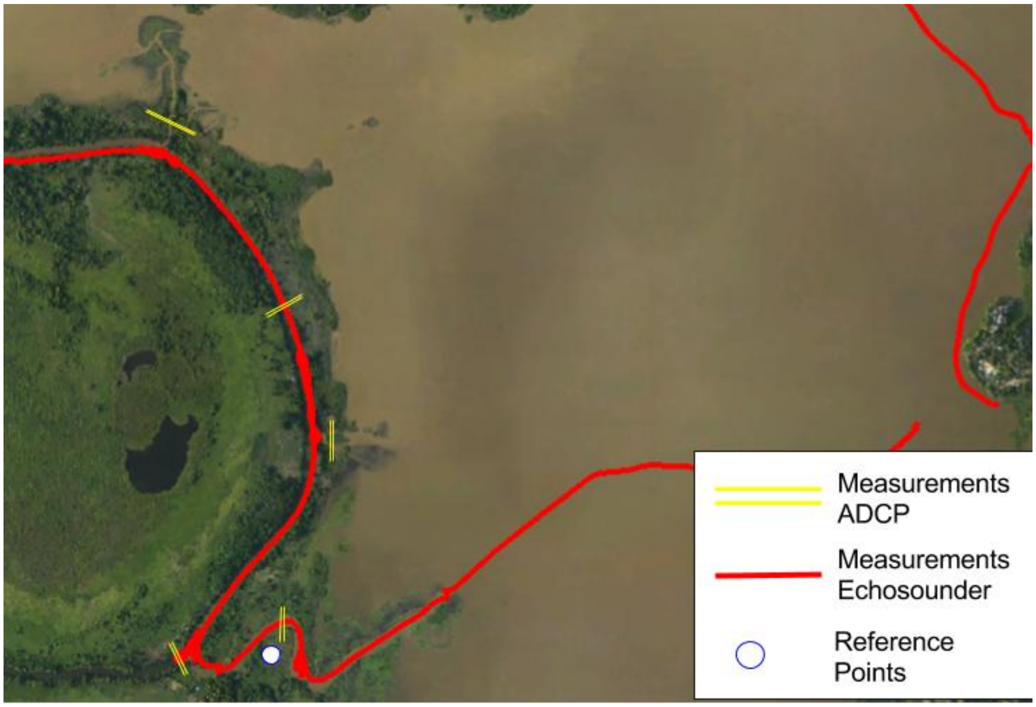


Figure C.2: Detailed location of measurements in area of interest

For the model the detailed bathymetry will be used, together with the discharges and depths. The ADCP measures many more parameters, however these measurements are not required for the model. The ADCP do not has a GPS, therefore the coordinates of the banks are written down. With these coordinates it is possible to create a line between the left and right bank, where every lines contains the bathymetry and depth. At the end, the total discharge can be used as an input for the model. An example of a the measured velocity and a bathymetry profiel can be seen in figure C.4.

C.2.3 Echosounder

Echosounders can be used to find the location of the sea bed or to look for objects such as fish. The echosounder is connected to a pole which is connect to the boat. The echosounder is held approximately 30 cm under the water surface when the boat moves around. It is transmitting a pulse of sound directly downwards from the bottom of the ship (or a pole that is connected with the echosounder). The pulse of sounds travels down trough the water, bounces off the sea bed and then travels

Figure C.3: Construction to stabilise the ADCP

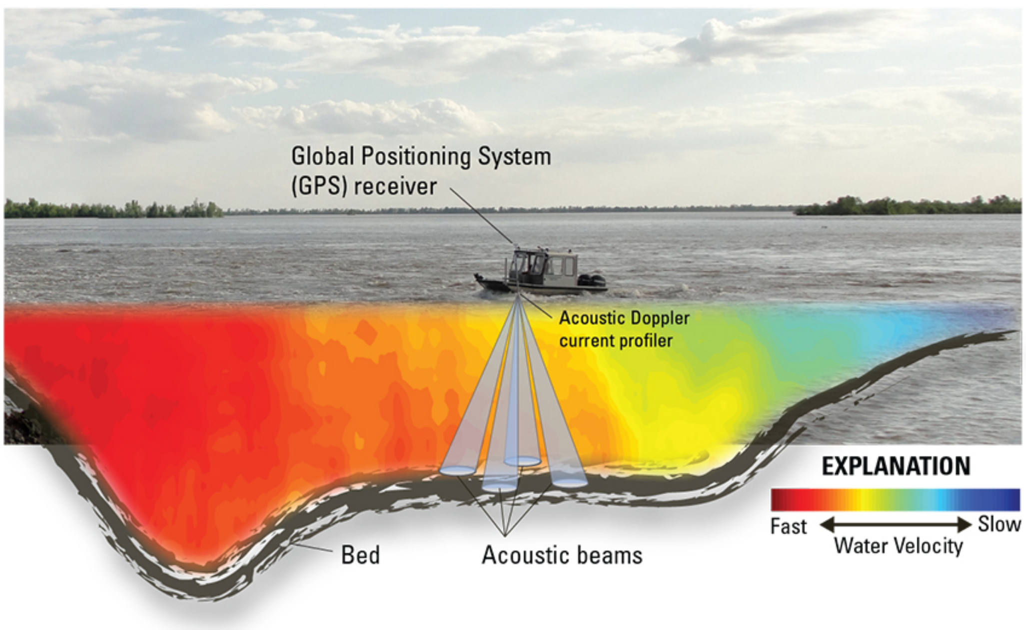


Figure C.4: Diagram of a vessel making ADCP measurements as it transects a river[Fricker, 2014] upwards until the reflection is heard by the echosounder. The device times how long the pulse of sounds takes to travel to the sea bed and back up to the ship. The water depth is calculated by equation C.1.

$$distance = \frac{time}{2} * \text{speed of sound in water} \tag{C.1}$$

The speed of sound in water is sometimes assumed to be 1500 ms^{-1}. The echosounder is included with GPS, by uploading the measurements, the track of the boat can be seen. Within this track it measures the depths during constant steps. In figure C.1 the track of the echosounder is given in red. The results were adjusted with the 30 cm, which is the distance between the echosounder and the water surface. The final outcome will be used adept the depth file of the model and create a more accurate bathymetry of the river.

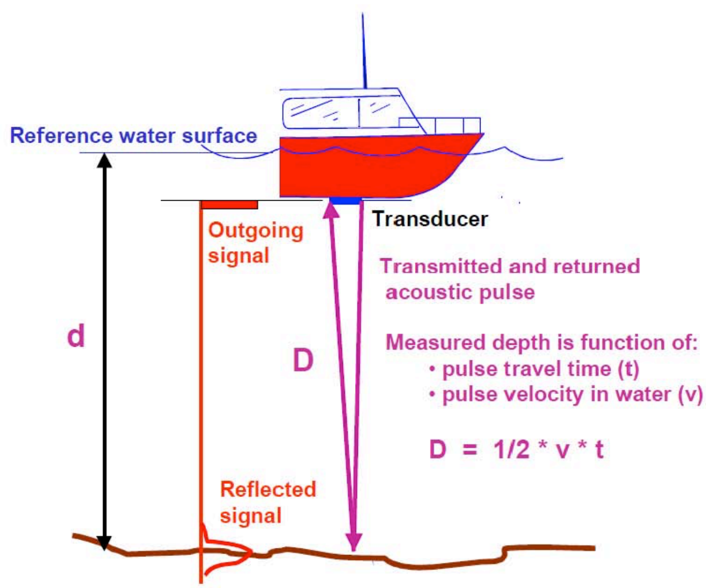


Figure C.5: Working of an echosounder [of Engineers, 2011]

C.2.4 Reference points

To create a correct depth file for the model, the data has to be referred to an elevation. By measuring the water level at the reference points, see figure C.6, the data can be referenced. ISAGEN is the owner of these reference points and will give the elevation per reference point. In figure C.1 the exact location of these points is shown.

Figure C.6: Reference points at caño silvestre

C.2.5 Van der Veen Grab sampler

The stainless steel of Van der Veen grabs are used for taking disturbed samples for the bottom of lakes, rivers or ciénagas. At the surface the jaws are pushed open and kept in that position by a hook. To keep the hook in the right position the grab should be sunk in a steady pace. The jaws have holes to allow air to escape during sinking. As soon as the jaws touch the bottom, the hook loosens its grip, when hosting the rope again the jaws will shut tight because of the leverage by the rods. The amount of sediment during a grab is dependent on the compactness of the bottom. A heavier grab catches more sediment than a light one. During strong currents, a heavier grab is recommended. In figure C.7 three different sizes of Van der Veen samplers are shown.

After collecting the samples, the grain sizes of the sediment were analysed in the laboratory.

Figure C.7: Van der Veen grab sampler

C.2.6 GPS

The Global Positioning System (GSP) is a satellite based navigation system made up of a network of 24 satellites placed into orbit by the U.S. Department of Defense. After 1980 the government made the system available for civilian use. The GPSmap 60csx (see figure C.8), manufactured by Garmin, is used to collect the GPS coordinates at the banks during the ADCP measurements. By creating waypoints, it is possible to save an exact location.
To combine the coordinates with other coordinate files like Google Earth and the echosounder, it is necessary to choose the same coordinates format. The GPS uses the coordinate system decimal degrees (latitude and longitude). Therefore the coordinates has to be converted to easting and nothings. These terms are geographic Cartesian coordinates for a point. Easting refers to the eastward measured distance (X coordinate), while northing refers to the northward measured distance (Y coordinate).

C.2.7 Water level measurements

During the measurements, water levels are measured in the ciénagas using a simple pole with a tapeline. By creating waypoints in the GPS and using these coordinates

Figure C.8: GPS Garmin 60csx

together with the water levels, an more accurate bathymetry can be created for the model.

Appendix C.3. Interview local parties

During the fieldwork trip different actors are interviewed. The following actors are interviewed;

- ISAGEN
- Fish community Asopesan
- Local fishers El Llanito
- Cormagdalena

The interview contained two parts, one was about understanding the way the water flooded during high water. The other part was about the social impact of the dam and the new solutions that are going to be build. In the stakeholder chapter these interviews are more elaborated.

Appendix D

SOBEK

Appendix D.1. Catchment area

The catchment area upstream of the Hidrosogamoso is formed by Chicamocha, Suarez, Fonce and Sogamoso river. Before the construction of the Hidrosogamoso, this drainiage network drained water to La Paz and flowed further into the downstream catchment area of the Sogamoso river. Now this water drains all into the reservoir of the Hidrosogamoso.

After the water passes the Hidrosogamoso it receives more water of other tributaries, like the Sucio river and Putana river. Further downstream, around Puente Sogamoso, the river flows through a flat zone that is rich in oil deposits, where almost no tributaries are located. For the determination of the catchment areas of those tributaries Google Earth and maps from Geographic Institute Agustn Codazzi are used.

Before the Hidrosogamoso, the discharge around Puente Sogamoso depends on the complete upstream area of the river, like normal natural rivers. However, the construction of Hidrosogamoso regulates the flow from a certain point in the catchment. The flow regime at Puente Sogamoso now depends on the operational discharge of the Dam and the tributaries between the Hidrosogamoso and Puente Sogamoso. The catchment areas of those tributaries are shown in figure D.1.

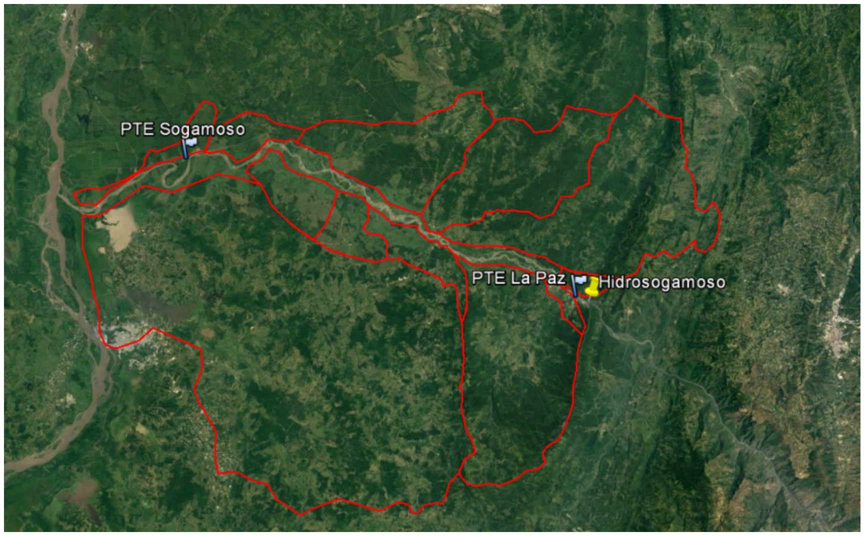


Figure D.1: Overview catchment areas downstream basin

Appendix D.2. Drainage upstream catchment

In this section the flow regimes of the upstream catchment will be analysed. The historical data of La Paz, for the years 1972 till 2009, will be used to perform this analysis. The goal is to get insights in the flow regimes in the upstream part, before the Hidrosogamoso became to regulate the flow.

The discharges at La Paz are formed by the catchment area upstream of that point, which has a surface area of 21.338 km^2. There is mad distinguish between the rainy and dry season, to see

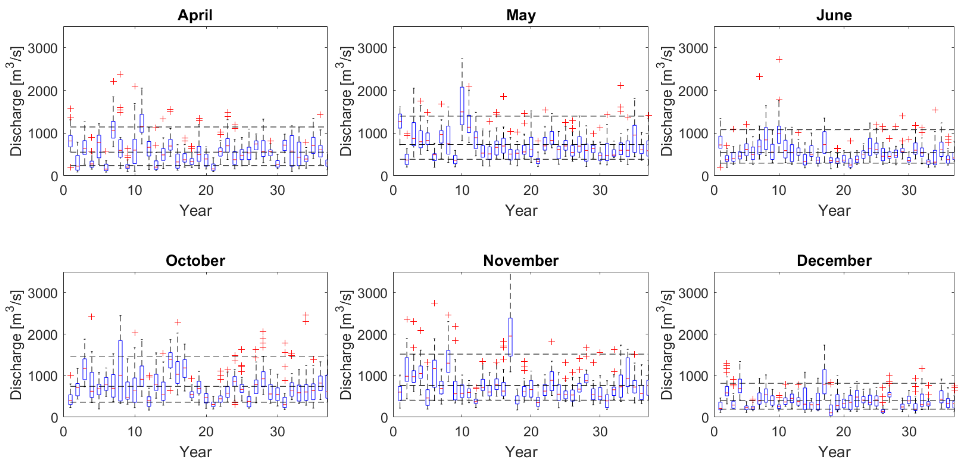


Figure D.2: Box plot of daily averaged discharges at La Paz for the years 1972 till 2009 for the months in the Rainy season

	Jan	Feb	Mar	Jul	Aug	Sept		Averaged
Maximum	430	490	670	660	640	950		640
Mean	220	220	300	390	370	480		330
Minimum	130	120	140	240	230	260		190

Table D.1: Daily averaged discharges during the rainy season for La Paz for the years 1972 till 2009 in m^3/s

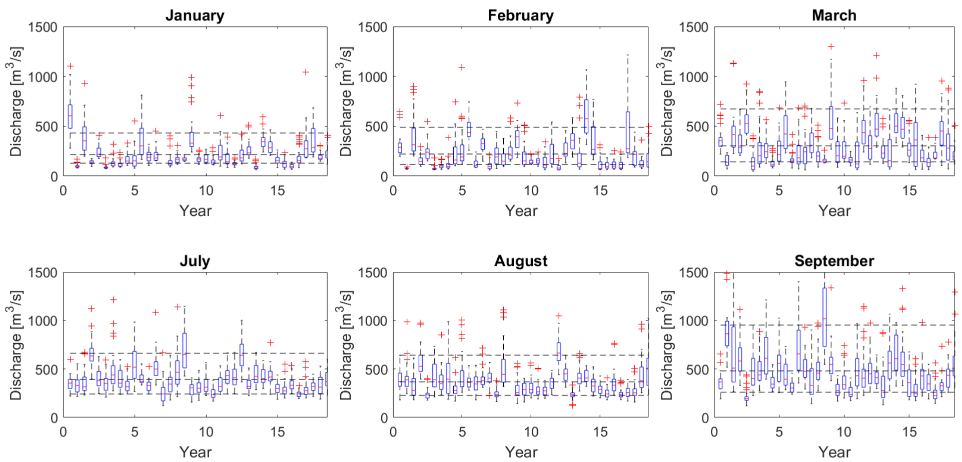


Figure D.3: Box plot of daily averaged discharges at La Paz for the years 1972 till 2009 for the months in the Dry season

	Apr	May	Jun	Oct	Nov	Dec		Averaged
Maximum	1140	1400	1080	1470	1520	820		1240
Mean	550	730	550	740	770	400		620
Minimum	240	390	300	360	410	200		310

Table D.2: Daily averaged discharges during the dry season for La Paz for the years 1972 till 2009 in m^3/s

This analysis will be used for the estimation of the discharges from the tributaries downstream of the Hidrosogamoso.

Appendix E

Delft 3D

Appendix E.1. Digital Elevation Map

A digital elevation map (DEM) is a digital map of a terrain surface. By using the NASA earth data, a map can be downloaded, which includes XYZ coordinates of the earth surface. The newest available maps, which have high resolutions, are from September 2011. This high resolution means that every 12 by 12 meter a value is given. These maps are the most accurate maps that are available for free. The elevation map of Google Earth has a resolution of 30 by 30 meters for example.
The result of this elevation map can be seen in figure E.1. The landboundary of our system is also given in the figure, which was setp-up by making use of recent satelite images. It can be concluded that the river has changed a lot from 2011 (DEM) and landboundary (2016). Therefore the DEM elevation will only be used around the ciénaga El Llanito, so that the floodplains around the ciénaga are given correctly.
In the following table, the reference water levels of important locations are given. It can be seen that there is a slope where there is approximately a altitude difference of 4 meter over a distance of 12 kilometers.

Table E.1: Water level references

Location	Reference water level [m]
Upper BC Sogamoso river	73
Lower BC Rio Magdalena	69
Upper BC Caño Silvestre	71.5
Ciénaga El Llanito	70

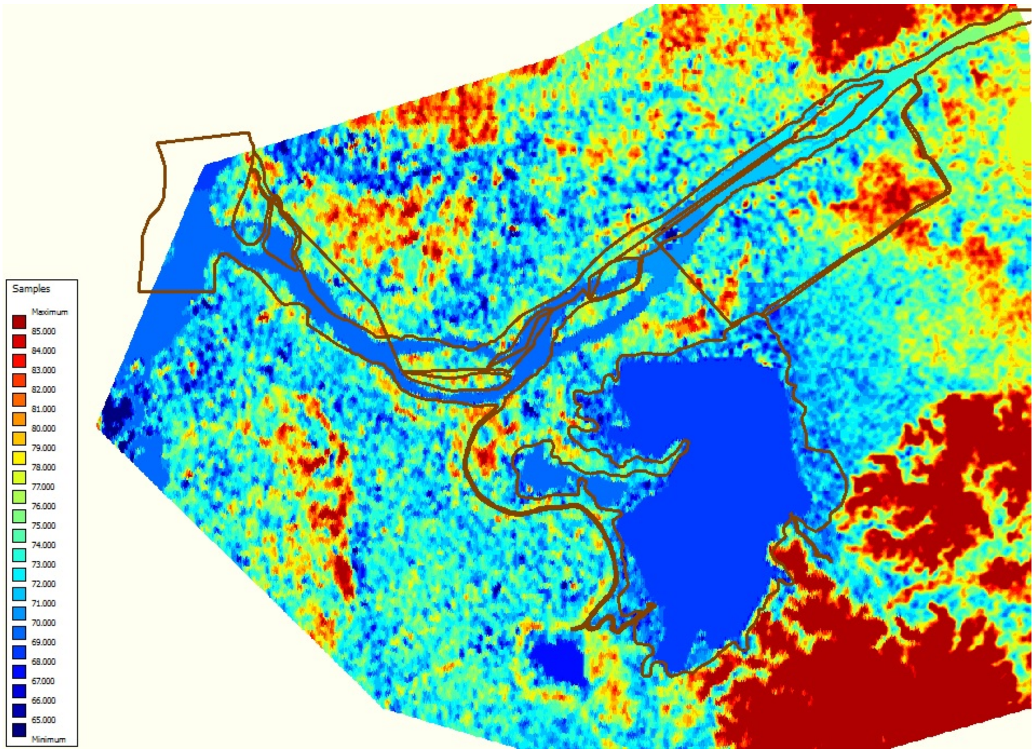


Figure E.1: Digital Elevation Map Model Area

Assumption

Because the difference between the DEM and the actual landboundaries is to large, the rivers and the caños are assumed to have vertical banks that can not flood. Without a correct DEM file, the elevations of the banks are unknown. During the fieldwork this conclusion is made. The banks are almost vertical, see figure E.2, also the local people and fishermen, said that these banks have not been flooded after the construction of the dam. After the dam was build, the high discharge peaks are eliminated and flooding are excluded.

Appendix E.2. Echosounder

During our fieldwork, measurements were done with the echosounder, see section Fieldwork. In figure E.3 the locations of the measurements with the echosounder are shown. This data contains the depth referred to a location measured with a GPS integrated in the echosounder. The echosounder was 30 cm elevated in the water such

Figure E.2: Vertical Bank Sogamoso

that it's necessary to add 30 cm to all the measured depths. First the locations are transformed to the right coordinate system. From this an .xyz file is created using notepad. For the caño San Silvestre the triangular interpolation method of Arcgis is used because there are a lot of measurements in the caño and this interpolation method is more advanced.

In the Sogamoso river less measurements are available. To avoid unrealistic depths it's chosen to use the grid cell averaging option of Delft3d. This option only adds depth values at grid cells where measurements are. By drawing polygons around the area of the Sogamoso river and using the internal diffusion option the empty cells are filled with a depth value that makes a smooth transitions between cells with a known depth value.

Appendix E.3. Coordinate systems

There are two often used geographic coordinate systems. The first one is the latitude-longitude-elevation coordinate system, this describes a location based on the equator, reference meridian and the angles between these locations and the earth centre of mass. The second coordinate system is the Eastings and Northings coordinate system, which describes the location by means of a horizontal and vertical distance from a certain reference. The Universal Transverse Mercator coordinate system has

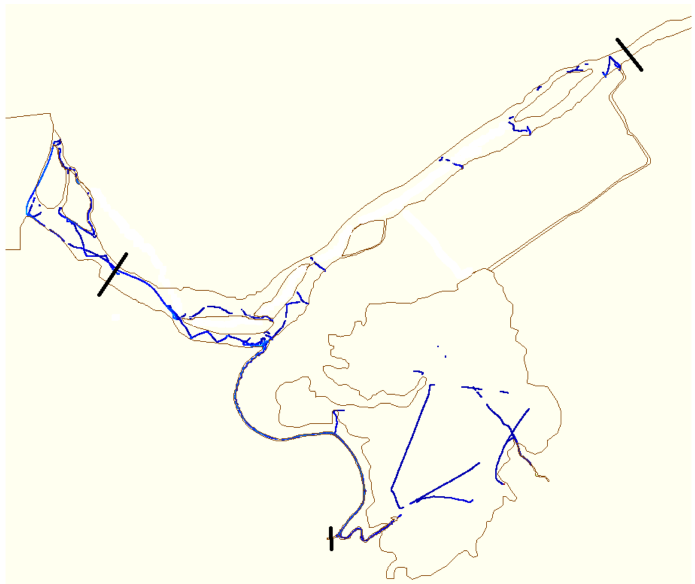


Figure E.3: Location of measurements with echosounder

divided the earth in zones with each there own reference. All the locations used in Delft3d are converted by using SuperTrans to the Eastings-Northings coordinate system with reference UTM zone 18N.

Appendix E.4. References

In the chapter Fieldwork, the orange measurements points are mentioned. It has showed out that neither ISAGEN, Cormagdalena and CIRMAQ know the elevation of the poles. Therefore the DEM elevation is used in the Sogamoso river, caño Silvestre and the ciénaga El Llanito. The values are given in table E.1. With this DEM values and smoothing function in Delft3D an elevation map with a smooth slope is created. See figure E.4. Outside this reference map, all the elevation of the bank surface (around the Caño Silvestre and the Sogamoso River) is assumed to be at least 2 meters higher than the water surface. It is assumed that these banks will not flood in the model. The entire ciénaga is referenced to the same reference level, it is assumed that there is no water surface slope in the ciénaga. This conclusion is also based on figure E.1.

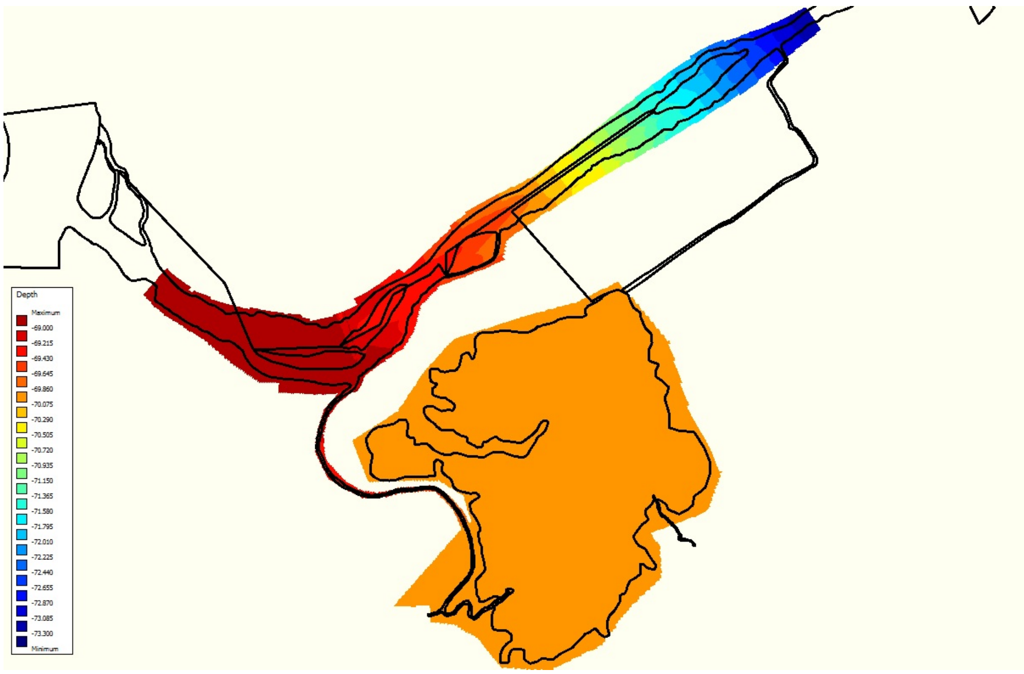


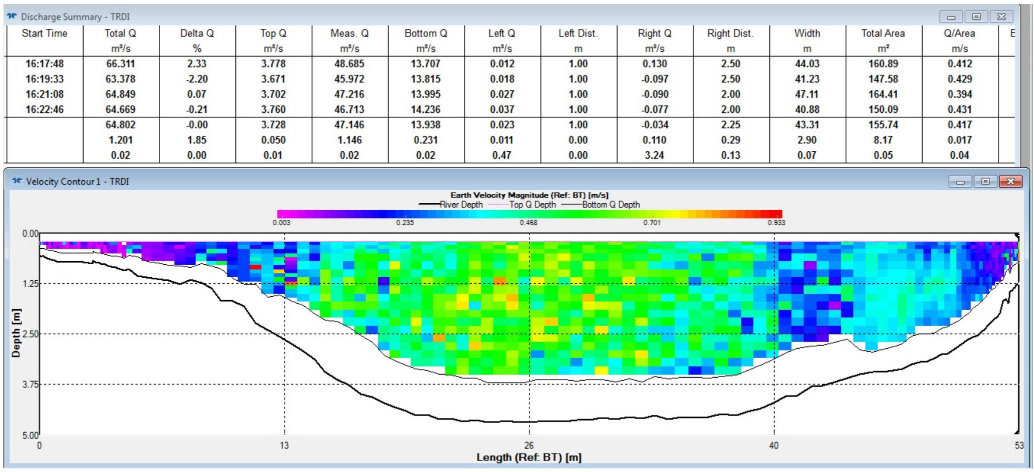
Figure E.4: Reference map Model area

Appendix E.5. ADCP

As mentioned earlier in the Chapter Fieldwork, during the Fieldwork several measurements were made in the caños, the ciénaga and Sogamoso River. By using the software Winriver, these measurements can show bathymetries, discharges, velocities and many more. In figure E.5 the bathymetry is shown, together with the summary of all four transections. When the standard deviations divided by the average is lower than 5%, no more transections are required. In this case this is 2% for the total discharge.
The data of the ADCP are used to adjust the depth files, which are created by the samples of the echosounder. The discharges and velocities in the caño San Silvestre, El Deseo and the discharges in the artificial caños are used to validate the model.

Appendix E.6. Landboundary file

In figure E.6 the images of ISAGEN are added on the map of Google Earth. This satellite images are made in April 2016, which are used to draw the landboundary polygon. This polygon is converted to XYZ coordinates.



Discharge Summary - TRDI

Start Time	Total Q m³/s	Delta Q %	Top Q m³/s	Meas. Q m³/s	Bottom Q m³/s	Left Q m³/s	Left Dist. m	Right Q m³/s	Right Dist. m	Width m	Total Area m²	Q/Area m/s	E
16:17:48	66.311	2.33	3.778	48.685	13.707	0.012	1.00	0.130	2.50	44.03	160.89	0.412	
16:19:33	63.378	-2.20	3.671	45.972	13.815	0.018	1.00	-0.097	2.50	41.23	147.58	0.429	
16:21:08	64.849	0.07	3.702	47.216	13.995	0.027	1.00	-0.090	2.00	47.11	164.41	0.394	
16:22:46	64.669	-0.21	3.760	46.713	14.236	0.037	1.00	-0.077	2.00	40.88	150.09	0.431	
	64.802	-0.00	3.728	47.146	13.938	0.023	1.00	-0.034	2.25	43.31	155.74	0.417	
	1.201	1.85	0.050	1.146	0.231	0.011	0.00	0.110	0.29	2.90	8.17	0.017	
	0.02	0.00	0.01	0.02	0.02	0.47	0.00	3.24	0.13	0.07	0.05	0.04	

Figure E.5: Measurements ADCP at the confluence of Caño Silvestre and Sogamoso river

Table E.2: Different Grid Sizes

Location	# of cells in M direction	# of cells in N direction	Grid Elements
Original Grid 1	478	394	133.010
Refined Grid 2	957	789	533.567
Re-Refined Grid 3	1912	1576	2.128.160

Appendix E.7. Grid file

E.7.1 Results Grid tests

In figure E.7 and figure E.8 the results of the grids are shown. It can be seen that the grid fulfils the requirements, see table 5.1.

E.7.2 Grid independent test

When a grid is created, the independence has to be proven between the grids. If a more refined grid than the used grid gives the same result, the results are grid independent. The grid that satisfies all the requirements is refined two times by a factor of 2.

To test the three grids on there independence, the same depth file is used for all the grids. With a simulation time of 2 hours, the results are compared. In figure E.9 the results are compared between the original grid and the refined grid. The results

Figure E.6: High resolution map ISAGEN in Google Earth

seems to be close to each other, however they are not the same. Another test was done with an even more refined grid, it is again refined by a factor 2. Unfortunately, the grid size became to large to run with Delft3D. Therefore the refined grid 2 is used for the model.

E.7.3 Grid size

E.7.4 Rectangular vs curved grid

Besides selecting a grid based on the size of grid cells, there are also multiple options in creating a grid file. A rectangular grid is has lower simulation time, because all the cells are orthogonal and the numerical calculations are less complex. By smoothing the curvel inear grid, it appeared that the simulation runs well and that

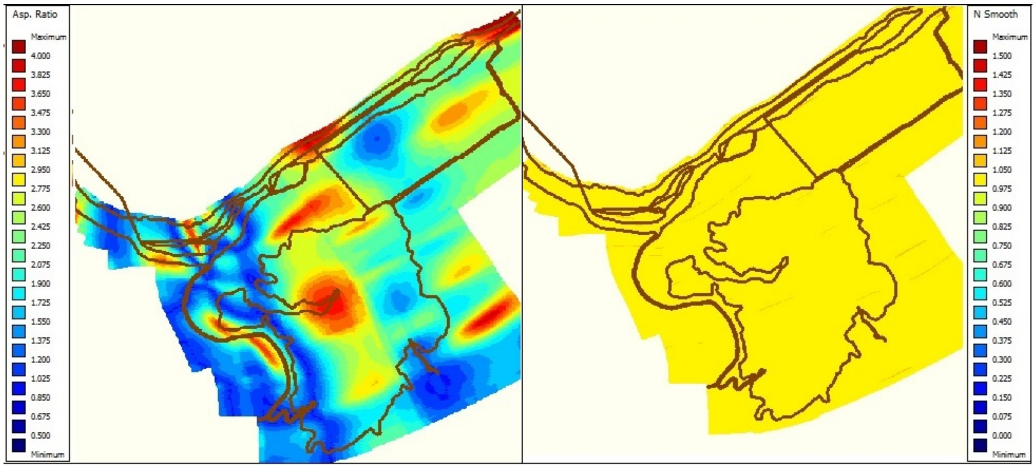


Figure E.7: Aspect ratio and Smooth (N) test

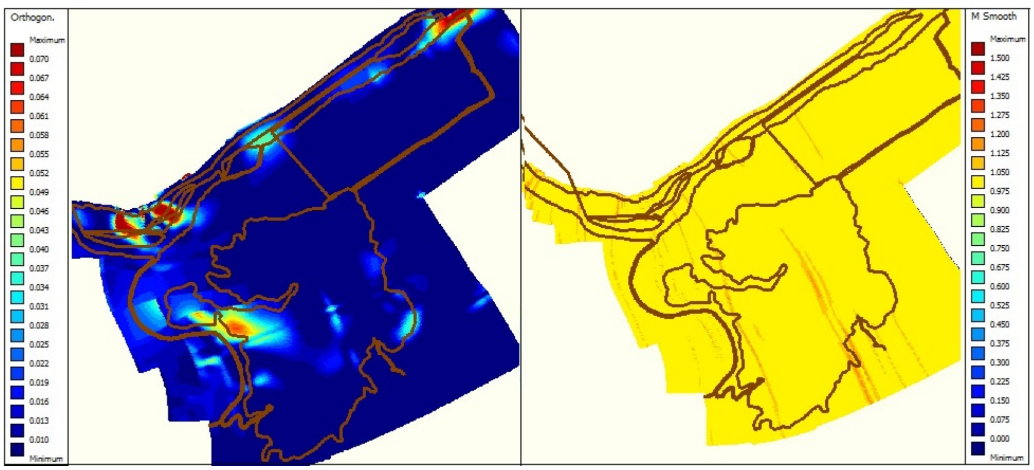


Figure E.8: Orthogonality and Smooth (M) test

the simulation time is not to long. The caño San Silvestre is also quite small compared the grid size. With an rectangular grid, the landboundaries of the caño become coarse and rough. See figure E.11 for the comparison of the two grids. The curve linear grid is used, because this one is more accurate compared with rectangular.

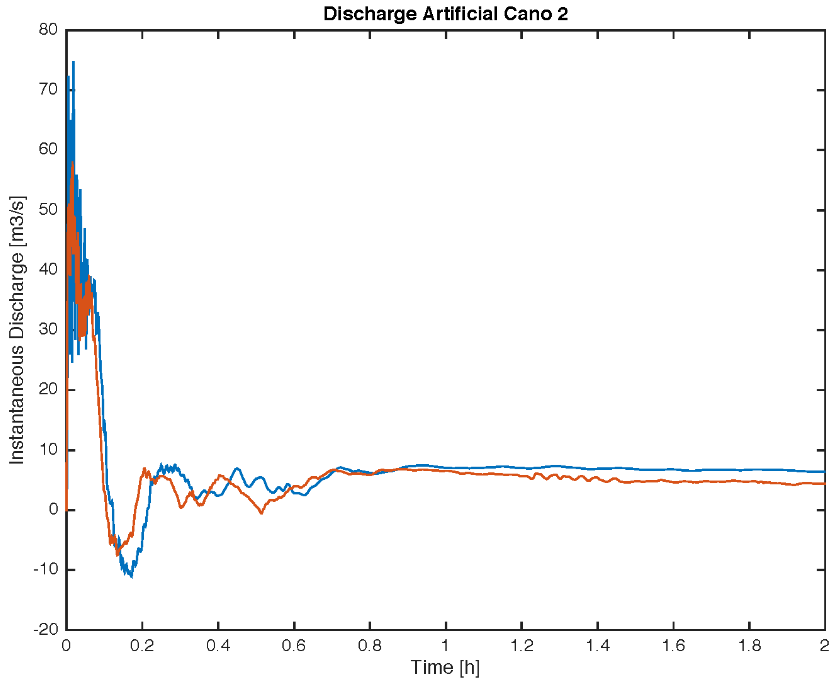


Figure E.9: Grid Independent test

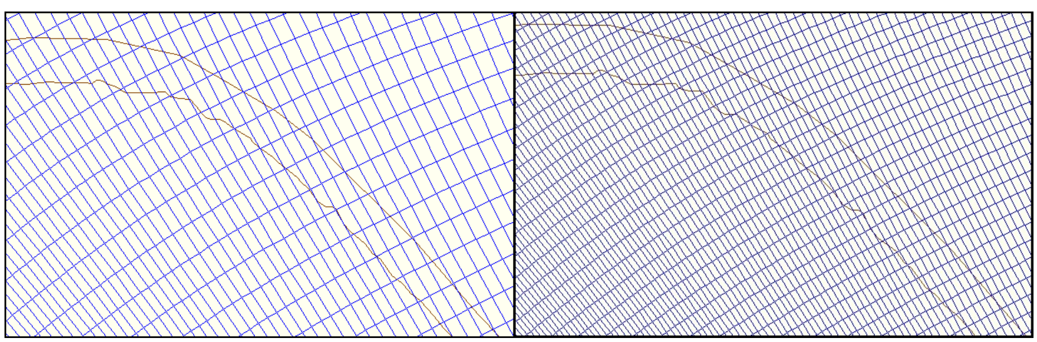


Figure E.10: Original Grid 1 VS Refined Grid 2

Appendix E.8. Depth file

In the following two figures two different elevation maps are given. Figure E.13 shows the depth values that are created by the measured samples. By using the measurements in the Sogamoso river, a depth file was created without reference. By referencing these two maps to the Mean Sea Level (MSL), the right depth file is

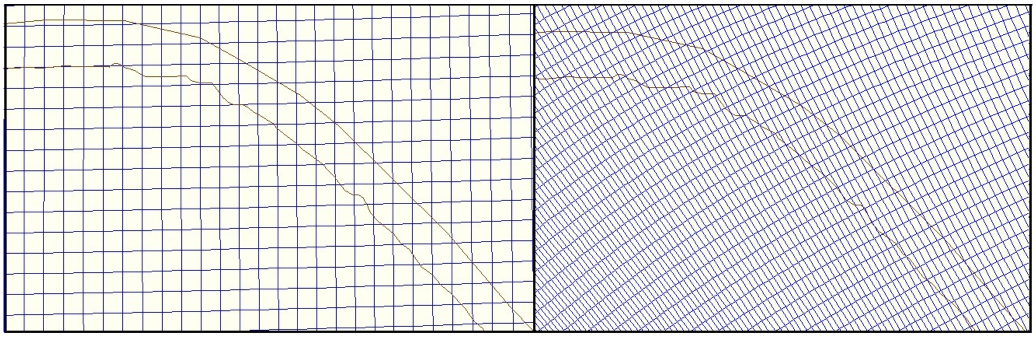


Figure E.11: Rectangular VS Curved

created.

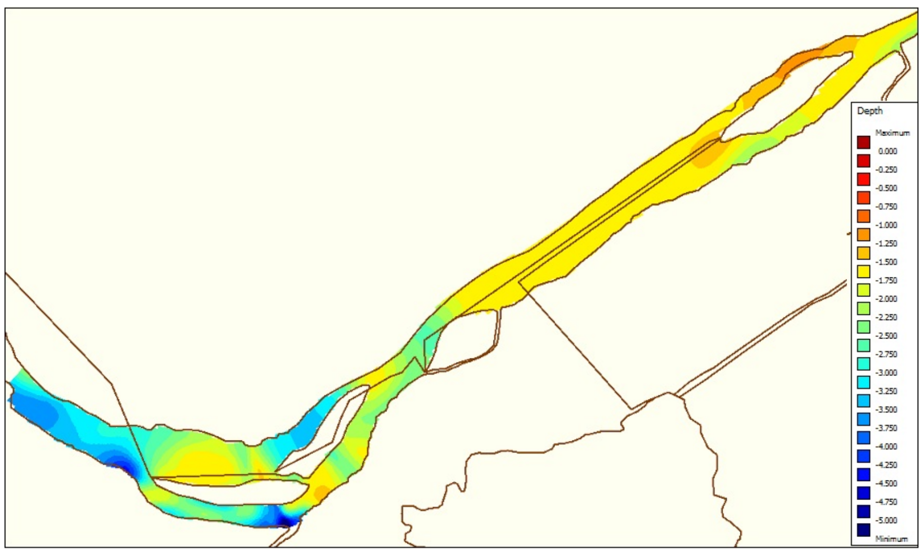


Figure E.12: Water level without reference

E.8.1 Adjusting the depth file by comparison to the model results

After the first run of the Delft3D model it followed that the discharge in El Deseo has the wrong direction and is to high, the discharges in the artificial caños are to low but with the right flow direction. When having a closer look to the velocities in the three connecting caños it can be observed that the highest velocity should

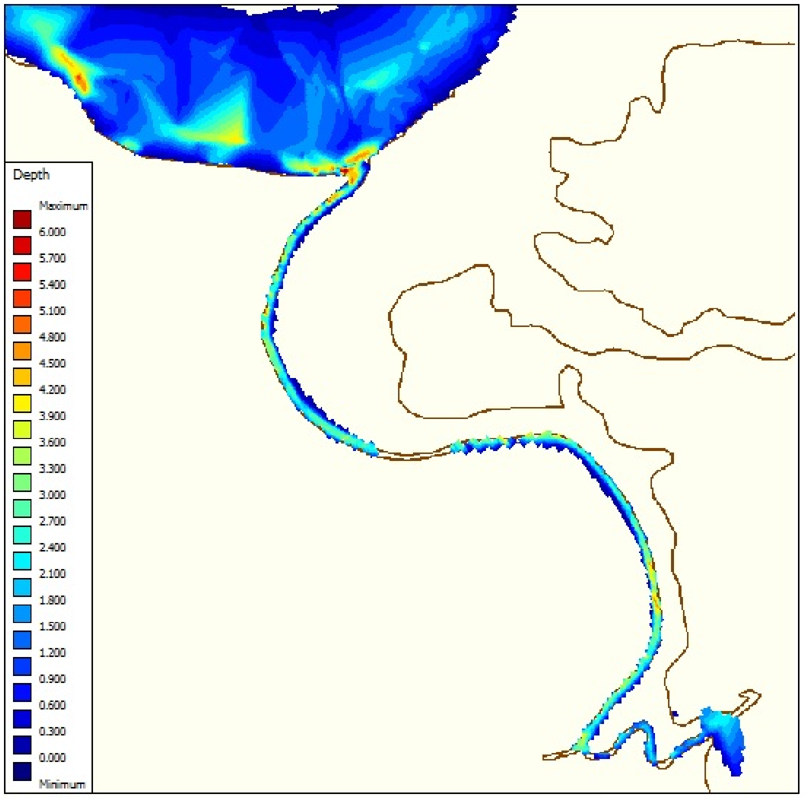


Figure E.13: Echosounder values to depth

be at artificial 2 and the lowest in El Deseo. Initially the elevation, see Appendix, of the caño San Silvestre and the ciénaga was assumed to be horizontal and equal. To create an increasing velocity in three connecting caños a linear slope with an 50 cm elevation at the caño San Silvestre boundary condition and 0 cm elevation at caño 2 is added to the depth file. Because no data was available of the reference at this location a change of the elevation profile is a possible assumption that does not change the depth profile. This also corresponds to the DEM file, see Appendix, despite that the caño San Silvestre is not clearly visible on this map, the elevation of the banks are increasing to the south.

After this adjustment to the depth file new runs were performed that still showed a wrong flow direction at El Deseo. Therefore the elevation of the El Deseo was increased, such that the surface level would be higher at the ciénaga side and lower at the side of the caño San Silvestre. Besides that, deeper channels were made in the ciénaga to create a higher flow from the ciénaga into caño 1 and 2. These deeper channels were not measured during the fieldwork, but due to the small amount of measurements in the ciénaga with the echo sounder, it is possible that these channels were not measured. Therefore we assumed that this channels are present. The assumption of these deeper connecting channels are also assumed to be valid because there will be higher velocities in these parts that will trigger erosion and thus deepen the channels.

Appendix F

Morphodynamics

Figure F.1: Overview measuring stations morphodynamic information

Measuring location	Before Hidrosogamoso [m^3/s]	After Hidrosogamoso [m^3/s]	Ratio 2015/2014 [µm]
S2	479	296	.62
S7	549	366	.67

Table F.1: Expected discharges before and after the construction of the Hidrosogamoso [Isagen, 2015a]

Measuring location	Dec 2014 [m]	Aug 2015 [m]	Ratio 2015/2014
S2	85	87	1.02
S5	135	150	1.11
S9	270	340	1.26
S17	45	45	1.00

Table F.2: Width distribution over space and time [Isagen, 2015a]

Measuring location	Dec 2014 [µm]	Aug 2015 [µm]	Ratio 2015/2014
S2	310	180	0.58
S3	160	180	1.13
S4	390	390	1.00
S5	150	170	1.13
S6	160	240	1.50
S7	160	240	1.50
S8	240	350	1.46
S9	230	290	1.26
S17	770	430	0.56

Table F.3: Median grain size distribution over space and time [Isagen, 2015a]

Measuring location	Dec 2014 [m^3/s]	Aug 2015 [m^3/s]	Ratio 2015/2014
S2	1.90E-2	9.80E-2	5.17
S3	1.69E-4	4.24E-4	2.51
S4	3.18E-4	7.64E-4	2.40
S5	7.72E-2	8.55E-1	11.07
S6	4.29E-2	3.00E-1	7.00
S7	6.39E-5	3.17E-4	4.96
S8	6.01E-3	2.32E-2	3.86
S9	3.45E-2	8.52E-2	2.47
S17	4.71E-4	1.27E-3	2.69

Table F.4: Total sediment transport capacity distribution over space and time [Isagen, 2015a]

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