Assessment of flood risk mitigation and water quality improvement measures in coastal lagoon systems

Modelling of the hydraulic behaviour of the Ciénaga de la Virgen in Cartagena de Indias, Colombia

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by

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Preface

This report presents an analysis of the complex nature of coastal lagoons. The report evaluates several measures for enhancing water quality and safety in coastal lagoons while considering the scarcity of available data in these areas. Specifically, this report addresses the conditions of the Ciénaga de la Virgen near Cartagena, Colombia.

This research was conducted as part of the ”Water as Leverage” program in collaboration with Arcadis, the lead consultant of the ConAgua consortium.

I would like to thank everybody who contributed to this report. First and foremost, I would like to start by thanking my committee, Cong Mai Van, Stuart Pearson and Erik van Berchum. Without them, this would not have been possible. I want to give a special thanks to Erik for the weekly guidance, discussions, and advice along the way. I also found the progress meetings with the whole committee really helpful. They always gave me a boost and renewed my energy.
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Finally, I want to thank my family and friends for their support and patience. Without everyone mentioned above, this report would not be the same.

Undertaking this project enabled me to develop both professionally and personally. I had to make the Delft3D program my own and get comfortable with topics outside my master's specification, both of which presented an opportunity to gain new insights.

It is my hope that the insights gained from the report will be implemented across a broad spectrum to enhance the water quality and safety of coastal lagoons worldwide.

K.L.(Kim) Damen
Delft, December 2024

Abstract

Coastal lagoons, encompassing nearly 13% of the world's coastline, represent a vital ecosystem for a considerable variety of flora and fauna. The appealing environment of coastal lagoons has resulted in the establishment of numerous communities around them. The intensification of extreme events due to climate change, the expansion of urban systems, and the release of more pollutants into surface water have altered the natural dynamics of the system. These alterations increase the challenges regarding water safety and quality. Therefore, it is genuinely important to ensure the long-term survival of coastal lagoons. Coastal lagoons are shallow waterbodies parallel to the coast, separated by a small barrier and connected to the sea or ocean by one or multiple inlets. Their behaviour is influenced by the tides, freshwater discharges, wind, geometry, and bathymetry. In a well-functioning lagoon, the water is of sufficient quality, and the surrounding area lives harmoniously with the lagoons, meaning fishing activities are balanced with the lagoon, and the surroundings can cope with floods and droughts.

The Ciénaga de la Virgen in Cartagena, Colombia, is a prime example of a coastal lagoon that faces problems such as pollution, contamination, floods, and droughts, which are common in the area. The consortium ConAgua had proposed multiple measures to enhance the natural dynamics of the Ciénaga, commissioned by the Dutch governmental organisation Rijksdienst voor Ondernemend Nederland.

This report analysed the influence of those measures on the water safety and quality of the Ciénaga. As part of this, the lagoon and its behaviour were simulated using the numerical hydrodynamic model Delft3D. The measures were implemented in this program, and by altering the boundary conditions, the effects of each measure under different circumstances were evaluated. The implemented baseline model represents a dry month, normal tides and current bathymetry. Modifications were adapted to evaluate the effect of the limited data and observe the impact of extreme rainfall, sea level rise and wind forcing. Combinations of measures and their behaviour were also simulated. For the water quality, the flushing time was considered by means of a tracer. Inserting a passive tracer, which either indicated polluted water (1) or clean water (0) into the model, made it possible to analyse the reduction and/or mixing of the pollution. For water safety, the rise in water level at any observation point within the Ciénaga was compared to the baseline model without measures, and the maximum water levels within the month were considered.

The simulations showed a significant impact of tides, wind, and sea level rise on the behaviour of the lagoon. Incorporating wind showed an improved refreshment rate due to the enhanced mixing and altered the plume formation into the Caribbean Sea. However, there are windless days on which the advantage of wind may not be taken into account. Other simulations, such as the simulation of the combined measures, showed that combinations are not merely the sum of the individual measures and their effect, but the total hydraulic behaviour is altered. Furthermore, the importance of a clean discharge from the urban and rural side into the Ciénaga was demonstrated. Due to the low refreshment rate, polluted water lingers inside the Ciénaga for a long time, affecting the ecology and the health of the surrounding residents.

In short, the rate of improvement of the water quality by the measures is limited, because the effects remain local. Therefore, achieving water of proper quality is a challenge. The measures did not negatively influence the water levels inside the Ciénaga. For flood risk, it is important to prioritise other effects since it remains a problem in the area.

The report shows that preserving healthy lagoons worldwide is important. To maintain proper water quality, the input of clean freshwater and sufficient mixing due to tidal (ensured by inlets) and/or wind forcing is important. Likewise, the effect of floods and droughts should be limited since many people live near the lagoon. However, water safety cannot be assessed solely by the water levels inside the lagoon. Models can help to assess challenging problems regarding water quality and safety in complex lagoon systems. In future steps, it is recommended that more data be gathered through measurements and observations to assess the quality of the lagoon with more certainty.

Contents

1 Introduction

1.1. Context

Of the world's coastline, 13% comprises of coastal lagoons (Herbert et al., 2020). A coastal lagoon is a shallow waterbody connected to the sea by a narrow channel(s). It is an important biodiverse environment due to hydrodynamic fluctuations and relatively high salinity (Conde et al., 2015). A well-functioning lagoon is important for the local environment in terms of water quality and safety; however, managing these factors is complex.

A coastal lagoon provides a great volume of surface water, serving various users. They are the foundation of an abundance of flora and fauna unique to the environment. Additionally, lagoons can be a source of income and/or food for local communities. Furthermore, lagoons provide recreational opportunities.
However, the quality of coastal lagoons degrades due to the release of water of poor quality into nearby water systems. The growing quantity of wastewater is part of the problem; globally, half of the wastewater is released untreated (Jones et al., 2021). Additionally, effluents from agricultural runoff are increasing (Pedersen and Borum, 1996). All of these factors contribute to the degradation of water quality. Poor water quality, in general, can result in water-related diseases, causing 5 to 10 million annual deaths worldwide (Ahuja, 2021).

In addition, coastal cities face problems regarding water safety. Worldwide, one in five people live in areas directly exposed to 1-in-100-year flood risk (McDermott, 2022). Primarily, lower-income households reside in those areas.

The Ciénaga de la Virgin (Ciénaga), a coastal lagoon, faces significant challenges related to the safety and health of the surrounding local communities. The Ciénaga is situated north of Cartagena de Indias in Colombia, bordering the Caribbean Sea (Figure 1.1), and translated directly to a virgen swamp. The city expanded in the last centuries. This expansion has been largely uncontrolled, contributing to the occupation of flood-prone zones. Previous floods in this region have inflicted damage to numerous homes and buildings.
The lack of effective water management of the Ciénaga has led to several challenges that need to be addressed to improve the living conditions around the lagoon.

First of all, pollution and contamination are recognised problems in the Ciénaga (Touza et al., 2021). Furthermore, extreme weather events resulting in floods and drought affect water safety and quality. Increasing manifestations of climate change exacerbate water challenges, such as flooding and water quality. Lastly, geological risks like subsidence and coastal erosion will complicate addressing these issues properly.

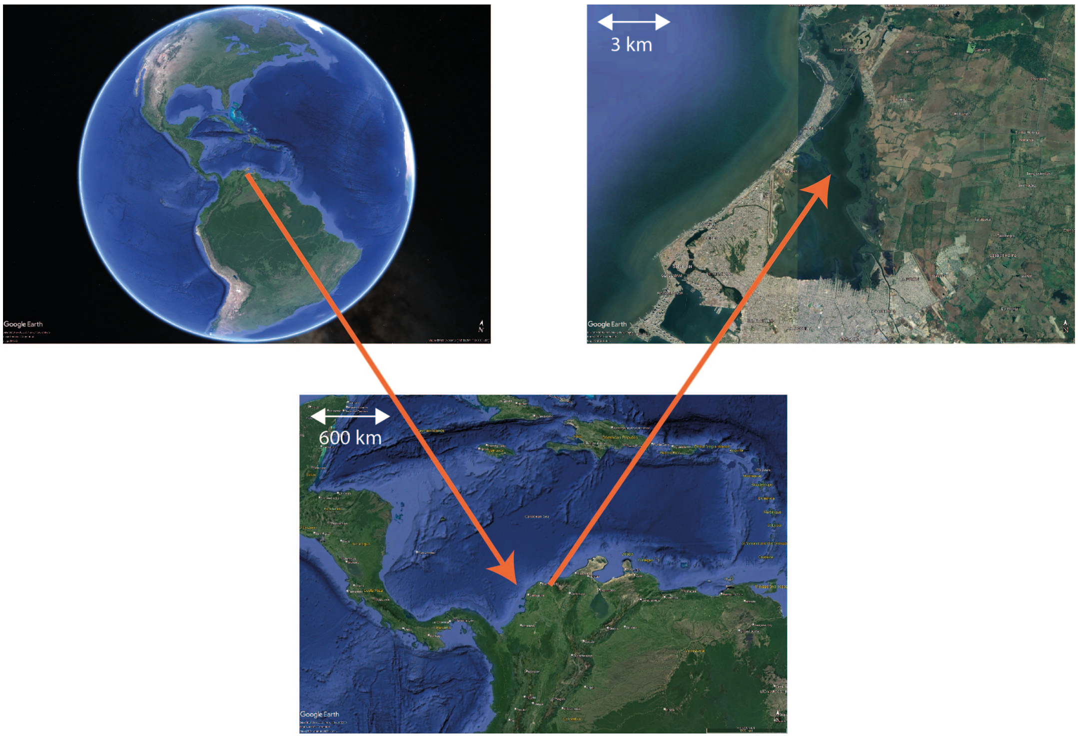


Figure 1.1: Location of the Ciénaga in Cartagena, Colombia (*adapted from Google Earth, 2024*)

This report aims to assess the lagoon challenges by a better understanding of the Ciénaga and the hydrological processes that drive it. This research is part of the ”Water as Leverage” program, initiated by the Dutch Government to address urban climate water-related issues in an integrated and inclusive way. The first adaptation was in Asia, within the cities of Chennai, Khulna and Semarang (Lieshout et al., 2021). Later, the program expanded globally, providing fair and sustainable urban water and climate resilience.

In Cartagena, the program commissioned two consortia to develop and assess measures to address these challenges. One of them is ConAgua[1], of which Arcadis is the lead consultant; therefore, this research is in collaboration with Arcadis. ConAgua focuses on the following five goals (Water as Leverage - Cartagena ConAgua, 2023):

- Re-establishing the amphibian and ecological relationships between humans and nature;
- Making water part of the city;
- Nature-based solutions with social perspective;
- Social benefits;
- Reinforcing the cultural identity of Cartagena.

The project's main clients are the Dutch government and the city of Cartagena. ConAgua provided co-designed solutions for water, urban and social challenges in Cartagena. The main focus of this report is on the functioning of the Ciénaga. The consortia designed measures to re-establish the natural dynamic of the Ciénaga. This research advises, in cooperation with Arcadis, on which (combination of) measure(s) is the most suitable for the Ciénaga and its surroundings in the short- and long-term.

[1] A partnership between Arcadis, Deltares, Taller Arquitectos, ONE Architecture, JESyCA, Fundación Herencia Ambiental Caribe and Selfinver

1.2. Problem definition

Coastal lagoons are hydrologically highly complex, which makes them hard to manage effectively. The Ciénaga is a coastal lagoon that greatly influences its surroundings, both from a human and an ecological perspective. Multiple drivers influence the behaviour of the Ciénaga, such as rivers from the rural area, channels from the city, and tides from the Caribbean Sea (Figure 1.2).

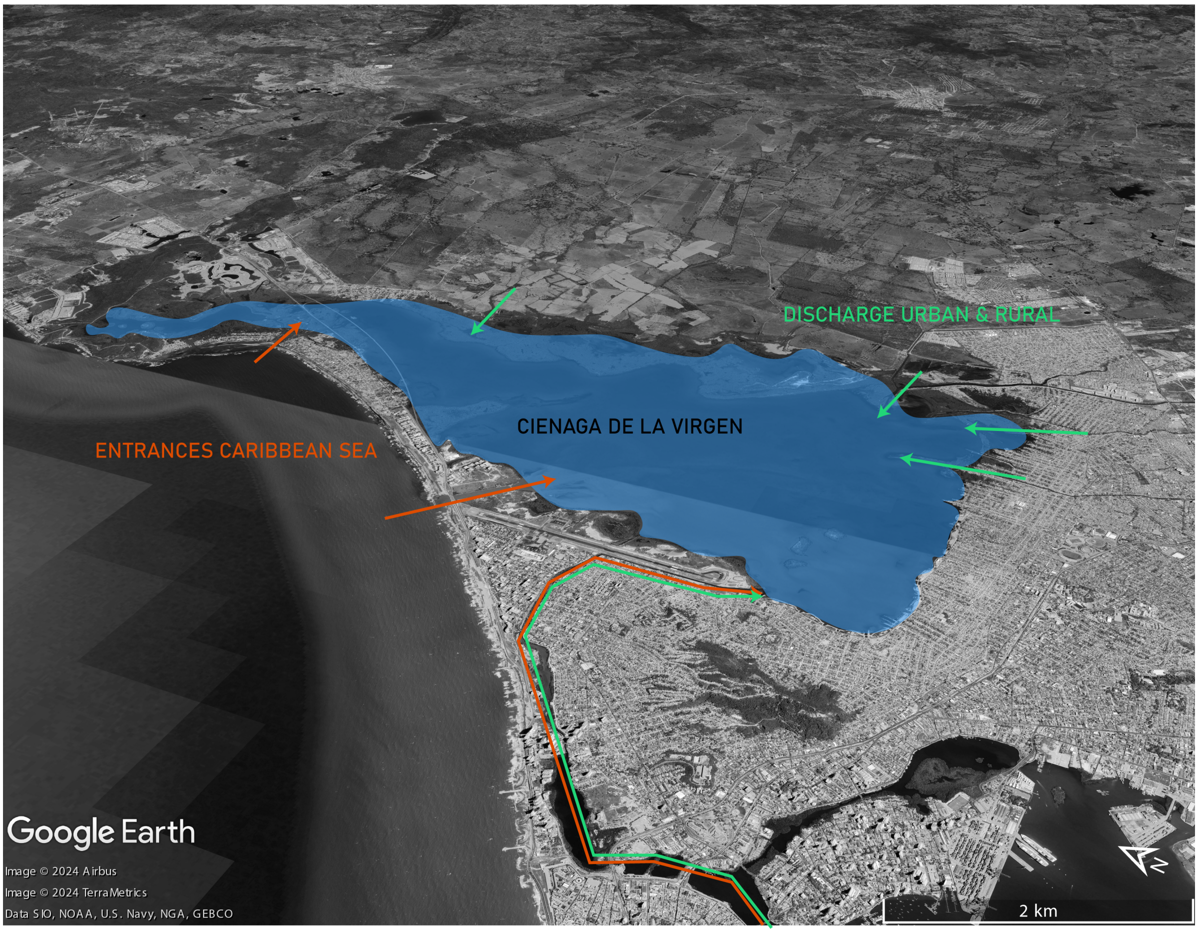


Figure 1.2: Most important parametres influencing the Ciénaga (the blue shape indicates the Ciénaga, the orange arrows indicate the connections with the Caribbean Sea, while the green arrows display the discharges from urban and rural streams) (*adapted from Google Earth, 2024*)

In Cartagena, 12% of the population lives in flood-prone areas, due to impacts from sea level rise and rainfall (Rojas et al., 2013). When no adaptation measures are applied, one of every five inhabitants could be affected by high tide. Moreover, 28% of the industrial area, 35% of the road infrastructure, 86% of the historical heritage, 70% of the mangrove swamps and 100% of the beaches in Cartagena are at risk of flooding by 2040 (Zamora Bornachera et al., 2014 and Cartagena ConAgua, 2024b). An additional issue is the inequality within Cartagena. Residents with higher socio-economic status mainly inhabit the coastal area and historic centre. The lower-income and indigenous communities are often located in informal settlements, most often located near waterbodies in more flood-prone areas. Within the informal settlement, 8% have no access to clean water, and 15% are not connected to sewage systems (Cartagena ConAgua, 2024b).

The consortium ConAgua has proposed multiple measures to improve the natural dynamics of the Ciénaga. The measures taken into account in this report are the restoration of the Bocana system, improvement of the Juan Angola channel, improvement of the Matute watershed and restoration of the connection to the location of the tidal inlet at La Boquilla (Figure 1.3). However, due to the complexity of coastal lagoons, the assessment of the measures is challenging.

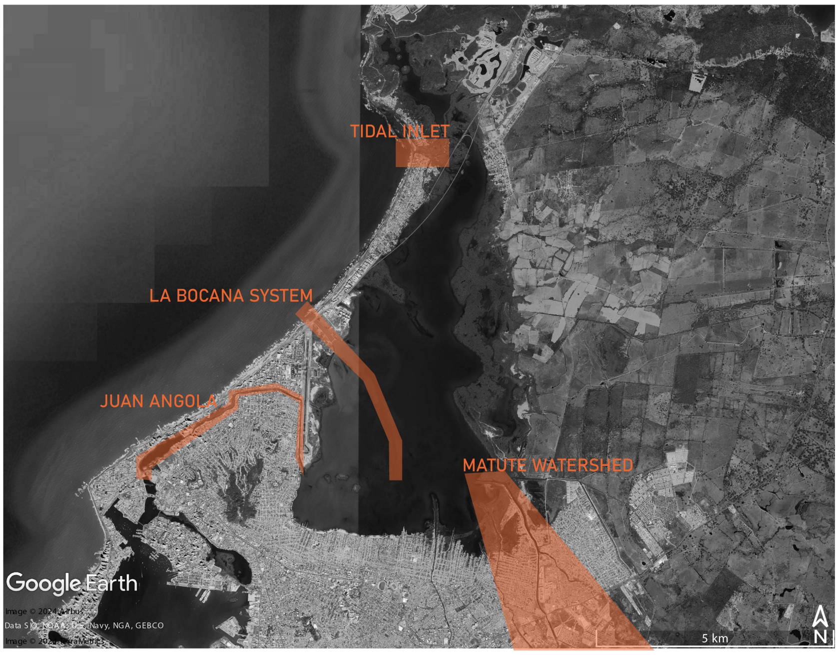


Figure 1.3: Location of the measures considered within this report

1.3. Research questions

This research determines the effectiveness of ConAgua's measures by a set of pre-defined indicators. The indicators are based on the short- and long-term demands to improve water quality and reduce the risk of flooding. The research examines how the measures work separately, how they interact, and how they might counteract each other under different circumstances. The urgency for a solution is high. Therefore, one has to make sure that the implemented set of measures is compatible with the ongoing projects, does not negatively influence the effects in the long term and is beneficial for all communities. The behaviour of the Ciénaga is simulated using a hydraulic model called Delft3D.

This resulted in the following research question:

How will the selected measures influence the flood risk and water quality of the Ciénaga de la Virgen?

The research question is answered by focussing on the following four sub-questions:

- Which natural processes influence the water distribution in the Ciénaga now and in the future?
  - How does the Caribbean Sea influence the Ciénaga?
  - How does the drained water originating from the city and rural areas influence the hydraulic behaviour of the Ciénaga?
  - How does precipitation, annual and maximal, influence the Ciénaga?
  - Which future scenarios concerning climate change will significantly influence the hydraulic behaviour of the Ciénaga?
- To what extent will the measures affect the hydraulic behaviour of the Ciénaga?
  - Which measures are considered, and what do they entail?
  - How do the measures act when considered separately?
  - How do separate measures act and counteract each other?
- Which measure or combination best reduces the area's flood risk and improves the water quality for the chosen indicators?

1.4. Research scope

The behaviour of the Ciénaga is modelled in Delft3D. The behaviour is evaluated using a baseline model which simulates one month, implying a dry month, average tides in the Caribbean and provided bathymetry. The baseline model is adapted by changing the bathymetry or adding extreme rainfall, wind, or sea level rise. The academic relevance resides in constructing the Delft3D model and simulating the effects of the measures. The process and strategies obtained describe a general approach for the assessment of coastal lagoons worldwide.

1.5. Thesis outline

First, the theory is outlined, explaining the functioning of coastal lagoons and how to assess the water quality and safety of lagoons.

Subsequently, the situation of the Ciénaga in Cartagena, Colombia and its surroundings are described. The behaviour of the Ciénaga is modelled by gathering the natural processes and corresponding data. To achieve this, the hydraulic balance is considered. A clear definition of the scenarios examined is provided. The baseline model and all the alterations, such as extreme events, climate change, and measures, are included. The conceptual design plans considered by ConAgua are also explained.
In Delft3D these combinations of measures and alterations are modelled. The results from this model are represented, among other things, with figures and tables.

Finally, the results are discussed by comparing them with the literature and highlighting their limitation. Thereafter the concluding statement about the water quality and safety of the Ciénaga is formulated. With the insights gained, general concepts are formulated. Finally, recommendations are provided for further research. It is recommended that further data be gathered through measurements and observations.

2

Theoretical Background

This chapter discusses the formation and functioning of coastal lagoons. Furthermore, methods are discussed to computationally monitor a coastal lagoon's water quality and the water safety of communities surrounding the lagoon with limited data. Finally, a checklist for a healthy lagoon is formulated.

2.1. Coastal lagoons

Coastal lagoons are characterised as shallow waterbodies parallel to the coast, separated by a small barrier interrupted by some inlets (Kjerfve, 1994). Coastal lagoons are special because they represent highly dynamic and productive ecosystems (Duck and Silva, 2012).

The European Union characterises lagoons as transitional water, a transition between freshwater and seawater (Duck and Silva, 2012). However, this term does not account for all coastal lagoons. Some lagoons have no freshwater input at all, while others are so closed off they display freshwater conditions.

As previously indicated, the definition is sometimes too broad, but others are too specific and exclude certain lagoon types. This section describes what a lagoon is and the reasons behind its uniqueness.

2.1.1. Formation of coastal lagoons

Coastal lagoons were formed due to the floods of river valleys and bays by the rising sea 6000-8000 years ago (Mahapatro et al., 2013). Partially or wholly isolated lagoonal environments were generated due to the submergence of low-lying coasts and the formation of barriers (mostly from sand or clay) by marine processes at the mouths of those flooded river valleys.
Sediments from rivers will fill the lagoon over time; therefore, lagoons are considered temporary features. In mature lagoons, sediment supply from rivers flows directly to the coast (Adlam, 2014). The energy regime determines the behaviour of the lagoon. However, some lagoons, such as along the coast of Texas and southeastern Australia are predominantly shaped by the relation between depth and average width. If a water depth is reached for which the wind waves continuously interact with the sediment particles, further deposition is prevented. An indicator of reaching this critical depth is turbid water (Adlam, 2014).

2.1.2. Natural drivers of lagoon ecosystem

The behaviour of lagoons mainly depends on the tides, freshwater input, and wind stress (Kjerfve and Magill, 1989). Water, salt and heath balances will all influence a lagoon's proper functioning.

Tides at sea influence the lagoon. The influence depends on the amplitude of the tides and the connections with the sea. The tides can be semidiurnal, diurnal or mixed. One tidal cycle is enough for analysis is the tide is not mixed; if it is mixed, an even number of tidal cycles is needed to minimize the effect of diurnal inequality. Differences between spring and neap tides may also be required to assess the influence of tides. Ideally, a time series of 29 days is required, representing a complete lunar

synodic month (Kjerfve, 1994). The interaction can be limited due to the few restricted connections with the sea or ocean. Lagoons with limited connections could have long flushing times. The phase of tides influences this mixing, meaning that during spring tides, currents and mixing intensity are stronger compared to neap tides (Kjerfve and Magill, 1989). Near the inlets of a lagoon, the tidal forcing is dominant; the inlet itself has a constricting effect. Therefore, the inlet configuration is important as it influences how the water levels outside influence the water levels inside, by means of the damping coefficient (Equation 2.1). It can be observed that the larger the inlet dimensions, the lower the reduction. The inlet controls the water exchange and, therefore, the residence time.
Tides also influence the salinity inside a lagoon, another important aspect of the proper functioning of lagoons (Mangor et al., 2008).

According to Kjerfve (1994) the channel damping coefficient can be defined as:

$$D = \frac{IH_0A_s}{A_cL} \tag{2.1}$$

in which:

- I , measure of the channel impedance
- H_0 , amplitude of the ocean time
- A_s , mean surface area of the lagoon
- A_c , mean cross sectional area of the channel connecting the lagoon and the ocean
- L , length of the channel

Another critical parameter is the freshwater input, as river discharge significantly influences the flushing time by affecting the water exchange rate within the lagoon system (Kjerfve and Magill, 1989). The importance of flushing time is better explained in Chapter 2.2.1.
Salinity reduction through precipitation can be minimal as freshwater remains a thin layer on the more saline water body. Mixing through the wind could take hours to days (Blanco et al., 2006).

Wind action can have a big influence because lagoons are shallow. Wind produces wave action and mixing of the water. This leads to (re)suspension of sediments (Esteves et al., 2008). Local phenomena of lagoons affected by the wind are wind-driven currents, setup and setdown, Langmuir cells (counterrotating vortices that result in turbulence (Carniel et al., 2005) and wind waves according to Kjerfve and Magill (1989). The wind setup mentioned is very important at the downwind end regarding flood risk. However, a significant change in water levels requires a lagoon with a length on the order of several tens of kilometres (Miller et al., 1990). According to Kjerfve (1994) a slope over the lagoon surface of $0.5\,cm/km$ can be found, as response to the wind (winds of $5-10\,m/s$). In the inner parts of the lagoon, the wind forcing is dominant.

Other forces that a lagoon experiences are direct precipitation, evaporation, and surface heat balance, all contributing to the change in the volume of a lagoon. All the contributing parametres can be summarized within the volume change equation (Kjerfve, 1994):

$$\frac{\Delta V}{\Delta t} = P - E + R + G \pm A \quad [\text{m}^3/\text{s}] \tag{2.2}$$

in which:

- $\frac{\Delta V}{\Delta t}$, time rate of change of volume in the lagoon
- P , precipitation
- E , evaporation (among others humidity measurements are required)
- R , surface runoff (including discharge by canals and rivers)
- G , groundwater seepage (difficult to quantify, in general, more research necessary)
- A , advective gain or loss

In a healthy lagoon a balance between autotrophic and heterotrophic metabolisms is important, in other words, producing and consuming organisms need to be balanced (Knoppers, 1994). Preventing hypoxia (low oxygen levels) or eutrophication (nutrient over-enrichment) can negatively influence the flora and fauna in the lagoon.

2.1.3. Evolution of coastal plumes

Coastal plumes are the discharge from the lagoon into the sea; due to the differences in the water composition, especially the difference in density, these plumes can be observed at connections. The principal physical parameter controlling the plume formation is freshwater availability. Other effects that define the transport of the plume are the Coriolis effect, tides and wind effects. Tides generate vertical and horizontal mixing of the plume, reducing the stratification and spreading the freshwater. (Marques et al., 2009). The wind increases the mixing process and produces a coastal current. Alongshore currents can reduce the transverse size of the plume. The asymmetry of the plume is due to the rotation of the earth. The bathymetry towards the lagoon also determines the plume formation, as well as the geometry of the outlet (Marques et al., 2009 & Fomin and Polozok, 2022 & Liu et al., 1997). Alteration in one of these parametres influences the plume formation. For example, rising sea levels could alter the circulation patterns and, therefore, the plume.

Small plumes have sharp salinity gradients. They are mainly wind-driven, and the role of sea circulation is negligible. As a consequence of changing wind and discharge, the shape changes rapidly. The initial energy input they imply decreases quickly. Turbulence and mixing are enhanced if the plume originates from a river with a high flow velocity. Small plumes are characterised by small residence time (hours and days) and do not influence the salinity of the sea (Osadchiev and Zavialov, 2019).

2.1.4. Anthropogenic impacts on lagoons

Coastal lagoons are usually known to offer a wide variety of rich flora and fauna, but they also have several functions that enable commercial and recreational activities (Mangor et al., 2008). For this reason, sometimes man-made interventions are implemented, altering a lagoon's natural ecosystem.

Historically, communities have settled near lagoons due to their economic, social, and environmental benefits. However, uncontrolled population growth around lagoon peripheries obstructs the natural dynamic of these systems. Which increases stress in such areas, e.g. increasing sewage waste, fishing overexploitation, plastic pollution, sound pollution (motor boats), and chemical pollution (Mahapatro et al., 2013).

The connections of the lagoon with the ocean influence the hydrodynamic processes. Changing and fixing this connection can result in different salinity and water levels altering the ecosystem. Fixing these connections affects the fish species. In general, it has negative impacts on freshwater species and positive effects on marine and brackish species (Conde et al., 2015).

Dredging is another example of human interference. For example, deepening a channel or increasing the lagoon area will result in higher tidal amplitude and an increase in tidal prism (Dias and Picado, 2011). Subsequently, if dredging is applied, the flow's capacity to transport sediments reduces, increasing the need for constant dredging.

Another anthropogenic impact on the lagoon is agricultural effluents, which affect the water quality. Due to nutrient enrichment, fast-growing plants dominate, such as phytoplankton and algae (Pedersen and Borum, 1996).

Sea level rise due to increasing manifestations of climate change may alter the average depth of the lagoon. If the water level increases and the sedimentation rate is high, the bottom level will also increase (Louters and Gerritsen, 1994). Differences in sea level rise and sediment availability influence the behaviour of a lagoon. The impact on the bottom level due to the rise in sea level is considered slow compared to the effect of a large storm. Two responses are possible under rising sea levels, inundation or silting-up (Carrasco et al., 2016). The adaptation to sea level rise depends mainly on three factors: the sediment demand, the sediment availability at the seaward side and the capability to distribute the sediment internally (Goor et al., 2001). Sea level changes can alter the tidal range, affecting the ecosystems and increasing the chance of nuisance flooding (Devlin and Pan, 2020).

2.1.5. Classifications of coastal lagoons

Lagoons have, in contrast with estuaries, restricted connections to the ocean and low freshwater input relative to their size (Adlam, 2014).

Depending on the type of connection to the sea, lagoons can be classified as follows (Duck and Silva, 2012 & Mahapatro et al., 2013 & Kjerfve, 1994 & Kjerfve, 1986):

- Choked lagoons: single entrance, which results in reduced tidal oscillations. The dominant hydro morphological conditions are microtidal. A characteristic of choked lagoons is slow flushing, in order of months. Wind forcing is the dominant process. They can be temporarily or permanently hypersaline. They are located along coasts with high wave energy and significant littoral drift.
- Restricted lagoons: two or more entrances. Usually well mixed due to tidal circulation and wind-generated wave action. Characterized as large and wide waterbodies. Less likely to have significant salinity fluctuation compared to choked lagoons.
- Leaky lagoons: many entrances due to strong tidal currents. Because of this, there are tidal circulations and large exchanges with the sea or ocean (often similar salinity). They have several (fixed) entrance channels, which can be separated from the sea by an incomplete barrier or coral reef. These are usually characterized as mesotidal. The flushing time is relatively fast compared to the others.

Maintaining the stability for connections and openings is an essential factor. Most important is the stability shear stress, which is influenced by the shape of the cross-section, soil conditions of the bed, sediment load, wave action, littoral drift and fresh-water discharge. The degree of stability can best be described by the ratio between the maximum rate of flow per second during a tidal cycle (Q_m) and the littoral drift (M), preferably $Q_m/M > 0.01$. For the entrances these parametres should be considered (Bruun and Gerritsen, 2011).

Another way to characterize a lagoon is by the salinity gradient. Coastal lagoons can have different gradients of salinity, reaching from marine water (euryhaline) to brackish (mesohaline) to freshwater (oligohaline). Biodiversity reflects the salinity gradient in the lagoon (Mahapatro et al., 2013). Next to the number of connections or salinity, lagoons can be distinguished into wave-dominated or marine-dominated lagoons; this has to do with the freshwater input (Tagliapietra et al., 2009).

2.2. Assessment of coastal lagoons

The overall quality of a coastal lagoon is determined by identifying indicators based on water quality and water safety. The overall quality is determined by grading those indicators. There are many ways to assess lagoons; within this report, the state of the lagoon is assessed by merely the water quality, which considers flushing time, and the water safety, which considers the water levels of the lagoon. While assessing only flushing time and water levels presents limitations, these parametres are key to understanding the basic concepts of a lagoon. These two indicators and corresponding requirements are discussed below.

2.2.1. Water quality indicator

Water must maintain a chemically and ecologically good condition for humans, animals and plants to thrive. The first one depends on which substances are detected in the water and in what concentrations. The last one considers the temperature, presence of nutrients and several chemical substances and looks if fish, algae, water plants and other small animals are present (Ministerie van Algemene Zaken, 2011).

A manner to evaluate water quality in situations with low quantity and quality of data is by assessing the water refreshment rate. Most contaminants, such as suspended particles, are transferred by the lagoon water. The transport time scale is a fundamental concept for the biological process; a form to estimate this is residence time (Monsen et al., 2002).

The exchange with the sea due to the tides and the discharges into the waterbody is known as exposure time/flushing time. According to Matso (2018), a system is considered flushed when 63% of the initial volume has exited the system. Flushing time reflects the average amount of time the mass spends in a system; this is equal to 37% (e^{-1}, an arbitrarily chosen constant based on an exponential decay function) of the initial mass still in the system (Monsen et al., 2002). The function of flushing can be seen as an exponential decay function because the reducing rate depends on how much is still left within the system. Given that it is never completely flushed, this percentage (63%) suffices. The time it takes to flush depends, among others, on the tidal influence, the volume of the lagoon, the opening dimensions, and discharges. Lagoons with more than one connection to the open sea are more likely to have sufficient flushing to avoid water quality issues through stagnant water (Mangor et al., 2008).

Flushing time is expressed as the time it takes before 50% has been exchanged. Seven days or less would be considered an acceptable timeframe in this context. The water quality needs monitoring during the most critical time, which is a calm and warm period, depending on the local climate. During this period, river discharge is negligible and tidal and wind forcing will be smaller, which increases the flushing time (Mangor et al., 2008 & Sámano et al., 2012).

If the flushing time improves, the natural balance will shift, impacting factors such as salinity and oxygen levels in the lagoon (Touza et al., 2021). The secondary effects need to be researched further to investigate if the ecosystem is not negatively influenced by improving the flushing time. One prime example of such an effect is the changing salinity gradient.

Another transport scale is residence time, this is slightly different concept, it indicates the time it takes for any water particle of the sample to leave the lagoon through it out in the sea (Monsen et al., 2002). Particles close to the inlets will have a lower residence time than particles in the inner areas of the lagoon (Molinaroli et al., 2007).
Nutrient over-enrichment will degrade the water quality. A residence time below 10 days decreases the vulnerability to nutrient over-enrichment. Over 40 days indicate a high vulnerability corresponding to poor water quality (Brylinsky, 2006).

A better mixing of the water reduces flushing time. According to Pan et al. (2020), in a model with tides and without wind forcing. The spring-neap cycle influences the circulation with the maximum circulation in the neap tide.

2.2.2. Water safety indicator

Water safety is based on the probability and impact of a flood event, which is called flood risk (Kok et al., 2016). The flood risk is defined by the depth of inundation, duration of flooding, and frequency of these events. The critical inundation depth are determined by combining data on the water levels, bathymetry, and elevation of the city.

According to Dang et al. (2011) flood duration is classified into four categories. The direct and indirect negative effects are bigger when the duration is longer. It interrupts the normal activities of the affected people.

- **< 1 day**: minor disturbance to routine activities
- **1-5 days**: damages to crops (agricultural area)
- **5-10 days**: contamination and impact health
- **> 10 days**: heavy pollution, outbreak of waterborne diseases, risk to health, and possible loss of lives

Risk can be expressed in economic risk, societal risk and individual risk. The first two risks are population-wide, while individual risk considers the risk an individual faces. Economic risk considers the cost of damage, while societal is about the number of casualties. Zero risk of flooding is almost impossible, which is why certain acceptable levels are defined (Kok et al., 2016).

Sites that are more vulnerable to floods are usually characterized by communities with lower income, fewer services (sewage system, potable water), and informal housing. Flood resilience requires, therefore, an understanding of social, cultural and ethical aspects (Vojinovic, 2015).

If only casualties and damages are considered, the following criterion in practice could be used according to Kok et al. (2016). Flooding is considered to have a low impact if the average water depth in an area stays below 0.2 metres. Experience suggests that below this value, casualties and large-scale damage are limited.

2.2.3. Checklist for a healthy lagoon

Next to the indicators for water quality and safety, there are other important criteria to increase the proper functioning of a healthy lagoon, such as (Mangor et al., 2008):

- Prevent hypoxia, low oxygen levels & eutrophication, nutrient over-enrichment;
- Sufficient clean freshwater input;
- The amount and type of flora and fauna inside the lagoon;
- Connection with ocean or sea needs to be a stable ($Q_m/M > 0.01$) opening free of sediments. The stability can be described by the ratio between the maximum rate of flow per second during a tidal cycle;
- Sufficient flushing requires more than one connection with the open sea;
- For flushing circulation, it is best if the water depth is not larger than 3-4 metres (based on artificial lagoons with a micro to moderate tidal range);
- Attractive beaches around lagoons require large dimensions, thus bigger than 2-5 kilometres and water depth over 2 metres;
- Small plumes indicate small residence times and, therefore, healthy lagoons;
- No discharge of pollutants into the lagoon, such as sewage, pesticides, or nutrients.

These indicators provide a means of assessing the health status of coastal lagoons.

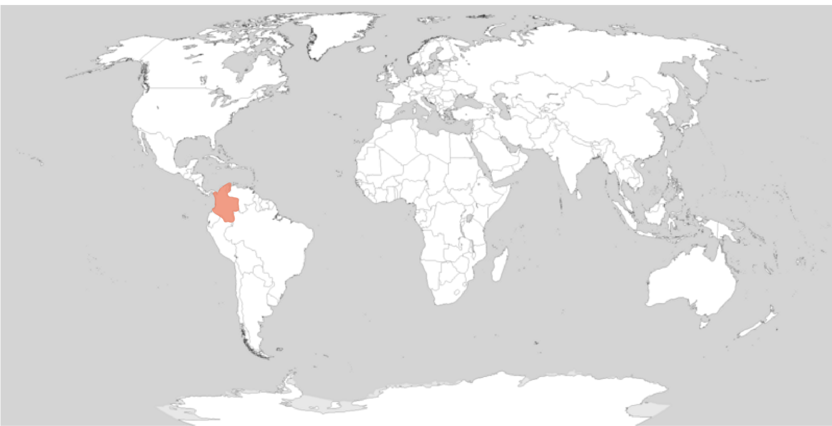
3

Analysis of the Ciénaga system

This chapter introduces the case study of Cartagena, Colombia. The climate characteristics that influence the behaviour of the Ciénaga are evaluated. Furthermore, the hydraulic system is considered, including the bathymetry, discharges, and effects of the Caribbean Sea.

3.1. Geographical characteristics Cartagena

In the North of Colombia, along the Caribbean coast, the city of Cartagena de Indias is located (Figure 3.1). In 1984, the city was declared a UNESCO World Heritage Site. Cartagena has a total area of $623\,km^2$, roughly 10% of this area is urban in which 90% of the total population lives (González-Álvarez et al., 2020).



(a) Worldmap with Colombia highlighted

(b) Colombia with Bolivar highlighted

Figure 3.1: Location of case study area[1]

Population growth leads the city of Cartagena to expand. Informal settlements have been pushed out of the city centre and formed near the lagoon and riverbanks. The evolution of those settlements at the lagoon's Southern banks is visible in Figure 3.2 and Figure 3.3. Significant differences exist between 1985 and 2024; the city's border has been moved hundreds of metres towards the Ciénaga. Those informal settlements have an increased risk regarding water safety and quality.

[1]Modified figures from Wikipedia, n.d. and "Kaart van Colombia, Colombiaanse kaart, zwart wit gedetailleerde effen omtrek grens landkaart van Colombia, Instant Digitale Download svg png eps ai - Etsy Nederland", n.d.

Figure 3.2: South side of the Ciénaga lagoon in 1985 with a blue line corresponding to the situation in 2024 (*adapted from Google Earth, 2024*)

Figure 3.3: Evolution South-East part, 2005-2024 (*adapted from Google Earth, 2024*)

Currently, the informal housing regions face challenges regarding water safety. It is expected that in 2040, other areas, such as the industry and the historical heritage site, will also be at risk (Cartagena ConAgua, 2024b).

Cartagena is situated at a relatively low elevation; most urban areas do not exceed + 10 m mean sea level (MSL). The low elevation suggests that the area near the Ciénaga is more susceptible to rising water levels and, consequently, to flooding. Only the area around Cerro de la Popa exceeds 100 metres above MSL. This can be observed in Figure 3.4.

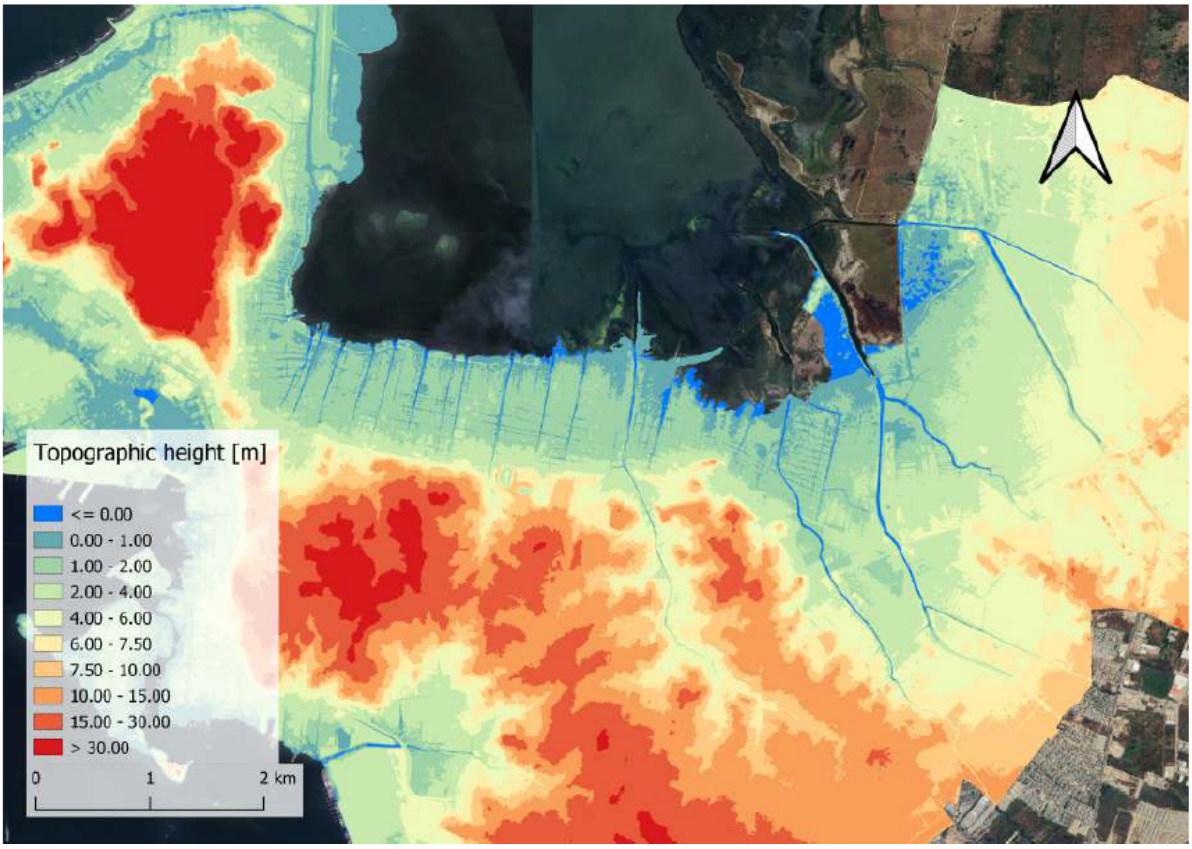


Figure 3.4: Elevation of the city Cartagena (Wakker, 2024)

The area's watershed is a combination of the rivers Mesa, Tabacal, Hormiga and Chiricoco on the eastern side of the Ciénaga, along with urban runoff. The urban runoff goes partly towards the Ciénaga and partly towards the Cartagena Bay, divided by a hill named Cerro de la Popa (Torregroza et al., 2014).

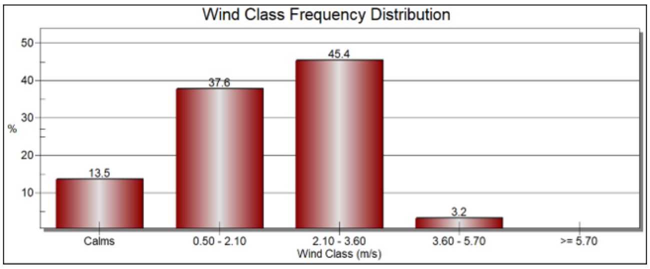
3.2. Climate characteristics

Colombia is located in the tropics and has wet and dry seasons with relatively limited variation in temperature throughout the year. More precisely, Cartagena lies within a Savanna climate zone. Several climate characteristics influence the area.

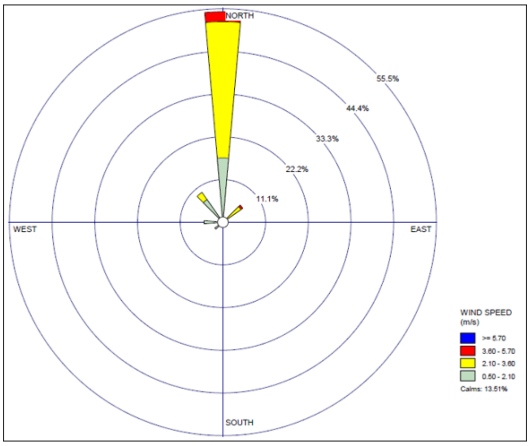
3.2.1. Wind climate

The wind characteristics result in an overall westward littoral drift along the Caribbean coast. This wind is active from December to September. In the other months, the transport is the other way around with a significantly lower magnitude (Stronkhorst et al., 2013).

The wind characteristics of the area are, according to EDURBE (2023), an average wind speed between 2.1-3.6 m/s with the majority of winds approaching from the north; see Figure 3.5. This wind is along the greatest dimension of the lagoon, roughly 7 km, resulting in a long fetch of the lagoon (estimated by Google Earth, 2024). Storm surge depends on the wind conditions (Mariotti et al., 2010).



(a) Wind speed distribution



(b) Wind direction

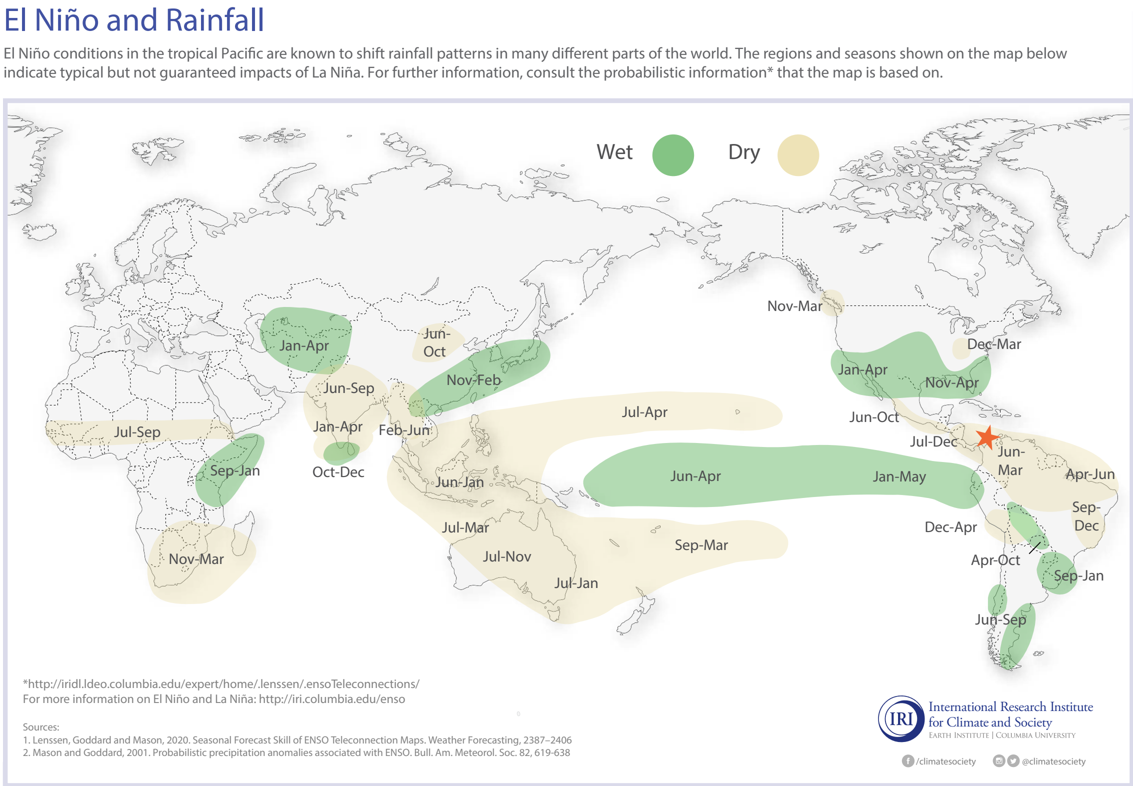
Figure 3.5: Wind speed and direction characteristics 1991-2019 (EDURBE, 2023)

3.2.2. El Niño-Southern Oscillation

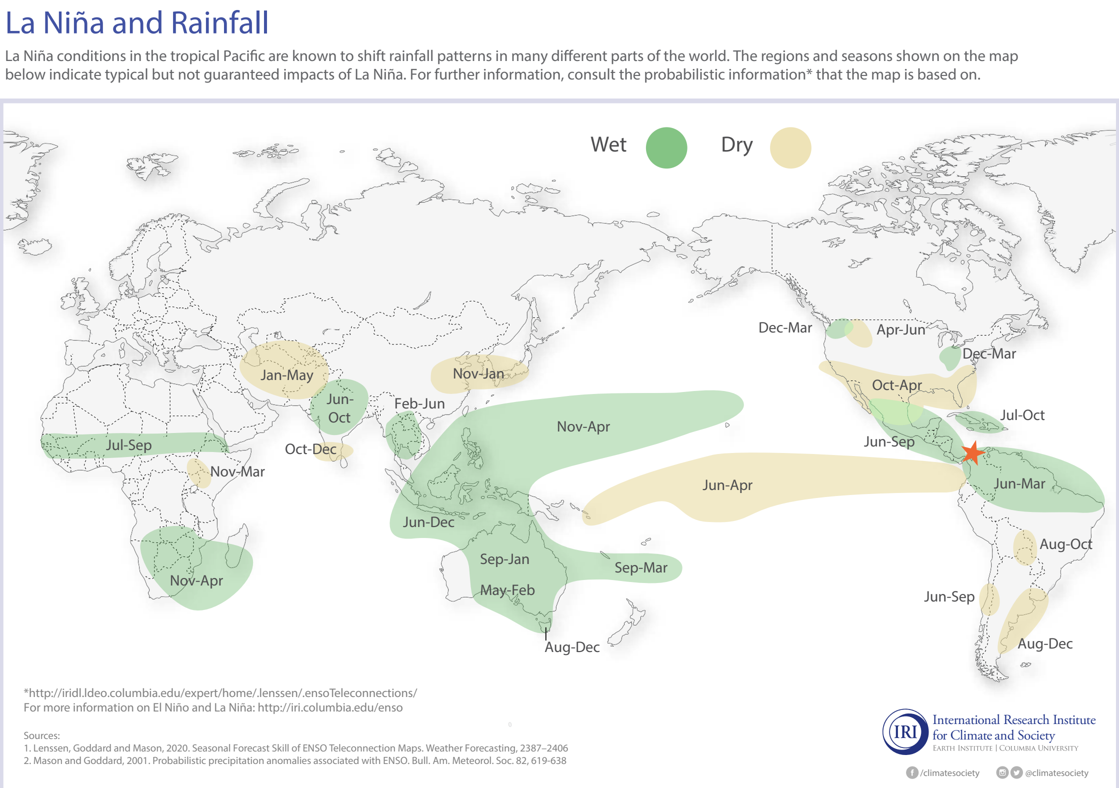
El Niño and La Niña are climate phenomena that alter the ocean temperature, wind and rainfall patterns across the tropics. Due to the ocean-atmosphere, there is an alteration between El Niño and La Niña. El Niño brings extreme warmth and drought, while La Niña brings coolness and flooding.

The El Niño southern oscillation (ENSO) was accountable for rainfall of less than 25% during the El Niño phase and more than 150% during the La Niña phase compared to normal levels at those times in the year in 2015/2016 (Touza et al., 2021 & Santoso et al., 2017 & Xie and Fang, 2020). According to Touza et al. (2021), in the long term, there may be an increase in the frequency of extreme rainfall events associated with La Niña.

The hydrological system of the Ciénaga is affected by the effects of El Niño and La Niña. El Niño brings extreme warmth and drought, which can result in high salinity increments of the lagoon (Blanco et al., 2006). While La Niña brings coolness and flooding, it increases the activities of hurricanes above the Atlantic, increasing the risk for the already flood-prone Cartagena ("El Niño & La Niña (El Niño-Southern Oscillation) | NOAA Climate.gov", n.d.).



(a) El Niño



(b) La Niña

Figure 3.6: Dry and wet season according to El Niño and La Niña, the star indicates Cartagena (International Research Institute for Climate and Society, 2022)

3.2.3. Hurricanes

Hurricanes occur in Colombia roughly five times per year. The hurricane season lasts from June to November, with peak activity in the Caribbean in August and September. Although they often do not make landfall, their wind and rain effects are still noticeable on land. Moreover, the indirect effects of hurricanes may become noticeable in the Caribbean. This results in heavy swell and rough seas along the coast ("Recent Hurricanes in Colombia", n.d. & Touza et al., 2021 & "South America pilot", 1983). Another factor that causes Cartagena not to suffer from tropical storms is its location at a low latitude and the coastline orientation, which poses a natural protection (Andrade et al., 2013). Other natural extremes, such as tsunamis, rarely affect Colombia.

The overview of hurricanes in Colombia can be seen in Figure 3.7 ("Recent Hurricanes in Colombia", n.d. & Touza et al., 2021 & "South America pilot", 1983); during hurricane Lenny, extreme levels of 0.31 m were measured at a tide gauge near Cartagena (Andrade et al., 2013).

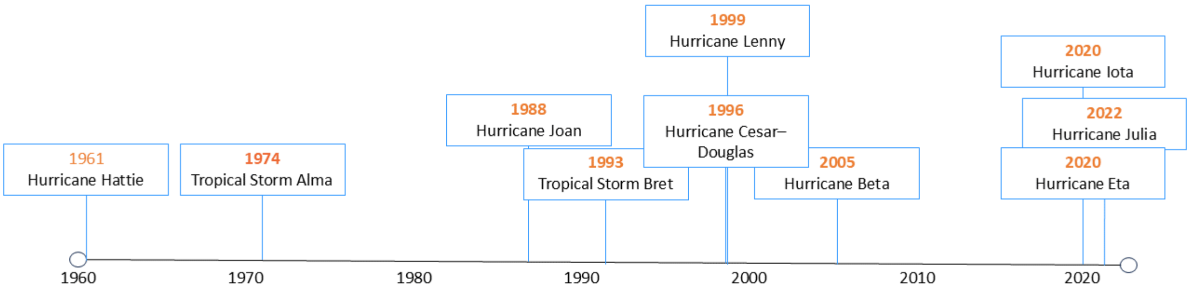


Figure 3.7: Timeline of hurricanes in Colombia

The effect of a hurricane and its risks in Cartagena is linked to the storm's trajectory. From Figure 3.8, one can conclude that the hurricane tracks do not reach Cartagena. Therefore, direct effects are unlikely, this is also mentioned by Moor et al. (2002). Hurricanes usually move westward, which is not a problem for Cartagena.

The intensity and location of storms vary seasonally, and they are formed at locations of high-temperature gradient, and the storm path is influenced by the jet stream. As a consequence of climate change, there is potential for variation in temperature gradients, as well as in the location and intensity of storms. The exact future projections are hard to predict (Shaw et al., 2016).

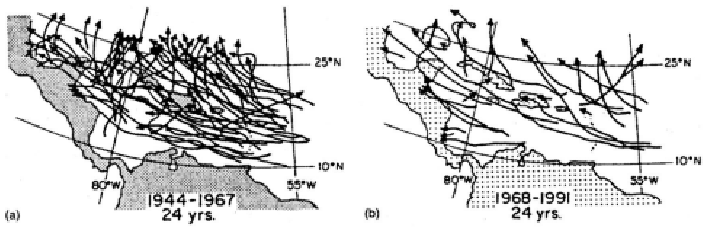


Fig. 1. Contrast of hurricane tracks in the Caribbean for multidecadal periods of: (a) 1944–1967; (b) 1968–1991 (Landsea 2000a)

Figure 3.8: Hurricane trajectories (Pielke et al., 2003)

3.2.4. Climate change

The temperature is expected to rise 0.5 to 2.0°C by 2050. The sea level is expected to rise by 0.24 to 0.26 m in this period [SLR-RCP 8.5] (Cartagena ConAgua, 2024b). In 21000 the sea level rise is 0.52 m according to Orejarena-Rondón et al. (2019). According to Oppenheimer et al. (2019) the global mean sea level will rise between 0.43 m (0.29–0.59 m, likely range; RCP2.6) and 0.84 m (0.61–1.10 m, likely range; RCP8.5) by 2100 (medium confidence) relative to 1986–2005. But according to sources such as Rahmstorf et al. (2012) & Vermeer and Rahmstorf (2009) the rise of 0.52m is too low. Therefore, it could be seen as the lower limit of the climate change scenario.

The effects of climate change are analysed for the year 2100. This is in line with common practise in other countries where hydraulic structures usually have a design life of 50 or 100 years. It is important to consider the functioning of a design during its whole design life, so up till the end (Roebers and Bakker, 2015).

Next to the rise in global mean sea level, there are other factors that change under the influence of climate change, such as the amplitude of the tides (Pickering et al., 2017) or precipitation patterns (Chaulagain et al., 2023 & Arregocés et al., 2024), and there are local variations. For example, an increasing temperature can result in a more extreme precipitation event because, for every 1°C increase, the air's potential to carry moisture increases by 7% ("World Bank Climate Change Knowledge Portal", n.d.).

3.3. Hydraulic system

The connections between the Caribbean Sea and the hydraulic structures in the Ciénaga influence the lagoon's hydrodynamics, including the bathymetry, tides and discharges. The functioning of those connections is questionable and is discussed later in this chapter, along with the discharges into the Ciénaga. Next to the reduced water exchange due to improper functioning of connections, other issues are altering the water system as well. For example, sewage water from the city and fertiliser-infused runoff from the rural area end up in the Ciénaga (Sánchez et al., 2015). During extreme events, this situation is worsened; there is no proper (waste)water management, and the rainwater takes contaminants in the solid and liquid form of the city into the Ciénaga (Cartagena ConAgua, 2024b).

Alongside these natural processes, man-made construction and human activities, such as the road Anillo Vial, modified the hydrodynamics in the Ciénaga (Touza et al., 2021).

The in and out-flowing discharges of the Ciénaga are represented in the water balance shown in Figure 3.9.

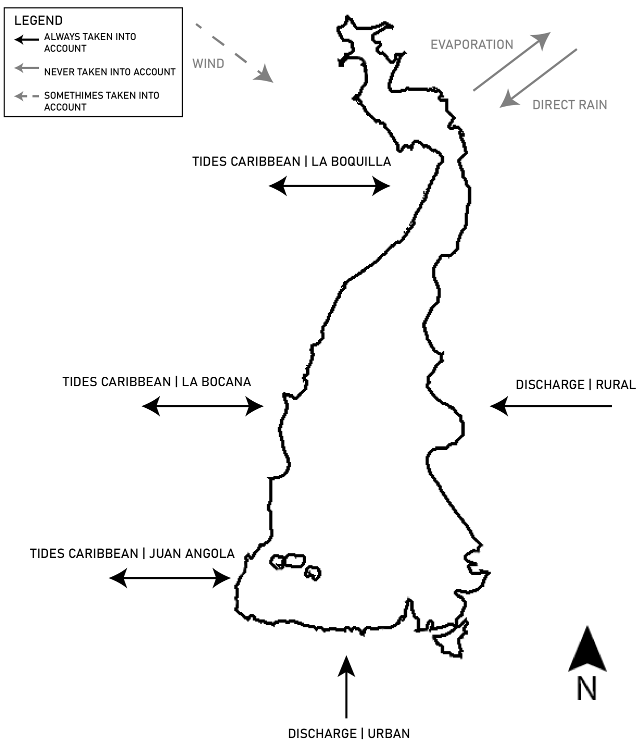


Figure 3.9: Considered parametres influencing the water balance of the Ciénaga

3.3.1. Bathymetry Ciénaga

One of the other companies in the consortium ConAgua is JESyCa; they provided a bathymetry file which originates from a study in 2019 by CARDIQUE called: "Acotamiento Ronda Hídrica Ciénaga de la Virgen y Cuerpos Internos". Although the date of the report is clear, it is not clear from which date the data, and therefore the bathymetry file originates. In this file, the bathymetry from the Ciénaga ranges from 0 to -2 m. The sedimentation rate of the marsh is quite high. Therefore, this bathymetry is expected to not correspond with the current situation (CARDIQUE, 2019).

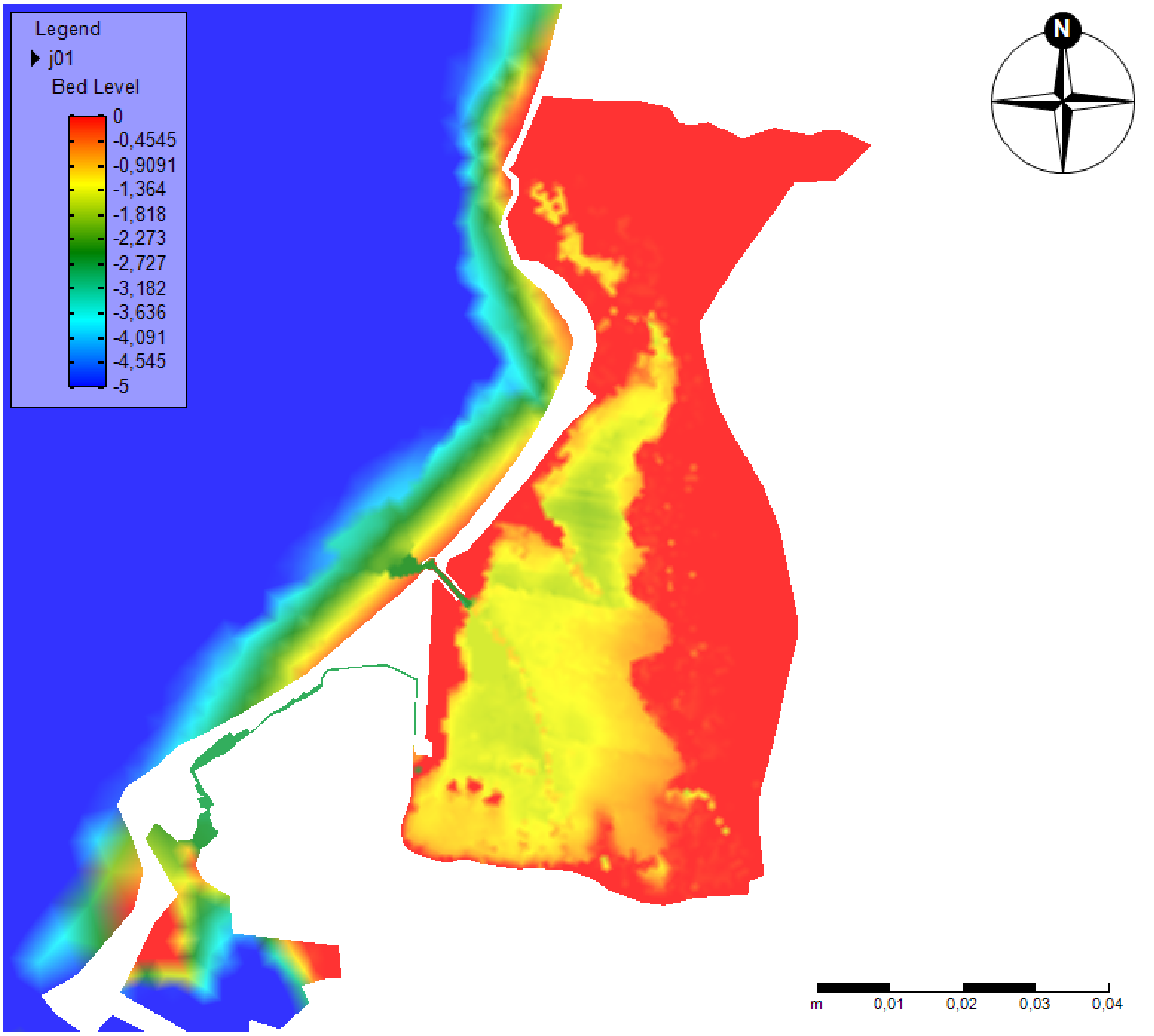


Figure 3.10: Bathymetry Ciénaga (CARDIQUE, 2019)

3.3.2. Tides and connections with the Caribbean Sea

On average, the sea level in the Caribbean Sea varies between 5-12 cm. For the annual cycle, the highest sea level occurs in September (Bosch et al., 2002) or October (Torres and Tsimplis, 2014).

The Ciénaga is connected to the Caribbean Sea by the La Bocana system and the Juan Angola channel trough the Bay of Cartagena, and it used to be connected by the tidal inlet up north of la Boquilla, see Figure 3.11. The proper functioning of the connections is questionable due to sedimentation and deterioration of the inlets. This resulted in a reduced water exchange, which negatively influenced the water quality.

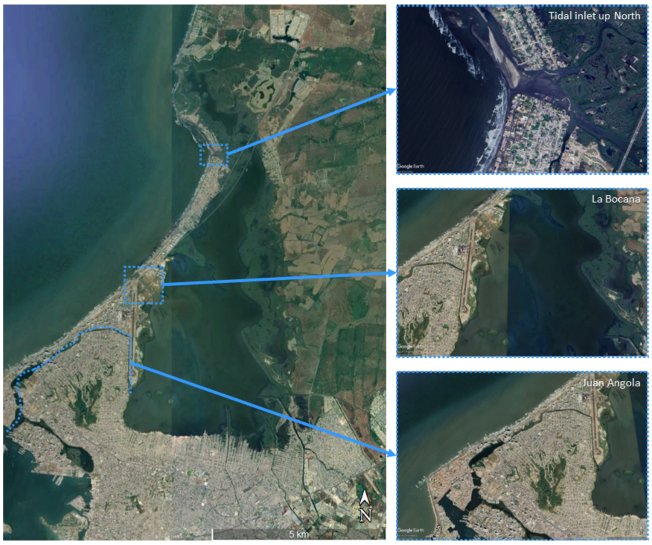


Figure 3.11: Connections with the Caribbean Sea from North to South; The Boquilla, La Bocana and Juan Angola Channel (*adapted from Google Earth, 2024*)

La Bocana system connects the Ciénaga with the Caribbean Sea. The main function of this system was to oxygenate the water and restore the biological balance by creating a circulation in the Ciénaga based on the tide (Yuca Pelá, 2023). This was necessary because the Ciénaga was very polluted. The sewage water of the city was dumped in the surrounding waterbody, which absorbed it for a long time, but around 1980, the pollution level became unacceptable. Moreover, the lagoon's water level increased during the rainy season, which flooded the surrounding areas taking even more waste into the lagoon. To overcome these challenges, the La Bocana system was constructed in 2000. According to Moor et al. (2002), dumping sewage into the lagoon was stopped between 2005 and 2007.

The La Bocana system consists of a breakwater in the Caribbean, a sluice and a kilometres long sheet pile wall into the Ciénaga called a directional wall (Figure 3.12). The sluice opens and closes as a result of the tides. The initiated technical lifetime of the inlet was between 40 and 50 years, and the yearly maintenance costs were expected to be low (*Stabilized tidal inlet, Cartagena, Colombia*, 1995). However, the system started to deteriorate over time, making its functioning defective. It is currently assumed to be an open, not controlled, connection with the Caribbean. The construction of artificial openings like La Bocana has altered the hydrodynamics (Touza et al., 2021). ConAgua is proposing to restore this system, among other measures, which aims to improve the water quality and flood resistance in the area. A schematisation of the operation of the system can be observed in Figure 3.13


(a) La Bocana at the entrance with the Caribbean, Ciénaga side


(b) End of the directional wall of La Bocana system in the Ciénaga


(c) La Bocana at the entrance with the Caribbean, looking into the Ciénaga

Figure 3.12: Impression of la Bocana system in the Ciénaga (ConAgua, 2023)

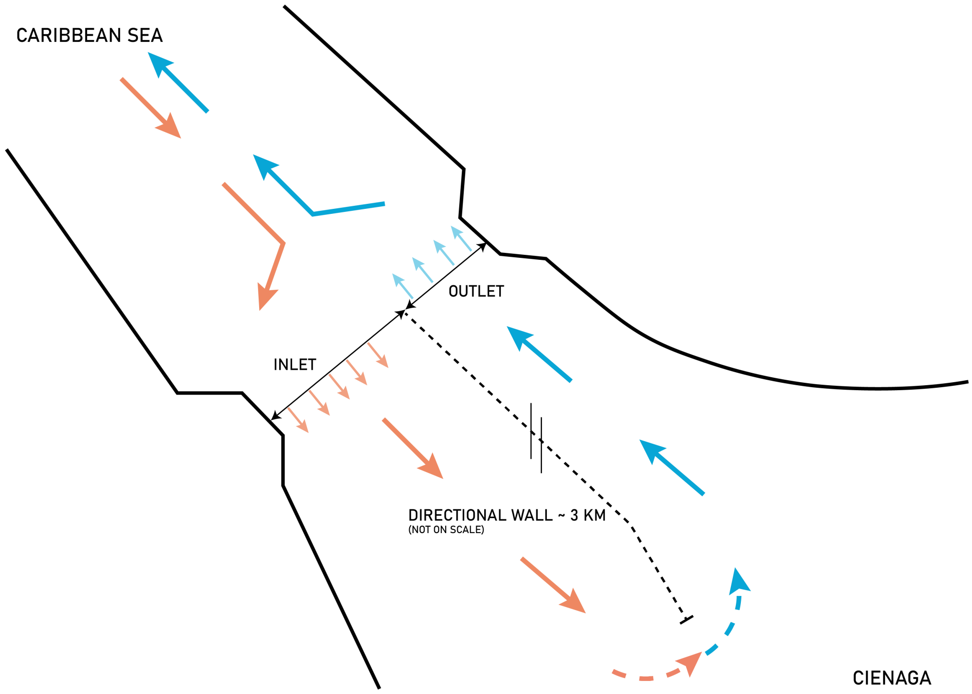
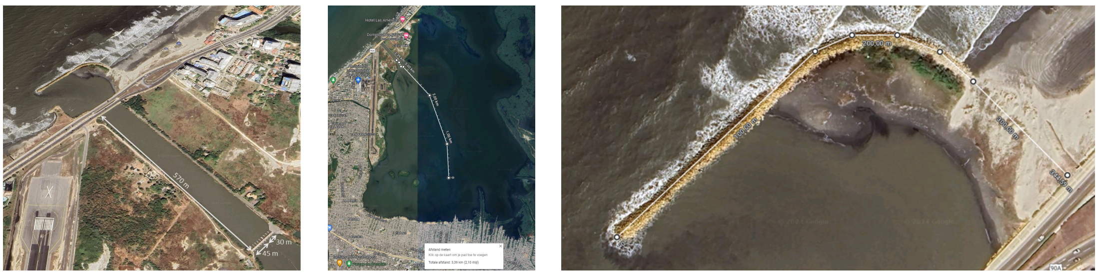


Figure 3.13: Schematisation of the proper functioning of La Bocana system

The dimensions of the la Bocana system are obtained from Google Earth (Figure 3.14):

- The lock has an inflow opening with a width of 45 metres and an outflow of 30 metres. The height of the gate is 4 metres, and the bed level is -2.5 metres;
- The directional wall in the Ciénaga is 3.4 kilometres long
- The breakwater is roughly 345 metres long, including the sandy part. It has an offset of 160 metres from the bridge and an opening of 70 metres



(a) Lock of La Bocana system **(b)** Directional wall inside the Ciénaga **(c)** Breakwater in the Caribbean Sea at the other side of the lock

Figure 3.14: Elements of la Bocana system (*Google Earth, 2024*)

Juan Angola Channel connects the Ciénaga with the Cartagena Bay and, in that way, with the Caribbean Sea. Within this channel a sluice is located. However, local experts mention that, in reality, this sluice is never closed and maybe even not operative. Currently, there is a lot of waste in the channel. According to Lara and Torres (2017), the Caño Juan Angola had an average depth of 2.76 m. It is assumed that this is still the case.

(a) Waste in Juan Angola channel **(b)** Broad part of Juan Angola channel

Figure 3.15: Photos of the Juan Angola channel (ConAgua, 2023)

Figure 3.16: Location of the sluice connecting the Ciénaga with the Cartagena Bay

The **tidal inlet** is located at the northern part of the barrier La Boquilla between the Caribbean and the Ciénaga. This sandbarrier is located in the eastern part of the Ciénaga. Due to the main current along the coast from north to south combined with the fact that the Boquilla is located in the lee of the current, this tidal inlet is closed off due to sedimentation. The tidal process stopped working because no water could flow in or out at this location (Devia, 2006).

(a) 2007, partly opened inlet **(b)** 2017, complete passage **(c)** 2023, disconnected inlet

Figure 3.17: Tidal inlet la Boquilla, snapshots from Google Earth

3.3.3. Discharge into the Ciénaga

The total watershed of the Ciénaga is between $516\,km^2$ (Brakel et al., 2017) and $609\,km^2$ (POMCA et al., 2014), more than $470\,km^2$ of this total is coming from the rural area. The discharge differ seasonally, and the easiest method to distinguish them is to define dry and rainy seasons.

Dry season

The discharge in the dry season is a combination of wastewater discharge and a minimal runoff from the rural area, the discharge location can be seen in Figure 3.18 (see Appendix A).

Wastewater from the city into the Ciénaga is considered to be 2.81 m^3/s (Devia, 2006). Some sources mention a plan to treat the sewage water, which would be disposed of into the sea through a pipeline (*Stabilized tidal inlet, Cartagena, Colombia*, 1995). Because this plan could not be validated, it is expected that (part of) the sewage discharge is dumped into the lagoon.

The minimal input from the rural area, during dry season, is considered to be (POMCA et al., 2014):

- Arroyo Caño Mesa: $0.077\,m^3/s$
- Arroyo Tabacal: $0.42\,m^3/s$
- Arroyo La Hormiga: $1.885\,m^3/s$

Figure 3.18: Discharge points into the Ciénaga during dry season

Rainy season

For the rainy season, the extreme discharge from the urban channels, the distribution and discharge according to EDURBE (2023) are considered. The discharges mentioned in the report are checked using the rational method (Appendix B). The extra input locations of the discharge, can be seen in Figure 3.19. The corresponding hydrograph can be seen in Figure 3.20.

Rainfall-runoff behaviour depends on many conditions, such as the rainfall itself and the characteristics of the catchment area. The part of the precipitation leading to changes in the river's discharge is called the direct runoff, where factors such as interception, storage and infiltration play a big role (Uijlenhoet and Ent, 2024b).

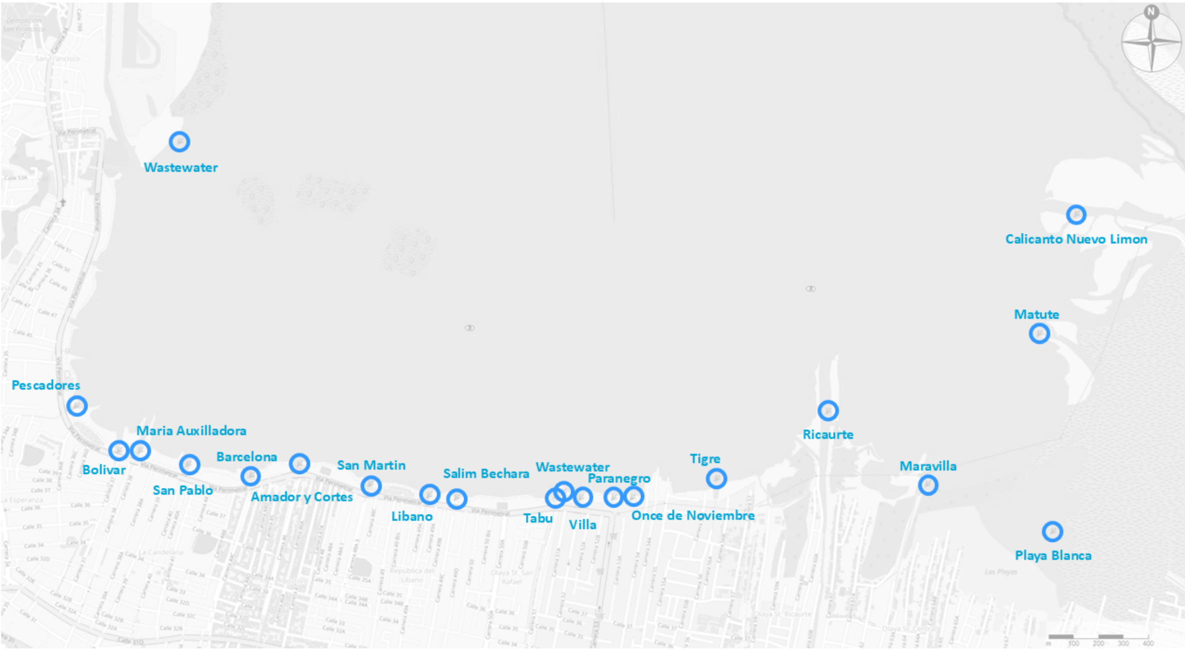


Figure 3.19: Additional discharge points during rainy season

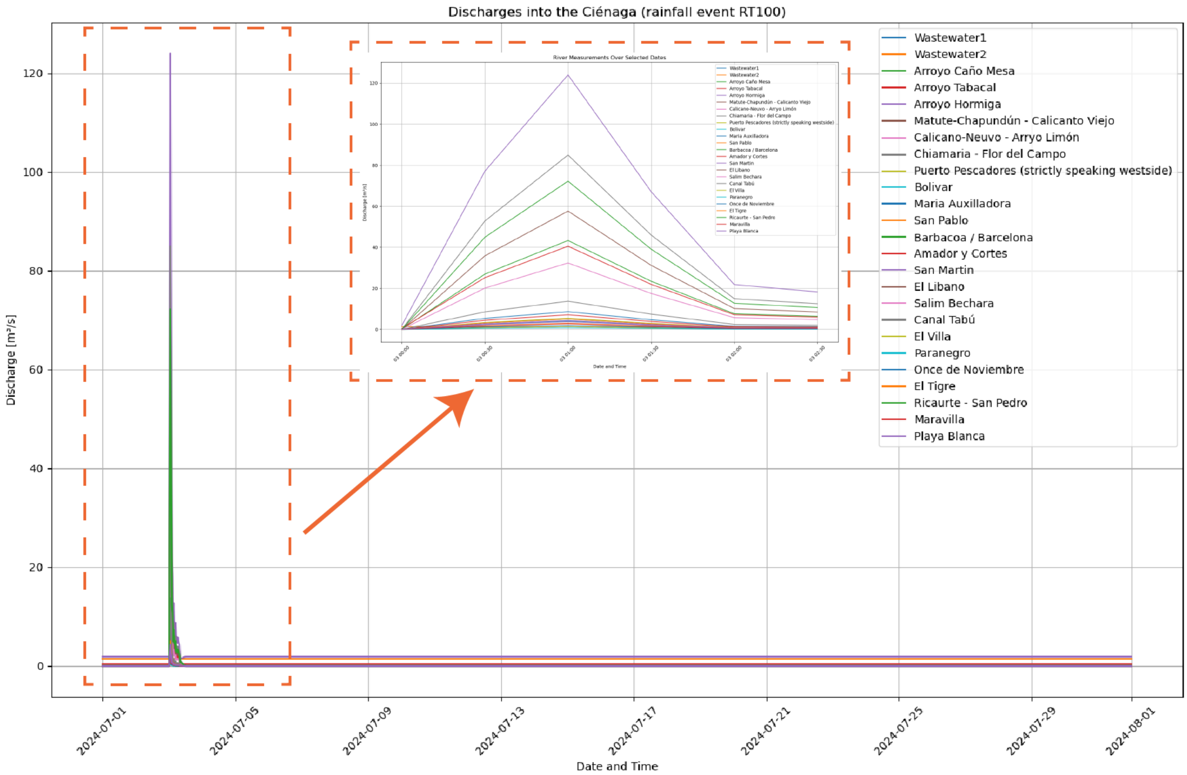


Figure 3.20: Discharge hydrograph due to precipitation (rainfall event RT100) - rainy season

3.4. Classification of the Ciénaga

The Ciénaga is a shallow lagoon, covering an area of $22.5\,km^2$ (Sánchez et al., 2015), and has a volume of $11 * 10(^6)\,m^3$ according to Brakel et al. (2017) making an average depth of 0.5 m.

The Ciénaga is categorised as either a restricted or a choked lagoon before human interventions were implemented based on the number of inlets (Duck and Silva, 2012).
In restricted lagoons, the circulation is determined by a combination of the tides, winds, and freshwater runoff, and they are usually well-mixed vertically (Kjerfve, 1994).
As opposed to choked lagoons, where winds are dominant processes. Choked lagoons are found on coasts with high wave energy and significant littoral drift. According to the degree of isolation, a choked lagoon has only narrow tidal inlets and dominant micro tidal hydro morphological conditions, and the dominant geomorphological features are open water and an intralagoon delta (Duck and Silva, 2012). Micro tides govern tidal range from 0 to 1 m (Tagliapietra et al., 2009). Barrier islands formed at microtidal coasts are usually long and linear (Kjerfve, 1994), which is the case for la Boquilla.
Both, choked and restricted lagoons are characterised by long residence time. Both have a longer turnover time compared to leaky lagoons (Kjerfve and Magill, 1989).

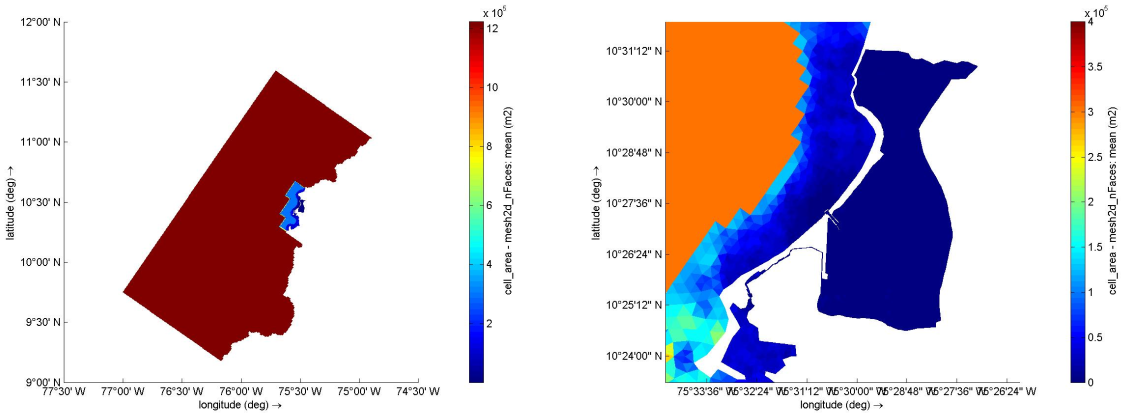
Because of this classification, the behaviour of the Ciénaga is expected to be mainly influenced by the wind and also, but to a lesser extent, by the tides and freshwater input. The lagoon will be vertically well-mixed. The expected residence time will be long.

4 Model Set up

This chapter explains the model setup of the Delft3D program. It gives the baseline model's input and describes how the alternative measures and scenarios are modelled. An overview of all the simulations in Delft3D is displayed within this chapter. After that, it discusses how several measures are being assessed and the limitations of the model because of the assumptions being made.

4.1. Model input

For the simulation of the behaviour of the Ciénaga, a depth-averaged hydrodynamic model is constructed in Delft3D flow-flexible mesh (a more extended description of Delft3D can be read in Appendix D). The grid resolution begins offshore with a rectangular grid with a horizontal resolution of 1100 m ($12 \times 10^5\,m^2$) and narrows down to 600 m nearshore ($4 \times 10^5\,m^2$). Closer to the inlets of the Ciénaga and the Ciénaga itself, the grid becomes triangular with a resolution increasing from 7000 to $2500\,m^2$. The grid resolution of the Delft3D model can be observed in Figure 4.1. The boundaries of the Delft3D model into the Caribbean Sea can be observed in Figure 4.2. At the boundaries of the Caribbean, the tides are imposed as mentioned in Chapter 3.3.2.



(a) Total Delft3D model (finer mesh indicates the Ciénaga)

(b) Detailed grid of the Ciénaga (zoomed in grid of (a))

Figure 4.1: Grid resolution Delft3D (remark: notice that (b) is a zoomed version of (a) and that the scale bar changes)

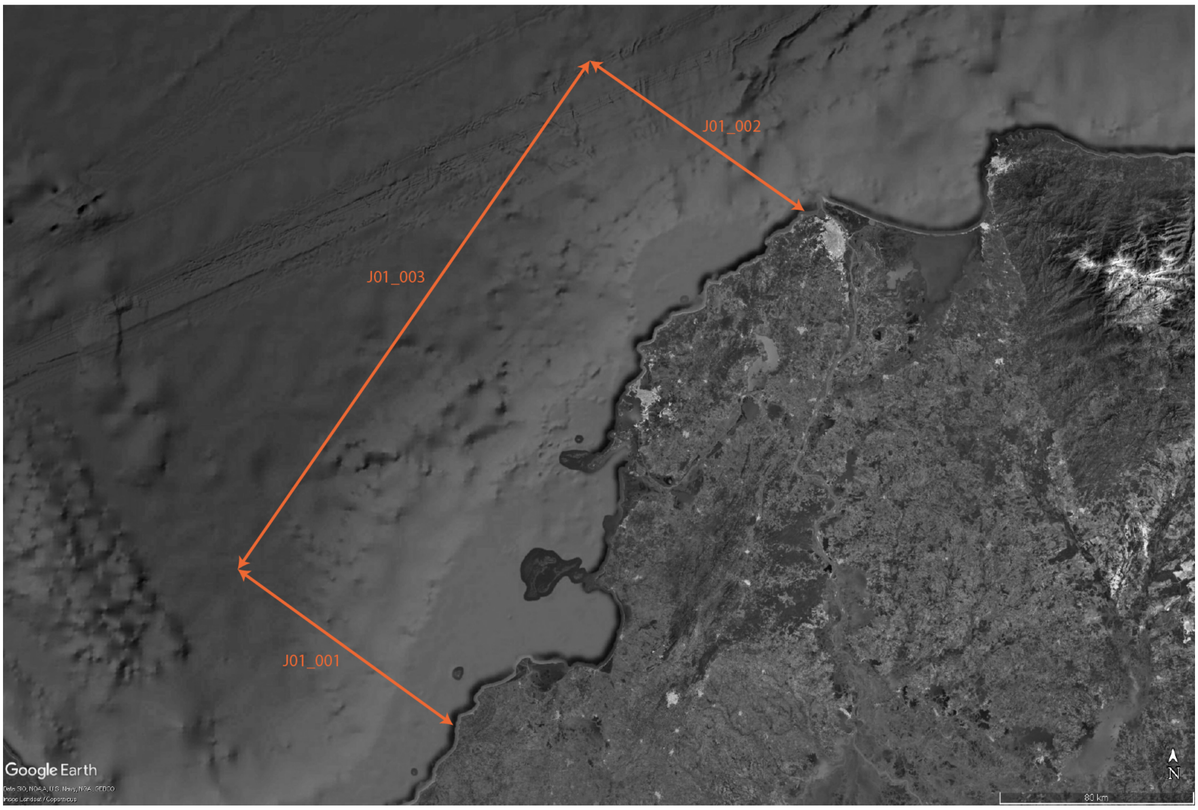


Figure 4.2: Boundaries of the Delft3D model, labels indicate the imposed tides as mentioned in Appendix C

For the bathymetry offshore, GEBCO is used, and in the Ciénaga, a bathymetry file was provided by JESyCA (CARDIQUE, 2019).

Several characteristics are incorporated into the model, while others are excluded. Although all factors represent relevant phenomena, their inclusion would excessively increase the model's complexity. Additionally, only a few data were available. Therefore, most parameters were left in the default setting, or simplifications were adapted by not taking them into account. The uniform manning roughness of $0.022\, s/m^{1/3}$ is used for the bottom roughness. The water density of the model is $1025\, kg/m^3$, corresponding to seawater.

In the simulation, July was chosen for the tides in the Caribbean Sea as it displayed a stable month, meaning no instabilities within the simulated water levels. The tidal range in the Caribbean is very small; therefore, the monthly variation is expected to be limited. According to Cubit et al. (1986) the monthly mean water levels fluctuated seasonally over a range of 10 cm. Next to the fact that the chosen month has a limited effect on the water levels, the critical months will vary per indicator (water safety versus quality). For example, for water safety, the crucial month is October when various elements have their maximum simultaneously (peaks seasonal cycle, storm surge due to hurricanes, spring tide) (Torres and Tsimplis, 2014). While the low sea levels are usually around March and April, they are more critical for the water quality (Cubit et al., 1986).

The initial water level starts at $0\, m$. Other influencing parameters, such as wind and air pressure, are not considered in the baseline model.

The dimensions of inlets and structures are obtained from Google Earth. The model uses a contraction coefficient of 0.75 for the La Bocana system, indicating an efficient flow.

4.1.1. Baseline model input

Geographical, climate and hydraulic characteristics are mentioned in Chapter 3. The parameters that are included in the Delft3D model are mentioned in Table 4.1.

The baseline model includes the discharges from the dry seasons, mentioned in Section 3.3.3. The release of wastewater into the Ciénaga is simplified to two input points at the corner of the western and southern banks of the lagoon, which is estimated to be the population density centre. The plan for the treatment of sewage water is not validated, therefore sewage discharge was included in the model as being of bad quality, representing a worst-case scenario.

The data that is used to take into account the effect of tides is sourced from TOPEX/POSEIDON satellite data 2006. The tidal constituents tables from the TOPEX/POSEIDON satellite are used at the boundaries in the model. Based on the tides at the boundary, the model generates a tide throughout the entire area. The amplitudes of the tidal constituents are represented in Appendix C, and the location of the boundaries can be seen in Figure 4.2. The data from 2006 is valid for the coming +50 years (personal communication with Jos van der Baan, July 28, 2024).

The baseline model has a runtime of one month, and the model time step is 15 seconds. There is a semi-diurnal tide in the Caribbean Sea, with a small tidal range (range -0.2 to +0.3 m relative to MSL) due to the size of the waterbody and geographic nature (Bijpost, 2022). If the tide is influenced by the orbital cycle of the moon (27.32 days) or by the lunar phases (29.52 days), both take roughly one month to compete, meaning a new tidal cycle is experienced. The modelled time frame is one month to complete a full tidal cycle. In the simulation, the model experiences two spring-neap cycles because, in a semidiurnal tide, approximately two spring tides occur (Kvale, 2006).

Table 4.1: Baseline model input

Model input parameter	Remark	Source	Explained in
Tides Caribbean	Spring tide amplitude of 0.09 m and neap tide amplitude of 0.05 m (roughly estimated based on the thresholds of the astronomic components)	TOPEX/POSEIDON satellite	Chapter 3.3.2
Discharge Rural & Urban	Minimal discharge river and waste water estimation	POMCA et al., 2014 & Devia, 2006	Chapter 3.3.3 & Appendix A
Bathymetry Ciénaga	Ranging between 0 till -2 m MSL	CARDIQUE, 2019	Chapter 3.3.1
Bathymetry Caribbean		TOPEX/POSEIDON satellite data 2006	
Elevation Cartagena	Resolution of file is 2 by 2 metres	EDURBE, 2023 & Wakker, 2024	Chapter 3.1
Geometry measures		Google Earth, 2024	

Figure 4.3: Hydraulic influences on the Ciénaga

4.1.2. Modelled measures

The different measures proposed by ConAgua are listed below. The measures are modelled in several ways, separate or combined. The measures are slightly simplified within the model:

- **No measure**: the simulation without measures, the structures in the Juan Angola channel and the structures of La Bocana are neglected for simplification. This results in an open connection through the Juan Angola channel, neglecting the lock in the channel within the model. As for the La Bocana structures, the sluice gates and the directional wall inside the Ciénaga do not exist in the model, so there is an open connection.
- **La Bocana system**: the lock gates are modelled so that with the switch in tides (difference between ebb and flood), part of the gates closes and the other opens, resulting in a circulation flow and altering the inlet geometry. This flow goes from the southern entrance of the lock around the directional wall towards the northern entrance. The inlet has a width of 30 metres (6 openings of 5m, with two gates for each opening), and the outlet is 20 metres (4 openings of 5m, with two gates for each opening). Another assumption in the model is that the sheet pile wall in the Ciénaga cannot be over-topped. The seawater coming in from the Caribbean is considered as clean.
- **Juan Angola**: this channel connects the Ciénaga with the Caribbean Sea by passing through Cartagena Bay. When this measure is implemented, the discharges within this channel are considered clean, meaning that the initial tracer value is zero. Another part of this measure concerns the floodgates near the monument of India Catalina, which can be closed during high tides.
- **Matute watershed**[1]: after adaptation, the discharge coming from this watershed (2834.6 hectares (Cartagena ConAgua, 2024a)) is considered clean. During extremes, part of the water is collected. The changes in the channel geometry can result in a higher discharge capacity, which could lower the risk of flooding in the direct surroundings of the river.

[1] This measure is only applied in the extreme scenario due to the fact that the basic version assumes no discharge coming from the Matute watershed

- **Tidal inlet of La Boquilla**: reopen the connection with the sea, with a width of 80 m and a depth of 0.25 m. The width was estimated based on Google Earth images taken prior to 2016. At that time, there was still a limited degree of water exchange visible at this location. The depth is estimated based on the expectation that overflow only occurs during high tide (Devia, 2006) [2].

4.1.3. Alternative scenarios

The modifications considered are listed below in random order. The modifications are a result of the limited amount of data. Such as the depth of the tidal inlet at la Boquilla, the sensitivity to the bathymetry, the contraction coefficient of La Bocana, or the wind forcing; due to uncertainty, those alterations are modelled to evaluate the importance of sound and accurate data for these parametres. The long-term impacts of the measures need to be considered, and the effects of climate change and extreme rainfall must be taken into account. Subsequently, the influence of clean discharge is considered this implementation gets to the root of the problem of the polluted Ciénaga.

Figure 4.5 shows a schematic overview of all the possible scenarios, and Table 4.3 is an overview of the simulations used in Delft3D.

Deeper tidal inlet of La Boquilla
The bathymetry of the tidal inlet is made deeper to understand the effect of this inlet better. It is manually adapted in Delft3D to a minimum value of -2.5 m inside the tidal inlet, and this was smoothed to the existing bathymetry of the Caribbean Sea and the Ciénaga.

Sensitivity bathymetry
The sensitivity of the hydraulic behaviour to the bathymetry and, therefore, the importance of knowing the exact bathymetry is studied by simulating a deeper lagoon (-4.1 m MSL) and a shallower lagoon (-0.8 m MSL). This is done given that the sedimentation rate of the marsh is quite high. It is expected that bathymetry from the CARDIQUE study does not correspond with the current situation (CARDIQUE, 2019).
The different bathymetry situations are simplified in the model by changing the entire depth of the Ciénaga to those values mentioned in Table 4.2 and manually smoothing this to the edges of the Ciénaga to create a natural inclination.
If the result is that changing the bathymetry has a significant influence on the effects of the measures, the bathymetry has to be determined to make a proper evaluation and eventually make a decision on which measures to favour.

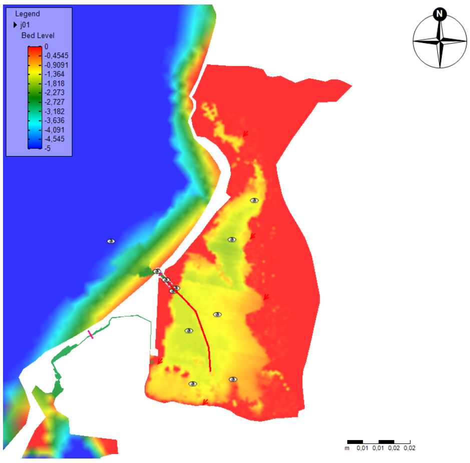
There are three bathymetry scenarios considered:

- The **current situation**, with bathymetry data from 2019 provided by JESyCA (section 3.3.1, CARDIQUE, 2019).
- The **shallow depth**, estimated to have a depth of a maximum of 0.8 m. This is estimated by the height of the waist of a fisherman because according to Cartagena ConAgua (2024b) this is the current depth near La Bocana & in combination with the average length of a Colombian (World Population Review, 2024).
- The other one is a **dredged** situation with a larger water depth. According to Cartagena ConAgua (2024b) in total $780440\,m^3$ is dredged, along the directional wall. This area is estimated with Google Earth and is $570 \times 75 = 42,750\,m^2$ when $140,000\,m^3$ (Cartagena ConAgua, 2024b) is dredged from this channel, the depth increases on average with $3.3\,m$. This results in a depth of $-4.1\,m$, with respect to the shallow water condition. This depth is considered as the dredged depth.

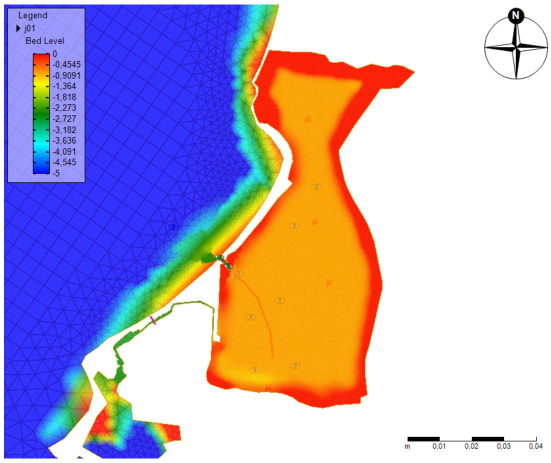
[2]Contrary to this assumption Moor et al. (2002) mentions that the overflow was only during low-wave season due to the longshore sand transport in combination with the rain season enabling a hydraulic gradient between the lagoon and sea

Table 4.2: Model scenarios to evaluate sensitivity to variations in bathymetry

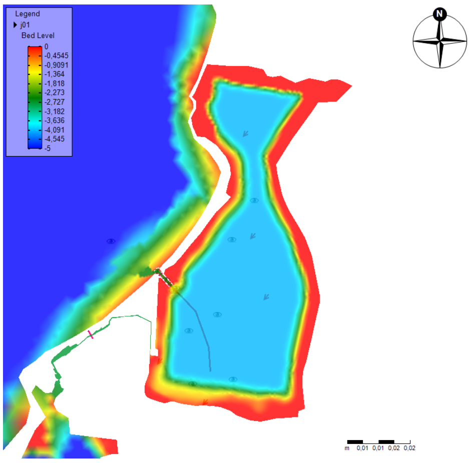
Model Situation	Bathymetry
Current situation	Bathymetry file obtained from CARDIQUE (2019), depth ranging from 0 to -2 m MSL
Shallow water	Depth of - 0.8 m MSL
Dredged	Depth of - 4.1 m MSL



(a) Current situation



(b) Shallow situation



(c) Dredged situation

Figure 4.4: Simplified bathymetry of the Ciénaga used for the sensitivity analysis

Contraction coefficient

Sensitivity contraction coefficient: For one simulation, 0.4 is used to investigate the influence of the contraction coefficient. This analysis is conducted given that it is difficult to know the exact coefficient, which is influenced by the flow conditions and type of gate opening, and 0.4 is seen as the minimum value compared to the value of 0.75 used in the baseline model (Lin et al., 2002 & Khalili Shayan and Farhoudi, 2013).

Wind forcing

Extension extreme scenario: wind is added to see the effect of the wind on the shallow lagoon, the constant wind coming from the North with a speed of $2.85\,m/s$.

Extreme discharge

An extreme rainfall event is added on top of the baseline model, there are more drainage sources in the southern part of the Ciénaga and the discharge has a peak of 8 hours (Appendix B). All the channels have their limited discharge simultaneously, a conservative approach. The extreme discharges are mentioned in section 3.3.3.

Sea level rise
For a future scenario including climate change, a sea level rise of 0.52m is incorporated, expected to happen in 2100. This rise is implemented by altering the MSL (component A in the tidal constituents, see Appendix C) at the boundary conditions of the Caribbean Sea in the Delft3D model.

Take note that an extreme rainfall event with a return period of 100 years is already considered, but it has not been adapted for the situation in 2100. Changes in precipitation are thus not considered, as well as changes in temperature and storm frequency due to climate change. Furthermore, be aware that mean sea level rise is considered and not the local relative sea level rise, which means that the subsidence of -1.88 ± 0.44 mm/year, according to Orejarena-Rondón et al. (2019), is not taken into account.

Clean discharge
Importance of clean water input: the impact of water discharge quality (rural and urban) at the input locations is expressed by simulating a clean input (tracer concentration = 0) as a result of an extreme rainfall event.

4.1.4. Research schematization

The schematization of the simulations used in Delft3D can be found in Figure 4.5. The baseline input is displayed by the combination of all boundary parametres in dark orange boxes. In this baseline model, no measure is applied for the baseline reference regarding water levels and tracer amount; thereafter, the effect of the other measures mentioned in the light orange boxes is evaluated by the baseline boundaries.
When the input of the baseline model with or without measures is implemented in the Delft3D model, the water levels and tracer amount over time are extracted, which tells something about water safety and water quality.
The input parametres can be altered by the alternative scenarios depicted in the dotted rhomboid shape. This alternation can either change the baseline boundary parametres or they can affect the measures.

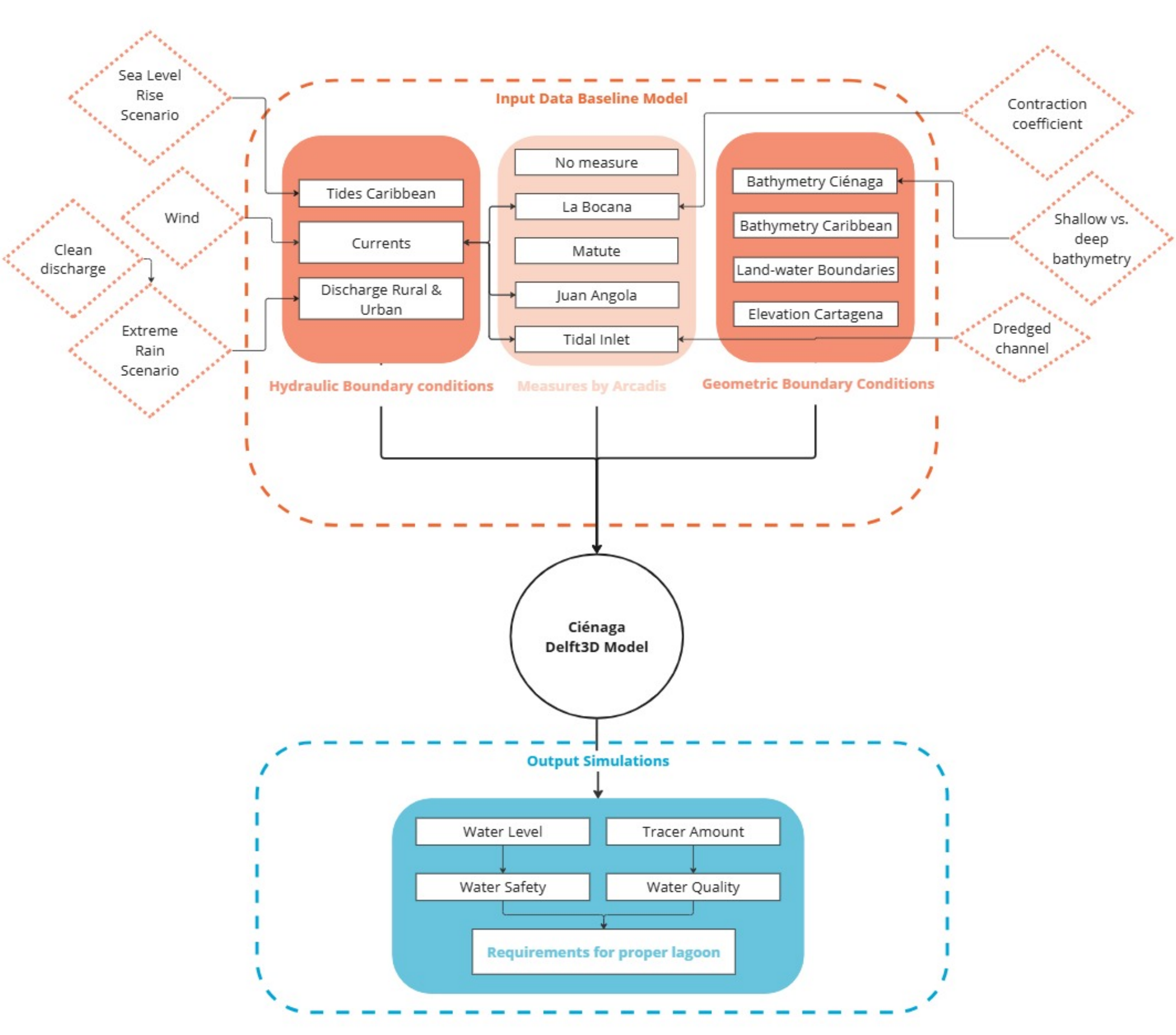


Figure 4.5: Schematisation Delft3D model

The above-mentioned scenarios are combined, and simulations are modelled. The simulations conducted in Delft3D are outlined in Table 4.3.

Table 4.3: Modelled simulations Delft3D with as default the baseline scenario

Modelled scenario		
Model run	**Measure**	**Altered boundary condition**
1	No Measure	
2	La Bocana	
3	La Bocana	Shallow bathymetry
4	La Bocana	Dredged bathymetry
5	Juan Angola	
6	tidal inlet of La Boquilla	
7	tidal inlet of La Boquilla	Deeper
8	No Measure	With extreme discharge
9	La Bocana	With extreme discharge
10	La Bocana	With With extreme discharge and average wind
11	La Bocana	With extreme discharge, and different contraction coefficient
12	La Bocana	With extreme discharge, and all discharge are of good quality
13	La Bocana	With extreme discharge, and sea level rise
14	Juan Angola	With extreme discharge
15	Matute	With extreme discharge
16	tidal inlet of La Boquilla	With extreme discharge
17	La Bocana	Extreme discharge, duration of two months
18	Combination	Combination of measure deepened tidal inlet of La Boquilla & La Bocana

4.2. Model assessment

The following chapter describes the requirements for water quality and safety to assess the state of the lagoon.

4.2.1. Water quality

The water quality of the Ciénaga is very poor, as mentioned in Chapter 1.1. There is inflow of untreated sewage water and pesticides from the rural side. Due to a lack of data on the current state of the Ciénaga, the water quality is solely evaluated by the water refreshment rate.

From the theory in Chapter 2.2, it can be concluded that the water quality can be divided into a preferred and a minimal condition. The preferred requirement is that the tracer concentration is reduced by 63% within 10 days (Matso, 2018), although some advocated for 5 to 7 days (Brylinsky, 2006). The minimal requirement is that it is flushed within 40 days because if the refreshment rate exceeds 40 days, the water quality is extremely poor.

The water quality is assessed by analysing the water refreshment rate. This refreshment rate is modelled by inserting a passive tracer in the Delft3D model. The tracer simulates the transport of the polluted water and how it blends. The maximum value of the tracer concentration is 1 (-, equal to 100%), indicating that water is of poor quality and thus completely contaminated. The minimum value of the tracer concentration is 0 (-, equal to 0%), the desired value, meaning water of good quality.
The grid cells in the lagoon and the discharges from the rural and urban areas start at a tracer concentration equal to one. The grid cell of the Caribbean Sea starts at a tracer condition equal to zero. Due to this difference, the tracer concentration changes over time. Because of this, the water refreshment rate can be determined.

In the simulation, a one-month period is considered, including a full tidal cycle. The requirement is that within this month, the tracer within the lagoon needs to be reduced at least by 50% and preferably by 63% within 10 days. Due to the residents living in the southern and western parts and the mangroves being located at the eastern banks of the Ciénaga. Proper water quality must be guaranteed at all observation points within the Ciénaga. The observation points can be seen in Figure 4.6, and the exact coordinates of the observation points can be seen in Appendix E.

Figure 4.6: Observation points in Delft3D

4.2.2. Water safety

Cartagena is prone to flooding; therefore, modelling water safety is urgent. This risk of flooding is evaluated by modelling the water levels at observation points in the Ciénaga (4.6) and analysing if those are higher than the elevation levels of Cartagena. Monitoring changes in water levels compared to the baseline model and the elevation of the urban landscape is essential for assessing water safety. Next to the water level, the duration of a high water level is important.

In this report, the change in the water level of the Ciénaga and the duration of extremes are combined to evaluate the risk of floods. Due to the complexity, the water levels are only monitored during one arbitrary month.

The effect of the change in water level downstream in Ciénaga could evolve into a backwater curve in the urban and rural streams. This can alter the capacity of the urban and rural streams. Flooding could occur as a secondary response due to rising water levels downstream. However, this is outside the scope of this research.

4.2.3. Summary of indicators

Summarised, the list of criteria to evaluate the measures is:

- Tracer concentration in the Ciénaga is reduced by 63% at all observation points in the lagoon within 10 days.
- Rise in water level can not be more than 0.2 m for more than 1 day at any observation point within the Ciénaga.

4.3. Model assumptions

For generating the model, the following is assumed:

- **Water quality, Ciénaga and inflows**: The literature consulted and conversations with people from Arcadis involved in the project indicated poor water quality. This is due to a lack of sewage systems, waste collections and agricultural pollutants. However, there is no quantitative information to determine the extent of pollution. Inflows into the Ciénaga and the Ciénaga itself, before the adaptation of the measures, are considered fully polluted (start value tracer concentration = 1).
- **Water quality, Caribbean Sea**: is considered as clean (start value tracer concentration = 0).
- Tidal changes move through the Juan Angola channel, meaning the water can move in both directions.
- Subsidence of Cartagena is neglected.
- The lagoon is well mixed (depth-averaged simulation, due to the shallow appearance of the lagoon, stratification expected to have no influence).
- Only tidal forcing at the boundaries is assumed in the baseline model (due to little data).
- Discharges from streams and rivers are added as point sources.
- Bathymetry is changed manually in Delft3D.
- The model month July is chosen arbitrarily as it displayed a robust system. The tidal range in the Caribbean is very small therefore the monthly variation is expected to be limited.
- The initial temperature and its variation are not taken into account, as it seems irrelevant to the current indicators.
- In the alterations with sea level rise due to climate change, no bathymetry changes are incorporated.
- Due to the fact that Cartagena is located on the leeward side of the Caribbean, hurricanes and tropical storms and their effects are not considered in the model (e.g. swell is neglected).
- The effects of El Niño-Southern Oscillation are neglected.
- Evaporation and groundwater seepage are neglected.

4.4. Model validation

Model validation is necessary to assess the degree of correspondence between the model and the actual situation. The simulated tides are evaluated for this reason by means of a comparison with the tides of the Caribbean as documented in the literature. Furthermore, some of the results of the model were discusses with experts from ConAgua, such as the simulated alongshore current which did not reem to resemble reality (personal communication with JESyCa, 2024). The local expert indicated that the alongshore current typically moves from north to south, a phenomenon that was not visible in the plume distribution of the simulations in which wind was absent. In the simulation incorporating wind, this alongshore current could be seen in the plume distribution. It can be concluded that this simulation more closely reflects the observed reality.

According to Kjerve (1981), the Caribbean has a mixed semidiurnal or mixed diurnal tide, with a mean tidal range below 30 cm and periods approximately 12.4 or 24 hours. This corresponds to the simulated water levels offshore for the different simulations, excluding the simulation with sea level rise (Figure 4.7). For an additional substantiation of the resemblance of the tides consult Appendix C.

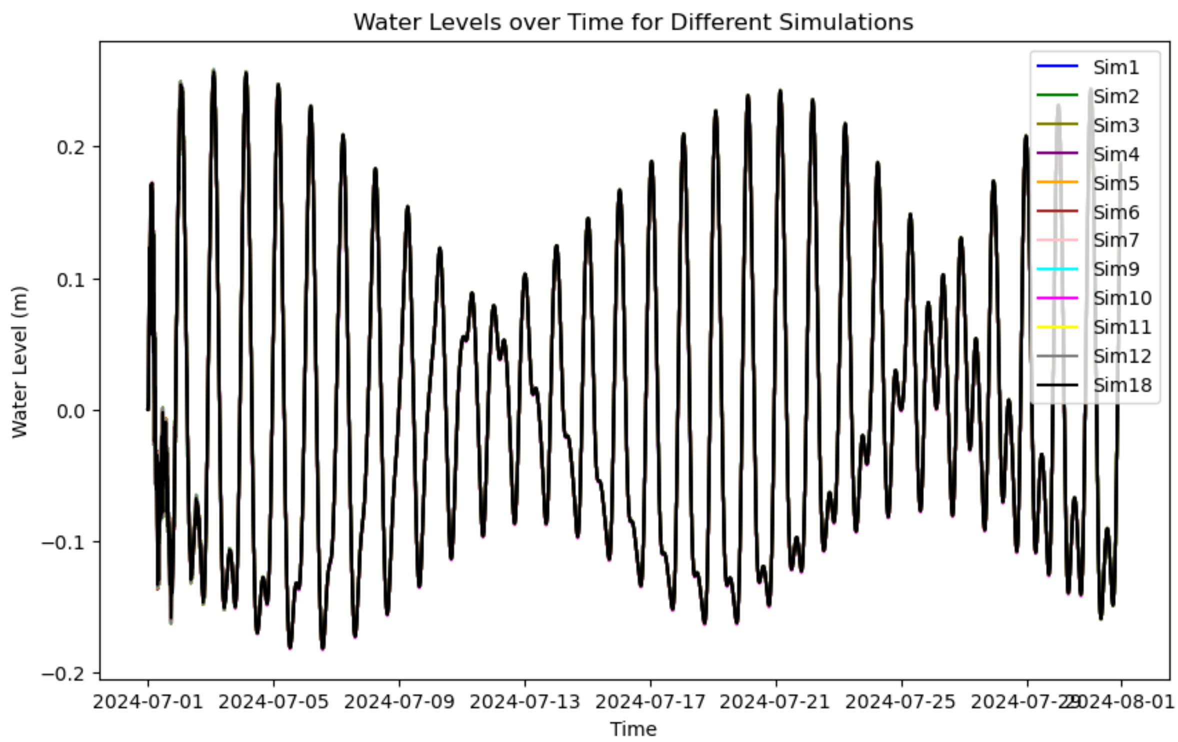


Figure 4.7: Water level at offshore observation points, showing that within all simulations the same offshore water levels are monitored (except for the simulation including sea level rise #13)

5

Results

The behaviour of the Ciénaga is modelled within the Delft3D environment. This way, the effects of the different measures and scenarios is evaluated based on the water safety and quality of the Ciénaga. First, the behaviour of the Ciénaga in the current situation is discussed, then the impact of the measures is made clear, and thereafter, the sensitive analysis is considered.

5.1. Current situation

Simulation #1: baseline model without measures

The baseline model has as input the discharge in a dry period, bathymetry from CARDIQUE (2019) and normal water levels at the boundaries in the Caribbean (Chapter 4.1.1). As a reference, the baseline model without measures has at all observation points within the Ciénaga a mean water level of 0.0035 m, the max water level reached is 0.09 m, and the tracer amount stays roughly equal to the initial value ($\approx 99\%$).

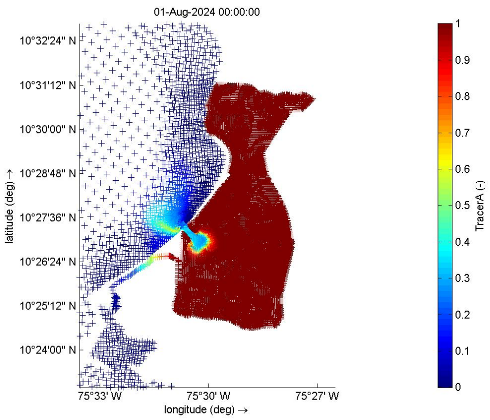


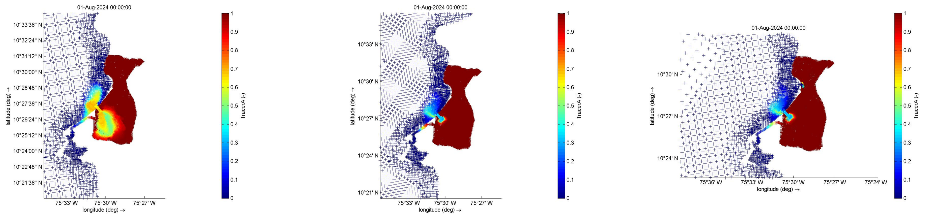
Figure 5.1: Tracer quantity after one month, current situation

5.2. Comparison measures

Simulation #2, #5, #6, (#7): baseline model with measures

Most of the measures proposed by the consortium have a maximum water level of 0.09 m (except for the measure with La Bocana, which is 0.08 m) within the modelled month for the baseline scenario. The measures score almost equal regarding water safety, meaning the water levels stay the same compared to the current situation.

However, regarding water refreshment, a significant difference is noticeable in the measure when La Bocana functions properly. The water refreshment of each simulation at the end of the month can be observed in the snapshot of Figure 5.2. From this, it can be seen that the refreshment rate and area affected is the highest when the measure of La Bocana is implemented.



(a) Measure La Bocana **(b)** Measure Juan Angola **(c)** Measure tidal inlet

Figure 5.2: Spatial change in tracer quantity after one month of simulation (baseline model with different measures)

5.2.1. Inlet dimensions tidal inlet la Boquilla

To better see the effect of reopening the tidal inlet up north of La Boquilla, there is another simulation (#7) with a slightly deeper bathymetry. Figure 5.3 shows the water depth profile near La Boquilla for the simulations with standard bathymetry (#6) and a deeper bathymetry (#7).

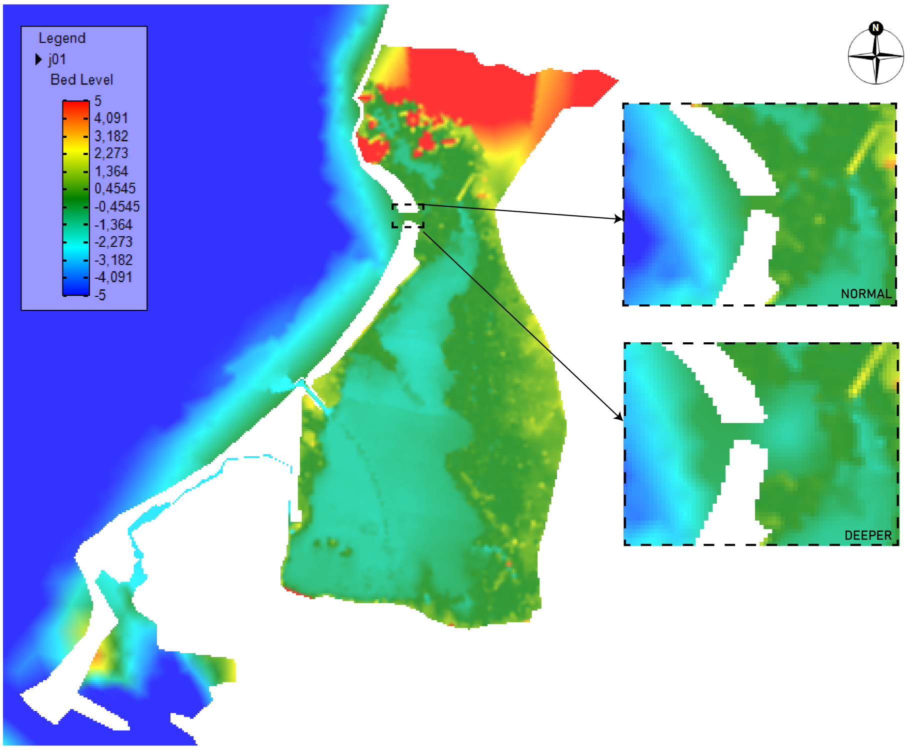
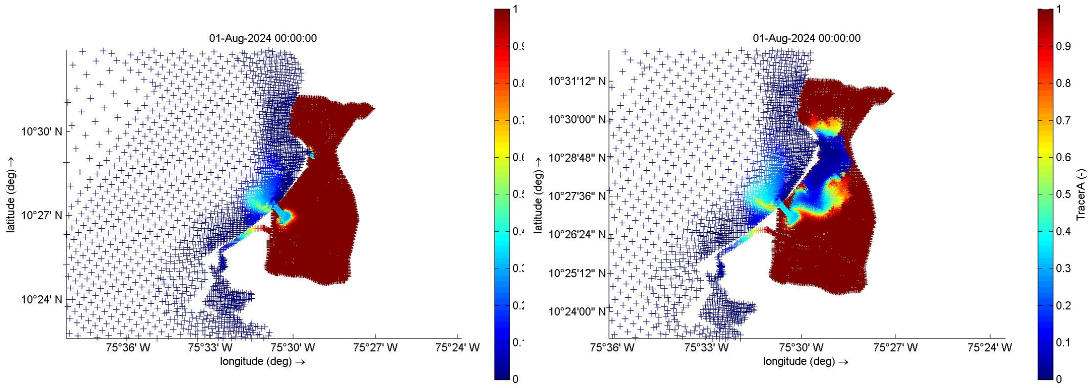


Figure 5.3: Difference in bathymetry for simulations with tidal inlet (max -0.25 m) and a deeper inlet (max -2.5 m) of La Boquilla

The resulting water refreshment at the end of the simulation is presented in Figure 5.4. It can be concluded from the results that the establishment of a considerably large opening at La Boquilla, both in depth and width (max -2.5 m and 80 m), facilitates significant water renewal in the northern part of the Ciénaga, observed in the last tracer value at observation point Cienaga04 (8% instead of 100% left of the tracer) and Cienaga05 (4% instead of 100%). The variation in tracer quantity, linked to the refreshment rate, can be observed in Figure 5.5. From this, one can conclude that the variation in tracer quantity close to La Bocana decreases for the deeper tidal inlet compared to the other measures.
Regarding water levels, a small variation inside the Ciénaga can be observed. The mean water level

rises from 0.00 to 0.01 m and the maximum from 0.09 m to 0.11 m.
However, reopening this tidal inlet is a highly sensitive social and political issue because communities live near the proposed location of the tidal inlet, which raises doubts about the feasibility of this scenario (personal communication with ConAgua team, 2024).



(a) Normal bathymetry (#6, max -0.25 m) **(b)** Deeper bathymetry (#7, max -2.5 m)

Figure 5.4: Water refreshment after one month of the tidal inlet of La Boquilla measure

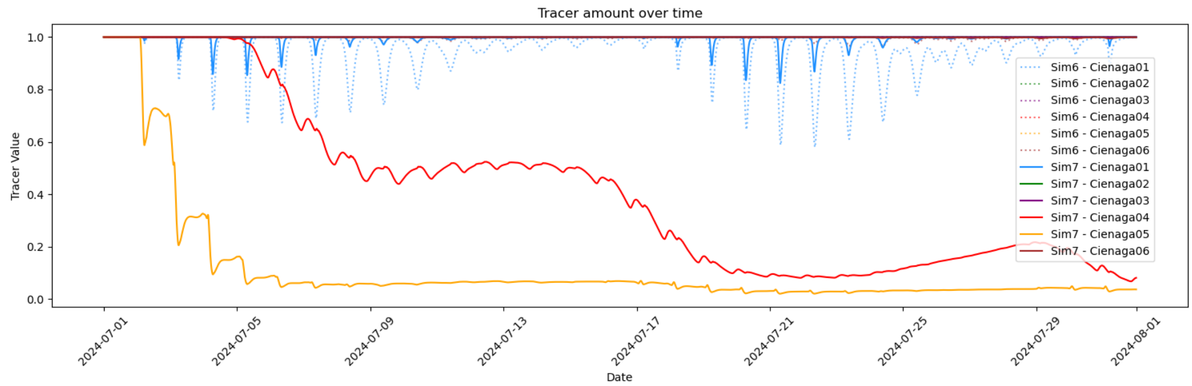


Figure 5.5: Tracer concentration over time for the normal (dotted line, -0.25 m) and deepened (solid line, -2.5 m) reopening of the tidal inlet of la Boquilla (colours correspond to observation points)

5.2.2. Combination of promising measures

Simulation #18: baseline model with a combination of measures

The simulations la Bocana (#2) and the deepened tidal inlet of la Boquilla (#7) showed promising behaviour regarding the water refreshment (mean tracer concentration of 83% and 75%). For la Bocana, the tracer was best reduced in Cienaga01, Cienaga02 and Cienaga03 and for La Boquilla, it is best reduced in Cienaga04 and Cienaga05. Therefore, a simulation is conducted by combining these measures.

The effect of both openings, restoring La Bocana and enlarging La Boquilla, at the tracer can be observed in Figure 5.6. For the simulation with only the deeper tidal inlet of La Boquilla, more points were flushed better. For this combination, only observation point Cienaga05 reaches the minimal required flushing. Remarkably, the area around the tidal inlet is flushed less effectively in the combined simulation than in the one without La Bocana, see Table 5.1. This is probably due to the fact that the outlet geometry of La Bocana reduces significantly (#7 vs #18), which alters the flow inside the lagoon going from north to south. This can also be noticed in the water level change with no measure and with la Bocana functioning (#1 and #2, see Figure 5.7).

The maximum water levels inside the Ciénaga do not show significant changes when comparing both simulations. However, the simulation with only the tidal inlet has lower minimum values for the water levels. Regarding the discharges, the discharge through observation points ”BocanaOutside” and ”BocanaMiddle” differ a lot. For the simulation with only the tidal inlet the maximal discharge in ”BocanaOutside” is 60 m^3/s, while for the simulation with La Bocana, this is 25 m^3/s (Figure 5.8). Thus, the total hydraulic behaviour changes and the interplay results in a water refreshment as simulated.

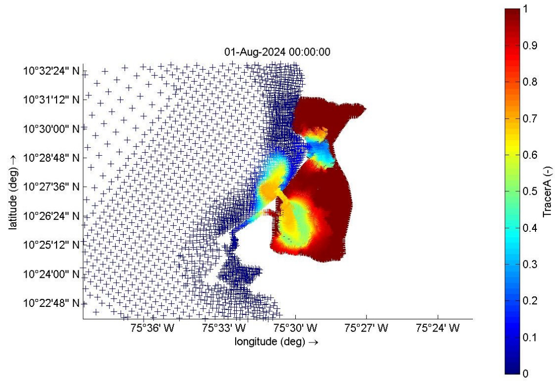
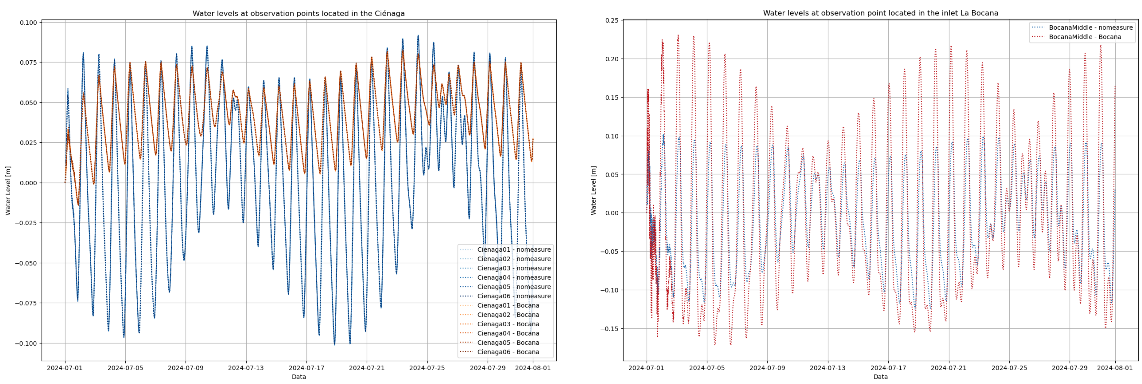


Figure 5.6: Water refreshment after one month of modelling with La Bocana and the deeper tidal inlet of La Boquilla



(a) Changin water level in the Ciénaga

(b) Changing water levels in La Bocana

Figure 5.7: Changing water levels inside the lagoon and in the inlet, due to changing the inlet conditions (blue indicating no measure, red indicating la Bocana, both baseline model)

Table 5.1: Tracer values for the combination of measures

Observation point	La Bocana (#2)		Tidal inlet (#7)		Combination (#18)	
	mean	last[1]	mean	last	mean	last
Cienaga01	0.58	0.67	0.99	1.00	0.60	0.68
Cienaga02	0.71	0.56	1.00	1.00	0.72	0.58
Cienaga03	0.93	0.88	1.00	1.00	0.94	0.89
Cienaga04	1.00	1.00	0.42	0.08	1.00	0.98
Cienaga05	1.00	1.00	0.12	0.04	0.56	0.40
Cienaga06	0.73	0.56	1.00	1.00	0.73	0.56

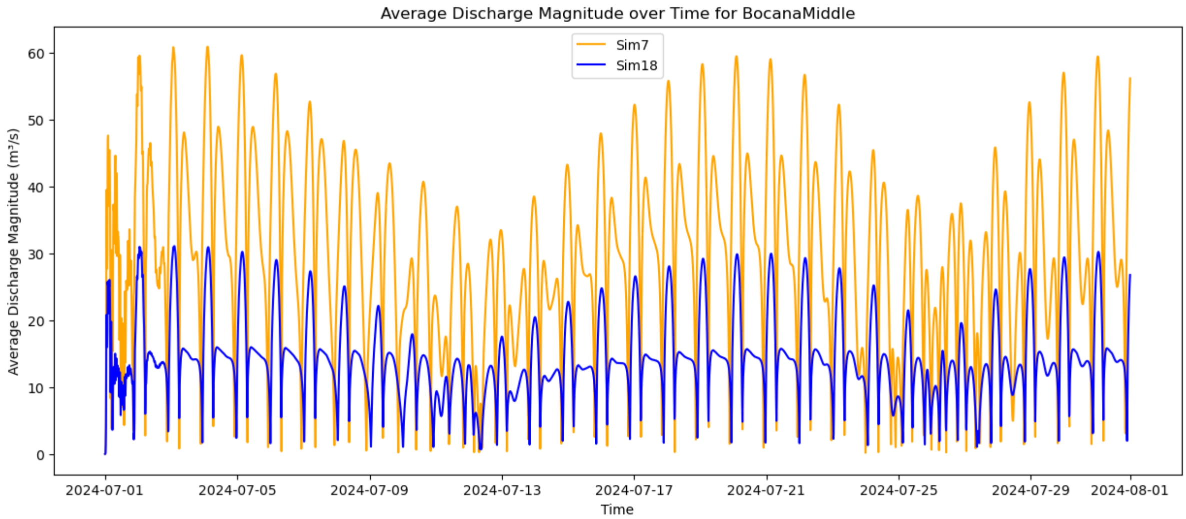


Figure 5.8: Average discharge at observation point BocanaMiddle

5.3. Sensitivity analysis

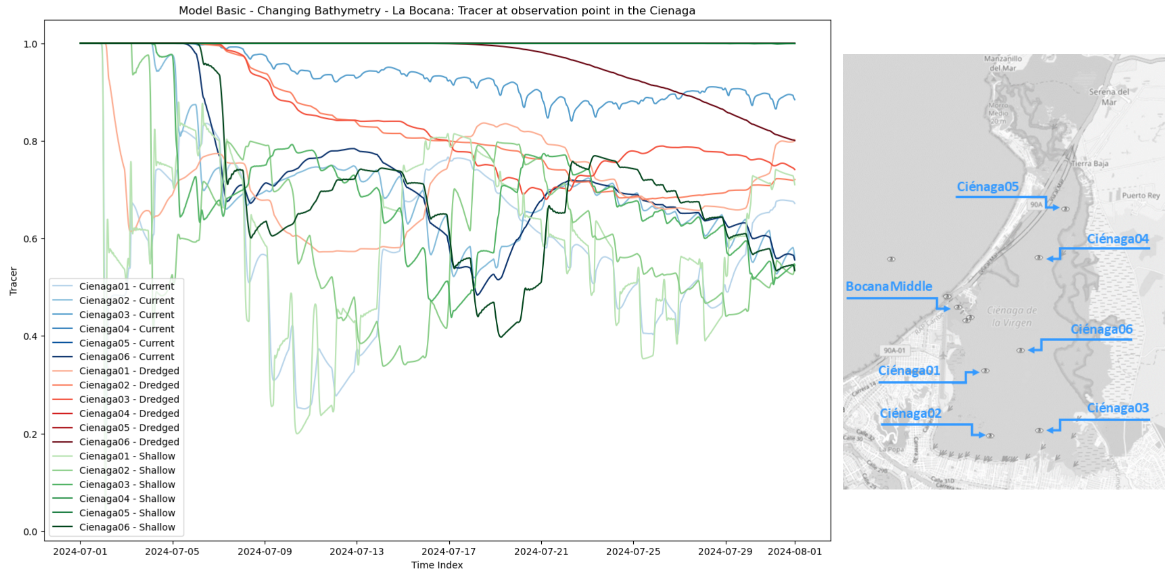
The sensitivity analysis will considered the effects of the uncertainties in the model. Due to absence of (up-to-date) data, some uncertainties arise within the chosen bathymetry, design parameters, the forces applied, discharges and the long-term effect. Furthermore, the effects of having clean discharge and the consequences of a more extended simulation are investigated.

5.3.1. Sensitivity to the bathymetry of the Ciénaga

Simulation #2, #3, #4: baseline model with la Bocana and changing bathymetry

The water refreshment is best in the simulation with the shallow bathymetry, as shown in Figure 5.9. This outcome is logical, as flushing time depends on the volume of the lagoon and the rate of water exchange (Kjerfve and Magill, 1989). The latter is influenced in the simulation of the Ciénaga by the tidal prism and river discharges (gravitational circulation and evaporation are neglected). The river discharge stays the same, but the volume of the lagoon has increased significantly. Therefore, it seems logical that the flushing time increases.

[1]Value of the tracer at the last time step (at the end of the month)



(a) Tracer concentration at observation points **(b)** Observation points

Figure 5.9: Amount of tracer over one month for several observation points within the Ciénaga; the current situation is blue (water depth between -2 to 0 m); the dredged situation is orange (water depth maximal -4.1 m); the shallow situation is green (water depth maximal -0.8 m)

Table 5.2: Mean tracer value of the modelled one month at the observation point within the Ciénaga

Observation point	**Baseline model with no measure**		**Baseline model with la Bocana (water depth between -2 to 0 m)**		**Baseline model with la Bocana and shallow bathymetry (maximal water depth -0.8 m)**		**Baseline model with la Bocana and deep bathymetry (maximal water depth -4.1 m)**	
	mean	**last**	**mean**	**last**	**mean**	**last**	**mean**	**last**
Cienaga01	0.95	1.00	0.58	0.67	0.61	0.71	0.71	0.80
Cienaga02	1.00	1.00	0.71	0.56	0.62	0.55	0.82	0.72
Cienaga03	1.00	1.00	0.93	0.88	0.70	0.55	0.84	0.74
Cienaga04	1.00	1.00	1.00	1.00	1.00	1.00	1.00	1.00
Cienaga05	1.00	1.00	1.00	1.00	1.00	1.00	1.00	1.00
Cienaga06	1.00	1.00	0.73	0.56	0.71	0.53	0.96	0.80
Mean	0.99		0.83		0.77		0.89	

5.3.2. Influence of contraction coefficient La Bocana

Simulation #9, #11: with extreme discharge and La Bocana

The simulation with an alternative contraction coefficient was conducted, given that this parameter influences the flow condition. Therefore, the impact of this parameter must be determined. The mean and max water levels in simulations #9 and #11 are equal. Thus, with respect to water safety, changing the model parameter "contraction coefficient" of la Bocana does not make a difference. The same holds for the last and mean tracer amount; in all observation points, the values do not differ when the contraction coefficient is changed (mean value stays equal to 84% inside the Ciénaga).

5.3.3. Difference with and without wind

Simulation #9, #10: model with extreme discharge and la Bocana with and without wind

According to local expert J.E. Sáenz (personal communication, September 5, 2024), the predominant alongshore current is north to south. Pelgrain and Giraldo (1996), pointed out that during the dry season,

the coastal current is from north to south, generated by swell due to strong trade winds.
However, this pattern was not observed across all time steps, demonstrated in Figure 5.12a. According to Pelgrain and Giraldo (1996), the water circulation is determined by the wind speed and direction (and underwater morphology). According to this source, the coastal processes can be observed in Figure 5.10. Furthermore, the waves along the coast can be observed in Figure 5.11.

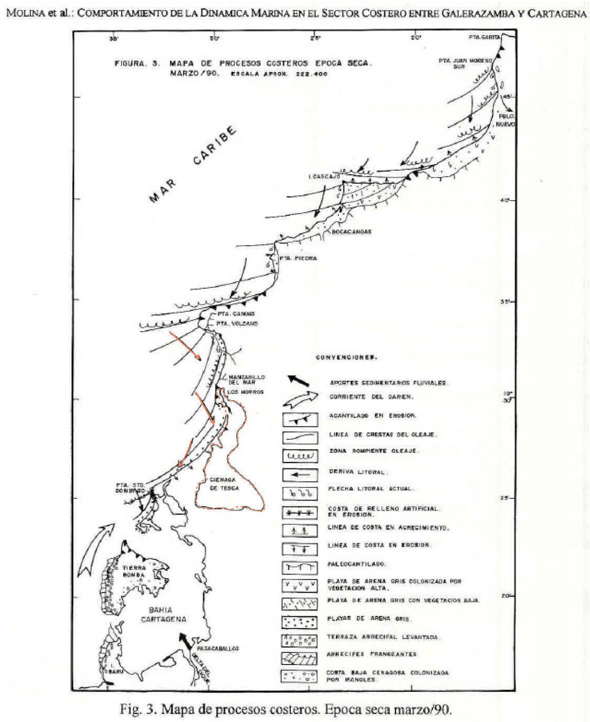


Figure 5.10: Coastal processes (Pelgrain and Giraldo, 1996)

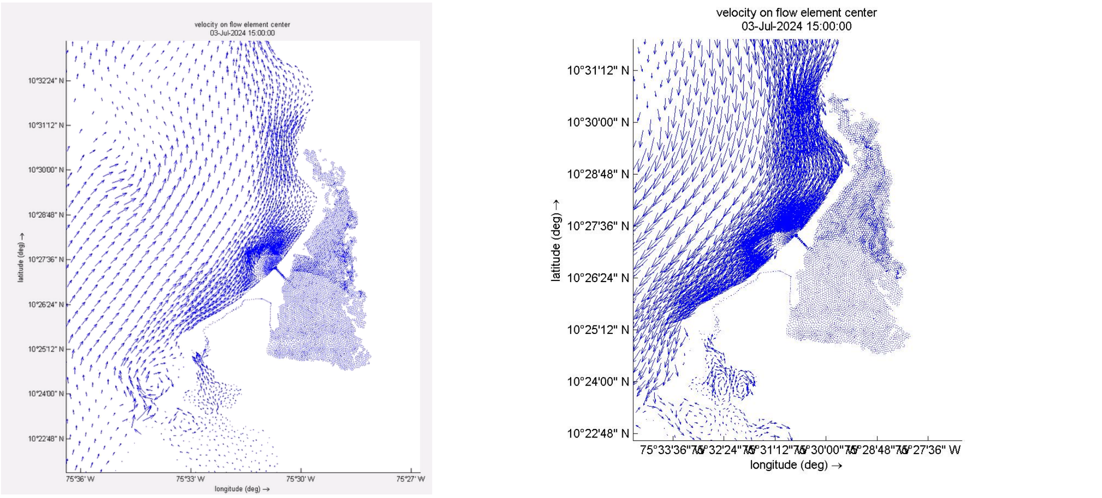
(a) 2009

(b) 2012 (note: the plume formation)

(c) 2024

Figure 5.11: Waves at the coastline of Cartagena (Google Earth, 2024))

Wind is introduced into the simulation, to observe how this alters the water levels and current inside the Ciénaga and evaluate if this is the main force driving the alongshore current in the Caribbean. Given the shallow nature of the lagoon, adding wind to the model is expected to have a significant effect on the amount of water refreshment in the Ciénaga. Remark: With this locally generated wind, the currents in the Caribbean could still differ from the ones influenced by the swell.

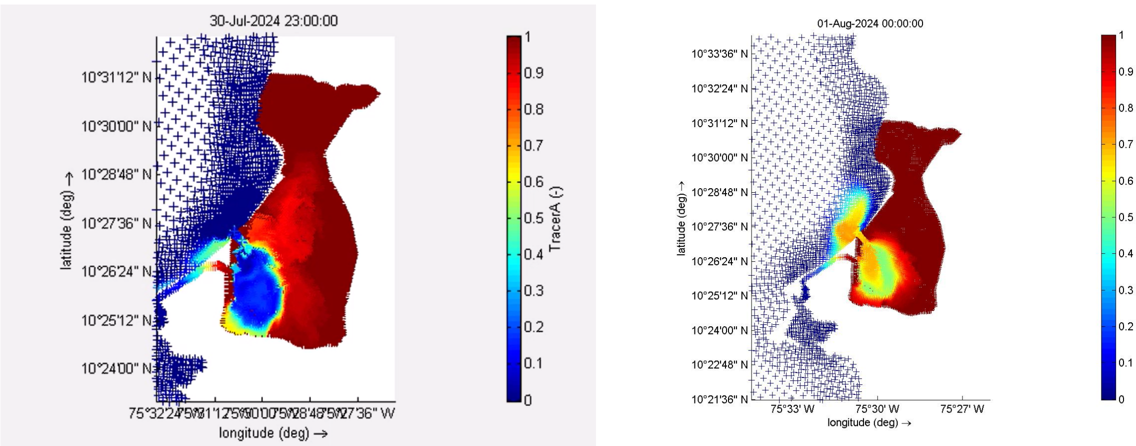


(a) Baseline model with La Bocana, velocity and direction profile snapshot 3 July

(b) Model with La Bocana, extreme discharge and wind, velocity and direction profile snapshot 3 July

Figure 5.12: Velocity and direction of each element in the simulation, snapshot on 3rd of July

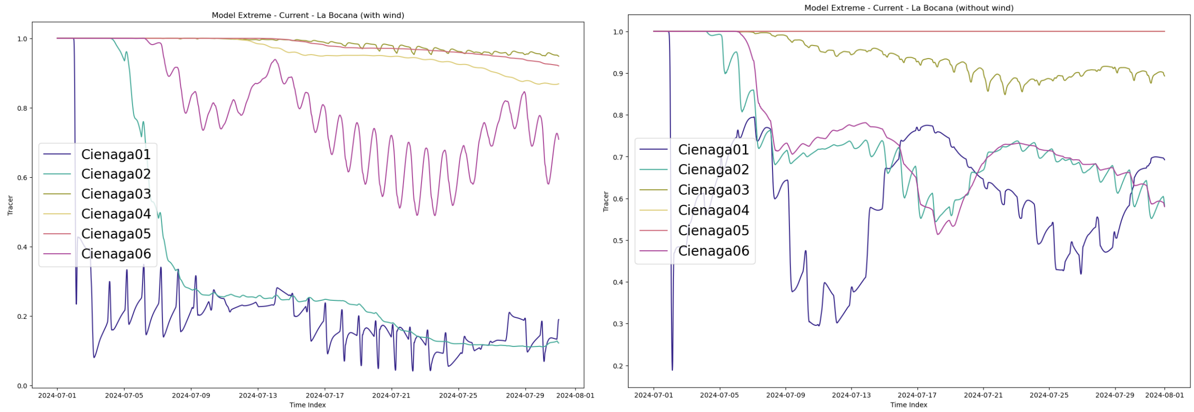
The difference in water refreshment rate with and without wind is illustrated in Figure 5.13 and Figure 5.14. A substantial reduction in tracer concentration south of the directional wall compared to the scenario without wind can be observed. Additionally, a wider spread of reduced water refreshment can be seen, demonstrating enhanced mixing.



(a) With wind

(b) Without wind

Figure 5.13: Water refreshment at the end of modelling period, with and without wind (2.85 m/s and approaching from the North)



(a) With wind

(b) Without wind

Figure 5.14: Tracer concentration over time, with and without wind (2.85 m/s approaching from the north)

Table 5.3: Values of tracer at observation points, impact of wind

Observation point	**With la Bocana and extreme discharge (#9)**		**With la Bocana and extreme discharge and wind (#10)**	
	mean	**last**	**mean**	**last**
Cienaga01	0.60	0.69	0.21	0.19
Cienaga02	0.73	0.58	0.34	0.12
Cienaga03	0.94	0.89	0.98	0.95
Cienaga04	1.00	1.00	0.96	0.86
Cienaga05	1.00	1.00	0.98	0.92
Cienaga06	0.75	0.58	0.79	0.71
Mean	0.84		0.71	

The last and mean tracer values at observation points Cienaga01 and Cienaga02 are sufficiently reduced, meaning below 37%, for the simulation with wind (Figure 5.14).
From this simulation, it can be observed that in the northern part of the Ciénaga, there is almost no reduction in tracer quantity.

Water levels inside the Ciénaga are almost the same at the various observation points, but in the simulation with the wind, a slight difference between the observation points is noticeable. This difference results in a higher water level at the observation point in the southern part (+2mm Cienaga02) and a lower water level at the northern part (-2mm Cienaga05).

5.3.4. Effect of extreme rainfall

Simulation #2, #9: model with la Bocana difference between normal and extreme discharge

The difference in water levels between the basic (#2) and extreme (#9) models can be seen in Figure 5.15. At the rainfall event, a clear rise in water levels is observed. The mean water levels rise from 0.04 m to 0.05 m, and the maximum water level reached goes from 0.08 m to almost 0.15 m in extreme situations. However, this rise in water level is quickly absorbed, after which the water levels are equal again. What is remarkable is the water levels at the different observation points only vary for a few millimetres; in the plot, the lines look the same.

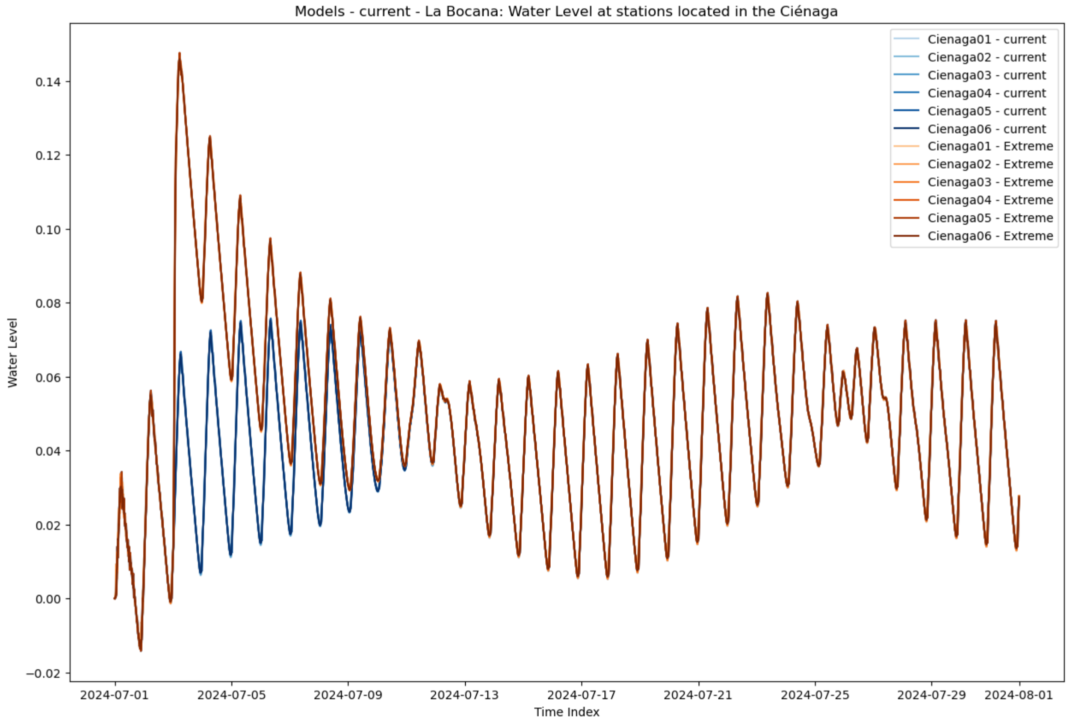
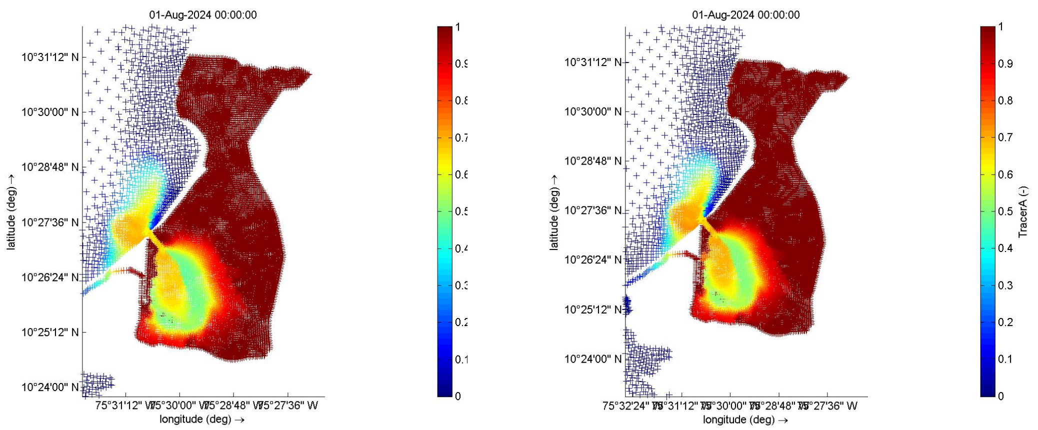


Figure 5.15: Water levels inside the Ciénaga - comparison of baseline model (blue) versus extreme discharges (red) (with and without rainfall event)

The maximum water level reached in the Ciénaga (Figure 5.15) is:

- **Baseline model with La Bocana (#2)**: 0.08 m
- **Extreme rainfall (#9)**: 0.15 m

Regarding the water refreshment, because the urban and rural discharge are modelled as poor quality, a slight increase in tracer amount can be observed for the extreme model (this difference is hardly visible, Figure 5.16). However, when the mean tracer value of the observation points within the Ciénaga are compared, those are almost equal (#2: 83% & #9: 84% tracer left). The observation points for which the tracer is reduced best are Cienaga01, Cienaga02 and Cienaga06, indicating limited movement in the northern part (Cienaga04, Cienaga05) and the southern eastern part (Cienaga03) of the Cienaga.



(a) Baseline model with La Bocana **(b)** Extreme discharges with La Bocana

Figure 5.16: Water refreshment at the end of the model runtime, difference between baseline and extreme discharge

5.3.5. Influence of sea level rise

Simulation #2, #9, #13: baseline model, extreme model and sea level rise with La Bocana system

For the long-term simulation, the initial water level is modified to 0.55 m, to fill the gap between the baseline and sea level rise simulation. In the simulation, only sea level rise (0.52 m) is changed at the boundaries of the model, and the bathymetry is not altered.

The maximum water level reached in the long-term extreme situation with La Bocana is 0.64 m (Figure 5.17). The potential effect of the rise in sea level (+0.52 metres) and how it could propagate in the city is visualised in Figure 5.18. Please note that the absolute elevation uncertainty is relatively high, which may lead to larger areas being inundated or not (results from the combined uncertainty in water levels and elevation map). Figure 5.18 demonstrates that the water safety in the baseline and extreme situations affect the same areas. For the sea level scenario, the area at risk increases significantly, particularly around the urban channels.

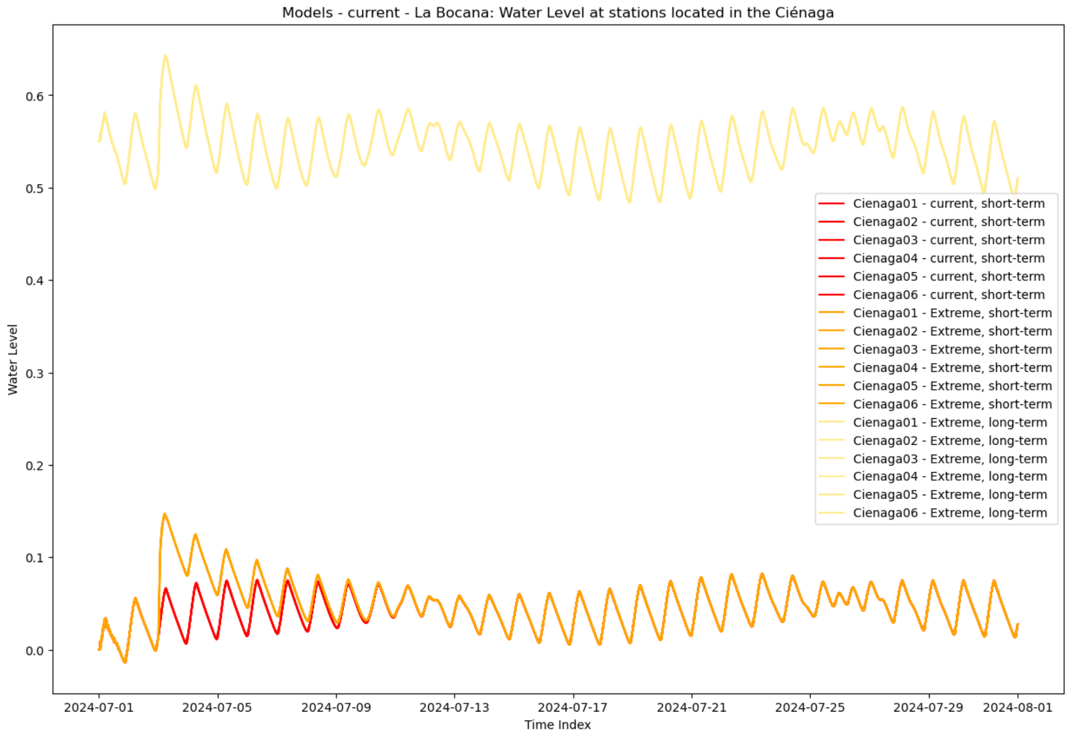


Figure 5.17: Water levels inside the Ciénaga - comparison of basic (red), extreme (orange) and sea level rise model (yellow, +0.52 m)

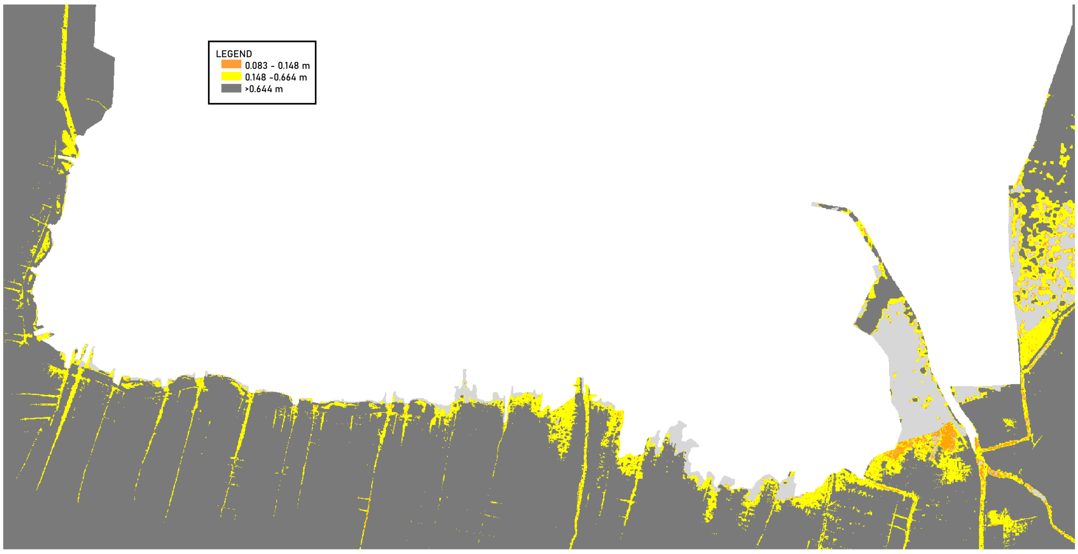


Figure 5.18: Areas exposed to higher risk as a result of inundations (Water levels; light gray is baseline model, orange is extreme discharges (rainfall event), and yellow is with sea level rise and extreme discharges (+0.52 m))

In terms of water quality, due to a bigger tidal prism, the water refreshment improves as the sea level rises, see Figure 5.19 for discharge changes inside La Bocana. At observation points Cienaga02, Cienaga03 and Cienaga06, the last tracer value is below 0.37, and Cienaga01 satisfies the minimal flushing of 50% in one month.

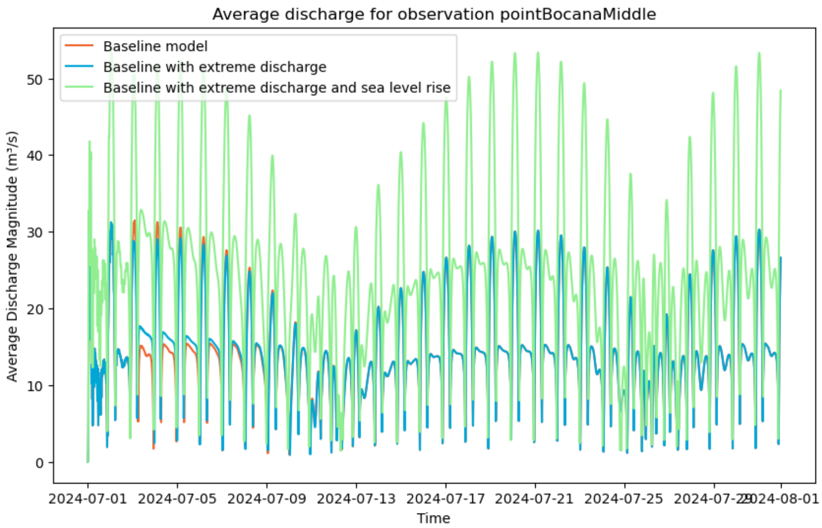


Figure 5.19: Discharge observation point BocanaMiddle for simulation baseline model and alteration with extreme rainfall and sea level rise (0.52 m)

5.3.6. Importance of clean input

Simulation #12: with extreme discharge and la Bocana

Due to the growth of Cartagena, the drainage system is no longer sufficient. Combining that with the fact that interventions in agriculture have resulted in using more pesticides to increase food production (Tudi et al., 2021), the average input into the Ciénaga is of poor quality.

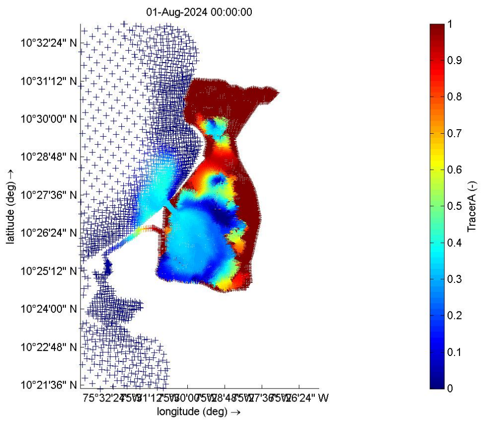
Simulation #12 shows the influence if the discharges into the Ciénaga are of good quality during an extreme rain event (Figure 3.19). This requires a (rainwater) drainage system of sufficient capacity in the city, no wastewater outflow in the Ciénaga, and pesticide-free water from the rural site. This way, the source of the problem is reduced.

From this, one can conclude that if the discharge is of good quality, this has a big positive impact on the water quality. One can conclude that a bigger area is flushed better; see Figure 5.20.

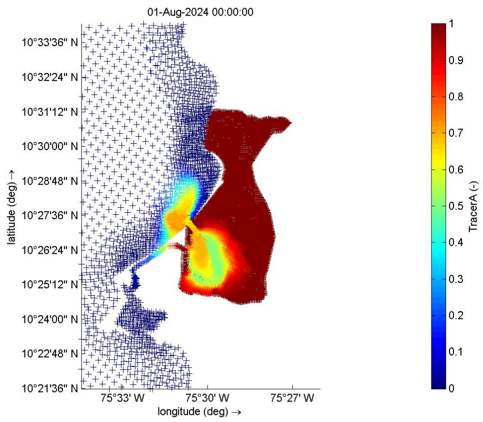
At observation points Cienaga01, Cienaga02, Cienaga03 and Cienaga06, the last value is below 0.37, thus 63% is flushed as preferred.

Table 5.4: Values of tracer at observation points, impact of clean discharge

Observation point	With la Bocana and extreme discharge (#9)		With la Bocana and extreme clean water discharge (#12)	
	Mean	Value at last time step	Mean	Value at last time step
Cienaga01	0.60	0.69	0.46	0.34
Cienaga02	0.73	0.58	0.57	0.31
Cienaga03	0.94	0.89	0.30	0.13
Cienaga04	1.00	1.00	0.66	0.51
Cienaga05	1.00	1.00	0.98	0.93
Cienaga06	0.75	0.58	0.60	0.32
Mean	**0.84**		**0.59**	



(a) Input of clean water



(b) Input of poor quality

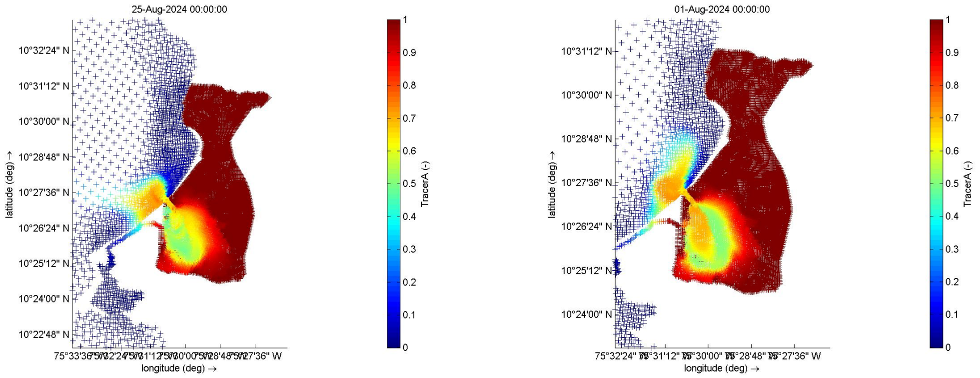
Figure 5.20: Effect of different discharge quality to the water refreshment, snapshot at the end of model

When the Bocana system was completed in the early 2000s, there were a lot of questions about the contamination of the surroundings if the lagoon water was discharge into the sea. According to a news article from 2004 (Gutiérrez, 2004), 90% of the city's sewage water is discharged into the Ciénaga, and also solid waste ends up in the Lagoon. However, the measured values showed that the water leaving the lagoon was of sufficient quality. Still, a good sewage system and the capture of solid waste should be safeguarded within the Lagoon. The water flushed into the sea should be monitored to guarantee sufficient quality outside the lagoon.

5.3.7. Longer runtime

Simulation #17: with extreme discharge and la Bocana

For the simulation with a longer runtime, one can notice that the tracer gets better reduced close to the entrance of La Bocana. But overall, there is not much difference. The water refreshment stays in the southern part of the Ciénaga. The mean tracer value for one month is 0.84, and after two months, this is reduced to 0.82. It is expected that the tracer value keeps reducing, but the effect remains local.



(a) Longer runtime, two months

(b) Baseline model, one month

Figure 5.21: Visualisation of water refreshment at the end of one month versus the end of two months

5.4. Main findings

The main findings of the simulations are:

- The water safety, regarding the Ciénaga de la Virgen waterbody, does not face significant long-standing problems. This means that surface water levels stay beneath the threshold value of 0.2 m. This holds for flood risk due to the rise of the Ciénaga itself;
- For most scenarios, the water is not refreshed sufficiently (i.e. below 37%). Most measures only affect the local conditions. The water quality, especially in the northern and southwestern parts of the lagoon, continues to be worrying (for most scenarios the tracer stay roughly equal to the initial value);
- Adapting the bathymetry results in different water levels in the Ciénaga. The shallow bathymetry deviates the most; in this simulation, water levels remain lower on average. The water refreshment rates differ depending on the bathymetry. A greater depth resulted in a higher flushing time;
- An advanced model that more accurately reflects real-world conditions could have significantly different water quality and safety outcomes;
- Wind forcing is an important parameter due to the enhanced mixing it promotes. This importance is encountered when a long period without wind occurs, resulting in insufficient mixing across the lagoon;
- If the incoming discharges from the rural and urban sites are used for flushing (i.e. clean water discharge), the tracer is reduced much faster. This will have a beneficial impact on the local ecology and the health of the residents.

The link between the results from the simulation in Delft3D and the literature on lagoons, in general, is reflected in Chapter 6 and 7; this chapter solely represented the result of the simulation.

6 Discussion

The study revealed that the water levels within the Ciénaga remained unchanged as a consequence of the implemented measures. The sole notable increase in water level was observed in the scenario wherein sea level rise was taken into account. It can be concluded that the measures in question do not have any negative impact on water safety. Regarding water quality, the water refreshment rate has not been sufficiently improved. None of the measures flush all parts of the lagoon more than the set requirement of 63% in one month. This chapter discusses these findings concerning the literature. It also discusses the effects of the limitations of the data and the assumptions within the model.

6.1. Agreement with literature

The requirements for water quality, meaning tracer reduction of 63%, were often not met. In contrast, the water safety of the Ciénaga requires less attention because it suffices, as stated by the requirements. However, there are also other factors crucial for the proper functioning of the lagoon (Chapter 2.2).

The preferred water depth for attractive lagoons (> 2 metres, Mangor et al. (2008)) is solely satisfied by the dredged bathymetry situation. However, this dredged scenario did not show the best tracer reduction, and although all bathymetry scenarios satisfy roughly the maximum water depth for flushing (< 4 metres, Mangor et al. (2008)), the required tracer reduction was never reached.
An additional problem for realising the dredged scenario is that when the activities occur, it is crucial to ensure the safety of both the disposal of the dredged material and the dredging process itself because it could be that the dredged material is contaminated, given the current state of the lagoon.

Furthermore, more than one connection with the sea is required to ensure sufficient flushing (Mangor et al., 2008); this is satisfied in the combined case with the tidal inlet at la Boquilla and the opening at La Bocana, but still, the flushing remained local. Next to the number of inlets, the inlet must be stable. This implies less sedimentation (Mangor et al., 2008), which is only accounted for in the measure of La Bocana. However, regular dredging is needed to keep a stable inlet due to sediments.
For the inlet, the dimensions also matter. The larger the inlet dimensions, the less the ocean tides dampen towards the lagoon.
Another indicator of a healthy lagoon is the offshore plume formation; small plumes indicate short residence times. It is hard to evaluate this since small plumes have no specific boundaries. In the scenario with wind, the plume seems smaller than in the other scenarios, indicating an improved residence time. However, the wind has the most significant impact on water quality, as it distributes polluted water rapidly towards the south, thereby allowing only clean water to enter the lagoon. The scenario with la Bocana properly functioning gives larger plumes than without this system, indicating a worsened residence time; however, the overall quality of the lagoon seems to improve, which contradicts this requirement.

The measure with Juan Angola and the Matute watershed partly covered the effect of pollutant-free discharge. The importance of the discharge being clean was modelled in simulation #12 (Touza et al., 2021). This has a direct positive impact on the Ciénaga, and it prevents further pollution of the Ciénaga.

Moreover, eventually, it will prevent polluted water from entering the Caribbean Sea. Addressing these discharge qualities, as big as the challenge of adapting the measures itself, is beyond the scope of this report.
Another requirement for healthy lagoons was sufficient clean freshwater input, to ensure mixing and no discharge of pollutant into the lagoon. However, sufficient is challenging to define. Compared to the total volume of the lagoon ($11 * 10(^6)\,m^3$), the freshwater discharge seems low (dry season $5.2\,m^3/s$); thus, mixing inside the lagoon stays limited. It is complicated to enlarge or control this discharge.

Regarding water safety and flood risk, the probability and impact of a flood event are usually considered. Within this study, the water level changes are analysed and compared to the city's elevation, which is a shortcoming for a proper assessment. In addition, the literature has shown that there are floods in the city, but this was not visible in the simulated water levels. This can be partly explained by the fact that other processes mainly cause the floods, such as the limited drainage capacity of the city.

6.2. Limitations data

The limited amount of data introduces major uncertainties but also makes it hard to define indicators for water safety and quality. In Chapter 3 & 4, the used data is displayed, the effects of the limited data are manifested in the following points.

In general, the model should be better validated. This can be achieved by conducting more accurate measurements of relevant variables, such as water levels offshore and inside the Ciénaga, which must be conducted. Knowing the discharge going through la Bocana is also helpful. The measures should be obtained during a whole tidal cycle for the critical month of the specific indicator. This would allow a more precise assessment of the model, thereby providing a more accurate reflection of reality.

In terms of the defined indicators, the refreshment rate and water levels within a month were evaluated. However, flood events with a return period of 100 years are usually considered for water safety, but it was hard to incorporate those events due to the limited amount of data. Furthermore, the flood risk analysis is complicated by the influence of geotechnical parameters, which have not yet been taken into account. The soil subsidence or erosion of the outer banks could already have a significant impact. The absence of change in water level does not exclude flood risk. It is essential to evaluate geotechnical processes. Flood risk can also pose a problem in the city due to the limited capacity of the drainage system (as indicated by Wakker (2024)). Likewise, especially in the la Boquilla area, coastal erosion could pose problems regarding water safety.
For water quality, other parameters should be observed as well, such as the oxygen levels, nutrient amount, salinity, temperature of the water and the amount and variety of flora and fauna. The current condition of the Ciénaga is estimated to be very poor. It is important to quantitatively determine the current state of the water quality of the lagoon and the quality of the inflow of the Caribbean Sea. Futhermore, the effects of a higher refreshment rate must be monitored because it may increase the water salinity, which could have a negative impact. Between 1990 and 1995, a salinity increase in a similar system, Ciénaga Grande de Santa Marta, resulted in mass fish killing and mangroves dying off. These kinds of negative consequences must be avoided.

6.3. Limitations model

The model simulation is subject to several limitations due to underlying assumptions. These are listed below and discussed in more detail afterwards (Chapter 4.3).

- Simplification towards a two-dimensional process
- Model's runtime
- Selected month for the tidal simulation
- Incorporated forces (only tides)
- Additional adjustments in Sea level rise scenario
- Simplification water balance

In the Delft3D model, the processes are assumed to be two-dimensional because depth averaging is applied. The effect of this simplification is minimal because of the shallow nature of the lagoon. It is expected to be well mixed. It is further assumed that the Ciénaga is completely polluted, whereas the Caribbean Sea is considered clean. However, this distinction will not be as clear-cut in reality.

The model's runtime could be too short, which could exclude extreme water levels offshore. Furthermore, it is possible that the required flushing time cannot be met within one month. Generally, a lagoon turnover time can vary between 10 and 100 days if tidal prism and river discharge are important factors of refresh rates (Kjerfve and Magill, 1989). After the original construction of La Bocana at the beginning of this century, it was expected that it would take months to a year to clean the Ciénaga. This period was based on a two-dimensional hydraulic model with the influence of the tides, with the requirement that the BOD (Biochemical oxygen demand) must be less than 6.5 mg/L (*Stabilized tidal inlet, Cartagena, Colombia*, 1995). However, Moor et al. (2002) claims that after constructing La Bocana, the Ciénaga had reached its desired state within three weeks.
The lagoon is still highly polluted; thus, the runtime of one month could be too short to obtain a Ciénaga with adequate water quality. However, the scenario which ran for two months suggested no significant difference from the simulation for one month. Therefore, it is concluded that with the current measures, the maximum possible reduction of the tracer will be reached in one month.
The effects of opening La Bocana were local. Still, they did show the significance of creating a water circulation that maintains the clean water inflow and the withdrawal of contaminated water. In simulations without the good functioning of the La Bocana system, the clean water entering the lagoon immediately leaves the lagoon as the tides change. The required runtime for completely flushing is doubtful, if other extremes or measures are considered the runtime should be extended to evaluate the effect.

Another simplification within the model is the chosen month; to visualise water safety and quality processes, the same month was modelled. The tidal range in the Caribbean Sea is small; however, monthly differences may occur, but it is expected to stay within the range of a few centimetres (Cubit et al., 1986). If monthly variation proves to be true, the crucial month is expected to vary depending on the indicator considered. The most critical month for water refreshment is a calm and warm month, whereas it is the opposite for water levels, namely extreme weather. Even more so, for water safety, one has to evaluate extreme moments in time, while water quality can better be observed daily. Although it is expected to have a limited influence, this seasonal variance must be examined more closely. Currently, it is chosen to model July since it does not favour water safety or quality. The chosen July is valid for the coming 50 years; thus, it represents an average month. This was also observed in the comparison with other observation points. The tides are modelled for the month of July; other variables, such as rain and sea level rise, do not depend on this chosen month. Thus, the limited monthly variation of the tides and the limited processes depending on this month suggest that the effects of this simplification are limited.

Other limitations are the physical processes incorporated in the model; solely tidal forcing is implied within the baseline model. Effects of the wind are shown to have a significant influence on the lagoon. Therefore, other processes that were not considered could also be important, such as the effect of El Niño-Southern oscillation. This issue requires further attention.

Another shortcoming is within the scenarios incorporating sea level rise. To account for the effects of sea level rise, the initial water level and mean sea level are changed in Delft3D. The effects are directly imposed. In reality, this process will happen more gradually. Furthermore, other parameters must also be adapted, such as bathymetry and elevation of Cartagena, but these stay the same.

In the water balance, the discharge regarding groundwater seepage and evaporation are neglected. This is done to reduce the complexity of the model and due to the limited data available, but it is acknowledged as an important factor.

6.4. Limitation measures

The feasibility of realising the measures must also be taken into account, this is especially important for the measure at la Boquilla. Due to the community living at the former la Boquilla site, reopening the tidal inlet may not be possible. Therefore, one could explore the possibilities for an artificial connection with pumps. This artificial connection would not pose additional flood risks compared to a tidal inlet, given that it can be closed and opened manually.

Furthermore, the effects of the measures were simplified, raising questions about the extent to which the simulation after implementation of the measure accurately reflects the real behaviour of the lagoon. This, in turn, complicates the evaluation process. For example, the expected effects of the Matute watershed were evaluated solely in the simulation involving extreme rainfall due to simplifications of the impact. Further investigation must be conducted into the consequences of the simplified measures.

6.5. Concluding remarks

Despite the limitations, new insights were gained on the functioning of the Ciénaga and the response to the measures. The importance of freshwater input and the circulation provided by La Bocana were visible. Next to that, the simulations showed that the wind force in this area is crucial, as is the tidal force. On the other hand, the simulation showed that the influence of extreme discharges remained limited.

In general, the quality of a lagoon can be assessed with minimal data. This will provide a better understanding of the measure's impact. However, it can be concluded that more data will represent reality better and give a more reliable evaluation. Due to the complex behaviour of coastal lagoons, it is hard to assess a lagoon's health based on requirements in literature; every lagoon is unique. With limited data (tides and geometry), it is possible to evaluate fundamental concepts such as flushing time, which provides a good insight into the water quality. Therefore, a hydraulic model such as Delft3D can be a favourable tool for assessing the quality of lagoons worldwide. Nevertheless, for the purposes of water safety, a greater quantity of data is required.

7 Conclusion

This report aimed to evaluate various measures to improve complex lagoon systems' water quality and safety. Answering this research's objective was made manageable by dividing it into four sub-questions.

1. Which natural processes influence the water distribution in the Ciénaga now and in the future?

The Ciénaga is the main waterbody in this system, it can be classified as a large, shallow lagoon with limited discharges. Despite the limited discharges, there are some processes influencing the lagoon's water balance, such as the tides, wind and freshwater input.

Tidal forcing is an important parameter influencing the behaviour inside the Ciénaga. However, due to the limited tidal range, the effects of the tide are limited. The greatest impact of the tides is visible close to the inlet locations, therefore, the tides and geometry of the connection are important.

The wind forcing showed to be an important parameter as well. It enhanced mixing inside the lagoon, which is positive for the water refreshment rate. Subsequently, it altered the plum directions (snapshots in Figure 5.13). Therefore, wind is another essential parameter for the transport outside and inside the Ciénaga.

The wind produces waves, and the tides create a current, the key factors for mixing in shallow lagoons. They provide mixing, which is relevant for the flushing time.

In the future, the effects of potential sea level rise may also be observed in the Ciénaga, where water levels are expected to increase. This consequently poses a significant risk to the water safety. Furthermore, due to climate change, more extreme weather events will occur, which influence the wind and rain discharge among others.

2. To what extent will the measures affect the hydraulic behaviour of the Ciénaga?

Several measures are considered to improve the water system of the Ciénaga.

In summary, the measure restoring the La Bocana system involves implementing gates that function with the tides, a directional wall within the Ciénaga to provide circulation, and breakwater into the Caribbean Sea. It restores the connection with the Caribbean Sea, altering the effects of the tides inside the Ciénaga.
The Juan Angola measure facilitates clean discharge and sufficient capacity of the city's drainage system. The floodgates included in this measure also affect hydraulic behaviour.
The Matute watershed measure ensures clean discharges and facilitates the collection of (rain)water during periods of extreme precipitation.
Reopening the tidal inlet at la Boquilla ensures another connection with the Caribbean Sea, which improves the refreshment rate.

Both measures, La Bocana and the tidal inlet at la Boquilla, alter the connection with the sea and, therefore, the tidal forcing. The tidal inlet provides an extra connection compared to the current situation. Because of this, it can be expected that the tidal influence is greater in the northern part of the Ciénaga. The restoration of the la Bocana system generates enhanced circulation inside the Ciénaga. This initiates a current in the lagoon, and the water will be distributed further in the southern part of the lagoon.
Both measures improved the local refreshment rate significantly.

There are additional benefits to some measures. The Juan Angola and Matute watershed measures also enlarged the city's drainage capacity.
Other benefits are the sluice gates in la Bocana and Juan Angola, which can also act as floodgates during extreme events in the Caribbean Sea.

Adapting the Juan Angola channel and the Matute is expected to influence the hydraulic behaviour of the Ciénaga barely.

Previous studies in this specific area looked into the city's drainage capacity. Combining this report with these studies gives a better understanding of the whole system. From this, it can be concluded that the most significant improvement regarding water safety can be made by enlarging the capacity of the city's drainage system.

3. Which measure or combination best reduces the area's flood risk and improves the water quality for the chosen indicators?

The flood risk is analysed by simulating the water system and analysing the water levels. Within the current situation, the water levels were almost equal for the different measures, indicating no reduced or increased flood risk. However, for the simulation with sea level rise (+0.52 m), the max water level (0.64 m) and the mean water level (0.54 m) increased significantly, but this was true for all measures. Water safety is therefore of greater urgency when the sea level rises and should be monitored; therefore (extra) measures should be taken to prevent flooding in the future. The measures of La Bocana and Juan Angola contain gates which can be closed off during extreme events to prevent the hinterland from flooding. These measures best reduce the area's flood risk. On the other hand, the measure of the tidal inlet at la Boquilla could increase the flood risk since it provides an extra open connection with the Caribbean Sea; this effect will be influenced by the tides and/or wind. This was not explicitly modelled in Delft3D.

The water refreshment rate is not sufficiently reduced across the lagoon in any simulation. However, there are simulations in which, at some observation points, the water refreshment is locally reduced sufficiently. Therefore, a combination of measures is needed to ensure the lagoon has proper water quality.
The measures restoring la Bocana system showed locally a significant improvement regarding water refreshment because of the circulation it provided. The circulation ensured that clean water from the Caribbean was not immediately leaving as the tides changed. The effect of la Bocana was only noticed in the southern side of the Ciénaga.
The same holds for the opening of the tidal inlet at la Boquilla; the tracer was reduced significantly, but only for the northern part of the Ciénaga.
For the other simulations, the tracer is not reduced at all, or the tracer was still 95% at the end; if it continues with this rate, it could take years to refresh, but it is even more likely that if nothing happens, several parts will not refresh at all.

The findings from the sub-questions were used to answer the main research question, which reads:

"How will the selected measures influence the flood risk and water quality of the Ciénaga de la Virgen?"

Water safety

Regarding flood risk, the simulations did not show significant water level changes inside the Ciénaga. For most simulations, the water levels across the Ciénaga were almost equal over time (partly explained since wind was not taken into account). The only significant effect on flood risk comes from sea level rise.

A lagoon is generally sensitive to fluctuations in sea level due to its shallow characteristics. Therefore, the rise in sea level ensures a rise in water levels in the Ciénaga.
In conclusion, it can be stated that the measures do not negatively influence the water levels in the short term and do not increase the risk of flooding. For the city's flood risk, prioritising the limitation of coastal erosion and enhancing the city's drainage system is of greater urgency. The enlargement of the city's drainage system is partly covered by the Juan Angola and Matute watershed measures. The enlargement of this system can result in larger discharges in a short time frame. Which could result in a rise of water levels in the Ciénaga, negatively influencing the water safety.
The measure of La Bocana with the lock system could safeguard the lagoon from extremely high water in the Caribbean Sea in the long term, as do the gates in the Juan Angola Channel, since they can be closed during extremes. On the other hand, the reopening of the tidal inlet may present an additional risk concerning water safety.

Water quality

With regard to water quality, the simulations did not show an adequate increase in the quality with respect to the water refreshment rate. However, the separate measures containing La Bocana and a deep tidal inlet at la Boquilla demonstrated a notable improvement in water quality locally compared to the alternative of taking no action. The combination of these measures did not result in the anticipated outcome. Nevertheless, it did demonstrate the importance of having multiple exchange points since the effects of the measures stayed local.
To conclude, the influence of the measures on the refreshment rate was limited, and only locally positive impacts were noticed.

The most significant impact on water quality observed was due to improving the discharge quality into the Ciénaga. A completely uncontaminated input showed an enormously increased water quality in several lagoon parts due to the reduced tracer amount. This highlights, the importance of addressing the problem at its source. The measure containing the Juan Angola Channel and the Matute watershed could improve the adjacent area's drainage system, but more action is needed to safeguard clean water discharge. Additionally, due to the low refreshment rate and mixing within the Ciénaga, having a clean input is even more important.

The simulation with wind showed the importance of including more natural processes and creating a model which better represented the real-world situation. This simulation, due to the enhanced circulation it provided, had a beneficial effect on the water refreshment rate. Next to the impact inside the Ciénaga, the wind influenced the offshore plume's direction. With this plume constantly moving southwards, the poor quality water leaving the system was diffused and mixed quicker, and the water entering the lagoon system was nearly always of good quality.

General

It can be concluded that with limited data, the water quality and safety of a lagoon can be assessed, and Delft3D is a powerful tool for achieving this. Based on the lessons learned within the Ciénaga system, the importance of parameters such as the tides, bathymetry, geometry, freshwater input and wind was demonstrated. For this, data is necessary, and more data will reduce uncertainty. For initial estimations, the present state of the previous parameters should be prioritised. After that, other parameters can be included as well.
The simulation showed that mixing inside the lagoon is important for the water quality, which is satisfied by plenty of freshwater input and much tidal mixing (and wind forcing). The latter can best be ensured if the lagoon has multiple connections with the sea because many measures only had a local impact. Moreover, measures to stimulate the circulation inside the lagoon are relevant and needed. In some lagoons, the effect of wind may be sufficient to enhance mixing, while in others, extra action is needed. The last thing is to supply sufficient clean freshwater input to improve the water quality; that way, pollution is tackled at its source. Moreover, this ensures that eventually, the discharge of polluted water into the Caribbean Sea is eliminated.
For water safety, it is better to evaluate other parts of the lagoon environment, such as the drainage capacity, the stability of the coastline or the secondary effects of high water levels at the lagoon itself (e.g. backwater curve, lower discharge possibilities). The mean water levels offshore and inside the lagoon corresponded, but the maximum levels inside the lagoon were reduced, as expected. It is

important to analyse if the lagoon can cope with extreme events; for example, can it be closed off from the main water body during extremes, or can the flora and fauna still thrive when it is partly inundated or drained during droughts?

In short, with limited data, it has been proved that the measures considered for the Ciénaga do not negatively influence water safety. Whereas, regarding water quality, the desired state is never reached. Valuable insights can be gained from limited data on lagoons worldwide. Water safety will be a more complex problem to assess. However, as lagoons are often large, shallow water bodies, it is essential to consider the influence of the wind, freshwater discharge, and the connection with the sea for water quality. Usually, a high refreshment rate is needed to obtain a healthy lagoon, which can be achieved by either large freshwater discharge, multiple connections to the sea, or a combination of both.

8 Recommendations

The recommendations for the consortium ConAgua are to gather more up-to-date data and make more elaborate models to make a proper statement about the lagoon's health. The difficulties in making a proper statement arise from the simplifications within the model, the difference with the literature and the fact that some parameters were not known at all.

The consortium should also model other combinations. The simulation with the combination showed that the whole hydraulic behaviour was altered, so it is more complex than just the summation of the effects of the individual measures.

Another simplification can be attributed to the land-lagoon boundaries, especially in the eastern part, which are modelled as rigid boundaries. Still, due to changing water levels, these boundaries will also vary over time. This is not accounted for in the model.

The literature and experts mentioned a main alongshore current from north to south, but this current could not be retrieved in all time steps in the simulation. Thus, the main driving force is probably not local and is still missing; this needs further investigation. Therefore it is important to monitor coastal currents; this can be done by measurements or by analysis of satellite figures.

It is recommended to gather the current bathymetry data since the simulation showed a sensitivity to the changing bathymetry with regard to the tracer reduction.

For some parameters, no data was available at all. For example, the water quality is solely evaluated based on the water refreshment rate. The freshwater balance (salinity), the ecological effects (amount and variety of flora and fauna), and dissolved particles are missing and should all be observed or measured to determine the ecological impact and the optimal environment of this coastal lagoon.
For water safety, it is useful to have more data about the real-time water levels inside the Ciénaga, especially near the inlet and near the southern bank. This is necessary to validate the model and to compare it directly with the elevation levels of the city regarding flood risk. A more up-to-date elevation map of the city is also required. Subsequently, the discharge going through the inlets is important. This gives insights into variables such as the amplitude damping of the tides offshore.

It is advised to gather those data before being able to make an appropriate decision on what measure to prefer. The simulations, and therefore the conclusion in this report, could also be validated with more data.

Subsequently, it is advised to keep monitoring after the installation of the measures. This monitoring should be performed over multiple seasons, as well as daily, in order to capture both tidal and seasonal variations. It is also important to monitor the discharge quality into the Caribbean Sea to mitigate the negative flushing effects.

In general, it is advised to simulate a variety of coastal lagoons due to the complex behaviour to establish more standardised requirements for maintaining healthy lagoons. The more lagoons, the more similarities can be discovered to understand better what factors are crucial for their health.

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A

Discharge baseline model

This appendix justifies the discharge used in the baseline model, for the wastewater and gives the coordinates for the discharge points.

A.1. Coordinates discharge points

The coordinates of the input sources in the Delft3D model can be seen in Table A.1 with the maximum value for the discharge and the value for the tracer when there are no measures considered, default value.

Table A.1: Coordinates discharge point baseline model[1]

What	Latitude	Longitude	Latitude	Longitude	Discharge $[m^3/s]$	Tracer $[kg/m^3]$
Wastewater	10°24'55.14"N	75°29'51.18"W	10,4153	75,49755	1.4	1
Wastewater	10°25'40.28"N	75°30'41.67"W	10,4279	75,51157	1.4	1
Arroyo Caño Mesa	10°29'54.36"N	75°29'6.44"W	10,4984	75,48512	0.077	1
Arroyo Tabacal	10°28'0.01"N	75°28'58.01"W	10,4667	75,48278	0.42	1
Arroyo Hormiga	10°26'52.01"N	75°28'43.00"W	10,4478	75,47861	1.885	1

A.2. Wastewater

First of all, the discharge of wastewater coming from the city into the Ciénaga is considered to be $10,106\,m3/hour = 2.81\,m^3/s$:

The population of Cartagena in 2024 is 1,096,463 (World Population Review, n.d. in combination with the fact that in developed countries, a person uses $300 - 380\,litres [= 0.3\,m^3]$ of wastewater per day (Ecoseptic, n.d.).

$$Discharge_{wastewater} = population \times wastewater$$
$$Discharge_{wastewater} = 1,096,463 \times \frac{0.3}{24} = 12,500\,m^3/hour$$

[1] Discharges are kept constant the whole model period

B

Discharge extreme rainfall

In Table B.1, the extreme discharge are mentioned. For the urban side, the rational method (Uijlenhoet and Ent, 2024a) is used to see if the values from this source appear to be logical since the catchment areas of those channels are less than $1km^2$. However, the catchment areas used in this calculation are also obtained from EDURBE (2023). Those watershed areas can be observed in Figure B.2. Next to that, there are some other simplifications within the rational method. For starters, the method assumes that the storm duration is equal to the time the water takes from the most remote point in the watershed to the outlet. Next, the intensity is uniform over the watershed and the duration. And, the runoff conditions do not change over time.

$$Q = C_f \times C \times i \times A \tag{B.1}$$

In which:

- Q: Storm runoff [m^3/s]
- C_f: Runoff coefficient adjustment factor to account for the reduction of infiltration and other losses during high-intensity storms [$-$]
- C: Runoff coefficient to reflect the ratio of surface runoff to rainfall [$-$]
- i: Rainfall intensity [m^3/s]
- A: Area [m^2]

Within this calculation, the following numbers are assumed.

- $C_f = 1.25$, return period of 100 years
- $C = 0.7$, dense residential
- $i = (37.8 + 60.8 + 32.9)\,mm$, with falls within 1.5 hours:

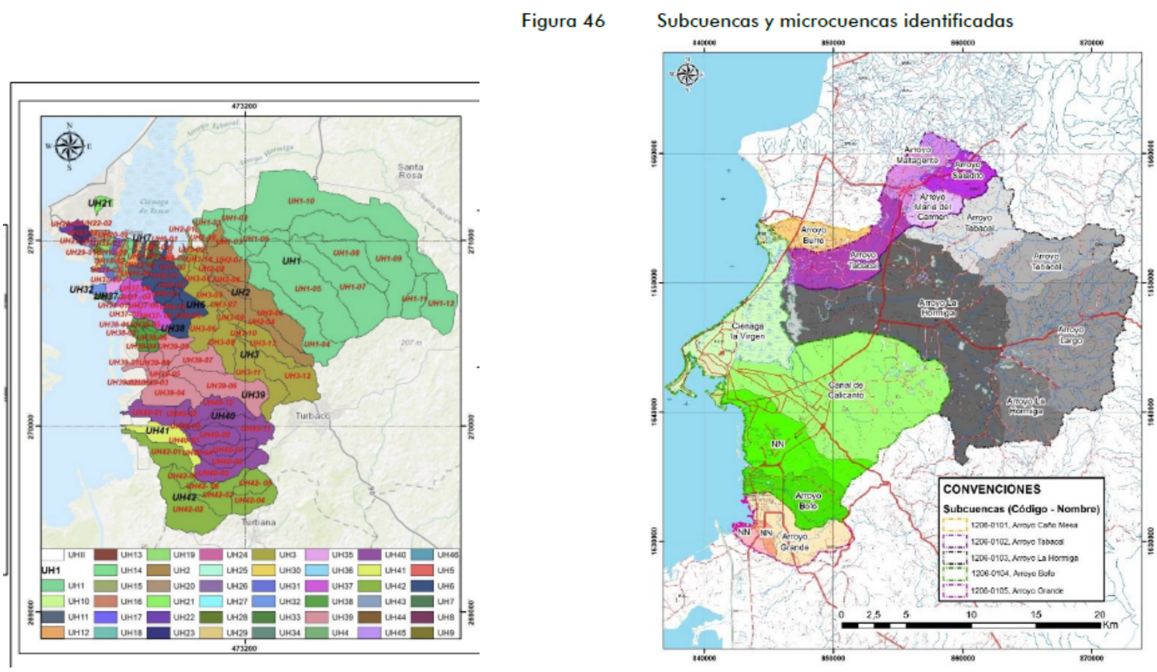
For the rainfall intensity the sum of the rainfall which falls within the first 1.5 hours is used, since this is assumed to be the most critical. In Figure B.1, from EDURBE (2023), one can see the distribution defined for maximum 24-hour rainfall events with 100- and 500-year return periods.

Resumen del cálculo de la distribución de la precipitación máximas en 24 horas, para la construcción de los hietogramas de la Lluvia típica definida para eventos con periodos de retornos de 15, 100 y 500 años.

HORA	PRECIPITACIÓN ACUMULADA (%)	DISTRIBUCION TIPICA DE LA LLUVIA (%)	PMAX24H (mm)	
			TR 100 AÑOS	TR 500 AÑOS
			185	*194*
0:00	0.00%	0.00%	0	0
0:30	20.41%	20.41%	37.8	39.6
1:00	53.24%	32.83%	60.8	63.7
1:30	71.01%	17.77%	32.9	34.5
2:00	76.78%	5.78%	10.7	11.2
2:30	81.61%	4.83%	8.9	9.4
3:00	83.80%	2.19%	4.1	4.3
3:30	87.16%	3.36%	6.2	6.5
4:00	89.25%	2.08%	3.9	4
4:30	91.55%	2.30%	4.3	4.5
5:00	92.87%	1.32%	2.4	2.6
5:30	94.41%	1.54%	2.9	3
6:00	95.64%	1.23%	2.3	2.4
6:30	97.16%	1.52%	2.8	3
7:00	98.43%	1.26%	2.3	2.5
7:30	99.61%	1.18%	2.2	2.3
8:00	100.00%	0.39%	0.7	0.8

Fuente: Los Autores (2022).

Figure B.1: Distribution of rainfall (EDURBE, 2023)



(a) Urban streams

(b) Rural streams

Figure B.2: Watershed of the rivers which end in the Ciénaga (EDURBE, 2023)

Table B.1: Extreme discharge recalculated

Channel	**Discharge source** [1]	**Rational method** $[m^3/s]$
Rural		
Eastside		
Arroyo Caño Mesa	131.9	
Arroyo Tabacal	123.4	
Arroyo Hormiga	377.6	
Matute-Chapundún - Calicanto Viejo	175.5	
Calicano-Neuvo - Arryo Limón	98.5	
Chiamaria - Flor del Campo	258.7	
Urban		
Southsite		
Bolivar	12.3	8.1
Maria Auxilladora	26.3	17.5
San Pablo	9	5.8
Barbacoa / Barcelona	15.5	10.2
Amador y Cortes	21.7	14.3
San Martin	11.3	7.5
El Libano	4.2	2.8
Salim Bechara	13	8.5
Canal Tabú	41.8	27.3
El Villa	4.2	2.8
Paranegro	2.3	1.7
Once de Noviembre	5.8	3.8
El Tigre	15.4	10.2
Ricaurte - San Pedro	219.9	156.6
Maravilla	8.3	5.5
Playa Blanca	13.3	8.7
Westside		
Puerto Pescadores	16.5	10.9
Caño Juan Angola	unknown	

[1] Extreme discharge with return period of 100 years ((EDURBE, 2023) & for Arroyo Tabacal & Hormiga (POMCA et al., 2014))

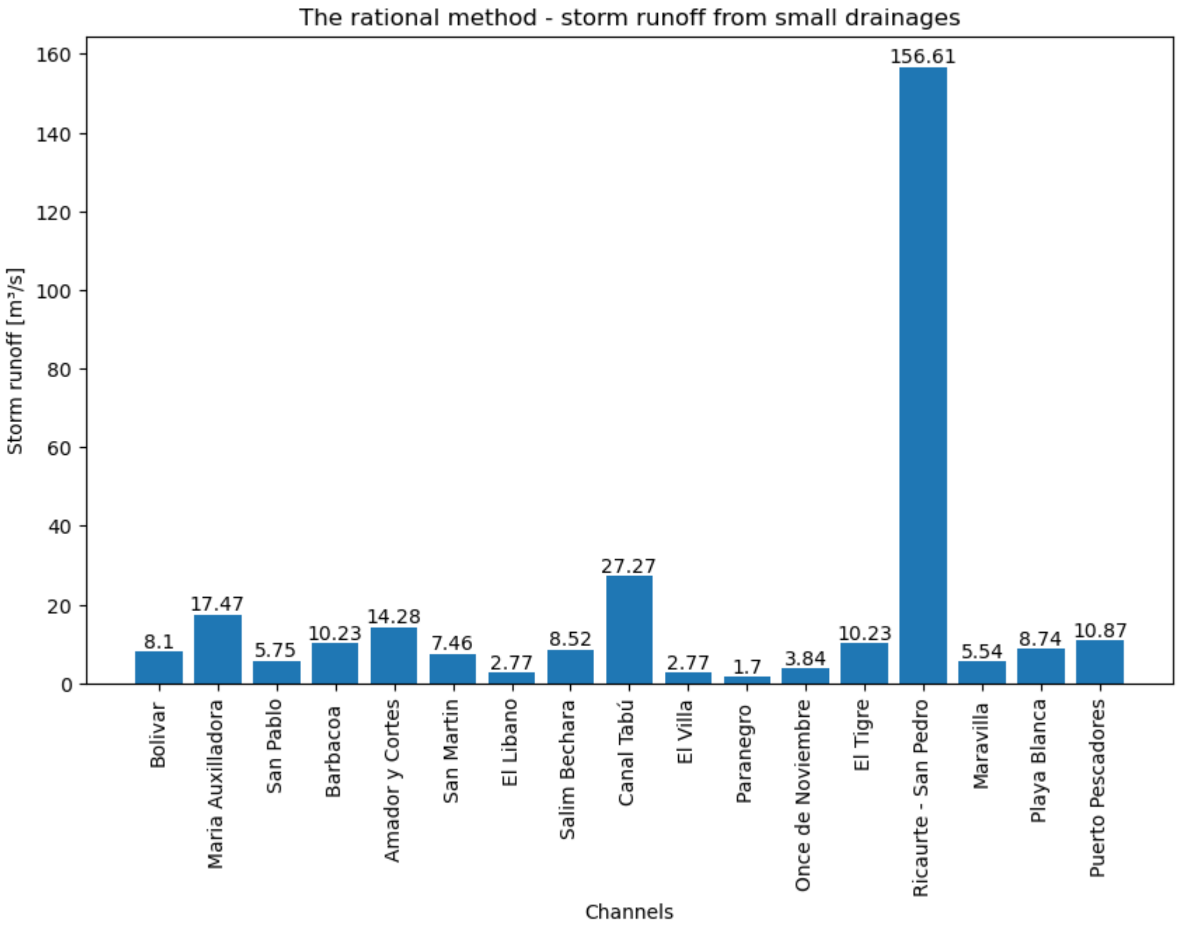


Figure B.3: The rational method - storm runoff urban channels from small drainages (obtained with python)

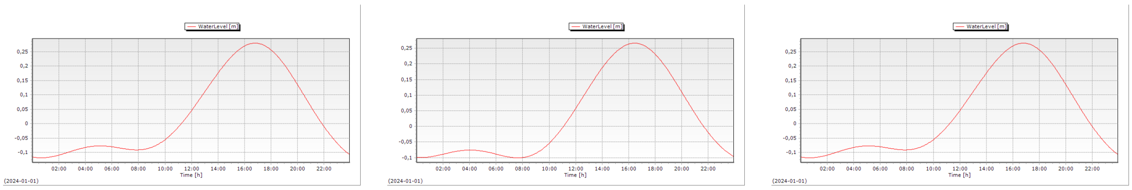
The coordinates of the input sources in the Delft3D model can be seen in Table B.2 with the maximum value for the discharge and the value for the tracer when there are no measures considered, default value.

Table B.2: Extreme scenario, discharge locations

What	Latitude	Longitude	Latitude	Longitude
Wastewater1	10°24’55.14”N	75°29’51.18”W	10,4153	75,49755
Wastewater2	10°25’40.28”N	75°30’41.67”W	10,4279	75,51157
Arroyo Caño Mesa	10°29’54.36”N	75°29’6.44”W	10,4984	75,48512
Arroyo Tabacal	10°28’0.01”N	75°28’58.01”W	10,4667	75,48278
Arroyo Hormiga	10°26’52.01”N	75°28’43.00”W	10,4478	75,47861
Matute-Chapundún - Calicanto Viejo	10°25’15.51”N	75°28’48.42”W	10,421	75,48012
Calicano-Neuvo - Arryo Limón	10°25’30.97”N	75°28’43.53”W	10,4253	75,47876
Chiamaria - Flor del Campo	10°25’30.97”N	75°28’43.53”W	10,4253	75,47876
Puerto Pescadores	10°25’6.07”N	75°30’55.33”W	10,4184	75,51537
Bolivar	10°25’0.34”N	75°30’49.63”W	10,4168	75,51379
Maria Auxilladora	10°25’0.45”N	75°30’46.89”W	10,4168	75,51302
San Pablo	10°24’58.83”N	75°30’40.54”W	10,4163	75,51126
Barbacoa / Barcelona	10°24’57.33”N	75°30’32.21”W	10,4159	75,50895
Amador y Cortes	10°24’58.77”N	75°30’25.89”W	10,4163	75,50719
San Martin	10°24’56.15”N	75°30’16.60”W	10,4156	75,50461
El Libano	10°24’54.66”N	75°30’8.83”W	10,4152	75,50245
Salim Bechara	10°24’54.38”N	75°30’5.23”W	10,4151	75,50145
Canal Tabú	10°24’54.59”N	75°29’52.06”W	10,4152	75,49779
El Villa	10°24’54.49”N	75°29’48.88”W	10,4151	75,49691
Paranegro	10°24’54.35”N	75°29’44.47”W	10,4151	75,49569
Once de Noviembre	10°24’54.46”N	75°29’42.02”W	10,4151	75,49501
El Tigre	10°24’56.82”N	75°29’30.90”W	10,4158	75,49192
Ricaurte - San Pedro	10°25’5.58”N	75°29’16.25”W	10,4182	75,48785
Maravilla	10°24’56.17”N	75°29’3.24”W	10,4156	75,48423
Playa Blanca	10°24’50.09”N	75°28’46.62”W	10,4139	75,47962

C Tides Caribbean Sea

In the model water levels generated with the tidal constituents from the TOPEX/POSEIDON satellite data are imposed at the boundaries, see Figure (4.2). Those tidal constituents can be seen at the end of this chapter, and some examples of the water level generated at the boundaries can be observed in Figure C.1.



(a) Boundary: J01 001 0001 **(b)** Boundary: J01 002 0001 **(c)** Boundary: J01 003 0001

Figure C.1: Generated water levels at boundaries

To check the simulated tide by the model, other sources are consulted. It is found that other sources that provided data on the tidal constituents are of similar magnitude. Data that is used for this comparison can be found in Table C.1 and the locations are found in Figure C.2

Table C.1: Tidal constituents (Latandret-Solana et al., 2023)

Tidal constituents	K_1	O_1	P_1	M_2	N_2	S_2	M_f
Cartagena							
Amplitude (cm)	9.8	5.8	3.1	7.4	2.9	1.6	1.3
Santa Martha							
Amplitude (cm)	9.6	5.6	3.1	6.4	2.4	1.8	1.2
Isla Naval							
Amplitude (cm)	10.0	6.0	3.1	7.4	2.8	1.7	1.3

Figure C.2: Measurement location tidal constituents

The tidal constituents table as input at the boundaries of the Delft3D model, can be seen below:

Astronomic component	Waterlevel amplitude [m]	Waterlevel amplitude [m]	Waterlevel amplitude [m]
Name	**j01_001_0001**	**j01_002_0001**	**j01_003_0001**
A0	0,00	0,00	0,00
M2	0.067873508	0.059066015	0.067873508
S2	0.016865989	0.017936974	0.016865989
N2	0.025178375	0.022802614	0.025178375
K2	0.005202801	0.0051574821	0.005202801
K1	0.09165477	0.087510431	0.09165477
O1	0.056079071	0.053335689	0.056079071
P1	0.028316338	0.026824162	0.028316338
Q1	0.00782221	0.0073064312	0.00782221
MF	0.016823351	0.016410836	0.016823351
MM	0.008119978	0.007882068	0.008119978
M4	0.0018121212	0.0011052543	0.0018121212
MS4	0.0046384577	0.0026173774	0.0046384577
MN4	0.0017263606	0.0010441155	0.0017263606
Name	**j01_001_0002**	**j01_002_0002**	**j01_003_0002**
A0	0,00	0,00	0,00
M2	0.068037711	0.05906627	0.06761029
S2	0.017036344	0.018005351	0.016996457
N2	0.025263565	0.022783859	0.025144309
K2	0.0052307478	0.0051623577	0.0052166451
K1	0.091848247	0.087728143	0.091384816
O1	0.056218496	0.053491233	0.05587634
P1	0.028383959	0.026894637	0.028221543
Q1	0.0078504793	0.0073342573	0.0077790317
MF	0.016819346	0.016423696	0.016802315
MM	0.0081198511	0.0078901499	0.0081063824
M4	0.0018165624	0.0010828604	0.0017885477
MS4	0.0046468685	0.0025400882	0.0045721898
MN4	0.0017296251	0.0010186811	0.0017038171
Name	**j01_001_0003**	**j01_002_0003**	**j01_003_0003**
A0	0,00	0,00	0,00
M2	0.068037711	0.05906627	0.06761029
S2	0.017036344	0.018005351	0.016996457
N2	0.025263565	0.022783859	0.025144309
K2	0.0052307478	0.0051623577	0.0052166451
K1	0.091848247	0.087728143	0.091384816
O1	0.056218496	0.053491233	0.05587634
P1	0.028383959	0.026894637	0.028221543
Q1	0.0078504793	0.0073342573	0.0077790317
MF	0.016819346	0.016423696	0.016802315
MM	0.0081198511	0.0078901499	0.0081063824
M4	0.0018165624	0.0010828604	0.0017885477
MS4	0.0046468685	0.0025400882	0.0045721898
MN4	0.0017296251	0.0010186811	0.0017038171
Name	**j01_001_0004**	**j01_002_0004**	**j01_003_0004**
A0	0,00	0,00	0,00
M2	0.068200739	0.059020592	0.06731767
S2	0.017207935	0.018095351	0.017113037
N2	0.025354758	0.022767262	0.025099009
K2	0.0052573977	0.0051723757	0.0052252701
K1	0.092032635	0.087928702	0.091111377
O1	0.056347783	0.053629927	0.055667002
P1	0.028449353	0.026958558	0.028124552
Q1	0.0078776617	0.0073595997	0.0077355805
MF	0.016813884	0.016423738	0.016782748
MM	0.0081188461	0.0078919025	0.0080936735
M4	0.0018231026	0.0010624648	0.0017620542
MS4	0.0046616019	0.0024680284	0.004497338
MN4	0.0017350106	0.00099494081	0.0016783941
Name	**j01_001_0005**	**j01_002_0005**	**j01_003_0005**
A0	0,00	0,00	0,00
M2	0.068200739	0.059020592	0.06731767
S2	0.017207935	0.018095351	0.017113037
N2	0.025354758	0.022767262	0.025099009
K2	0.0052573977	0.0051723757	0.0052252701
K1	0.092032635	0.087928702	0.091111377
O1	0.056347783	0.053629927	0.055667002
P1	0.028449353	0.026958558	0.028124552
Q1	0.0078776617	0.0073595997	0.0077355805
MF	0.016813884	0.016423738	0.016782748
MM	0.0081188461	0.0078919025	0.0080936735
M4	0.0018231026	0.0010624648	0.0017620542
MS4	0.0046616019	0.0024680284	0.004497338
MN4	0.0017350106	0.00099494081	0.0016783941
Name	**j01_001_0006**	**j01_002_0006**	**j01_003_0006**
A0	0,00	0,00	0,00
M2	0.068461015	0.058860523	0.066974734
S2	0.017381139	0.018170993	0.017212024
N2	0.025467978	0.022719395	0.025028374
K2	0.0052880127	0.005177043	0.0052306056
K1	0.092214385	0.088114562	0.09083686
O1	0.05647014	0.053757616	0.05546377
P1	0.028514897	0.027017346	0.028028009
Q1	0.0079036623	0.0073843375	0.0076940374
MF	0.016805538	0.016421383	0.016756907
MM	0.0081159932	0.0078912761	0.0080787222
M4	0.0018356013	0.0010370756	0.0017306155
MS4	0.0046928751	0.002379725	0.004408219
MN4	0.0017460411	0.0009657141	0.0016481938
Name	**j01_001_0007**	**j01_002_0007**	**j01_003_0007**
A0	0,00	0,00	0,00
M2	0.068461015	0.058860523	0.066974734
S2	0.017381139	0.018170993	0.017212024
N2	0.025467978	0.022719395	0.025028374
K2	0.0052880127	0.005177043	0.0052306056
K1	0.092214385	0.088114562	0.09083686
O1	0.05647014	0.053757616	0.05546377
P1	0.028514897	0.027017346	0.028028009
Q1	0.0079036623	0.0073843375	0.0076940374
MF	0.016805538	0.016421383	0.016756907
MM	0.0081159932	0.0078912761	0.0080787222
M4	0.0018356013	0.0010370756	0.0017306155
MS4	0.0046928751	0.002379725	0.004408219
MN4	0.0017460411	0.0009657141	0.0016481938
Name	**j01_001_0008**	**j01_002_0008**	**j01_003_0008**
A0	0,00	0,00	0,00
M2	0.068723516	0.058652245	0.066575324
S2	0.017542453	0.018240992	0.017324988
N2	0.025582427	0.022653798	0.024935261
K2	0.0053158565	0.0051802523	0.0052402394
K1	0.092394958	0.088301551	0.090551935
O1	0.056589051	0.053887961	0.055263703
P1	0.028578909	0.027076613	0.02792889
Q1	0.0079295108	0.007409829	0.007653189
MF	0.016778162	0.016413559	0.016732085
MM	0.0080992703	0.0078867833	0.0080640513
M4	0.0018479939	0.0010080408	0.0016952671
MS4	0.0047240604	0.0022798835	0.0043075485
MN4	0.0017570605	0.00093260958	0.0016140886
Name	**j01_001_0009**	**j01_002_0009**	**j01_003_0009**
A0	0,00	0,00	0,00
M2	0.068723516	0.058652245	0.066575324
S2	0.017542453	0.018240992	0.017324988
N2	0.025582427	0.022653798	0.024935261
K2	0.0053158565	0.0051802523	0.0052402394
K1	0.092394958	0.088301551	0.090551935
O1	0.056589051	0.053887961	0.055263703
P1	0.028578909	0.027076613	0.02792889
Q1	0.0079295108	0.007409829	0.007653189
MF	0.016778162	0.016413559	0.016732085
MM	0.0080992703	0.0078867833	0.0080640513
M4	0.0018479939	0.0010080408	0.0016952671
MS4	0.0047240604	0.0022798835	0.0043075485
MN4	0.0017570605	0.00093260958	0.0016140886
Name	**j01_001_0010**	**j01_002_0010**	**j01_003_0010**
A0	0,00	0,00	0,00
M2	0.069184219	0.058403244	0.066106874
S2	0.017743637	0.01835039	0.017431833
N2	0.025744329	0.022562686	0.024827027
K2	0.0053510254	0.0051903387	0.0052470252
K1	0.092523724	0.088490662	0.090259976
O1	0.056670732	0.054026579	0.055060172
P1	0.028628448	0.02713737	0.027826451
Q1	0.0079510437	0.0074396269	0.007613523
MF	0.016754365	0.016394584	0.016708549
MM	0.0080834424	0.0078751072	0.0080497624
M4	0.0018755677	0.00097815241	0.0016571487
MS4	0.0047944091	0.0021750818	0.0041990494
MN4	0.0017817529	0.00089803318	0.0015773786
Name	**j01_001_0011**	**j01_002_0011**	**j01_003_0011**
A0	0,00	0,00	0,00
M2	0.069184219	0.058403244	0.066106874
S2	0.017743637	0.01835039	0.017431833
N2	0.025744329	0.022562686	0.024827027
K2	0.0053510254	0.0051903387	0.0052470252
K1	0.092523724	0.088490662	0.090259976
O1	0.056670732	0.054026579	0.055060172
P1	0.028628448	0.02713737	0.027826451
Q1	0.0079510437	0.0074396269	0.007613523
MF	0.016754365	0.016394584	0.016708549
MM	0.0080834424	0.0078751072	0.0080497624
M4	0.0018755677	0.00097815241	0.0016571487
MS4	0.0047944091	0.0021750818	0.0041990494
MN4	0.0017817529	0.00089803318	0.0015773786
Name	**j01_001_0012**	**j01_002_0012**	**j01_003_0012**
A0	0,00	0,00	0,00
M2	0.069761679	0.058121714	0.06562751
S2	0.017939551	0.018408886	0.017522566
N2	0.02593456	0.022455255	0.024713333
K2	0.0053849192	0.0051897483	0.0052494112
K1	0.092597628	0.088643556	0.089974189
O1	0.056715201	0.054141669	0.054858656
P1	0.028662619	0.027184092	0.027725386

Q1	0.0079679496	0.0074677611	0.0075744284
MF	0.016750366	0.016382484	0.016685092
MM	0.0080800624	0.007867068	0.0080353437
M4	0.0019124857	0.00094824152	0.0016168081
MS4	0.0048885988	0.0020695888	0.0040838854
MN4	0.0018146935	0.00086330085	0.0015384544
Name			**j01_003_0013**
A0			0,00
M2			0.06562751
S2			0.017522566
N2			0.024713333
K2			0.0052494112
K1			0.089974189
O1			0.054858656
P1			0.027725386
Q1			0.0075744284
MF			0.016685092
MM			0.0080353437
M4			0.0016168081
MS4			0.0040838854
MN4			0.0015384544
Name			**j01_003_0014**
A0			0,00
M2			0.06507613
S2			0.017622231
N2			0.024572844
K2			0.005251926
K1			0.089686179
O1			0.054659879
P1			0.027621394
Q1			0.0075364669
MF			0.016652586
MM			0.0080174473
M4			0.0015727345
MS4			0.0039579055
MN4			0.0014958781
Name			**j01_003_0015**
A0			0,00
M2			0.06507613
S2			0.017622231
N2			0.024572844
K2			0.005251926
K1			0.089686179
O1			0.054659879

P1	0.027621394
Q1	0.0075364669
MF	0.016652586
MM	0.0080174473
M4	0.0015727345
MS4	0.0039579055
MN4	0.0014958781
Name	**j01_003_0016**
A0	0,00
M2	0.064519181
S2	0.017714841
N2	0.024425108
K2	0.0052548886
K1	0.089397485
O1	0.054464438
P1	0.027517805
Q1	0.0074996625
MF	0.016621807
MM	0.0080004221
M4	0.0015274228
MS4	0.0038281865
MN4	0.0014520724
Name	**j01_003_0017**
A0	0,00
M2	0.064519181
S2	0.017714841
N2	0.024425108
K2	0.0052548886
K1	0.089397485
O1	0.054464438
P1	0.027517805
Q1	0.0074996625
MF	0.016621807
MM	0.0080004221
M4	0.0015274228
MS4	0.0038281865
MN4	0.0014520724
Name	**j01_003_0018**
A0	0,00
M2	0.063901632
S2	0.017786072
N2	0.02425535
K2	0.0052515061
K1	0.089105846

O1	0.054274136
P1	0.027413843
Q1	0.0074646852
MF	0.016593408
MM	0.0079845076
M4	0.0014777676
MS4	0.0036861797
MN4	0.0014041381
Name	**j01_003_0019**
A0	0,00
M2	0.063901632
S2	0.017786072
N2	0.02425535
K2	0.0052515061
K1	0.089105846
O1	0.054274136
P1	0.027413843
Q1	0.0074646852
MF	0.016593408
MM	0.0079845076
M4	0.0014777676
MS4	0.0036861797
MN4	0.0014041381
Name	**j01_003_0020**
A0	0,00
M2	0.063271481
S2	0.017839994
N2	0.024071168
K2	0.0052435798
K1	0.088818516
O1	0.054091668
P1	0.027311323
Q1	0.0074307518
MF	0.016567389
MM	0.0079697042
M4	0.0014246336
MS4	0.0035336927
MN4	0.0013526918
Name	**j01_003_0021**
A0	0,00
M2	0.063271481
S2	0.017839994
N2	0.024071168
K2	0.0052435798

K1	0.088818516
O1	0.054091668
P1	0.027311323
Q1	0.0074307518
MF	0.016567389
MM	0.0079697042
M4	0.0014246336
MS4	0.0035336927
MN4	0.0013526918
Name	**j01_003_0022**
A0	0,00
M2	0.062549284
S2	0.017884398
N2	0.023855792
K2	0.0052331625
K1	0.08853778
O1	0.053919324
P1	0.027209365
Q1	0.0074004824
MF	0.01653693
MM	0.0079528024
M4	0.001366683
MS4	0.0033677717
MN4	0.0012967472
Name	**j01_003_0023**
A0	0,00
M2	0.062549284
S2	0.017884398
N2	0.023855792
K2	0.0052331625
K1	0.08853778
O1	0.053919324
P1	0.027209365
Q1	0.0074004824
MF	0.01653693
MM	0.0079528024
M4	0.001366683
MS4	0.0033677717
MN4	0.0012967472
Name	**j01_003_0024**
A0	0,00
M2	0.061739456
S2	0.01791146
N2	0.023612483

K2	0.005217276
K1	0.088262934
O1	0.053753338
P1	0.027107455
Q1	0.0073724042
MF	0.01650421
MM	0.0079349869
M4	0.0013038202
MS4	0.0031873611
MN4	0.0012359681
Name	**j01_003_0025**
A0	0,00
M2	0.061739456
S2	0.01791146
N2	0.023612483
K2	0.005217276
K1	0.088262934
O1	0.053753338
P1	0.027107455
Q1	0.0073724042
MF	0.01650421
MM	0.0079349869
M4	0.0013038202
MS4	0.0031873611
MN4	0.0012359681
Name	**j01_003_0026**
A0	0,00
M2	0.060882928
S2	0.017924351
N2	0.023351153
K2	0.00519794
K1	0.088010484
O1	0.053605708
P1	0.027011306
Q1	0.0073481215
MF	0.016471555
MM	0.0079172212
M4	0.0012379688
MS4	0.0029982451
MN4	0.0011722887
Name	**j01_003_0027**
A0	0,00
M2	0.060882928
S2	0.017924351
N2	0.023351153
K2	0.00519794
K1	0.088010484
O1	0.053605708
P1	0.027011306
Q1	0.0073481215
MF	0.016471555
MM	0.0079172212
M4	0.0012379688
MS4	0.0029982451
MN4	0.0011722887
Name	**j01_003_0028**
A0	0,00
M2	0.059995415
S2	0.017928134
N2	0.023076436
K2	0.0051755252
K1	0.087755079
O1	0.053465541
P1	0.026916649
Q1	0.0073261646
MF	0.016443763
MM	0.0079012756
M4	0.0011707198
MS4	0.0028052811
MN4	0.0011073498
Name	**j01_003_0029**
A0	0,00
M2	0.059995415
S2	0.017928134
N2	0.023076436
K2	0.0051755252
K1	0.087755079
O1	0.053465541
P1	0.026916649
Q1	0.0073261646
MF	0.016443763
MM	0.0079012756
M4	0.0011707198
MS4	0.0028052811
MN4	0.0011073498
Name	**j01_003_0030**
A0	0,00
M2	0.059066015
S2	0.017936974
N2	0.022802614
K2	0.0051574821
K1	0.087510431
O1	0.053335689
P1	0.026824162
Q1	0.0073064312
MF	0.016410836
MM	0.007882068
M4	0.0011052543
MS4	0.0026173774
MN4	0.0010441155

D

Delft3D

The hydrodynamic behaviour is modelled in Delft3D flow-flexible mesh model, a numerical model developed by Deltares. It is a combination and improved version of the Delft3D-Flow, SOBEK-FLOW, morphology (MOR) and waves (WAVE) modules (Deltares, n.d.-a). It generates hydrodynamic, hydrological, real-time control, morphodynamic, wave and water quality processes for coastal, estuarine, river, rural and urban applications (Deltares, n.d.-b).

The D-Flow FM implements a finite volume solver that calculates non-steady flow in shallow waters and transport processes due to tidal and meteorological forces. It also considers Coriolis forcing and horizontal eddy viscosity, and therefore, it is, among others, suitable for supercritical flow and tidal and estuarine computations.

The MOR module computes sediment transport due to the currents and wave forcing. In order to achieve this, several transport formulae are incorporated.

For a more elaborated overview of the Delft3D flow-flexible mesh model, the Deltares manual can be consulted (Deltares, n.d.-c).

E

Coordinates observation points Delft3D

Table E.1: Coordinates observations point Delft3D

Observation point	Longitude	Latitude
OffShoreClose01	-75,52618369	10,46548839
Cienaga06	-75,4931872	10,44269792
OffshoreFar01	-75,54358285	10,562614
OffshoreFar03	-75,59625409	10,45307625
OffshoreFar02	-75,6111847	10,53632272
BocanaOutsideBW	-75,5118522108382	10,4561905056569
BocanaMiddle	-75,5090838821781	10,4534681360357
InsideIntake	-75,506964678859	10,4501073847608
InsideOutfall	-75,5059718989258	10,4509898201803
Cienaga01	-75,5021281103977	10,437663994508
Cienaga02	-75,5009033254308	10,4212383162419
Cienaga03	-75,488432787586	10,4226619093222
Cienaga04	-75,4886554757618	10,4659141313524
Cienaga05	-75,4818634863999	10,4780674688263