Morphological modelling of the Atrato river delta in Colombia

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Cover Photo: Aerial photograph of the Atrato delta [ANDRES CALLE, 2008]
Preface

This document concludes my Master of Science in Hydraulic Engineering at the faculty of Civil Engineering and Geosciences of Delft University of Technology. The graduation project was carried out at Deltares and partly at various locations in Colombia. This thesis report concerns the study of improving the navigability of the delta of the Atrato River. This report will show some similarities with the report "Navigability restrictions around a bifurcation due to sedimentation, a Río Atrato case study" of Frank Melman. However, this report will elaborate on navigation issues at the delta.

I owe a special word of thanks to the people who assist me in my graduation.

First of all, I want to thank my graduation committee for their interest and support. I appreciate all the valuable comments of Professor Huib de Vriend during the meetings. I would like to thank Arjen Luijendijk for his advice to use an unstructured grid and all his other valuable advices. I enjoyed the discussions with Nathanael Geleynse about morphodynamic modelling of deltas. His enthusiasm was very inspiring to me. Finally, special thanks to Kees Sloff and Erik Mosselman for their daily support. I could bother them with all my questions and they were always willing to answer them.

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I would like to thank my Colombian counterparts Jaime Jimenez and Alejandro Montes for a wonderful stay in Colombia and their efforts to collect data. I will never forget our boat trip at the Río Atrato and the lomos we ate. Furthermore I would like to thank the port authorities of Quibdó for financing the trip to Colombia.

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Executive summary

The Colombian government aims to establish a connection that bridges the Atlantic Ocean and the Pacific Ocean. The construction of this corridor will stimulate the local economy and enables the Colombian government to exploit the unique geography of Colombia, having coasts on both oceans. The navigation route will largely take place on the current Atrato River, which has not yet been upgraded for a more extensive use of navigation in the near future. A bottleneck for the future navigation in the river corridor is the delta area, where the river bifurcates into several branches. However, the main problem arises at the river mouths, where the rate of sediment deposition is enormous. Without structural dredging activities the river is completely inaccessible for larger ships.

This study investigates the morphodynamics of a river mouth of the Atrato delta, in order to improve its accessibility to provide navigation in the future and to minimize the dredging activities. In short, the main objectives of this study are (1) to gain insights into the morphodynamics of the delta, (2) to develop a hydrodynamic model on an unstructured grid, (3) to develop a morphodynamic model on a structured grid and consequently (4) apply these models to investigate measures that aim to improve the accessibility of a river mouth.

The performed literature study showed that the combination of a high sediment load, a small tidal range and a mild wave regime qualify the delta as highly river-dominated. It appeared that, despite the differences in discharge and sediment discharge regime, the Atrato delta shows considerable similarities with the Mississippi delta. A large difference is that the Atrato delta is relatively undisturbed by human activities, whereas the Mississippi is regulated to a large extent. Therefore, the Mississippi river can serve as a good reference if river measures in the Atrato delta are considered.

In this study an approach is used to model the hydrodynamics first at a large scale and subsequently modelling the morphodynamics at a much more detailed level. The hydrodynamic model is set up with an unstructured grid, which appears to be a powerful tool to model a topographical complex area such as the Atrato delta. Furthermore, an unstructured grid has the advantage that it can work with a great diversity in terms of resolution. The hydrodynamic model gives insights into the hydrodynamics of the delta and indicates the major influence of the wetlands on these dynamics. In addition, the hydrodynamic model is capable to create specific time-dependent boundary conditions for the more detailed morphodynamic models. This approach solves the problem of enormous backwater adaptation lengths, which are initiated by the tidal movement and the large amount of bifurcations in the delta.

Subsequently, a depth-averaged Delft3D model with a structured grid has been set up to simulate the morphology around a river mouth. Besides the depth-averaged flow simplification, also other assumptions have been made. The most important one is that the sediment reworking process induced by waves is not included in this model. To partly overcome this shortcoming the river branch is modelled with the mildest wave attack. This is the Leoncito branch, the most southern river outlet and therefore the most sheltered river outlet. All the investigated measures are also applied to this branch. Furthermore, it is assumed that ionic constituents in saline seawater will stimulate the flocculation process of the large volume of fine sediments in the system. To schematize this process in the model, two different sediment fall velocities have been used; one for fresh water conditions and a higher one for saline water conditions.

The morphodynamic model is able to identify the major processes that cause the sediment deposition at a river mouth. The key process that causes the poor accessibility of a river mouth appears to be the sudden spreading and deceleration of the riverine water when the river flows into the Golfo de Urabá. As the flow expands, the momentum decreases and subsequently its capacity to carry sediments decreases. This eventually results in sediment deposition. As the result of the relative strength of the outflowing fresh water compared to the tidal power, the flow velocities are located seawards for almost all conditions. This directly explains the low sediment deposition rates in the river part of the delta. The assumed higher
fall velocity in saline water results in an even more compact zone of sediment deposition at a river mouth. Especially during high flow conditions, flow separation is predicted by the model for the southern river mouth of the Leoncito branch. This process eventually leads to an obstacle for navigation.

This report discusses four possible measures that aim to improve the navigability in the delta and to minimize dredging activities. In order to find justification for these different measures, a model is set up to simulate their effects on the delta hydrodynamically as well as morphodynamically. Other possible measures are only briefly described. The modelled measures are (1) a sand trap, (2) an artificial outlet channel, (3) sediment diversion channels and (4) the artificial extension of a river mouth. In this report no budget constraints have been taken into account. The model forecasts that none of the investigated measures will avoid dredging activities completely. However, the exact location of the dredging activities can differ compared to the dredging location for the current situation. The implementation of an artificial river mouth situated more upstream in the river leads to avulsion or to very low flow rates through the current river mouths. Of the examined measures, the implementation of a sand trap and the implementation of sediment diversion channels raise the most potential to reduce the sediment supply to the current river mouths, without deteriorating the navigability in other parts of the river. The artificial extension of a river mouth with breakwaters does not decrease the sediment supply towards the river mouths. However, the sediment deposition process takes place in deeper water, which minimizes the dredging maintenance for at least several years.

The findings of this study should be regarded as the first step in the extension of knowledge on the morphodynamics of the Atrato delta. For this study the amount of available data was limited and therefore an extensive calibration and verification process of the model is still missing. At this stage the models will help to understand the morphodynamics at the delta in more detail and hopefully encourage the collection of more valuable data. For that purpose a measuring and monitoring program is presented in this report. The developed models offer opportunities for further elaboration on the hydrodynamics and morphodynamics of the Atrato delta and can easily be adapted as soon as more data are available. Due to the lack of data the presented model results should be interpreted with caution. An extensive calibration and verification process will be necessary to achieve more certainty about the results.
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1. Introduction

1.1 Structure of report

This report involves finding the causes for the navigation problems in the delta area of the Río Atrato. Subsequently, possible solutions to improve the current situation are tested in a simplified approach, which pertains to the preliminary character of this study.

At the moment, the problems for navigation at the delta arise primarily at the river mouths. However, in the projected scenario other problem areas may arise. The goal of this study is to gain insights in the morphodynamics of the Atrato delta and to use this knowledge in order to guarantee navigation in one of the river mouths, without deteriorating the situation more upstream in the river.

This report describes the background, the problem description followed by the objectives all in the first chapter. Next the system area is elaborated in more detail in chapter 2. A literature study is presented in chapter 3, whereas the following chapter defines the set-up of the models used. The model set-up and calibration process in this chapter are described with some important notions regarding the ‘preliminary character’ of the study. In chapter 5, the results of the computer simulations are given for the current situation and for scenarios with the implementation of navigability improvement measures. As the study concerns a river which has not been investigated thoroughly yet, a measurement and monitoring plan is introduced in chapter 6.

This report ends with conclusions and recommendations.

Once again, this report should be interpreted as a starting point for future studies involving the navigability of the Atrato delta.
1.2 Background

Since the discovery of the Pacific Ocean in 1513 by Vasco Nuñez de Balboa studies were conducted to investigate the feasibility of an inter-oceanic connection over water in the west of Colombia. This interest was especially based on the presence of a wide and deep river, the Río Atrato that flows into the Caribbean Sea and its nearness to rivers, the Río San Juan in present-day Colombia and the Río Chucunaque in present-day Panama that flow into the Pacific Ocean. A navigation route formed mainly by an existing network of rivers, streams and lakes should form the connection between the two oceans. However, in the 19th century the current Panama Canal was preferred. Until now, Colombia has not taken advantage of its unique geographical location.

Nevertheless, over the last decade the government of Colombia has become more and more interested in realizing an inter-oceanic connection. The economic infrastructure in Colombia is nowadays fully focused on the Atlantic Ocean. Gradually it became a wish of the government to stimulate also the economy in the poor areas at the Pacific coast. Furthermore, the coffee and banana industries were very interested in a more developed distribution network to the Pacific coast. The corridor could serve to improve the marketing possibilities in Asia. Finally, an inter-oceanic connection in Colombia reduces the costs of a part of the "inland navigation", which currently uses the Panama Canal. The transport costs will reduce and money will be saved on the toll rates.
The Ministry of Transport of Colombia has set itself the goal of taking benefit from the privileged geographical position that allows it to establish an inter-oceanic connection. Additionally, the Ministry has identified some sub-goals:

i. Reduction of the transport costs within the country;
ii. Integration of remote areas into the distribution network, hence improving the local productivity;
iii. Improving the living standards in the Chocó region.

Consequently, the focus of the Ministry is not to compete with the Panama Canal, but claims only to stimulate the economy of Colombia and especially the economy of the local region.

The National Road Institute (INVIAL) selected the Technological University of the Chocó (UTCH), to accomplish feasibility studies and analyses to present corridors between the Pacific Ocean and the Caribbean Sea [UTCH, 2010a]. These studies resulted in four possible inter-oceanic connections, which have been compared with each other in detail on basis of technical, economical, environmental and sociological considerations. Eventually one corridor has been selected. The selected corridor consists of an existing river stretch and a road and could be separated in three parts:

- **Gulf of Urabá (Caribbean Sea) - City of Quibdó**
  Transport over approximately 500 km of the Río Atrato

- **Quibdó - Las Anímas**
  Transport over an existing road of 54 km

- **Las Anímas - Tribuga (Port of Nuquí)**
  Transport over an to be constructed road for 66 km

In Figure 1.2, the selected corridor is shown.
The corridor will consist of at least three ports (Quibdó, Turbo and Nuqui) and a transfer dock in Las Animas. The ports of Quibdó, Turbo and Nuqui have to be upgraded extensively to process the growing cargo properly. The local authorities believe an additional port in the Gulf of Urabá will be necessary. The exact location of this new port is still uncertain. The latest known plan is that the port will be built near a mouth of the Río Atrato, where natural depths up to 40 metres are present and the wave climate is relatively calm.

To establish the corridor the river also has to be adapted to more extensive use of navigation in the near future. The vessel dimensions will also increase and the current river depths and width may not be sufficient in some sections of the river.

The required minimum depth for navigation should be at least 2.5 metre in the corridor. This corresponds to a navigation width of 25 metre, widening up to 40 metre in sharp bends. This will allow one-way operation for typical barge-towboat combinations with a length of 90 m and a width of 14 m [D’ANGREMOND, et al., 2003].

An inter-oceanic connection is worthless when bottlenecks in the river corridor reduce navigability of passing vessels.

River navigability is affected by [MOSSELMAN, 2010]:
- Shoals on the river bed (rendering the water depth smaller than the draught plus a certain keel clearance);
- Bank-line positions (making the river too narrow or making river bends too tight for manoeuvring);
- Cross-currents (at confluences and entering where overbank flows re-enter the main channel);
- Low river discharges in dry season (rendering the water depth smaller than the draught plus a certain keel clearance).

Except for some sharp bends in the river, the only real problems for navigation occur at the various river branches of the delta of the Río Atrato at the moment. All river mouths are poorly accessible and some branches do not provide enough navigable width. The most suitable branch and river mouth have still to be selected. The local authorities of the Chocó province opted in their reports for the use of the Tarena branch. The Tarena branch is not the most accessible branch at the moment, but the only branch that lies entirely in the territory of the Chocó province. All the other stretches of the river delta lie in Antioquia province, which is one of the wealthiest and most developed provinces. Therefore, the preference for the Tarena branch seems to be an entirely political decision in order to boost the economy of the Chocó province as much as possible. In this report the Tarena branch is not automatically preferred.

NOTE: This report will elaborate only on navigation issues at the delta.
The need for raw materials forces China to invest in upcoming economies, which are rich in raw materials. In February 2011 the news came out that the Chinese are now very interested in the Colombian coal. Due to the current lack of infrastructure in Colombia, the Chinese are forced to transport the Colombian coal to China through the Panama Canal, which is very expensive due to the high toll rates. The Chinese government is now willing to invest in the construction of a railway network between the Pacific and a major coal district located at the Atlantic. An important part of Chinese investment will be the rail connection between the newly constructed docking station at Urabá (located at the Golfo de Urabá) and Cupica (located at the Pacific). This project is popularly called “the dry canal project”. Figure 1.3 presents a clear overview. What this project really means for the corridor is not entirely known at the moment. However, it seems that one project does not rule out the other and may collaborate to result in a significant economic growth in the region.
1.3 Problem description

An inter-oceanic connection is not sustainable if bottlenecks in the river corridor reduce navigability of passing vessels. In the delta area of the river there are bottlenecks for navigation at present. In this area the river bifurcates into several branches. In addition, a delta is a dynamic environment and the undergoing changes of the delta may hinder navigation. At the moment, the main problems arise at the river mouths where also coastal morphological processes are present. The final location of the port plays a key role in determining which particular branches should be navigable. Measures in the river will probably be inevitable to achieve a sustainable navigation route.

1.4 Objectives and research questions

It is clear that navigability plays a key role in this thesis. Studying 2D morphology of critical points in the delta and proposing cost-effective solutions are paramount in creating sufficient navigability and complying to the wishes of INVIAS and the port of Quibdó at the same time.

In order to achieve this objective it is important to gain insight into the morphological processes in the Atrato delta. A proper process-based model in combination with an extensive literature study will help to reach this goal.

Due to a lack of hydrodynamic information and the topographical complexity of a delta, the modelling process will be partly executed with a model that is able to use an unstructured grid. The system used is still under development, so the results of the modelling process have to be tested against a widely used modelling system. The obtained hydrodynamic results of the model on an unstructured grid will serve as hydrodynamic boundary conditions for the more detailed morphodynamic modelling process on a structured grid. Some conclusions of the applicability of this method have to be drawn in this report.

To analyse the morphological processes near a river mouth in a morphodynamic model, a lot of assumptions are made. To indicate the extent of the reliability of the model will be extremely important.

In combination with the output of the models for the base case and the knowledge gained from the literature study a few possible measures, which might improve the navigability of the Atrato delta are identified. The effectiveness of these possible measures are tested in both models. Finally, some advices are given on which strategies raise the most potential for further investigations in follow-up studies.

All in all, four main research objectives have been defined for this study, based on the problems detected so far. The main objectives of this study are:

1. To gain insight into the morphological and hydrodynamic processes in the Atrato delta.
2. To use a new model with an unstructured grid to forecast the hydrodynamics of the Atrato delta in more detail.
3. To develop a process-based morphodynamic model that properly simulates the morphological processes in the Atrato delta.
4. To apply the models to investigate measures which aim to improve the accessibility of a river mouth.

These study objectives are elaborated in more detail with the following research questions, given per main objective:

1. To gain insight into the morphological and hydrodynamic processes in the Atrato delta.
   - Which processes determine the geometry of the delta and how do these interact with each other?
2. To use a new model with an unstructured grid to forecast the hydrodynamics of the Atrato delta in more detail.
3 To develop a process-based morphodynamic model that properly simulates the morphological processes in the Atrato delta.
- What are the key processes that cause the poor accessibility of a river mouth according to the model?
- Is the model reliable given the potential lack of data?
- Is the interaction between the different processes that occur in the deltaic environment modelled realistic?

4 To apply the models to investigate measures which aim to improve the accessibility of a river mouth.
- How does the delta react to (human) interferences?
- Do the proposed measures lead to an improvement of the navigability of the delta?
- Which navigability improvement measure raises the most potential to investigate further in follow-up studies?

1.5 Methodology

To reach the objectives and to answer the research questions, a methodology is followed.

Within the first stage of the graduation the available project reports have been read and a clear view of the project has been obtained. To gain better insight into the morphological processes in a delta a literature study has been executed. In addition, some literature has been read on the possibilities to improve the navigability of a river.

In October and November 2010 a data-collection trip on site has been made to pinpoint the current bottlenecks for navigation in the delta area. Local authorities and stakeholders have been visited to share thoughts and to collect as many data as possible. Available data were reviewed and modelling issues were discussed. A boat trip over the Atrato delta has been made to get a feel of the characteristics of the river and to perform some additional measurements. Also some sediment samples were taken, see Appendix D. Simultaneously, an existing SOBEK 1D hydrodynamic model of the system has been reviewed and adapted where necessary, see appendix E. For example, the existing SOBEK model did not included the various delta branches. The different delta branches were added to this model.

To create insights in the local hydrodynamics and morphodynamics of the delta a 2D hydrodynamic and a 2D morphological model have been constructed. To model the topographically complex delta hydrodynamically a new modelling system has been used, which is able to work with an unstructured grid. The advantages of this new system are compared to a widely used model, which only works with structured grids. Different navigability improvement measures are calculated in the hydrodynamic model and the output of these calculations served as input for a detailed morphodynamic model. To analyse the morphological processes at a river mouth, a separate branch is selected. To model the whole delta morphodynamically would be too much time consuming at this stage of the project. The choice of this particular branch should not be regarded as final.

The available data of the project area are very limited. The results presented in this report are therefore not sufficiently calibrated and should therefore be treated with caution. Nevertheless, the results provide insight into the hydrodynamics and morphodynamics of the delta and in its response to (human) interventions. In order to calibrate and to modify the models used in the future a measuring and monitoring plan is set up in this report in order to gather more data.

Finally, the results of the simulations and the knowledge gained from the literature study are used to draw some conclusions and to give some recommendations to guarantee a more navigable delta in the future.
2. Atrato river

2.1 General

The Atrato is a river in the north western part of Colombia and flows mainly through the province of the Chocó. As mentioned before, the province is one of the less developed parts of Colombia. This especially holds for the infrastructure. A problem is that the Chocó is very densely vegetated and hence large areas are almost inaccessible. The settlement is therefore primarily limited to the banks of the river. The river acts as the most important infrastructural connection. Also the trade in the Chocó department takes mainly place over this river, which is why the Atrato River is of exceptional importance to the people of the Chocó.

The Atrato River originates from the Cerro de Caramanta Mountains, on an elevation of 3,700 metres, in the department of the Chocó. Its total length is 750 km. From the city of Quibdó (located 494 km upstream) the river flows in a relatively narrow valley bordered by great mountain ranges, such as the Cordillera Occidental of the Andes. The river eventually flows into the Gulf of Urabá, which is directly connected to the Caribbean Sea. The catchment area of the river is 38,500 km² and thereby has a relatively small basin, see Figure 2.1. However, the river is located in one of the wettest places on earth and its volume is potentially huge. The discharge of the river in relation to its catchment area is the highest of the world, namely 0.161 m³/(s*km²) [UTCH, 2010b].

The Atrato River is known for its natural character. Along the river only some small quay walls are present in the direct vicinity of the small villages. Furthermore there are no man-made embankments. Other hydraulic structures are also not present in the river and thus the river is fully free to find its own way downstream. The dredging activities of the river are limited to the delta area and to small areas near the city of Quibdó. Although in some stretches of the river it is believed illegal gold mining takes place on a considerable scale. Due to the absence of levees the floodplains of the river are often flooded. Especially for the lower parts of the river this is almost constantly the case. The floodplains are very densely vegetated.

![Figure 2.1 Catchment area of Río Atrato [modified from GARCIA-VALENCIA, 2007]](image)
In the Chocó region a clear difference between a wet season and a dry season is hard to make, because of its tropical location. However the precipitation rates and therefore also the discharges of the Río Atrato are in the period from January to mid-April usually lower compared to other months. These months could be considered as critical for navigation. However, the precipitations rates during these months are still in the order of 100 mm/month. The wetter period runs from May till the end of November, with an average precipitation of 250 mm/month. The annual total of precipitation in the delta area is approximately 2,500 mm. Nevertheless, further upstream of the river the precipitation rates are much higher during the whole year and contribute to significant river discharges all year round. Figure 2.2 presents the precipitation rates for an average month in the wet season and for an average month in the dry season.

Figure 2.2  Precipitation for an average dry month (left) and an average wet month (right) [García-Valencia, 2007]
2.2 Hydrodynamics

2.2.1 Discharge regime

The available hydrodynamic data of the Río Atrato are limited. Until now no extensive research or data collection has been carried out at the Atrato River. There are only six official measuring stations located along the river. The current stations are also concentrated in the middle section of the river where the larger settlements are located. For the two stations (Domingodó, Riosucio) that are located relatively close to the delta, the hydrodynamic data are limited to daily average water levels. The authorities assume that the tidal influence is still noticeable at both stations. Due to this assumption and the presence of natural large depths for navigation purposes, there has never been any reason to execute discharge measurements for this part of the river. Only in the years 1988 and 1989 three discharge measurements have been carried out for both stations for a specific low water level, an intermediate water level and a high water level. Table 2.1 presents an overview.

<table>
<thead>
<tr>
<th>Station</th>
<th>Distance to El Roto mouth [km]</th>
<th>availability daily average water levels</th>
<th>availability daily average discharge</th>
<th>Period</th>
</tr>
</thead>
<tbody>
<tr>
<td>1 Quibdó</td>
<td>493.5</td>
<td>v</td>
<td>v</td>
<td>1984 - present</td>
</tr>
<tr>
<td>2 Belén</td>
<td>484.5</td>
<td>v</td>
<td>v</td>
<td>1974 - present</td>
</tr>
<tr>
<td>3 Tagachí</td>
<td>386.9</td>
<td>v</td>
<td>v</td>
<td>1971 - 2002</td>
</tr>
<tr>
<td>4 Bellavista</td>
<td>303.7</td>
<td>v</td>
<td>v</td>
<td>1970 - present</td>
</tr>
<tr>
<td>5 Domingodó</td>
<td>167.2</td>
<td>v</td>
<td>v</td>
<td>1970 - present</td>
</tr>
<tr>
<td>6 Riosucio</td>
<td>122.5</td>
<td>v</td>
<td>v</td>
<td>1970 - present</td>
</tr>
</tbody>
</table>

Table 2.1 Measuring stations of the Atrato river and the availability of the data [modified from UTCH 2010d]

The Bellavista station is certainly located outside the area of tidal intrusion. This station is situated 304 km upstream of the Gulf of Urabá, yet it is the nearest station to the delta with daily discharge data. From this station a rating curve was established consisting of nine discharge measurements over the past six years, which obviously results in rather unreliable values. However it does provide sufficient information about the discharge regime over a year and about the order of magnitude of the discharge. A histogram of average monthly discharge for the station is given in Figure 2.3.

![Histogram of the average monthly flows at Bellavista station (1966-2009) [modified from UTCH 2010c]](image-url)
The average discharge of the river at the city of Bellavista is 2527 m³/s. Based on estimates of the catchment areas of the downstream distributaries the average outflow discharge at the river mouths will be approximately 5000 to 6000 m³/s [UTCH 2010c].

2.2.2 Tidal forcing

The river flows into the Gulf of Urabá. This gulf is shaped as a bay and its tidal climate is mild. It is not exactly known how far the tide penetrates into the river. However, despite the small tidal range it is assumed that the tidal influence is felt up to Domingodó (more than 150 kilometres upstream). In the Gulf of Urabá there are probably no measuring stations. However the IDEAM institute provides daily tidal forecast data for the city of Turbo, which is located on the other side of the bay only 12 kilometres from the river mouth, Boca Coquitos. The tidal forecast of the month March in 2010 at Turbo is plotted in Figure 2.5. A clear spring-neap cycle could be identified.

The tidal cycle was in March 2010 for Turbo mainly semi-diurnal, although with large daily inequalities. The mean tidal range is about 0.5 m and the maximum tidal range is about 0.7 m. For periods with stronger winds the water level pattern in Turbo is rather different. The wind-driven currents counteract the tidal penetration. Due to the bay shape of the gulf it is likely that the tidal wave is distorted. Despite the location of Turbo near the delta, the water level pattern at the river mouths can be quite different. Turbo is also enclosed by the Bahia of Turbo. Therefore, the dataset of water levels in Turbo has been used for model calibration and not as input data.

![Tidal cycle Turbo March 2010](image)
2.2.3 Wave climate

As a result of the shape of the Gulf of Urabá the wave climate is relatively calm. The direction and the height of the waves are directly dependent on the wind direction and speed over the gulf. The wind regime and hence the wave climate are consequently fairly predictable.

The wind climate shows the preponderance of the trade winds in the definition of speed and direction. During the rainier season the Gulf is mainly affected by winds from the Atlantic. Although the records show highly variable directions, the generally dominant wind direction is north to northeast. The average values are less than 4 m/s and also the wave heights are small.

In the dry season the trade winds change direction and enter the gulf mainly from southern direction. The trade winds have their maximum intensity in this season. The winds can reach speeds over 7 m/s, including periods up to 24 hours in which the speed exceeds 10 m/s. The average wind speed is 6 m/s, which roughly corresponds to wave heights up to 1 metre in the vicinity of the river mouths. The weak winds recorded between May and November show highly variable directions, but the predominant direction is from the North. The average wind speeds are usually lower than 4 m/s however, during storms, often accompanied with heavy rains, the situation can differ strongly. During normal conditions the wave heights are relatively small, but during storm conditions the wave heights can reach values above 2 metres. Figure 2.5 shows average wave fields for the dry and wet period. The picture most to the right in Figure 2.5 shows a wave field during storm conditions.

![Wave field images](image-url)

**Figure 2.5** Average wave conditions in the Gulf of Urabá

Note: The images show the significant wave height, which corresponds to the average of the 33% highest waves over a certain period (day). The maximum wave height is approximately equal to 2 times the significant wave height.

Note: [source](http://www.cioh.org.co/meteorologia/PreCaMaritima.php?pmc=ura)
2.3 Morphodynamics

Little is known regarding the river’s morphodynamics. Data on average sediment transport rates are limited. However, the river is regarded as being ‘one of the most navigable’ rivers in the world [UTCH, 2010e]. This statement tells us that the morphodynamics do not cause massive problems for shipping purposes. Also in most branches of the delta area navigation problems are only expected very locally.

Sediment supply
The Atrato drainage basin is characterized by strong tectonic activity, high rates of runoff, low discharge variability and steep mountainous slopes that all promote high sediment yields. Even though the Atrato drains a small basin, this unique combination of geomorphic factors stimulates a high sediment delivery and the construction of an extensive delta. Nevertheless, the sediment yield which effectively drains into the ocean appears to be relatively low, because of the extensive low-lying alluvial flood plains, in which significant sediment deposition and storage occurs.[RESTREPO AND KJERFVE, 2000]

In 2009 the sediment yield rates for the principal rivers of Colombia were examined [RESTREPO et al., 2009]. Because there are no measurements of sediment load of the Atrato river at its lower course, estimates are made based on the sediment load for other similar rivers in South America and Asia. Multi regression analyses estimated an average sediment load into the Caribbean Sea for the Atrato river of 25 Mtons/year. This corresponds to an average sediment concentration in the order of 200 mg/l in the delta area.

Transport mechanism in a river and a river mouth
The river flow generates forces on the bed particles of a river bed, which tend to move the particle. The forces induced by the surrounding particles and the gravity tend to counterbalance the currents at the river bed. The sediment particle starts moving if the forces induced by the river flow cannot be counterbalanced anymore, a certain critical value is reached. If the flow velocity increases further, more and heavier particles will be transported. Sediment in a river can be transported in different ways, which is presented in Figure 2.6.

Figure 2.6 Sediment transport types [modified from JANSEN et al, 1979]

Bed load transport is the sediment which is moving along the river bed by rolling, sliding and hopping. Suspended transport is the transport of material over the whole water column; the carried sediment touches the bed only sporadically. Wash load transport is the transport of sediment in the water, which does not touch the bed at all over long distances. In which mode the sediment is transported highly depends on the differences between the types of sediment. The sediment supplied by the river varies in grain size and cohesiveness. In general, coarse sediment is transported mainly as bed load transport, whereas the finer sediment is transported primarily in suspension or even as wash load. At high concentrations of sand and silt the sediment transport can also occur as fluid mud in a layer near the bed. This layer will act as a viscous layer on top of the bed and will block the exchange of sand between the water column and the bed.

The sediment in the shallow river mouth area faces forces induced by the river system and the coastal system. The forces now originate from currents (river flow, tidal currents, wind induced currents, longshore current) and breaking waves. The different transport types shown in Figure 2.6 still apply. However the transport processes in this area are more complex and
can change direction repeatedly. As a result of the continuous forces on the bed, the top layer of sediment is moving constantly.

**Sediment properties**

As explained previously, the sediment characteristics determine which sediment transport mechanism will occur. It is therefore important for the morphology to schematize the variation of sediment grain size in more detail. According to a common classification system (Wentworth) sand is defined as grains with sizes between 63 µm and 2 mm. Sand is mainly qualified as a non-cohesive material, which means that individual grains do not stick together. Sediments with grain sizes between 63 µm and 4 µm are defined as silt, whereas even smaller particles are qualified as clay. Clay has very strong cohesive properties. When the distance between individual clay particles is small, the particles can stick together. This process is called flocculation. Although silt is not a cohesive material, in nature often silt and clay particles are found together in a cohesive mixture. A fluid-sediment mixture of water, silt, clay, fine sands and organic materials is called mud. Especially in the vicinity of the river mouths the top layer of the river bed is muddy. The soil samples taken in October 2010 during the fieldtrip indicate that kind of mixtures in the delta, see Appendix D. Also measurements in 1969 executed by U.S. Army Corps of Engineers indicated fine sediments for the Atrato River. The sediment samples taken at the Lower Atrato in 1969 almost completely passed the 200-mesh sieve, which corresponds to a sieve size of 0.075 mm. Furthermore, the U.S. Army, corps of engineers found a high suspended-sediment load with a charged colloidal sediment mixture. A depth integrated sediment sample taken at the delta area indicated a total suspended sediment load varying from 300 to 450 mg/l [LINDNER, 1969].

**Sediment transport modelling**

Sediment transport equations are mathematical expressions of the conservation of mass and momentum. The conservation of mass is presented by the Exner principle, which actually states that erosion occurs in areas of accelerating flow and deposition occurs at decelerating flow. Derivations for the sediment momentum equation are still highly empirical. Mathematical morphodynamic models regularly use an empirical predictor to relate the local flow conditions to the amount of sediment transport. The transport in suspension is calculated by solving an advection/diffusion equation.

In sediment transport modelling, the exchange processes between water column and bottom layer are often assumed to be governed by the critical bed shear stress of the bottom material and the actual occurring bed shear stresses. In most sediment transport formulations the critical Shields parameter and the Shields curve are used to define the initiation of motion. If actual bed shear stresses are larger than critical bed shear stresses of the bed material, erosion can occur and for situations where the actual bed shear stresses are smaller than the critical bed shear stresses of the bed material sediment can settle. The formulas for different transport formulations are given in Appendix C.

Another important parameter to determine in sediment transport modelling is the fall velocity of sediment. The fall velocity depends on the grain characteristics as well as on the fluid characteristics. The formula is given in Appendix C. The fall velocity determines how long it takes for a particle to settle and where this eventually occurs. In Table 2.2 the order of magnitude of the fall velocity for different types of sediment is given. In the vicinity of the river mouth the size of individual mud particles can increase as a result of flocculation. This process is enhanced by ionic constituents present in saline waters and the presence of organic material. Due to this increase the particles become heavier and the settling process will accelerate.

<table>
<thead>
<tr>
<th>Sediment type</th>
<th>Sediment size [mm]</th>
<th>Fall velocity [m/s]</th>
</tr>
</thead>
<tbody>
<tr>
<td>Sand</td>
<td>0.063 - 2</td>
<td>0.01</td>
</tr>
<tr>
<td>Silt</td>
<td>0.004 - 0.063</td>
<td>0.001</td>
</tr>
<tr>
<td>Clay</td>
<td>&lt;0.004</td>
<td>0.0001</td>
</tr>
</tbody>
</table>

*Table 2.2 Order of magnitude of fall velocity for different sediment types*
2.4 Delta

The Atrato River has built an enormous sediment accumulation in the gulf of Urabá, see Figure 2.7. The Atrato River delta is a sparsely populated area with vast wetlands. Besides the ecological value of these wetlands the hydrological importance cannot be neglected. The wetlands are actively working as floodplains and prevent extreme flooding, which can occur due to heavy precipitation or when water levels at sea are higher than those in the river [INVIAS, 1992]. The delta area of the Río Atrato consists of a branched system with a total of 16 outflows into sea. Currently there are only three different branches that are used for small scale navigation (Coquitos, El Roto, Leoncito branch), mainly due to their location close to the town of Turbo, which is at this time the main port in the Urabá Gulf. For larger ships the gulf itself serves as port, only without quays. The current navigation in this area consists of passenger transportation and small-scale shipping of groceries, wood, banana and fuel. The cargo and barges that are currently used are not very draught demanding, but even so, periodical dredging of these branches is required due to high sedimentation in the vicinity of the river mouth [INVIAS, 2010]. The Atrato delta has some remarkable features. The banks both above and below water are comparatively steep. The lower Atrato does not manifest the sinuosity common for low-slope streams in flat, delta type floodplains. The meandering of the river at the delta is very slow. This may be due to the comparative densely vegetated floodplains, to the usually low velocity in the stream, and the erosion-resistant characteristics of the banks. As bank-full discharge is not so different from average discharge, it is to be expected that only severe floods are capable of eroding riverbanks. However, even for the severe floods the tough banks will probably prevent massive erosion.

Figure 2.7 Aerial photograph of the Atrato delta [Andres Calle, 2008]
2.4.1 Description of delta branches

In this report the names of the different outflows of the Atrato delta will be used extensively. With the aim of improving the readability the main branches are listed below in order from North to South. The current situation is described for each branch briefly. In addition, the exact locations of the branches are given in Figure 2.8.

**Brazo Tarena**
The Brazo Tarena is the only river branch which lies entirely in the Chocó. In this branch shipping takes place on a modest scale. The navigability of the river branch has been greatly reduced since the formation of the El Roto mouth. Due to the current limited natural depth and width of this branch, increased navigation in the near future seems to be an unlikely option, in advance.

**El Roto**
This river mouth was created in 1898 and subsequently developed into the main river mouth of the Atrato River. This mouth has been greatly expanded in seaward direction and this process still continues. The shipping through this river outlet is strongly negatively affected by the large mouth bar formation. This mouth bar is much larger than the other mouth bars in front of the other river mouths.

**Brazo Pavas**
This branch is not used for navigation purposes. The limited width and dense vegetation in this branch provide poor conditions for shipping.

**Brazo Matuntugo**
The Brazo Matuntugo is one of the larger branches of the Río Atrato. It is likely the Brazo Matuntugo offers good opportunities for navigability. However there is a military base situated on this river branch, so commercial shipping is not allowed to enter this branch.

**Brazo Coquitos**
The branch is located most near the port of Turbo and is therefore frequently used by shipping. Shallow areas are not known in this river branch. However, structural dredging maintenance in necessary to ensure ships are able to enter the river branch. This river branch has two separate outflows into the sea.

**Brazo Burrera**
This is a small branch to the sea. The conditions do not provide navigation on a large scale.

**Brazo Leoncito**
This branch is much longer than the other branches. The meandering pattern in the beginning of this river branch does not limit the navigation so far. Its convenient location to the port of Turbo has led to the fact this branch is regularly being sailed. Similar to the Brazo Coquitos, this river branch has two separate outflows into the sea. The southern mouth is the most preferred one for navigation activities. Nevertheless, structural dredging maintenance is also essential for this river mouth.

Figure 2.8 presents an overview of the delta.
2.4.2 Problems at delta

At this moment, the sedimentation at the river mouths of the delta causes minor navigability problems. Nevertheless, in the projected scenario where convoy and draught demands are much higher problems may arise. As mentioned before, current navigation takes mainly place along two of the delta branches, not necessarily because they possess the best conditions, but primarily because of their locations. Nonetheless, it is believed that the Tarena branch is less suitable for navigation. The main problems in the delta probably will be depth related, although also problems with bank-line positions are plausible. Problems with strong cross-currents are not noted and not likely.

Although the current navigation is not that draught demanding, periodical dredging is required due to high sedimentation rates near the river mouths. The most important reason for these high sedimentation rates is that, when the river enters the Gulf of Urabá, the currents slow down and lose their capacity to carry sediment. Consequently sediments accumulate in the river mouth area.

The flocculation process, explained in section 2.3, probably also enhances the sedimentation problems at the river mouth. The very fine sediments transported by the river form flocs when the fresh river water mixes with salt water of the ocean. The flocs have a greater propensity
for settlement than does sediment in its original state. Moreover, the heavier salt water tends to underrun the fresh water and to penetrate along the bottom upstream, which can cause sedimentation problems in the river near the tip of the salt wedge. This process can be counteracted if the freshwater flow is sufficient to push the salt water beyond the mouth of the stream. For the Atrato, it is believed that the shallow mouth bars enables the fresh water discharge to prevent salt water penetration along the bottom [LINDNER, 1969]. In the current situation, the flocculation process mainly takes place at the seaward part of the river mouths. Apparently, the huge force of the fresh outflowing water of the Atrato prevents mixing with saline water in the river, as we will see in section 5.1.

Nevertheless, a maintained deeper, dredged channel into the gulf will potentially permit the salt water to flow upstream along the riverbed. The flocculated sediment that settles into this bottom saline water will be trapped and will move back and forth with the tide until it deposits to form shoals or will be washed away during a flood discharge.
3. Literature study

The concept of a delta is one of the oldest in earth sciences, dating back to c. 450 B.C., when the ancient voyager and historian Herodotus observed that the alluvial plain at the mouth of the Nile was similar, in plain-view shape, to the Greek letter delta (Δ). Over the years, the term “delta” is not used exclusively for the Nile delta. For centuries, deltas intrigued researchers from different disciplines. The different studies can be roughly divided into studies on the development of the stratigraphy of the delta and morphodynamics of a delta. Both processes usually have a completely different time scale. The morphology corresponds to a normally short-term process, whereas the development of the stratigraphy usually corresponds to a long-term process. A typical example of a short-term morphological process in the deltaic area is the longshore sediment transport. The development of the shape of a delta over centuries is an example of stratigraphy as a research discipline. In this study, the knowledge gained from some of the major studies on the stratigraphy and morphology of a delta will be presented, hopefully giving one more insights into the deltaic environment of the Río Atrato.

This chapter gives an overview of the relevant literature on the processes that determine the deltaic environment. First, it addresses the definition of a delta. There are many classification systems for deltas. The most common three of these classifications are presented and reviewed. Subsequently, the dynamics at river mouths and bifurcations is treated. At the end of each section, the knowledge gained is applied to the Atrato delta.

3.1 Introduction to deltas

Alluvial rivers carry sediments downstream. When the river reaches the shore the sediments will be exposed to so called basinal processes. These processes will redistribute the sediments. At a river mouth various basinal processes may interfere with the redistribution process, such as longshore current drift, coastal current drift, waves, tidal currents and storms. The redistribution of sediments will be called the reworking of sediments in this study. The basinal processes and their interaction with the fluvial input mainly determine the shape of a coastline. Also the basin’s geometry is a key condition for the development of a particular coastline over time. A (sudden) imbalance between fluvial and basinal processes can cause a coastline shift. A coastline that migrates land inwards is called a degrading or a transgressive coast, whereas a seawards migration refers to a prograding or a regressive coast. Attributable to large differences in the strength of fluvial and basinal processes, many different types of coasts can be distinguished worldwide, such as deltas, lagoons, estuaries and strandplains. Figure 3.1 shows an overview for which conditions the different types of coastal formations can develop.
This study will obviously focus on delta formations. During the 20th century the definition and hence the classification of deltas was still under discussion. Nemec (1990) reviewed the delta terminology and rephrased the different definitions into a general one: "A delta is a deposit built by a terrestrial feeder system, typically alluvial, into or against a body of standing water, either a lake or a sea. The result is a localized, often irregular progradation of the shoreline controlled directly by the terrestrial feeder system, with possible modification by basinal processes, such as the action of waves or tides." This definition deals also with other terrestrial feeder systems than a river. Reading and Collison presented another definition in which the role of the sediment supply of the river was more prominent. This definition reads: "where a river supplies sediment more rapidly than basinal energy can redistribute, a discrete shoreline protuberance is developed, which is called a delta." In this study the definition of Reading and Collison is preferred.
3.2 Delta classification

Over the years, several delta classification systems have been developed. Many of these systems enable us to understand the stratigraphy and the morphology of a delta in more detail. This literature study is mainly about the morphological subdivision of several deltas and their morphological features.

The classification schemes of deltas can help to distinguish the various morphological processes which played a role in the formation of the current deltas worldwide and sort these processes on their relevance. Therefore the schemes may serve to predict the distribution of sediment in the future. In addition, the classifications assist to improve the communication about delta related problems. In this report the main emphasis is on the gaining of insights about the morphological features in the deltaic environment.

Nemec (1990) reviewed the large supply of different classification schemes in order to categorize the various classifications and to indicate their specific advantages and disadvantages for application activities. Nemec's work has a strong geological character, also classification schemes for non-river deltas are described extensively. This chapter will only elaborate on the results for the schemes for river deltas.

Nemec made distinctions for alluvial river deltas on the basis of three criteria:
- Thickness distribution
- Delta front regime
- Delta front regime combined with grain size

Classifications based on thickness distributions examine the relationship between the morphology of a delta and the stratigraphy of a delta. In this study the process of stratigraphy of deltas is not modelled. Nevertheless, this chapter briefly describes this classification because it explains the major driving forces to form a delta. Obviously the schemes which are based on delta front regime are of paramount interest for this study. As described before, the navigation problems, concerning the shallow water depths, are mainly concentrated in this area. The sediment reworking is described in these classifications by the interplay of fluvial and basinal processes in the area where the river meets the ocean.

The most widely used delta classifications schemes are COLEMAN AND WRIGHT (1975), GALLOWAY (1975) and ORTON AND READING (1993). Each of these three has its own main classification criterion. According to Nemec the Coleman and Wright classification belongs to a thickness distribution. On the other hand the Galloway classification with the world-wide known triangular scheme primarily concentrates in the field of delta front regime. Orton and Reading combined the work of Galloway with sediment characteristics and is consequently probably the most interesting for this study. However, WRIGHT (1985) judged that each delta has its own unique and distinct characteristics and that no classification scheme could adequately contain all deltas in the world.

Coleman and Wright

In the 1970s Coleman and Wright published a series of papers about the processes that have contributed to the development of today’s river deltas [WRIGHT AND COLEMAN, 1972; WRIGHT AND COLEMAN, 1973; WRIGHT et al., 1974; COLEMAN AND WRIGHT, 1975]. They included so-called control processes in their work, which are often used as a basis for classification schemes. Coleman and Wright revealed twelve processes that either directly or indirectly contribute to the formation of deltas, as we know them today. The list illustrates the wide variety of processes that affect the deltaic environment.
The twelve factors which have influence on the formation of a delta are:

- Climate
- Drainage basin
- Discharge regime
- Sediment yield
- River mouth processes
- Wave power
- Tidal forcing
- Wind systems
- Currents
- Shelf-slope
- Receiving basin geometry
- Tectonics of receiving basin

Coleman and Wright defined four separate parts of a river delta:

- The basin. The basin has major influence on the river and the sediment discharge.
- The alluvial valley. The characteristics of the alluvial valley mainly determine the shapes and the course of the river.
- The delta. In the study of Coleman and Wright the delta forms the link between the alluvial valley and the receiving basin.
- The receiving basin. The processes of the receiving basin determine largely the resulting shape of the coastal formations of a delta.

Figure 3.2 shows a schematization of the twelve processes and in which part of the delta these processes are involved.

![Diagram](image_url)
The resulting delta shape, with some remarkable characteristics, is based on a combination of these control processes. Based on these twelve different control processes, it would be in line with the expectations that there is a huge list of different types of deltas. However, Coleman and Wright identified six broad classes of deltas because they argued that only certain combinations are common. The types of sediment distribution patterns are described below:

**Type 1**
The river is completely dominant over the marine forces. The delta is shaped as a pattern of prograding, branching distributary channels. Often from a top view, a typical bird-foot pattern could be recognized. Also the appearance of extensive marshes is a feature of this type. The most classical example of this type of delta is the Mississippi, which not only transports an enormous amount of sediment, but also empties into the Gulf of Mexico with its low tide-range and low wave-energy.

**Type 2**
The shape of a type 2 delta corresponds to a macro tidal environment in which the location of the land-sea interface and therefore the zone of riverine-marine interactions is varying largely over time. Great linear tidal sand ridges are formed and replace the distributary mouth bars, which are common at other types of deltas. As the delta progrades over time, large and straight tidal channels are shaped by the growth of the sand ridges. An example of this type is the Ganges-Brahmaputra.

**Type 3**
The third model of delta geometry is characterized by a broad range of characteristics. The morphology is the result of a combination of riverine, tidal and wave forces, without that any of these forces is actually much stronger than the other ones. However, in this class of deltas the formation of beach ridges is a common feature. In addition, features may vary seasonally in this class. River discharge and waves can change considerably during the year. An example of this seasonally varying character is the Mekong delta in Vietnam.

**Type 4**
Type four is another example of an intermediate form. This type of delta is characterized by the presence of offshore bay-mouth beach barriers that shelter lagoons, bays, or estuaries into which low-energy deltas prograde. The contrast to river dominant models is that the major accumulation of sediment occurs landward of the main sand body (the barrier) within the protected bay. Nonetheless fine suspended material could reach the open sea, where the wave action is strong enough to prevent closures.

**Type 5**
The distributary mouth bar deposits are restricted to the direct vicinity of the river mouth. The high wave energy reworks the sediment directly. Due to the continuous wave energy the riverine sediment is redistributed and large sand sheets are formed. The waves approach the coast almost perpendicularly and therefore the littoral drift is low. As a result of strong winds, the delta plain often consists of dunes. The best example for this type of delta is the Río São Francisco in Brazil.

**Type 6**
Similar as type 5 this type of delta is wave dominated. However, this type of delta has quite some different features. The main differences are a result of the high littoral drift, which is presented for this type of deltas. Quite a number of abundant beach ridges parallel to the prevailing shoreline trend can be found. The shoreline is frequently straight because of the high wave energy and a strong unidirectional littoral drift. The Senegal River in the western part of Africa is the most extreme example of this type.

In Figure 3.3 all the sediment distribution patterns according to Coleman and Wright (1975) are presented.
An advantage of this classification system is that it provides a clear understanding of the processes that form a delta. One downside is that the detailed input results only in a general classification of a set of six end-member types.
Galloway

The most famous work on classifications of deltas has been written by Galloway (1975). Galloway assumed that delta morphology and stratigraphy are the result of an interplay of fluvial sediment input and the reworking of basinal processes. This interplay is responsible for the transport and depositing of sediment. Galloway made a major simplification to focus his classification scheme on the two main basinal processes, wave and tidal energy. Other basinal processes (oceanic currents, storm surges and wind drift) do play an important role in the formation of a delta, but are much less important.

Galloway presented a triangular diagram (see Figure 3.4), in which every corner schematizes the influence of fluvial, wave and tidal processes. In this figure deltas can be plotted with respect to the influence of fluvial, wave and tidal processes. Six example deltas have been plotted in the figure to improve the user’s assessment to implement the scheme. The schedule can be regarded as a first instrument to classify deltas and to determine the prevailing basinal processes. Nemeč (1990) argued that this scheme largely depends on the personal qualitative estimates of the user. In addition to that it is not possible to represent specific features of deltas separately in the diagram. This makes the schedule rather general.
Orton and Reading (1993)

In 1993, Orton and Reading presented an elaboration of the scheme of Galloway. In the triangle of Galloway little attention is paid to the influence of sediment input. The effect of sediment rework is still strongly dependent on sediment characteristics. Orton and Reading paid attention to the influence of sediment characteristics and implemented their results in the diagram of Galloway. Their study showed that the shape of a delta is highly dependent on the available type of sediment. The dots combined with two letters in the diagram represent a certain delta, see Figure 3.5. In Appendix A, the diagram is also presented combined with the complete list of explanations of the abbreviations used in the scheme. The figure shows that for most deltas the median sediment diameter is categorized as fine sand. Furthermore coarse grained deltas are subject to little tidal influence and no mud/silt deltas are wave-dominated.

Figure 3.5  Delta classification with the influence of sediment input (ORTON AND READING, 1993)

This classification scheme is a useful elaboration of the scheme of Galloway. Without measurements a first indication of the sediment characteristic could be obtained. Nonetheless, the diagram does not include the influence of density differences and cohesiveness, while they are important parameters for the morphology of the delta as well. Next to these missing parameters, another important shortcoming of this classification is that not all the variables are independent. The sediment reworking strongly depends on the sediment size. This makes the scheme less reliable.
The Atrato delta

The small tidal range, the mild wave regime and the large river flow and the large sediment load qualify the delta clearly as river-dominated according to Galloway's classification [GALLOWAY, 1975]. In addition, the relative shallowness of the seabed of the Gulf of Urabá has a major role in the development of the delta. From above a clear bird foot geometry could be recognized, see Figure 2.7.

The Río Atrato shows considerable similarities with the Mississippi River, although the river discharge and the sediment discharge of this river are of a completely different order magnitude. With some imagination, the Río Atrato can be considered as a little brother of the Mississippi, with the major difference that the Río Atrato is still relatively untouched by human activities. In the three treated classification systems, the position of the Río Atrato is always very close to the position of the Mississippi. This conclusion can be extremely useful, if major interventions in the river are considered in the future. The Mississippi river can serve as reference and the morphological response to interventions could be easily predicted for the Río Atrato. Currently, the Mississippi delta is more and more drowning, which causes severe wetland losses. The delta receives too little sediment, which is probably due to the large amount of interventions in the river [DAY et al., 2007; BARRAS et al., 2003]. With this information in mind, a better policy for the Río Atrato could be made.

The Atrato delta can be classified as more wave dominated than tidal dominated. In the delta absolutely no features are present, that would indicate that the delta responds to the influence of tide. This is in contrast to the wave impact. There are a few locations where the influence of a littoral drift is visible. This is particularly true for areas closer to the open ocean, where the delta can be exposed to moderate wave energy. One example is the spit formation at the mouth of Matuntugo, see Figure 3.6.

![Figure 3.6 Spit formation at Matuntugo mouth (Joel Kike 2010)](image)

Nevertheless, the classification of the delta remains highly fluvial dominated, with a slight deviation to wave dominated. The classification scheme of Orton and Reading describes a muddy and silty sediment supply for the Mississippi delta and thus probably also for the Atrato delta, which is in line with the sediment sample taken in November 2010.
Conclusion

This section presented a short overview of classification systems for deltas. All the schemes put emphasis on the zone where all the forces come together (i.e. the river mouths). Less attention is paid to the river behaviour. A change in the course of the river will have great impact on the evolution of the delta. For example, the evolution of the Mississippi river (over the past 6000 years) can be divided in six delta lobes. A lobe is a distinct area of sediment deposits, related to a specific course of the river to the sea. Major lobes are not present for the Atrato. However, the river behaviour and its capability to change the course to the sea is still enormously important for the evolution of the Atrato delta [GARCIA-VALENCIA, 2007].

Furthermore, the classification schemes described in this section are rather descriptive. Nevertheless, the classification schemes can be used to determine certain features and helps to explain certain morphological behaviour. Delta classifications show that deltas are dynamic and complex systems in which different processes interact with one another. In particular this interaction of different processes can be modelled well in a process-based model. The classification systems can be used to check the output of such a model, although the model requires much more detailed and site-specific information. Therefore, the model results will never be completely equal to the examples of the classifications schemes.
3.3 River mouth flow and sediment deposition

In this study, the river mouth geometry and its mouth bar dynamics are of paramount interest. The sediment accumulations at the river mouths are currently causing severe problems for navigation. In this section, some patterns of these sediment accumulations are described for river-dominated deltas according to Wright (1977). In addition, this chapter aims to gain insights into the patterns of the river mouth deposition and to distinguish the relevant morphological processes at the mouths of the Atrato delta.

The diffusion of the fresh river water and the subsequent sediment dispersion depend on the relative strength of three main factors:

- Buoyancy as a result of a density difference between the river flow and the sea water
- The inertia of the outflowing river water and the related turbulent diffusion
- Friction between the effluent and the seabed, just seaward of the river mouth.

Based on these factors, three depositional models are identified for typical river-dominated deltas.

1. Buoyancy dominant depositional model
   As a result of a density difference between fresh water and saline water, a stratified situation can occur. In case of stratification, the fresh water flows over the saline water and a salt-wedge at the river bottom can be formed. The sediment rich fresh water becomes isolated from the effects of bottom friction. The buoyancy prevents mixing and the effluent is spread over a wide area. The velocity of the fresh water is decelerated by the upward entrainment of seawater across the density interface and deposition occurs. The typical depositional pattern of buoyant effluent are narrow bar deposits that prograde seaward as laterally restricted ‘bar-finger sands’.

2. Inertia dominated depositional model
   When the outflow velocities are considerable, the depths at the river and immediately seaward of the mouth are likely to be large. The density difference between the outflowing water and the saline sea water are also low immediately seaward of the mouth. When outflowing, the effluent spreads and diffuses as a turbulent jet. In this case the inertial forces dominate. As the jet expands, its momentum decreases and subsequently its capacity to carry sediments decreases. As a result, the sediments are deposited in an area, which in plan view looks like an elongated bubble. A strong sediment sorting process can occur, because the coarser sediment will obviously settle sooner than the more fine material.

   This depositional model often turns out to be unstable. Due to the growing bar in front of the river mouth the friction forces become more and more important and cause a rapid deceleration of the jet. This depositional model can eventually change into a friction dominated one.

3. Friction dominated depositional model
   In this depositional model a clear pattern of bars and levees is formed. In the first stage a broad bar is formed in front of the river mouth by the fast expansion of the outflowing jet. At the sides of river mouths often natural subaqueous levees are shaped, because there the velocity also decreases suddenly very rapidly. The jet is now forced to mainly flow around the bar and is constricted by the formation of the subaqueous levees. Eventually the formation of a bifurcating channel can arise with a triangular shoal that separates the diverging channel arms. The flow tends to be concentrated fully in the diverging channel arms and the flow over the bar will be tranquil, which enhances further sedimentation.

   This is the most ordinary type of river mouth flow and sediment deposition, where non stratified outflow enters a relatively shallow basin.
Conclusion
It is difficult, without extensive data of bed level changes and salinity, to choose a deposition model which approaches the situation at the mouths of the Atrato most optimally. In this study, this is also not a goal. More important is to understand the deposition behaviour in the delta. Besides, a combination between the three models seems most likely and the situation will differ for each river mouth. The output of the models is checked on whether they meet the behaviour, described in these deposition models.
3.4 Wave influence on deltas

In this report the influence of waves is not considered. Nevertheless, waves are considered as a governing marine process in coastline development. Especially the sediments in the shallow river mouth are subject to the reworking process by waves. Combined with the variability in sediment supply and the tidal power, the wave action determines the shape of the river mouth and the different features, which can develop in a deltaic environment. The influence of the tide is in common noticeable in large parts upstream the river mouth, whereas the wave action only influences the morphodynamics of the system in the vicinity of the river mouth. The waves are able to rework the sediment. If the waves approach the coast under a certain angle, the waves may cause a shift in the river outflow orientation.

The sediment reworking by waves is often divided in two steps. The threshold of the initiation of motion has to be exceeded by the oscillating motion of waves and the energy of breaking waves. If so, the sediments in the bed are stirred up and transported by currents. The sediment characteristics have a main impact on the process of sediment reworking. The initiation of motion and transport of sediments particles depends on grain size. Fine sediments will be stirred up and transported more easily than coarser sediment. This can cause sediment sorting and enhance the possible formation of coastal features as beach-ridges, barriers and spits.

Waves induce currents and therefore also possible sediment transport, which can be directed in both onshore and offshore direction. Near the surface the sediment transport is, in general, directed landwards and near the bottom a return current is formed which transports the sediment seawards. If waves approach the shoreline under a certain angle also a net longshore transport is present.

The variation and the interaction of fluvial and wave processes make the morphology hard to predict. Waves can have a key role in the development of the delta and its navigability. Especially for the river mouths located relatively close to the open sea (i.e. Tarena, El Roto, Pavas and Matuntugo) the influence of waves on the local mouth morphology is hard to neglect. The typical shape of a bird-foot delta provides shelter for the more southern river mouths. WRIGHT (1977) determined sediment distribution patterns near river mouths under the influence of waves in detail. Figure 3.7 shows two typical examples:

a. This figure presents a classical example of a wave dominated river mouth with perpendicularly incoming waves. A very symmetric profile is obtained with swash bars on both sides of the river mouth.

b. This figure shows an example of a river mouth, where oblique waves shift the river mouth, a longshore current is formed.

![Figure 3.7 Features of a river mouth with a large influence of waves (WRIGHT, 1977)](image-url)
The wave action in the Gulf of Urabá is not strong enough to produce swash bars as shown in Figure 3.7. Besides, the great amount of very fine sediments did not favour the formation of typical wave-induced features.

**Conclusion**

The impact of waves on the river mouths of the Atrato will play an important role in the distribution of the deposited sediments from the river branches. However, as a result of the specific shape of the Gulf of Urabá and its shallowness the occurring wave heights are limited, and the mouths will likely remain river-dominant. Nonetheless, for the more northern mouths of the Río Atrato, the influence of waves could be observed in the layout of the river mouth. The oblique incoming waves have resulted in a spit formation. The influence of waves at the more southern river mouths is probably less. However, the waves probably distribute the sediments to both sides of a mouth, which has a positive effect for navigability. The effect of waves is not modelled in this study. Yet, it is expected that the models used are able to approach the occurring morphological behaviour at the southern river mouths rather well. A follow-up study could examine the impact of waves.
3.5 Bifurcation dynamics

At the delta, the Atrato River is divided into various branches. Bifurcations can produce bottlenecks in the navigation corridor, because the dynamics of the bifurcation determine the long-term evolution of the downstream branches. To understand the processes at bifurcations fully, one needs some insight into the dynamics. This section outlines some of the fundamental basics on this topic briefly.

A river bifurcation divides water and sediment over two branches. This is a dynamic process, where the division of flow and the sediment distribution at the bifurcation ultimately leads to two stable bifurcates or closure. In physical terms, the bifurcation is not in equilibrium if one channel receives less sediment than its transport capacity, so that it erodes, and the other channel receives more than its transport capacity, so that it silts up. This process may still lead to a final stable situation. A bifurcation becomes truly unstable if a small disturbance in one branch leads to a stronger increase in sediment supply than the increase in transport capacity.

It is understandable that the distribution of discharge and sediment plays a key role in bifurcation issues. To solve this problem a nodal point formulation has been introduced in one-dimensional models to relate the discharge division and the sediment division. The division of discharge $Q_0$ into discharge $Q_1$ and discharge $Q_2$ at the nodal point has been derived by imposing the conservation of mass and the conservation of momentum. The water levels have to be equal at the nodal point for each branch. For the division of sediment discharge $S_0$ into sediment discharge $S_1$ and sediment discharge $S_2$ this condition is not sufficient. A nodal point relation is required to determine this division. WANG et al. (1995) analysed the hypothetical relation:

$$\frac{S_1}{S_2} = \left(\frac{Q_1}{Q_2}\right)^k \left(\frac{W_1}{W_2}\right)^{1-k}$$

In which $W$ represents the width of the bifurcate channel and $k$ an empirical value. The value of $k$ could be found from a nonlinear stability analyses (phase-plane).

In order to determine the occurring sediment distribution at a river bifurcation, one needs to know the local transport mechanism. When most of the sediment is transported in suspension, the sediment distribution will be almost in line with the discharge distribution. However, when the suspended load component is relatively low compared to the bed load transport, the transverse circulation flow, which occurs in bend flow, becomes of great influence.

This chapter discusses a number of causes that may lead to a disproportionate or even an unstable sediment distribution. Though, some factors play mainly an important role for dominant bed-load mechanisms. In the lower part of the Río Atrato, the sediments are primarily transported in suspension. Therefore, some causes are considered as less important. However, even for suspended load the highest sediment concentration is located near the river bottom.

**Higher flow resistance**
The branch with a larger distance to the sea will be more subject to silting up.

Besides this reason also local conditions are important in the division of sediment over the two branches. The geometry at the bifurcation makes every bifurcation unique and acting differently. Four local causes which can cause unstable sediment distributions are treated below.

**Bulle effect**
The river and an off-taking branch form a bend together, in which spiral flow occurs. At the bottom of the bifurcation, the water flow will be oriented towards the off-taking branch, while at
the water surface the flow will be directed towards the main river. Because the sediment concentration at the bottom is larger than the sediment concentration at the water surface, relatively more sediment will flow in the off-taking branch than into the main river. This effect was for the first time described in a publication of BULLE (1926) and therefore this principle is called the Bulle-effect. The occurrence of the Bulle-effect depends on the discharge distribution over the branches, the width-depth ratio and the local geometry of the dividing point.

Gravity pull
Also the local bed topography might cause the bed transport to favour one branch. This can occur due to the gravity pull on a side slope in the river. Figure 3.8 shows a situation in which relatively more sediment is transported into the off-taking channel.

Asymmetrical approach conditions
If in the upstream part of the bifurcation large differences in the bed topography in transverse direction are present, the sediment division can be influenced. For example, deeper parts near one of the banks causes higher flow velocities and higher sediment transport in this area. Therefore one branch can receive more sediment, than would be expected based on geometry of the bifurcation itself. This process can also cause sediment sorting, because the coarsest sediments are only transported by the high flow velocities.

Flow separation
In case of a sharp edge in the off-taking river branch, the flow cannot follow the bank line. A kind of reattachment point can be introduced where the flow hits the river bank again. Between the bank and the corresponding reattachment flow line an eddy is formed. However, exchange between the water in the eddy area and the main stream occurs due to turbulence between the dividing line of the main stream and the eddy. In this way, the sediments can go into the eddy and be brought to the centre, where the sediments become trapped. The water flowing out of the eddy is relatively clear. This mechanism also explains a situation where relatively more sediment flows into one branch than into the other one. The mechanism of flow separation is sketched in Figure 3.9. The effective flow width ($W_1$) in the off-taking bifurcate is smaller than the real width ($W_2$).
One can make use of the local geometry and bathymetry, in order to distribute the sediment in a more desirable way. For example, a shallow bifurcate in an outside bend can be used to minimize sediment supply in the off taking bifurcate, because the upper part of the water column contains less sediment. This holds even for suspended load. This strategy is often implemented to connect irrigation channels with a river system, in order to achieve relatively low sediment concentrations in the irrigation canals. Other way around, a bifurcate in the inner bend will probably extract a higher sediment load.

A process-based model tends to predict a development to a stable bifurcation, hence highly asymmetric discharge divisions can be predicted. This is explained in KLEINHANS et al. (2008). However, in the closure process of a particular branch several processes do interact, which are not well included in current process based models. The effect of captured sediment by vegetation is until now not included in various process based models. This effect can enhance the closure of a bifurcate channel.
Closure of branch
Because process-based models often do not predict a complete closure of a certain branch, the natural process is here described briefly in combination with Figure 3.10.
(1) If more sediment is entering a branch than its sediment transport capacity, immediately after the bifurcation a sedimentation shock wave is formed.
(2) The sediment will squeeze the entrance. Due to this obstacle locally a steeper water level profile arises, which means that the backwater curve corresponding to matching water levels at the bifurcation now represents a lower discharge.
(3) Once the discharge becomes smaller, the riverbed can be exposed during low flow conditions and vegetation can be able to take possession of these areas.
(4) Vegetation will capture sediment, even wash load, and the sedimentation process continues. Also a likely M1 backwater curve introduced by the sea will enhance further sedimentation, because the flow will decelerate.
So several processes can actually contribute to a closure of a river branch.

![Figure 3.10 Closure of a branch](image)

Conclusion
Some insights into the dynamics of bifurcations is of paramount interest in this study. The delta counts various bifurcations. Eventually at least one bifurcate has to serve as a sustainable navigation route in the future. A number of local processes which may lead to a disproportionate or even an unstable sediment distribution have been treated in this chapter. Because most of the sediments will be transported in suspension, most processes are not relevant for this study. However, the process of flow separation will probably be important, because there are various bifurcations in the delta present with an off-taking bifurcate under a large angle.
It is not likely the morphological models will forecast a complete closure of a particular branch, because in reality a complete closure could be initiated by processes which are not described in a process-based model. It is very important to take this into account when the model output is analysed.
4. Model Approach

4.1 Model purposes

The hydrodynamic and the morphodynamic models set up in this study are not meant as exact replicas of the river delta, but rather as tools that can help in the management and in the optimum development of the delta system. Above all the models can serve as tools for:

- Gaining insight into the morphological processes for site-specific areas of the Atrato delta
- Improving the understanding of the system functioning as a whole
- Increasing the accuracy of system response to given events.
- Assessing the effects of alternative measures
- Providing design conditions for eventual measures
- Communication with different stakeholders

It is important to note that the model output should be taken with great caution. Due to the unavailability or the incompleteness of some important data several assumptions were made. The models are to a large extent dependent on these assumptions. A further calibration, validation and a sensitivity analysis are strongly recommended.

An extensive calibration is necessary before the predictions of the models are usable to present to the policy makers. First, a comprehensive hydraulic calibration has to be executed, followed by a morphological calibration.

4.2 Choice of numerical models

To investigate 2D/3D hydrodynamic and morphodynamic processes in a large and a topographically complex delta area a hydraulic software package with a flexible grid generator is required. A world-wide often used system capable to model such areas is Delft3D, developed by Deltares. The Delft3D model is used in this study, because of its proven capabilities and because the software package is free to use at Delft University of Technology and Deltares. However, other available modelling packages like Mike (DHI, Denmark) are capable to model the same phenomena. Nevertheless, Delft3D has gone open source, possibly leading to an increase in Delft3D usage over the world and, important for this study, the models used are easily adaptable if further research is executed.

The Delft3D system is based on finite volumes and on curvilinear grids (quadrilateral grid cells). To accurately resolve flow processes in large topographically complex areas, a locally variable grid resolution is desirable. Delft3D offers this modelling capability by local grid refinement often referred to as domain decomposition.

At the moment (2011), Deltares and Delft University of Technology are developing an unstructured grid system based upon the successful numerical concepts of SOBEK and Delft3D. Despite all the possibilities of a curvilinear grid, some drawbacks cannot be ignored. The most important one is the sometimes unavoidable staircase representation of coastlines and banklines in rivers. Another one is the problem in inner bends of meandering rivers, where gridlines are concentrated, leading to undesirable small grid cells. Also problems in grid orthogonality can occur by flow bifurcations. Without application of domain decomposition, local grid refinement often leads to undesirable high resolution of the grid in other parts of the modelled area.

In view of the drawbacks of a curvilinear grid and the amount of bifurcations in the delta, it was decided to use the new unstructured system, D-Flow Flexible Mesh. An unstructured grid (often referred to as a network) is capable of dealing with the problems mentioned above. The high degree of freedom of using a combination of triangles and quadrilaterals or even other types of cells like pentagons and hexagons illustrate the possibilities of an unstructured grid in complex areas, like a delta.
At present, the unstructured model system can only be used to model the hydrodynamics of the delta. Currently, the software department of Deltares is working to realize the link to morphology. Unfortunately, the extension to morphology of the system could not be completed during this graduation. However, at this stage of the project, more detailed insights into the hydrodynamics of the delta are very valuable. At present, little is known about how the river system responds to tidal intrusion, flood waves, etc. Moreover, a large hydrodynamic model partly solves the problem of the large backwater adaptation lengths, see Appendix C. The unstructured model is capable of modelling the division of discharge at the numerous bifurcations in the delta more adequately and could serve as a first tool to set up a morphodynamic (detail) model. To compose an accurate morphological detail model comprehensive time-dependent boundary conditions are necessary. These boundary conditions are obtained from a large D-Flow Flexible Mesh model.

It was decided to model both the hydrodynamics and the morphodynamics in two dimensions (2DH). A two-dimensional horizontal model (2DH) is the result of integration over the water depth (vertical dimension) of the partial differential equations. In a 2DH model, often simply referred to as 2D model, the flow velocities near the water surface and near the river bed are not computed individually. The equations only deal with the depth-averaged velocity. If applied in large areas, three-dimensional models require massive computational power. Besides, three-dimensional effects can be included in 2DH models in a parameterized way to overcome the shortcomings of a model of a lower number of dimensions. For example, the parameterization of helical flow is a standard feature of the better 2DH models. Helical flow arises in river bends and results in differences in direction between sediment transport and the depth-averaged velocity. A 3D approach can be useful in future, more detailed studies. However, a 2DH approach is preferred in this stage.

The software packages Delft3D and D-Flow FM are both process based numerical models, which means that they are based on several physical principles, such as the conservation of mass principle, the conservation of momentum principle and the conservation of energy principle. The fundamental equations are given in Appendix C.
4.3 Input data

This chapter elaborates on the available and the required data to attain accurate and representative models of the Atrato delta. A table of desired data is given with attached the reason of importance and the availability of the data. Until now, only very limited research and data surveys have been carried out at the Río Atrato. Therefore the availability of data is limited and the data of the few surveys executed are difficult to collect. However, these limitations do not need to pose impediments to the modelling. The questions in the modelling in this thesis do not require accuracies of centimetres, and combined with some educated assumptions the present data are sufficient to start the development of models which can help to improve the navigability of the Atrato delta.

A sub-goal of this study is to present, despite a lack of data, a model as accurate as possible, which is also easy to adapt. Today’s open source approach of the Delft3D program and the open source approach of D-Flow FM in the near future make the models easy to adapt in the future if more data become available. For example, the results of new bathymetrical surveys can be implemented quickly and easily in the model.

4.3.1 Data requirements and availability

In this section a table (Table 4.1) is presented of specific data requirements and the current availability of these data in order to attain realistic model results. Of all data, the reason of importance is given and for which model (hydrodynamic/morphodynamic) the data are relevant.

<table>
<thead>
<tr>
<th>Data requirements</th>
<th>Reason of importance</th>
<th>Availability</th>
<th>Model</th>
</tr>
</thead>
<tbody>
<tr>
<td>- River hydrodynamics</td>
<td>The river hydrodynamics have a key role in the morphodynamics in the delta. The river flow strongly determines where erosion and deposition occur and the rate of these processes.</td>
<td></td>
<td>H/M</td>
</tr>
<tr>
<td>- Discharges</td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>- Water levels</td>
<td></td>
<td></td>
<td></td>
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<tr>
<td>- Velocities</td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>- Discharge distributions over the several branches</td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>- Discharge of tributaries</td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>- Hydraulic roughness</td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>- Tidal information</td>
<td>The astronomical tide presents an energy which influences the delta environment and geometry.</td>
<td></td>
<td>H/M</td>
</tr>
<tr>
<td>- Bathymetry Golfo de Urabá</td>
<td>The bathymetry of the Golfo de Urabá is of great importance. It affects the incoming waves and will influence the propagating/degrading character of the delta.</td>
<td></td>
<td>H/M</td>
</tr>
<tr>
<td>- Planform of the delta area</td>
<td>The topography of the area will determine the shape of the delta. Due to the topography the river can shift to a shorter route to the basin.</td>
<td></td>
<td>H/M</td>
</tr>
<tr>
<td>- Land use</td>
<td>The delta area consists mainly of elongated wetlands and marshes, but also of populated areas. The land-use should be taken into account in this study.</td>
<td></td>
<td>M</td>
</tr>
<tr>
<td>- Populated areas</td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>- Floodplains</td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>- River Bathymetry</td>
<td>The river bathymetry is necessary to detect possible bottlenecks for navigation.</td>
<td></td>
<td>H/M</td>
</tr>
<tr>
<td>- Floodplain bathymetry</td>
<td>The floodplains will influence the morphodynamics and hydrodynamics in</td>
<td></td>
<td>H/M</td>
</tr>
</tbody>
</table>
- Wave climate
  - Frequencies of occurrence of:
    - Wave heights
    - Wave directions
    - Wave periods
  Waves can play a crucial role in the deltaic development. Waves can initiate motion of sediment in the bed by stirring up sediments due to oscillating motion and the energy of breaking waves. The sediments are stirred up and can be transported by currents. If waves approach the shoreline under a certain angle a net longshore transport is present.

- Sediment transport in the river
  - Quantities over varying seasons
  The transport of sediment can be considered as the main driver of a delta. A difference in the sediment transport regime will affect the geometry of the delta enormously.

- Sediment statistics
  - Sediment types (sand/silt)
  - Grain sizes
  The sediments, distributed by the river, are of great importance for the deltaic environment. The type and size of the sediments will determine the location where the sediments will settle.

- Aerial photographs
  - Pictures of multiple years
  - Historical maps
  These photographs and historical maps will gain insight in the dynamics of the delta evolution over years. It is of major importance to determine the development of the delta.

- Current dredging maintenance
  - Quantities
  - Locations
  - Criteria
  It is obvious dredging will interfere with the natural deltaic environment. In combination with other data, one can obtain better understanding of the response to changes.

- Occurrence of hydraulic structures
  - Year of construction
  For hydraulic structures the same holds as for dredging maintenance.

- Occurrence of possible coastal currents
  Coastal currents will cause redistribution of alluvial sediments along the shore. Combined with the basin’s geometry and the interplay of fluvial input and other basal processes it determines the shape (development) of a coastline.

- Wind statistics
  - Wind directions
  - Wind speeds
  Wind can cause wind set-up in the Golfo de Urabá. Besides it actually can result in currents in the water and can contribute to the development of the delta.

- Seismic activity
  - Dates and effects of recorded earthquakes
  The delta is situated in a seismically active location. The uplift/subsidence of the tectonic plate will cause enormous effects in the river, delta and coastal regime.

- Salinity properties
  In an area where saline water and fresh water meet, salt intrusion can occur. The intrusion of saline water can affect the sedimentation process.

<table>
<thead>
<tr>
<th>Table 4.1</th>
<th>Data requirements and availability</th>
</tr>
</thead>
<tbody>
<tr>
<td>delta. The extent of these influences depends on the bathymetry of these wetlands</td>
<td>M</td>
</tr>
<tr>
<td>Waves can play a crucial role in the deltaic development. Waves can initiate motion of sediment in the bed by stirring up sediments due to oscillating motion and the energy of breaking waves. The sediments are stirred up and can be transported by currents. If waves approach the shoreline under a certain angle a net longshore transport is present.</td>
<td>M</td>
</tr>
<tr>
<td>The transport of sediment can be considered as the main driver of a delta. A difference in the sediment transport regime will affect the geometry of the delta enormously.</td>
<td>M</td>
</tr>
<tr>
<td>The sediments, distributed by the river, are of great importance for the deltaic environment. The type and size of the sediments will determine the location where the sediments will settle.</td>
<td>M</td>
</tr>
<tr>
<td>These photographs and historical maps will gain insight in the dynamics of the delta evolution over years. It is of major importance to determine the development of the delta.</td>
<td>H/M</td>
</tr>
<tr>
<td>It is obvious dredging will interfere with the natural deltaic environment. In combination with other data, one can obtain better understanding of the response to changes.</td>
<td>M</td>
</tr>
<tr>
<td>For hydraulic structures the same holds as for dredging maintenance.</td>
<td>H/M</td>
</tr>
<tr>
<td>Coastal currents will cause redistribution of alluvial sediments along the shore. Combined with the basin’s geometry and the interplay of fluvial input and other basal processes it determines the shape (development) of a coastline.</td>
<td>H/M</td>
</tr>
<tr>
<td>Wind can cause wind set-up in the Golfo de Urabá. Besides it actually can result in currents in the water and can contribute to the development of the delta.</td>
<td>H/M</td>
</tr>
<tr>
<td>The delta is situated in a seismically active location. The uplift/subsidence of the tectonic plate will cause enormous effects in the river, delta and coastal regime.</td>
<td>H/M</td>
</tr>
<tr>
<td>In an area where saline water and fresh water meet, salt intrusion can occur. The intrusion of saline water can affect the sedimentation process.</td>
<td>M</td>
</tr>
</tbody>
</table>
The previous listing of data availability indicates that the data on some topics are lacking. However, some data topics are not limited. The data topics that are marked as no limitations are further discussed below.

**Bathymetry Golfo de Urabá**

Two sources have been considered to reproduce the bathymetry of the gulf as accurately as possible. In the Atlas of the Gulf of Urabá [GARCÍA-VALENCA, 2007] a picture is shown of a digital elevation model, which has been made in 2001. This source of data is mainly used to get a rough idea of deeper and shallow areas in the Gulf of Urabá. To model the bathymetry of the gulf in more detail in the model digital nautical charts have been used. The charts of TheMap ® 10VR 3d professional of Chartworx have been used. Data from these charts use a special reference level, namely LLWS (low low water spring). The differences in reference level are taken into account.

**Planform of the delta area**

The planform of the river is made available by combining basic chart topography with satellite images. The most recent bank-line file is used as a closed boundary in generating a numerical grid.

**Land use**

The fieldtrip has shown that the delta areas is barely populated and almost entirely consist of extensive wetlands. In the hydrodynamic models a large part of these wetlands are included, in order to investigate the influence of these areas on the hydrodynamic behaviour of the delta.

**Aerial photographs and historical maps**

Several historical maps from the atlas of the Golfo de Urabá have been used to investigate the evolution of the delta [GARCÍA-VALENCA, 2007].

**Occurrence of hydraulic structures**

In the delta area no hydraulic structures are present.

**Occurrence of possible coastal currents**

There are significant coastal currents present in the Golfo de Urabá [GARCÍA-VALENCA, 2007].

**Wind statistics**

Wind statistics of the area can be provided at the website of DIMAR. The influence of wind on the hydrodynamics and morphodynamics of the delta is not investigated in this report and may be interesting to investigate further in a follow-up study.
4.3.2 Assumptions for limited data

The listing of data availability in Table 4.1 indicates that multiple assumptions should be made. The data that are marked as limited or even as not available are discussed below. The assumptions made in this study to achieve a proper model are explained.

River hydrodynamics

At the moment no data are available on the river hydrodynamics in the delta area. At the moment, the Bellavista station is the closest station with a data set that contains average daily discharges. Therefore the data of this station were preferred for use in this study. However, this station is located relatively far upstream of the delta area. In order to gain insights into the river hydrodynamics a large model was set up in this study with the upstream boundary located at Bellavista.

In order to examine the influence of different discharge regimes to the delta, five specific discharge conditions have been selected; two relatively low discharges, an average discharge and two relatively high discharges. These conditions are based on the discharge exceedance curve of Bellavista, which is given in Appendix F. For this report, two specific low daily discharges are chosen with a probability of exceeding of 95% (347 days a year) and 75% (274 days a year). For the average daily discharge a condition is selected which is exceeded 182 days a year (50%). Furthermore, a daily discharge condition is modelled with a probability of exceedance of 25%. The most extreme condition which is modelled, presents an average daily discharge with an exceedance probability of 10% (37 days a year). More extreme conditions are unlikely to be modelled properly, because flooding will almost certainly occur.

Attributable to the selection of the location of the upstream boundary (the Bellavista station), several tributaries of the Río Atrato between Bellavista and the Gulf of Urabá should be taken into account. Currently, the discharge contribution of each tributary is not known, but data are available about the sizes of each catchment area. Based on the sizes of catchment areas a first estimate has been made on the likely discharge of a tributary. The size of each individual catchment area is obtained from the SOBEK report [UTCH, 2010e].

First, the contribution to runoff is determined for tributaries between the measuring stations Belen and Bellavista. Subsequently, a relationship between the size of each individual catchment area and the contribution to discharge is set up. Based on the obtained relationship rough estimates have been made for the discharges of the tributaries downstream of Bellavista, see table 4.2

<table>
<thead>
<tr>
<th>Discharge Regimes Tributaries</th>
<th>Catchment area [km²]</th>
<th>95% exceedance [m³/s]</th>
<th>50% exceedance [m³/s]</th>
<th>10% exceedance [m³/s]</th>
<th>25% exceedance [m³/s]</th>
<th>75% exceedance [m³/s]</th>
</tr>
</thead>
<tbody>
<tr>
<td>Bellavista</td>
<td>17163</td>
<td>1142</td>
<td>2527</td>
<td>3374</td>
<td>3000</td>
<td>1946</td>
</tr>
<tr>
<td>Bojaya</td>
<td>1906</td>
<td>101</td>
<td>267</td>
<td>356</td>
<td>317</td>
<td>205</td>
</tr>
<tr>
<td>Napii</td>
<td>563</td>
<td>30</td>
<td>79</td>
<td>105</td>
<td>94</td>
<td>61</td>
</tr>
<tr>
<td>Murindo</td>
<td>2759.8</td>
<td>146</td>
<td>386</td>
<td>515</td>
<td>458</td>
<td>297</td>
</tr>
<tr>
<td>Opopogo</td>
<td>702.9</td>
<td>37</td>
<td>98</td>
<td>131</td>
<td>116</td>
<td>75</td>
</tr>
<tr>
<td>Curvarado</td>
<td>4300.3</td>
<td>228</td>
<td>602</td>
<td>804</td>
<td>714</td>
<td>463</td>
</tr>
<tr>
<td>Domingodo</td>
<td>1277.6</td>
<td>68</td>
<td>179</td>
<td>239</td>
<td>212</td>
<td>137</td>
</tr>
<tr>
<td>Truando</td>
<td>2121.9</td>
<td>112</td>
<td>297</td>
<td>396</td>
<td>352</td>
<td>228</td>
</tr>
<tr>
<td>Salaqui</td>
<td>2323</td>
<td>123</td>
<td>325</td>
<td>434</td>
<td>385</td>
<td>250</td>
</tr>
<tr>
<td>Riosucio</td>
<td>628.6</td>
<td>33</td>
<td>88</td>
<td>117</td>
<td>104</td>
<td>67</td>
</tr>
<tr>
<td>Tumaradocito</td>
<td>2099.1</td>
<td>111</td>
<td>294</td>
<td>392</td>
<td>349</td>
<td>226</td>
</tr>
<tr>
<td>Cacarica</td>
<td>1218.8</td>
<td>65</td>
<td>171</td>
<td>228</td>
<td>203</td>
<td>132</td>
</tr>
<tr>
<td>Tanela</td>
<td>1435.4</td>
<td>76</td>
<td>201</td>
<td>268</td>
<td>238</td>
<td>155</td>
</tr>
<tr>
<td><strong>Total</strong></td>
<td><strong>38499.4</strong></td>
<td><strong>2272</strong></td>
<td><strong>5514</strong></td>
<td><strong>7359</strong></td>
<td><strong>6542</strong></td>
<td><strong>4242</strong></td>
</tr>
</tbody>
</table>

Table 4.2 Discharge regimes of tributaries of the Atrato River
Note: The catchment area given at Bellavista concerns the whole catchment area of the Río Atrato up to the station Bellavista. For this station the ratio between catchment area and discharge is higher than for downstream tributaries, because of the significantly higher rates of precipitation in the upper parts of the Atrato River. However, the known fact that the cumulative precipitation rates decrease further in northern direction is not taken into account in the approach.

To achieve realistic results also the hydraulic roughness value has to be determined. The hydraulic roughness is a parameter that is rather uncertain and dependent on a lot of factors. It often also varies along the longitudinal river profile.

Tidal information

As described before, in the Gulf of Urabá there are no tidal stations at the Gulf of Urabá, only a daily tidal forecast for the port of Turbo. For this port tidal predictions are available for the last two years and a prediction for the varying water level is given for a range of 72 hours. The data are not specific enough to use them as boundary condition in the model input. It is likely the shape of the bay will distort the tidal wave. The Delft Dashboard software has been used to generate a detailed offshore water level boundary. The Delft Dashboard software has been developed by Deltares and contains online datasets of global bathymetric data, tide data and output from meteorological models. The software is capable of using different sources of data to generate tidal boundary conditions. In order to reach reliable data the boundary should be in offshore waters. A grid that connects the Gulf of Urabá with the Caribbean Sea has been set up. This grid will be connected to the grid of the study area. The grid used is shown in Figure 4.1.

The generation of an astronomical forced boundary provides a list of various astronomical components accompanied with their amplitude and phase. To regard the effects of shallow areas and deep areas at the boundary, the boundary has been separated in eight parts. The combination of the sets of the astronomical components and the phases results in a well-simulated astronomical forced boundary. An example of a set of astronomical components for a boundary is given in Table 4.3.

<table>
<thead>
<tr>
<th>Boundary C Astronomical Component</th>
<th>Amplitude [cm]</th>
<th>Phase [degree]</th>
</tr>
</thead>
<tbody>
<tr>
<td>M2</td>
<td>6.78</td>
<td>148.06</td>
</tr>
<tr>
<td>S2</td>
<td>1.69</td>
<td>14.48</td>
</tr>
<tr>
<td>N2</td>
<td>2.52</td>
<td>118.60</td>
</tr>
<tr>
<td>K2</td>
<td>0.52</td>
<td>20.93</td>
</tr>
<tr>
<td>K1</td>
<td>9.16</td>
<td>238.50</td>
</tr>
<tr>
<td>O1</td>
<td>5.60</td>
<td>239.27</td>
</tr>
<tr>
<td>P1</td>
<td>2.83</td>
<td>243.57</td>
</tr>
<tr>
<td>Q1</td>
<td>0.78</td>
<td>234.50</td>
</tr>
<tr>
<td>MF</td>
<td>1.68</td>
<td>356.54</td>
</tr>
<tr>
<td>MM</td>
<td>0.81</td>
<td>353.36</td>
</tr>
<tr>
<td>M4</td>
<td>0.18</td>
<td>152.15</td>
</tr>
<tr>
<td>MS4</td>
<td>0.46</td>
<td>339.00</td>
</tr>
</tbody>
</table>
| MN4                               | 0.17           | 192.87         

Figure 4.11 Offshore grid used in Delft Dashboard

Table 4.3 astronomical components of boundary C

Morphological modelling of the Atrato river delta in Colombia
Wave statistics

In January 2010 a wave buoy has been installed in the Gulf of Urabá by the Centre for Oceanographic and Hydrographic Research (CIOH) and the General Maritime Service Agent (DIMAR). The wave buoy transmits real-time marine conditions such as wave heights, wave directions, wave frequency, etc. That kind of data is extremely useful for application in numerical models and for calibration purposes. However, the full datasets are not given, but a daily ocean climate is schematized. The exact location of the buoy has not been released either.

The influence of waves is not included in the models in this preliminary study. The waves at the Golfo de Urabá have no influence on the sediment supply to the river mouths. Nevertheless, the wave energy has a direct effect on the distribution of sediments in the river mouth area. The effects of waves can possibly be further investigated in follow-up studies.

River bathymetry

There is one dataset of bed topography data. In November 2009, UTCH executed a bathymetrical survey at the Atrato River. A boat equipped with sonar and GPS devices sailed a zig-zag pattern from the El Roto mouth up to the city of Quibdó. At that time, there appeared no need to include the other branches of the delta in the survey, as originally the plans were to use the Tarena branch and/or the El Roto mouth for the river corridor. Furthermore, the survey was executed for the talweg only, so there are relatively little data from shallower parts in the river and river depths along the banks. An overview of the available bathymetrical samples is given in Figure 4.2. A follow-up survey in October 2010 without accurate GPS equipment showed that most of the delta branches have larger depths (depths larger than 8 metres are common). Even directly next to the densely vegetated flood plains and in sharp bends the lower river depths do not hinder shipping navigation.

Urging the Colombian authorities did not help to obtain further bathymetry data. The bed topography is of great influence on hydrodynamic modelling. Well considered estimates are necessary to achieve reasonable values for the bed topography of the other delta branches. The assumptions made for the bed topography of the river are based on experiences obtained during the fieldtrip of the author in October 2010, interviews with local people and a derivation of the Chézy formula.

In original form, the Chézy formula is as follows: \[ u = C\sqrt{hi} \]

One can express this formula also in a relation, which contains the discharge as follows:

Figure 4.2  Available bathymetrical samples
\[ Q = Bh = BCh^{3/2}i^{1/2} \]

For a river bifurcation holds: \( Q_i = Q_2 + Q_3 \), and therefore also holds:

\[ B_1C_1h_1^{3/2}i_1^{1/2} = B_2C_2h_2^{3/2}i_2^{1/2} + B_3C_3h_3^{3/2}i_3^{1/2} \]

An assumption that the Chézy roughness, \( C \), and the slope, \( i \), are approximately equal for all branches leads to the simplified formulation: \( B_1h_1^{3/2} = B_2h_2^{3/2} + B_3h_3^{3/2} \)

In combination with the available data this simplified formulation has been used to achieve proper values for the unknown bathymetry in most of the delta branches. First, the available data have been schematized as rectangular cross section with an average width and an average depth. Successively, an average width of the unknown branch has been determined and the formulation has been used to obtain an average depth for the unknown branch. In some cases, the findings of the interviews with the local people were more decisive than the simplified formulation. However, the contradictions between both methods were considered as rather small. The results are given in Table 4.4.

<table>
<thead>
<tr>
<th>Branch</th>
<th>Availability bathymetry</th>
<th>Average Width</th>
<th>Average Depth</th>
</tr>
</thead>
<tbody>
<tr>
<td>Río Atrato - Leoncito</td>
<td>Yes</td>
<td>460</td>
<td>12.5</td>
</tr>
<tr>
<td>Leońcito 1</td>
<td>No</td>
<td>145</td>
<td>8</td>
</tr>
<tr>
<td>Leońcito 2</td>
<td>No</td>
<td>100</td>
<td>8</td>
</tr>
<tr>
<td>Burrera</td>
<td>No</td>
<td>45</td>
<td>5</td>
</tr>
<tr>
<td>Río Atrato - Matuntugo</td>
<td>Yes</td>
<td>320</td>
<td>12</td>
</tr>
<tr>
<td>Matuntugo 1</td>
<td>No</td>
<td>105</td>
<td>11.5</td>
</tr>
<tr>
<td>Matuntugo 2</td>
<td>No</td>
<td>95</td>
<td>9</td>
</tr>
<tr>
<td>Coquitos</td>
<td>No</td>
<td>50</td>
<td>9</td>
</tr>
<tr>
<td>Río Atrato – Pavas</td>
<td>Yes</td>
<td>268</td>
<td>10</td>
</tr>
<tr>
<td>Pavas</td>
<td>No</td>
<td>35</td>
<td>6</td>
</tr>
<tr>
<td>Río Atrato – Tarena</td>
<td>Yes</td>
<td>250</td>
<td>9</td>
</tr>
<tr>
<td>Tarena</td>
<td>Yes</td>
<td>70</td>
<td>3</td>
</tr>
<tr>
<td>Boca Léoncito (south)</td>
<td>Yes</td>
<td>60</td>
<td>8</td>
</tr>
<tr>
<td>Boca Léoncito (north)</td>
<td>No</td>
<td>70</td>
<td>6</td>
</tr>
<tr>
<td>Boca Coquitos (south)</td>
<td>No</td>
<td>25</td>
<td>2.5</td>
</tr>
<tr>
<td>Boca Coquitos (north)</td>
<td>Yes</td>
<td>35</td>
<td>3.5</td>
</tr>
<tr>
<td>Boca El Roto</td>
<td>No</td>
<td>480</td>
<td>5.5</td>
</tr>
</tbody>
</table>

Table 4.4 Assumed bathymetry of delta branches

**Floodplain bathymetry**

Little is known about the bathymetry of the wetlands of the Atrato delta. The area is densely vegetated and therefore measurements are not easy to execute. A digital elevation model of NASA\(^2\) has been used to determine the bed topography of the floodplains. The digital elevation model uses a grid of 90 metres by 90 metres, so the accuracy is not very high. Furthermore, it is important to note that a digital elevation model is not equal to a digital terrain model. In a digital elevation model one must take the influence of trees (and buildings) into account, which is not the case for a digital terrain model. In Figure 4.3 a part of the digital elevation model of the Atrato delta is shown.

\(^2\)Source: http://www.ambiotek.com/srtm
Figure 4.3  Digital elevation model of the Atrato delta in metres above mean sea level

Sediment transport in the river

Exact figures about the sediment transport in the river are not present. Nevertheless, in the literature an average sediment concentration in the delta in the order of 200 mg/l is estimated [RESTREPO et al, 2009]. The variation of this sediment concentration for different discharge conditions is not known. To model the morphodynamics in this study accurately for longer periods, the variation of runoff during different seasons has to be schematized. In this study two approaches will be investigated.

- A scenario with three months a discharge condition with a probability of exceedance of 75%, 6 months a daily discharge condition with a probability of 50% and 3 months a discharge condition with an exceedance probability of 25%. The upstream sediment concentration is set at 200 mg/l for all conditions.
- A scenario with an average daily discharge during the whole year. Again, the upstream sediment concentration during the year is kept constantly at a level of 200 mg/l.

The schematization of the first approach is given in Figure 4.4.

In order to save computation time morphological acceleration factors have been used. See Appendix B and Appendix C for more information about the morphological acceleration factors.
Sediment characteristics

Some data are available about the sediment characteristics in the delta. A study executed by UTCH in 1989 includes some data about grain sizes found in the river and even for the delta area. Besides the fact the data about the sediment properties are out-dated, the data are totally not in line with the samples the author took in October 2010. The sediment samples taken in 2010 have been sieved at the laboratories of the faculty of Civil Engineering and Geosciences at Delft University of Technology. The full results and an explanation about the executed hydrometer test are given in appendix D. The grain sizes according to UTCH are given in Table 4.5, whereas the results of the survey in 2010 are given in Table 4.6.

<table>
<thead>
<tr>
<th>Location</th>
<th>D50 [μm]</th>
<th>D90 [μm]</th>
</tr>
</thead>
<tbody>
<tr>
<td>Sautata (High discharge)</td>
<td>193</td>
<td>295</td>
</tr>
<tr>
<td>Sautata (Low discharge)</td>
<td>151</td>
<td>208</td>
</tr>
<tr>
<td>Brazo Leoncito</td>
<td>200</td>
<td>263</td>
</tr>
<tr>
<td>Brazo coquitos</td>
<td>150</td>
<td>252</td>
</tr>
<tr>
<td>Brazo Pava</td>
<td>121</td>
<td>191</td>
</tr>
</tbody>
</table>

<table>
<thead>
<tr>
<th>Location</th>
<th>D50 [μm]</th>
<th>D90 [μm]</th>
</tr>
</thead>
<tbody>
<tr>
<td>Sautata</td>
<td>25</td>
<td>70</td>
</tr>
<tr>
<td>Coquitos</td>
<td>13</td>
<td>50</td>
</tr>
<tr>
<td>El Roto</td>
<td>21</td>
<td>50</td>
</tr>
<tr>
<td>Tarena</td>
<td>120</td>
<td>190</td>
</tr>
</tbody>
</table>

Table 4.5 Sediment properties according to UTCH

Table 4.6 Sediment properties according to 2010 survey

Note: Sautata is located just a few kilometres upstream of the first delta bifurcate, the Leoncito branch.

In this study, the measurements at Sautata (Appendix D) taken in October 2010 served as input for the morphological models. The choice for these sediment characteristics is also supported by research in the lower Atrato conducted by the U.S. Army Corps of Engineers in 1969 [LINDNER, 1969]. The large differences with the measurements of UTCH are difficult to clarify. Perhaps the sieving procedures were different.
Current dredging activities and occurrence of hydraulic structures

In the delta on-going dredging is necessary at the locations of the river mouths to provide enough depth for navigation purposes. At the moment mainly three river mouths are dredged continuously, El Roto, Boca Leoncito and Boca Coquitos. This does not mean that the other river mouths provide navigable depths, but it explains that there is very little navigation in the other river branches. No data are available about quantities and strict criteria. In this report no dredging activities are modelled to fully investigate the natural dynamics of the delta.

Seismic activity

A report of the tectonics of the Northern Andean Block is available. However, the content of the report does not contain numbers of occurred tectonic uplifting/subsidence in the region. The Atrato River originates from the cordilleras of the Andes, which are highly vulnerable to soil erosion due to extreme geologic events, such as landslides and earthquakes [RESTREPO et al., 2009]. One can imagine that such events can lead to drastic changes in the sediment supply to the delta and for the river plan form. Also more downstream, coastal deformations will affect the morphodynamics and hydrodynamics at the delta. Uplift will hinder the river runoff, while a subsidence will favour the river runoff. Figure 4.5 underlines the seismic activity in the area.

In this report no further attention is paid to changes caused by the seismic activity. As stated, the influence could be enormous.

Figure 4.5 Location and magnitude of earthquakes that occurred in Colombia between 1993 and 2008 (Courtesy of the Colombian Seismological Network, INGEOMINAS in: RESTREPO et al., 2009)
Salinity

There are no data available on the salt intrusion rates in the Atrato River. To model salt intrusion accurately, actually a 3D model is required. However, this will be rather computationally expensive and the input data to work with such a detailed model are missing. However, the influence of salinity in an area where a river empties into an ocean is certainly not negligible. The salinity will stimulate the process of flocculation and thus play an important role in the morphological processes. Therefore, this process is included in the 2DH morphological models in a simplified way. The fall velocity of the sediments is taken dependent on the rate of salinity. The fall velocity of sediment can increase by a factor 100 after the flocculation process [personal communication with VAN MAREN, 2010]. This condition has been implemented in the morphological models. For areas with a depth-averaged density level of 1015 kg/m³ or higher the fall velocity is increased by a factor 100.
4.4 Modelled measures to improve navigation

Although, this report focuses on creating insights into the hydrodynamics and the morphodynamics of the Atrato delta, also possible measures to improve the navigability are investigated. Four possible measures are modelled both hydrodynamically and morphodynamically to determine their effects. This does not mean there are no other suitable measures to improve the navigability of the Atrato delta. In this study only four measures are examined. The four tested measures to improve the navigation in the delta are described briefly below.

**Sand trap**

A sand trap is designed to capture sediments in a river before they lead to sedimentation problems more downstream in the river, in this case the river mouths. In a sand trap the sediment transport capacity is locally decreased in order to favour deposition in a desirable area. This is obtained by an extension in terms of depth or width in the river. Because the sediment in the delta is very fine and primarily transported in suspension, the optimum size of a sand trap is likely very large.

**Artificial navigable outlet channel**

This measure describes an opportunity to distribute sediments through an artificial outlet channel to improve the current situation around the already existing river mouths. However, it is also possible that the new outlet channel turns out to be the best option to serve as a navigation route.

**Sediment diversions channels**

Sediment diversions channels are small bifurcates of a main river branch to distribute river sediments over a larger area. At this moment, the feasibility of the implementation of sediment diversions in the levees of the Lower Mississippi River is investigated in order to divert sediment into the delta and to stop the radically subsiding and eroding of the wetlands in the delta, also known as the “drowning effect” [Bos, 2011]. Although the reason to implement sediment diversions is completely different for the Atrato delta, the sediment diversions may have a beneficial effect on the current problems for the Atrato delta.

**River outlet extension**

Currently the various branches of the Río Atrato flow into shallow areas of the Golfo de Urabá. By artificially extending a river outlet with breakwaters, it becomes possible to prevent the process of outflow to take place in shallow water, where sedimentation directly hinders navigation. After the construction of breakwaters, the sediment deposition likely occurs in deeper water, where it does not impede the navigation directly.

*NOTE: In chapter 7 some possible other measures are discussed to improve the navigability around the river mouths of the Río Atrato.*
4.5 Hydrodynamic modelling on unstructured grid

4.5.1 Study area

A new unstructured grid system, D-Flow Flexible Mesh, has been used to model the Atrato delta hydrodynamically. The area of interest concerns the delta with all its bifurcations and the outlets into the Golfo de Urabá. Also a part of the surrounding land and a part of the Golfo de Urabá belong to the area of interest. Figure 4.6 specifies the area of interest more precisely.

![Figure 4.6 Río Atrato delta, study area inside the red lines [GARCIA-VALENCIA, 2007]](image)

The hydrodynamic D-Flow Flexible Mesh model aims at efficiently and accurately representing the water movement in the study area. Currently, there is very little understanding of how the upstream river discharge is distributed over the various river branches in the delta. The hydrodynamic model starts at the location of the Bellavista station, which is roughly located 300 km upstream of the El Roto mouth. This is the closest station with the most data. The downstream boundary lies in the Caribbean Sea. Thus, the hydrodynamic models contain large areas outside the real study area. The model is capable of simulating the water movement in the area for different discharge conditions. Because the models also include parts of the floodplains, also insights into the influence of these areas on the water movement are gained. In addition, more insights on the influence of the tide in the area can be obtained quickly. The model is easy to adjust, so the impact of human activities on the hydrodynamic situation can be investigated rapidly. For chosen cross-sections and observation points in the model, one can request detailed hydrodynamic information.
4.5.2 Grid Design

The hydrodynamic unstructured grid of D-Flow FM has the advantage that it can work with a great diversity in terms of resolution, which is necessary to prevent exorbitant computational time. The network set up in this study has a total length of approximately 500 kilometres and has a varying width between 200 metres up to 200 kilometres wide. The total number of cells is 68,271 with 135,337 flow links. The grid cells vary greatly in size. The smallest cells are only 250 m$^2$, whereas the largest cells in the ocean have a surface of approximately 30 km$^2$. The total network is shown in Figure 4.7.

![Figure 4.7 Overview of grid (Google earth, 2011)](image)

This network includes 13 flow boundaries and a water level boundary in the ocean, which is divided in 6 individual boundaries. In this network 18 areas are specified with a different bottom roughness value than the bottom roughness value in the main river.

River bifurcations are accurately implemented in the network. By the use of triangular grid cells bifurcations are created, which are not possible to reconstruct using a curvilinear grid only. However, the network is still mainly curvilinear. For computational efficiency, it is favourable to use curvilinear grids in main flow direction, tied together by triangles. Using curvilinear grid cells that are elongated in the channel length direction still leads to the higher resolution in the relevant channel length direction than for example triangles. This explains the preference for application of curvilinear grids parallel to the main flow direction.

A transition between regions with different resolutions is also achieved with the use of triangles. However, a certain transition does often not meet with the strict requirements based on aspect ratio. On the other hand, the network is extremely orthogonal. Much more one should obtain by using a curvilinear grid only. The explanation and the results of this grid requirement and several other grid requirements are given in Appendix C.

The tributaries are connected to the network via a 1D link. The coupling of 2D grid cells and 1D flow links is not possible in most of the hydrodynamic software packages, but it is possible in D-Flow Flexible Mesh package. The coupling of 1D flow links with 2D grid cells is not possible in the current Delft3D package.

Some features of the network are shown in Figure 4.8.
Figure 4.8  River bifurcation (upper left), transition between different resolutions (upper right), 1D flow links of a tributary (lower left), different grid resolutions in study area.
4.5.3 Bathymetry

The available bathymetrical samples are supplemented with samples that are added by hand. Subsequently, a triangular interpolation technique has been applied to insert the bathymetry into the network. Figure 4.9 shows all the bathymetrical samples used and the result after the interpolation technique applied. The results of a new bathymetrical survey can quickly be incorporated into the model.

![Figure 4.9 Bathymetrical samples (left), result after a triangular interpolation (right)](image)

4.5.4 Calibration

The aim of this calibration is mainly to reproduce the processes in the right order of magnitude. Therefore, the presented modelled quantities in the report are probably not entirely correct. If the model is calibrated, possible measures, which aim at improving the navigation, can be compared to the current state. In chapter 6 a measuring and monitoring plan is set up to calibrate the model in more detail in the near future.

In a hydrodynamic calibration the purpose is to match the model calculations with measured water levels and discharge distributions. The main parameters to achieve this goal are the hydraulic roughness and the bed topography. However, measured data of water levels and discharge distributions in the delta area are not available. At this time, only limited data of locations outside the study area are available for calibration.

Despite the lacking data, the hydrodynamic model is calibrated as much as possible. The available SOBEK model included the main branch of the river only. The model has been adapted to include the other delta branches as well, see Appendix E. The discharge distributions of the SOBEK model and the D-Flow FM model are compared with each other based on a tide-free situation. The differences between the two models often arise from a different schematization of the bed topography, as a result of dissimilar interpolation techniques used in the models. However, the major differences between the two models have been investigated well, because the representation of the bed topography in the D-Flow FM model could be wrong. Small interpolation errors are located and removed.

The SOBEK model has not served as calibration reference for the water levels in the delta. The influence of the large floodplains is not included in the SOBEK model. The riverbanks are in fact modelled as infinitely high walls, which mean that the water levels in the SOBEK model may be considerably overestimated.

Data for further calibration are not yet available in the area of interest. Because of the large model setup, there are calibration opportunities outside the area of interest. The measuring stations Domingodó and Riosucio record daily water levels since 1970. From these records exceedance curves exist [UTCH, 2010c].
For the chosen specific discharges, the water levels at these stations were compared to find the best hydraulic roughness value to apply in the model. Finally, it was decided to specify two distinct hydraulic roughness values for two parts in the river. One for the course from Bellavista to Domingodó and one for the course from Domingodó to the Golfo de Urabá. The roughness value for the part from Bellavista till Domingodó is higher, due to the occurrence of steeper slopes and smaller water depths in this part of the river. Hydraulic roughness values also vary for different discharges. A higher discharge results in higher flow velocities and more sediment transport which cause larger bedforms and successively higher Manning values. This is indicated in the following formula.

$$\bar{U} = \frac{1}{n} R^{2/3} i^{1/2}$$

Where:
- $\bar{U}$ = depth averaged mean velocity, [m/s];
- $n$ = manning roughness coefficient, [s/m$^{1/3}$];
- $R$ = hydraulic radius, [m];
- $i$ = slope of the water surface [-].

Nevertheless, the roughness values are in this study assumed to be independent of the discharge. The best fit for the Manning values was found for values of 0.026 s/m$^{1/3}$ and 0.021 s/m$^{1/3}$. The results are given in Figure 4.10 and Figure 4.11 respectively. Especially for high discharges, the values still do not match with the data.

![Figure 4.10 Calibrattion results for hydraulic roughness at Domingodó ($n=0.026$ s/m$^{1/3}$)](image-url)
The roughness value of the floodplains in the delta has also been calibrated. Due to the dense vegetation in the floodplains, the main requirement was that the flow velocities in these areas has to be significantly lower compared to those in the main channels. The Manning value of the floodplain is set at 0.1 s/m$^{1/3}$.

The representation of the tide and the Manning-values in the Gulf of Urabá are calibrated based on tidal predictions at the city of Turbo, provided by IDEAM. It is not known how accurate these predictions are. Nevertheless, the modelled tidal cycle at the location of Turbo is almost the same for the predictions of IDEAM and the model results. There is one big difference, according to the IDEAM the average water level at Turbo is 0.14 metres, while the model shows an average elevation of 0 metres. Besides, as a result of spin-up some inadequate results are visible for the first two days in the model results, see Figure 4.12.
If the model results and the predictions of IDEAM are compared in more detail for a period of two days, more differences can be discovered. Figure 4.13 shows the model results, the model results with an additional elevation of 14 centimetres, and the tidal forecast of the IDEAM. Despite the differences, the prediction of the moment of high water and low water are very similar and also the tidal range is comparable for the model results and the predictions of the IDEAM. Assuming that the model used by IDEAM is calibrated, it can be concluded that the hydrodynamic model of the Río Atrato is capable of approaching the tidal forcing rather well.

![Figure 4.13 Model results versus tidal predictions of IDEAM](image)

In summary, for different areas different roughness values have been used. Table 4.7 shows an overview of the applied values.

<table>
<thead>
<tr>
<th>Area</th>
<th>Roughness value</th>
<th>Manning [s/m(^{1/3})]</th>
</tr>
</thead>
<tbody>
<tr>
<td>Domingodó – River mouths</td>
<td>0.021</td>
<td></td>
</tr>
<tr>
<td>Bellavista - Domingodó</td>
<td>0.026</td>
<td></td>
</tr>
<tr>
<td>Floodplain</td>
<td>0.1</td>
<td></td>
</tr>
<tr>
<td>Golfo de Urabá</td>
<td>0.02 – 0.03</td>
<td></td>
</tr>
</tbody>
</table>

Table 4.7 Applied roughness values
4.5.5 Application to navigability improvement measures

This chapter elaborates the hydrodynamic unstructured grid design of the examined measures to improve the navigability. Some adaptations in the network and its bathymetry were made to achieve adequate networks to investigate the measures. The constructed networks have all been checked on several requirements regarding orthogonality, smoothness, aspect ratio and the Courant number.

**Sand trap**

The sand trap is implemented in the network at the Leoncito branch, see Figure 4.14. An average depth of 10 metre below mean sea level and an average width of 1800 metres have been determined. To apply a sand trap in the network the available bathymetrical samples have been adjusted and a bathymetrical interpolation has been executed. No further changes in the structure of the network were necessary to schematize a potential sand trap. The location of the sand trap is indicated with the green circle in Figure 4.14.

![Figure 4.14 Sand trap in the hydrodynamic model](image)

**Artificial outlet channel 1**

The artificial outlet channel is placed in the Leoncito branch, about 9.2 kilometres more upstream than the current river mouths. To make navigation possible through the new outlet channel, the width is set at 150 metres and the depth at 6 metres below mean sea level. To achieve a proper outlet channel in the network, local grid refinement has been applied. The location of the artificial outlet channel is indicated with the green circle in Figure 4.15.

![Figure 4.15 Artificial outlet in hydrodynamic model](image)

**Artificial outlet channel 2**

This measure is quite identical to the previous measure, but now the outlet channel is located much more downstream, just 2.7 kilometres upstream of the current river mouths of the Leoncito branch. In Figure 4.16 the location of the channel is sketched. Again, the network is refined locally and the bathymetry is adapted to achieve a good outlet channel.

![Figure 4.16 Artificial outlet more downstream](image)
**Sediment diversion channels**

Three small diversion channels are implemented in the network. All located in the Leoncito branch, one at 9.2 kilometres upstream of the current river mouths, one at 2.7 kilometres upstream of the current river mouths and one at 500 metre downstream the current river mouths. The width of the diversions is set at only 25 metres. The depth is set at 4 metres below mean sea level. Some changes in the grid were necessary to connect the diversions in a proper way to the main stream. The network has also been refined locally. The exact location of the diversions is also shown in Figure 4.17

**River outlet extension**

The northern river outlet of the Leoncito branch is now extended with 2 kilometres in seaward direction. The extension represents possible breakwaters, which in the model are set at 1 metre above mean sea level. The depth between the breakwaters is set at 5 metres below mean sea level. The northern river mouth now flows out in a relatively deep part of the Golfo de Urabá, see the green circle in Figure 4.18.
4.6 Morphodynamic modelling on structured grid

4.6.1 Study area

For this report it was too much time consuming to model the whole delta area morphodynamically. Therefore the important decision is made to analyse the morphological processes near one separate branch only on a structured grid of the Delft3D package. For various reasons it was decided to examine the Leoncito branch in more detail. First, the Leoncito branch is being used as a navigation route already. This could be due to its convenient location or because the river mouths of the Leoncito branch require minimum maintenance. The exact reason is not known. In addition, the wave influence at the Leoncito mouths is probably smaller than the wave influence on the other river mouths of the Río Atrato. The specific shape of the delta and the Golf of Urabá provides shelter for the more southern river outlets. The influence of waves is not included in the study. To concentrate the study to the Leoncito branch is therefore almost certainly the best option. Furthermore, a report about the realisation of the project recommended to construct a new port located very close to the Leoncito river mouths [INVIAS, 2010]. However, the choice for the Leoncito branch should not be regarded as a final decision.

Despite the lacking data, the morphodynamic model aims to represent the morphodynamics in the delta efficiently and accurately. At this moment, the processes have never been investigated fully and there is a strong wish to minimize the dredging costs during the construction of the new navigation corridor and during the maintenance of this corridor. The morphodynamic model starts roughly 27.5 kilometres upstream of the two river mouths of the Leoncito branch. The discharge regime of this upstream boundary is described as a time series with an interval of 5 minutes. This time series is obtained from the hydrodynamic model. The model contains two downstream boundaries, one at the end of the Burrera branch and one in the Golfo de Urabá. Also for these two boundaries time series are obtained from the hydrodynamic model, but now the water level movement is described with an interval of 5 minutes.

The model is easy to adjust and several grid adaptations have been made to investigate some measures to improve the navigability of the delta.

4.6.2 Grid design

The morphological model is much smaller than the hydrodynamic model. The grid is completely curvilinear and structured, otherwise no morphological results could be achieved. The orthogonality of the curvilinear grid is much more problematic around river bifurcations than the orthogonality of the unstructured grid. This is shown in Appendices C and E. This appendix also contains more checks on a few requirements in order to achieve model results that are stable and accurate.

The grid does not include floodplain areas, because this resulted in huge problems at sharp bends and at bifurcation points. The grid does include a significant part of the Gulf of Urabá.

The main river branches consist of 6 grid cells over the width. The grid cell sizes vary from 20 metres to 100 metres in m-direction and from 20 metres to 100 metres in n-direction. Figure 4.19 also shows some undesirable high resolution of the grid in the Golfo de Urabá.

Figure 4.19 Morphological grid
4.6.3 Bathymetry

The dataset of bathymetrical sample points, which are used for the hydrodynamic models, have also been applied to schematize the bathymetry in the morphological model. Some sample points were added by hand to achieve enough samples for an interpolation technique. A triangular interpolation is used to obtain the model bathymetry (Figure 4.20). Some adjustments in the bathymetry of the model have been made to test the possible measures for preventing massive river mouth sediment deposition.

![Figure 4.20 Bathymetry of the model](image)

4.6.4 Calibration

The morphological model that has been used in this study was calibrated based on limited data. Therefore, the quantities modelled in this study are probably not entirely correct. The calibration process was mainly focused on reproducing morphological behaviour as well correctly as possible, in order to identify possible measures and their order of magnitudes. In chapter 6 a set-up of a measuring and monitoring plan is proposed to calibrate the models in the near future more accurately.

The objective in a morphological calibration is to match the output of the model with measured bed level changes and measured sediment transport rates. The key parameters that need to be calibrated are the different sediment transport parameters and the sediment characteristics. These measurements were not available and therefore other data have been used for an initial calibration.

The two hydrodynamic schematizations of the yearly runoff, proposed in section 4.3.2, have been tested to simulate the morphodynamics for a complete year with different sediment transport formulas. However, the obtained differences in bed level between the two model runs were very small. Therefore it was chosen to use a constant average discharge only for further simulations.

The sediment transport in this study area consists predominantly of suspended load transport, because only very fine fractions are transported. To represent the morphodynamics a sediment transport formula has to be selected, which is able to calculate suspended load transport. Moreover, a significant part of the sediments in the Atrato delta have cohesive properties. Due to these specific sediment characteristics a combination of sediment transport formulas has to be used to represent the morphodynamics of the Atrato delta correctly. The well-known sediment transport formulas Meyer-Peter & Müller and Engelund & Hansen are not suitable to use in this study, because the sediment grain sizes are too small in the Atrato River. The Van Rijn transport formula 1993 is capable of reproducing bed-load transport and suspended sediment transport for non-cohesive sediment larger than 64 µm. However, Van Rijn increased the applicability of this formula to even 8 µm in his new formula, The Van Rijn 2004. Partheniades-Krone achieved a formulation for the smallest sediments of the spectrum. For a brief description of these formulas, see Appendix C. Combinations of the Van Rijn 1993, the Van Rijn 2004 and the Partheniades-Krone formulations have been used in this study.
To calibrate the morphodynamics as a whole, a simplified procedure is followed, because real calibration data were not available. The deposition and erosion patterns are checked based on common sense. Subsequently, the relationship between sediment transport and discharge is checked.

**Deposition and erosion patterns**

The bed composition is schematized as uniformly mixed, which means that there is no specific layering in the bed. In this study the bed composition is not known and hence a uniformly mixed composition is used. All tested combinations of sediment transport formulas showed heavy sedimentation directly after the river outlets. However, combinations with the Van Rijn 2004 formula appeared to result in inaccurate morphology in river bends. Often the results of the model showed a pattern of erosion in the inner bend and sedimentation in the outer bend (Figure 4.21), while this is strongly against the basic principles of river morphology. This might be explained, by the fact that this formula was primarily developed for coastal areas [WALSTRA et al., 2004]. In order to schematize the morphology also correctly in the river reaches of the model, eventually the Van Rijn 2004 formula has not been used in further computations. A schematization of the sediment sample where a coarse fraction is described by the Van Rijn 2003 formula and the finer sediments are described by the Partheniades-Krone formula resulted in the best deposition and erosion patterns.

![Figure 4.21](image1.png)  
**Figure 4.21** Morphological development in river bends with Van Rijn (2004) formula, initial bed level (left) and bed level after 6 months (right)

**Relationship between sediment transport and discharge**

The large amount of fine material makes the Partheniades-Krone formula the most important formula to calibrate. In the Partheniades-Krone formulations the most important calibration parameters are the erosion parameter, the critical shear stress for erosion and the fall velocity. These parameters were derived empirically from previous studies (WINTERWERP, 1989; VAN RIJN, 2007a; VAN RIJN, 2007b) and these parameters determine the amount of erosion and deposition which will occur. The ranges of applicability for these parameters are wide and consequently the results differ strongly for different parameter settings. More research is necessary to calibrate these parameters in more detail. At this moment personal advice of Van Maren [personal communication with VAN MAREN, 2010] led to the values chosen in the formulation.

However, for the values chosen the relationship between sediment transport and flow velocity is evaluated. The relationship between sediment transport $Q_s$ and discharge $Q$ is non-linear. For higher discharges (high flow velocities), the rate of sediment transport is higher than for
low discharges (low flow velocities), see Appendix C for a more detailed description. The relation between sediment transport and discharge is:

\[ Q_s = B^{1-\frac{2}{3}} m Q^{\frac{2n}{3}} C^{\frac{n}{3}} \]

In which \( Q_s \) is the sediment transport, \( B \) is the width of the river, \( m \) is the transport parameter, \( Q \) is the discharge, \( C \) is the Chézy roughness value, \( i \) is the slope and \( n \) is the degree of non-linearity.

The literature study showed that the Mississippi River is quite similar to the Río Atrato. Assuming that the degree of non-linearity of the Río Atrato is approximately equal to the degree of the Mississippi River, the term \( \frac{2n}{3} \) in the formula above should be between 1 and 1.3. [Bos, 2011]. The parameters used in this study meet this requirement, see Figure 4.22.

For the sand a median grain size of 64 µm is chosen, with an initial layer thickness of 5 metres. For the mud fraction a critical bed shear stress has to be selected instead of a grain size, a value of 0.15 N/m² has been used. All values used are presented in Figure 4.23.
4.6.5 Application to navigability improvement measures

This chapter elaborates on the morphodynamic structured grid design of the examined measures to improve the navigability. The applied lay-out in the hydrodynamic unstructured grids is followed as much as possible. However some minor changes in the lay-out could not be avoided, because of the limitations of a structured grid. Two possible lay-outs have been designed for an artificial outlet at 9.2 kilometres upstream of the existing river mouths. The constructed networks have all been checked on several requirements regarding orthogonality, smoothness, aspect ratio and the Courant number.

Sand trap

The sizes of the implemented sand trap in the morphological grid are entirely equal to those in the hydrodynamic grid. However, the grid resolution is higher. The grid cell sizes vary from 80 metres to 120 metres in m-direction and from 20 metres to 120 metres in n-direction. The whole sand trap contains 1980 grid cells. Figure 4.24 represents the grid of the tested sand trap.

Artificial outlet channel 1

By implementing an artificial outlet channel in the grid a new bifurcation point arises, which is problematic in the grid administration. Therefore the grid in the left part of the Golfo de Urabá had to be refined to achieve one functioning grid (Figure 4.25). The opportunity to split the model into two or more individual domains, which are connected with each other (domain composition) was also tested. However, the use of domain decomposition did not result in reliable results for the morphology. The off-take angle with the main channel is relatively small.

Artificial outlet channel 2

To investigate the degree of off-take of the artificial channel, the artificial outlet channel is now connected with the main channel with a relatively high angle of off-take, almost 90 degrees. Again high undesirable resolution is visible in a great part of the Golfo de Urabá, see Figure 4.26.
Artificial outlet channel 3

To investigate the location of a possible artificial channel, a grid is set up where the artificial channel is now located more downstream, see Figure 4.27. The chosen off-taking angle is around 90 degrees.

Sediment diversion channels

The sediment diversion channels are only 25 metres wide. Therefore, the three diversions consist of 3 grid cells over the width, whereas the main river branches still consist of 6 grid cells over the width. The grid used is given in Figure 4.28.

River outlet extension

To implement breakwaters in the model a special function has been used in the Delft3D model. The “Thin dams function” enables to quickly implement a fixed impermeable wall in the model, which serves as first approach to schematize breakwaters. No further changes in the structure of the grid were necessary to schematize the potential breakwaters with a length of 2 kilometres. The breakwaters are indicated in red in Figure 4.29.
5. Results

This chapter discusses the results of the numerical simulations conducted in this study. A distinction between the hydrodynamic results obtained on an unstructured grid and the morphodynamic results obtained on a structured grid is made. For each section the processes observed in the current state are described first. Subsequently, the results of the examined measures to improve the navigability in the delta are interpreted and discussed. Certain processes are checked with available literature.

5.1 Hydrodynamic modelling on unstructured grid

This chapter discusses the results obtained from the hydrodynamic model. The main purpose of this model is to create detailed hydrodynamic boundary conditions for the morphological model. However, some attention is paid to the hydrodynamic processes in the delta which affect the local morphology.

The model is capable of displaying time series of hydrodynamic parameters for given cross-sections and observation points. In this study, especially time series of cross-sections have been used. It is important to note that the bathymetry is assumed for large areas of the model. The model output should be taken therefore with caution. For a correct picture of the hydrodynamics of the Atrato delta, more bathymetrical samples are required and an extensive calibration should be executed.

5.1.1 Current state

The modelling of the current hydrodynamics of the Atrato River has three goals. First, to gain more knowledge about the current hydrodynamics in the delta and secondly to attain time-series for the boundary conditions in the morphodynamic mode, which is set up at a more detailed level. Finally, the model results of the navigability improvement measures can be compared with the model results of the current state.

Discharge distribution

As described before, the modelled discharge distribution must be interpreted with caution. To display a potential discharge distribution in the delta, the results of the model are given in Table 5.1. Figure 5.1 indicates the locations of the cross-sections. The values in this table are mean discharges during an entire spring-neap tidal cycle. It is remarkable that for each discharge contribution a misbalance exists for water that flows into the delta and water that flows into the ocean through one of the main river mouths. This indicates that the model predicts outflow through wetlands.

<table>
<thead>
<tr>
<th>Discharge condition</th>
<th>95% discharge [m³/s]</th>
<th>50% discharge [m³/s]</th>
<th>10% discharge [m³/s]</th>
</tr>
</thead>
<tbody>
<tr>
<td>river section</td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>1 Inflow</td>
<td>2196</td>
<td>5300</td>
<td>7090</td>
</tr>
<tr>
<td>2 Leon branch</td>
<td>410</td>
<td>901</td>
<td>1225</td>
</tr>
<tr>
<td>3 Main</td>
<td>1600</td>
<td>3896</td>
<td>4943</td>
</tr>
<tr>
<td>4 Leoncito</td>
<td>305</td>
<td>650</td>
<td>800</td>
</tr>
<tr>
<td>5 Burrera</td>
<td>100</td>
<td>180</td>
<td>200</td>
</tr>
<tr>
<td>6 Matuntugo branch</td>
<td>504</td>
<td>1167</td>
<td>1500</td>
</tr>
<tr>
<td>7 Coquitos</td>
<td>180</td>
<td>370</td>
<td>407</td>
</tr>
<tr>
<td>8 Pavas</td>
<td>215</td>
<td>415</td>
<td>470</td>
</tr>
<tr>
<td>9 Matuntugo</td>
<td>306</td>
<td>560</td>
<td>660</td>
</tr>
<tr>
<td>10 Tarena</td>
<td>65</td>
<td>106</td>
<td>154</td>
</tr>
<tr>
<td>11 El Roto</td>
<td>780</td>
<td>1621</td>
<td>2330</td>
</tr>
<tr>
<td>Outflow in ocean</td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>through river mouths</td>
<td>1951</td>
<td>3902</td>
<td>5021</td>
</tr>
</tbody>
</table>

Table 5.1 Modelled discharge distribution in the delta
Flow velocities in the delta.

The model provides a clear overview of the flow velocities, which can occur in the delta. The model shows that the velocities in the Leoncito branch are much lower than those in the main river branch. Figure 5.1 shows the flow velocities in the vicinity of the first bifurcation of the delta for three different discharge conditions.

The flow decreases rapidly when the riverine water flows into the Golfo de Urabá, see Figure 5.3 for an average outflow pattern at Coquitos.

Water levels in the delta

The modelled water levels can be used in the future to calibrate the model. Currently, the model predicts average water levels at the bifurcation of the Leoncito branch of about 0.5 metres for low discharge conditions, 1 metre for average conditions and up to 1.5 metres for high discharge conditions. This is also shown in figure 5.4.
Tidal influence

The tide in the Gulf of Urabá is limited (average tidal range of 40 cm). The discharges of the river branches are almost constantly large enough to prevent flow in upstream direction. Only the combination of spring tide and very low discharge conditions resulted in small upstream flow velocities, see Figure 5.5.

Despite the relatively weak tidal forces, the tide produces backwater effects constantly which has major effects on the water level, the flow velocities and the discharge distributions. This influence can be felt in a large part of the river. During low flow conditions the model predicts water level variations up to 10 centimetres at the Domingodó measuring station (167 kilometres upstream), as a result of the tidal range.

The hydrodynamic D-Flow FM model also gives a first indication of the mixing process of the fresh river water with saline seawater of the Gulf of Urabá. The model of the delta predicts that the mixing processes only occur in the Golfo de Urabá for average and high flow conditions, see Figure 5.6. For low flow conditions the model predicts that the mixing processes occur in the direct vicinity of the river mouths.
Flood wave (10% exceedance discharge)

The effects of a flood wave are greatly flattened by the large wetlands of the delta. Nevertheless, the flow velocities in the main river branches remain much higher during a flood wave. A significant part of the flood wave flows in the floodplains. This was previously noted from Table 5.1. The right image in Figure 5.7 clearly shows the model prediction that during high water, a part of water in a river branch flows through the wetlands directly into the Gulf of Urabá.

Effect of a period with a constant low discharge (95% exceedance discharge)

The model forecasts that small tidal prisms are formed at almost all river outlets, which indicates that during periods of low discharge the formation of salt wedges may be occur. Obviously, the average flow velocities in the river are lower than normal. This will significantly affect the morphology; this will be shown in the morphological model.

Effect of the wetlands in the delta

The model predicts that the effects of the wetlands on the hydrodynamics of the delta are very important. The wetlands act as a storage basin, which conveniently prevents a massive flooding in the area. Besides this storing character, the water in the floodplain also follows slightly the flow in the mainstream. The model predicts average flow velocities during a period of high runoff (10% probability of exceedance) between 0.1 and 0.2 m/s in the floodplains.

5.1.2 Navigability improvement measures

The network and the bathymetry of the hydrodynamic model have been adapted to achieve proper boundary conditions for the possible navigability improvement measures. The obtained boundary conditions have been used in the more detailed morphological model, which is capable to forecast their morphodynamic effects in the delta. To present the exact obtained discharge distributions is at this stage not very useful, because the distributions strongly depend on the location and the lay-out of the measures and the bed topography. In this study the main purpose is to examine the possible effects. The bathymetric data used are insufficient to identify the best locations and the most effective lay-out for the measures. Further research will be necessary. Small changes in the location or the layout of the measures will have great influence on the discharge distribution. The results are therefore described qualitatively. Most attention is paid to differences in boundary conditions between the current state model and the model which is adapted to reproduce the hydrodynamics of a measure. Other notable results are briefly described, because the morphological model is more detailed and probably more adequate to focus on these phenomena.
The model forecasts that none of the navigation measures will change the water level boundaries at the end of Brazo Burrera. Only the extension of a river outlet slightly changed the water level boundary at the Golfo de Urabá. The upstream discharge boundary conditions do change for each investigated measure. The model predicts a lower discharge rate through the Leoncito branch after a possible implementation of a sand trap and after the construction of breakwaters at the river mouth. The flow velocities also decrease in the entire river section. For all the other measures the model forecasts an increase in the rate of discharge and higher flow velocities. When an artificial river outlet is modelled, the model predicts substantially higher flow velocities in the first part of the Brazo Leoncito. The investigated new river outlet is in fact the outlet with the shortest distance to sea of the whole river. The model shows a remarkable drop of the flow velocity at the reach from the new river outlet till the existing river mouths. An average flow velocity pattern in case an artificial river mouth is implemented as shown in Figure 5.8.

![Flow velocity pattern in case for the artificial outlet channel measure during low flow conditions](image)

The model forecast only a small increase of runoff through the Leoncito bifurcate for the examined scenario of sediment diversions.
5.2 Morphodynamic modelling on structured grid

This chapter discusses the results obtained from the morphological model. Again, the model only forecasts the morphology of the Leoncito branch and its mouths. This section starts to describe the morphodynamics at the current state, where much attention is paid to the influence of salinity on the morphology at the river mouths. Subsequently, the model morphological results are analysed for the possible measures, which aim to improve the navigation in the delta. In order to investigate their applicability a morphological period of six months is modelled. Dredging activities are not modelled with the intention of fully investigating the natural morphodynamics and the reaction of the delta to the interferences.

5.2.1 Current state

The modelling of the current situation in the delta has two goals. First, to gain more knowledge about the current morphodynamics in the delta and secondly to compare the model results of navigability improvement measures with the current state situation.

Flow velocities

The river outlet of the Leoncito branch consists of two separate river mouths. For sake of simplicity, the two mouths will be called Boca North and Boca South respectively in this report. The highest flow velocities do occur at Boca North, probably due to the perpendicular orientation of Boca South with the main channel. Because of this large angle the model even predicts flow separation in the Boca South. This process is described in chapter 3.5. The model forecasts a discharge distribution in the order of 1:3 for average conditions.

Figure 5.9 shows depth averaged velocities at Boca North and Boca South.

![Figure 5.9 Depth averaged velocity near the river mouth: normal condition (left), flow separation during high flow conditions (right)](image)

When the river flows into the Golf of Urabá the flow velocities drop significantly, see Figure 5.10.
Sediment transport

The model predicts that almost all the sediment is transported in suspension (99.7%). Therefore the direction of the sediment transport and the flow direction are almost completely equal. In the left picture of Figure 5.11 the direction of sediment transport is indicated with red arrows, whereas the depth averaged flow direction is indicated with blue arrows. No differences can be observed.

In the right picture of Figure 5.11 the total sediment transport through the river mouths is given. The minus sign in the figure for Boca South is purely a grid administration matter. The model forecasts a sediment transport distribution in the order of 1:3. Figure 5.11 has two horizontal axes, for more information about these axes see Appendix B.
Morphodynamics

The morphodynamics of the current situation are modelled with an average upstream discharge of 900 m$^3$/s. The initial bed level at the mouth is set at 5 metres. No dredging activities are included in the model. Figure 5.12 shows the changing bed for four specific moments.

![Figure 5.12 Bed level changes in current situation; initial condition (upper left), after 1 month (upper right), after 3 months (lower left), after 6 months (lower right)]

Based on the figures above, the model predicts substantial sedimentation immediately after the river mouths. Without human interventions, the navigability of the mouths will be quickly precarious. Especially the entrance of Boca South will soon be inaccessible for larger ships. The sediments at the northern mouth settle over a larger area. In the river part of Boca South small scale sedimentation occurs, which is possibly initiated by the eddy as a result of the flow separation. Further upstream, the model predicts no problems for navigation.

Influence of salinity

From Figure 5.12 it is not immediately clear what the effects of the mixing of saline water with fresh water are for the morphology. An approximation is used to include the influence of salinity on the morphodynamics of a 2DH model; the fall velocity of the sediments has been taken dependent on the salinity. At a density of 1015 kg/m$^3$ the fall velocity is taken 100 times faster than for areas with densities lower than 1015 kg/m$^3$. In this way, the process of enhanced flocculation in saline water is somewhat imitated, but it remains a rough estimate. Figure 5.13 shows that the model predicts that for both river mouths the real mixing process takes place in the Golfo de Urabá, in average conditions. This is in line with the results of the hydrodynamic model.
The approach to schematize the enhanced flocculation process has a major influence on the morphology near Boca South and Boca North. This becomes clear when the results of a model run with and a model run without the increased fall velocity in saline waters are compared with each other, see Figure 5.14. The simplified flocculation process exacerbates the sedimentation problems at the entrances of the river mouths. The area where the sedimentation occurs is much more concentrated. In the model without the increase in fall velocity only the largest sediments settle directly at the mouth, whereas the finer sediments settle in a much larger area. The smallest sediments even settle in the deep water, which is indicated in the figure with the colour dark red.
Influence of a period with a constant low discharge

To determine the influence of a long period with a low discharge, a model run is executed with a constant daily discharge which is 95% of the time exceeded for a period of three months. This is a very extreme condition, but does explain the influence of a low discharge most optimally.

The output shows a very low rate of sediment transport, which is a direct result of the low flow conditions in the delta. A period of low water has its effects on the sediment deposition process at the river mouths. The model shows that after three months of modelling the deposition at the mouths is not very large and no problems for navigation arise. Also, further upstream in the river significant changes in bed level are present.

The changes in bed level between three months are given in Figure 5.15.

Influence of a period with a constant high discharge

To determine the influence of a long period of high discharge conditions, also a period of 3 months with high discharge conditions is modelled (10% probability of exceedance).

The high velocities that now occur also result in a high amount of sediment transport. The transported sediments start settling when the river flows into the Golfo de Urabá. Therefore, the model forecasts that the river mouths become quickly inaccessible. Remarkable is the sedimentation that occurs in the river reach of the southern mouth. The model predicts that during high discharges flow separation occurs, which directly causes sedimentation. This sediment deposition process will also be problematic for navigation. The bed level changes are given in Figure 5.16.
Long-term development

To gain insights into the long-term development of the Leoncito branch, a period of ten years is modelled. Figure 5.17 shows the development of the discharge distribution of Boca North (blue), Boca South (red) and the Burrera branch (green). A remarkable result is that the model predicts that the discharge through Boca South decreases considerably. The sediment deposition in the river section of Boca South plays a key role in this reduction. However, the results shown in Figure 5.17 are based on many assumptions and model settings and should therefore be interpreted with caution. In addition, the discharge distribution may change if during the period of ten years dredging activities are carried out.

Figure 5.17 Discharge distribution for ten years
5.2.2 Navigability improvement measures

The model results of the current-state model clearly show that the sediment deposition at the river mouths causes problems for navigation. In this section measures are examined, which might reduce the high sediment deposition rates at the river mouths of the Leoncito branch. Again, no dredging activities are modelled to investigate the natural behaviour of the delta after implementing a measure.

Sand Trap

As a result of the large quantities of fine material which are transported, a large sand trap in terms of width and length is modelled. Fine sediments have slow fall velocities and therefore the settling processes take time and the sand trap only works properly when the sand trap is large enough.

The model predicts a decrease in depth-averaged flow velocities directly after inflowing in the sand trap. The flow in the sand trap is not well distributed over the entire width, but is concentrated as a narrow gully. However, at the beginning of the sand trap two eddies are created. Also after the sand trap the flow velocities in the river remain lower compared to those in the current-state model. The velocities at the river mouths are also considerably lower.

Figure 5.18 shows the depth-averaged velocities which are predicted by the model. In the left picture, the decrease in velocity at the sand trap and at the mouth are clearly visible, while the right picture shows the formation of two eddies directly at the beginning of the sand trap.

The applicability of the sand trap was reviewed to compare the total sediment transport rate before and after the sand trap, see Figure 5.19. It appears that the sand trap is able to reduce the sediment transport. With the settings and lay-out used, the model calculates a decrease in sediment transport of more than 50%. The differences in amplitude which are observed are explained by the tidal influence, which is much larger downstream. Furthermore, the values shown are expressed in negative values, which is only model administration related. Figure 5.19 has two horizontal axes, for more information about these axes see Appendix B.
The reduction in sediment transport has its effects on the sediment deposition patterns at the river mouths. The total amount of sedimentation is lower than in the current-state model. However, the model predicts a remarkable deposition pattern for the changes in bed level at the southern estuary. The model results show more severe sedimentation in the river part of Boca South. Figure 5.18 already showed that the flow velocities are very low in this section, which also indicates a lower transport capacity. The deposition is even enhanced by the influence of salinity. The mixing between saline and fresh water is for high water at the Golfo de Urabá located in the estuary itself and not anymore in the Golfo de Urabá, as observed in the current-state model.

The changes in bed level for the whole model domain and for the river mouth in more detail are given in figure 5.20.
Artificial outlet channel 1

In this study three navigable artificial outlet channels have been investigated, two located 9.2 kilometres upstream of the existing river mouths of the Leoncito branch and one at 2.7 kilometres upstream the existing river mouths.
First, the artificial outlet channel with a small angle of off-take with the main channel at 9.2 kilometres upstream is modelled. The results which are discussed in the section can also be used to determine the morphological effects of a natural breakthrough of the river.

The hydrodynamic model already showed that a navigable additional outlet channel located more upstream than the existing outlets will result in a considerably higher rate of runoff through the Leoncito branch. In that model, the morphological response was not yet investigated. In the morphodynamic model the increase in discharge directly results in an increase in sediment supply. Large differences in flow velocities within the Leoncito branch are predicted by the model, see Figure 5.21.
The output of the model shows very interesting morphological dynamics, see Figure 5.22. Immediately after the construction of a new outlet, the new river bifurcation is not in equilibrium. The new channel provides the shortest distance to the sea. Therefore the outflowing discharge and the flow velocities that take place in this new channel are huge. The flow velocities in the bifurcate from the artificial river outlet to the current river mouths decrease. Immediately after the bifurcation a sedimentation shock wave is formed. The timescale to achieve a new stable equilibrium condition is longer period than the period modelled. However, the process to achieve this new stable equilibrium condition is clearly shown in the model.

Figure 5.21  Depth averaged velocity in case of artificial channel with a small angle of off-take

Figure 5.22  Bed level changes after applying an artificial outlet channel with a small angle of off-take; initial condition (upper left), after 1 month (upper right), after 3 months (lower left), after 6 months (lower right)
The sediment deposition in the current river outlets reduces, but the sedimentation shock wave makes the navigation problems only more precarious. This is even more noticeable when the discharge development over the next ten years is examined, see Figure 5.23. In this model run no human interferences are taken into account. Without interferences, the discharge through Boca South will reduce drastically the first five years. However, the model does not forecast a complete closure. Nevertheless, in practice it is common that vegetation takes possession over shallow areas and eventually leads to a complete closure. This process is described in section 3.5. In the first three years the model predicts that the discharge through Boca North will increase as a result of the virtual closures of Boca South and the Burrera branch. Finally, the model forecasts a virtual closure of the northern river mouth of the Leoncito branch as well. Again, a long-term model prediction will be sensitive to model input [MELMAN, 2011].

The river bank lines in the model are fixed, which means that the model is not capable to reproduce potential widening of the new outlet channel. In reality, the high flow velocities that occur in the new outlet channel might cause eroding banks. Properly constructed bank protection can be applied to counteract this process. Widening of the banks of the new outlet channel will change the discharge distribution and sediment distribution at the bifurcation and will therefore change the final layout of the delta.
Artificial outlet channel 2

The previously investigated navigable artificial outlet channel had no beneficial effects for navigation. The new bifurcation caused a process to attain a new equilibrium state, where eventually the river depth will be too shallow for navigation. The flow was disproportionately divided at the bifurcation. Now another design of an artificial outlet is investigated. In the new scenario the off-take angle is much higher, see Figure 5.24.

Figure 5.24  Orientation of the artificial outlet channel; small off-take angle (left) and large off-take angle (right)

Because of the new layout of the channel flow separation occurs. The river flow cannot follow the bank lines of the new artificial channel. The effective flow width of the new outlet channel becomes smaller and subsequently the discharge through the outlet decreases. The flow velocities through the new outlet channel remain high, see Figure 5.25.

Figure 5.25  Average flow velocities in case of an artificial outlet channel with a large angle of off-take

Figure 5.26 shows the modelled dynamics for the river bed for a period of 6 months.
Again, the required time to achieve a new stable equilibrium condition is not completely modelled. Nonetheless, the process to achieve an equilibrium state is visible. In the Leoncito branch the same processes occur as for the outlet channel with a small angle of off-take, but the sedimentation shock wave is a little bit less severe. Figure 5.27 shows the modelled discharge distribution for a period of ten years. For the long-term the model forecasts virtual closures of the current river mouths. The process towards these virtual closures is almost similar as for the artificial outlet channel with a small off-take angle.
Due to the location of the artificial river outlet the division of flow and sediment is still not optimal. Likely the difference in distance to the sea between the current river outlets and the new river outlet channel is too large to achieve this optimum. More research might eventually lead to an optimum, where the Leoncito branch remains navigable and a substantial part of the sediments are deposited at the newly constructed river mouth.

**Artificial outlet channel 3**

The previous two examined measures show that an navigable artificial channel located 9.2 kilometres upstream of the current river mouths of the Leoncito branch does not lead to an improvement for navigation. In the long-term the current river mouths are subject to severe sedimentation. In this section, again an artificial outlet channel is discussed, but now the channel is situated 2.7 kilometres upstream.

The morphological evolution of six months is shown in Figure 5.28.
Figure 5.28 Bed level changes after applying an artificial outlet channel situated 2.7 kilometres upstream the current river mouths; initial condition (upper left), after 1 month (upper right), after 3 months (lower left), after 6 months (lower right)

Again, the process of flow separation is observed in the new river outlet, see Figure 5.29. The angle of off-take of the new outlet channel has to be reduced to avoid the sediment deposition that is induced by flow separation.
The total discharge through the Leoncito is considerably lower than for the previously examined artificial outlet channels that are positioned more upstream in the river. Therefore the sediment supply is also lower. Moreover, the transported sediment through the new river outlet is deposited over a large area, which will be beneficial for future navigation. In principle, this measure raises potential to improve the navigation and to minimize the dredging activities in the delta. However, the navigation has to use the new river mouth. The predicted discharge for a period of ten years for Boca North (blue), Burrera branch (green), Boca South (red) and the artificial channel (purple) is given in Figure 5.30. Remarkably, the model now predicts that the discharge through the Burrera branch will increase, whereas the model predicted a virtual closure of the Burrera branch for the other two river outlet channels studied.

![Discharge distribution artificial channel 3](image)

**Figure 5.30** Discharge distribution artificial channel 3

### Sediment diversions channels

The morphodynamics after the implementation of three little sediment diversion channels has been investigated. The channels aim to distract sediment in order to reduce the sediment deposition at the current river outlets. The channels are not designed for navigation purposes, because the three channels are only 25 metres wide. The first branch is now located 9.2 kilometres upstream. In the model, it is again assumed that the river banks are non-erodible. The model forecasted that all the investigated artificial river mouths lead to a sediment shock wave through the Leoncito branch and eventually to inaccessibility of the current river mouths. It is now examined if also small river outlets will result in the inaccessibility of the current river mouths.

The model forecasts high flow velocities at the first diversion channel. Consequently, properly constructed bank protection should be applied to counteract the bank erosion and with that the widening of this diversion channel. Despite the relatively narrowness of the channel, large amounts of sediments are transported through the first diversions. Due to the high velocities that occur in this channel a typical inertia dominated sediment depositional pattern can be observed at this mouth. The predicted changes of the river bed level by the model are given in Figure 5.31.
Figure 5.31 Bed level changes after applying three sediment diversion channels; initial condition (upper left), after 1 month (upper right), after 3 months (lower left), after 6 months (lower right).

Figure 5.32 shows the effectiveness of the applied diversion channels for a period of six months. In fact it appears that diversion 1 is much more effective than the other two diversions. Also Brazo Burrera reduces the sediment transport in the river significantly. Diversion 1 combined with Brazo Burrera transports more than 60% of the initial sediment supply at the upstream boundary of the model. The effectiveness of the diversion sites depend mainly on their location and decrease rapidly when applied more downstream. Figure 5.32 has two horizontal axes, for more information about these axes see Appendix B.
Figure 5.32 sediment transport at various locations in the river after applying sediment diversion channels.

Figure 5.33 shows the long term discharge distribution. It appears that diversion 2, diversion 3 and Boca South eventually will silt up entirely.

Figure 5.33 Discharge distribution sediment diversion channels.
River outlet extension

The previous simulations showed that the sediment deposition immediately occurs when the riverine water flows into the sea. It seems to be impossible to prevent the sudden spreading and deceleration process of the riverine sediment-rich water when the water flows into the sea. However, at the moment, all the river branches flow out in relatively shallow water and therefore the sediment deposition directly results in navigation problems. The possibility to extend one of the river mouths artificially till a deeper part of the Golfo de Urabá is now examined.

The output of the model shows very promising morphological results for navigation through the northern river outlet, see Figure 5.34. As a result of the artificial extension of the northern river outlet, the sediment deposition at this river mouth occurs in relatively deep water. The model clearly shows that for at least a period of six months, the sediment deposition directly after the extended northern river outlet of the Leoncito branch will not impede the navigation. However, the model predicts sediment deposition between the breakwaters, which may impede the navigation if no dredging maintenance will be carried out. The advantage of sediment deposition in deeper water will probably be temporary, because the deposited sediments will raise the seabed Golfo de Urabá.

Figure 5.34 Bed level changes after the extending of the northern river mouth of Leoncito; initial condition (upper left), after 1 month (upper right), after 3 months (lower left), after 6 months (lower right)
Navigation through the southern outlet will soon be impossible, because the entrance will be almost entirely blocked by the deposited sediments. The southern river outlet provides now the shortest distance to sea, which directly results in an increase of flow through this river outlet, see Figure 5.35. The increased flow causes an increase in sediment transport through the river outlet and even leads to erosion in the river outlet. The sediment deposition directly after the river mouth will be much larger than the sediment position in the current state. Figure 5.36 shows the long term computation. Also in this scenario, the southern river mouth will eventually silt up. The discharge through the Burrera branch increases considerably.

Figure 5.35  Depth averaged flow velocity after constructing breakwaters at Boca North

Figure 5.36  Discharge distribution after constructing breakwaters at the river mouth
Conclusions regarding morphodynamic modelling of navigability measures

The simulations show that the different measures do affect the sediment deposition processes near a river mouth and some even reduce the rate of sediment deposition. However, none of the measures will make dredging at the mouths unnecessary. In addition, the results of the modelling are uncertain because the possible bank erosion is not modelled. The process of bank erosion should therefore be implemented in the models in a follow-up study.

The implementation of an artificial river mouth creates a shock wave through the Leoncito branch. Eventually this shock wave reduces the navigability of the current river outlets in the Leoncito branch. The construction of an artificial river mouth upstream of the existing river outlet also directly results in an increase of discharge and consequently an increase in sediment supply. The accessibility over ten years for the current river mouths of the Leoncito branch for the different scenarios is given in Table 5.2.

<table>
<thead>
<tr>
<th></th>
<th>Boca South</th>
<th>Boca North</th>
</tr>
</thead>
<tbody>
<tr>
<td>No Measure</td>
<td>X</td>
<td>V</td>
</tr>
<tr>
<td>Sand Trap</td>
<td>X</td>
<td>V</td>
</tr>
<tr>
<td>Artificial Outlet 1</td>
<td>X</td>
<td>X</td>
</tr>
<tr>
<td>Artificial Outlet 2</td>
<td>X</td>
<td>X</td>
</tr>
<tr>
<td>Artificial Outlet 3</td>
<td>X</td>
<td>X</td>
</tr>
<tr>
<td>Diversion Channels</td>
<td>X</td>
<td>V</td>
</tr>
<tr>
<td>Extended river mouth</td>
<td>X</td>
<td>V</td>
</tr>
</tbody>
</table>

Table 5.2  Accessibility over ten years for different scenarios

For the measures that provide accessibility over ten years, the sediment transport just upstream of the two river outlets after 6 months of morphology is given in Table 5.3.

<table>
<thead>
<tr>
<th></th>
<th>Sediment Transport [m$^3$/s]</th>
</tr>
</thead>
<tbody>
<tr>
<td>No Measure</td>
<td>0.08</td>
</tr>
<tr>
<td>Sand Trap</td>
<td>0.06</td>
</tr>
<tr>
<td>Diversion Channels</td>
<td>0.05</td>
</tr>
<tr>
<td>Extended river mouth</td>
<td>0.08</td>
</tr>
</tbody>
</table>

Table 5.3  Sediment transport for different scenarios

At the moment, a sand trap, the sediment diversion channels and the construction of breakwaters appears to be the most promising measures to investigate in follow-up studies. However, the resulting reduction in sediment concentration is small. Therefore, it will be much more effective to reduce the sediment supply to the Leoncito branch and the whole delta. The cost-effective measures to improve the navigability in the delta might be found more upstream in the river.

The presented long-term model results should be considered as rather uncertain as a result of the uncertainties in the model input and the neglecting of some sediment reworking processes. Moreover, no dredging activities have been included. The long-term results should therefore be regarded as an indication of what might occur. Moreover, no possible changes in the total deltaic environment are included in the long term computations.
6. Measuring and monitoring plan

This chapter elaborates a strategy to collect more data of the Río Atrato and indicates the essentialness of this process.

6.1 Introduction

This research has been executed to gain more insights in the morphodynamics in the delta of the Río Atrato. Unfortunately, the data were insufficient in both terms of quantity and quality for very detailed modelling. To enable more detailed hydrodynamic and morphodynamic modelling in the future, a short measuring plan is introduced in this report. The new data can be used to calibrate and validate the current models and to set up new models. Besides, the data will also be very useful for analysing the hydrodynamic and morphological processes analytically. The measurements described in the plan may also be used for the final choice which particular branch will be selected for the new navigation corridor. In this report the outcomes of the survey of INVIAS [INVIAS, 2010] are taken into account. In this report the selection of the Coquitos or the Leoncito branch is preferred.

Calibration and verification of a model is necessary, because a model is only a representation of the real world. The model describes this real world by mathematical laws and therefore assumptions and simplifications had to be made. Moreover, limitations in data increase the amount of assumptions and simplifications which have to be made in a model. Therefore a model never becomes an exact replica of the real world, but when a model is calibrated and verified well, a workable representation of the reality could be achieved. At that point, the model can be applied to forecast the morphodynamics in the delta and to review the effects of possible measures, which aim at improving the local navigability.

The current number of measurement stations and surveys of the river are currently insufficient for performing a calibration and a validation procedure or even to set-up more detailed models. Furthermore, no measuring stations are situated in the delta area. In addition, the frequency of measurements is, especially for the more downstream situated stations, insufficient. To overcome these shortcomings in the future, recommendations are given to increase the amount of data significantly in the next years, while the remoteness of the delta is taken into account.
6.2 Data required

To gain clear insights in a unique and complex system such as a river delta, an extensive amount of data is required. The full list of required data to perform an in-depth analysis is given in table 4.1. This section only elaborates the most important data, which have to be gathered by measurements. The key measurements which should be performed or intensified in the delta are:

- River bathymetry measurements
- Sediment characteristics measurements
- River bed stratification measurements
- Stage measurements
- Discharge measurements
- Sediment concentration measurements
- Salinity measurements
- Dredging quantities measurements

In this section, the reason of importance for each mentioned data topic in the list above is briefly explained. Subsequently, the location where these measurements at least should be taken is discussed. Next the period of measuring and the minimum frequency of the measurements are determined. Finally a measuring technique is proposed to execute the measurements. Simple but well-functioning equipment is recommended, but also other types of equipment may work properly.

The gathering of more data is of course better, but obviously time and cost constraints will also determine the data collection process. An assessment should be made to determine how much money will be available to perform more measuring and how accurate the measurements can be for that amount of money.
6.2.1 River bathymetry measurements

A good representation of the river bathymetry is obviously of great importance to determine properly where erosion and sedimentation will occur and at which locations problems for navigation can arise. It is very time-consuming and costly to map the entire bathymetry of the river accurately. To minimize this process some cross-sections in the river can be introduced to determine how strong the river bed changes at certain locations during the years. With the obtained data it will be easier to determine if a new bathymetrical survey of the whole delta will be necessary. In addition, the data can be used to calibrate the models.

- **Location**
  Firstly, the whole river bathymetry of the delta should be completely mapped during preferably average discharge conditions. Subsequently some cross-sections in the river should be selected to examine the changes in riverbed in time. It is recommendable to select a cross section upstream of the first bifurcation of the delta and at the delta branches, which at this moment appears to be most promising to serve as river corridor in the future. In Figure 6.1 the proposed locations of the cross-section are indicated in red.

- **Period and frequency**
  It is recommended to start as soon as possible with a large-scale river bathymetry survey during average discharge conditions. The bathymetry of the cross-sections should be at least measured once a month, to gain insight into the differences during the various seasons.

- **Proposed measuring technique**
  Different techniques can be applied to measure the river bathymetry. These techniques vary in accuracy and costs. However, the method applied in November 2009 (a combination of an echo sounder and a GPS system) is a good technique. However, in November 2009 not the entire river width was measured, see page 44. This time it is recommended to include the entire river width in the measurements. An echo-sounder combined with a GPS-device could also be applied to measure the cross-sections in the river. The measurements should be performed at the same locations constantly. Reference marks or beacons have to be applied to indicate the cross-section and to define the orientation of the cross section. The use of two beacons or two reference marks placed directly in line with each other on each river side is highly recommended. This will help the boat operator to sail the cross section in a perfectly straight line. However, this could be hard to realize in the densely vegetated Atrato delta.
6.2.2 Sediment characteristics measurements

Sediment characteristic measurements are of paramount importance in the river morphodynamics. The type and size of the sediments largely determine the pattern of sedimentation and erosion in the delta.

- Location
At this moment it is recommendable to take samples of the riverbed in at least nine locations, indicated with red boxes in Figure 6.2. These measuring locations are located in the most promising river branches to use in the near future for the river corridor and at the river mouths. Measurement locations which are located in an inner bend or an outer bend should be avoided, unless multiple samples over the width will be taken.

- Period and frequency
It is proposed to measure the sediment characteristics at least three times, during a low discharge period, an average discharge time and a high discharge period respectively.

- Proposed measuring technique
A hydrometer test in a laboratory should be performed. Due to the large amount of very small particles a traditional sieving procedure will not be sufficient. In Appendix D more information is given about a hydrometer test.

6.2.3 River bed stratification measurements

River bed stratification measurements are strongly related to sediment characteristics measurements. However, these measurements have to be executed to determine the layering of different sediment types (stratification) of the river bed. These different types of sediment layers do all have their own erosion resistance and will strongly determine the morphological activeness of the river bed. Besides, a possible non-erodible layer could be detected.

- Location
The same locations as described in sediment characteristics measurements will be interesting to measure.

- Period and frequency
It is recommended to measure the bottom composition one time during an average discharge period.

- Proposed measuring technique
Probing is a method in which the full bottom composition and its stratification is obtained.
6.2.4 Stage measurements

Stage measurements are important to achieve stage-discharge relations and to use for calibration purposes. Currently, there are no water level monitoring stations in the area of interest. The water levels in the delta depend strongly on the tidal amplitude and should therefore always be reviewed time-dependently.

- Location
  The tide plays an important role in the hydrodynamics and the morphology of the delta. At present, there are tidal forecasts available for the port in Turbo. To simulate the water level movement induced by the tide more accurately, it is recommended to record water levels for at least one station in the Golfo de Urabá. Processes of wind set-up will influence this measuring station, but the data will still be valuable for further studies and to calibrate the current models.
  In addition, at least one additional measuring station in the delta area should be installed to check whether the influence of the tide and peak flows is well modelled in the current models and to analyse the influence of these processes analytically. The best location of this measuring station will be just downstream the first rivers bifurcate.
  Furthermore, it is recommended to intensify the frequency of water level measurements in Riosucio and Domingodó.

- Period and frequency
  The measures should be executed permanently and the interval between those measurements should be small, in the order of minutes.

- Proposed measuring technique
  To measure water levels in the Golfo de Urabá, a wave buoy is recommended. Possibly the already present wave buoy of DIMAR can be used. For the stations in the delta, Domingodó and Riosucio, the installation of float gauges is recommended, see Figure 6.3. In a float gauging station an automatically recording device measures the water stage continuously.

6.2.5 Discharge measurements

Discharge conditions are extremely important in both the hydrodynamic and the morphological processes of the delta. In hydrodynamic and morphological models usually an upstream discharge condition is applied, although a measured discharge distribution in the delta can also serve in a calibration or verification method. Therefore it would be valuable to calibrate a modelled discharge distribution in the delta with a measured discharge distribution.
  Nevertheless, at the delta the river flow is strongly influenced by the tide and due to this tidal influence a discharge distribution is not easily measured in a proper way. For that reason, no discharge measurements are recommended in this area, but at a location more upstream in the river. Eventually these new measurements can lead to a newly-constructed rating curve or exceedance curve. With the obtained curve the current hydrodynamic model can be calibrated. The newly obtained hydrodynamic data can also serve as an upstream boundary in the current model or in new models, which will save a lot of computation time.

- Location
  The hydrodynamic model showed that at the location of the current measuring station in Domingodó the tidal influences are damped strongly enough to execute discharge measurements with a reliable result.
- **Period and frequency**
  To establish a rating curve or exceedance curve several stage and discharge measurements have to be performed. At least six measurements per year will be required in order to establish a rating curve within two or three years. Moreover, these measurements must represent different discharge regimes. After a severe flood, the rating curve should be recalibrated.

- **Proposed measuring technique**
  At this moment IDEAM uses the velocity-area principle to compute a near-instantaneous discharge of the river at a certain cross-section. At pre-determined depths the velocity is measured for representative parts $\Delta A_i$ of the area ($A$). In equation form, the method approach is:

$$Q = \int u \cdot dA \approx \sum u_i \cdot \Delta A_i$$

In principal, this is a correct method to determine discharges and therefore it is encouraged to do it more often. However, it is important to note that the depth-averaged velocity occurs at approximately 0.6 times the local water depth. [JANSEN et al., 1979]

### 6.2.6 Sediment concentration measurements

Sediment concentrations are vital to assess the amount of sediment which is transported into the delta. The sediment concentrations can be divided in suspended load and bed load concentrations. The models have shown that sediments are primarily transported in suspension in the delta. Therefore the measurements should measure this transport mainly.

- **Location**
  The sediment concentration should be measured at least at the upstream boundary location of the model. However, another four measuring locations are recommended for investigation as well. See Figure 6.4 for the positions of the proposed measuring sites that are indicated with red boxes. The measurements at the other four locations will gain insights in the sediment load which flows in or out the floodplain and the other bifurcates in the delta. The resulting data can be used to calibrate the morphodynamic model or as model input.

- **Period and frequency**
  The measurements should be taken at least three times a year, for periods with specific low, high and average flow conditions. The measurements should also be performed at the same day and the exact discharge conditions upstream should be known when the measurements are executed.

- **Proposed measuring technique**
  A very easy method to measure suspended load is bottle sampling, which can give a first estimate of the sediment concentration in the water. The sediment concentration is probably not uniformly distributed over the depth. Therefore, not only concentrations near the surface
should be measured, but also near the bottom. A more sophisticated piece of equipment is a turbidity meter, which can measure sediment concentration continuously. An even more sophisticated technique is an Acoustic Doppler Current Profiler (ADCP), see Figure 6.5. The ADCP is able to determine flow velocity magnitude and direction at selected depths in the vertical. But it is also able to determine the sediment concentrations in the water. Combined with the measured flow velocity, sediment transport rates can be obtained. It is noted that this technique is also very suitable for the velocity-area measurement mentioned above for discharge measurements.

\[ \text{Figure 6.5  ADCP current profiler (Luxemburg & Savenije, 2007)} \]

6.2.7 Salinity measurements

To investigate how the fresh water and salt water mix with each other more data are required. If the system is strongly stratified, the morphodynamic processes around the river mouth should be modelled 3-dimensionally. A depth-averaged model is in that case not suitable, because the fresh water flows now over the saline water where it becomes isolated from the effects of bottom friction.

- Location
The measurements should be concentrated near the river mouths. A measurement should include at least three salinity levels over the depths. In this case, a measurement on the surface, a measurement on half of the water depth and a measurement close to the bed should be sufficient. Also the salinity levels just upstream in the river have to be included in the survey, to examine if a possible salt wedge intrudes in the river.

- Period and frequency
The measurements should be performed in both the wet and the dry season, to regard the effects of the trade winds as well as the differences in discharge regime on the salinity in the delta as much as possible.

- Proposed measuring technique
A simple but accurate piece of equipment that is capable of measuring differences in salinity is a handheld conductivity meter.

6.2.8 Measuring dredging quantities

The exact amounts of dredging quantities are a very useful calibration parameter for the amount of sedimentation in the river mouth area. From now on, every dredging operation in delta should be recorded and published for future modelling.
6.3 Conclusion

If the project is going to be realized, it is very important to intensify the number of measurement and surveys on the river. This is in order to set up more detailed models in the future. In the Netherlands the slogan "meten is weten" which is freely translated into “Measuring is knowing” emphasizes the importance of measuring. And the slogan “doorzien is voorzien” (understanding is predicting) emphasizes the importance of modelling. The proposed measurements and the corresponding period and frequency to execute these measurements in the report should be regarded as an absolute minimum in order to come to a reliable model and obviously the gathering of more measurements is always better. The location of the measurements is also important. All the measurements should preferably be carried out in a straight section of the river in order to minimize the effects of local disturbances. The water level and discharge measurements should be performed in such a way that the backwater effects can be neglected, see Appendix C for more information. The strict requirements concerning backwater cannot be fully met, because the very mild bed slope of the lower part of river causes large backwater adaptation lengths. Additionally, the stage and discharge measurements should actually be executed on a site which is only flooded during very severe conditions. This requirement is not easily met for the low-lying natural Río Atrato, where inundations are very common due to the immense precipitation rates in the region.

Table 6.1 summarizes the necessary data to collect. Besides, a degree of importance is given for each data topic in order to determine the mutual importance. The table emphasizes that the three most vital variants are river bathymetry, sediment characteristics and sediment concentrations, for which measurements should be conducted as soon as possible.

<table>
<thead>
<tr>
<th>Required data</th>
<th>Degree of importance</th>
</tr>
</thead>
<tbody>
<tr>
<td>River bathymetry</td>
<td>*****</td>
</tr>
<tr>
<td>Bottom composition</td>
<td>**</td>
</tr>
<tr>
<td>Sediment characteristics</td>
<td>*****</td>
</tr>
<tr>
<td>Water levels</td>
<td>***</td>
</tr>
<tr>
<td>Discharges</td>
<td>***</td>
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<tr>
<td>Sediment concentrations</td>
<td>*****</td>
</tr>
<tr>
<td>Salinity</td>
<td>****</td>
</tr>
<tr>
<td>Dredging quantities</td>
<td>***</td>
</tr>
</tbody>
</table>

Table 6.1 Required data for morphodynamic modelling
7. Discussion

This chapter discusses the chosen methodology within this research and the performance of
the numerical models used in this study. As a result of this discussion also points of interest
for follow-up studies are highlighted.

Both the hydrodynamic model and the morphological model are only calibrated with limited
data. The results should therefore be treated with caution until more extensive calibration and
verification processes are executed. Moreover, a large number of assumptions are made in
modelling process. Therefore, until now the models' results are possibly inaccurate and
consequently not a good source to use for policy making. The question that now arises is how
reliable the results of the models are. Still the models show hydrodynamic and
morphodynamic processes that at first sight are very likely to occur, but an extended
 calibration process is needed to attain more certainty about the occurrence of these
processes and their quantities.

In this study an approach is used to model the hydrodynamics at a large scale first and
subsequently the morphodynamics modelling is conducted at a more detailed level. The
hydrodynamic boundary conditions for the morphodynamic model are obtained from the
large-scale hydrodynamic model. In the hydrodynamic model the bank lines and the
bathymetry of the river are immovable during a simulation. You can wonder how accurate this
approach really is, because the morphological changes in the river or even changes to the
river planform do affect the hydrodynamics. To model the whole area in one morphodynamic
model was too much time consuming at this time, but do improve the accuracy of the model
results. Conversely, the unstructured grid used in the hydrodynamic model is better applicable
to model topographical complex areas like a delta, than the structured grid used in the
morphological models. Therefore, the best option at this moment seems to update the applied
bathymetry in the hydrodynamic model constantly if the results of a new bathymetrical survey
become available. To model large time scales will still be problematic in this approach.
Fortunately, it will be possible to perform morphodynamic computations on the unstructured
grid as well in the near future.

The influence of density differences on the morphodynamics is highly schematized. First, 2D
models have been used instead of 3D models. A 3D model is more commonly used to
establish density differences accurately. Secondly, the enhanced flocculation process in
saline water is simplified even more.
At the moment the mouth bars probably prevent the formation of a salt wedge in the river. Still
a high level of stratification can occur in the Golfo de Urabá itself. At this moment, it was
decided to prefer less computation above achieving extremely accurate results. Salinity
measurements have to be executed to determine the stratification in the delta and to answer
the question whether a 3D model approach is necessary in the future.
The applied simplification to reproduce enhanced flocculation in saline water appears to be a
good first method to approach the flocculation process and to determine its importance. The
model results indicate that flocculation has a key role in the morphology at the river mouths.
Given the high concentrations of very fine sediments that are transported in the delta, this
could have been concluded in advance. The occurring flocculation in the delta is undoubtedly
a lot more complicated than the greatly simplified flocculation process in the model. More
research is necessary to determine this effect on the morphology in the delta.

Some of the examined measures to improve the navigability improve the local situation near
the Leoncito mouths. However, in all the examined strategies maintenance dredging remains
required. The exact location of these dredging activities can differ compared to current
dredging activities and therefore do not hinder the navigation in the delta. At the moment the
question of where you want to dredge is of more importance than the measure of how you
can prevent the high rate of sediment deposition in the delta. To lower these high sediment
deposition rates, the total sediment supply to the delta has to be reduced. This will have a
significant impact on the entire deltaic environment. The question now arises whether one
allows major ecological losses to occur. The Mississippi delta can serve as a reference,
because this delta currently undergoes a drowning process of the wetlands. The delta receives too little sediment, which is probably due to the large amount of interventions in the river. With this information in mind, a better policy for the Río Atrato could be made.

This report does not take the construction cost of the measures into account. In further policy for development of the navigation corridor, it is important to determine the discomfort the navigation will experience during dredging activities around the river mouths at first. Subsequently, it can be decided which amount of budget and effort it is worth to spend on a navigation improvement measure. A break-even point should be determined.

Apart from for the investigated measures to reduce the sediment deposition at a river mouth there are other options that are worth examining in further studies. Detailed research could be executed to one of the bifurcations in the delta. An optimum result would be a structure, which leads sediment-rich water towards a particular branch and sediment-poor water towards the other branch. Achieving this ideal situation seems not feasible in advance. Besides, the sustainability of such a scenario is doubtful, because the sediment-rich part might congest at some stage. As a result of the large proportion of suspended load the sediment transport will follow the flow direction, as we saw in Figure 5.11, which makes the optimum scenario unachievable. Nevertheless, the implementation of submerged vanes might help to interfere the natural flow [Odgaard, 2009] and the sediment transport simultaneously. Additional research will be necessary. Of course, these vanes may not hinder the navigation either.

More simple measures to investigate are local bathymetry interventions at a bifurcation point. One could take advantage of the fact that the highest sediment concentrations are located at the river bed. A shallow off-taking bifurcate of a deep main channel will receive relatively sediment-poor water. This principle is already widely used to connect irrigation channels to main channels, but should also work at a larger scale. The most optimal location to research such connection is at the bifurcation between the main channel and the Leoncito branch, because at that particular location the main branch already has a large natural depth. Given the large amount of very fine material that is transported in the delta, the distribution of the sediment concentration over the water depth is expected to be rather uniform.

A very simple possible strategy to minimize the inconvenience for sailing ships can be obtained to take turns in the dredging-activities for two or more river mouths. The navigation should be guided by channel buoying and traffic regulation to the river mouth which is navigable at that time. The navigation can be guided to another river mouth if the dredging activities at that location are completed.
8. Conclusions and recommendations

This study investigates the morphodynamics of a river mouth of the Atrato delta, in order to improve its accessibility for more extensive use of navigation in the future. The key processes for causing the current poorly accessible river mouths were determined by the execution of a literature study and the development of two process-based models, each with their own strengths and weaknesses, as is discussed in chapter 7.

In short, the main objectives of this study were (1) to gain insights into the morphodynamics of the delta, (2) to develop a hydrodynamic model on an unstructured grid, (3) to develop a morphodynamic model on a structured grid and consequently (4) apply these models to investigate measures which aim to improve the accessibility of a river mouths.

This chapter elaborates on the results of the literature study and the modelling results in relation to the objectives of this study. Subsequently, further improvements of the models are recommended and recommendations for the project in its fullness are formulated. The conclusions of these topics are provided in section 8.1, whereas in section 8.2 recommendations with respect to these conclusions are given.

8.1 Conclusions

The first main objective was to gain insights in the morphological and hydrodynamic processes in the Atrato delta and the interaction between these processes. The key conclusions based on the literature study and the modelling processes are:

- According to literature, the morphology and the geometry of a delta are often assumed as the result of the interplay of river-, tidal- and wave-related processes. The river carries sediment towards the coast and deposits a large amount of these sediments beyond the mouths. Tidal currents and waves tend to spread these sediments, affecting the shape of the resulting geometry. Besides, changes in the course of the river will have great impact in the resulting geometry of a delta.

- The discharge variation of the Atrato River during the year is quite small. Even during periods of low discharge, the runoff and also the sediment load is considerable. At the delta the Río Atrato branches into various outflows to the sea, which results in a large spreading of sediments to the Golfo de Urabá.

- The delta area consists of extensive wetlands, because the Atrato delta is still relatively untouched by navigation regulation methods, which enables the river to freely flow into the extensive wetlands of the delta. The hydrodynamic model showed that the wetlands act actively as storage basins and prevent a massive flooding in the delta area.

- The conducted study of the evolution of the Atrato delta shows that the rate of meandering of the river at the delta is slow. This may be due to the comparatively densely vegetated floodplains and erosion-resistant characteristics of the banks, which counteract the meandering process.

- The sediment samples taken in the river indicate that flocculation is expected to occur. Saline water will enhance this process. The models predict that mixing between fresh water and saline water will mainly take place in the Golfo de Urabá and not in the river.

- The Atrato shows no specific geometric features that indicate that the delta experiences tidal influence. The tidal range is therefore too limited. The hydrodynamic model shows that the discharges of the various river branches are almost constantly large enough to prevent flow in upstream direction. Only the combination of spring tide and very low discharge conditions resulted in small upstream flow velocities. However, the tide produces backwater effects constantly, which have major effects on the water level, the
flow velocities and the discharge distributions in the delta. This influence can be felt in a large part of the river. The model predicts water level influences up to Isla Grande.

- The specific shape of the Gulf of Urabá and its shallowness limits the occurring wave heights significantly. The influence of waves has not been modelled, still it is believed that the wave attack will be an important driver in the distribution process of deposited sediments at the river mouths. Typical wave-induced features are less visible on the delta geometry. Only at the more northern mouths of the Río Atrato, the oblique incoming waves have resulted in a spit formation. A direct effect of wave energy on the geometry for the southern river mouths is not visible for the southern river mouths.

- The high quantities of transported sediment by the Río Atrato resulted in a large sediment accumulation in the Gulf of Urabá. The combination of this high sediment load, the small tidal range and mild wave regime in the Golfo de Urabá qualify the delta as highly river-dominated. The typical bird foot pattern is also a result of the weak sediment reworking processes in the Golfo de Urabá in relation to the fluvial sediment input. In addition, the relative shallowness of the Golfo de Urabá favours further progradation of the delta.

The second main objective was to investigate the hydrodynamics of the Atrato delta in more detail in a model with an unstructured grid using the D-Flow FM software that is presently (2011) developed by Deltares. Besides, the hydrodynamic model should be capable of simulating applicable data for boundary conditions in more detailed models. The most important conclusions regarding this objective are:

- An unstructured grid has the advantage that it can easily work with a great diversity in terms of resolution, which is necessary to prevent exorbitantly long computational time.

- The used combination of triangles, quadrilaterals and 1D links appears to be a very powerful combination to model complex areas, like a delta. The drawbacks when using a curvilinear grid cells only are completely solved.

- Tributaries can be coupled via a 1D link, which enables the modelling of large parts of the catchment area. Besides, 1D flow links require little computation time.

- For the applied unstructured grid the hydrodynamic model gives insights into the hydrodynamics of the Atrato delta. The model also includes a significant part of the wetlands of the delta, which have a major influence on the hydrodynamics in the delta.

- The model is able to create specific time-dependent boundary conditions for a smaller model. This approach solves the problem of enormous backwater adaptation lengths, which are initiated by the tidal movement and the large amount of bifurcations in the delta.

- The main reason for the hydrodynamic differences between the Delft3D, SOBEK and D-Flow FM computations is that only the D-Flow FM model includes a significant part of the wetlands of the delta.

The third main objective was to develop a process-based morphodynamic model on a structured grid that properly simulates the morphological processes in the Atrato delta. The model had to be able to identify the key processes that cause the poor accessibility of a river mouth and to model the interaction between these processes realistically. In addition, given the potential lack of data the extent of the reliability had to be indicated. The most important conclusions regarding this objective are:

- The wave reworking process has not been included in this model. To overcome this shortcoming partly the Leoncito branch is modelled, where the wave attack is least severe. However, the choice to investigate the Leoncito branch in this report should not be regarded as a final decision.
The key process that causes the poor accessibility of a river mouth appears to be the sudden spreading and deceleration of the riverine water, when outflowing in the Golfo de Urabá. As the flow expands, its momentum decreases and subsequently its capacity to carry sediments decreases. This eventually results in deposition of the sediments. Due to the relative strength of the outflowing fresh water compared to the tidal power the flow velocities are directed seawards for almost all conditions, which explains the low sedimentation rates in the river part of the delta.

During high flow conditions the model forecasts the process of flow separation in the southern mouth of Leoncito. This process leads to sediment deposition in this branch and eventually in an obstacle for the navigation through this mouth.

Due to a lack of data until now the models’ results are possibly inaccurate. The hydrodynamic and morphodynamic processes will likely reflect reality, but the exact quantities do probably not match reality. At this stage the models will help to understand the morphodynamics at the delta and hopefully encourage the collection of more data. Furthermore, the models can be used for policy making.

Given the high concentrations of very fine sediments that are transported in the delta, the enhanced flocculation process that occurs when the fresh sediment-rich water mixes with saline water, will play a key role in the morphology in the delta. This process is highly schematized in the model, but the model is able to show its effect on the morphology in the delta. The sediment deposition is much more concentrated in the direct vicinity of a river mouth.

For a period with a high discharge the problems to access a river mouth are the most precarious. During certain periods, the river transports a large sediment load, which is to a large extent deposited at the river mouths.

The model predicts that the southern river mouth of the Leoncito branch will silt up if no dredging maintenance will be carried out.

The final objective was to apply the models to investigate measures which aim to improve the accessibility of a river mouth. The models had to show whether the proposed measures led to an improvement of the navigation of the delta. Furthermore the models had to forecast the response of the delta to these interventions. Finally, a suggestion had to be given which navigability improvement measure raises the most potential for further research in follow-up studies.

Some of the examined strategies to improve the navigability improve the local situation near the Leoncito mouths. However, in all the examined strategies dredging maintenance will still be required. The exact location of these dredging activities can differ compared to the dredging activities at the moment and could therefore not hinder the navigation in the delta. But all the measures have in common that dredging activities at river mouths cannot be avoided totally.

In follow-up studies, the measures have to be optimized. But the likelihood that a measure could be implemented in such a way that no dredging activities are needed seems very small.

The model predicts that a navigable artificial river outlet, which is located at 9.2 kilometres upstream in the Leoncito branch and around 200 metres wide, eventually results in inaccessibility in the river reach between the new outlet and the current river mouths.

A sand trap and sediment diversion channels raise the most potential to reduce the sediment supply towards the current river mouths, without deteriorating the navigability in other parts of the river too much. To minimize the river dredging activities for at least several years, the extension of a river mouth with breakwaters till deeper water will be
the most promising measure. An additional optimization has to be performed to
determine the best dimensions and locations for the measures.

8.2 Recommendations

This study aims at gaining more understanding of the hydrodynamics and morphodynamics of
the Atrato delta, in order to improve its accessibility for more extensive use of navigation in
the future and to minimize the dredging activities. However, before the implementation of real
structures or measures are going to be considered, one should first determine how much
inconvenience the navigation will experience as a result of dredging activities in a river mouth
and what the yearly costs are of these activities. Subsequently, one can decide how much
budget and effort it is worth to spend on a navigation improvement measure.

Based on the findings of this study the following recommendations are given to guarantee a
more navigable delta:

- The deepest and widest river branches in the delta are in principle the most navigable.
  However, they also deliver the largest amounts of sediments to the sea and form the
  largest shoals that are obstacles for navigation. Therefore a relatively small river branch
  is recommended to use for the future river corridor.

- The northern river mouth of the Leoncito branch remains longer at navigable depth than
  the southern mouth. Nevertheless, the sediments are deposited over a much larger area.
  If the Leoncito branch will be chosen as the final navigation route, it must be a
  considered that the southern mouth requires frequently dredging activities, whereas the
  northern mouth requires dredging activities in a large area.

- Extending a river mouth to deep water by constructing breakwaters on either side
  prevents the formation of shoals, but the associated reduction of sediment fluxes to the
  shallow areas of the delta may set off coastal erosion. Future research is necessary to
  investigate the effects in more detail.

- In order to minimize the inconvenience for sailing ships it is recommended to take turns
  in the dredging-activities for two or more river mouths. The navigation should be guided
  by channel buoying and traffic regulation to the river mouth which is navigable at that
  time. The navigation can be guided to another river mouth if the dredging activities at that
  location are completed.

- The construction of an extra navigable outlet in the Leoncito branch will increase the total
  sediment transport through the branch and eventually results in inaccessibility of the
  current river mouths. Therefore this measure should not be implemented.

- The construction of a sand trap reduces the sediment supply towards the current river
  mouths. For the construction of a sand trap in the Atrato delta holds: a sudden increase
  in terms of width is more effective than a sudden increase in depth. The eddies which are
  formed when the river suddenly increase in width are effective to deposit sediments.
  Multiple widening in a river branch raise therefore the most potential to reduce the
  sediment deposition at the river mouths.

- The creation of new small distributary channels can improve the situation for some time if
  these channels are not located too far upstream. It is recommended to dredge the
  sediment deposition in front of the distributary channels frequently, in order to maintain
  optimal effectiveness.

Based on the findings of this study the following extensions and adjustments of the models
used are recommended:

- In order to model the hydrodynamics and morphodynamics of the Atrato delta more
  accurately and to calibrate the current models, it is strongly advised to perform
  measurements, according to the measurement plan provided in chapter 6.
- Calibration and verification of the present models was not possible since the current data were lacking. If more data are available it is strongly recommended to perform a thorough calibration and validation.

- The impact of waves should be included in the simulations. A yearly representation of an average wave climate in the gulf with wave fields with varying significant wave heights and varying approach angles will better simulate the dynamic environment at a river mouth.

- Biological effects should be included in the morphodynamic model. The Atrato delta has a unique ecology with the large wetlands and densely vegetated floodplains. The vegetation strongly affects the hydrodynamics and morphodynamics in the delta. To include all these effects will be a real modelling challenge, but several assumptions could be made.

- A larger area of the delta should be modelled morphodynamically. The morphological changes in one branch or river mouth will affect the hydrodynamics and the morphology throughout the delta.

- A longer model time scale should be determined in which the effects of the navigation improvement measures is tested for the whole delta area. The timescale to achieve a new stable equilibrium condition after a (human) modification should be in the model time.

- Due to the two periods of continuous persistent wind in opposite direction it is recommended to investigate the wind effect on the local hydrodynamics and morphodynamics with the models. The wind may cause set-up and a wind-driven current. In theory, the water flows in the direction of the wind (neglecting Coriolis) near the surface, while continuity requires a return flow in the deeper water. This effect can affect the morphology of the delta. This holds even more because density differences over the water depth becomes more likely near a river mouth. This process can only be modelled in 3D, which is achieved by adding layers to the models.

- The impacts of tectonic subsidence of uplift can be assessed with the models by adjusting the bathymetry of the models and the boundary conditions.

The next step in the project should be the collection of more data. After the gathering of more data, the current models can be calibrated and validated. Possible modifications and elaborations can also be applied. The implementation of wave influence to the models will achieve more realistic long-term sediment deposition patterns.
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UNIVERSIDAD TECNOLÓGICA DEL CHOCÓ (2010d) Estudios y análisis para la investigación de la factibilidad técnica, socio-económica y ambiental del corridor Atrato- San Juan; Volumen II Dimensionamiento de las obras, Capítulos 3 Hydraulicá (preliminary unauthorised document). Convenio 3479 de 2008 INVIAS – Universidad Tecnológica del Chocó

UNIVERSIDAD TECNOLÓGICA DEL CHOCÓ (2010e) Estudios y análisis para la investigación de la factibilidad técnica, socio-económica y ambiental del corridor Atrato- San Juan; Volumen II Dimensionamiento de las obras, Anexo 1 Modelación hidrodinámica del Río Atrato. Convenio 3479 de 2008 INVIAS – Universidad Tecnológica del Chocó

UNIVERSIDAD TECNOLÓGICA DEL CHOCÓ (2010f) Estudios y análisis para la investigación de la factibilidad técnica, socio-económica y ambiental del corridor Atrato- San Juan; Volumen III Factibilidad y escenario futuro del corridor seleccionado. Convenio 3479 de 2008 INVIAS – Universidad Tecnológica del Chocó

UNIVERSIDAD TECNOLÓGICA DEL CHOCÓ (2010g) Estudios y análisis para la investigación de la factibilidad técnica, socio-económica y ambiental del corridor Atrato- San Juan; Volumen IV Recomendaciones para la implementación del proyecto. Convenio 3479 de 2008 INVIAS – Universidad Tecnológica del Chocó


Morphological modelling of the Atrato river delta in Colombia

-Appendices-
Appendix A. Abbreviations in Orton and Reading

This appendix shows the diagram of Orton and Reading (1993) with a list of the abbreviations of the delta systems. The Figure A1 shows the diagram and Table A1 provides the list of abbreviations.

![Diagram of Orton and Reading (1993)](image)

**Table A.1  Abbreviations in Orton and Reading (1993)**

<table>
<thead>
<tr>
<th>Abbreviation</th>
<th>Delta System</th>
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Appendix B. Hydrodynamic and morphodynamic time scale

This study contains three figures (Figure 5.11, Figure 5.19 and Figure 5.32) with two horizontal time axes. One axis corresponds to the hydrodynamic evolution and the other one corresponds to the morphodynamic evolution. In this appendix a short explanation is given in order to avoid obscurities.

Figure B.1 shows the sediment transport for twelve days through Boca North and Boca South for a constant discharge. The changes in sediment transport are completely caused by the tidal energy.

![Figure B.1 Sediment transport for 12 days](image)

Morphological changes usually take place over much longer periods as compared to hydrodynamic changes. In order to present morphological changes, without extensive computation times a morphological acceleration factor has been used. This factor accounts the difference in time scales of hydrodynamics and morphodynamics. The concept is rather simple; the morphological changes are multiplied with the acceleration factor. Now, the morphological time step is extended by:

\[
\Delta_{t_{\text{mor}}} = M_{\text{orfac}} \Delta_{t_{\text{hyd}}}
\]

Where:
- \(\Delta_{t_{\text{mor}}}\) morphological time step, [s];
- \(M_{\text{orfac}}\) morphological acceleration factor;
- \(\Delta_{t_{\text{hyd}}}\) hydrodynamic time step, [s].

Figure B.2 shows the sediment transport with a morphological acceleration factor of 15.
Figure B.2 Sediment transport with a morphological acceleration factor of 15.

Figure B.2 has two horizontal axes, because the morphological development for a period of six months can be discovered in the figure if the tidal movement is excluded, see Figure B.3. For this reason two horizontal axis are included in the figures.
Figure B.3 Daily average sediment transport for six months
Appendix C. Fundamental equations and requirements in the numerical models

In this study models are set up in Delft3D and D-Flow FM. In order to understand the model set-up a short explanation is given. D-Flow FM and Delft3D are both process-based numerical models, which are continuously under development by Deltares. The models make use of a finite-difference numerical approach, which actually is a finite volume approach.

This chapter describes the mathematical background of Delft3D and D-Flow FM and gives insight into the underlying principles of the modeling systems. The modeling systems are based on a few assumptions. The relevant main assumptions and approximations for this study are:

- The flow is assumed to be incompressible.
- The horizontal length scale and time scales are assumed to be much larger than the vertical scales. The vertical accelerations other than the gravitational acceleration are assumed to be very small and are therefore neglected. Now, the shallow water equations and the hydrostatic pressure equation can be applied.
- The process of drying and flooding is determined by the water depth. When the water depth is below a user-specified threshold depth, the point is set dry. When the water level reaches the threshold depth, the grid cell is set wet again. The grid points which become dry are removed from the active flow domain and are added again when they become wet. The process of drying and flooding may generate small oscillations in water levels and velocities.

A detailed list of assumptions and simplifications are provided in the Delft3D-FLOW User Manual [DELTARES, 2010a].

The movement of water is described by a set of equations. Both models solve the non-linear shallow water equations, which are derived from the 3-dimensional Navier Stokes equations for an incompressible fluid and under Boussinesq assumptions. The depth averaged shallow water equations are derived from the 3D turbulent equations by integration over the depth. Once more, this can only be provided by the assumption that the accelerations in the z direction are much smaller than the gravitational acceleration. Under this assumption, the water pressure equation over the vertical becomes:

\[
\frac{\partial p}{\partial z} = -\rho g \quad (C.1)
\]

Where:
- \( p \) = pressure \([N/m^2]\)
- \( g \) = acceleration due to gravity \([m/s^2]\)
- \( \rho \) = density \([kg/m^3]\)
- \( z \) = vertical direction

Integration over the depth results in:

\[
p = -\rho gz \quad (C.2)
\]

This is the hydrostatic pressure equation.

At the bottom \((z = z_b)\) and at surface \((z = \zeta)\) the following conditions hold:

\[
U \frac{\partial z_b}{\partial x} + V \frac{\partial z_b}{\partial y} - w = 0 \quad (z = z_b) \quad (C.3)
\]

\[
\frac{\partial \zeta}{\partial t} + U \frac{\partial \zeta}{\partial x} + V \frac{\partial \zeta}{\partial y} - w = 0 \quad (z = \zeta)
\]
Where:

- \( U, V, W \) = velocities in \( x, y, z \) direction [m/s]
- \( z_\text{b} \) = bottom level above/ below a certain reference plane [m]
- \( \zeta \) = water level above/ below a certain reference plane [m]

### Continuity equation

Continuity implies a situation where the gradient of the flow is equal to zero in all directions. Often this equation is called the conservation of mass.

The 3D-continuity equation is as follows:

\[
\frac{\partial U}{\partial x} + \frac{\partial V}{\partial y} + \frac{\partial W}{\partial z} = 0 \tag{C.4}
\]

Integration over the depth and substitution of both boundary conditions provide the depth-averaged continuity equation, which is:

\[
\frac{\partial \zeta}{\partial t} + \frac{\partial (HU)}{\partial x} + \frac{\partial (HV)}{\partial y} = 0 \tag{C.5}
\]

In which \( H \) [m] is the water depth, which refers to \( H = \zeta - z_\text{b} \).

### Momentum equation

The momentum equation originates from Newton’s second law (force is mass times acceleration). It states that no momentum can be lost and therefore it is also a balance equation as the continuity equation.

The depth-averaged momentum equations in \( x \) and \( y \) directions are:

\[
\frac{\partial \zeta}{\partial t} + U \frac{\partial U}{\partial x} + V \frac{\partial U}{\partial y} - fV + g \frac{\partial \zeta}{\partial x} + v_H \frac{\partial^2 U}{\partial x^2} + v_H \frac{\partial^2 U}{\partial y^2} + \frac{gU\sqrt{U^2 + V^2}}{Hc^2} = 0 \tag{C.6}
\]
\[
\frac{\partial \zeta}{\partial t} + U \frac{\partial V}{\partial x} + V \frac{\partial V}{\partial y} + fU + g \frac{\partial \zeta}{\partial y} + v_H \frac{\partial^2 V}{\partial x^2} + v_H \frac{\partial^2 V}{\partial y^2} + \frac{gV\sqrt{U^2 + V^2}}{Hc^2} = 0 \tag{C.7}
\]

Where:

- \( f \) = Coriolis parameter, [1/s];
- \( C \) = Chézy coefficient, [m^{0.5}/s];
- \( v_H \) = Horizontal eddy viscosity, [m^2/s].

The first term is the local flow acceleration, the second and the third term correspond to advection terms in \( x \) and \( y \) direction. The fourth term is the Coriolis force, while the fifth term the acceleration due to pressure gradients represents. The sixth and the seventh term are the turbulent Reynolds stresses. The last term is the friction term.

The bottom friction terms are in this formula described as:

\[
\tau_{bx} = \frac{g}{c^2} U \sqrt{U^2 + V^2} \quad \text{and} \quad \tau_{by} = \frac{g}{c^2} V \sqrt{U^2 + V^2} \tag{C.8}
\]

### Grid

Models constructed in Delft3D are only able to work from a rectilinear or a curvilinear boundary fitted grid, while the models constructed in D-Flow FM are able to work from an unstructured grid. However, the similarities of the numerical schemes are abundant. Delft3D and D-Flow FM are both numerical based models based on finite volumes, which means that the shallow water equations have to be discretized. For both models the equations are discretized according to a staggered grid approach (see Figure C.1). The different quantities are defined at different locations on the staggered grid. The water levels are specified at the cell center, while the velocity components are defined at the cell faces of the numerical grid. Therefore, the computational control volume and a staggered grid cell are not equal to each other. One of the main advantages of a staggered grid is that different types of boundary conditions easily can be implemented. Water level boundaries are defined at...
water level points (+ points), whereas closed boundaries and discharge boundaries are defined at the velocity points (-, | points)

Figure C.1 Staggered grid of Delft3D with (left) staggered grid cell and (right) computational control volume [DELTARES, 2010].

In the figure the following is shown:
- full lines: numerical grid;
- grey area: control volume;
- •: depth below reference level;
- +: water level, concentration, salinity, temperature;
- -: velocity component in m-direction;
- |: velocity component in n-direction;

The staggered grid of D-Flow FM is a little different [KERNKAMP et al., 2011]. The pressure gradient depends on two pressure points, which are specified in cell circumcentres. The circumcentre is the midpoint of a circumscribed circle that goes through the vertices of a grid cell (see the green circle in Figure C2) For quadrangles there is some freedom in choosing the circumcentre, whereas the circumcentre is unique for triangles. This uniqueness is important in achieving orthogonality. The pressure point for 1D points is the network point itself. Also for this staggered grid, the water levels are specified at the cell center, while the velocity components are defined at the cell faces of the numerical grid, see Figure C.2.

Figure C.2 Example of unstructured grid with triangles and quadrangles [KERNKAMP et al., 2011]

Grid requirements:

A constructed grid should be checked on several requirements in order to achieve stable and accurate model results. Next to the CFL condition, the grids must fulfill criteria regarding
orthogonality, smoothness and aspect ratio. The requirements for grid design are described in more detail by Ottevang et al., 2006.

**Orthogonality**

In a curvilinear grid, the measure for the orthogonality is based on the cosine of the angle between the grid lines. The cosine should be smaller than 0.02. However, near closed boundaries larger values can be tolerated. See Figure C.3 for the orthogonality of the used Delft3D grid. The grid is rather orthogonal. Only non-blue areas are not within the preferable range. These areas are situated at bifurcations and at the closed boundaries.

![Figure C.3 Orthogonality of structured grid](image)

For a unstructured grid in D-Flow FM orthogonality implies [Kernkamp, et al., 2011]:
- The circumcentre of each cell lies within that cell and therefore triangles should have acute angles.
- The flow link (the line which connects the circumcentres of two neighbouring cells) should intersect the interface between them orthogonal.

The used grid in D-Flow FM is enormous orthogonal, see Figure C.4. Even at bifurcations no problems arise, which is shown in the right picture of Figure C.4.

![Figure C.4 Orthogonality of the unstructured grid: whole delta area (left) and at bifurcation (right)](image)
**Aspect ratio**

The aspect ratio is the ratio between the lengths of a grid cell in two directions. In a Delft3D grid these are the m- and n-direction. For a curvilinear grid a range of 1-5 in the main channel is tolerated. Figure C.5 shows that the aspect ratio of the structured grid is almost entirely within the preferable range.

![Aspect ratio of the structured grid](image)

In a D-Flow FM network there are no specific directions defined. In order to check on the grid the aspect requirement, the smallest cell face is divided by the largest cell face. According to the requirement for a structured grid, the aspect ratio should now be >0.2 for the unstructured grid. Figure C.6 shows that the aspect ratio of the unstructured network is almost entirely within the preferable range.

![Aspect ratio of the unstructured grid](image)
Smoothness

In order to avoid inaccurate results the ratio between adjacent grid cell lengths should not be too large in the area of interest (preferably <1.2). For the structured grid only at bifurcation points the smoothness is a somewhat higher than the preferable range, see Figure C.7. In a structured grid it is nearly impossible to obtain a well orthogonal and a well smooth grid at a bifurcation point.

The unstructured network has a great diversity in terms of resolution. The smoothness ratio at a connection between quadrangle cells and triangle cells is not within the required range (Figure C.8). But such connections are perfectly orthogonal. In the mainstreams the smoothness ratio is within the preferable range.
Numerical stability

The numerical stability of every model built in Delft3D and D-Flow FM can be tested with the Courant number. The Courant number (CFL condition) can serve to determine the required time step to achieve stable results. A stable simulation holds convergence of the numerical solution. If the CFL condition is not met the numerical solution becomes unstable.

The CFL condition for D-Flow FM and Delft3D are not equal. Delft3D uses an implicit scheme and is unconditionally stable. Nevertheless, the accuracy of flow calculations decreases with increasing time steps. In D-Flow FM the advection terms in the momentum equation (C.6 and C.7) are integrated explicitly in time and are formulated in a momentum-conservative way.

The reason for this conservative formulation is found in the choice of a closed pair of advective fluxes and advected quantities. The advected quantity is defined in a cell circumcentre and the advective fluxes, which transports this quantity are defined on the cell faces. For a full explanation, the reference is made to KERNKAMP et al., 2006.

For Delft3D the CFL condition for hydrodynamics reads:

\[
CFL = \frac{\Delta t}{\Delta x \Delta y} (u + \sqrt{gh}) \leq 8 \tag{C.9}
\]

For D-Flow FM the CFL condition for hydrodynamics reads:

\[
CFL = \frac{\Delta t}{\Delta x \Delta y} (u + \sqrt{gh}) \leq 1 \tag{C.10}
\]

In which;
- CFL: Courant number;
- \(\Delta t\): time step, [s];
- \(g\): gravitational acceleration, [m/s²];
- \(h\): local water depth, [m];
- \(\Delta x, \Delta y\): grid spacing in x- and y-direction, [m];

The condition tells that when grid cells become smaller, the time step should be smaller as well. A smaller time step will result in a more accurate simulation, but the computational time will increase considerably. Therefore, one attempts usually to maximize the time step, without obtaining an unstable solution. For both models a time step of 30 seconds has been used. A particular solver in the D-Flow FM is still accurate for CFL = 1.5.
The morphodynamic model simulations in the Delft3D system also must fulfill a CFL condition for morphology. The CFL condition for morphology reads:

\[
CFL = \text{MorFac} \frac{\Delta t}{\Delta x} c_b \leq 0.9 \tag{C.11}
\]

In which MorFac is a morphological acceleration factor defined by the user and \(c_b\) refers to the celerity of a bed disturbance.

**Morphological acceleration factor**

Morphological changes usually take place over much longer periods as compared to hydrodynamic changes. In order to present morphological changes, without extensive computation times a morphological acceleration factor has been introduced. This factor accounts the difference in time scales of hydrodynamics and morphodynamics. The concept is rather simple; the morphological changes are multiplied with the acceleration factor. Now, the morphological time step is extended by:

\[
\Delta t_{\text{mor}} = \text{MorFac}\Delta t_{\text{hyd}} \tag{C.12}
\]

Where:

- \(\Delta t_{\text{mor}}\): morphological time step, [s];
- \(\text{MorFac}\): morphological acceleration factor;
- \(\Delta t_{\text{hyd}}\): hydrodynamic time step, [s].

The use of acceleration factor could be justified, because the morphological changes due to changes in hydrodynamics are often small and do not directly affect the hydrodynamics. However, as a result of the acceleration factor, the short term changes in the bed by varying hydrodynamics can be inaccurate. Furthermore, a spin-up interval should be applied to allow the hydrodynamics to adjust to the initial bathymetry. Otherwise, unrealistic morphodynamic behavior will be observed at the start of a model run.

In this study morphological acceleration factors up to 120 have been used.

**Celerity of the bed**

The celerity of a bed disturbance provides insights into the rate of morphodynamic changes and the time scale of these changes. The celerity of bed disturbances can be a formulated by a simple wave approximation. The formula reads:

\[
c_b = \frac{b q_s}{(1-Fr^2)u} \quad Fr = \frac{u}{\sqrt{g h}} \tag{C.13}
\]

In which:

- \(b\): degree of non-linearity;
- \(q_s\): sediment transport, [m²/s];
- \(Fr\): Froude number.

The celerity of bed disturbances can be used to determine the location of the upstream boundary. A certain distance is needed between the upstream boundary and the area of interest in order to avoid effects from errors at the boundary within the period of interest. The travel distance and travel time of bed disturbance can easily be determined by the relations:

\[
L = TC_b \quad T = \frac{L}{c_b} \tag{C.14}
\]

With \(L\), the travel distance and \(T\), the travel time.
Degree of non-linearity

All sediment transport equations attempt to relate local flow conditions to sediment transport rates. The relationship between flow velocity and sediment transport is non-linear. This degree of non-linearity is not known for the Atrato river. However, the degree of non-linearity in the Mississippi river is between 3 and 4 [Bos, 2011]. As shown in chapter 3, the Atrato river is in its behaviour, remarkable similar to the Mississippi. A similar degree of non-linearity is to be expected for the Atrato river. This degree of non-linearity can be used to calibrate the morphological model results.

\[ q_s = y U^b \]  \hspace{1cm} \text{(C.15)}

Where:
- \( y \) factor which includes various parameters, the most important one is the roughness.

Backwater

Backwater effects are very important phenomena in the low-lying delta. In a river, morphological changes (sedimentation and erosion) take place where these effects are felt, due to the longitudinal gradients of the flow velocity. Besides, backwater effects will have influence on the discharge distribution over the various river branches of the Atrato delta. Backwater occurs when the water depth is not equal to a certain equilibrium depth. In the delta the varying water level at the Gulf of Urabá produces backwater curves. In addition, the confluences also cause backwater. Due to the mild slope the part of the river which is subject to backwater effects is large.

The general equation for a backwater curve is presented as:

\[ \frac{\partial h}{\partial x} = b \frac{h^3 - h_c^3}{h_c^3 - h_e^3} \]  \hspace{1cm} \text{with: } h_c = \frac{3 Q^2}{bg} \quad h_n = \frac{3 Q^2}{bc^2} \]  \hspace{1cm} \text{(C.16)}

Two types of backwater can be distinguished for a mild slope, a convex M1-type and a concave M2-type, see Figure C.9.

![Figure C.8 Backwater on a mild slope](image)

In the region of a backwater curve the relation between discharge and water level is not uniquely defined. It is, for example, affected by the discharge in another branch or by the tide. In order to rule out these backwater effects, a model domain or new measuring stations should be located outside the backwater adaptation length (i.e. length over which the effect of backwater is damped with 63%):

The backwater adaptation length for the Río Atrato is approximately:

\[ \lambda_{bw} = \frac{1}{3} h_n = \frac{1}{3} \frac{9}{1 \times 10^{-5}} = 300 \text{ km} \]  \hspace{1cm} \text{(C.17)}
It is clear that this requirement cannot fully be met. Nevertheless, the use of the large hydrodynamic model partly solves the problem of enormous backwater adaptation lengths.

**Length and time scales**

In contrast to bed-load transport suspended load is transported over the whole water depth. Therefore the transport cannot always follow the changes of the water movement that makes adaptation in space and time important. The adaptation length scale \( L_a \) and time scale \( T_a \) gives insights in the morphology of the river with suspended load. \( L_a \) is the horizontal distance travelled for a sediment particle during the settling in flowing water. \( T_a \) is the time needed for a sediment particle to settle from the water surface to the bed.

The formulas read:

\[
L_a = \frac{n_u}{w_s} \quad \text{(C.18)}
\]

\[
T_a = \frac{h}{w_s} \quad \text{(C.19)}
\]

In which \( w_s \) is the settling velocity of the sediment particles \([\text{m/s}]\).

For the Leoncito branch the adaptation length is approximately 22.5 kilometres and the time scale is approximately 275 minutes.

**Sediment transport in Delft3D**

The Delft3D model is capable to model bed load transport for non-cohesive sediment and the suspended load transport for cohesive and non-cohesive sediment. Different transport formulas can be selected. Only the sediment transport formulas used in this report are described. For a full overview of the formulations, the reference is made to the Delft3D Flow manual (DELTAES, 2010a).

In the delta the sediments are primarily transported in suspension. The two-dimensional suspended sediment transport is calculated by solving the following advection/diffusion equation for each control volume and for each sediment fraction:

\[
\frac{\partial c}{\partial t} + \frac{\partial uc}{\partial x} + \frac{\partial uc}{\partial y} - \frac{\partial}{\partial x} \left( \varepsilon_{x,x} \frac{\partial c}{\partial x} \right) - \frac{\partial}{\partial y} \left( \varepsilon_{x,y} \frac{\partial c}{\partial y} \right) = E - D
\]

Where:

- \( c \) mass concentration of sediment, \([\text{kg/m}^3]\);
- \( u,v \) flow velocity components, \([\text{m/s}]\);
- \( \varepsilon_{x,x} \varepsilon_{x,y} \) eddy diffusivities in three directions, \([\text{m}^2/\text{s}]\);
- \( E \) source term, \([\text{kg/m}^3/\text{s}]\);
- \( D \) sink term, \([\text{kg/m}^3/\text{s}]\).

The second and the third term corresponds to advection terms in \( x \) and \( y \) direction. The fourth and the fifth term corresponds to the diffusion terms in \( x \) and \( y \) direction.

**Van Rijn 1993**

The Van Rijn 1993 transport formula can be used in Delft3D for non-cohesive sediment fractions only. This formula describes the bed load transport and suspended load transport as a result of waves and currents and is therefore an extension of the Van Rijn 1984 formula, which did not include transport due to waves.

The distinction between bed-load transport and suspended load transport is made by the introduction of certain reference height. Sediment transport below a certain reference height is treated as bed load transport and the sediment transport above this reference height is treated as suspended load transport. Sediment is entrained in the water column by imposing a reference concentration at the reference height. The reference concentration in the Van Rijn 1993 formula reads:
\[
c_a = 0.015 \rho_s \frac{\rho_a T_a^{1.5}}{a \theta_b^{0.3}} \tag{C.21}
\]

Where:

- \(c_a\) mass concentration at reference height \(a\)
- \(T_a\) non-dimensional bed shear stress
- \(D_\ast\) dimensionless particle diameter

Which are individually described as:

\[
D_\ast = D_{50} \left[ \frac{\rho_s}{\rho_a} \right]^{1/3} \tag{C.22}
\]
\[
T_a = \frac{\rho_c \frac{\tau_{cr}}{g} + \rho_w \frac{\tau_{cr}}{g} - \tau_{cr}}{\tau_{cr}} \tag{C.23}
\]
\[
\tau_{cr} = (\rho_s - \rho_w) g D_{50} \theta_{cr} \tag{C.24}
\]

The exchange of sediment between the water column and the bed is implemented via sediment source and sink terms. These sediment source and sink terms acting on a layer directly above the reference height, this layer is called the kmx-layer, see Figure C.10. It is assumed that the layers below the kmx-layer adapt rapidly towards the same concentration as the kmx-layer.

![Figure C.0.9 Schematic arrangement of the flux bottom boundary condition](image)

With the reference concentration and the deposition and erosion fluxes the source and sink term are calculated at each time step. This defines the transfer of sediment between the bed and the flow and gives the corresponding sedimentation and erosion that determine the bed level changes. The source terms read:

\[
Source = \alpha_2 c_a \left( \frac{\tau_s}{\tau_\ast} \right) \tag{C.25}
\]
\[
Sink = \left[ \alpha_2 \left( \frac{\tau_s}{\tau_\ast} \right) + \alpha_1 \psi \right] c_{kmx} \tag{C.26}
\]

**Van Rijn 2004**

The formula of van Rijn 2004 is quite similar as the previous one. However, the formula is also applicable for smaller sediments. The van Rijn 2004 formula makes a distinction between bed load and suspended load. The total sand transport is the sum of these two transport loads. The van Rijn (2004) sediment transport formula reads:

\[
m_s = b + s \\
b = \alpha_p 0.1 \sqrt{\Delta g D_{50}^{-3} D_{\ast}^{-0.3} T^{-1.5}} \tag{C.27}
\]
\[
s = \alpha_f u_h C_a
\]
Where:

$m_s$ total transport per unit width, excluding pores, [m$^2$/s];
$b$ bed load transport per unit width, excluding pores, [m$^2$/s];
$s$ suspended load transport per unit width, excluding pores, [m$^2$/s];
$\alpha_s$, $\alpha_b$ calibration parameter, [-];
$D*$ dimensionless particle diameter, [-];
$T$ stage parameter, [-];
$f_{cs}$ shape factor, [-];
$C_a$ dimensionless reference concentration, [-].

**Partheniades-Krone**

For cohesive sediments the Delft3D model uses the transport formulation of Partheniades-Krone (1965). The formulation consists of two formulas and describes when a sediment particle is depositing to the bed or eroding from the bed:

\[
E = M \left( \frac{\tau}{\tau_{cr,e}} - 1 \right) \quad \text{for } \tau > \tau_{cr} \tag{C.28}
\]
\[
E = 0 \quad \text{for } \tau \leq \tau_{cr}
\]
\[
D = w_s C_b \left( 1 - \frac{\tau}{\tau_{cr,d}} \right) \quad \text{for } \tau < \tau_{cr} \tag{C.29}
\]
\[
D = 0 \quad \text{for } \tau \geq \tau_{cr}
\]

In which:

$E$ Erosion flux, [kg/m$^2$/s];
$D$ Deposition flux, [kg/m$^2$/s];
$M$ Erosion parameter, [kg/m$^2$/s];
$\tau$ Bed shear stress, [N/m$^2$];
$\tau_{cr,e}$ Critical shear stress for erosion, [N/m$^2$];
$\tau_{cr,d}$ Critical shear stress for deposition, [N/m$^2$];
$C_b$ Average sediment concentration, [kg/m$^3$];
$w_s$ Fall velocity, [m/s].

Winterwerp (1989) disagreed the formulation of deposition, because in his opinion sediment can always settle and a specific critical bed shear stress for deposition does not exist. Therefore Winterwerp strongly advice to rule out the term $\left( 1 - \frac{\tau}{\tau_{cr,d}} \right)$ by using a very large value for the critical deposition shear stress. The fall velocity can be calculated with van Rijn 1993 [De Vriend (2007)] with the relation:

\[
w_s = \frac{18 \rho_0 g D^2}{18 \rho} \quad \text{for } 1 < D < 100 \mu m \tag{C.30}
\]
Appendix D. Sediment Characteristics

In October 2010 four sediment samples were taken in the delta during a field trip. One near Sautata (1) that is located just a few kilometres upstream of the first bifurcation of the delta and three others at the river mouths; EL Roto (2), Tarena (3) and Coquitos (4). The exact locations are given in Figure F.1. The sediments were taken during high flow conditions.

The most common sieving method “wet sieving method” has been applied to obtain the distribution of the particle sizes. In a wet sieving method, a weighed amount of a sample is put in a tower of executive sieve sizes. Subsequently, water is guided through this tower of sieves. When the out flowing water is completely clear, the residues in the sieves have to be weighed. With the obtained weighs a sieve curve can be constructed. The used wet sieving method setup is given in Figure F.2.

However, it appeared that the sediment samples consisted of large quantities of fine grains and a large extent of the sediment sample passed the finest sieve. The construction of a sieve curve is therefore problematic, because there is no information about grain sizes smaller than 63 µm. A hydrometer test is a method to obtain a distribution of particle sizes in the silt range (4-63 µm) and the percentage of clay (<4 µm). The hydrometer test is usually performed as more than 10% of the material passes the 63 µm sieve (the smallest sieve of a normal ‘wet sieving method’). Only for the sample taken at the Tarena branch no additional hydrometer test had to be executed.

A hydrometer analysis is based on the fact that large particles in a liquid settle more quickly than small particles, by assuming that all the particles have similar densities and shapes. The sediments are brought into suspension by stirring a 1000 ml sedimentation cylinder filled with distilled water and a given weight of the dried sample. The cylinder is placed in a constant-temperature bath (see Figure F3) of 25 °C. Directly after the stirring the sediments will start to...
A density hydrometer of special design is used to measure the density of the soil at various intervals of time. Due to the sedimentation of the particles in the fluid the density of the suspension decreases. This process is directly proportional to the grain size and the corresponding fall velocity. Subsequently, a relation is made to the mass percentages in the sample. A reference is made to Mulder and Verwaal (2006) for a full set of equations.

Now, an additional sieve curve can be set up for the smaller grains of the sample. Combined with the established curve from the wet sieving method a complete grain size distribution curve is obtained.

Figure D.3  Hydrometer test

Figure D.4 up to Figure D.7 show the results of the sieving procedure. The median grain sizes are summarised in Table D.1 for each sample.

<table>
<thead>
<tr>
<th>Location</th>
<th>D50 [µm]</th>
<th>D90 [µm]</th>
</tr>
</thead>
<tbody>
<tr>
<td>Sautata</td>
<td>25</td>
<td>70</td>
</tr>
<tr>
<td>Coquitos</td>
<td>13</td>
<td>50</td>
</tr>
<tr>
<td>El Roto</td>
<td>21</td>
<td>50</td>
</tr>
<tr>
<td>Tarena</td>
<td>120</td>
<td>190</td>
</tr>
</tbody>
</table>

Table D.1 Summarised grain sizes of the samples
Figure D.4 Sieve curve upstream of bifurcation Leoncito

Figure D.5 Sieve curve Tarena mouth
Figure D.6 Sieve curve El Roto mouth

Figure D.7 Sieve curve Coquitos mouth
Appendix E. Comparison of numerical models

This appendix shortly compares the SOBEK model, the D-Flow FM model and a Delft3D model with each other.

In 2010, a 1D hydrodynamic model of the Atrato River was created using SOBEK-River [UTCH, 2010c]. The model served as an initial tool to visualise the hydrodynamics of the river and to store available hydrological data. However, the initial model only included the main branch of the river in the delta area. Moreover, the geometric schematisation of the branches was made from a very limited number of cross-sections. Between two cross-sections the river reach is calculated by linear interpolation, which can be quite different of the real river bed topography. In this study, the various branches in the delta are added to SOBEK model. Figure A.1 shows the model.

The model was calibrated hydrodynamically by varying the Manning roughness value until measured and modelled water levels corresponded. Finally, a Manning roughness of n=0.026 proved to be the most suitable roughness value.

In order to model in 2D and to perform morphological computations a Delft3D grid of the delta area has been set up, see Figure A.2. In the left picture the two model domains are visible. In the right picture shows the bathymetry of the two model domains.
However, due to the amount of bifurcations the grid administration was problematic; the grid had to be separated in two individual domains, which are coupled with domain decomposition. However to connect the domains three artificial river bends had to created, see Figure A.3. The bends are not perfectly orthogonal. Furthermore, the grid does not include the floodplains of the delta.

The constructed unstructured grid in D-Flow FM is capable to handle topographically complex areas and even includes the floodplains.

The results of the models are given in Table E.1. Figure E.4 indicates the locations of the cross-sections. For the SOBEK model a constant water level at the downstream boundary has been used. The differences between Delft3D and D-flow FM are most likely due to the fact that the D-Flow FM model includes the floodplains.
<table>
<thead>
<tr>
<th>MODEL</th>
<th>SOBEK discharge [m³/s]</th>
<th>D-Flow FM discharge [m³/s]</th>
<th>Delft 3D discharge [m³/s]</th>
</tr>
</thead>
<tbody>
<tr>
<td>river section</td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>1</td>
<td>Inflow</td>
<td>5313</td>
<td>5300</td>
</tr>
<tr>
<td>2</td>
<td>Leon branch</td>
<td>947</td>
<td>901</td>
</tr>
<tr>
<td>3</td>
<td>Main</td>
<td>4366</td>
<td>3896</td>
</tr>
<tr>
<td>4</td>
<td>Leoncito</td>
<td>800</td>
<td>650</td>
</tr>
<tr>
<td>5</td>
<td>Burrera</td>
<td>147</td>
<td>180</td>
</tr>
<tr>
<td>6</td>
<td>Matuntugo branch</td>
<td>900</td>
<td>1167</td>
</tr>
<tr>
<td>7</td>
<td>Coquitos</td>
<td>312</td>
<td>370</td>
</tr>
<tr>
<td>8</td>
<td>Pavas</td>
<td>150</td>
<td>415</td>
</tr>
<tr>
<td>9</td>
<td>Matuntugo</td>
<td>588</td>
<td>560</td>
</tr>
<tr>
<td>10</td>
<td>Tarena</td>
<td>96</td>
<td>106</td>
</tr>
<tr>
<td>11</td>
<td>El Roto</td>
<td>3421</td>
<td>1621</td>
</tr>
<tr>
<td></td>
<td>Outflow in ocean through river mouths</td>
<td>5513</td>
<td>3902</td>
</tr>
</tbody>
</table>

Table E.1 Modelled discharge distribution for three models

Figure E.4 Locations of the cross-sections
Appendix F. Exceedance curves

In this appendix three used exceedance curves are given. An exceedance curve is a chart which lists the daily average water level or daily average discharge of a river, sorted by their magnitude versus frequency of occurrence of the event in terms of total percentage. The curves show the percentage of time that a certain discharge or water level is exceeded. In this study the discharge exceedance curve for the Bellavista Station and the water level exceedance curves for the Domingodó Station and the Riosucio station were used. The curves are shown in Figures F.1, Figure F.2 and Figure F.3.

Figure F.1  Discharge exceedance curve Bellavista Station [modified from UTCH, 2010c]

Figure F.2  Water level exceedance curve Domingodó Station [UTCH, 2010c]
Figure F.3  Water level exceedance curve Riosucio Station [UTCH, 2010c]