Delft University of Technology

CIE4061-09 Multidisciplinary Project

Valdivia Estuary Project

Multidisciplinary Project Group 223

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Preface

This report covers the final result of the multidisciplinary project named 'Valdivia Estuary Project'. This multidisciplinary project is carried out as part of the master programme Civil Engineering at Delft University of Technology, with course code CIE4061-09. The project was realised for the Universidad Católica de la Santisíma Concepción in Chile. Valdivia Estuary Project was carried out by six students with different educational master specialisations, which are Hydraulic Engineering, Watermanagement and Transport, Infrastructure and Logistics. The project is realised under supervision of Dr. Ir. R. Aránguiz Muñoz and Dr. Ir. D. Caamaño Avendaño from the Universidad Católica de la Santisíma Concepción and Dr. Ir. R.J. Labeur, Dr. Ir. A.J. Pel and Prof. Dr. Ir. H.H.G. Savenije from Delft University of Technology.

This report is the result from an eight week research carried out for the Ministry of Public Works of the Region 'de Los Ríos' in Chile. Due to their interest in the Valdivia river as the only navigable river in Chile, the research looked into the sedimentation problems in the Valdivia river and social and economic impacts as a result of a possible solution to these problems on the city of Valdivia.

In order to finance the project group in their expenses for the research, sponsors were approached. Dutch Process Innovators, Van Oord and Business Mediation Rotterdam sponsored the project financially. Dutch Process Innovators and Deltares also supported the project group when it comes to group processes and modelling.

Enjoy reading the report. If there are any questions, do not hesitate in contacting the group via valdivia.project.chile@gmail.com.

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Our gratitude goes out to our supervisors, Dr. Ir. A.J. Pel, Prof. Dr. Ir. H.H.G. Savenije and Dr. Ir. R.J. Labeur from Delft University of Technology for their supportive criticism during the research.

Furthermore, we would like to express our gratitude to Dr. Ir. R. Aránguiz Muñoz and Dr. Ir. D. Caamaño Avendaño from the Universidad Católica de la Santisíma Concepción. They helped us with our problem definition on beforehand and introduced us to the country of Chile directly when we arrived.

Also, our thankfulness goes out to Ir. R.F. Cheuque Aroca as a representative of the Ministry of Public Works of the region 'de Los Ríos'. He showed us around at the project location in Valdivia and was very supportive in answering our questions.

We thank Ir. S. Loyer Correa for providing crucial insights into the transport problems in the area. Next to that, we thank Dr. Ir. E. Muñoz Ortiz from the UCSC as well for helping us gathering information about the hydrological background in the research field. Also, our gratitude goes out to the students Mathias and Pedro from the UCSC who spent their time helping us setting up the Delft3D model.

Next to the support on the model at the UCSC, we received a lot of valuable advice from Ir. R. Hoekstra from Deltares. We would like to thank him for sharing his modelling expertise with us so we could enhance our research.

From our leading sponsor Dutch Process Innovators we received a lot of enthusiasm about our project. Our gratitude goes out to Ir. P. Goldbohm for her advice in the process of the project.

Lastly, we would like to thank all other people at the UCSC for their warm welcome and M. Hayes with her help in finding our accommodation in Concepción.

Summary

Valdivia is a Chilean city located near an estuary system, 800 km south of Santiago. The navigation capacity of the Valdivia river mainly determines the present state and future possibilities for the welfare of the city. Since sedimentation problems arose in the river, the capacity for navigation became limited. The ministry of Valdivia therefore desires a solution for this problem in order to create possibilities for future growth. However, it is not known to what extent solutions for the sedimentation problem will actually contribute to an increase of welfare.

By identifying the problem for the Ministry of Public Works of Chile, the boundaries and goal of the project could be set. In this research an attempt is made to answer the following research question: *How can the surplus of sediment in the Valdivia river be remedied and to what extent will this contribute to the economic and social values of the city of Valdivia?*

In order to know how to remedy the surplus of sediment, a qualitative analysis of probable causes of the sedimentation was necessary. The main subjects which were researched by means of data and literature are tidal influence, river discharges, sediment composition and salt intrusion.

With this knowledge it was concluded that the directions and magnitudes of flow lines in the river system can give good indications on what locations sedimentation can occur. The interaction between tidal currents and river discharges are the main drivers behind these flow characteristics. To verify the theoretical analysis, a basic Delft3D model was set up containing only tidal movement and river discharges. The pattern of the flow lines which was obtained from the Delft3D model supports the possibility that sedimentation occurs on the current identified sedimentation locations. Although other hydrological and morphological processes were found to possibly influence sedimentation rates in the river, qualitative data for studying these processes were missing. The current Delft3D model is therefore a good result regarding the available data and can be seen as a part of preliminary research in order to support further studies.

Because the exact causes of the sedimentation were not identified in this research, it was not possible to come up with suitable solutions and to research how these solutions could affect the system. However, in order to gain insight in the effects of a river system without sedimentation problems, a fictitious scenario was studied by means of a social cost benefit analysis. The goal of the social costs and benefits analysis was to give insight in what factors should be taken into account when considering a project plan which solves the sedimentation problem.

A dredging design was made in order to make the Valdivia river navigable for larger cargo vessels to increase the trading capacity of Valdivia. This dredging design comprises the deepening of the Valdivia river to a minimum water depth of 10 meters. Considering investment and maintenance costs of the dredging activities of this magnitude, it is concluded that the costs are not profitable compared to the social and economic effects of a higher traffic intensity on the river. With the social costs and benefits analysis all effects of solving the sedimentation problem are inventoried. When the Delft3D model can identify what the remedy of the sedimentation could be, the impact on the economic and social values of Valdivia can be determined.

This research was not sufficient to answer the research question. Both the Delft3D model and the SCBA model were lacking accurate and reliable data. To expand this research, it is necessary to collect the data of which an overview has been made. Therefore, this research can serve as a preliminary study for further research.

It is recommended that after data collection, solutions will be identified which can solve the sedimentation problem. These solutions need to be compared with a scenario analysis in order to decide on which is the most suitable solution for the sedimentation problem. Besides this, it is advised to research whether it is actually necessary to expand the river for transport when looking at all actors involved.

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1. Introduction

The Ministry of Public Works has a desire to have high welfare in Valdivia. This means that the city has both a high economic and a high social value. Increasing the export might be a solution for the Ministry to increase the economic value of Valdivia. However, in order to be able to increase the export of Valdivia, sufficient infrastructural capacity is needed. Unfortunately, the current capacity of infrastructure around Valdivia is not sufficient.

There is a growth of residents and tourists and there is a total increase in mobility (Ministerio de Transporte y Telecomunicaciones, 2014). Not only are there more people that make use of the city's infrastructure, but there is also an increase in the number of vehicles per household. These factors lead to high pressure on the capacity of infrastructure on land, which in turn leads to congestion and delays. Research from SECTRA shows that the population of Valdivia increased between 2002 and 2015 to more than 167 thousand residents (Ministerio de Transporte y Telecomunicaciones, 2014). This is a 19% growth. The number of motorised vehicles increased with 151% between 2002 and 2013 up to more than 29 thousand vehicles. These trends are still proceeding and are even expected to proceed in the future. The current infrastructure on land is not sufficient for the present values of transport. Furthermore, the river is also subject to capacity problems. There are seven sedimentation points identified in the Valdivia river, where the navigation depth is not acceptable for the local cargo vessels without dredging activities (Austral Valdiva, 2013).

To ensure sufficient capacity for the present values of transport, a few measures have been executed. In trying to increase the capacity on land, the Ministry decided to built the Cau Cau bridge to improve the accessibility of the city centre. The bridge was planned to open in 2014 but due to an engineering mistake, the bridge is still not in use. Besides the Cau Cau bridge, there are several projects running in order to improve the capacity on land for the present values (SECTRA, 2017). Currently, there is no policy on ensuring sufficient capacity in the river. Once in a while private companies, who use the river to transport wood over the Valdivia river, complain to the Ministry about the water depth when the echo sounders of their ships measure a too low water depth to navigate safely. In reaction to that the Ministry hires a dredging company to solve the problem. Recently, a large dredging project took place to maintain the depth of the Valdivia river. The dredging project started in 2013 and it was expected that it would take two years. However, in March 2017 only 90% of the dredging was done (Bracho, 2017).

To ensure sufficient capacity for the future values of transport, it is necessary to expand the current infrastructure. Because the capacity of infrastructure on land is already lagging behind for the present values, it is not profitable to further look into expanding the infrastructure on land for future export. Therefore, it would be logical to look into the possibilities on the river for the expansion of export. On top of that, the Ministry has asked to do research on the future possibilities of transport on the river (personal communication, September 4^{th}, 2017). Moreover, the Ministry wants to change their dredging policy from a reactive character to a preventive character.

Not only the economic value is important for the Ministry, also the social value needs to be taken into consideration. For the Ministry it is important what the effects of increasing the export on the river are for the residents and tourists in Valdivia. Little research has been done on this subject. Most of the research done in the past is about the economic benefits of export, but not about what the consequences are for the society. By executing research, policymakers can be guided which policies to take in consideration.

If the Ministry wants to expand the export on the river, more knowledge is needed for a good insight into the sedimentation problem in order to prevent it in the future. By gaining more insight about the causes of the sedimentation problems in the river, a future development policy can be made which clarifies the added value of increasing the export. Besides that, there is no insight in what the increase of transport on the river will add to the economic and social values of the city. The lack of available information on the sedimentation problem in the river and the possible social consequences that the solution can have, has led to the following research question:

How can the surplus of sediment in the Valdivia river be remedied and to what extent will this contribute to the economic and social values of the city of Valdivia?

The goal of this research is to gain insight in the sedimentation problem and its main driving processes. Furthermore, there will be looked into a solution, where it will be considered if increasing the export really contributes to the welfare of Valdivia.

2. Methodology

The methodology is used as a guideline for the project, in which every step will be defined. In Figure 2.1 the general roadmap of this research is shown. Every step is a chapter and contains methods which will be described.

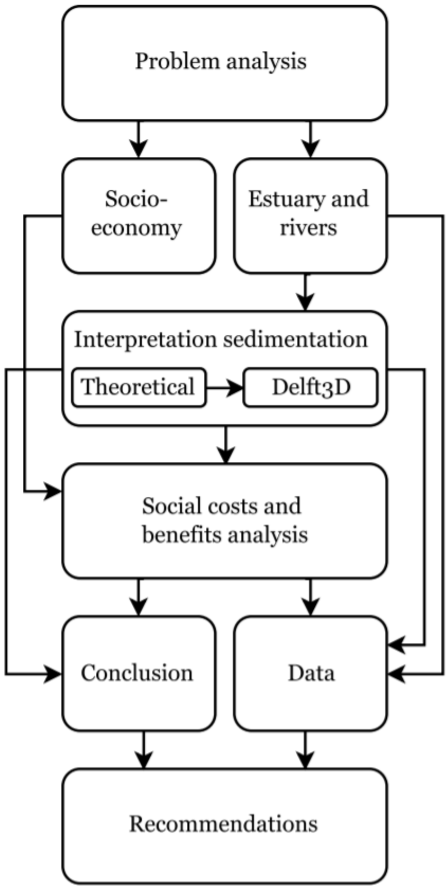

Figure 2.1: Methodology (Own work)

Problem analysis

The project starts by making a problem analysis. First, the problem owner will be assigned. The main goal, desire and dilemma of this problem owner will be described with an objective tree. To map the entire situation, also a means-end tree and a system diagram will be designed. The means-end tree shows the main goal and the subgoals of the problem owner. With the system diagram the system boundaries can be clearly set. It defines the interplay between criteria, means, external factors and the possible solutions. Furthermore, an actor analysis is carried out which will be used to give an overview of all stakeholders involved. In the end, the problem analysis leads to a formulation of a suitable research question.

Socio-enonomy

With the information from the problem analysis the socio-economy of the research area can be analysed. The goal of defining the socio-economy is to make clear which social and economic domains might be influenced by the project outcome. This chapter describes the importance of the river for the people and economy of the area. This section focuses on gathering recent information from the area.

Estuary and rivers

With the boundaries determined in the problem analysis, a theoretical research will be carried out in this chapter. In order to understand the presence and cause of the sedimentation points, it is important to gain understanding of all hydrological and morphological processes and hydraulic structures that are present within the chosen boundaries. This means that in this chapter the topography, tides, rivers, waves, salt intrusion and sediment will be analysed. Also, the sedimentation locations will be identified. The analysis is based on processing data, literature and existing study reports on the area. The topography is also analysed using the tools Google Earth and Navionics.

Interpretation sedimentation

In this chapter, all information gathered in the chapter 'Estuary and Rivers' will be used to clarify the sedimentation points. Besides this, river engineering theory is key to make this clarification.

The results of the theoretical interpretation will be verified by means of a numerical model. The program 'Delft3D' is used as the numerical model. Delft3D is a modelling program to investigate hydrodynamics, sediment transport, morphology and water quality for fluvial, estuarine and coastal environments (Deltares, 2017). The modelling process is extensively described in Appendix C.2.

Social costs and benefits analysis

With the information from the description of the socio-economy of the area, a social costs and benefits analysis will be carried out. In this chapter a comparison will be made between the current situation and a future situation in terms of economic and social impact. The social costs and benefits analysis can determine whether there is an added value to implement a certain solution. From the interpretation of the sedimentation and the current maintenance activities the situations can be identified. New boundaries are set for the situations. Within these boundaries the social and economic impacts will be calculated. The impacts will be expressed in US dollar. In the end, the analysis will point out to what extent the project area is suitable for the development that is desired by the problem owner.

Data

The data that is used during the research will be checked by means of reliability, applicability and completeness. The goal of this chapter is to give insight into the priorities of data necessary for future research.

Conclusion

The outcome of the research is an analysis of the entire current situation. The conclusion will contain a clear overview of the problem within the chosen scope. The aim of the conclusion is to give an answer to the research question.

Recommendations

The conclusion can serve as a base for further research. The recommendations will give advice on the next steps the problem owner should consider. An overview will be given of possible areas where future researches can be beneficial for the desired development.

3. Problem description

To clarify the research problem, insight is given into the background and the history of the Valdivia area. In Section 3.3, the problem is analysed.

3.1 Background

Valdivia is the capital of the 'Region de Los Rios' in Chile, see Figure 3.1. The city is located in the centre of Chile, along the Valdivia river. Valdivia is connected to the Pacific Ocean via the port of Corral in the Valdivia estuary. The Valdivia river is the only river in Chile that is navigable and therefore a strategic point for fluvial trade (Feria, 2012).

Figure 3.1: Location of Valdivia (SECTRA, 2014)

3.2 History

In 1900, Valdivia was listed as one of the major industrial and commercial centres in the country. The port of Corral was after Valparaíso the largest port of Chile (Ministerio de Obras Publicas, 2015), because the route along the coast of Chile was the only way to sail from the Pacific to the Atlantic. In 1906 the largest steel industry of South America, the Altos Hornos, was built in Corral. After the construction of a railway connection between Valdivia and central Chile and the opening of the Panama Canal in 1914((Smith, 2014), the port activities started losing competitiveness. The international traffic circuits changed towards the Panama canal and the Chilean traffic was diverted by railroads. As a result the Altos Hornos was closed in 1958((Ministerio de Obras Publicas, 2015)). Due to this closure the amount of wood transported from upstream of Valdivia towards Corral decreased (Direccion de Obras Portuarias, 2017).

Although the ports of Corral and Valdivia lost a lot of their trade traffic, it was still important to maintain the river as the main transport mode for the region 'de Los Ríos', because there was no land connection between Valdivia and Corral. However, there appeared to be sedimentation problems in the Valdivia river. The problem was that the river depth became insufficient for the cargo ships to continue their transport. In response to the problem, the government started to do research on this sedimentation problem in 1910. The research led to the design of multiple longitudinal breakwaters in the Valdivia river (see Figure 5.4). The function of these breakwaters was to decrease the width of the flow in the river and therefore increase the flow velocity. By increasing the flow velocity the sedimentation would decrease and the river depth would restore itself. In 1922 the construction of 15 kilometres of longitudinal breakwaters started and in 1944 the construction was finished (Direccion de Obras Portuarias, 2017). After the construction of the breakwaters the sedimentation decreased and the river was maintained as the main transport mode of this region.

In 1960 the Valdivia region was hit by the most powerful earthquake ever recorded, with a power of nine on the moment magnitude scale (Ministerio de Obras Publicas, 2015). Due to the earthquake, the whole area around Valdivia subsided with an average amount of 1,60 meters which caused the destruction of port facilities and the subsidence of the breakwaters. Due to the subsidence, the breakwaters became submerged and after a while the sedimentation started increasing again. Currently, the sedimentation problem is still present and the Ministry of Public Works has a desire to solve this problem.

3.3 Problem analysis

In this Section the problem is framed by explaining the problem owner and the problem definition. The research goal has been derived from this. Also the actor analysis, the scope and the limitations are described. In Appendix A the complete problem analysis can be found.

3.3.1 Problem owner

The Ministry of Public Works, more specifically the department of Port Works, of region 'de Los Ríos' has defined the problem of this research (personal communication, September 4^{th}, 2017). This Ministry is, among others, responsible for the maintenance of ports and dredging activities on a national level. Therefore, they are the most concerned with the waterway in the Valdivia river. They have the ability, power and interest to improve the usability of the river of Valdivia. For more detailed information concerning the problem owner, see Appendix A.4.

3.3.2 Problem definition

The primary goal of the Ministry of Public Works is to have high welfare in Valdivia. High welfare means that the city has both a high economic and a high social value, as described in Appendix A. To ensure a high economic value, the Ministry wants to have a good trading position in the global market. However, the accessibility of Valdivia is a major obstacle.

In order to improve the accessibility for trade of cargo, it is possible to use infrastructure either on land or on the river, as shown in the Figure A.3. On land there is little space to expand the infrastructure. The Ministry asked to look into the possibilities to increase cargo transport on the river. The main obstacle for expanding the river usage is the sedimentation problem. To improve the river infrastructure, this problem needs to be solved.

The economic value of Valdivia is not the only part to take into account. The social value also contributes to the welfare of the city. Therefore, the satisfaction of the residents and tourists is important for the Ministry.

To map the possibilities of cargo transport on the river, an insight is needed into the sedimentation problem. Next to that, the consequences of an increase in cargo transport on the river for the residents and tourists of Valdivia needs to be analysed. Therefore, the purpose of this research is to answer the following question:

How can the surplus of sediment in the Valdivia river be remedied and to what extent will this contribute to the economic and social values of the city of Valdivia?

3.3.3 Research goal

In order to be able to increase the fluvial trade of Valdivia, it is necessary to investigate the sedimentation problem. The goal is to look at the main driving processes behind the sedimentation problem. By analysing this, the behaviour of the river can be better understood and estimations can be made about a possible increase of the river usage in the future.

The increase of river usage for cargo transport will have an impact on the city. The goal is to research what this impact is socially and economically.

The collected information in this report is not necessarily a direct solution for this particular project. The aim of the research is to make an analysis for the Ministry and guide them in the future policy-making. Therefore, it serves as a basis for further research.

3.3.4 Actor analysis

For the Ministry of Public Works, it is important to take into account the other actors involved in the problem. For this particular problem, all actors involved are analysed in Appendix A.4. Most actors involved are other Ministries with similar interests and authority. The most important actors with conflicting interests are residents and tourists. They have little authority and therefore it is difficult to have influence on the policy. However, it is very important to keep these actors satisfied, because if their satisfaction decreases, chances are that they will leave the city. Besides the residents and tourists, the port of Corral can have conflicting interests as well. They might be afraid to lose their market share.

3.3.5 Scope

The system boundaries can be viewed in the system diagram in Figure A.4 in Appendix A. This research focuses on cargo transport. The impact of the measures on the passenger transport are not taken into account. There will be an analysis on how measures can influence the possibilities of cargo transport and how this increase will affect the city economically and socially.

There will not be an analysis on how cargo transport on the road and on the water influence each other. The different methods on how to improve the transport for the sake of cargo do not have a connection with each other, because one of these options will be chosen.

Geographically, for the Delft3D model, the scope will reach from the estuary mouth up until just upstream of Valdivia, which includes all the locations where dredging activities are currently taking place (see Figure 3.2). To research the origin of the sediment, the entire river catchment will be studied. To study the social and economic impacts the study area will be the surrounding area of the waterway between Las Mulatas and Corral, because this area is where an expansion of the transport on the river might be carried out.

The social and economic impact will be studied on behalf of the city of Valdivia. For a high economic welfare of Valdivia it is beneficial to have prosperous companies in the region. Therefore, for the economic impact the positive and negative effects will be taken into account for the companies that provide export for the region. On the other hand, for the social impact it is important to take into account the positive and negative effects for the residents and tourists of the surrounding area of the waterway between Las Mulatas and Corral.

3.4 Limitations

There were several limitations known prior to the start of the project. In the first place, the amount of available data is limited. In some cases, it is not clear whether the data exists or where it can be found. Besides that, some data exists, but is not accessible to use.

Another limitation is the difference in culture between Chile and The Netherlands. There is a big gap because of the Spanish language. All the documents are in Spanish which means that they need to be translated before they can be used. Also the government is organised in a different way. This makes it unclear who is in charge of what and who owns the right data. All in all it takes time to map this.

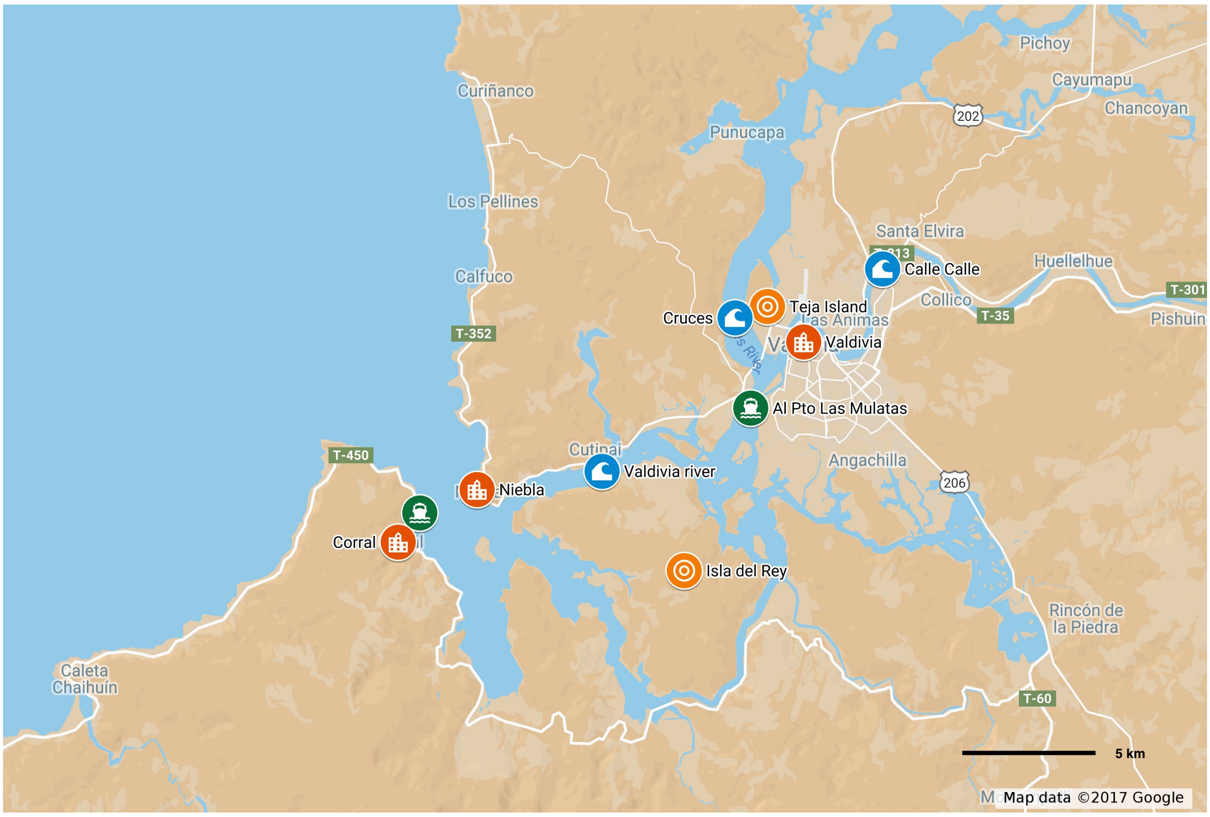

Figure 3.2: Overview of the Valdivia estuary area (Map data: Google, 2017)

4. Socio-economy

The socio-economy is analysed to give insight in the importance of the area. The population, economy and river usage are described to make clear which social and economic domains might be influenced by the project outcome.

4.1 Population

Valdivia had 140,559 residents in 2002 and 167,861 residents in 2015. This is an increase of 19%. The expectation is that the population of Valdivia will continue to increase in the future. The Tables about the population can be found in Appendix B.1.

In Figure 4.1, the distribution of the population in the twelve macro zones of the Valdivia is shown. For analysing the social costs and benefits, macro zone Poniente (number 12) is important, because this zone is between the ports of Las Mulatas and Corral. This zone only has 4% residents.

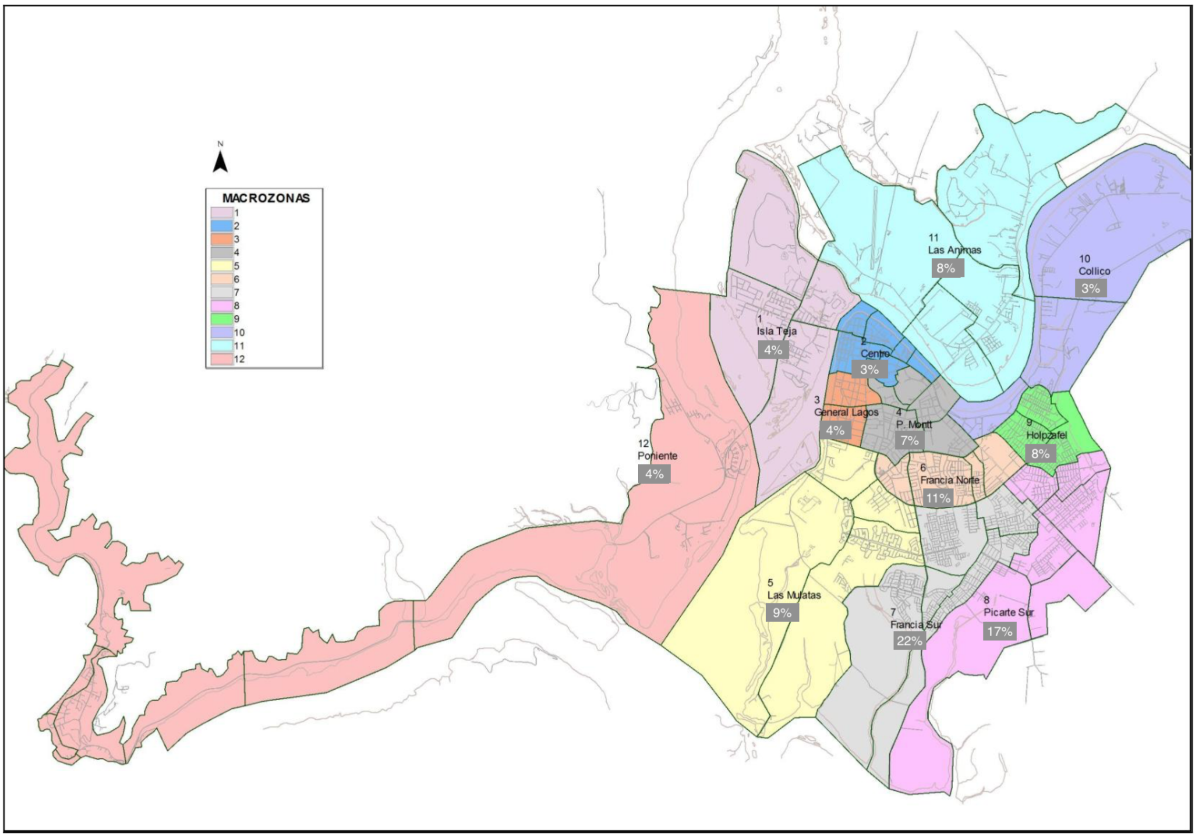

Figure 4.1: Distribution of the population in the 12 macro zones of Valdivia (SECTRA, 2014)

The highest percentage of industrial labourers is working in the construction sector (15%), followed by the trade industry (11%) (Port of Corral, 2017b). If the sedimentation problem would be solved, the port has the opportunity to grow, which can increase the amount of employees in the trade industry.

4.2 Economy

Socio-economic statistics show that the municipality of Valdivia has an average household income of about 1,207 US dollar per month (see Appendix D.5). This is more than the average income at regional level of 1,028 US dollar, but below the national level of 1,416 US dollar per month (see Figure B.3).

In economic terms, the municipality of Valdivia is an important tourist centre in the region and in the south of Chile (SECTRA, 2014). It has a diversity in business types, which can be observed in Figure B.4. The municipality of Valdivia represents more than 40% of the total companies in the region, followed by the municipality of La Unión, which represents 10%.

4.3 River usage

In order to understand the necessity of analysing the river system, it is desired to gain insight about the usage of the river. The river usage comprises cargo transport, recreational activities and waste water dumping. The intensity of each of these activities varies for each river section. Tourism is found mainly along the Calle Calle river, while cargo is only transported on the Valdivia river (see Figure 3.2). Therefore, the focus is on the import and export industry, which is assumed to be affected the most by the sedimentation problem. The cargo transport will be analysed thoroughly in order to estimate the development of cargo transport with and without the sedimentation problem. Tourism and waste water dumping are described more briefly as these types of river usages are assumed to be less subject to the sedimentation problem.

4.3.1 Cargo transport

Chile is a well-developed country which strives to follow the trends of the world globalisation. Due to Chiles topography, around 95% of the foreign trade is mobilised by sea (Armada de Chile, 2016). Port development is therefore an important part in the growth of Chiles national economy. The most important export products are, in descending order: copper, ore, fruit, fish and wood. In a period of 7 years (2007-2014), the export of wood has increased with 51.3% (World's Top Exports, 2017).

The port of Corral is the only port in the Region de Los Ríos which is accessible for sea-going vessels of significant size. It allows the arrival of 'Panamax' vessels with a draft of 12.5 meters. Because of this, the port is a transition point where cargo from smaller inland ports arrives which is then further transferred onto larger vessels for foreign export. This makes the port of Las Mulatas an important port as well (Port of Corral, 2017b).

Wood is the main export product of Corral. Nearly all the export are wood chips of which the major part is exported to Asia (Armada de Chile, 2016). Figure 4.2 presents an increasing trend of export from Corral. In 2016, over 980 thousand ton was exported with a value of 70 million US dollar. These increasing export rates indicate a raising demand for better port facilities in order to keep up with the developments.

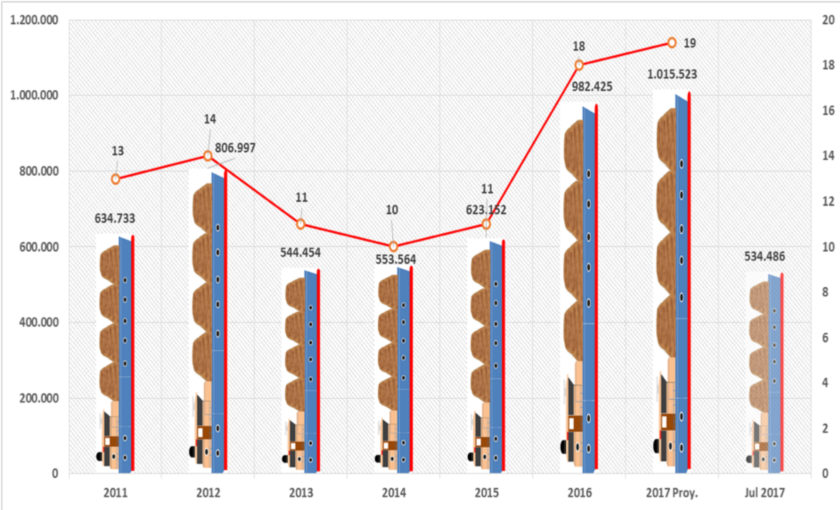

Figure 4.2: Export results 2011-2017, Port of Corral (Port of Corral, 2017b)

The Valdivia river is mainly used for cargo navigation because there is an absence of a suitable and safe road access for trucks to the port of Corral. This makes the port of Corral less accessible than Valdivia for trucks coming from the hinterland. Wood from the hinterland is therefore collected at several collection points in and near Valdivia. The port of Las Mulatas is the most significant port in Valdivia with the potential to accommodate larger amounts of cargo transport. Therefore, focus will be on the river connection between Corral and the port of Las Mulatas. A more detailed description of the ports and inland cargo transport in the Valdivia area is given in Appendix B.2.1.

4.3.2 Tourism

Region de Los Ríos is one of the regions in Chile which possesses a high potential and touristic development in the country. The most popular place for tourists in this area is Valdivia (Feria, 2012). Figure 4.3 presents the monthly arrivals of tourists in the Valdivia-Corral area, also compared with the arrivals in the whole region. It is clear that the tourism is season dependent. Most of the tourists arrive in the summer days.

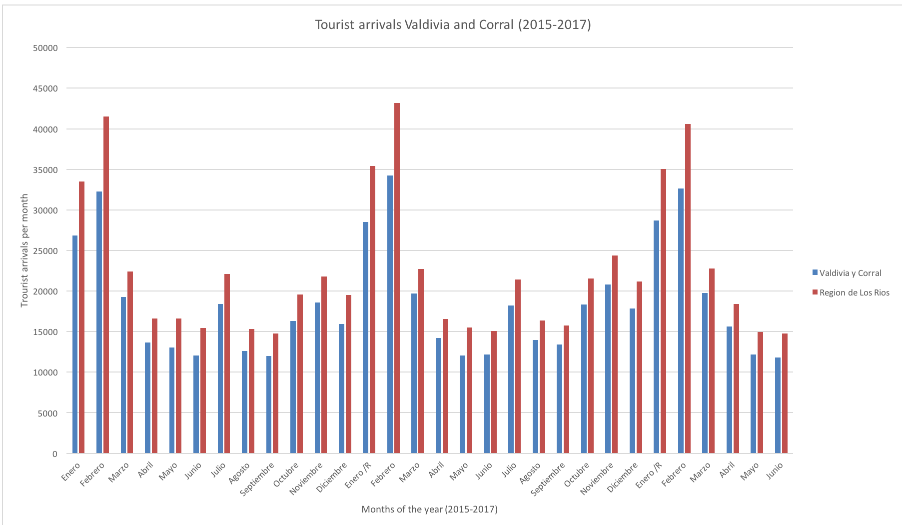

Figure 4.3: Tourist arrivals in Valdivia-Corral and Region de Los Ríos (Instuto Nacional de Estadisticas, 2017)

The Valdivia estuary has a lot to offer for tourists of which the most important are fluvial activities and nature enjoyment. Boat trips along the Valdivia estuary offer the combination between transport along the area and sightseeing opportunities and are thus a popular tourist attraction. The river also facilitates recreational beaches which are popular along residents and tourists during summer season (Feria, 2012). The passenger transport along the Valdivia estuary is currently regulated by means of ferries and road transport which is further described in Appendix B.2.2 (Ministerio de Obras Publicas, 2015).

4.3.3 Waste water

The future development of the Valdivia area will also influence the amount of waste water that is dumped into the Valdivia river. In regular river systems, the waste water is transported with the river flow into the sea. However, in this estuarine system, the tides play a part. The Ministry believes that the industrial waste water that is dumped into the Valdivia river remains in the system (personal communication, September 4^{th}, 2017). With this statement they assume that industrial waste accumulates in the estuary system.

However, when there is a net outflow of water the minerals from the industrial waste are supposed to be flowing out of the system as well. If it is true that the industrial waste remains in the system, then there should also be a high salinity indicating that minerals accumulate in the estuary system. Studies showed that salinity decreases further away from the river mouth in estuaries (Nguyen & Savenije, 2006). More about this phenomenon is described in Section 5.5. Also, it is proven that there is a net outflow of the Valdivia estuary system (Pino et al., 1993). Therefore it can be stated that if there is no more input of industrial water, the waste water will eventually flow out of the system.

Although theoretically the industrial waste should be flowing out, the Valdivia government experiences problems regarding industrial waste in the Valdivia river. A reason could be that the input of waste water exceeds the outflow because the exact outflow of industrial waste is not known. In order to minimise contamination in the river, the government tries to cover the industrial waste by installing waste water treatment plants (Cartulinas CMP, 2008). The future development of the Valdivia area initiates a huge challenge in order to keep the industrial waste within the limits and to prevent unacceptable contamination rates in the Valdivia river.

5. Estuary and Rivers

Every coastal system around the world is different. There are many factors that play their part in the shape and characteristics of the system. This chapter will consider the available information of the main characteristics in the system in order to get a broad overview of the Valdivia river and estuary. Not all information will be used for this particular research. However, it creates a extensive analysis of the important processes which gives a suitable basis for further research.

5.1 Topography

The topography of the research area already says a lot about the characteristics of the coastal system. This section is focused on the analysis of the position of the Valdivia estuary. Analysing the topography of the Valdivia estuary is done by starting on macro scale zooming in until the topography inside the estuary.

5.1.1 Coast

The coast of Chile is a so called leading edge coast (see Figure 5.1). A leading edge coast is a coast which is located next to a convergent boundary of two tectonic plates (Bosboom & Stive, 2015). Due to the collision of the plates mountains and submarine canyons are created. Leading edge coasts, or collision coasts, are therefore characterised by rugged, cliffed coastlines, tectonic activity and a narrow continental shelf. Because of the narrow continental shelf, submarine canyon heads lay relatively close to the shore. As a result, most of the sediment deposited along the coast moves offshore through canyons and thus into the deeper water beyond the shelf. Therefore the coastal zone of Chile has relatively little sediment even if large amounts of sediments are transported to the coast by the rivers.

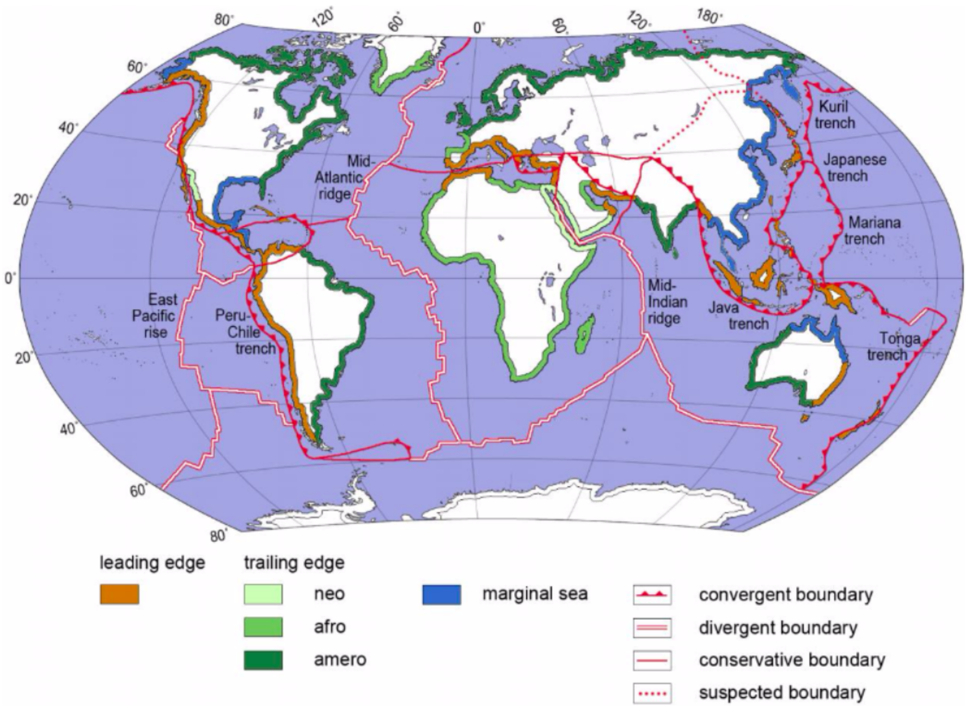

Figure 5.1: Tectonic classification of coasts around the world (Bosboom & Stive, 2015)

5.1.2 Estuary classification

An estuary system always consists of one or more rivers near the sea side, where the fresh water discharges meet the salt water of the ocean (Bosboom & Stive, 2015). Coastal systems can be influenced by the rivers, the tides and the waves. For each system the dominance of these factors is distributed differently. Because of this, every coastal morphology is unique. Looking at the large scale morphology some first conclusions can be made regarding the type of system Valdivia represents.

Figure B.8 shows eight main coastal morphologies in which the Valdivia system is mostly represented by sketch number six. Morphology six is most representative for an estuarine system with the tide being the dominant component over fluvial and wave influences. Figure 5.2 confirms the expectations of the relative influences in the Valdivia system.

The relative influence of these three components gives an indication of the type of system, but the exact influence and effect of the components need to be researched in more detail to analyse the flow patterns and eventually the sedimentation and erosion trends.

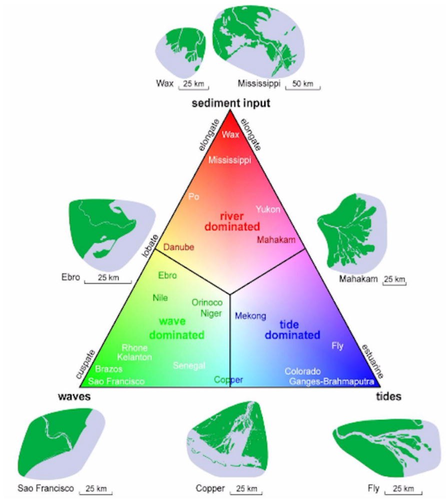

Figure 5.2: William Gallow's diagram; the influences of waves, tides and rivers (Bosboom & Stive, 2015)

An alluvial estuary has movable beds, consisting of sediments of both riverine and marine sediments, in which there is a measurable influence of fresh water inflow (Savenije, 2012). In principle, a river always adapts to its present hydraulic characteristics in order to reach a morphological equilibrium (Jansen, van Bendegom, van den Berg, de Vries, & Zanen, 1979). This system is unique because it will never reach a stage of morphological equilibrium due to the tectonic behaviour of the surface. The tectonic behaviour is expressed by the frequent occurrence of earthquakes causing subsidence or uplift of the surface. The sedimentation can not keep up with these geological changes. Due to these characteristics, the Valdivia estuary can be geologically classified as a 'short alluvial estuary' (Savenije, 2012).

In an alluvial estuary, the water movement depends on the topography. Therefore the shape of the estuary tells a lot about the hydrological processes that are present.

One of the characteristics that identifies the shape, is the convergence. This refers to how strong an estuary converges from the sea towards the river which is why the convergence is analysed from downstream to upstream. Between Corral and Isla del Rey, the banks of the estuary are nearly parallel (see Figure 3.2). This is typical for shipping estuaries in which the banks are artificially made which is the case in the Valdivia river. Beyond Isla del Rey, the river converges after which it reaches the confluence point of the Calle Calle river and the Cruces river. Due to this long convergence distance, the estuary should topographically be classified as prismatic shaped. This is also confirmed by the presence of channelling structures causing parallel banks in the Valdivia river. Characteristics of a prismatic shaped estuary are a progressive tidal wave type and stratified salt intrusion (Savenije, 2012).

5.1.3 River catchment

The area contributing to the discharge at a particular river cross-section is defined as the river catchment (Savenije, 2006). The topographic divide between two watersheds can be seen as the boundaries of the catchment. The total water resources of a catchment are formed by the sum of surface water and groundwater.

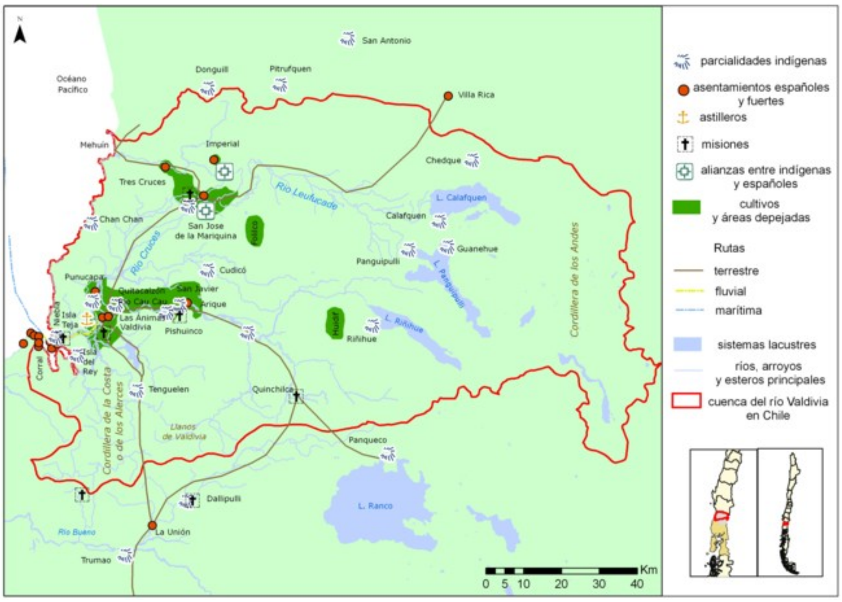

Figure 5.3: Catchment of the Valdivia River (Camus et al., 2011)

The total drainage area of the water that flows into the Valdivia river can be seen in Figure 5.3. The red line defines the boundaries of the catchment of the Valdivia river. The water resources of the river reach up to the Andes mountains in Argentina at the eastern end, where three large lakes facilitate a flow which changes seasonally, due to the melting glaciers in summer and heavier rain events in winter. The southern boundary of the catchment is formed because of the low permeability of the rocks of the Coastal Cordillera (Moreno & Gibbons, 2007). In the Valdivia river catchment, three subcatchments can be distinguished. An overview of all characteristics of the subcatchments and their rivers is displayed in Table 5.1.

5.1.3.1 Subcatchment of Calle Calle river

The subcatchment of the Calle Calle river is the largest of the three watersheds. The Calle Calle river finds its origins in the Andes mountains at the Argentinian border. A chain of three large lakes, Calafquén, Panguipulli and Riñihue, at the eastern end of Chile are filled with melting water from glaciers and rainwater. The lakes are interconnected and finally pour out into the San Pedro river. This part of the subcatchment has a surface area of 4135 km^2 (Cerda et al., 1996).

The San Pedro river on its turn flows in Western direction towards Valdivia. Multiple small pluvial rivers pour into the San Pedro river. At the city of Calle Calle the name changes into Calle Calle river. The part of the subcatchment from the beginning of the San Pedro river up until Valdivia has a surface area of 2289 km^2 (Cerda et al., 1996).

The total surface area of the subcatchment of the Calle Calle river amounts 6424 km^2. The predominant direction of flow is from East to West.

5.1.3.2 Subcatchment of Cruces river

The subcatchment of the Cruces river reaches up to the same area as the Calle Calle river subcatchment. The Cruces river originates from the mountain range of the Andes. The subcatchment has three large contributing rivers: the Cruces river, the Iñaque river and the Santo Domingo river. The surface area of the catchment of the Iñaque river amounts 724 km^2 and of the other part of the Cruces river catchment 1910 km^2. In total the surface area of the subcatchment of the Cruces river 2634 km^2 (Cerda et al., 1996). The predominant direction of flow is from Northeast to Southwest.

5.1.3.3 Subcatchment of Futa river

The third subcatchment lies in the South, where the Futa river originates. In comparison to the other two rivers, this river only depends on precipitation. The Futa river drains off the Cordillera de Oncol and has a much smaller catchment area than the other two rivers. The predominant flow direction of the subcatchment of the Futa river is from South to North. The total surface area is 524 km^2 (Cerda et al., 1996), from which the Naguilán river is also a small contributor with 90 km^2.

Table 5.1: Overview subcatchments (Cerda et al., 1996)

Subcatchment	Calle Calle	Cruces	Futa	Valdivia
Surface area [km^2]	6,424	2,634	524	9,582
Rivers	San Pedro, Calle Calle	Cruces, Iñaque, Santo Domingo	Futa, Naguilán	
Flow direction	West-East	Northeast-Southwest	South-North	
Origin	Lakes near Andes	Andes	Cordillera de Oncol	
Type	Pluvial and Glacial	Pluvial and Glacial	Pluvial	

5.1.4 Precipitation

The monthly averaged precipitation in Chile shows a peak in winter in June and a low in summer in November (see Appendix B.3.2). It ranges from 88.9 mm in June to 31.2 mm in November (World Bank, 2017). However, due to the fact that Chile's length from North to South is more than 4200 kilometers, the precipitation in Chile largely depends on latitude (Abarza et al., 2012). The station in the Valdivia river catchment measured a yearly average rainfall of 2113.7 millimeter (Abarza et al., 2012). That would mean that there is a monthly average rainfall of 352 millimeter. This is considerably larger than the monthly precipitation of Chile as a whole. Assumed is that the precipitation does follow the same shape as shown in Figure B.13, but the order of magnitude is expected to be around the values from the measuring station in the catchment.

5.1.5 Structures

In order to analyse the system correctly, a good bathymetry is required. One big unknown within this subject is the presence of submerged breakwaters. Due to their major influence on the hydraulic processes in the river, these structures are important to take into account.

As mentioned in Section 3.2, before the 1960 earthquake the Valdivia river was intervened by means of emerged channelling structures (see Figure 5.4). Due to the earthquake, the structures became submerged. In addition, the tsunami caused by the earthquake damaged the channelling works in the lower course of the river. The present state of the channelling works was investigated in 2017 (Direccion de Obras Portuarias, 2017). Several sections between the Cutipay river and the Guacamayo river were checked by means of underwater photographs (see Figure B.21 for the location).

The conclusions state that on average, the heads of the structures are located between 1.5 meter and 2.5 meter below the average water surface. The structure at the mouth of the Guacamayo river has collapsed so that the head of the structures do not reach beyond 4 meter under the water. The same holds for the opposite shore. Also, just upstream from the Cutipay river the structures are found to be situated around 3 meter below the average water surface. These findings indicate that in the river section between the Guacamayo and Cutipay river, the flows have not been channelled as intended by the original structures (Direccion de Obras Portuarias, 2017). This information is useful in order to assess the cause of the sedimentation problems in this particular area.

Figure 5.4: Channelling structures in the Valdivia river displayed by solid black lines (Direccion de Obras Portuarias, 2017)

5.2 Tides

The Valdivia estuary is a microtidal estuary which means that the tidal range is smaller than 2 meter (Pino et al., 1993). Although the tidal range is not large, the tidal influence on the sedimentation problems in the river is expected to be significant. This is because the tide has relatively large influence on the flow velocities and water levels in the Valdivia river as can be concluded from velocity measurements at Valdivia (see Figures B.10 and B.11).

5.2.1 Tidal constituents

The main tidal constituents on earth are the principal lunar and principal solar tide, formulated by M2 and S2 respectively (Bosboom & Stive, 2015). The index 2 indicates that the occurrence of tide changes twice per day, called semi-diurnal. Declination of the moon and sun influences the phase difference between the M2 and the S2 signal, which lead to possible daily inequality, or even a diurnal signal when the M2 and S2 are 45 degrees out of face. This happens for some parts of the world where the latitude is very high (see Figure B.9). However, Figure B.9 predicts a mixed: predominantly semi-diurnal tide for the coast near Valdivia (Bosboom & Stive, 2015).

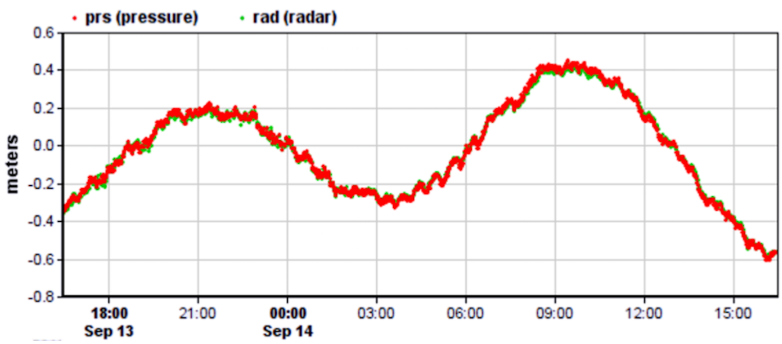

Figure 5.5: Tidal signal for one day in Corral (Unesco-IOC, 2017)

The Corral tide signal shows a daily inequality for the semi-diurnal tide in Figure 5.5. This shows the influence of diurnal tidal constituents. The concept of daily inequality is further explained in Appendix B.2. This daily inequality in Valdivia causes two different high and low water levels during the day. Since the period of the separate cycles remains almost equal, the ebb and flood flows caused by the tide are also different for the two parts of the day (Bosboom & Stive, 2015).

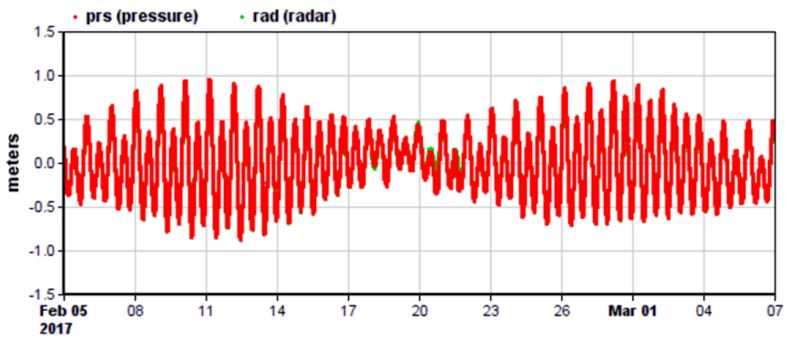

Figure 5.6: Tidal signal for 30 days in Corral (Unesco-IOC, 2017)

Even though the two main tidal constituents are both semi-diurnal, they are slightly out of phase causing a tidal variation by the name of spring and neap tide. Spring and neap tide are created due to the rotation of the moon around the earth (its location relative to the sun) and causes a tidal variation with a period of one lunar cycle which equals around one month (29.5 days) which is clearly shown in Figure 5.6 for Corral.

5.2.2 Flood and ebb dominance

For the understanding of hydrodynamics and morphological changes it is important to figure out if the hydrodynamic system has a flood dominant or an ebb dominant character. Flood or ebb dominance is a way of expression for how the tide influences the flow of water in the estuary. A system is flood dominant when the peak velocities during flood are higher than the peak velocities during ebb. These higher velocities result in the ability of transporting coarser sediment during flood than during ebb (Bosboom & Stive, 2015).

Whether a tidal basin is flood or ebb dominant can be determined in different ways. One way is to analyse the tidal signal (Bosboom & Stive, 2015). From the signal it can be seen whether the flow velocities are higher during flood or ebb by looking at the steepness of the graph. When the tide changes from low water to high water in a shorter time than it changes from high water to low water, the flow velocities into the system are higher than the flow velocities directed outward the system which can lead to the import of sediment. When analysing the tidal signal at Corral (see Figure 5.7), it can be seen that the steepness of the graph during outflow hardly differs from the steepness of the graph during inflow. It is thus hard to determine whether the estuary is flood or ebb dominant.

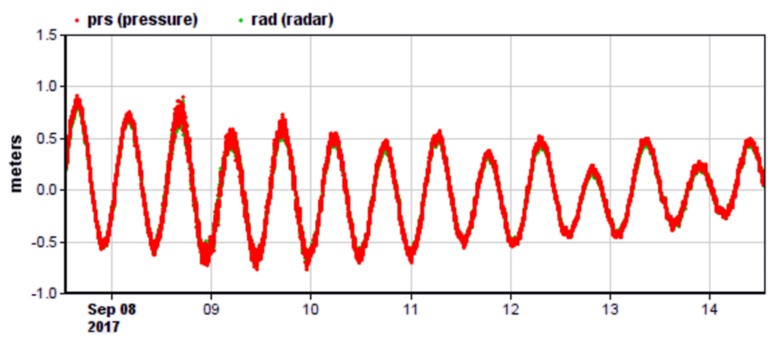

Figure 5.7: Tidal signal for 12 days in Corral (Unesco-IOC, 2017)

Another way to analyse the system is by looking at the bathymetry. How the bathymetry influences the tide will be explained using Figure 5.8.

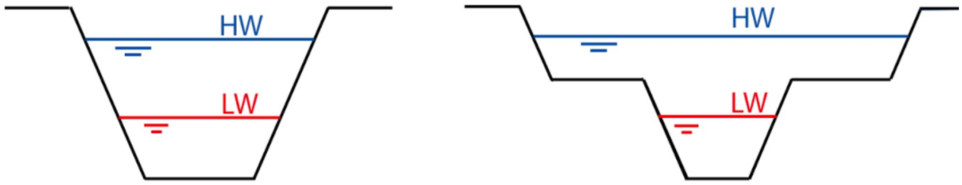

Figure 5.8: Typical bottom profiles for flood dominant (left) and ebb dominant (right) systems (Bosboom & Stive, 2015)

If only the tidal influence is regarded (as for a tidal basin), it can be said that the amount of water that flows into the system during flood is equal to the amount of water that flows out during ebb. From Figure 5.8 it can be noticed that when systems have large tidal flats, the system probably will be ebb dominant. This is because during flood the water level is higher and therefore the water flows over the floodplains. Due to the larger cross section of the water column the water flows slower during flood than during ebb which leads to more sediment flowing out of the system (Bosboom & Stive, 2015). The estuary has a flood dominant profile rather than a lot of tidal flats. However, the research focuses on the Valdivia river section where the sedimentation takes place. The Valdivia river has a mostly rectangular or trapezoidal profile in the entire river with more wetlands at the upstream river half and in the Cruces and Calle Calle rivers. Figures B.11 and B.10 show the bottom profile for one cross section upstream, which show the mainly found bottom profile for the rivers and the included small part of the floodplain section in the left bank (Caamano-Avendano, 2017).

To conclude, it is hard to specify the estuary basin by means of flood or ebb dominance and it can be seen that the tidal signal in Corral shows no particular dominance. The Valdivia river must be ebb dominant considering the wetlands and the fact that clearly larger flow velocities are found during ebb than during flood when the high tide reaches far into the river and also floods the floodplains (Bosboom & Stive, 2015) (Caamano-Avendano, 2017).

5.2.3 Tidal wave

To understand how the tide will propagate through the estuary, it is important to know which type of tidal wave propagates in the Valdivia estuary and river. There are three main classifications of tidal waves: progressive, standing and mixed. As described in Section 5.1 the Valdivia estuary is prismatic shaped and thus subject to a progressive tidal wave. A progressive wave is a wave, at the maximum elevation there is also a high discharge. The phase difference between the elevation and the velocity is zero. Purely progressive waves occur in frictionless channels of infinite length and constant cross-section. A standing wave is different, it can be compared to the wave that is created in a tub by rocking it. The maximum and minimum water levels are reached at the same time. When the elevation is maximum, the velocity is zero. Therefore standing waves have a phase lag between the elevation and velocity of $\pi/2$. A purely standing wave occurs in harbours and semi-closed basins. A mixed wave is a mixture of a progressive and a standing wave (Bosboom & Stive, 2015).

5.2.4 Tidal prism

The Valdivia estuary can be seen as a tidal basin. This tidal basin wants to reach an equilibrium situation which is dependent on, amongst others, its tidal prism (see Appendix B.3.1). Because the Valdivia estuary is characterised by its tectonic activity the tidal prism varies constantly. This can have huge effects on the amount of sediment exported out of or imported into the estuary.

Because of the large subsidence during to the earthquake in 1960 more wetlands were created and the wet surface of the estuary increased (Feria, 2012). Due to this event, both the tidal prism as the channel volumes might have increased. Their relative change compared to each other is important to know to draw conclusions. However, this is yet unknown.

Although this subject has not been further analysed in detail, the tectonic activity is assumed to be an important long term process to be taken into account for the Valdivia estuary.

5.3 Rivers

Figure 5.9 shows an overview of the rivers in the Valdivia river catchment and the measuring stations for the river discharges. Concluded from Section 5.1.3 is that the most important contributing rivers for the Valdivia river are the Calle Calle, Cruces and Futa river. From the river shape it can be seen that these rivers are meandering. The river system south of the Valdivia river around the Futa river are described in more detail in Appendix B.3.5. In this section, the river discharges are further investigated.

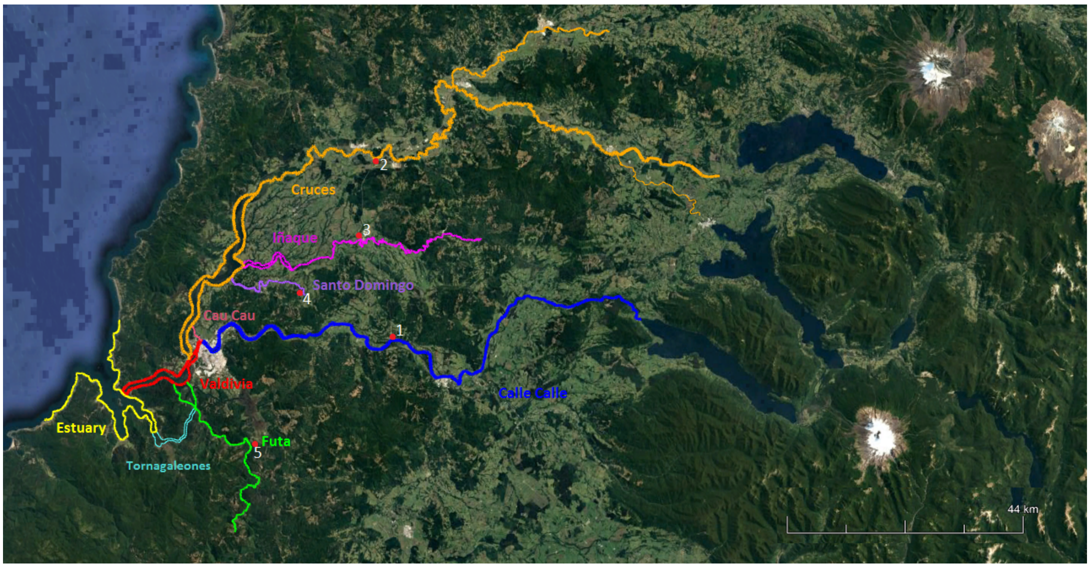

Figure 5.9: Overview of all rivers and measuring stations (Source: Google Earth, 2017)

For the river discharges, only the data of the largest contributing rivers will be collected and analysed. The Calle Calle, Cruces and Futa rivers are identified as the three significant rivers, as showed schematically in Figure 5.10. The Cau Cau river, Angachilla river, Naguilán river and the Cutipay river are relatively small compared to the entire river catchment and therefore assumed to have little influence on the river system.

From the locations of the measuring stations shown as red dots in Figure 5.9 can already be seen that not the entire drainage area of the catchment is measured.

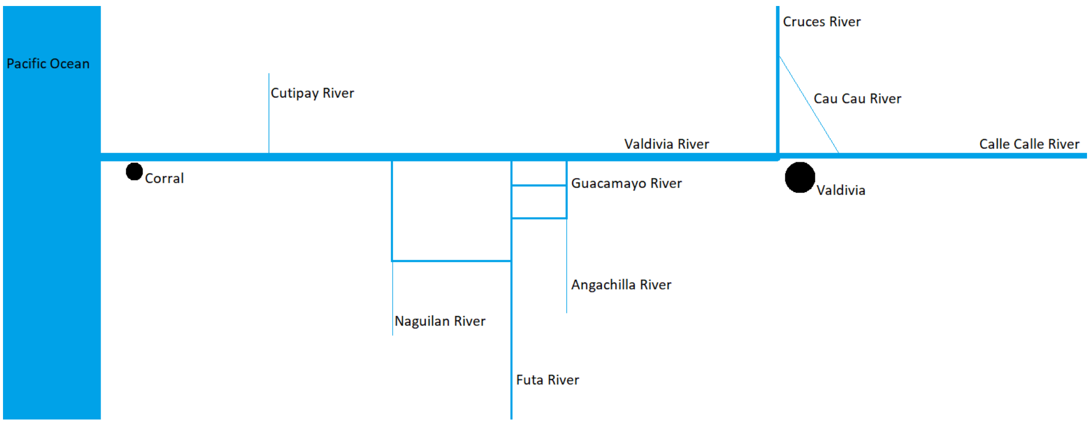

Figure 5.10: Schematic view on rivers contributing to Valdivia river (Own work)

5.3.1 Calle Calle

The discharge of the Calle Calle river is measured at Pupanahue, located 38 kilometers upstream from Valdivia (measuring station 1 in Figure 5.9). Data is found of the daily discharge of this river from September 2016 until August 2017 (Ministerio de Obras Publicas, 2017a). The monthly averaged discharge for the Calle Calle river is displayed in Table 5.2. In August is the highest averaged discharge of 855.34 m^3/s and in February the lowest average discharge of 153.79 m^3/s is measured.

Table 5.2: Monthly discharge of the Calle Calle river (Ministerio de Obras Publicas, 2017a)

Month	Discharge $[m^3/s]$
January	236.25
February	153.79
March	166.42
April	159.72
May	373.38
June	593.48
July	637.75
August	855.34
September	453.91
October	380.64
November	341.93
December	251.66

The Calle Calle river originates from the glaciers in the Andes mountains (Cerda et al., 1996). This makes that the river consists of both melting water as rain water. Figure B.13 shows that the largest peak of rainfall in Chile is in June. However, the discharge of the Calle Calle river shows the largest peak in August. This can be explained by the lag time (Savenije, 2006). In catchments there is a certain delay between inflow and outflow. The larger the catchment, the more storage area in surface water, ground water and interception on vegetation. All year round, there is a stable flow of water running down the Calle Calle river. The discharge in August is 5.5 times larger than in February. This can be explained by the inflow of melting water in summer and the inflow of water due to precipitation in winter.

5.3.2 Cruces

For the Cruces river, there is a measuring station at Rucaco, 59 kilometers upstream from the Valdivia river. There are more rivers contributing to the Cruces river more downstream from the Rucaco measuring station, the Iñaque and the Santo Domingo river. Therefore, the contribution of the Cruces river to the discharge of the Valdivia river consists of three components.

- **Cruces until Rucaco**

  The Rucaco measuring station can be seen as measuring station 2 in Figure 5.9. Data is found of the daily discharge of this part of the Cruces river from September 2016 until August 2017 (Ministerio de Obras Publicas, 2017a). The highest discharge of 194.40 m^3/s is measured in August and the lowest of 14.27 m^3/s is measured in February.

- **Iñaque**

  The measuring station of the Iñaque river is located in Máfil, 18 kilometers upstream from where it flows into the Cruces river (measuring station 3 in Figure 5.9). There is data available of the monthly discharge from 2000 until 2010 (Ministerio de Obras Publicas, 2017a). The highest discharge is 45.63 m^3/s in July and the lowest discharge is 4.43 m^3/s in March.

- **Santo Domingo**

  At the Santo Domingo river the measuring station is located in Rinconada de Piedra, 16 kilometers upstream from the Cruces river (measuring station 4 in Figure 5.9). Data is available of the monthly discharge from 2000 until 2013 (Ministerio de Obras Publicas, 2017a). In June the highest discharge is measured of 19.38 m^3/s, but this value is not that different from the 19.34 m^3/s in July. The lowest discharge of 2.71 m^3/s is measured in March.

In total these monthly averaged discharges lead to the estimated discharge of the Cruces river in Table 5.3. The total discharge is estimated to be the largest in August, where 247.33 m^3/s flow in the Valdivia river. The lowest discharge is measured in February, where there is a flow of only 22.12 m^3/s.

Table 5.3: Monthly averaged discharge of the Cruces river (Ministerio de Obras Publicas, 2017a)

Month	Cruces (Rucaco) $[m^3/s]$	Iñaque $[m^3/s]$	Santo Domingo $[m^3/s]$	Total $[m^3/s]$
January	19.19	6.32	3.46	28.98
February	14.27	4.81	3.03	22.12
March	16.51	4.43	2.71	23.65
April	17.62	5.24	3.79	26.65
May	45.84	12.41	8.82	67.07
June	125.10	36.80	19.38	181.28
July	122.94	45.63	19.34	187.91
August	194.40	35.88	17.05	247.33
September	64.21	30.02	10.80	105.03
October	51.10	19.16	8.21	78.47
November	37.25	13.95	6.38	57.57
December	25.13	9.35	4.80	39.28

Just like the discharge of the Calle Calle river, the peak in discharge in August can be explained by the lag time of the river catchment (Savenije, 2006). In comparison to the Calle Calle river, the difference between the low flows and high flows are much larger. The discharge in August is more than 11 times larger than in February. This can be an indication that the Cruces river does not depend on an inflow from melting water as much as the Calle Calle river.

5.3.3 Futa

The measuring station Tres Chiflones, where the measurements for the discharge of the Futa river are collected, is located 18 kilometres upstream from the Valdivia river (measuring station 5 in Figure 5.9). The data collected from this station is the monthly averaged discharge from July 2002 until October 2013 (Ministerio de Obras Publicas, 2017a). In Table 5.4 the total monthly averaged discharge from this time frame is displayed. In March the lowest discharge is measured of 4.80 m^3/s and in June the largest discharge is measured, of 62.35 m^3/s.

Table 5.4: Monthly average discharge of the Futa river (Ministerio de Obras Publicas, 2017a)

Month	**Discharge** $[m^3/s]$
January	7.05
February	5.95
March	4.80
April	12.12
May	29.32
June	62.35
July	61.17
August	53.90
September	35.53
October	26.28
November	14.35
December	11.57

Just as expected from the catchment size of the Futa river, the peak in discharge is earlier than the catchments of the Calle Calle and Cruces rivers. The peak of discharge is in June, there is almost no lag time (Savenije, 2006). Also, there is a large difference between the discharge in summer and in winter. In June the discharge is 13 times larger than in March. This can be explained by the fact that the Futa river is only dependent on rain. There is a relatively modest flow in summer, because there is no inflow from melting water.

5.3.4 Valdivia river

Together the discharges from Table 5.2, Table 5.3 and Table 5.4 will result in an estimation of the total discharge of the Valdivia river. In Figure 5.11 the total discharge per month is displayed. The largest total discharge is in August, where 1,156.57 cubic meters per second flow into the Pacific Ocean. In February the lowest discharge is estimated, where the total of the three river discharges is only 181.85 cubic meters per second.

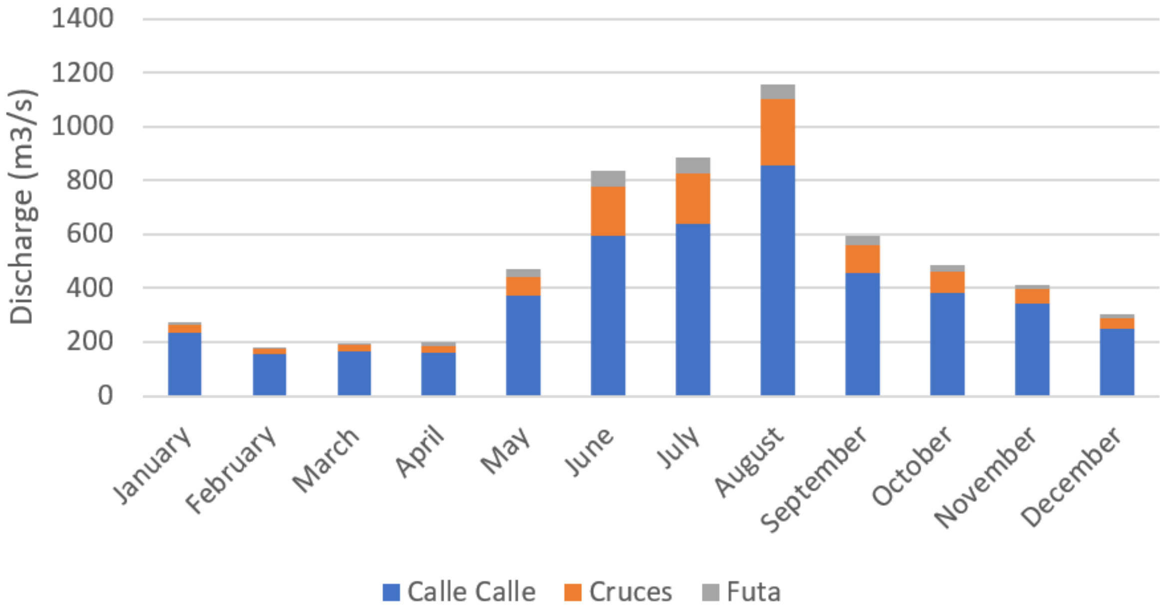

Figure 5.11: Estimated total river discharge Valdivia river [m^3/s] (Own work)

The discharges were measured in different years, so the graph does not show the discharge for a particular year. Next to that, there were a few more small rivers that are not adding up to the total of the river discharges, because most measuring station are located upstream. These small rivers are now neglected. Therefore, the projected total river discharge for the Valdivia river can only be seen as an estimation or a direction for the order of magnitude.

5.4 Waves

In a microtidal estuary, the estuarine processes are dominated by upland discharge and wave action from the sea (Savenije, 2012). The extent of wave influence in the Valdivia river can be determined from by comparing the dominant swell wave direction with the positioning of the Valdivia river entrance. In Figure B.14 it is showed that the dominant swell direction is South-West. Looking at the topography, it is not likely that these swell waves can intrude into the Valdivia river (Wisuki, 2017).

5.5 Salt intrusion

The rivers discharge fresh water into the estuary, and the sea fills the estuary with salty water on the rhythm of the tide (Savenije, 2012). These events result in a brackish environment in the estuary (and possibly in the river). The salinity of the estuary depends on the balance between the tide-driven saltwater flux and the fresh water flux.

Density differences between salt and fresh water initiate gravitational mixing which is a dominant mixing process in (near) prismatic estuaries like the Valdivia river (see Section 5.1). The denser salt water is concentrated near the bottom and the less dense fresh water is concentrated near the surface. Due to this formation of layers there is a residual circulation that transports salt water in upstream direction and fresh water in downstream direction (Savenije, 2012). This circulation phenomenon influences not only the water flows but also the sediment transport. If the saltwater flows upstream, sediment is transported upstream as well. The behaviour of the salt intrusion into the estuary is therefore important to analyse. This is further explained in Section 5.6.3.

5.5.1 Stratification

Stratification can be defined as the difference between the salinity at the water surface and the salinity near the bottom, divided by their average (Savenije, 2012). Based on the stratification of a water column, the main factors affecting estuaries are river discharge, mixing and tidal currents. A halocline is the transition zone between water bodies with a different density. The presence of a strong halocline indicates that layers of a (almost) homogeneous composition are separated. A weak halocline indicates a more mixed character between both layers.

Based on this, an estuary can be classified by means of three types of salt intrusion: stratified (or saline wedge), partially mixed, and well mixed (Figure 5.12).

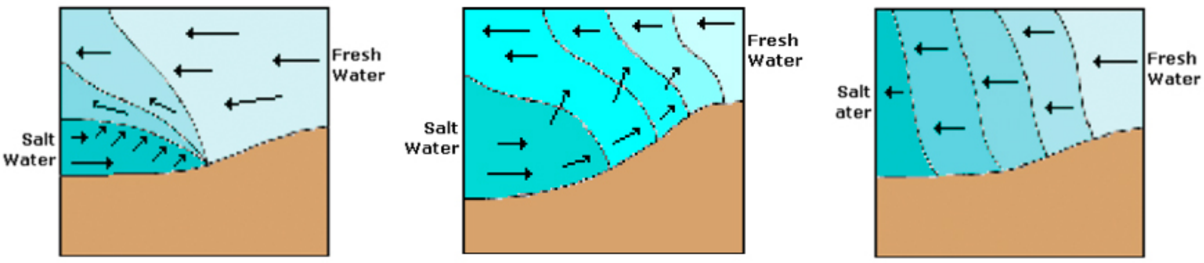

Figure 5.12: Different types of intrusion: saline wedge (left), partially mixed (middle), and well-mixed (right) (US Environmental Protection Agency, 2001)

Saline wedge estuaries are characterised by a high river discharge, low tidal mixing, and weak tidal currents. In these conditions, a strong halocline is present. Well mixed estuaries represent the contrary: low river discharge, maximum tidal mixing, and large tidal currents. With these estuarine conditions, the halocline is weak or not even existent. Between these extremes is the partially mixed type.

The Valdivia estuary varies seasonally, behaving like a saline-wedge estuary in winter and spring due to high river discharges (Garces-Vargas et al., 2013). During summer and autumn, the river discharges are low resulting in a partly mixed behaviour. The variability of interaction between the acting forces are thus the reason of the seasonal variability in the estuary. However, not only the river discharges and the tidal currents seemed to be important. The wind and temperature also affect the degree of salt intrusion into the estuary. In June a saline wedge was observed due to the large river discharges, but this was strengthened even more by the wind which forced the salt water more land inwards. Besides, high evaporation rates can increase the salinity of the estuary as well (Garces-Vargas et al., 2013).

5.5.2 Import of sediment

According to these characteristics, the Valdivia estuary is likely to import marine sediment, especially during seasons with large river discharges. The sea water is able to intrude up to beyond the Río Cutipay (14 kilometers from the mouth) during the period with the lowest discharge values (Garces-Vargas et al., 2013). However, as described in Section 5.1, it is questionable whether enough marine sediment is available at the coast to be imported into the Valdivia river.

For now, mainly mixing of salt and fresh water due to river forcing was discussed. This is assumed to be the main mixing process because the Valdivia estuary is near prismatic with a long convergence length. However, due to the earthquake in 1960 a large area of salt marshes and tidal flats developed in the Valdivia estuary. Besides, irregularities like dead-end branches also occur. These characteristics cause that tidal mixing may possibly not be ignored compared to river forced mixing. An example of a possible present form of tidal mixing is tidal trapping. In a dead-end branch and on tidal flats, slack occurs at high water whereas the water in the estuary is still flowing upstream at high water. Between high water and high water slack, the water level drops and the dead-end branch already starts emptying while the estuary still flows upstream with relatively saline water. Hence, a dead-end branch discharges relatively fresh water into the flood flow (Savenije, 2012). This is called tidal trapping. An example of a (nearly) dead-end branch in the Valdivia estuary is the Cutipay river which delivers a non-significant discharge into the estuary (see Section 5.3).

5.6 Sediment

An excess of sediment is the main cause of the issues in the Valdivia river. In this section, the seven sedimentation points in the river are identified and the origin and composition of the sediment is analysed.

5.6.1 Dredging activities

After the earthquake in 1960 the sedimentation problem, that was thought to be solved by the construction of emerged breakwaters, started to return. Due to the amount of sedimentation the water depth becomes insufficient for the cargo ships to navigate the river. Yet, there is not a clear policy on how to respond to this problem. Once in a while private companies, who used the river to transport wood over the Valdivia river, just complained to the Ministry of Public Works about the water depth when the echo sounders of their ships measured a too low water depth to navigate safely (personal communication, September 4^{th}, 2017). In reaction to that the Ministry hired a dredging company to solve the problem. Nowadays the Ministry wants to change their policy from a reactive character to a preventive character. In 2010 the Ministry of Public Works started with a large dredging project to deepen seven points in the river which hinder cargo ships that navigate from Corral to Valdivia and vice versa. The seven points which have been dredged are shown in Figure 5.13. The dredging project started in 2013 and was planned to be executed within two years (Austral Valdiva, 2013). The project costs were estimated on 4.5 million US dollar. The amount of dredged material is shown in Table 5.5.

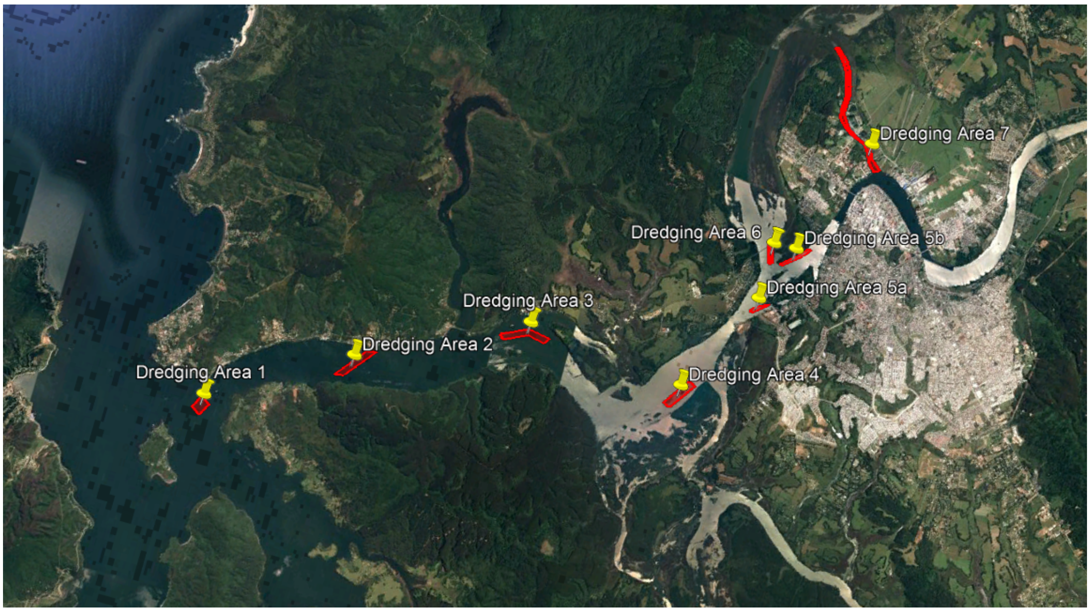

Figure 5.13: The seven dredging areas (Source: Google Earth, 2017)

Table 5.5: Dredging locations (Direccion de Obras Portuarias, 2017)

Area	Location	Cutting depth [m]	Dredged volume [m^3]	Dredge area [m^2]
1	Bahia Corral	4.5	14,476	31,871
2	Ex Vapor Canelo	4.5	69,423	127,412
3	Isla Sofia	4.5	28,730	58,277
4	Confluencia Rio Guacamayo (Norte Isla Mota)	4.5	6,788	20,271
5	Islote Haverberck Rio Valdivia	4.5	72,726	83,356
5	Islote Haverberck	4.5	21,677	24,805
6	Confluencia Rio Cruces (Puente)	4.5	3,314	9.062
7	Rio Cau Cau	4.5	22,416	30,800
Total			238,551	

5.6.2 Composition sediment

As described in Section 5.1.3, the Cruces river and the Calle Calle river find their origin at the lakes Calafquén, Panguipulli and Riñihue. Close to these lakes, the volcanoes Villarrica, Lanín and Choshuenco are located (see Figure 5.9). These volcanoes indicate that the soil is likely to consist of volcanic rock. The lakes act as natural traps and therefore the sediment transported by the rivers coming from these lakes is the product of the erosion of volcanic and glacial deposits of the Central Valley (Pino et al., 1993). To get an idea about the sediment in the Valdivia river, the analysed material of 2010 pre-dredging research activities has been analysed.

Tables B.8 and B.9 show the sediment grainsize distribution in 14 different places. The seven areas are showed in Section 5.13. These distributions have to be translated to a specific value of the median grainsize in the river because this is one of the input values of the Delft3D model. The median grainsize is called the D50. With a standard soil mechanics method (Verruijt, 2012), the distribution is plotted on a logarithmic scale. Figures B.22 until B.35 represent these graphs (Silob Chile Laboratorios, 2010). Using these graphs, the D50 is found by crossing the graph with the 50% line and notate the comparing grainsize. This leads to 14 different values for D50 with an averaged value of 40 μm (see Table 5.6). This can be classified as silt.

Table 5.6: D50 values (Silob Chile Laboratorios, 2010)

Location	D50 (μm)
M1	37
M2	47
M3	39
M4	39
M5	40
M6	40
M7	35
M8	37
M9	22
M10	28
M11	77
M12	38
M13	40
M14	40
Average	**40**

5.6.3 Sources

There are two possible sediment sources of the Valdivia river that have to be considered: the sea and upstream of the Valdvia river.

5.6.3.1 Sea sources

Three modes of transport of sediment due to the sea are considered in this report. These transport modes are: cross shore transport, alongshore transport and redistribution of sediment in the estuary.

As described in Section 5.1.1, there is little sediment transported in cross shore and alongshore direction. Furthermore, the estuary has an ebb dominant character as described in Section 5.2.2. Therefore, most of the sediment on the narrow continental shelf will flow in offshore direction. More important is the redistribution of sediment that has been deposited in the estuary. Most of the sediment that is transported by the river all the way down to the estuary will deposit in the estuary because the quickly decreasing flow velocity. The flow velocity decreases relatively fast because the cross section of the estuary is much larger than the depth in the Valdivia river (Bosboom & Stive, 2015). The deposited sediment in the estuary can be redistributed along the river due to the tides. In Section 5.5, it is described how the salt water is flowing upstream of the river during flood. Furthermore, it is described that the tide generates stratified flows in upstream direction of the Valdivia river. In general, the concentration of sediment will be higher lower in the water column. This leads to the transport of coarser sediment during flood in upstream direction and transport of finer sediment in downstream direction. The tide can therefore result in a net import of sediment even though the system of the estuary and the river has an ebb dominant character. Figure 5.14 further explains this matter (Bosboom & Stive, 2015).

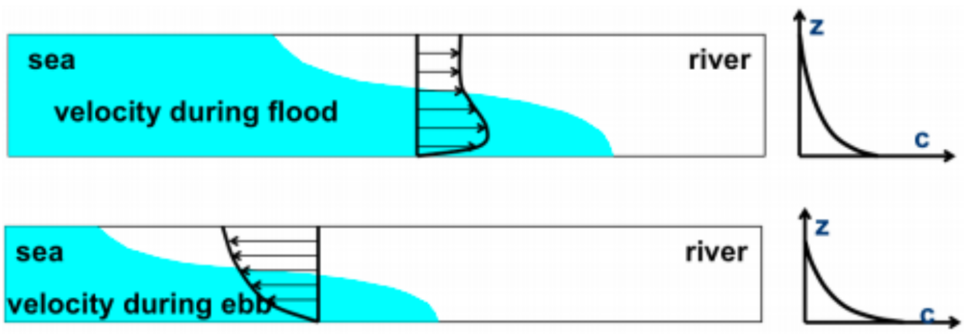

Figure 5.14: Tidal salt and fresh water flows with concentration of sediments distributed over the depth (van Prooijen, 2016)

5.6.3.2 River sources

The Valdivia river catchment is defined in Section 5.1.3. According to data from 2004, the land use mostly exists of meadows (28%), forestry (13%) and natural forests (45%) (Ministerio de Obras Publicas, 2004). The Cruces, Calle Calle and Futa river are identified as the three significant contributors to the total discharge of the Valdivia river. Therefore, in this section, there will be an analysis on what the land uses are around these rivers. The land use can influence the transport of sediment from upstream into the Valdivia estuary.

As can be seen in Figure 5.15, there must have been changes in land use since 2004, as it is clear that less than 45% of the catchment area is natural forest now. It is assumed that the area covered with natural forests has been scaled down. This has been done to give space to agricultural and forest plantation lands. In Appendix B.3.4 there are more detailed satellite images of the river catchment to clarify what is happening with the area. Figure B.18 shows a lot of agriculture around the Cruces river, mostly directly next to the river. Around the Calle Calle river it is obvious that there also is agricultural land right next to the river (see Figure B.17). Besides that, south of the river there are some chopped forest plantations (see Figure B.16). At the Futa river catchment in Figure B.19 it is visible that there are mostly forest plantations near this river.

Figure 5.15: Satellite image of Valdivia river catchment (Source: Google Earth, 2017)

It is not known what the exact current distribution of land use in the Valdivia river catchment is. What might seem like natural forests from the satellite images, can also be a plantation in the sake of forestry. Of course the entire river catchment should be taken into account, not only upstream the three large rivers. Sources of sediment from the river side can for example also be washed away from certain areas where there is a back-and-forth movement of water caused by the tides. However, there is no data available about the composition of the sediment in terms of percentage sand, clay or loam. Therefore, in this section it is only possible to make predictions and explain the major processes leading to sediment in the estuary. It is not possible to draw conclusions, because there is very little data available to analyse.

Deforestation and substitution of native forests into meadows or agricultural land are two of the main causes of soil erosion. This could ultimately lead to an increase in sediment load into rivers (Garcia-Ruiz, 2009). Factors that explain the intensity of soil erosion are slope gradient, rainfall intensity, land use and plant cover. In forest areas, the strength of the soil depends on root strength, root density, life cycle of the trees and the slope of forests (Meng et al., 2014). Also canopy cover, sapling density, litter depth and woody debris are factors that influence the magnitude of soil loss (Sharma & Correia, 1988). There are indications of very high erosion rates after forest removal (Garcia-Ruiz, 2009). After deforestation soils lose structure, organic matter and nutrients, therefore plant recolonisation is difficult. Rainfall also has a big influence on soil erosion, when there is an annual precipitation of more than 380 mm. In the region of Valdivia, there is a much larger annual precipitation of 2114 mm (see Section 5.1.4). Deforestation could be caused by natural and human disturbances, for example by wildfires and forestry.

The change in land use has an influence on the soil erosion and therefore also on the sediment load into the rivers. In the Valdivia river catchment the causes of an increase in sediment load could be explained by the replacement of the native forests with land for forestry, meadows and agriculture. There is clear evidence that there has already been extensive forestry in the Valdivia river catchment (see Appendix B.3.4). Moreover, it is the desire of the Ministry of Public Works to increase the export of wood chips produced by the forest plantations.

Future development most likely indicates an increase in forestry in the Valdivia river catchment. However, this increase could ultimately lead to an even higher sediment load into the river system. If there is no action taken either on the cause-side, preventing soil erosion, or on the effect-side, dredging sediment in the estuary, the higher sediment rate could have large effects on the environment. Landslides have occurred in a researched area in Japan (Imaizumi et al., 2007). These landslides were caused by soil instability that was in turn caused by forestry and followed reforestation. In the study it was found that there is a time lag between harvesting and the occurrence of landslides. When no action is taken, an increase in sediment load into the estuary could lead to the accumulation of all sediment in the estuary. When the sediments accumulate at the bottom of the river, the river can get less deep. With the same river discharge, this would mean that the river needs to get wider, which might lead to floods. The river could also change its natural course as an effect. These effects are identified as possible risks when the sediment load from the rivers will keep on increasing. What will actually happen, depends on much more variables than the factors described in this section.

6. Interpretation sedimentation

In this chapter the sedimentation points in the Valdivia river are analysed in detail. This is done in two steps. First, all the information about the system is processed in combination with general knowledge to define theoretical explanations. After this, a numerical model is used to verify the theoretical interpretations. These two parts are therefore likely to differ in terms of interpretations about the presence of the sedimentation point.

6.1 Theoretical

In this section, all seven sedimentation points are analysed by means of theoretical interpretations. Knowledge about river engineering principles is applied to the topographic and hydraulic characteristics of the Valdivia estuary system. This way, the presence of each sedimentation point can be explained. This is necessary in order to understand the results of a Delft3D model. Several used methods and relevant hydraulic processes are explained in Appendix C.

The presence of the submerged channelling structures is of major importance for this theoretical analysis. Therefore, it must be well understood that the structures which were once emerged, are now submerged (see Section 5.1.5). The nautical charts show that the water depth in the navigation channel is much deeper than on the other side of the structures (Navionics, 2017). The main flow is therefore still concentrated between the channelling structures, indicating that the structures did not completely lose their function due to the submergence. However, one huge difference is that the water is now able to flow over the structures which creates a whole new situation.

6.1.1 Point 1

The flow from the Valdivia river into the estuary experiences a sudden change in conveyance area as soon as now submerged channelling structures enter the estuary area. The cross section suddenly increases causing the flow velocity to decrease gradually from upstream towards the mouth. Since the transport capacity of a river is directly affected by the flow velocity, the sediment transport capacity decreases which initiates sedimentation (Section C.1.2).

In order for sedimentation to take place upstream from the tip of the channelling structures due to a difference in equilibrium water level, a M2 backwater curve is required (Blom, 2016). This backwater curve leads to a decrease in flow velocity within the channelling structures. Whether this M2 backwater curve is present depends on the tidal water levels in the estuary and the water levels in the Valdivia river. Section C.1.4 explains the basic theory of backwater curves. There is no information on the water levels within the Valdivia river so the Delft3D model could help to identify whether this M2 curve is present at location one.

Also, gravitational mixing due to salt water intrusion is likely to occur at this point as well as at sedimentation point 2. The maximum distance for the sea water to intrude into the Valdivia river was measured near the mouth of the Cutipay which is located 14 km from the estuary mouth (Garces-Vargas et al., 2013). So the points between the mouth of the estuary and the Cutipay river are likely to be influenced by gravitational mixing. These are points 1 and 2.

6.1.2 Point 2

In point 2 there is sedimentation in the navigation channel where the channel is transitioning from the northern bank to the southern bank. The part of the channel that is less deep due to the sedimentation can be clearly seen in Figure C.2. There can be given several explanations for the sedimentation in this part of the Valdivia river.

As described in the introduction of this chapter, the discharge flow of the river is concentrated in the deeper navigation channel, but there is also water flowing over the less shallower parts in the river with a lower flow velocity. Because the water depth outside the navigation channel is smaller, the friction has more influence on the flow velocity. A friction dominated situation occurs and therefore the flow velocity is calculated with the Chézy equation (6.1) and not with the, on continuity based, equation for discharge (6.2) (Jansen et al., 1979) (Battjes & Labeur, 2017).

$$u = C \cdot \sqrt{d * i} \tag{6.1}$$

$$Q = \int\int u_s dA = U \cdot A_c \tag{6.2}$$

Because there is relatively more friction at the shallow area, the flow velocity at the shallow area is smaller than in the deeper navigation channel. Due to viscosity, this slower flow lowers the average flow over the whole cross section.

From Figures 6.1 and 6.2 it can be noticed that the shallow area in cross-section B is much larger than the cross-section in A. The larger shallow area can be the reason for a reduction in flow velocity. The reduction in flow velocity reduces the sediment transport capacity which results in sedimentation (Section 5.2.2).

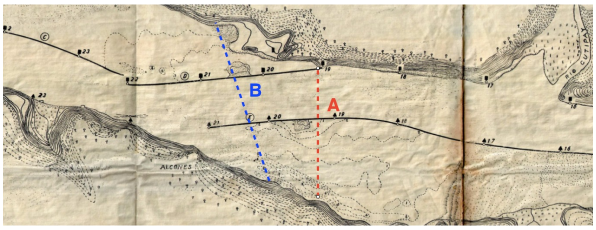

Figure 6.1: Different cross section in point 2 (Own work)

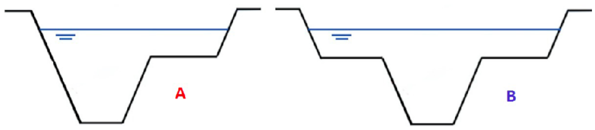

Figure 6.2: River cross sections A and B in point 2 (Own work)

Another cause of the sedimentation in point 2 can be the interaction between the primary and secondary flow lines which are created due to the submergence of the channelling structures and the separation between a main channel and shallow areas. In Figure 6.3, the primary and secondary flow lines are visualised. The red line expresses the possible secondary current with submerged structures. The flow follows the outer bend. The blue line expresses the main current in the navigation channel.

After the submergence, the flow direction has probably become a combination of the red and the blue line. Therefore the flow lines can cross each other in the navigation channel which can cause an eddy as shown in Figure 6.4. However this can only be the case when the two flow lines have the same order of flow velocity. When the flow lines cross each other an eddy could arise which leads to sedimentation.

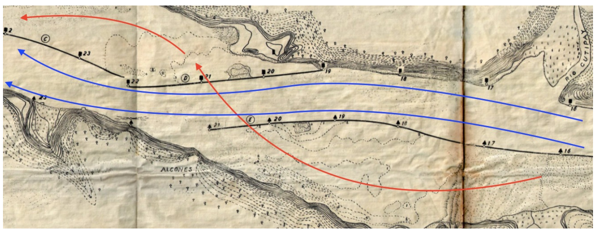

Figure 6.3: Secondary flow line (red) and primary flow line (blue) in point 2 (Own work)

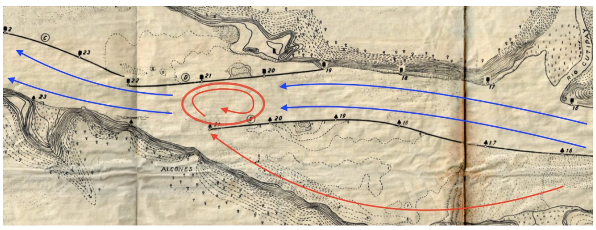

Figure 6.4: Eddy in the navigation channel in point 2 (Own work)

When the flow velocity in the navigation channel is too large, the flow from the shallow area is not able to enter the navigation channel and therefore it is reflected. Due to this reflection the flow on the shallow area is creating an eddy. Although the water cannot enter the navigation channel, the sediment that is flowing on the shallow area can slip into navigation channel causing sedimentation. When the flood flow is trying to pass the navigation channel but gets reflected, an eddy on the north side of the navigation channel can occur (Figure 6.5). When the flow velocity in downstream direction over the shallow area is too low compared to the flow velocity in the navigation channel, an eddy on the south side of the navigation channel can occur (Figure 6.6).

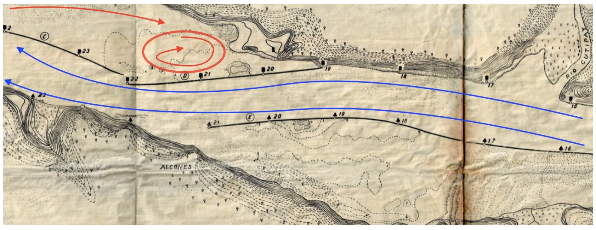

Figure 6.5: Eddy on the north side of the navigation channel in point 2 (Own work)

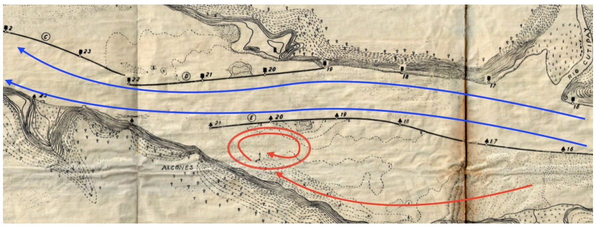

Figure 6.6: Eddy on the south side of the navigation channel in point 2 (Own work)

6.1.3 Point 3

Location 3 is located in the river bend just downstream of Isla San Francisco, in the main navigation channel. Here the channelling structures are not only submerged but also partly broken as proven by underwater pictures (Direccion de Obras Portuarias, 2017). Therefore there is a good reason to believe that the flow lines are much different from the original situation before the earthquake.

Figure 6.7 shows the flow lines with full emerged and intact structures, whereas Figure 6.8 shows the expected new flow lines in the area which are far more diverged in the main channel.

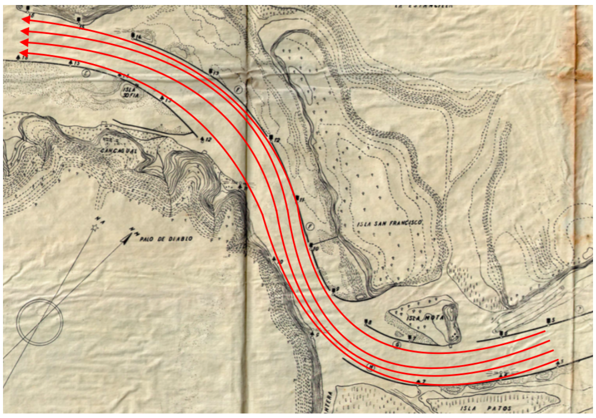

Figure 6.7: Point 3. Old situation flow lines with good quality of channelling structures (Own work)

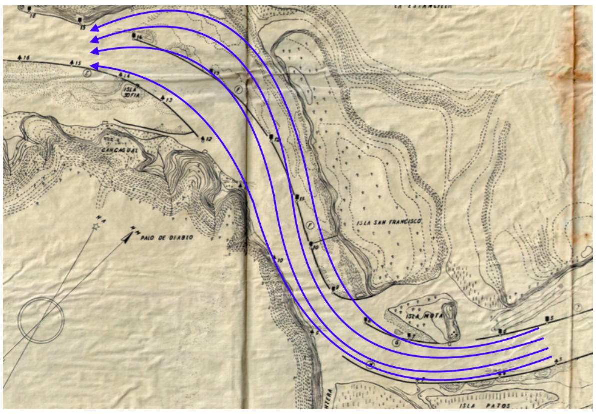

Figure 6.8: Point 3. New situation flow lines with low quality of channelling structures (Own work)

When a flow line diverts, the cross-section increases and the flow velocity decreases, given that the discharge remains unchanged (Jansen et al., 1979). This is likely the main cause for the sedimentation at this point.

Moreover, like point 2 the flow coming from the north side of the navigation channel could cause turbulent eddies at the north bank or inside of the channel causing sedimentation.

Also, some water can flow around the east side of Isla San Francisco during high tides, however no information is available about the intensity of these flows.

6.1.4 Point 4

Sedimentation point 4 is located at the confluence point of the Guacamayo river and the Valdivia river. The channelling structures in front of the mouth were originally built to stop the sediment coming from the Guacamayo entering the Valdivia river. According to new findings, the structure in front of the mouth has collapsed and thus lost its function (see Section 5.1.5). Just downstream of the mouth, the structure is still present thus representing a sharp corner.

The fresh water discharge of the Guacamayo river is assumed to be negligible, because of the relatively small discharge of the Futa river (see Section 5.3) and how the rivers south of the Valdivia river are connected (see Appendix B.3.5). Therefore it is assumed that the flow in this river is dominated by the tidal movement. During ebb tidal flows, the sediment in this river is likely to be flushed towards the Valdivia river where it either transports with the main flow, or deposits at the confluence point. The latter is happening, looking at this sedimentation point. Two possible processes responsible for the sedimentation are discussed. These processes are focused on the development of eddies (see Section C.1.3).

At the confluence point, the flow lines of the Guacamayo river meet the flow lines of the Valdivia river. If the momentum of the Guacamayo flow lines are not strong enough to enter the main flow, the Valdivia river flow will act like a wall and the Guacamayo flow lines bump into this wall. As a result an eddy will develop at the mouth of the Guacamayo river causing sedimentation (see Figure 6.9). Depending on the amount of sediment coming out of the Guacamayo river, a small ebb tidal delta can be developed. With this, it is assumed that the sediment can pass the 'wall' of the Valdivia river due to inertia.

If the Guacamayo flow lines can deliver sufficient momentum to enter the main flow, another phenomenon will occur. The Guacamayo flow can confluence with the Valdivia river flow assuming that the main flow is directed downstream. Due to the sharpness of the corner, a low pressure area develops just downstream of the edge of the structure. This low pressure area initiates an eddy to develop causing sedimentation (see Figure 6.10). The difference with the first case is that the sedimentation is located more downstream of the mouth.

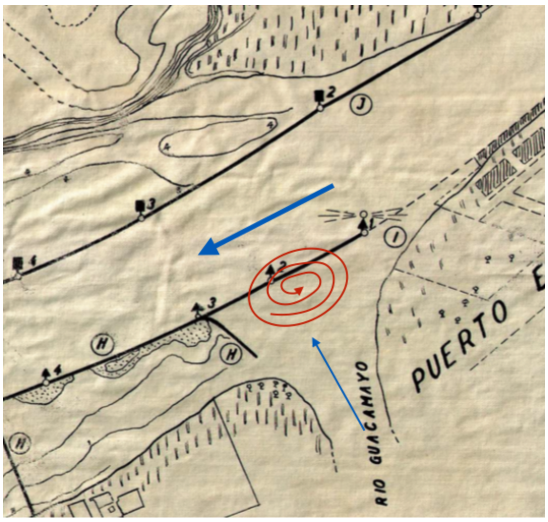

Figure 6.9: Point 4. Eddy formation at the mouth of the Guacamayo river (Own work)

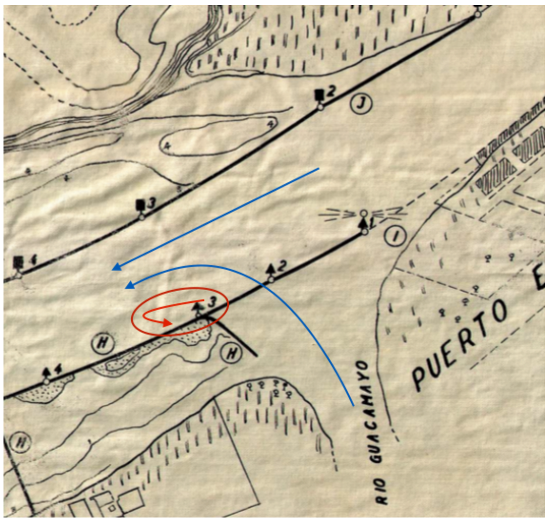

Figure 6.10: Point 4. Eddy formation West of the Guacamayo river mouth (Own work)

6.1.5 Point 5a

Sedimentation point 5a is located at the northeast side of the confluence point between the Calle Calle and the Cruces rivers. At this point, the Calle Calle river diverts. This diversion was first limited due to the presence of the structures, but their submergence allowed for diversion. This is possibly the main cause for the sedimentation at this point. In Figures 6.11 and 6.12, the flow lines are sketched in both situations.

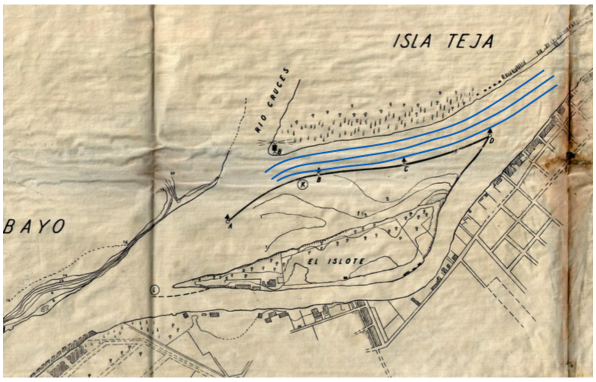

Figure 6.11: Point 5a. Flow lines with emerged structures (Own work)

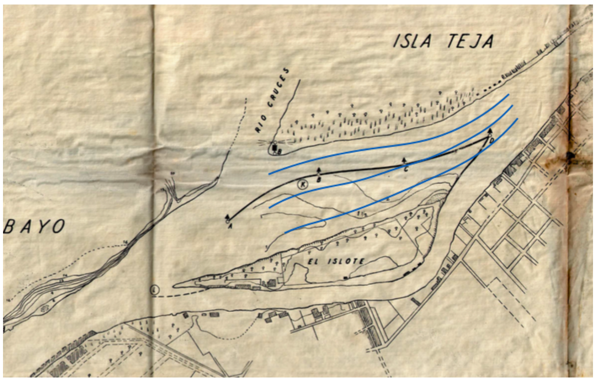

Figure 6.12: Point 5a. Flow lines with submerged structures (Own work)

6.1.6 Point 5b

Sedimentation point 5b is located at the end of the Haverbeck canal, which is a side channel just downstream of Valdivia (see Figure 6.11).

When the Valdivia river approaches Isla Haverbeck, the channel bifurcates by means of structures into a main channel and the Haverbeck side channel. Just after the bifurcation point the side channel converges after which is diverges along the second half of the side channel.

Also, the side channel is more narrow than the main channel, thus likely subject to more friction from the river banks. This could affect the flow velocity in the side channel negatively.

Taking into account these effects, it is expected that especially in the second half of the side channel the flow velocities heavily decrease. In the first half it is unclear whether the convergence or the increase in friction dominates.

6.1.7 Point 6

Sedimentation point six is located at the confluence point of the Cruces river and the Valdivia river (Figure 5.13). Due to the different flow velocities and different water depth in both rivers, there are two possible explanations for the sedimentation in point six. One explanation can be the M1 type backwater curve that arises due to a smaller water depth in the Cruces river compared to the water depth in the Valdivia river. When a M1 type backwater curve occurs is explained in section C.1.4. Due to the backwater curve the cross-section of the Cruces increases towards the mouth but the discharge remains the same, which causes a decrease in flow velocity and therefore a decrease in sediment transport capacity. A second reason for the sedimentation in point six can be the difference in flow velocity between the Cruces and the Valdivia river. When the flow velocity in the Cruces river is too slow compared to the flow velocity in the Valdivia river, the same happens as described in 6.1.2. The flow of the Cruces river gets reflected and creates an eddy. The eddy causes sedimentation. This visualisation is similar to the situation at point 4 (see Figure 6.9).

6.1.8 Point 7

Sedimentation point 7 is actually the whole Cau Cau river. This is a small river section between the Calle Calle river and the Cruces river, on the north side of Isla Teja (Figure C.1). Because the tidal influence is still significantly noticeable in this section of the Valdivia area, it is likely that the tide has the most dominant influence on the sedimentation in the Cau Cau river. This will be explained hereafter.

When a flood (tidal) wave enters the estuary, it takes time for the wave to affect each single point within its reach. The Cau Cau river is a special section of the rivers-system. It is likely that at both sides of the river (north side and south side) the flood wave arrives at a different time. This is because both points have a different distance towards the estuary mouth. Because of this difference, the tidal wave could first reach the south side and then the north side. The result is a difference in hydrostatic pressure on both sides of the river. This principle is similar to a tidal divide or tidal watershed (Vroom, 2011).

Depending on the stage of the tidal cycle, the hydrostatic pressure is largest at the north side or at the south side. This causes that the water flows back and forth through the Cau Cau river. So, the average flow velocity can be assumed to be low which initiates sedimentation.

Sediment may be imported from the Calle Calle river, looking at the location of the mouth of the river section (in the outer bend of the Calle Calle river). Due to the water movement in the Cau Cau, it is assumed that it is possible that sediment does not leave the river section, causing large sedimentation rates.

6.2 Delft3D model

The theoretical interpretations from Section 6 need to be verified by means of a Delft3D model. The causes of sedimentation are mainly explained by means of the direction and magnitude of flow lines. This is the most important information that needs to be extracted from the model. Therefore, this model is a 2-dimensional flow model in which sediment transport is excluded. Due to a bathymetry with a limited level of detail this model aims to describe tendencies of flow whereas exact magnitudes do not lie within the feasibility of the model. With this output information some sedimentation spots can possibly be verified.

Due to the tidal influence and yearly varying discharges, the model is analysed by looking at four particular situations. Focus lies on maximum tidal flow velocities which occur between high tide and low tide. These moments in time are compared for high and low river discharges. This way, insight is gained in whether the tide or the river discharge is dominant per situation and location.

It is important to understand that this model will serve as a basis which should be further expanded in future research. In this section, the results are described. The model settings are described in detail in Appendix C.

6.2.1 General overview

The Delft3D model includes a basic, smooth bathymetry, tidal movement and river discharges from the Calle Calle, Cruces and Futa rivers. Although the model is rather basic, the tendencies in flow directions and magnitudes are obtained.

The model shows that during low discharges, the tidal currents determine the flow directions in the whole system. This influence is weakened during high discharges. Then the tidal flow in upstream direction only reaches up to sedimentation point 6, where especially the discharge of the Calle Calle river becomes dominant over the tidal flow. This is further explained in Section 6.2.8.

The influence of the river discharge can also be seen in the water level elevation graph. As displayed in Figure C.23 and C.22, during low discharge, the duration from low to high water is the same as the duration from high to low water. During high discharge, the duration from high water to low water is longer. The influence of the discharge is thus clearly visible as a larger amount of water needs to leave the system compared to the amount of water flowing in during flood.

When analysing the sedimentation points, focus is on the tendencies in directions and magnitudes of the flow lines. Since there is no constant flow direction, sediment is transported back and forth through the system. In these model interpretations, exact magnitudes are missing in order to quantify sediment transport. Therefore the interpretations only refer to possibilities of sedimentation on the particular points of interest.

6.2.2 Point 1

It is not possible to verify sedimentation point 1 with the model. The geographical scope of the model is not large enough at the downstream end to locate differences in water depths and flow velocities. To verify this point, the model has to be extended towards the coastline.

6.2.3 Point 2

It can be seen that the flow velocities at shallow areas are lower than in the main channel. This verifies the possibility that the average velocity at this sedimentation point is lower than in the river bends where only one flood plain is present next to the main channel. The model shows that there is indeed a larger flow velocity in cross-section A than in cross-section B, especially during high discharges (see Figure C.13 and C.14). The cross sections are displayed in Figure 6.1.

The sedimentation causing eddies described in the theoretical analysis are quite clearly returning in the numerical model. Figure 6.13 shows relative small eddies on both sides of the navigation channel while Figure 6.14 shows a large on the southern side.

Figure 6.13 shows the moment just after the lowest water level has passed and water levels start to rise. The discharge through the main channel is dominant over the tide. However outside of the navigation channel in the shallow areas the tide is almost directly able to change the flow direction upstream. This secondary flow over the shallow areas however interacts with the main channel as expected and creates turbulence and low flow velocities in between the two opposite flow directions. Especially since there is no room for the upstream flow at the Northern bank to continue its path parallel to the main channel, low velocity circular flows are unavoidable during this period.

During maximum upstream flow forcing by the tide (around mid-tide) the flow direction is upstream in both the navigation channel and the shallow areas. Figure C.15 shows that for this moment in time no eddies are created due to the lack of interaction between two different flow directions. The tide is now dominant over the discharge. Evidently, the same goes for almost the entire falling period of the tide, at which the flow direction due to tidal forcing is equal to that of the discharges.

At the end of the rising water level, the discharge starts to reclaim dominance in point two, at which the flow direction of the navigation channel starts turning back in downstream direction. Before this happens though, the discharge has already changed the flow direction in the shallow areas and therefore the same yet reversed phenomenon occurs as just after the lowest water level.

During the time at which flow velocities on the shallow areas are higher than in the main channel, sediment could be lifted from the shallow areas and transported into the main channel.

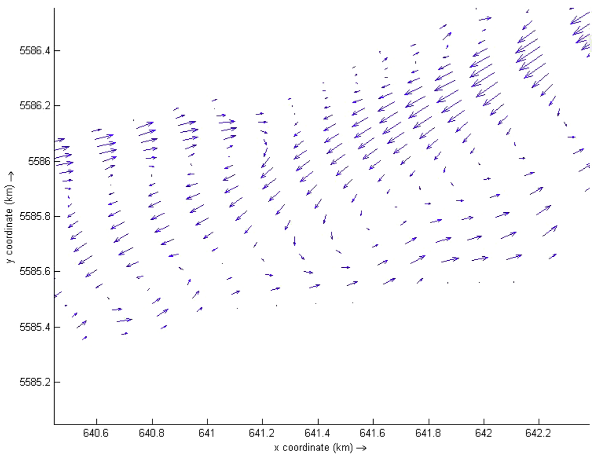

Figure 6.13: Flow lines in point 2 at high-tide during rising water levels (Own work)

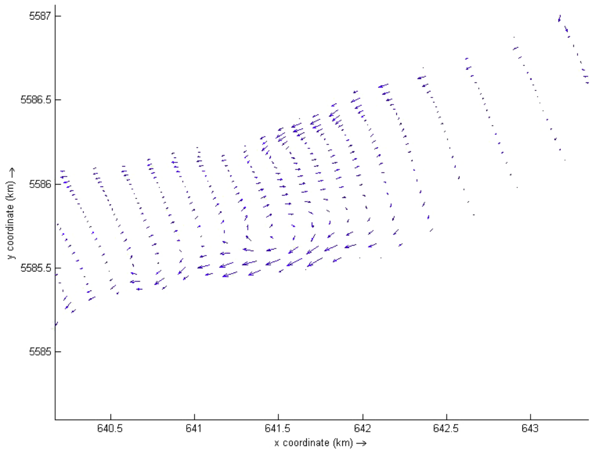

Figure 6.14: Flow lines in point 2 at low tide during rising water levels (Own work)

6.2.4 Point 3

The model results verify the diverging flow lines which were explained in the theoretical interpretations. This happens during ebb tidal flows as can be seen in Figures 6.15 and 6.16 at (645, 5587). Due to the diverging flow lines, the flow velocity is likely to decrease in this river section causing sedimentation.

This diverging flow lines indicate that the channelling structures are not fulfilling there purpose as well as before anymore, as was expected.

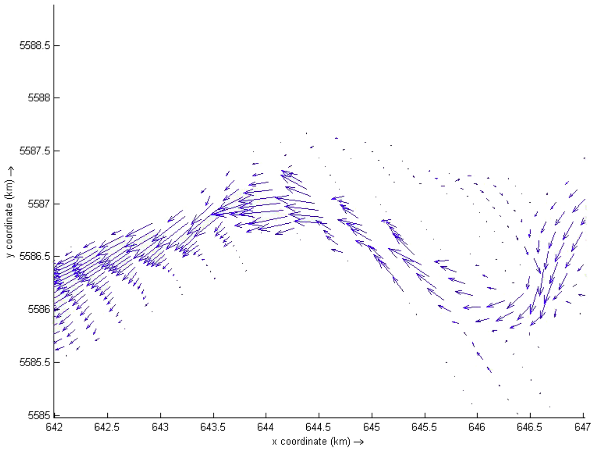

Figure 6.15: Flow lines in point 3 during maximum ebb flow and high discharge (Own work)

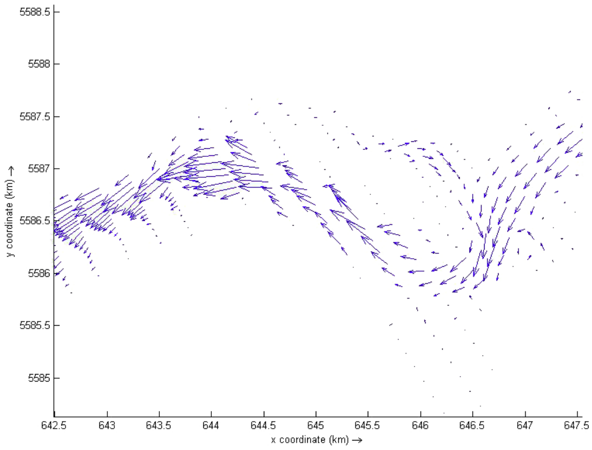

Figure 6.16: Flow lines in point 3 during maximum ebb flow and low discharge (Own work)

6.2.5 Point 4

In this point the influence of the discharge in the Guacamayo river is important. In the model this discharge is based on the Futa river discharge. Comparing the flow velocities coming out of the Guacamayo river and the flow velocities in the Valdivia river, it can be concluded that the flows highly differ in magnitude. With this fact, two expectations from Section 6.1.4 can be reviewed.

The first expectation, that the flow of the Guacamayo river will create a low pressure area downstream of the confluence point, is not likely to happen because the flow in the Valdiva river will probably be dominant over the flow from the Guacamayo river and therefore the Guacamayo flow lines barely influence the main flow lines in the Valdivia river. The dominance of the flow in the Valdivia river can be seen in Figure 6.17.

The second expectation is that because the flow in the Guacamayo river is not strong enough to enter the main flow, an eddy is created in the mouth of the Guacamayo river. This happens because the flow velocity in the Guacamayo river is so low compared to the flow velocity in the Valdivia river that significant eddies or turbulence do not show in the model results.

Another explanation for the sedimentation in point 4 can be seen in the model. The model shows that during maximum flood currents, water is discharged from the Valdivia river into the Guacamayo river (see Figure 6.18). The sediment that is transported by the flow in the Valdivia river can be deposited in the mouth of the Guacamayo river where the flow velocity of the Guacamayo river rapidly decreases and loses its transport capabilities.

These results from the model indicate that it is most likely that sedimentation occurs in the mouth of the Guacamayo river. However, this is not due to an eddy but due to the change in direction of the Valdivia river currents. During times of low discharge this phenomenon is even more prominent (see Figure C.19).

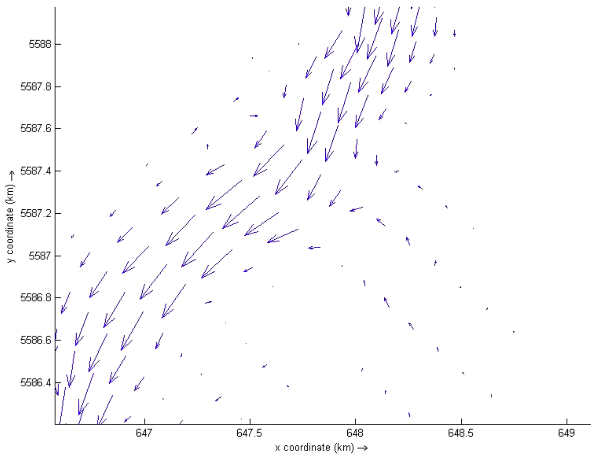

Figure 6.17: Flow lines in point 4 during maximum ebb velocities and high discharge (Own work)

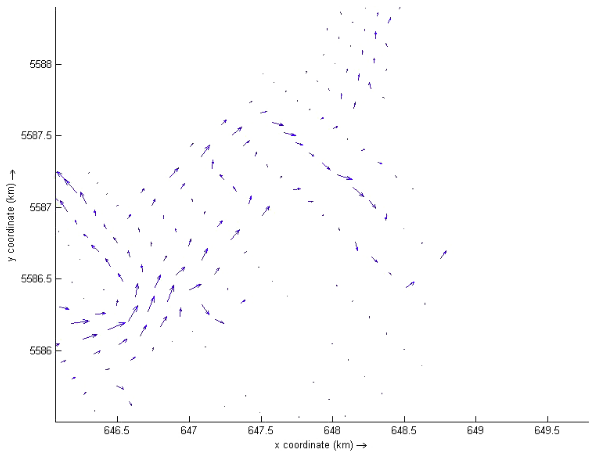

Figure 6.18: Flow lines in point 4 during maximum flood velocities and high discharge (Own work)

6.2.6 Point 5a

Since sedimentation points 5a, 5b and 6 are located close together, they are plotted in the same figures (see Figures 6.19, 6.20, 6.21 and 6.22).

The flow lines generated by the model show divergence when the Calle Calle reaches the confluence point with the Cruces. The flow lines also show a slight decrease in magnitude when the Calle Calle reaches towards this divergence. This verifies the theoretical interpretations and also shows that the channelling structures at this location do not fulfill their convergence function as previously intended.

6.2.7 Point 5b

The model shows that just after the bifurcation point, the channel converges creating higher flow velocities for the incoming discharge (see Figure 6.19. This likely causes bed erosion which is also noticeable in the bathymetry. Directly after the bend, the side channel diverges towards the confluence with the Valdivia river and the model shows lower flow velocities in this part of the side channel. This indicates sedimentation along the second half of the side channel.

6.2.8 Point 6

The first consideration in the theoretical interpretation describes the possibility of water depth differences between the Calle Calle and Cruces rivers which could cause an M1 curve into the Cruces causing sedimentation at its downstream end. Due to large irregularities in the bathymetry it is not possible to compare water depths between the Calle Calle and Cruces rivers with the model. To verify this theoretical explanation, the equilibrium water depths of the Cruces and Calle Calle rivers need to be determined. This is not possible with the current model.

The second consideration is about the differences in flow velocities between the two rivers. A low momentum from the Cruces river flow could cause this flow to reflect on the stronger Calle Calle river flow indicating eddy development. The model shows that the flow velocity in the Cruces is indeed on average significantly lower than in the Calle Calle (see Figure 6.19 and 6.21). However, exact magnitudes of flow velocity are necessary to verify the existence of this phenomenon in detail.

The model also shows that during maximum flood velocities and high discharges, the downstream directed flow from the Calle Calle and the upstream directed tidal flow meet at the confluence point between the Cruces and Calle Calle (see Figure 6.20). During this moment in time, the main flow is directed into the Cruces river. This also happens during maximum flood velocities and low river discharges (see Figure 6.22). In that case the tide is dominant over the river discharges. The flow into the Cruces river is now even stronger than during high discharges. On average the flow velocities are directed upstream the Cruces river. It is therefore expected that the Cruces river is subject to a net import of sediment in the considered section.

Furthermore, it can be concluded that the Cruces always has a too low discharge to be dominant over the tide in contrast to the Calle Calle which dominates the tide during high discharges. Therefore the flow direction in the Cruces river is always dependent on the direction of the tidal flows.

Since the flow velocities and directions differ so much a the Cruces side of the confluence, it is likely that this is the main driving force behind the sedimentation. The model shows that especially at the Isla Teja side of the Cruces, flow velocities are relatively low most of the time illustrating the main location of sedimentation.

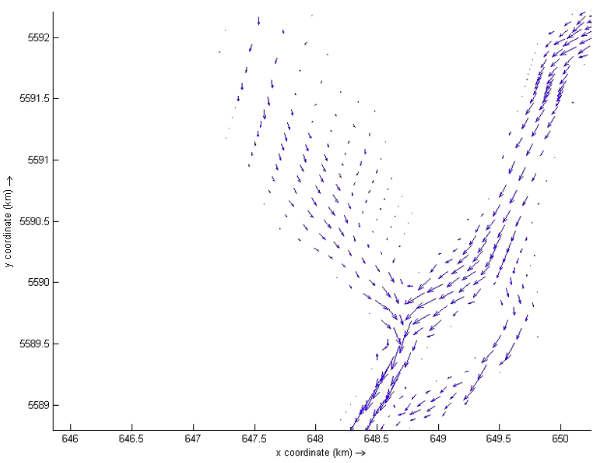

Figure 6.19: Flow lines in points 5a, 5b and 6 during maximum ebb velocities and high discharge (Own work)

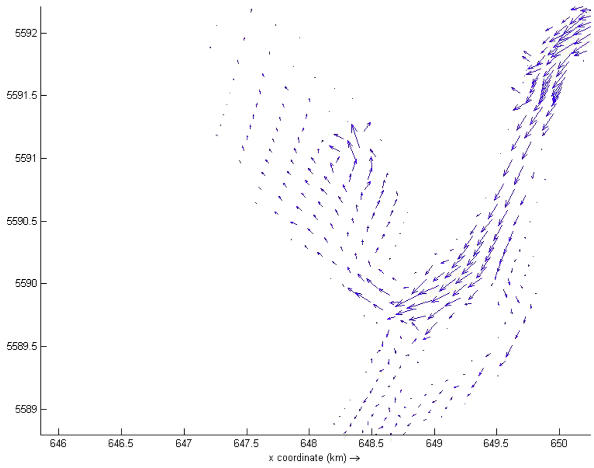

Figure 6.20: Flow lines in points 5a, 5b and 6 during maximum flood velocities and high discharge (Own work)

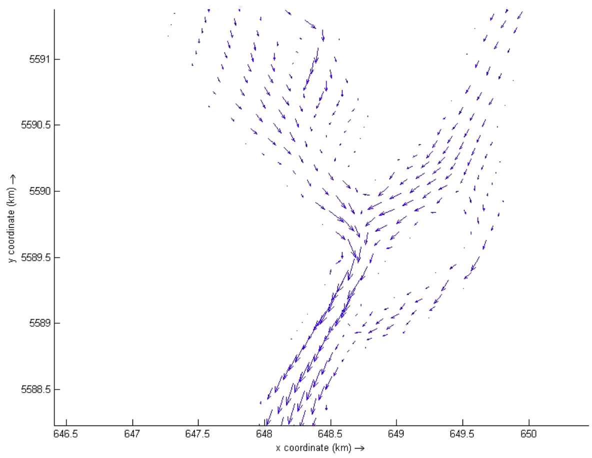

Figure 6.21: Flow lines in points 5a, 5b and 6 during maximum ebb velocities and low discharge (Own work)

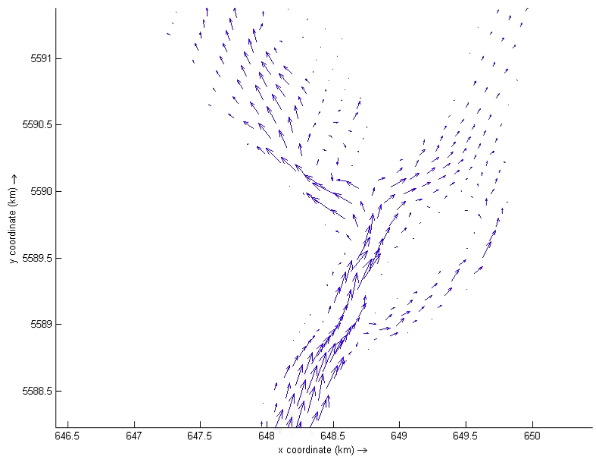

Figure 6.22: Flow lines in points 5a, 5b and 6 during maximum flood velocities and low discharge (Own work)

6.2.9 Point 7

The main theoretical explanation for sedimentation in the Cau Cau river was the difference in hydrostatic pressure between both entrances of the Cau Cau river due to different arrival moments of the tidal wave. Figure C.22 and C.23 show that this difference is negligible. Therefore this interpretation can be rejected.

The model shows that the flow directions and magnitudes in the Cau Cau river highly depend on the variations in river discharge. During minimum discharges, the tidal currents are dominant as these currents determine the flow direction in the Cau Cau river. This is displayed in figure 6.25 and 6.26. Since the flow direction changes constantly, the average flow velocity is low.

During maximum discharges, the general tendency of the flow direction in the Cau Cau river is constantly towards the Cruces river (see Figure 6.23 and 6.24). This is because the Cau Cau river is located in the outer bend of the Calle Calle. In this case, the discharge from the Calle Calle river dominates the tidal currents. Figure C.22 also shows that the water level in the Cruces river is, most of the time, lower than the Calle Calle river. This hydrostatic pressure difference increases the already present flow direction.

The flow velocity in the Cau Cau river is minimal while the flow velocity in the Calle Calle is always relatively high. Since the entrance of the Cau Cau river is located in the outer bend of the Calle Calle, the Cau Cau gets a continuous inflow of sediment. Immediately after entering the Cau Cau river, the flow velocities decrease and so does the sediment transport capacity. This seems to be the main driving process behind the sedimentation in the river section.

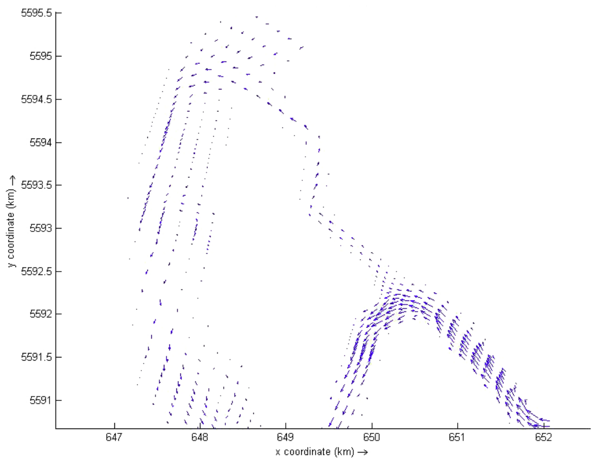

Figure 6.23: Flow lines in point 7 during maximum ebb velocities and high discharge (Own work)

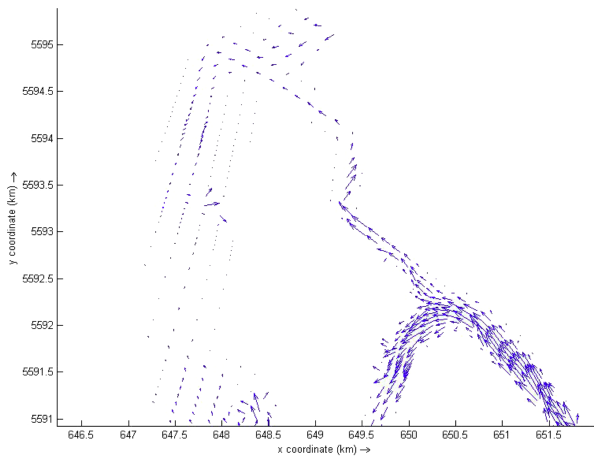

Figure 6.24: Flow lines in point 7 during maximum flood velocities and high discharge (Own work)

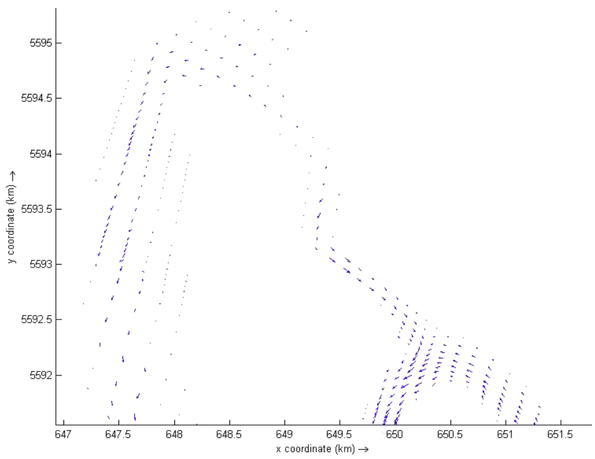

Figure 6.25: Flow lines in point 7 during maximum ebb velocities and low discharge (Own work)

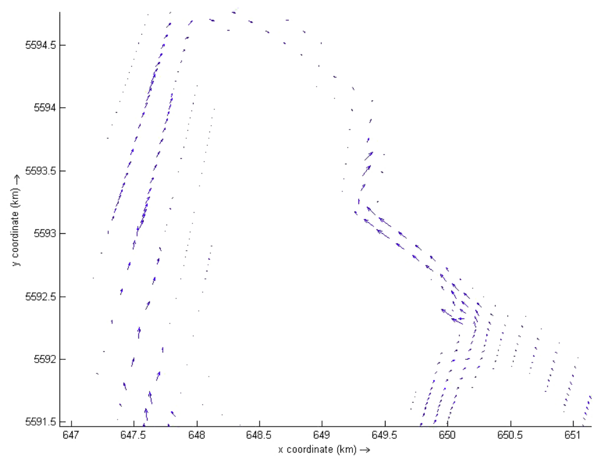

Figure 6.26: Flow lines in point 7 during maximum flood velocities and low discharge (Own work)

6.2.10 Calibration

The tides currently measured in Corral are different from the tides in the model. This is because there is little data on water levels in the system. The only way to calibrate the current model was to use the known spring tidal ranges in 1990 knowing the decreased tidal range of 1.29 meters located around 16 kilometers upstream from the mouth (Pino et al., 1993). This is done by adjusting the Chezy roughness coefficient.

A problem is that it is not known where exactly this 1.29 meters tidal range was measured upstream in the river system and also the moment of measuring (high or low discharge) is unknown. Therefore, this calibration method is not accurate. More specific data about periodic water levels in the Valdivia river is necessary in order to make this calibration method more reliable.

7. Social costs and benefits analysis

In this chapter an analysis will be carried out where the positive and negative welfare effects of a deepening of the Valdivia river will be researched. In order to gain insight in the effects of a river system without sedimentation problems, a fictitious scenario is used in this research.

7.1 Background information

The area of interest is located between the port of Las Mulatas and the port of Corral which covers a distance of 15.5 kilometres (see Figure 7.1).

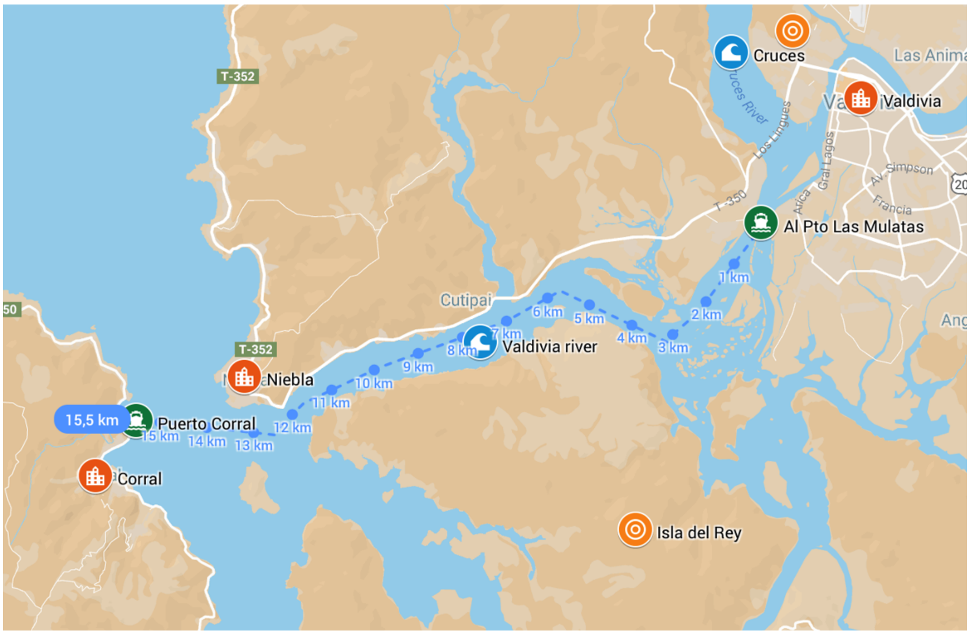

Figure 7.1: Area of interest (Map data: Google, 2017)

Due to the fact that there are already vessels navigating the Valdivia river, the waterway currently needs to be sustained at a depth of 4.5 meters (Direccion de Obras Portuarias, 2017). There are seven sedimentation points identified in the Valdivia river, where the depth is not sufficient (see Section 5.6). Four of those sedimentation points are located between Las Mulatas and Corral (see Figure 5.13).

The Ministry of Public Works has the desire to increase the transport of Valdivia. They asked to research the maximum capacity of the Valdivia river to facilitate better access of the river with the aim of stimulating export and creating possibilities for the arrival of cruise ships in Valdivia (personal communication, September 4^{th}, 2017). In order to increase the capacity of the river for vessels with a larger draft, the river needs to be deepened.

To increase the export of Valdivia, it is assumed that the Ministry desires the presence of prosperous companies in the Valdivia area. For the economic impact in the SCBA the positive and negative effects will be taken into account for the companies that provide export for the region. On the other hand, for the social impact of the project alternative it is important to take into account the positive and negative effects for the residents and tourists of the area. The interplay between the economic and social impact is stated before in Chapter 3 and described in Appendix A.

7.2 Approach

The goal of the social costs and benefits analysis (SCBA) is to give insight in what factors should be taken into account when considering a project plan which solves the sedimentation problem. This SCBA can be used for further research when more information is available about the sedimentation problem and possible solutions. Which information is needed can be found in Chapter 8. The SCBA model serves as a basis in which variables can be changed easily according to new available data. This analysis can give an insight in whether it is socially and economically beneficial to implement the project alternative.

The SCBA that is presented here, shows the costs and benefits of the fictitious project alternative that is explained in Section 7.3.

7.3 Alternatives

In this social costs and benefits analysis a comparison will be made between the zero alternative and the project alternative. The zero alternative is the most likely development without a new policy or implementation of a project (Mouter et al., n.d.).

7.3.1 Zero Alternative

In the zero alternative, there is no deepening of the Valdivia river. Currently, there is no policy on ensuring sufficient capacity in the river, which is explained in Chapter 1. For the current navigation depth of 4.5 meters, it is assumed that there are no maintenance costs because currently there is no policy about dredging. This assumption also states that the river will not silt up further and the current vessel traffic remains unchanged.

It is assumed that still the same types of vessels will be used for transport between Las Mulatas and the port of Corral. The Comau vessel has been taken as a reference for all current inland vessels, which are now classified as 'smaller vessels'.

There is not a detailed prediction available about the amount of cargo transport in the future. Therefore, different scenarios are defined. A low scenario with annual growth of 1%, a medium scenario with annual growth of 3.5% and a high scenario with annual growth of 7.6%, see Appendix D.1.

7.3.2 Project Alternative

At the port of Corral, cargo is currently loaded on larger vessels. The project alternative aims on the possibility to navigate a part of the larger vessels through to Las Mulatas in order to improve the exporting process. This requires a deepening of the Valdivia river between Las Mulatas and Corral.

There is a rule of thumb for a certain minimum keel clearance which should be provided to prevent the vessel from touching the bottom at certain places due to squat. This rule assumes that the minimum depth of the waterway divided by the maximum draft of the vessel at rest should be higher than 1.3 (Environmental Commission, 2003). A waterway depth of 10 meters can therefore provide transport for vessels with a maximum draft of 7.8 meters.

In this project alternative the area of interest will thus be deepened to 10 meters below the water level by means of dredging activities. It will be maintained at that depth. According to Navionics (Navionics, 2017), the water level difference between the sedimentation spots and the rest of the channel section is on average 10 meters. Therefore, it is assumed that only the four identified sedimentation spots need to be dredged to 10 meters.

Two different classifications of vessels are used in the project alternative. The currently used inland vessel, the 'Comau' remains the same and is now classified as 'smaller vessels'. The four different vessels that have a draft of 7.8 or less are the Surabaya Express, Nanjig Express and Kalimantan Express (Section D.2). The Surabaya vessel has been taken as a measure for the these vessels, this is classified as 'handy size'.

For the project alternative, the same scenarios are used: an economic growth of 1%, 3.5% and 7.6%.

7.4 Assumptions

The general assumptions and principles for the SCBA are described in this section. Assumptions related to a particular factor are included in Sections 7.5, 7.6 and 7.7.

- Processes and circumstances that effect waiting times and efficiency of ports remain out of consideration
- The modifications of the berths and terminals are not included
- It is assumed that the safety situation remains the same. No significant safety effects are expected
- Port fees are excluded in the research
- It has not been investigated whether these specific handy size vessels actually are suitable to use the river, looking at their dimensions. These vessels are only used to show the costs and effects of vessels with a larger DWT (Deadweight Tonnage)

7.5 Costs

The project costs are mainly based on assumptions, estimations and the previous dredging project in the Valdivia river. Therefore, the calculation is not necessarily reliable but it gives a good estimation.

7.5.1 Investment costs

The investment costs of the project alternative comprise only the costs for the dredging works. Cost calculations present that the investment costs are 7.36 million US dollar with an execution duration of 126 weeks. The calculations are based on reference projects and described in detail in Appendix D.2.

7.5.2 Maintenance costs

To define maintenance costs for the dredging works, it is necessary to know the sedimentation rate at the sedimentation spots. On average, dredging activities took place approximately every 15 years. The last dredging project comprised the dredging of a 15 centimeter layer, which comes to a sedimentation rate of 1 centimeter per year (Direccion de Obras Portuarias, 2017).

By increasing the depth of the river, maintaining the width and no change in river discharge, the flow velocities in the river will decrease, according to the following formula: $u = \frac{Q}{A}$. Therefore, the sediment transport capacity of the river reduces, increasing sedimentation as described in Section 5.6. Also, the river wants to reach equilibrium as described in Section 5.2. The sedimentation areas are currently present because at these points, sedimentation is required to reach an equilibrium situation. When the sedimentation spots are deepened to 10 meters instead of 4.5 meters, the morphological situation is further away from equilibrium and the sedimentation rates at these areas are likely to increase. Therefore, it is expected that a more frequent maintenance is required to keep the desired channel depth and the sedimentation rate is assumed at 5 centimeter per year. Based on this, it is decided that maintenance can be done each 10 years. Maintenance dredging will then take 15 weeks and costs 670 thousand US dollar. See Appendix D.2 for the calculations.

7.6 Quantitative benefits

There are two benefits that could be monetised in US dollar, travel time and air quality.

7.6.1 Travel time

An effect of the project alternative will be a reduction in travel time. In the project alternative, handy size vessels are able to navigate the Valdivia river. To export the same amount of cargo, less vessels are needed. This leads to a change of fleet mix. This is monetised by using the change of fleet mix, the average costs of transport and the waiting time.

- Change of fleet mix

  An overview of the vessels which are currently arriving in Corral is presented in Table D.2. In the zero alternative, the smaller vessels have a 100% dead weight tonnage (DWT) share in inland transport. With the usage of handy size vessels, this share shifts to 74%. The other 26% is covered by the handy size vessels (see Table 7.1).

Table 7.1: Change of fleet mix (Own work)

Vessel Type	Draught [m]	Share in transport Zero Alternative	Share in transport Project Alternative
Smaller vessels	<7	100%	74%
Handy size	7 - 8	0%	26%

- Difference in average costs of transport

  Due to the change in fleetmix the traffic intensity of vessels on the Valdivia river decreases. One handy size vessel covers 68 smaller vessels. Because less vessels are needed, there is a reduction in total travel time. However, the transport costs for larger vessels are higher then for smaller vessels (see Table D.5). Hence, the reduction in transport costs are calculated.

- Reduction in waiting time

  In the zero alternative, the smaller vessels coming from Las Mulatas need to transship their cargo to the larger vessels at the port of Corral for foreign transport. The total transshipment time (t_w) can thus be formulated as follows:

$$t_w = t_1 + t_2 + t_3 \tag{7.1}$$

  If the handy size vessels are able to moor at Las Mulatas, this transshipment becomes unnecessary. Therefore the total waiting time can be reduced with the loading time (t_1) and unloading time (t_2) of the smaller vessel, leaving the loading time of the handy size vessel (t_3) to represent the total transshipment time.

  Besides a benefit in the transshipment time, there will be a benefit in the loading time of the vessels. Instead of loading 68 smaller vessels, only one handy size vessel needs to be loaded. This is calculated by dividing the DWT of a handy size vessel with the DWT of a smaller vessel. Calculations show that it is more beneficial for the waiting time to fill one large vessel instead of 68 smaller vessels (see Appendix D.3.3).

- Reduction of transport costs in the new market share

  Corral is a small port compared to other coastal ports in Chile (Armada de Chile, 2016). To determine the market share of Corral compared to Chile, the export values of Corral are compared with the total export values of Chile. The year 2016 is used as a reference. The total export of Corral in 2016 was 560,254 tonnages. The total export of Chile in 2016 was 60,734,833 tonnages (Armada de Chile, 2016). Thus, the market share of Corral in 2016 was 0.9%. This is not a precise calculation, looking at the fact that Corral mainly exports wood while this is not the main national export product. However, there is no transport information available that focuses on wood only. Also, in the SCBA calculation, focus is on the port of Las Mulatas. This port is related to Corral, but to calculate the market share of Corral through to port of Las Mulatas brings another uncertainty, so the increase of the extra market share will not be included.

The travel time gains can be calculated with the change of fleetmix, average costs of transport and the reduction in waiting time. In the project alternative with a growing factor of 1% and 3.5% there is a reduction of travel time gains of 146.874 US dollar per year. Remarkably, travel time gains are the same for the first two growth scenarios. This is because the number of handy size vessels did not change with this growth. With a growing factor of 7.6%, 183.146 US dollar per year can be saved on travel time costs. More calculations can be found in Appendix D.3.2.

7.6.2 Emission

The emission rates of the smaller and handy size vessels are used to define what amount of gases the two ships emit per round trip from Las Mulatas to Corral and back (den Boer et al., 2008). Emission comprises the following gases: carbon dioxide (CO2), nitrogen oxides (NOx), suspended particles (PM10) and sulfur dioxide (SO2). Carbon dioxide negatively affects the climate, while the other gases affect the air quality of the area.

The effects of each of the four gases are different in terms of monetised value (Ruijgrok & Sluis, 2011). Together with the fleet mixes per scenario identified in Section 7.6.1, the costs per scenario for the air quality can be calculated (see Table D.12). For a detailed description of the calculations, see Appendix D.3.4.

7.6.2.1 Air quality

The values presented in Table D.12 are yearly costs for all emissions. The benefits are separated by air quality and climate. For the benefits of air quality in the scenario of 1% and 3.5% there is a reduction of 263,901 US dollar, for the scenario of 7.6% there is a reduction in costs of 329.603 US dollar.

7.6.2.2 Climate

In the scenario of 1% and 3.5% there is a reduction of 42.146 US dollar because of less CO2. In the scenario of 7.6% there is a reduction in costs of 52.640 US dollar.

7.7 Qualitative benefits

Qualitative effects are the effects that are too complex to monetise due to a lack of time or data. The effects described in this section are noise, ecology, recreation and 'added value'.

7.7.1 Noise

The experienced noise level of vessels depends on different aspects such as the intensity and speed of vessels passing, the distance of buildings to the waterway, the height of ground level, the width of the waterway and the individual sensitivity to sound (der Meulen et al., 2009).

Research about the sound effects of shipping noise showed that for engine vessels, the average source power is 110.4 dB(A) $\pm$ 3.3 dB(A). Besides that, the source power is independent on the size, age, speed and load rate of the vessel and technical progress does not decrease the sound power of vessels (der Meulen et al., 2009) (van Lieshout, 2004). The area between the port of Corral and Las Mulatas is outside the urban area (see Section 4.1). So, it is assumed that people do not suffer significantly from noise.

Based on this information, it is concluded that the project alternative leads to a decrease in noise, because one handy size vessel will replace 68 smaller vessels with the same source power.

7.7.2 Ecology and structures

By deepening the Valdivia river, the ecology of the river will be affected. Also the present channelling structures are likely to suffer from a different bathymetry situation.

- Structures

  The structures that were constructed in the river (see Section 5.4) may be affected by a difference in soil pressure distribution. When soil is removed on one side of the structure, the structure might collapse. The state of the structures is mostly unknown and will require more research.

- Nature

  Dredging has an impact on the ecology within the river. The Ernesto Pinto is a Trailing Suction Hopper Dredger (TSHD). These dredging vessels produce turbidity plumes at the dredging locations (Becker et al., 2014). These turbidity plumes affect the local water quality and might negatively influence the habitat of underwater species. This is especially relevant because of the long execution time of the dredging activities.

7.7.3 Recreation

The Ministry of Public Works has mentioned that one of the possible future scenarios is to navigate cruise ships on the Valdivia river (personal communication, September 4^{th}, 2017). An increase in depth of the river will give the opportunity to do this. Deepening the Valdivia river will have positive effects on recreation when looking at the possibilities for cruise ships. However, there are also negative effects of deepening of the river for recreation. It is likely that tourists and residents of the area will make less use of beaches and recreation on the water when the river will be used by large handy size vessels instead of smaller vessels. The project alternative will therefore have positive and negative effects on the recreation around the river.

7.8 Analyses

In these analyses the dredging operations will start in year 1. From year 2, the new depth of the Valdivia has been reached. From year 3 the effects are taken into account. Maintenance takes place every ten years, starting in year 13.

A time horizon of 100 years is generally used in this type of study (Ministerie van Infrastructuur en Milieu, 2012). To properly compare the costs and the effects, the expected costs and effects are recalculated with a discount rate to year 1. In Chile, the discount rate is set at 10% (Consorcio Mercados Interconectados, 2015). Due to this discount rate, costs and effects are less valuable in the future than they are in the base year (van Ewijk et al., 2015). Effects can either be direct or indirect. Direct effects are a direct consequence of the project and act on the markets on which the project alternative intervenes. Indirect effects are derived from a direct effect and act on other markets (Mouter et al., n.d.). The indirect effects are valued at 15% of the direct effects (Elhorst, Heyma, Koopmans, & Oosterhaven, 2014).

7.8.1 Results scenarios

By deducting the back-calculated cost of the income, the net present value (NPV) of the project can be calculated (Mouter et al., n.d.). This NPV, together with the qualitative results, provides results that can be reasoned. A positive balance means that a project is profitable. The balance will be considered for the different growth scenarios. When it is positive, it is advisable to carry out the project. The final results of the fictitious project alternative can be found in Table 7.2.

Table 7.2: Results of Scenario's (Own work)

	SCBA 1% Total (US dollar)	SCBA 3.5% Total (US dollar)	SCBA 7.6% Total (US dollar)
Investment costs			
Deepening Valdivia River	-7,360,908	-7,360,908	-7,360,908
Maintenance costs			
Maintenance costs	-461,776	-461,776	-461,776
Direct effects			
Reduction transport costs	1,335,104	1,335,104	1,664,819
Indirect effects			
Air quality (PM_{10}, SO_2, NO_x)	263,901	263,901	329,603
Climate (CO_2)	42,146	42,146	52,640
Recreation			
Noise	(+)	(+)	(+)
Ecology	(-)	(-)	(-)
Results			
Total costs	-7,822,684	-7,822,684	-7,822,684
Total effects	1,614,151	1,641,151	2,047,062
NPV (Net Present Value)	**-6,181,533**	**-6,181,533**	**-5,775,622**

The total costs are 7.8 million US dollar. The total benefits are 1.6 million US dollar in scenario 1% and 3.5% and 2.0 million US dollar in 7.8%. This results in a negative balance of 6.2 million or 5.8 million US dollar.

In addition, the qualitative effects (recreation, noise and ecology) are not monetised but have an influence on the NPV as well. These qualitative effects are shown in the Table by plus and minus signs. The impact on noise will be positive for the total outcome on the NPV, the impact on ecology will be negative and the impact on recreation is unknown. As a result, the total Net Present Value will even be lower or higher than shown in Table 7.2. In the SCBA calculations the results for every year are included of the three scenarios.

7.8.2 Sensitivity analysis

To map knowledge and policy uncertainties, a sensitivity analysis is done. Many assumptions are made and lots of key figures are used in the SCBA.

The sensitivity of the result in the base scenario is mainly influenced by variables with high uncertainties. These are: transport costs, dredging costs, air quality, climate costs and growth factor. In addition, the level of the discount rate has a major impact on the result. Table 7.3 shows to what values these costs and effects are changed and what the new NPV will be. For further explanation of the chosen factors and values and the calculations, see Appendix D.4.

Table 7.3: Sensitivity analysis I (Own work)

Scenario	Costs *in mln USD*	Benefits *in mln USD*	NPV *in mln USD*	Change in NPV
Basic	-7.82	1.64	-6.18	
Discount rate (set to 8%)	-7.98	2.09	-5.90	4.6%
Discount rate (set to 12%)	-7.72	1.34	-6.37	-3.1%
Transport costs (+25%)	-7.82	1.97	-5.85	5.4%
Transport costs (-25%)	-7.82	1.31	-6.52	-5.4%
Dredging costs (-25%)	-5.87	1.64	-4.23	31.6%
Dredging costs (+25%)	-9.78	1.64	-8.14	-31.6%
Air quality + climate (+10%)	-7.82	1.67	-6.15	0.5%
Air quality + climate (-10%)	-7.82	1.61	-6.21	-0.5%

The result is negative in all the scenarios. No scenario is leading to a positive NPV or is even getting close to zero.

Since the assumptions related to the input variables mentioned in Table 7.3 have a high uncertainty, it is chosen to do a second sensitivity analysis by changing the values of some of these assumptions. These are, transport costs handy size vessel, change of fleetmix, depth, and growth factor. For a further explanation of the chosen factors and values and the calculations, see Appendix D.4. The in- and output of this analysis is shown in Table 7.4.

Table 7.4: Sensitivity analysis II (Own work)

Scenario	Costs *in mln USD*	Benefits *in mln USD*	NPV *in mln USD*	Change in NPV
Basic	-7.82	1.64	-6.18	
Growth factor (set to -1%)	-7.82	1.64	-6.18	0.0%
Growth factor (set to -7.6%)	-7.82	1.24	-6.59	-6.6%
Fleetmix (100% Handy size)	-7.82	5.58	-2.24	63.7%
Depth and fleetmix (6m, 100%)	-1.82	10.06	8.23	233.2%
Transport costs Handy size (+25%)	-8.68	1.74	-6.94	-12.3%
Transport costs Handy size (-25%)	-7.27	1.84	-5.42	12.3%

The extreme scenario in which the dredging depth and the fleetmix are changed leads to the highest NPV. The depth of dredging is changed to 6 meters instead of 10 meters and the Comau vessels are replaced by vessels with 8000 DWT. This scenario results in an extreme positive NPV of 8.23 million US dollar.

Although the output of the sensitivity analysis is as expected, it can not be concluded that the SCBA is robust, because most of the used data is not reliable and some tested factors have an result with a large bandwidth.

It can be concluded that the SCBA is negative. Only with the extreme scenario, when the level of deepening is much lower and when vessels with other load capacity and costs will be deployed, it will lead to a positive result.

7.8.3 Uncertainties

There are several uncertainties in this study, because not all the costs and effects were clear.

It is not clear whether the costs of investment and maintenance are within or without VAT (Value Added Tax), so it should be kept in mind that those costs can be higher or lower.

In addition, there are more added values for the port of Las Mulatas that are not included in this SCBA. The increased transport in the port of Las Mulatas can lead to a strengthening of the competitive position. This can in turn cause indirect effects for Las Mulatas (Schenk & Pohl, 2016). These effects are:

- Economies of scale
  The increase in transshipment at the port can lead to economies of scale. When the facilities at the port are used more, then these can be used more efficiently and also it is more beneficial to augment the production process.
- Competitive position
  Because of the higher accessibility of the port of Las Mulatas, the competitive position of the port can be strengthened. Higher accessibility can also lead to an increase in possibilities concerning suppliers, which can in turn lead to optimisation and efficiency.
- Cost advantages
  The port of Las Mulatas might get more attractive for new businesses. An increase in interaction between companies will lead to cost advantages, because of an increase in knowledge.
- Employment
  An increase in transshipment at the port of Las Mulatas can lead to more jobs at this port. However, it should be taken into account that at the port of Corral the employment can also decrease due to the project alternative.

There are several uncertainties about the used data in specific. These can be found in detail in chapter 8. Recommendations for the SCBA can be found in Appendix D.4.3.

8. Data

During this research, assumptions had to be made in order to fill the gaps that were created by missing data. This chapter gives an overview of the used data and lacking data.

8.1 Used data

The classification of data is divided into two tables. Classifications of Delft3D and SCBA data are presented in Table 8.1 and 8.1, respectively. The data is classified by means of reliability, applicability, completeness and priority.

- Reliability

  The reliability is based on the quality and academic level of the source of the data.

- Applicability

  The applicability of the found data refers to which extent the data is applicable for this particular research.

- Completeness

  The completeness indicates whether the data contains all components. This comprises all parts of the data that are necessary for the research.

- Priority

  The priority refers to how the specific data will affect the final result of the model. The higher the impact on the results, the higher the priority of the data.

The components of the data are rated with minus and plus signs. A high value is rated with '++', a low value is rated with '- -'. Unknown values are rated with '0'. An extended description of the data classification can be found in Appendix E.

Table 8.1: Data classification Delft3D model (Own work)

Data content	Reliability	Applicability	Completeness	Priority	
Bathymetry		+	-	- -	++
Discharges	Calle Calle river	++	+	+	+
	Cruces river	++	+	+	+
	Futa river	++	+	+	+
Tides		+	-	+	+
Roughness	Chezy	- -	-	- -	+

Table 8.2: Data classification SCBA model (Own work)

Data content		Reliability	Applicability	Completeness	Priority
Dredging costs	Total dredging volume	+	+	-	+
	Operational costs	+	-	-	++
Travel time	Vessel specifications	++	-	++	- -
	General waiting time	+	++	+	+
	Waiting time for freight	++	0	- -	++
Air quality and climate change	Emission costs	++	0	-	++

8.2 Lacking data

In some cases assumptions could not be made to replace the missing data. Due to a lack of data, some parts of the research could not be executed. This also had an influence on the ability of answering the research question. These data are the following:

- Land use in Valdivia river catchment
- Composition of sediment in terms of soil types
- River discharges smaller rivers
- Water levels in the river system
- Evaporation
- Sedimentation rates
- Salt intrusion

9. Conclusion

In this research an attempt is made to answer the following research question: *How can the surplus of sediment in the Valdivia river be remedied and to what extent will this contribute to the economic and social values of the city of Valdivia?*

The driving processes behind the sedimentation in the river system have been qualitatively analysed. As a result of this analysis, a simplified Delft3D model was built by implementing the main driving processes being tidal movement and river discharges. With this it was concluded that the directions and magnitudes of flow lines in the river system can give good indications on what locations sedimentation can occur. Although there has been an identification of what processes induce sedimentation, further research can help quantify the sedimentation rates and thus give an insight on possible remedies of the surplus of sediment.

Furthermore, after analysing a fictitious solution scenario, it is concluded that solving the sedimentation problem by means of dredging does not necessarily result in an increase of the welfare in Valdivia. The result of the social costs and benefits analysis is a basis model where all effects of solving the sedimentation problem are inventoried. These effects will eventually map the impact on the economic and social values of Valdivia. With the future sedimentation rates, the SCBA can give an insight on which dredging scenarios could be lucrative solutions.

It can be stated that this research serves as a preliminary study in which further investigation is needed to answer the research question properly.

10. Recommendations

With the results of the analyses in this research, an advice can be given for the problem owner. The current Delft3D and SCBA models should be used as a basis. By adding new and more accurate data, it can be ensured that the models improve their representation of the entire situation.

To do this, it is necessary to have accurate data from reliable sources. The first recommendation is to collect the data of which an overview is given in Chapter 8. The extended recommendations for the Delft3D and SCBA models can be consulted to implement the required data correctly (see Appendix C and D.4.3).

After the data collection, the models can give a more detailed output. This will make it more clear what covers the real sedimentation problem. With this knowledge, research can be done about ways to solve the sedimentation problem. Perhaps, the dredging activities might not be the best solution. Especially looking at the available dredging equipment, this will not be profitable.

Other possible solutions can be restoring the channelling structures or approaching the problem by looking at the sedimentation sources. When these options are investigated, a scenario analysis can be made to compare the solutions with each other. Only then, the most suitable solution of the sedimentation problem can be chosen.

Besides the sedimentation problem, it is necessary to do research about the need of the expansion of the river for transport. In this way it is possible to decide if there is actually a necessity to deepen the Valdivia river. For this the interests of the ports, export companies of wood chips, residents, tourists and also the current infrastructure must be taken into account.

11. Remarks

Some elements in the research were remarkable and had an influence on the outcome of the project. These remarks are more based on the process than on the content of the research. Therefore, the remarks are slightly subjective.

- Starting point of research
  The problem stated by the Ministry was the sedimentation problem. However, this is already thinking in solutions instead of thinking about what the real problem is. In order to find out the real problem of the Ministry the problem analysis was carried out. Even though the real problem of the Ministry was now found, the focus of this research remained on the sedimentation problem, because this was what the Ministry desired to be researched.
- Problem owner
  In this report, the problem owner is the Ministry of Public Works and not the municipality of Valdivia. In Chile it seems that the municipality is only a little involved. The municipality in Chile has a budget and has the right to ask for funds from the ministries and central government. Before receiving a fund, they have to make a plan daccion to show what they need funding for. The problem was coming from the Ministry instead of the municipality, which was remarkable. It was expected that the municipality would have more interest and involvement in this particular problem than the Ministry, because the problem is related to their city. According to trade it makes sense that the Ministry is involved, but according to the effects on the residents and tourists it makes more sense that the Municipality would be the problem owner.
- Collaboration of the Ministries
  Chile is a centralised country, which has representatives of the central Ministries in every region. In the research it was noticed that all Ministries work separately and seems that there is little cooperation. For example, there is no central overview over what is already researched, what is currently done and what the plans of other Ministries are. This follows from the fact that one Ministry wanted to build a beach and another Ministry wanted to build new infrastructure at the same location. They only noticed this when they wanted to start building and met each other at that specific location.
- Access to data
  Already a lot of research has been done in Chile. However, most of the researches are not easy accessible. It is not clear where to find the data or it is not accessible without paying. It was noticed during the research that also universities do not have access to the researches of the government. This leads to redundant work for the universities. Better research can be done and more can be achieved if the government would make this data open for use.

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A. Problem analysis

A.1 Objective tree

An objective tree is used to describe how the goals of an actor can be expressed into measurable criteria (Enserink et al., 2010). In this problem analysis, two objective trees are identified. The first tree for an analysis of the accessibility of Valdivia in detail, the second tree focused on the cargo transport.

A.1.1 Objective tree general accessibility

The main goal of the Ministry of Public Works is to improve the attractiveness of the city according to transport of trade, tourists and residents.

By using an objective tree, this primary goal is defined into secondary goals, particularly high quality transport Valdivia and high economic value Valdivia (see Figure A.1). The subgoals are defined below by making use of measurable criteria.

High quality of transport can be defined into the following subgoals:

- **High accessibility of public transport**

  High accessibility of public transport means, in the first place, a low total travel time to reach a destination. This can be measured by the minutes per trip. Secondly, the sufficient frequency of public transport, measured in the departures per hour, leads to a higher accessibility. When the density is normal for public transport, the accessibility of public transport is better. This can be measured in the number of seats per transport mode.

- **High accessibility for cars and freight**

  High accessibility for cars and freight means, in the first place, a need of a normal density on the infrastructure. This can be measured in cars per kilometer. The lower the travel time, the higher the accessibility for cars and freight. The total travel time is separated into the low minimum travel time and the low variance loss hours. The low minimum travel time will be measured in minutes per trip. The higher the vehicle loss hours, for example due to congestion, the higher the uncertainty to reach a destination in a specific time and the lower the accessibility will be. The vehicle loss hours is measured in hours per trip.

- **High accessibility for vessels**

  High accessibility for vessels is also expressed in a low total travel time, as can be seen in Figure A.1. Secondly, the normal density of waterways will make the accessibility for vessels higher, this is measured in vessels per kilometer.

The other secondary goal, high economic value Valdivia, can be defined into the following subgoals:

- **High export rate**

  More export of goods will lead to a higher economic value of Valdivia, this is measured in respectively the number of containers going in and out, set in TEU per year.

- **Number of tourists**

  Tourism is a big source of income and therefore contributes to the economic value of the city.

- **Number of residents**

  More residents means that more people are contributing to the economy of the city. This contributes to a higher economic value of Valdivia.

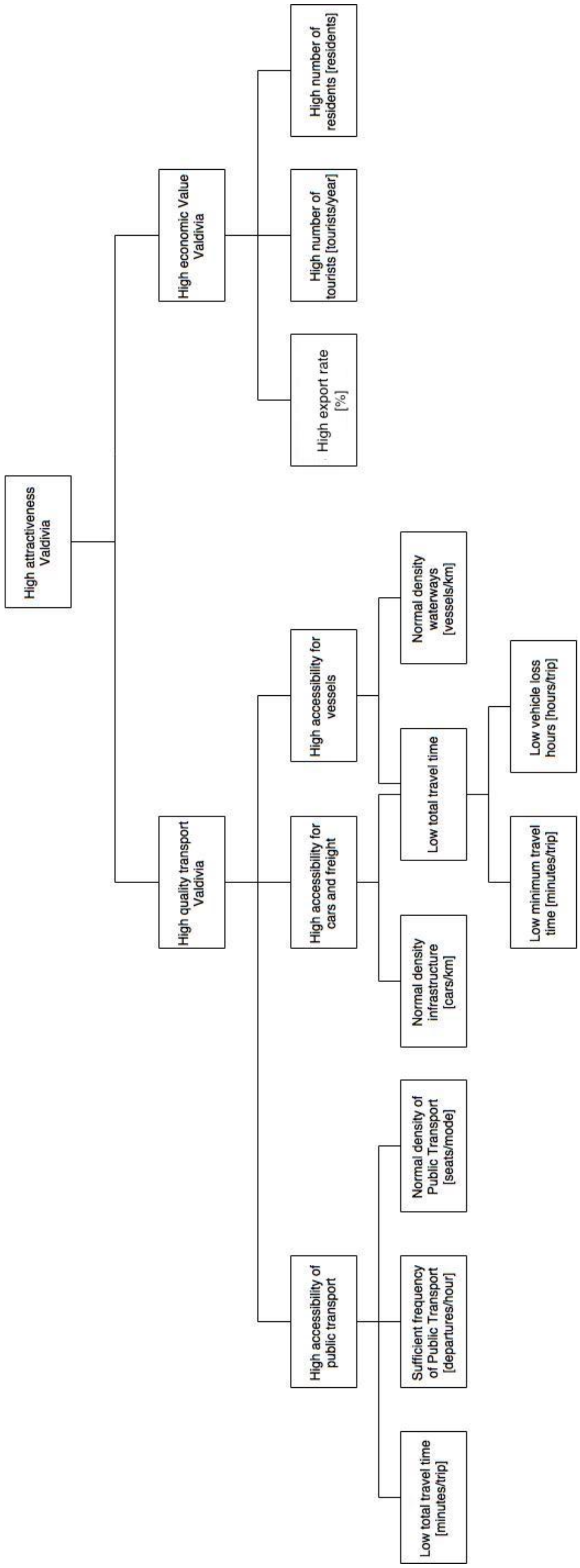

Figure A.1: Objective tree general accessibility (Own work)

A.1.2 Objective tree cargo transport

A second objective tree is defined to clarify the desire of the Ministry of Public Works, focused on the cargo transport (see Figure A.2). The ministry wants a high welfare of Valdivia. This primary goal is defined into two secondary goals, namely:

- **High economic value**

  A high economic value can be achieved by a high export rate, but also a high accessibility of the city for these goods. The accessibility can be measured in number of ways to reach the city. It is not about accessibility for passenger transport in the city, but about the cargo transport for the purpose of trade.

- **High social value**

  A high social value on the other hand can be measured by the satisfaction of residents and the amount of tourists. To measure the satisfaction of residents, only the immigration and emigration rates are taken into account. High immigration and low emigration indicate that residents are satisfied and do not want to leave the city. In this objective tree it is not clarified what satisfies the residents, because this is left out of scope.

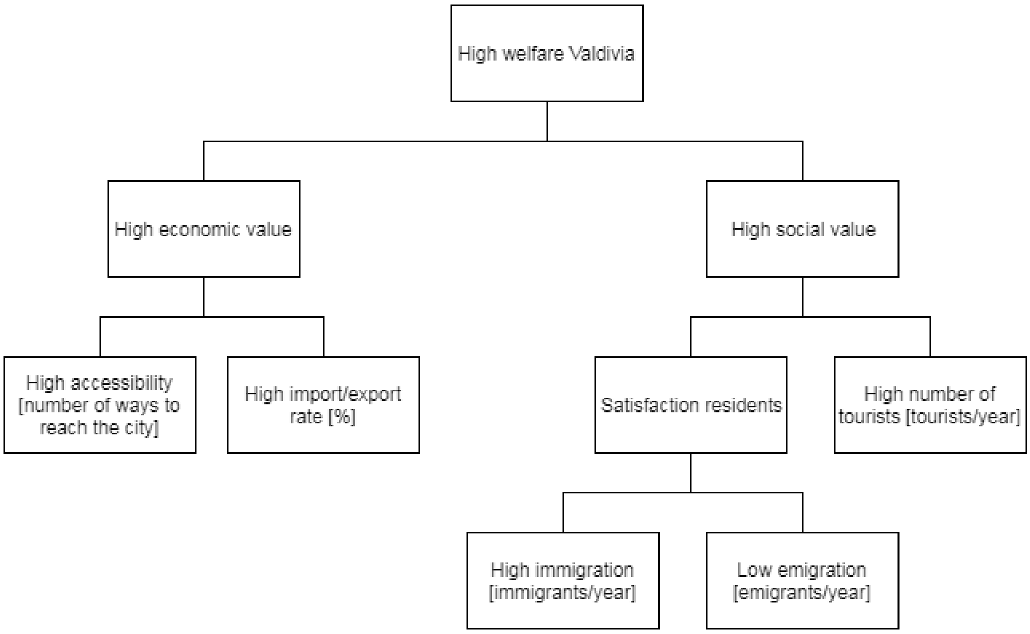

Figure A.2: Objective tree focused on cargo transport (Own work)

A.2 Means-end tree

The means-end tree is used to define the main goal and the subgoals of the Ministry of Public Works and how these goals can be achieved by making use of different means (Enserink et al., 2010).

The main goal of the Ministry is to increase the accessibility of Valdivia for the purpose of export. To reach this goal the Ministry has three options. Increasing the accessibility can be done by either maintaining the existing infrastructure, expanding the existing infrastructure or building new infrastructure. These options can be executed by using several means. These means are elaborated below and shown in Figure A.3. All means include either the infrastructure on land or on water, both in purpose of the cargo transport.

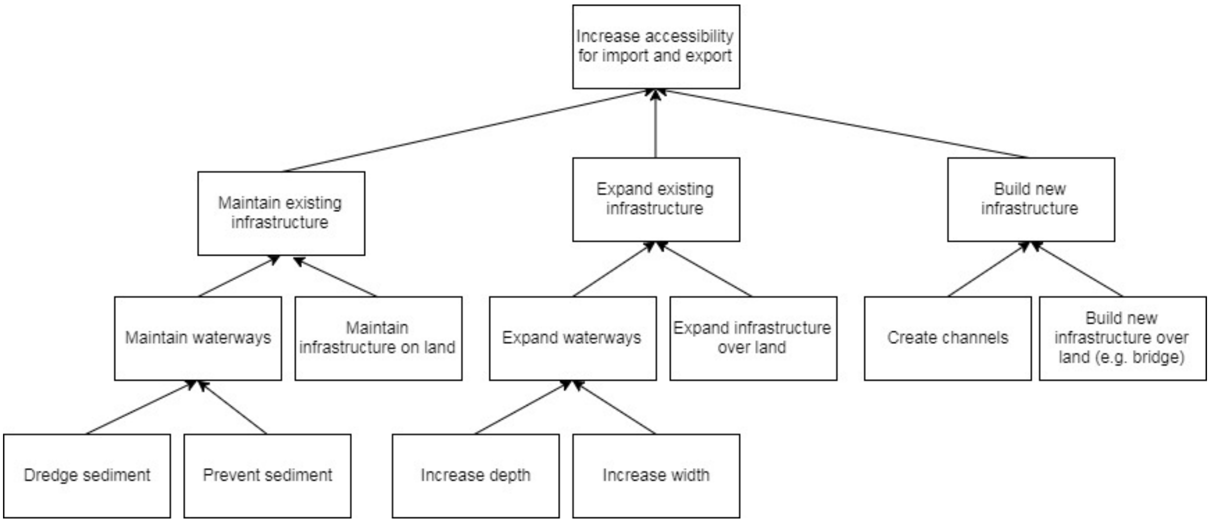

Figure A.3: Means-end tree (Own work)

- **Maintain existing infrastructure**

  By maintaining the existing infrastructure, such as maintaining the infrastructure on land and the waterways, obstacles and therefore delays will be prevented. By doing this, the accessibility will be ensured. Maintaining the infrastructure on land means for example refurbishing the road surface when necessary. Maintaining the waterways includes making sure that the waterways have a sufficient depth and width by preventing and dredging sediment.

- **Expand existing infrastructure**

  Conversations with the Ministry showed that at some places in the city of Valdivia, the existing infrastructure is not sufficient. For example, loaded trucks have to deliver their goods between 9pm and 7am, so that passenger traffic during the day is not suffering from it. Besides that, the increasing number of residents and tourists leads to a lot of congestion, especially during summer (Ministerio de Transporte y Telecomunicaciones, 2014). By expanding existing infrastructure, for example by expanding waterways, road lanes or bridges, the capacity of the infrastructure will increase. This also leads to higher accessibility. Expanding waterways can be done by increasing the depth and width.

- **Build new infrastructure**

  Another way to improve the accessibility for export is by building new infrastructure, for example by building new bridges and waterways. The Ministry already tried to improve the infrastructure by building the Cau Cau bridge in 2014. The intention of this bridge was to connect Valdivia with the adjacent Teja Island so that heavy loaded trucks could use this bridge instead of driving through the city centre. However, the bridge was installed incorrectly can still not be used (Ministerio de Transporte y Telecomunicaciones, 2014). At present, the time slots for trucks also limit the roads for freight, which leads to a decrease of the accessibility of the freight transport.

In this research, the focus lies only on increasing the accessibility for export by maintaining or expanding the water infrastructure. Several efforts in improving the land infrastructure went wrong, for example with the Cau Cau bridge. Because of this failure, the Ministry asked to do research about the transport possibilities on the river.

A.3 System Diagram

The system diagram shows the behaviour of a system. It shows the influence of different means on the factors and criteria. In the system diagram, as shown in Figure A.4, the means or actions are shown in green on the left side, the external factors are shown at the top in blue and the criteria are shown in orange on the right side. This system diagram is about the cargo transport. The influence of the means is specified on how these means can lead to an increase of cargo transport. Other transport is left out of scope.

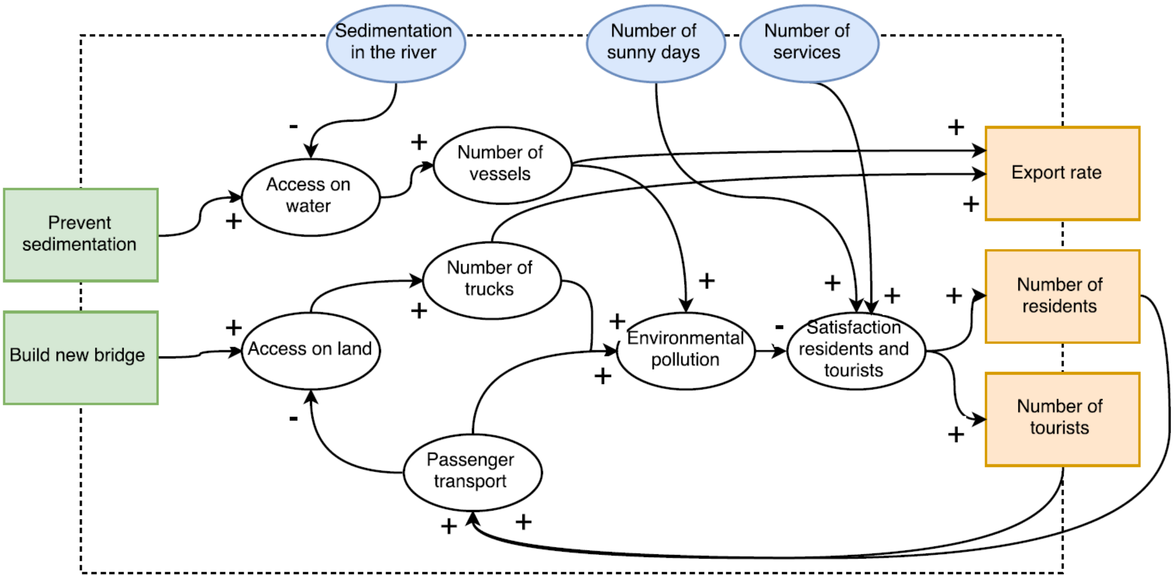

Figure A.4: System Diagram (Own work)

A.3.1 Criteria

The most important criteria defined in the objectives tree, are taken into account in the system diagram. How these criteria are influenced by the different means and external factors is explained below. The criteria are:

- Export rate
- Number of residents
- Number of tourists

A.3.2 Means

The means for increasing the accessibility for export are elaborated in the means-end tree. Two means are chosen to be included in the system diagram, prevent sedimentation and build new bridges. The influence of these means on the different criteria are shown in Table A.1.

Table A.1: Influence means on criteria (Own work)

criteria/ means	export rate	number of residents	number of tourists
Prevent sediment	+	-	-
Build new bridges	+	-	-

In the table, a minus means a negative causal relation and a plus means a positive causal relation. The explanation of the causal relations are listed below.

- Build new bridges

  Building new bridges is an example of how the accessibility of the city can be increased. Building new bridges influences the capacity of the infrastructure on land. The access will be better and can lead to the opportunity of an increase of trucks for transportation. This has a positive effect on the export rate of the city. On the other hand, more trucks contribute to more environmental pollution, such as an increase of greenhouse gases, noise and vision pollution. This can influence the satisfaction of residents and tourists negatively. Building new bridges will therefore have a negative effect on the number of residents and tourists in Valdivia, because environmental pollution causes a lower satisfaction of residents and tourists.

- Prevent sedimentation

  Preventing sediment leads to better access of waterways. The better the access, the higher the opportunity for vessels to use it. This can have a positive effect on the export rate of the city. On the other hand, more vessels result in more environmental pollution, such as noise, vision and emissions, and therefore can have a negative effect on the satisfaction of residents and tourists. Preventing sediment in this scope will lead to a decreasing number of residents and tourists.

For both means, it does not mean that there are no other effects influencing the satisfaction of residents and tourists. However, this system diagram shows that it is not only necessary to focus on the economic impact, but also on the social impact of certain measures.

This system diagram focuses only on the influence of the means on the cargo transport, keeping in mind that building a new bridge or preventing sedimentation also has positive effects on the satisfaction of tourists and residents. For example, their own mobility increases or they can use the river for their own pleasure.

A.3.3 External factors

The following factors are listed as external factors, because the problem owner can not influence these factors:

- Sediment

  The amount of sediment in the river has a negative effect on the access of the waterway. The worse the access, the lower number of vessels will use the river. This can lead to a lower export rate.

  On the other hand, the number of vessels affects the environmental pollution and therefore influences the satisfaction of residents and tourists, because the more pollution, the less people want to live or visit the city. This results in a lower number of residents and tourists. This relation is also within the chosen scope. In reality, more sedimentation causing less vessels will not necessarily lead to more residents and tourists, because other factors are influencing their satisfaction as well. However, for these other factors are left out of scope for this research.

- Number of sunny days

  The weather of a certain area influences the satisfaction of residents and tourists. Sunny weather has a positive effect on the mood and therefore satisfaction. The more satisfied the people about the city, the more people want to visit and live in the city, resulting in a higher number of residents and tourists.

- Number of Services

  The number of services, or in other words the facilities in the city, is an external effect in this research. The number of services is outside of the system boundaries, it is not used as something the Ministry will influence in this case. The number of services positively influences the satisfaction of residents and tourists, because the more facilities and activities available in a city, the more attractive it is for people to go there. This results in a higher number of residents and tourists.

The table below (Table A.2) shows the effects of the external factors on the criteria.

Table A.2: Influence external factors on criteria (Own work)

criteria means	export rate	number of residents	number of tourists
Sediment	-	+	+
Number of sunny days		+	+
Number of services		+	+

A.4 Actor analysis

An actor analysis gives an insight in which people, groups and organisations are involved in the problem and how they perceive the problem.

Based on the interests of the other players, it can be determined with whom the problem owner can work together and to whom the problem owner has to adapt (Enserink et al., 2010). The actor analysis consist several steps. Firstly, in Section A.4.1 is indicated which actors are involved in the sedimentation problem. The actors are presented in Section A.4.2 in a formal chart to give an overview of the relation between the actors. After that, the actors and their interests are discussed in Section A.4.3. Lastly, in Section A.4.4 the critical actors are identified and the classification of their dependencies are shown in a table.

A.4.1 Involved parties

Problem owner

Chile is a centralised country, the most projects are organised from Santiago. In Chile there are 23 ministries and each ministry has a delegation in the 15 regions of Chile (Ministerio de Obras Publicas, 2017b). The city Valdivia belongs to the municipality of Valdivia, and to the Region de Los Ríos (Intendencia de Region Los Rios, 2017). The ministries are divided in several departments.

The problem owner in this research is the Ministry of Public Works.

The Ministry of Public Works is divided in six departments (Ministry of Public Works, 2017). In this research five departments are involved with the sedimentation problem:

- Coordination of Public Works
- Concession Department of Architecture
- Department of Hydraulic Works
- Department of Port Works
- Department of Roads

In specific, the department of Port Works is the problem owner and is responsible for planning the port infrastructure, develop and supervise port works projects and supervise the dredging operations (Ministry of Public Works, 2017).

Relevant actors

Besides the Ministry of Public Works, there are several other actors involved with the problem.

- Public parties of Region de Los Ríos
  - Ministry of Public Works
  - Ministry of Finance
  - Ministry of Transportation and Communication
  - Ministry of Housing and Urban Planning
  - Ministry of Economy, Development and Tourism
  - Ministry of Environment
  - Municipality of Valdivia
- Other stakeholders
  - Residents of Valdivia
  - Tourists of Valdivia
  - Truck drivers
  - Water users (Freight vessels and Boat tours)
- Ports (Corral and Las Mulatas)
- Nature conservationists
- Dredging company

A.4.2 Formal Chart

The relationships between the stakeholders in a formal and informal way are shown in the formal chart below, see Figure A.5. The four different arrows, expressing different relationships, are explained in the legend. The most important stakeholders are explained here. Conversations with Chilean professors and the Dutch embassy of Chile have led to insight into the structure of the government and the relationships between different stakeholders in Chile (personal communication, September 22^{th}, 2017) (personal communication, September 26^{th}, 2017).

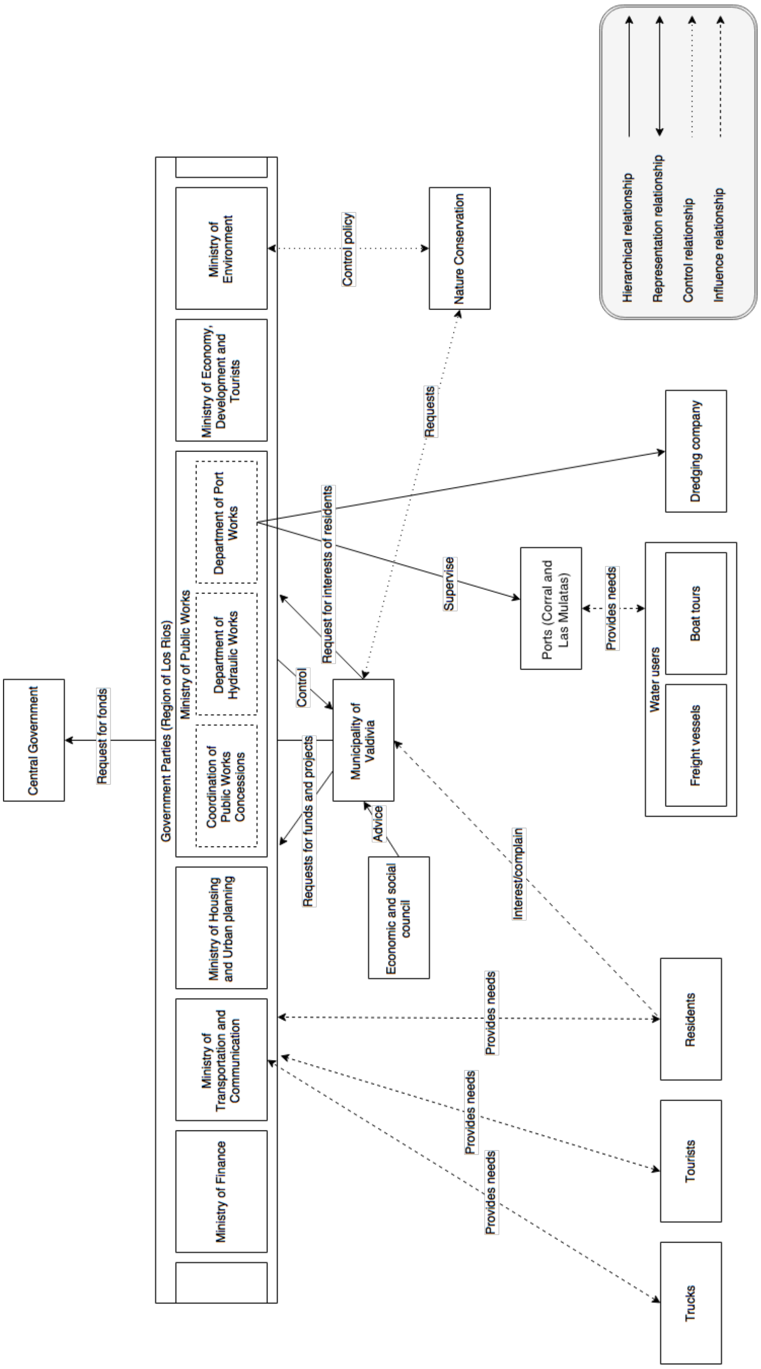

Figure A.5: Formal chart (Own work)

A.4.3 Problem formulation actors

In Table A.4 the stakeholders are shown with their interests and desired situation. In addition, the current situation, the gap between these two situations, the causes of this gap and the possible solutions are shown.

Table A.3: Overview of actors, Part I (Own work)

Actors	Interests	Desired situation	Existing gap	Causes	Possible solutions
Residents of Valdivia	Sustainable environment with low inconvenience and good air quality, good accessibility	No nuisance (air, noise, congestion), high welfare of Valdivia	Nuisance of traffic	Growing amount of road users, growing amount of tourists and residents, little involvement	Expanding infrastructure, investment in sustainable infrastructure, participation in policy
Trucks	Transport freight from A to B by truck	Move and deliver goods from A to B safely and without delays.	Limited access to deliver their goods, access city only between 9 and 7 during the night. [1]	No sufficient capacity of the infrastructure. Growing amount of transport.	Expand the infrastructure for freight.
Freight vessels	Transport freight from A to B by vessel	Move and deliver freight from A to B safely and without delays	Access of the waterways is limited	Sedimentation, Bridges over the waterways	Dredge the waterways, prevent sedimentation, build bridges which can be opened
Tourists of Valdivia	A nice stay in Valdivia	Attractive city with a lot of touristic activities. Good access.	Congestion on the roads	Limited capacity of the infrastructure.	Expand the infrastructure, build other transport modes
Port of Las Mulatas	Prosperous port with a lot of trade	Highly accessible for vessels	Acces of the waterway is limited	Sedimentation	Dredge sediment, prevent sediment.
Port of Corral	Prosperous port with a lot of trade	Maintain market position for trade	Possible decrease in market position	Higher accessibility to Las Mulatas	Increase cooperation with Las Mulatas, prevent competition
Nature conservationists	Protecting the nature	Nature without damage	Increase in damage of nature on land and in the water	Increase of transport emissions and dredging activities	Sustainable transport, alternatives for dredging
Ministry of Public Works	Planning, studying, designing, constructing, maintaining and operating public infrastructure in Chile [2]	High connectivity, high economic, social and cultural development of los Rios	Accessibility of the Valdivia River is not sufficient	Sedimentation	Prevent sedimentation, Dredge

[1] (SECTRA, 2014), [2] (Ministry of Public Works, 2017)

Table A.4: Overview of actors, Part II (Own work)

Actors	Interests	Desired situation	Existing gap	Causes	Possible solutions
Ministry of Finance	Economic growth, more efficient use of the nation's productive resources, sustainable growth, better quality of life [3]	Economic development with spending as less money as possible	Current way of maintaining the infrastructure is expensive	No policy on dredging, insufficient knowledge and cooperation between authorities	Proactive policy, more cooperation between authorities, gathering more knowledge about the sedimentation problems
Ministry of Economy, Development and Tourists	Promote modernization and competitiveness of the country, efficient market forces, innovation. Sustainable and fair growth [4]	High welfare of Valdivia in terms of tourism and export	Limited opportunity to grow	Limited accessibility	Improve infrastructure, prevent sedimentation
Ministry of Transportation and Communication	Promote efficient, safe and sustainable transport systems [5]	High accessibility of Valdivia	Limited accessibility	Sedimentation, growing amount of transport	Prevent sedimentation, dredging, improve infrastructure
Ministry of Environment	Sustainable development of los rios [6]	Sustainable region	Current infrastructure is not sustainable	Limited sustainable development of infrastructure, increase of transport, little cooperation between ministries	Gain knowledge in sustainable infrastructure, improve cooperation between ministries
Municipality of Valdivia	Attractive city for the residents. [7]	Satisfied residents	residents experience nuisance	Little involvement	Improve cooperation with ministries, listen more to residents
Ministry of Housing and Urban Planning	Sustainable neighbourhoods and cities, improve quality of life and welfare of people [8]	Sustainable and attractive city	Little space available for urban development	Increase of transport, higher density of the city	Expand the city boundaries
Dredging company	Dredge sediment	Good equipment for dredging			

[3] (Ministerio de Hacienda, 2017), [4] (Ministerio de Economia, Fomento y Turismo, 2017), [5] (Ministerio de Transporte y Telecomunicaciones, 2017), [6] (Ministerio del Medio Ambiente, 2017), [7] (Municipad Valdivia, 2017), [8] (Ministerio de Vivienda y Urbanismo, 2017)

A.4.4 Identification of critical actors

The following Table A.5 identifies the critical actors. Critical actors are actors which are important because of their ability to realise or block a particular project (Enserink et al., 2010). These critical actors are identified by looking at their resources, their degree of substitution and to what extend the problem owner depends on them.

Table A.5: Replaceability and dependence of resources (Own work)

Actor	Important resources	Replaceable	Dependency	Critical actor
Ministry of Public Works	Authority	No	High	Yes
Residents of Valdivia	Protests	No	High	Yes
Trucks	-	Yes	Medium	No
Freight vessels	-	Yes	Medium	No
Tourists of Valdivia	Money	No	Medium	Yes
Port of Las Mulatas	Dominant position for trade	No	High	Yes
Port of Corral	Dominant position for trade	No	High	Yes
Nature conservationists	Protests and act of power	No	Low	No
Ministry of Finance	Authority and money	No	High	Yes
Ministry of Economy, Development and Tourists	Authority	No	High	Yes
Ministry of Transportation and Communication	Authority	No	Medium	Yes
Ministry of Environment	Authority	No	Medium	Yes
Municipality of Valdivia	Money	No	Low	No
Ministry of Housing and Urban Planning	Authority	No	Medium	Yes
Dredging company	-	Yes	Low	No

All the Ministries have their authority as important resource and can make use of laws. Those ministries are critical actors; they have power and are irreplaceable.

Residents and tourists are critical actors. They do not have authority, however they are important to take into account because they can delay implementation processes and can leave the city if they are not satisfied.

Trucks and freight vessels are non-critical actors. They are replaceable and do not have resources. They have the same interest and want a solution for the lack of accessibility of the city. However, it is not their problem how the Ministry is going to solve the sedimentation problem.

The Port of Las Mulatas and the Port of Corral are critical actors. These ports are not replaceable and very important for the trade and therefore the economic value of Valdivia and the region. However, the Port of Corral has conflicting interests, because improving the accessibility of the waterway to Las Mulatas might influence their economic value.

The municipality of Valdivia has little power and is therefore not a critical actor. A dredging company is not a critical actor, because it is replaceable by another company and has no resources.

In Table A.5 the critical actors are determined. In Table A.6 is indicated whether the actors are dedicated or non-dedicated and whether they have similar or conflicting interests. This information is useful for the problem owner, because it shows which actors should be taken into account and which actors are easier to convince (Enserink et al., 2010).

Table A.6: Classification dependencies actors (Own work)

	Dedicated actors		**Non-dedicated actors**	
	Critical actors	**Non-critical actors**	**Critical actors**	**Non-critical actors**
Similar interests	- Ministry of Public Works - Ministry of Finance - Ministry of Economy, Development and Tourists - Ministry of Transportation and Communication - Ministry of Housing and Urban Planning - Port of Las Mulatas			- Trucks - Freight vessels - Dredging company
Conflicting interests	- Port of Corral - Ministry of Environment - Residents - Tourists	- Municipality of Valdivia		- Nature conservationists

All the Ministries except from the Ministry of Environment are dedicated critical actors with similar interests. They want a development and growth of the city, however, all the Ministries have their own focus and that is the reason why the Ministry of Environment has a conflicting interest for this problem. The Ministry of Environment is a dedicated critical actor with conflicting interests. Dredging will lead to damage of the nature and nuisance. The Port of Las Mulatas has similar interest and is a dedicated critical actor.

The residents and tourists have similar interests when it comes to infrastructure, however conflicting interests when it comes to nuisance. It is important for them to live and be a good environment. Therefore, they are dedicated.

Trucks, freight vessels and dredging company are non-dedicated non-critical actors. although, freight vessels and dredging companies have an interest in increasing the accessibility of the river, because vessels make use of this river and it means more work for dredging companies.

The Port of Corral is a dedicated critical actor, but as mentioned before, they might be afraid of losing their position on the trade market.

The Municipality of Valdivia is a non-critical dedicated actor with conflicting interests. The municipality of Valdivia wants satisfied residents. Dredging the river can lead to nuisance and other negative effects.

Nature conservationists are non-dedicated non-critical actors with conflicting interests. Dredging the river will possibly lead to damage of the nature and can influence the importance of Corral. They are non-dedicated, because it is assumed that dredging will not lead to an enormous modification of the nature and therefore this problem will not be the first priority for them.

To conclude, as can be seen in the table, the problem owner has a lot of supporters which are critical and dedicated. Therefore, the obstruction will be low given the fact that the power of actors with conflicting interests is very low. However, some of them are critical and are important to take into account, because they can delay the implementation of projects and some are necessary for the city. For example, if all residents leave because they are not satisfied there will not be a city anymore.

B. Location analysis

B.1 Population

Table B.1: Characteristics of the population by municipalities (Ilustre Municipalidad de Valdivia, 2017)

PROVINCIA DE VALDIVIA. CARACTERÍSTICAS GENERALES DE LAS COMUNAS. SUPERFICIE - POBLACION.

PROVINCIA DE VALDIVIA			Población Censo 2002	
COMUNA	SUPERFICIE Km²	%	TOTAL (hab)	%
VALDIVIA	**1.015,6**	**9,96**	**140.559**	**54,22**
CORRAL	766,7	7,52	5.463	2,10
LANCO	532,4	5,22	15.107	5,83
LOS LAGOS	1.791,2	17,57	20.168	7,78
MÁFIL	582,7	5,71	7.213	2,78
MARIQUINA	1320,5	12,95	18.223	7,03
PAILLACO	896,0	8,79	19.237	7,42
PANGUIPULLI	3.292,1	32,28	33.273	12,84
	10.197,2	100%	259.243	100%

Cuadro elaboración propia. Datos Superficies y Población INE Región de Los Ríos. Censo 2002.

Table B.2: Evaluation of the population of Valdivia, 1992-2030 (Ilustre Municipalidad de Valdivia, 2017)

EVOLUCIÓN POBLACIÓN URBANA DE VALDIVIA, 1992-2030

Año	Población. (hab)
1992	112.712
2002	129.952
2005	132.498
2010	142.243
2015	152.705
2020	163.576
2030	187.696

Table B.3: Total population (Bibliotheca de Congreso Nacional de Chile, 2015)

	Year 2002	Year 2015	Change (%)
Valdivia	140,559	167,861	19.42
Region Los Rios	356,396	404,432	13.48
Chile	15,116,435	18,006,407	19.12

Table B.4: Population per sex Valdivia 2015 (Bibliotheca de Congreso Nacional de Chile, 2015)

	Man	Woman
Number	81,700	86,161
Percentage (%)	48,67	51,33

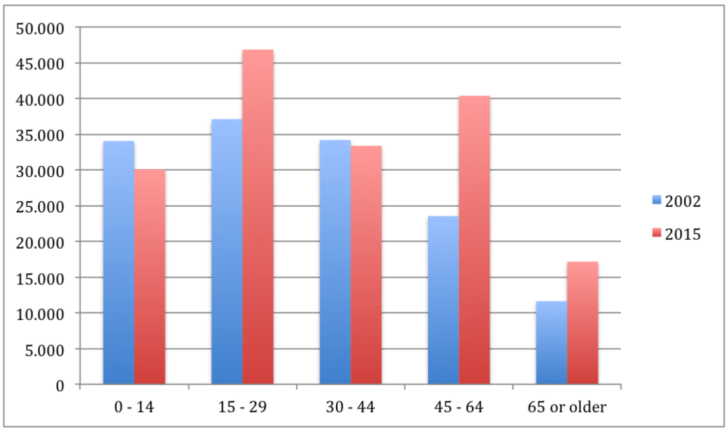

Figure B.1: Population of Valdivia by age groups (Bibliotheca de Congreso Nacional de Chile, 2015)

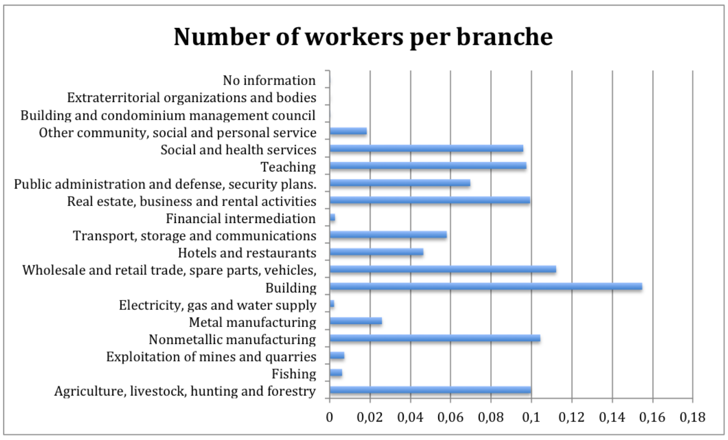

Figure B.2: Number of workers by industry in 2013 of Valdivia (Bibliotheca de Congreso Nacional de Chile, 2015)

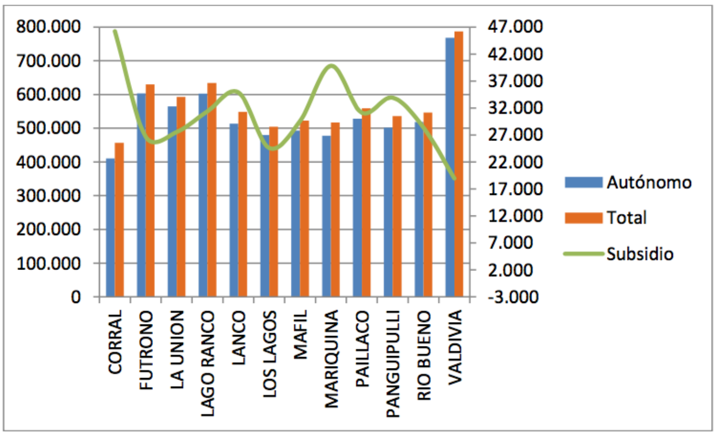

Figure B.3: Distribution of community income, Region Los Rios, 2011 (SECTRA, 2014)

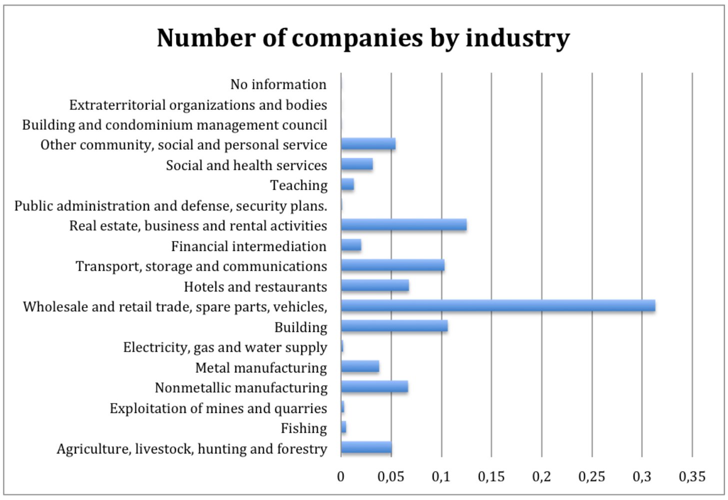

Figure B.4: Number of companies by industry in 2013 by Valdivia (Bibliotheca de Congreso Nacional de Chile, 2015)

B.2 River usage

B.2.1 Collection areas and ports

The collection of export products before foreign shipment is composed of two collection sites in Corral and three in Valdivia. The sizes of these collection sites are presented in Table B.5 and an overview of the locations is shown in Figure B.5. The Cancha Acopio Amargos collection field in Corral is the main reception area of forest bulk coming from Valdivia by fluvial transport. From here the bulk can be transferred directly to the port of Corral by means of conveyor belts. The Cancha Acopio Corral Bajo collection site is only used as a storage area to and from where cargo is transported by means of trucks.

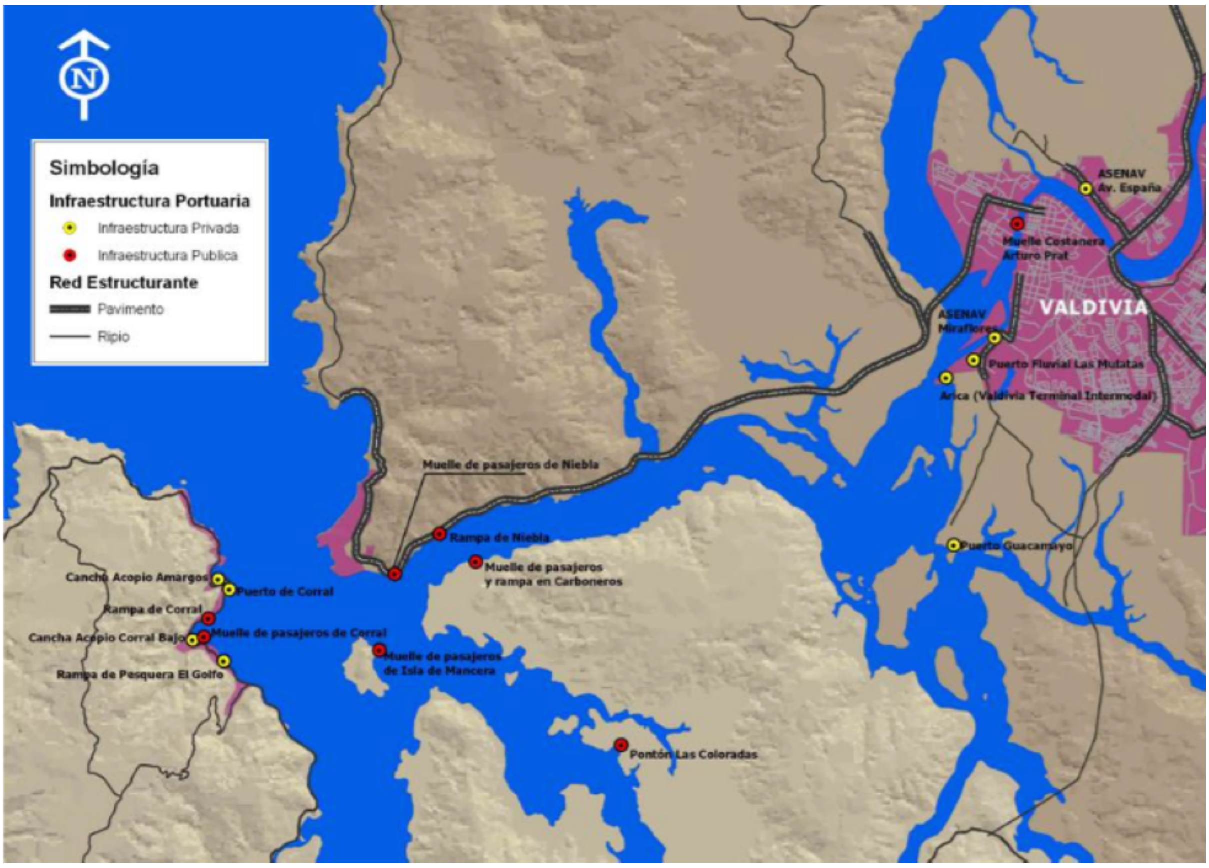

Figure B.5: Overview of ports in the Valdivia estuary. (Port of Corral, 2017b)

The collection fields in Valdivia are of a larger size then those in Corral and are also referred to as ports. The larger size is because of an absence of a suitable, safe and expeditious road access for trucks to the port of Corral, which makes the port of Corral less accessible than Valdivia for trucks coming from the hinterland. The wood is delivered to these ports by trucks coming from collection fields between Region Araucas and Region Los Lagos. At the Valdivia ports, the wood is processed into chips and shipped to Corral. A schematisation of the handling process of wood from the forest until Corral is presented in Figure B.6.

The Las Mulatas port is the most significant port in Valdivia. It offers accommodation for vessels with a maximum length of 100 meters and a maximum draught of 3.8 meters. Since the port only has one berth, it can only accommodate for one cargo vessel.

The fluvial transport between the collection sites in Valdivia and Corral is carried out by three barges, presented in Table B.6. As can be seen in the table, the largest draught is reached by the 'Comau'. Because of its draft, the Comau is only able to moor at the Las Mulatas port. The other two barges are used for transport from the Guacamayo and Arica port.

B.2.2 Passenger transport

The passenger transport along the Valdivia estuary is regulated by means of ferries and road transport. At the bay of Corral, the locations Corral, Niebla, Carboneras, and Isla Mancera are connected by means of ferry infrastructure. Between the bay of Corral and Valdivia, passengers are transported by road transport. There is one available road situated between Niebla and Valdivia (Figure B.5) (Ministerio de Obras Publicas, 2015).

Table B.5: Collection sites (Ministerio de Obras Publicas, 2015)

Collection site	Location	Area [hectares]
Amargos	Corral	1.8
Corral Bajo	Corral	0.9
Total Corral		2.7
Puerto Las Mulatas	Valdivia	7.0
Puerto Arrica (Valdivia Terminal Intermodal)	Valdivia	3.5
Puerto Guacamayo	Valdivia	6.0
Total Valdivia		16.5

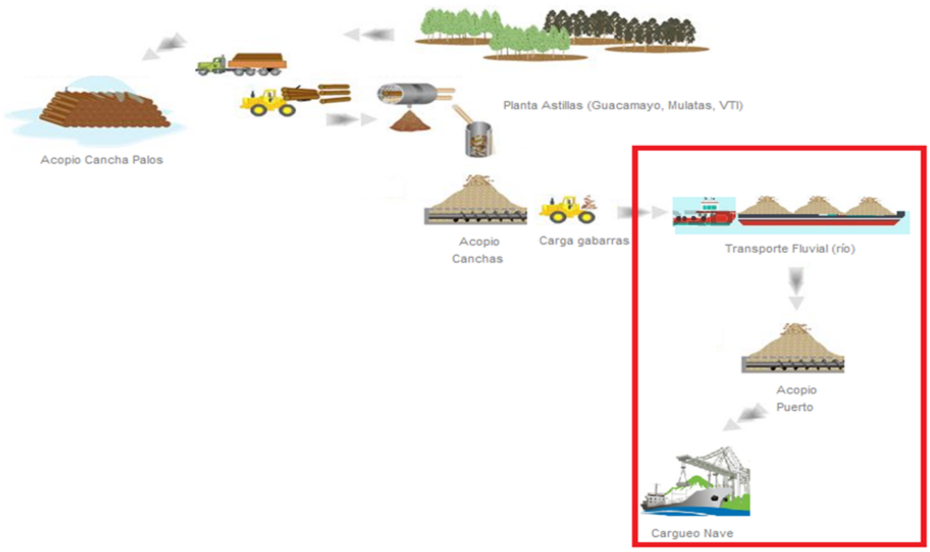

Figure B.6: Processing and fluvial transport of forest cargo (Port of Corral, 2017b)

Table B.6: Cargo vessels Valdivia - Corral (Port of Corral, 2017a)

Name	Vessel type	Length [m]	Draught [m]
Amargos	Barge	54	2.2
Angachilla	Barge	54	2.2
Comau	Self-propelling barge	65	3.8
San Martin	Tug	18	2.9

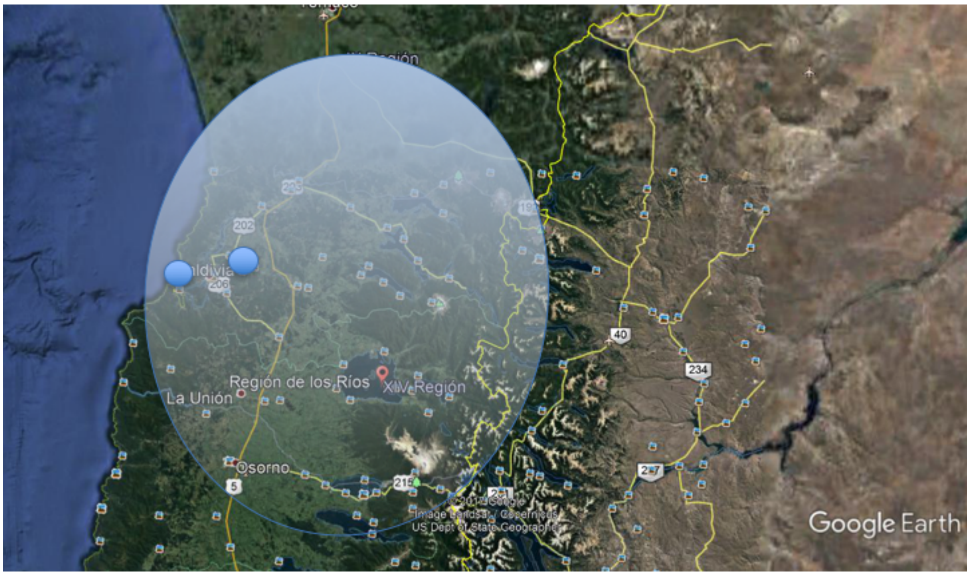

Figure B.7: Influenced area for the port of Corral (Port of Corral, 2017b)

B.3 Estuary and rivers

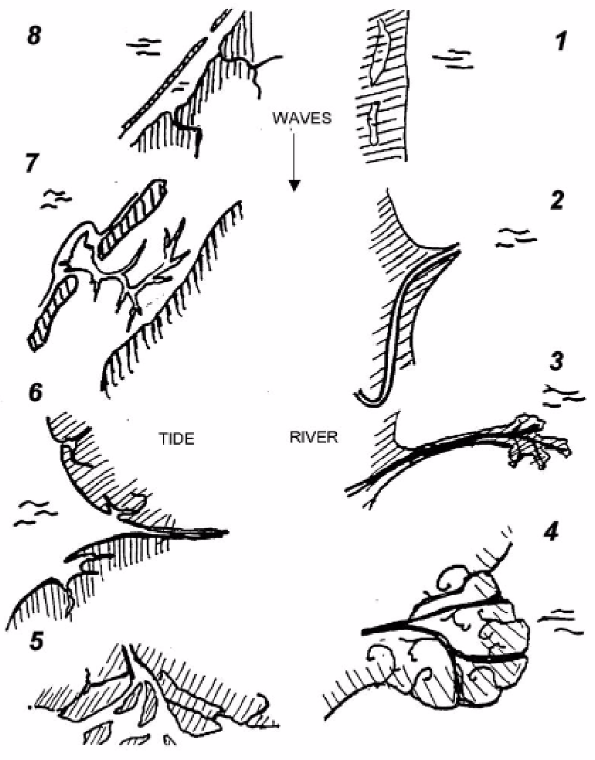

Figure B.8: Example sketches of coastal morphologies with different distributions hydraulic of influences (Bosboom & Stive, 2015)

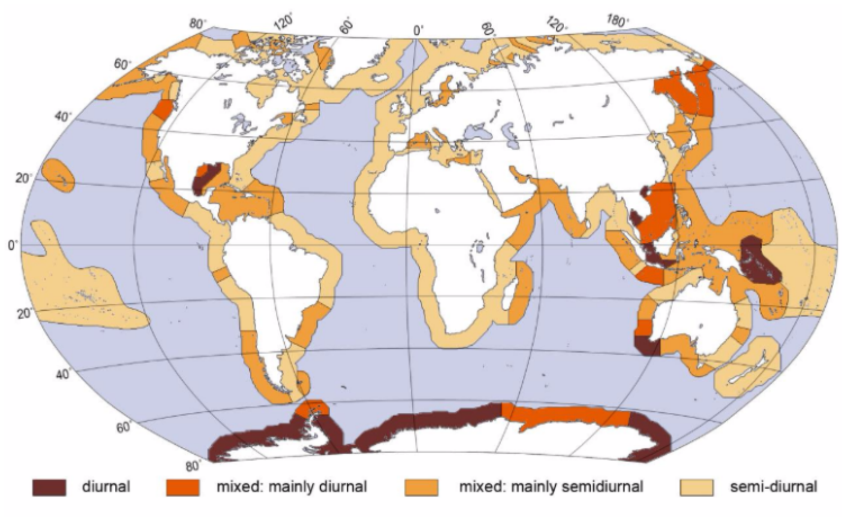

Figure B.9: Tidal environment around the world (Bosboom & Stive, 2015)

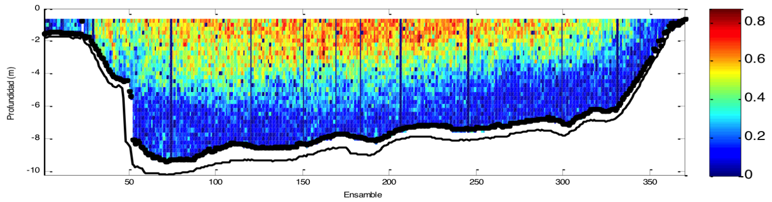

Figure B.10: Bottom profile in the Calle Calle river with flow speeds during low tide. Measured at the Pedro de Valdivia bridge (Caamano-Avendano, 2017)

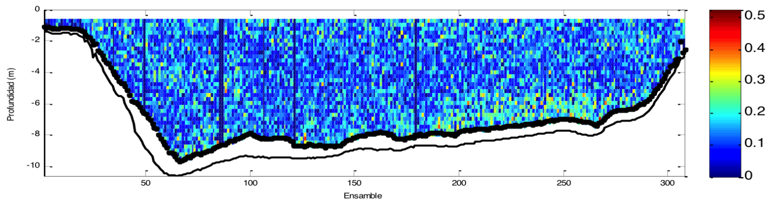

Figure B.11: Bottom profile in the Calle Calle river with flow speeds during high tide. Measured at the Pedro de Valdivia bridge (Caamano-Avendano, 2017)

B.3.1 Tidal prism

The definition for tidal prism is: the volume of water entering or leaving the basin per half tidal cycle. The tidal prism can be expressed by the following formula (Bosboom & Stive, 2015).

$$P = \text{tidal range} \cdot A \tag{B.1}$$

P = tidal prism(m^3)
A = area of the basin(m^2)

The two parameters that are important for the equilibrium of a tidal basin are:

- Equilibrium total channel volume below MSL in the basin (V_{MSL})
- Volume of the ebb tidal delta (V_od)

These parameters are influenced by the tidal prism by means of the following formulas:

$$V_{MSL} = C \cdot P^{3/2} \tag{B.2}$$

$$V_{od} = C \cdot P^{1.23} \tag{B.3}$$

The effect of changes of these parameters on the sediment import or export is clarified by means of Figure B.12 (Bosboom & Stive, 2015). If the tidal prism changes, the equilibrium volumes of V_{MSL} and V_{od} change as well. The basin reacts by adapting to these new equilibrium values.

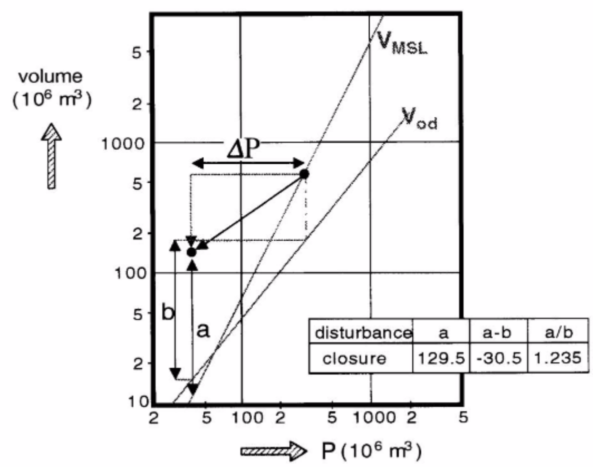

Figure B.12: The effect of closure part of a basin. P decreases so the channel volume becomes too large and starts importing sediment from the outer delta which also became too large. (Bosboom & Stive, 2015)

B.3.2 Water cycle in Chile

- **Monthly precipitation**

  The data of the montly precipitation from Table B.7 show a development of precipitation as shown in Figure B.13. It shows a peak in winter in June and a low in summer in November.

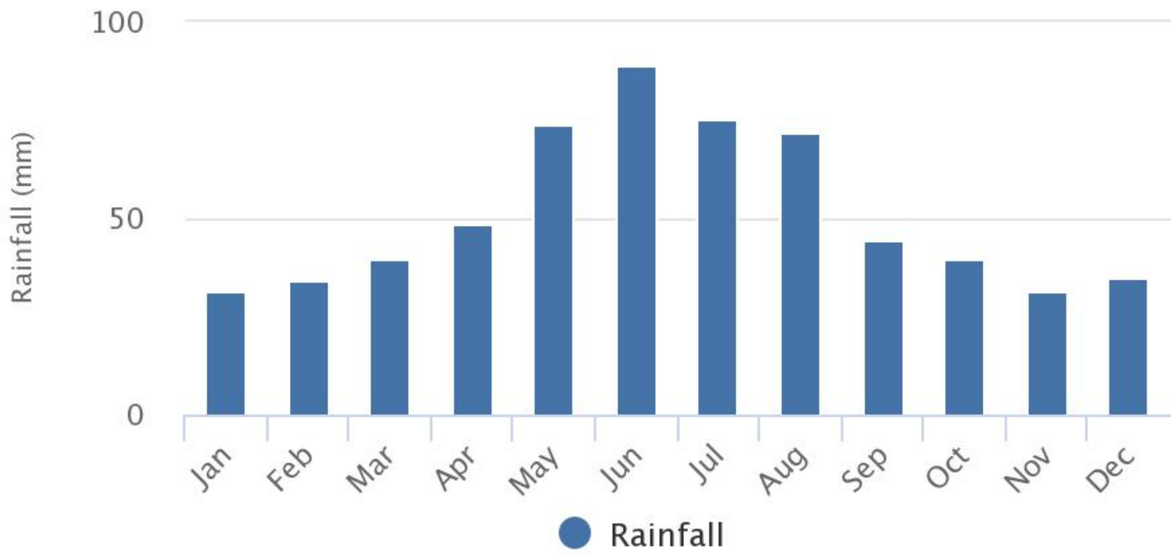

Figure B.13: Precipitation in Chile per month (World Bank, 2017)

Table B.7: Monthly precipitation in Chile (World Bank, 2017)

Month	**Precipitation** [mm]
January	31,8
February	34,5
March	40
April	48,9
May	74,1
June	88,9
July	75,3
August	71,8
September	44,8
October	40
November	31,2
December	34,9

- **Precipitation per latitude**

  In Chile the average precipitation per month ranges from 88.9 mm in June to 31.2 mm in November (World Bank, 2017). However, due to the fact that Chile's length from North to South is more than 4200 km, the precipitation in Chile largely depends on latitude (Abarza et al., 2012). The measuring station near the lake Calafquén is located at 39°34′S and Valdivia is located at 39°81′S and these places are less than 100 kilometres apart as the crow flies. Due to the fact that these two places are relatively close to each other, it is assumed that the precipitation in these places are similar. At the measuring station at lake Calafquén, a yearly average rainfall of 2113.7 mm was measured (Abarza et al., 2012). That would mean that there is a monthly average rainfall of 352 mm. This is much larger than the monthly precipitation of the entire country of Chile. Assumed is that the precipitation does follow the same shape as shown in Figure B.13, but the order of magnitude are assumed to around the values from the measuring station at lake Calafquén.

- **Evaporation**
  There is no data available of the evaporation in the Valdivia river catchment. For an overview of the hydrological cycle it is advised that there is future research about the evaporation.

B.3.3 Waves

Figure B.14: Swell climate measured at the coast, just north of the estuary mouth (Wisuki, 2017)

B.3.4 Satellite images land use

In this section a few satellite images will be shown, retrieved from Google Earth. Figure B.15 shows the total river catchment. Figure B.16 and B.17 show satellite images from around the Calle Calle river. Figure B.18 show a satellite image from the Cruces river and B.19 the image from around the Futa river. These images display the land use in the Valdivia river catchment and are used in the explanation for the sediment sources from the rivers.

Figure B.15: Satellite image of Valdivia river catchment (Source: Google Earth, 2017)

Figure B.16: Satellite image of catchment near Calle Calle river (forestry) (Source: Google Earth, 2017)

Figure B.17: Satellite image of catchment near Calle Calle river (agriculture) (Source: Google Earth, 2017)

Figure B.18: Satellite image of catchment near Cruces river (Source: Google Earth, 2017)

Figure B.19: Satellite image of catchment near Futa river (Source: Google Earth, 2017)

B.3.5 Rivers south of Valdivia river

To make clear how the rivers south of the Valdivia river are organised, the images from Google Maps and Aquamonitor can be used (see Figure B.20 and Figure B.21). There is one big island, South of Cutipay, Isla del Rey. There are three rivers flowing towards the estuary from the South. From the East there is the Angachilla river. At the far East side of the river there is a large wetland area. It is assumed that there is no significant outflow from this river. There are no discharges measured and there is no river or source identified where the water in the wetlands can come from. The middle river from the South is the Futa river. The Futa river has a significant discharge for the Valdivia river. This is described in Section 5.3.3. The river on the West side is the Naguilán river. This river does not reach very far and has no data about its discharge. It is not known whether this river has an (significant) discharge. Because of the small size of the river as can be seen from Figure B.20 and B.21 it is assumed that the discharge of the Naguilán river is not significant for the total river discharge of the Valdivia river. At the West side of the Isla del Rey flows the Tornagaleones River. The Naguilán river flows out into this river. The Tornagaleones flows also South of the Isla del Rey, towards the Futa river. Where the Futa river and the Tornagaleones river meet, the river changes into the Guacamayo river. The Angachilla river also flows into the Guacamayo river. It is assumed that the Futa river discharge flows out into the Guacamayo river, because the Tornagaleones river is influenced by the tides, which causes a flow from West to East.

Figure B.20: Rivers south of Valdivia river (source: Google Maps)

Figure B.21: Rivers south of Valdivia river (source: Aquamonitor)

B.4 Sediment classification

Table B.8: Grainsize distribution (part 1) (Silob Chile Laboratorios, 2010)

	Area 1		Area 2		Area 3		Area 4	
Sieve size (μm)	M1	M2	M3	M4	M5	M6	M7	M8
4	0.00	0.00	0.00	0.00	0.00	0.00	0.00	4.00
8	0.45	0.41	0.19	0.23	0.14	0.53	0.80	0.71
16	2.38	0.83	1.34	0.18	0.70	1.25	3.56	3.23
30	31.24	6.30	15.94	17.79	10.75	15.09	33.89	28.36
50	53.91	50.87	63.57	69.26	67.95	59.74	42.23	49.18
100	8.98	34.45	15.99	9.88	16.31	20.89	10.86	11.16
200	2.47	5.14	1.82	1.70	2.66	1.60	4.95	5.43
>200	0.56	2.00	1.15	0.97	1.86	0.90	3.72	1.92

Table B.9: Grainsize distribution (part 2) (Silob Chile Laboratorios, 2010)

	Area 5		Area 6		Area 7	
Sieve size (μm)	M9	M10	M11	M12	M13	M14
4	16.75	2.04	0.00	0.00	0.45	0.00
8	8.71	5.34	0.49	2.49	2.17	0.45
16	13.25	16.41	1.22	5.20	6.84	0.04
30	24.03	30.05	2.21	18.24	18.04	4.17
50	16.35	23.21	22.54	58.46	40.89	78.02
100	9.90	11.01	57.48	12.58	12.87	14.40
200	4.82	6.37	10.77	1.95	9.14	2.19
>200	6.18	5.58	5.28	1.07	9.60	1.03

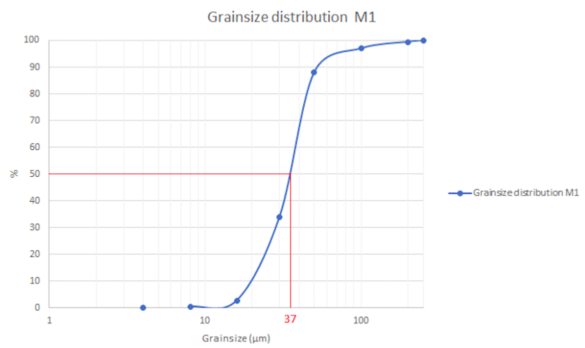

Figure B.22: D50 for the location M1 (Own work)

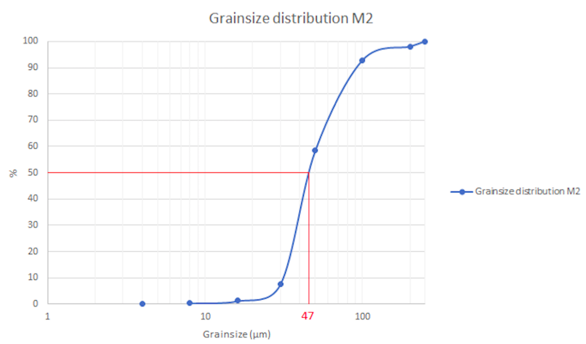

Figure B.23: D50 for the location M2 (Own work)

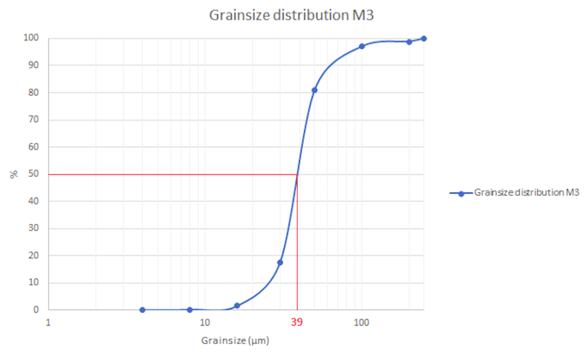

Figure B.24: D50 for the location M3 (Own work)

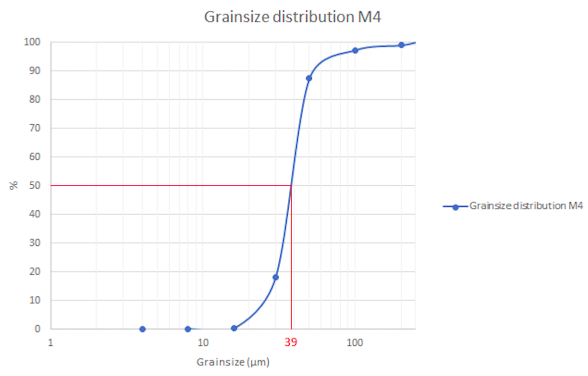

Figure B.25: D50 for the location M4 (Own work)

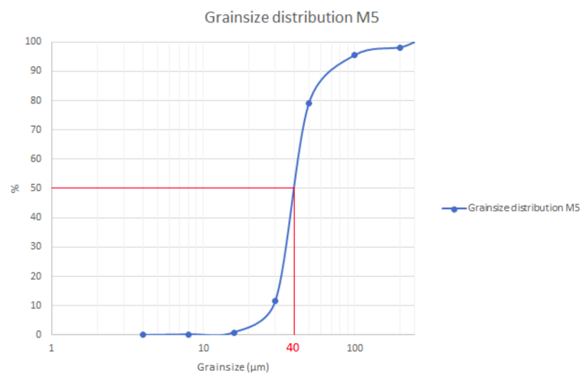

Figure B.26: D50 for the location M5 (Own work)

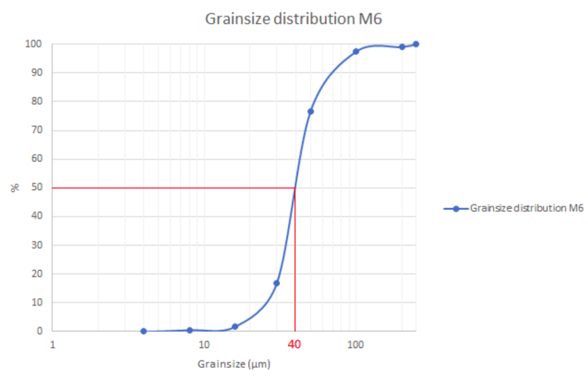

Figure B.27: D50 for the location M6 (Own work)

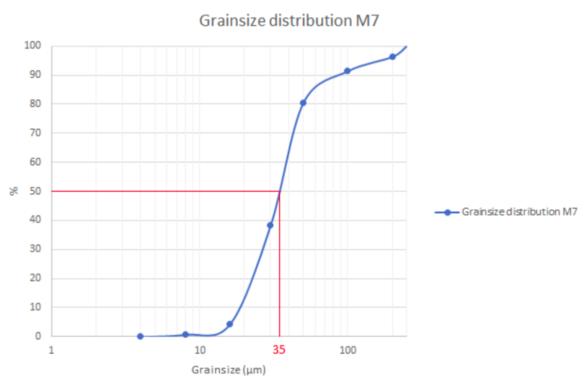

Figure B.28: D50 for the location M7 (Own work)

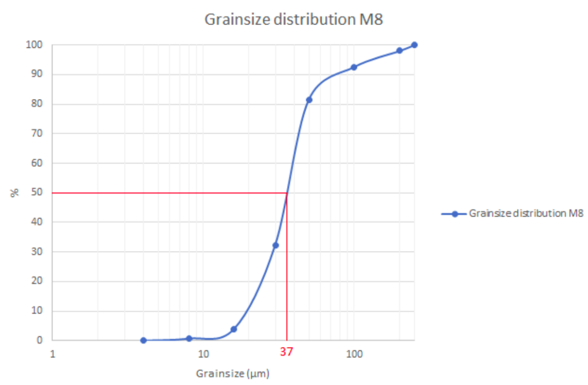

Figure B.29: D50 for the location M8 (Own work)

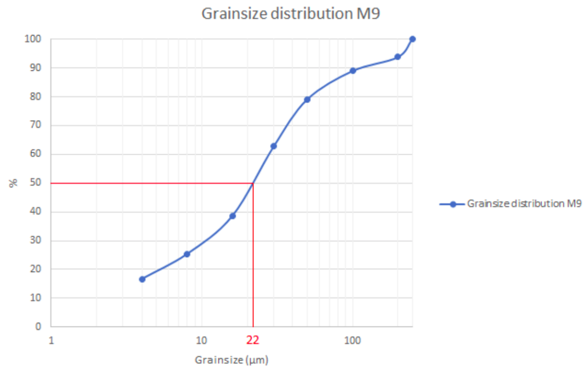

Figure B.30: D50 for the location M9 (Own work)

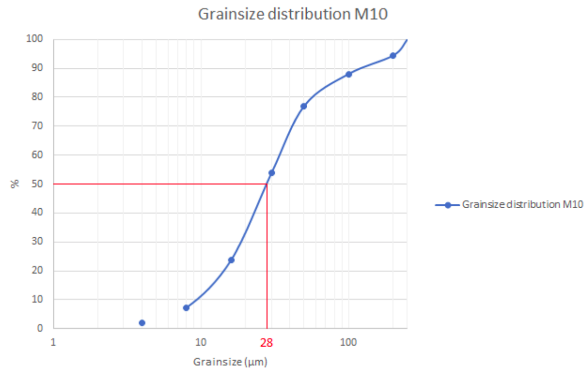

Figure B.31: D50 for the location M10 (Own work)

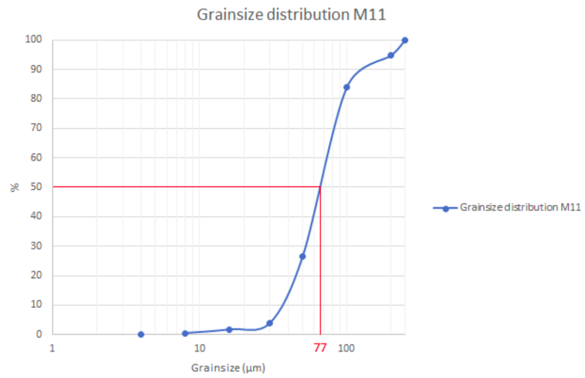

Figure B.32: D50 for the location M11 (Own work)

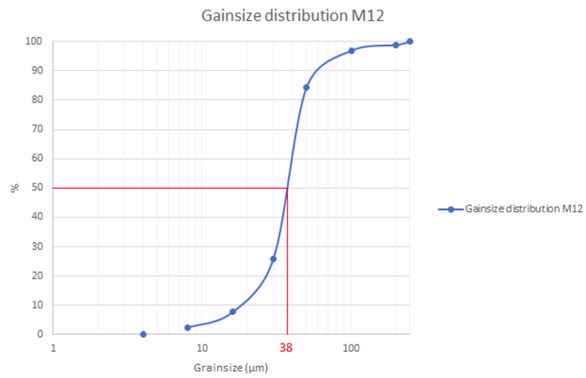

Figure B.33: D50 for the location M12 (Own work)

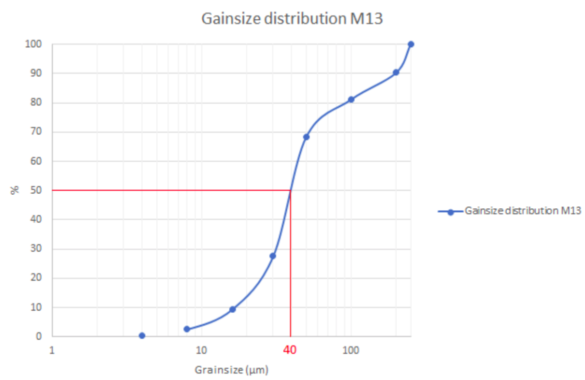

Figure B.34: D50 for the location M13 (Own work)

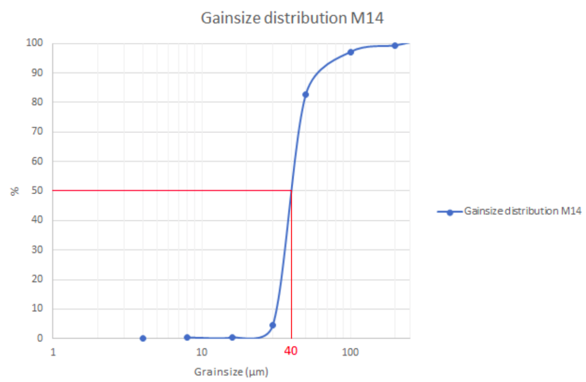

Figure B.35: D50 for the location M14 (Own work)

C. Interpretation sedimentation

C.1 Theoretical

C.1.1 Navionics

To get a good view on the bathymetry of the Valdivia river, a nautical chart from Navionics is used (Navionics, 2017). In Navionics, shallow areas are clearly displayed which allows to identify the areas of sedimentation properly as well as the tidal flats. Furthermore, the navigation channel is clearly visible because the submerged breakwaters are highlighted.

Figure C.1: Situation of the Cau Cau river (Navionics, 2017)

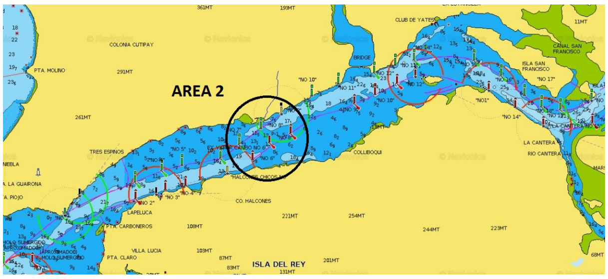

Figure C.2: Situation for point 2 (Navionics, 2017)

C.1.2 Sediment transport capacity

The sediment transport by water is described by many people and in many forms. A popular relation is the Engelund-Hansen relation (Blom, 2016) described by Equation C.1 in which s is the sediment transport dependent on the flow velocity U. The Engelund-Hansen relation is one of many examples that the sediment transport is related to the flow velocity.

$$s = \frac{k}{D} * U^n \tag{C.1}$$

C.1.3 Eddies

Eddies are secondary flow phenomena which occur in the case of sudden expansions or contractions in a river cross-section, or at sharp bends. When this happens, the flow lines can not follow the boundaries and separation occurs, leading to low pressure areas where eddies develop (Jansen et al., 1979). Inside an eddy, the flow circulates and the sediment concentrates in the centre of the circle after which it deposits ("teacup-effect") (Mosselman, 2016).

C.1.4 Backwater curves

The Valdivia river mild bed slope and subcritical normal flow all year around (Direccion de Obras Portuarias, 2017). In case of subcritical flow, the upstream reach flow is determined by the downstream boundary condition (Blom, 2016), in this case the 'flow' depth of the estuary. This depth is dependent on the water level during the tidal cycle of Valdivia. The two main backwater curves for mild slopes are called M1 and M2. They are presented in Figure C.3 and C.4

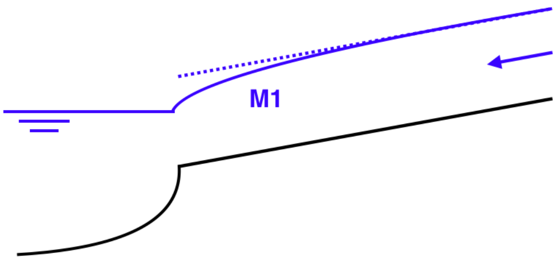

Figure C.3: A M1 backwater curve (Own work)

Figure C.4: A M2 backwater curve (Own work)

The discharge of the Valdivia river determines in both cases the equilibrium flow depth (indicated by the striped lines) Dependent on the type of curve, the water depth changes upstream of the estuary. If the discharge is constant, the M1 curve will cause an increase in flow velocity near the mouth whereas the M2 curve will cause a decrease in flow velocity near the mouth.

So in case of an M2 curve, the transport capacity of the Valdivia river will decrease while approaching the estuary, as this is a direct effect of the flow velocities (Equation C.1)

C.2 Delft3d model

The Delft3D model is used to confirm some currently sedimentation locations, confirm or dispute possible theoretical expectations and possibly to quantify the specific dredge areas.

This appendix will go over the input values and the settings that were used in order to make a basic model which can later be expended to include more processes and improved data for further and more detailed analysis.

C.2.1 Bathymetry

The bathymetry is the basis of every Delft3D model. It shows the map with all the ground heights compared to one reference level. A basic bathymetry is needed in order to even start any simplistic model. This section will explain the bathymetry that is used for this particular model with all the added boundaries, splines and grids.

C.2.1.1 Land Boundary

The land boundary is used in order to clearly see the river and estuarine flow boundaries and to identify the location of the data samples with respect to the area of interest. Also, it gives insight on the data thickness and whether there is sufficient data in all of the required areas. The land boundary for this model is made by drawing simple paths in Google Earth and importing the coordinates of the path into Delft3D, the used land boundary is displayed by the dark lines in Figure C.7.

C.2.1.2 Data Samples

The data samples loaded into Delft3D form the basis for the bathymetry calculations, as they are points on the map that show ground levels which can be interpolated to create the final bathymetry.

The data samples used in the model were provided by the Ministry of Public Works. However the provided data samples were mainly used for previous tsunami research. Some river data samples were also included, however not many.

The river samples were included through digitising two nautical maps of the ministry. However not many points were added in the river since it was not the main focus of the other tsunami research. One of the Delft3D experts in the UCSC used an interpolation method to try and solve the low point density of the sample file. Unfortunately the resulting depths were not correct and it was decided to create a rectangular point grid with a 100 meters width in order to recreated the nautical maps digitally by hand on a basic level.

For the Delft3D bathymetry a file is used with the mean sea level as reference level. Since the nautical maps both have the mean sea level as reference level as well, no additional changes were made to the provided depths in the nautical maps.

The nautical maps were combined to form one sample file. Figure C.5 shows one of these nautical maps.

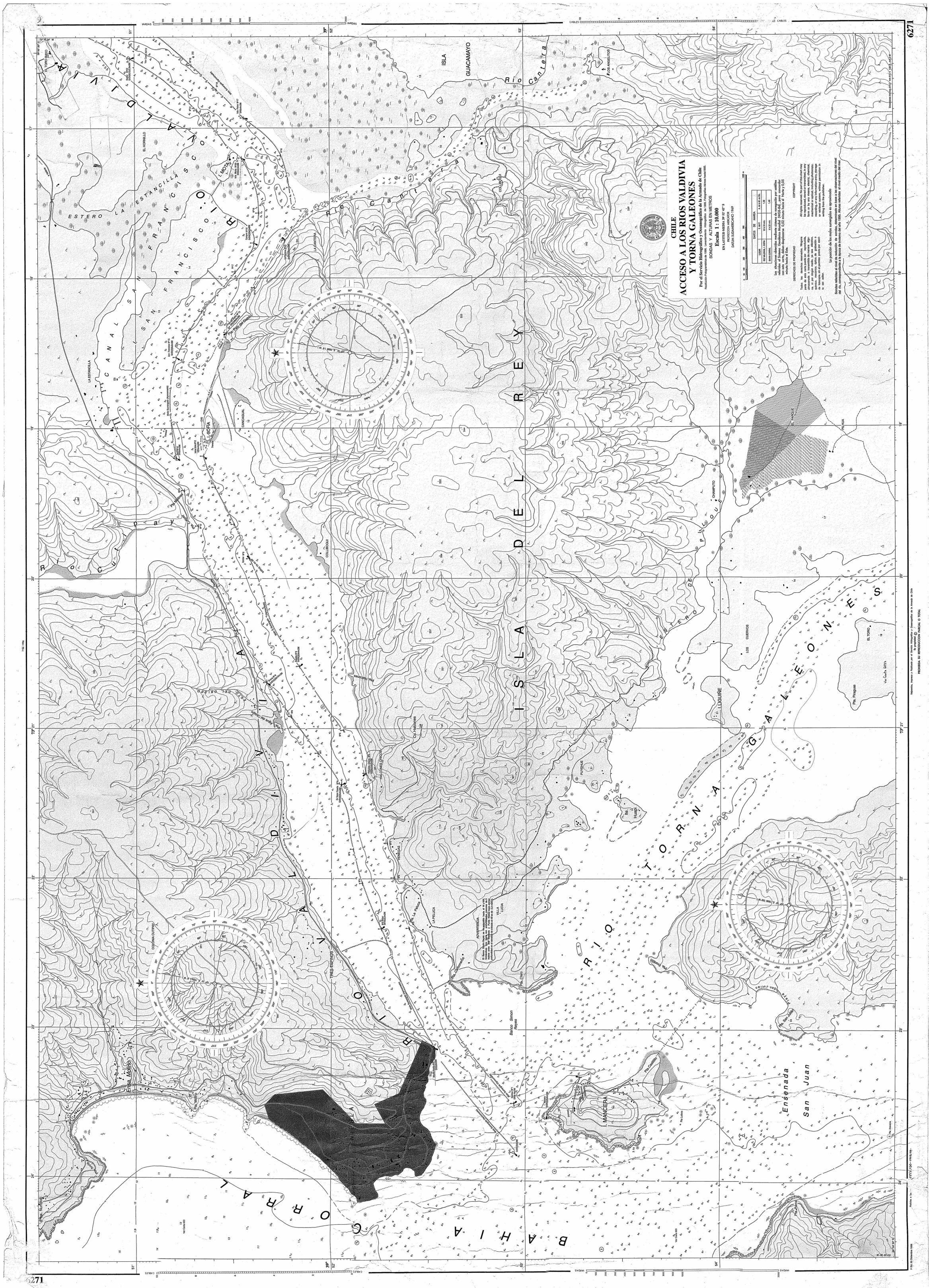

Figure C.5: One of the two nautical maps used to recreate the bathymetry (Direccion de Obras Portuarias, 2017)

The map with the large values for ground levels contains a lot of data that is not useful for the Delft3D model and including it can even slow the numerical calculation process. Ground levels right on the riverbanks and just outside the river are useful for the model, however some large hills and mountains were also included in the file with height of up to 500 metres above mean sea level. Many of these excessive heights were removed in order to speed up the model calculations. Also, the density of points was decreased. The final point sample file that was used is shown in Figure C.6.

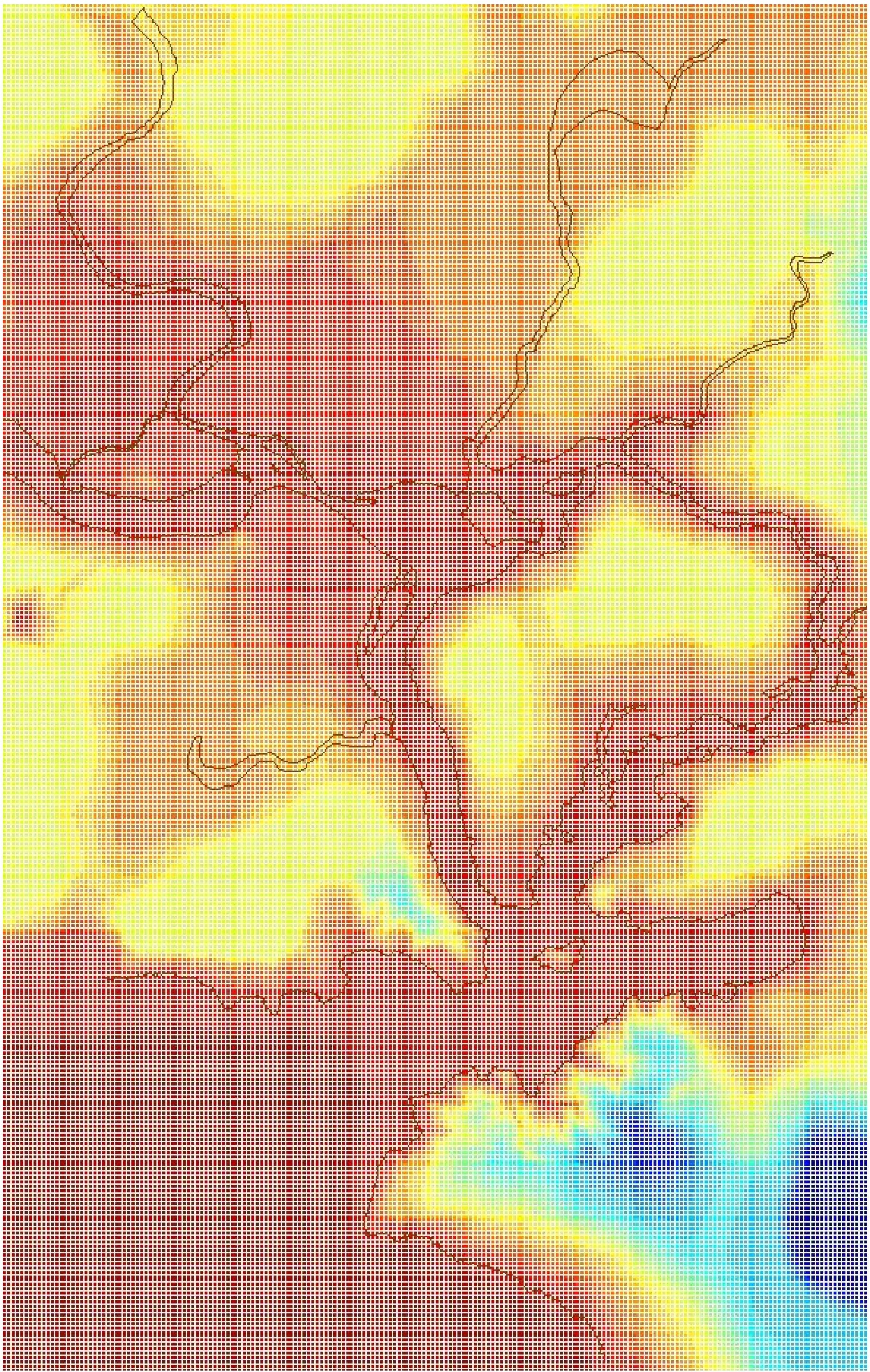

Figure C.6: Final point sample file with a 100 meters grid (Own work)

C.2.1.3 Splines

Splines in Delft3D are the basis for the modelling grid that is later generated. The splines can be used to distribute the grid density of the area and help to also distribute the focus of the model, in this case the Valdivia river. Figure C.7 shows the splines more closely packed around the river so that the river has a higher grid density.

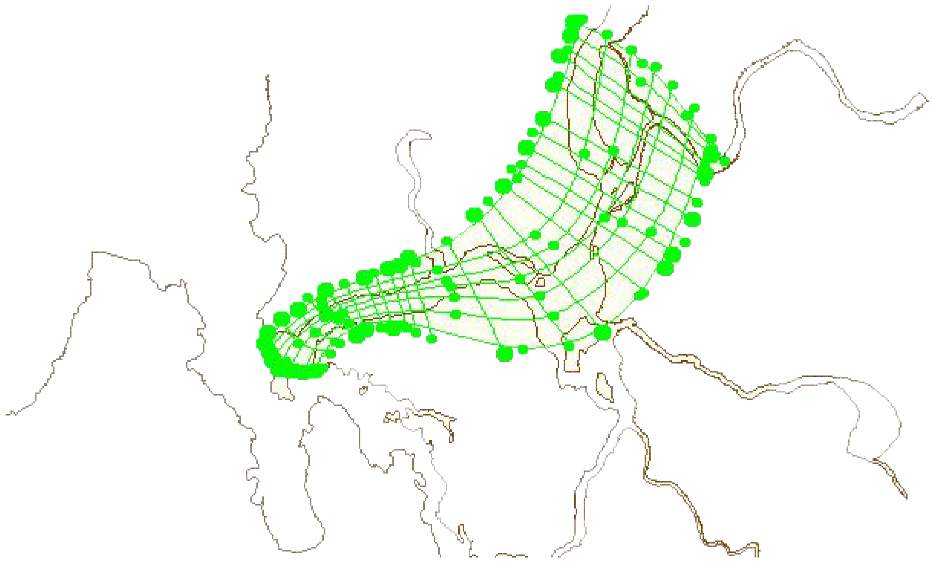

Figure C.7: Final splines used to created the grid (Own work)

C.2.1.4 Grid

The grid is generated by defining the amount of gridpoints between the splines in the M and N direction. The M and N factor are chosen in such way that the grid in the Valdivia river has around 20 cells across the river cross-section. Figure C.8 shows the final grid (M=7 and N=7) that was used in the model following from the splines.

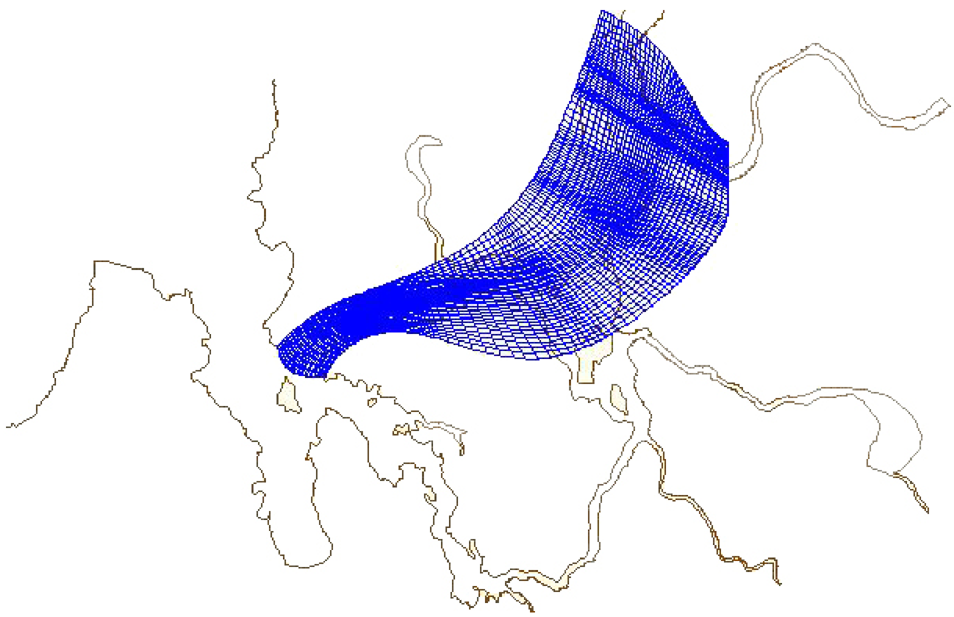

Figure C.8: Final grid of the scope (Own work)

C.2.1.5 Depths

With the grid and the point sample file, triangular interpolation can be used to create a depth file. Triangular interpolation overall gave good results, expect for some locations with big differences in height. These locations were identified within Delft3D and if any strange depths or flow bottlenecks were found, the point sample file was corrected to improve the triangular interpolation. The final depth file is shown in Figure C.9. For better visualisation Figure C.10 shows the same depth file without the high altitude points. High altitudes were deleted because the scale of the legend becomes more detailed and the depths in the river are better visible.

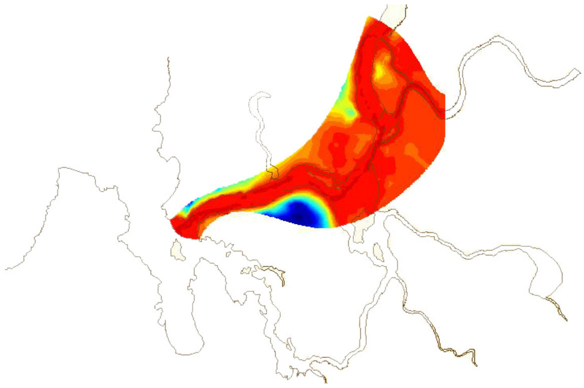

Figure C.9: Final depth file (Own work)

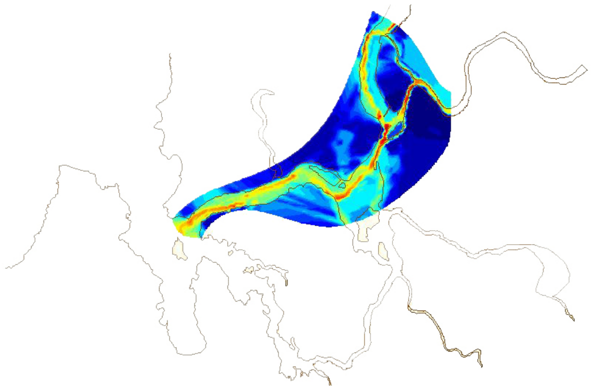

Figure C.10: Depth no high altitudes (Own work)

C.2.2 Inflexible model conditions

The model requires boundary conditions to work with. The most important boundary conditions are the hydraulic conditions. In this case it mainly requires the tidal wave input downstream and the river discharges upstream. These boundary conditions were determined in Chapter 5 and are inflexible parameters. They cannot be altered in order to calibrate the model, only to implement actual fluctuations throughout the year.

Since the depth file was created with point samples relative to the mean sea levels, the whole model is based on the initial condition of the average water level. This initial water level condition is set to 0.0 meters, so that most of the system is already filled with still water (as the slope in the system is extremely small). The various boundary conditions will affect this initial condition in the model.

C.2.2.1 Tides

The tide for this model in not put in as an offshore boundary condition. Rather, the tide is put in as boundary condition at the downstream end of the Valdivia river. At this location, the tide is assumed to be equal to the very closely located city of Corral. In Section 5.2 the tidal signal for Corral is analysed in more detail.

Since there is very little information on water levels within the Valdivia river, the model is calibrated with the only known tidal range upstream around the Valdivia city of 1.29 meters (Pino et al., 1993). Since this maximum tidal range is found during spring tide in 1990, the boundary condition for the tide is set to the spring tide in 1990 of Corral: a semidiurnal tidal signal with a range of 1.48 meters. The resulting calibrated water levels are shown in Figure C.11

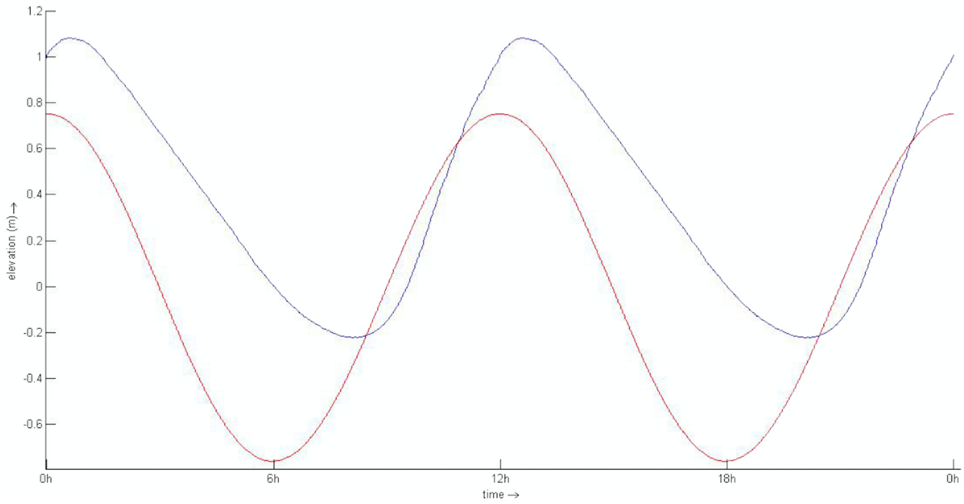

Figure C.11: Tidal signals for the Valdivia river mouth (red) and Valdivia city (blue) (Own work)

The tide is implemented as a harmonic water level forcing boundary. The frequency is set to form a semidiurnal tidal signal with the amplitude matching the 1990 tidal range. The boundary does not reflect in any way and thus has a reflection parameter (α) of zero.

C.2.2.2 Rivers

For the rivers is known the monthly average discharges or of the Calle Calle, Cruces and Futa rivers (see Section 5.3). For these rivers, August is the month with the highest discharges. February serves as the month with the lowest discharge boundary conditions. This way model is used to compare the two situations. The interactions between tide and discharges during August and during February (high and low discharge situations). Table C.1 shows the river boundary inputs.

Table C.1: River boundary discharges (Own work)

Boundary location	Discharge August [m^3/s]	Discharge February [m^3/s]
Calle Calle River	860	155
Cruces River	200	15
Futa River	50	6

The discharge boundaries require a value for the reflection parameter (α). In this case the parameter is set to zero in order to allow no reflection at the boundaries should a flow reach to one of the discharge boundaries.

Moreover, the discharges are implemented as a 'discharge per cell' boundary instead of a total discharge boundary. This way the discharge is evenly distributed over the width of each river. With the grid described in Section C.2.1.4 the Calle Calle river has four boundary cells, the Cruces has two and the Futa river has one. The total discharges (as presented in Table C.1) were therefore divided by the amount of grid cells.

C.2.3 Flexible model conditions

Many conditions that are used for the Delft3D model are inflexible like the discharges and the tide, since they represent actual measured phenomena. In order to calibrate the model certain parameters need to be adjusted to fine tune the results and calibrate the model. In the case of this basic flow model it mostly comes down to the roughness parameter.

C.2.3.1 Roughness

In Section C.2.2.1 it is described that the roughness is used to calibrate the model. Roughness is one of the four components that can be a cause of flow resistance (Rouse, 1965).

Within the model, the Chezy value is increased to such a level that the maximum tidal range in Valdivia matches with results from an earlier research (Pino et al., 1993). The final Chezy value is equal to 110 $m^{1/2}/s$. With equation C.2.3.1 the Chezy value can be rewritten into a Manning roughness coefficient of 0.040. For the hydraulic radius (R) a value of 8 meters was used, referring to the nautical map on which the bathymetry is based.

$$\frac{n}{R^{1/6}} = \frac{\sqrt{g}}{C} \tag{C.2}$$

This roughness coefficient refers to mountain streams with rocky beds (Barnes, 1967). As described in Section 5.6, the Valdivia river bed consists of fine, silty material. Therefore, the used roughness coefficient in the model is not representative for the real situation. However, since the bathymetry in the model is smoothened, it does not include irregularities on the river bed which induce form resistance (Rouse, 1965). Also, the submerged structures are assumed to exert friction on the tidal wave. Since these two bathymetry characteristics are not included in the model, their contribution to the tidal wave friction is assumed to be included in the Manning coefficient that is found by calibrating the model.

C.2.4 Recommendations

The created model is a relatively simple one. Processes such as salinity, sedimentation, waves and wind are currently not included. The current model is meant to confirm some of the expected sedimentation causes of Section 6.

Even more so, the current state of the model is meant so serve as a basis for further computational modelling when more information is available of the area. Also, the current basic model can be improved in several ways to enhance its outcomes.

Since the model is based on a smooth bathymetry coming from a sample file with a relatively low point density, the model is mainly used in relative sense. The flow velocities from the model likely differ from the actual flow velocities in several locations. So using a method like the graph of Hjulström (Figure C.12) to predict sedimentation rates is not recommended.

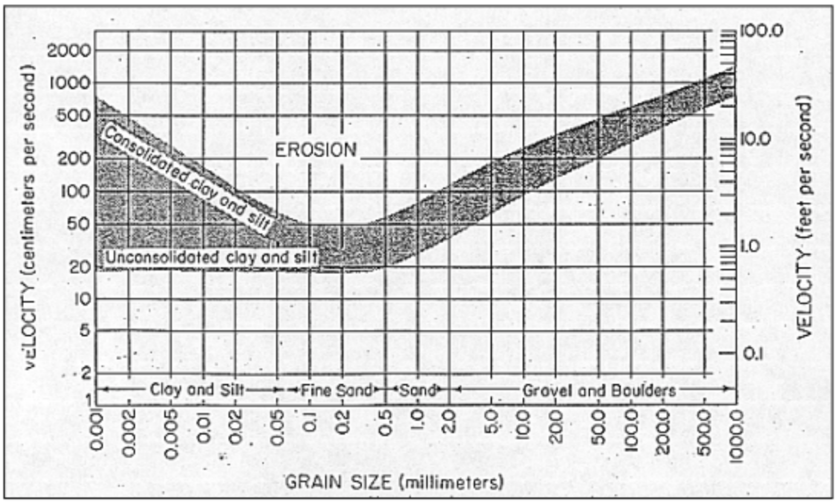

Figure C.12: Hjulström curve (Miedema, 2012)

On top of that no thorough soil research has been done so the exact characteristics of the bed sediment are unknown. The dredged material was documented by the dredging company and further analysed in Section 5.6. However, this only concerns the dredged material within the channel and is only an indication for the rest of the system. Not knowing the types of grains in the river also limits the possibility of quantitative predictions.

C.2.4.1 Bathymetry

The bathymetry is currently purely based on old nautical maps of the year 1995 and converted by hand into an point sample file. On top of the fact that the maps are rather outdated, the conversion by hand is very much prone to human error. The exact locations of the depth profiles on the nautical maps are purely based on the spacial awareness of the person converting them into the digital version, since the nautical map points do not have any coordinates. Also, any mistakes in the positioning of the landboundary file can lead to misdirection of the person digitising the water depths.

The current bathymetry has a point density of one point per 100 meters in both M and N direction. This is a very low point density to nicely represent the actual bathymetry. In order to include for example the sedimentation processes in Delft3D, a far more detailed bathymetry is recommended. With the current point density triangular interpolation creates a smooth bed whereas with a denser point density, gaps and bars in the bed are far better represented. The effect of the current smooth bed shows in the Chezy roughness coefficient that is needed to calibrate the model (Section C.2.3.1).

The structures that were previously present in the river system are not included in the bathymetry. However, it is known that some of the structures are still partly existent. More information is needed in order to implement the structures. Currently it is not nearly enough to enter them into the bathymetry and including them as thin walls is unrealistic because we do know that they are now all submerged. Depending on the state of the structures, they can have a high influence on the results of the model.

A good method for a bathymetric survey is differential positioning by means of a GPS system. This way an updated bathymetry can be created with a higher point density serving the needs of a better triangular interpolation. Also, the lacking information regarding the state of the structures can be supplemented by combining the GPS information of depths with some extra underwater photographs.

C.2.4.2 Tides and calibration

The tides currently measured in Corral are different from the tides in the model. Simply because there is very little data on water levels in the system. The only way to calibrate this simple model was to use the known spring tidal ranges in 1990 knowing the decreased tidal range of 1.29 meters located around 16 kilometres upstream from the mouth (Pino et al., 1993). A problem is that it is not known where exactly this 1.29 meters tidal range was measured upstream in the river system.

If water levels were measured upstream of Corral (preferably around Valdivia to match the old measurement location), the model could be made with the current tidal signal at Corral and calibrated with the new tidal range measurements upstream. Also, knowing the exact location of the upstream measurements, the calibration can be done more accurately. Especially since there is no information on the discharges during 1990 tidal range measurements. For the current calibration the high discharges of August were used, but again upstream water level measurements could improve the calibration in by matching the tidal ranges, discharges and measurement locations.

C.2.4.3 Salinity

Even though Section 5.5 predicted the salt intrusion to possibly play a significant role in the system, salinity is currently not included in the model. Including the salinity would increase the complexity of the model which is currently undesired due to the current improvement possibilities in the simple model. With the current bathymetry, salanity could create new unrealistic effects. Therefor it is recommended to improve the bathymetry first. This prevents the addition of uncertainties in the results.

C.2.4.4 Sediments

Including sediment transport in the current model has the same effect as salinity, creating too many uncertainties. The main problem with including sediment transport is the lacking quality of the bathymetry. With the current bathymetry accuracy to many local flow velocity effects are missing. Also, the type of grains are of high importance and the current knowledge is not enough. An educated guess could be made based on the type of sediment at the dredging locations, but further research is recommended for accurate results.

C.2.4.5 Flow boundaries

The discharges in the model currently are steady (constant in time) conditions. This is obviously not the case in real life. Steady conditions were used for now since the daily discharge data is not available for every river (Section 5.3). The discharges used are monthly averaged discharges, specifically for February and August representing the highest and lowest total discharge months.

Using the average monthly data gives a good first impression of the river influences however the peak discharges are filtered out. It would be interesting to acquire daily discharges in order to take into account the peak situations and the effect of fluctuations in incoming water.

C.2.4.6 Scope of the Model

The current model scope from the river mouth to just upstream of Valdivia is the best fit considering the available project time and data availability. However, it would be very interesting to change the scope and include the effect of the estuary and the Naguilan river. This way the interactions between the large components of the Valdivian watersystem can be investigated. This would require a significant amount of extra research in discharges, water levels and water depths yet could give a nice insight on the complete downstream system and all its interactions.

For example, the model now contains the Futa river discharge, yet the Futa river could have an extra influence since the tide can travel around the Naguilan river and re-enter the Valdivia river via the Futa river mouth.

C.3 Model plots

Point 2

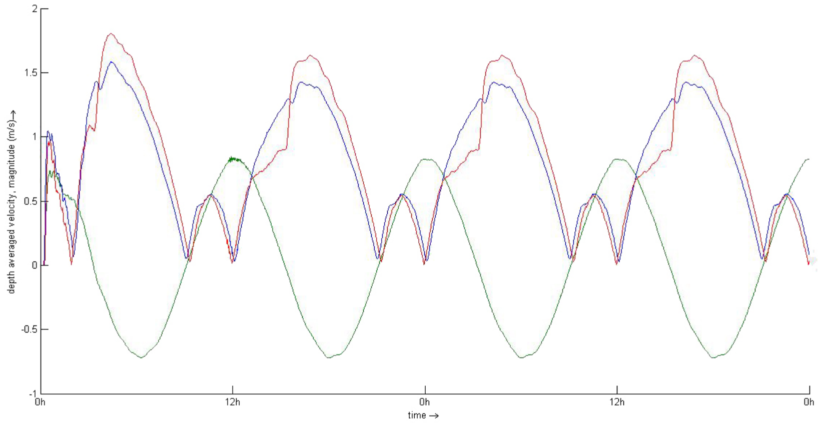

Figure C.13: Absolute flow velocities for cross-sections A (red) and B (blue) during tidal cycle (green) for high discharge (Own work)

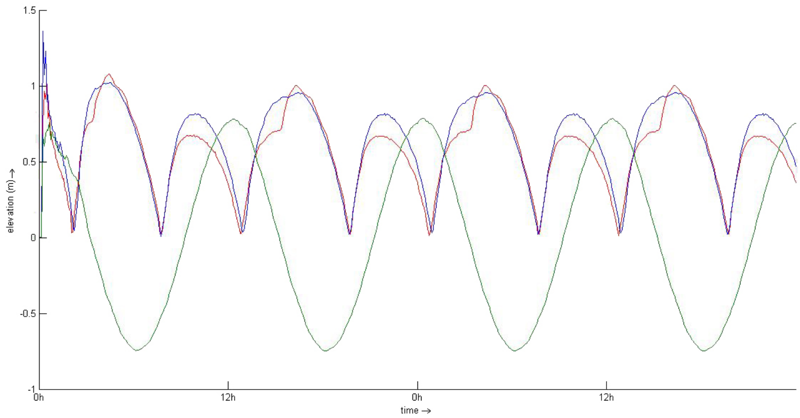

Figure C.14: Absolute flow velocities for cross-sections A (red) and B (blue) during tidal cycle (green) for low discharge (Own work)

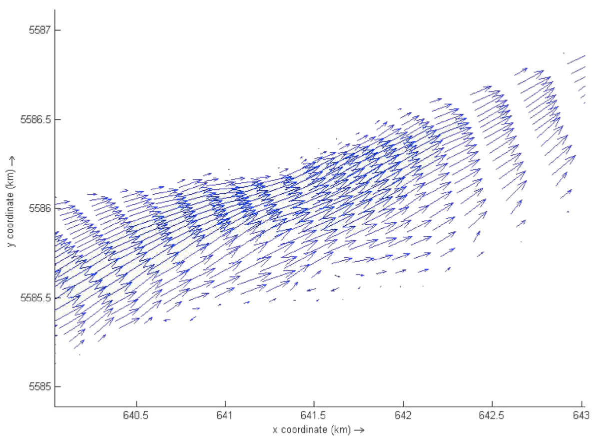

Figure C.15: Flow lines in point 2 at mid-tide during rising water levels (Own work)

Point 3

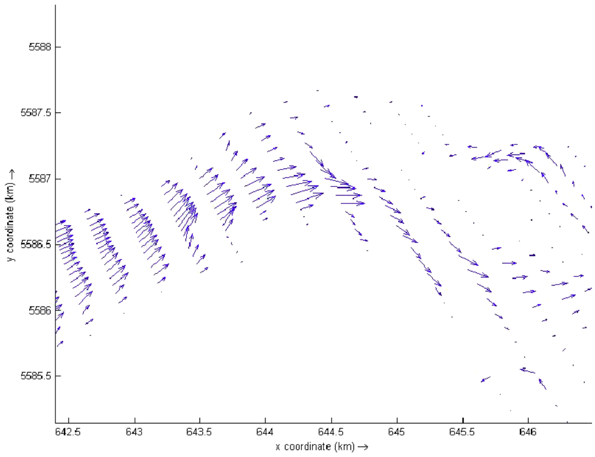

Figure C.16: Flow lines in point 3 during maximum flood flow and high discharge (Own work)

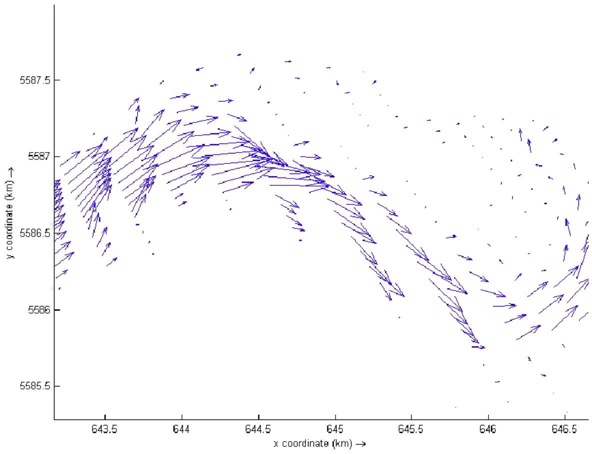

Figure C.17: Flow lines in point 3 during maximum flood flow and low discharge (Own work)

Point 4

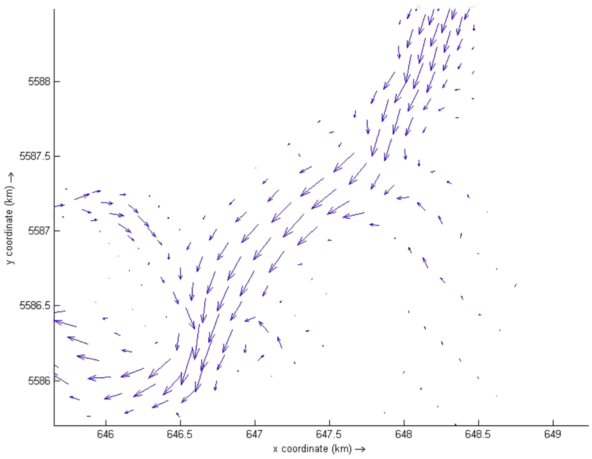

Figure C.18: Flow lines in point 4 during maximum ebb velocities and low discharge (Own work)

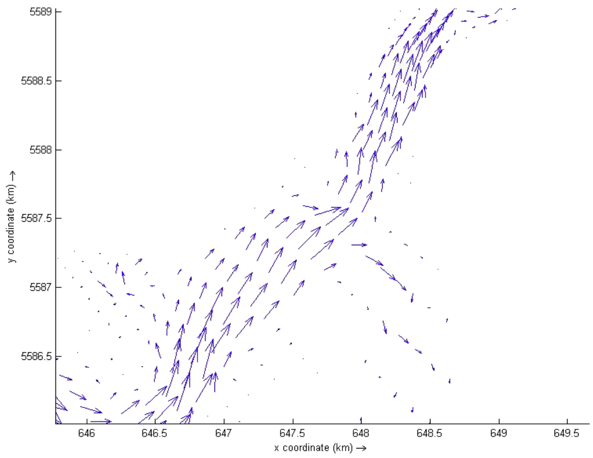

Figure C.19: Flow lines in point 4 during maximum flood velocities and low discharge (Own work)

Point 6

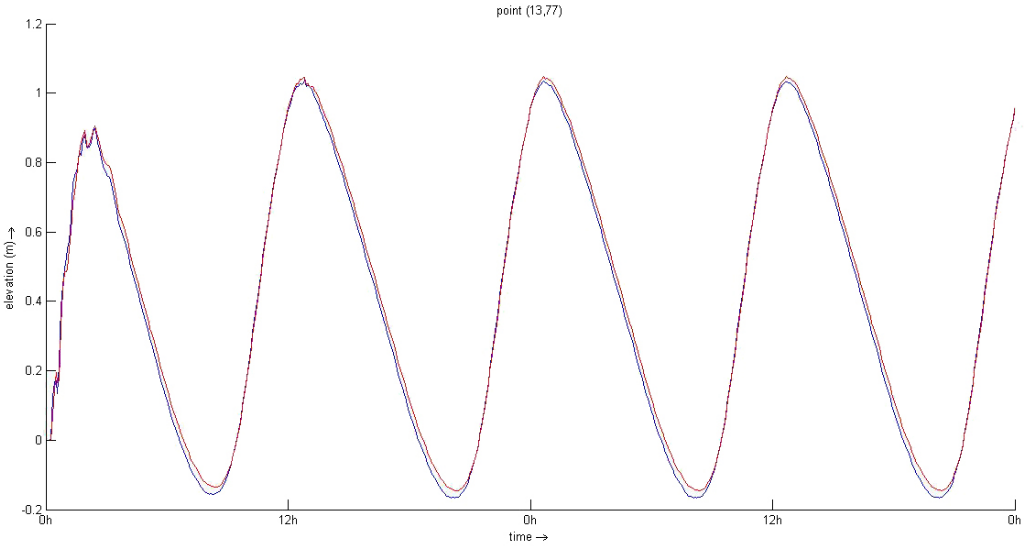

Figure C.20: Water levels in the Cruces (red) and Calle Calle (blue) rivers around sedimentation point 6 during high discharges (Own work)

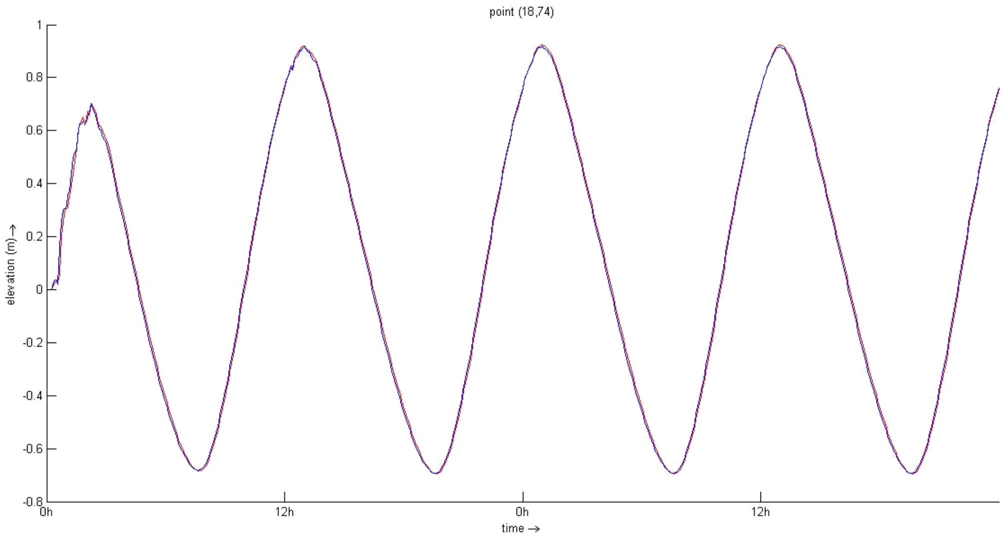

Figure C.21: Water levels in the Cruces (red) and Calle Calle (blue) rivers around sedimentation point 6 during low discharges (Own work)

Point 7

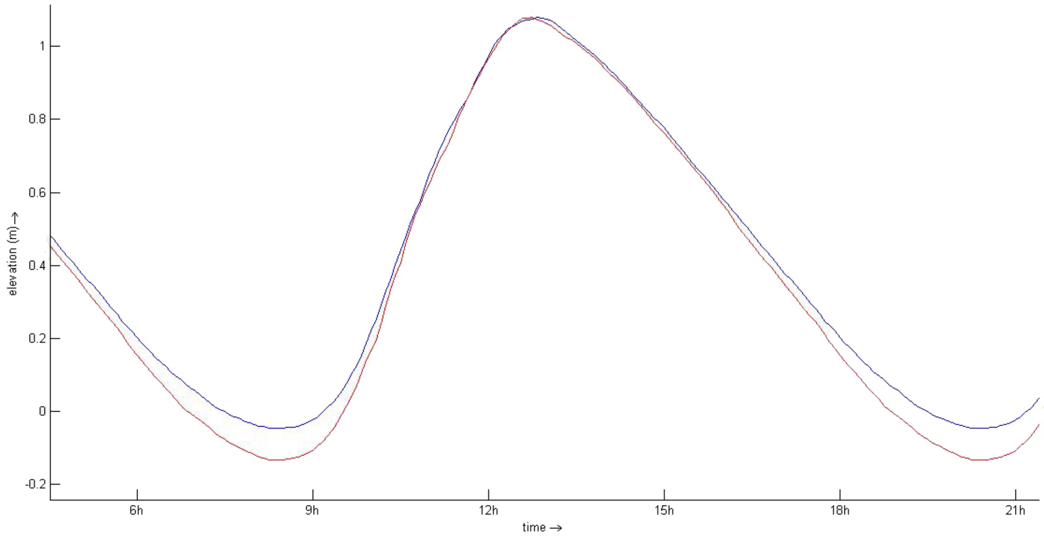

Figure C.22: Water levels during tidal cycle and high discharge at both ends of the Cau Cau river. Cruces river (red) and Calle Calle river (blue) (Own work)

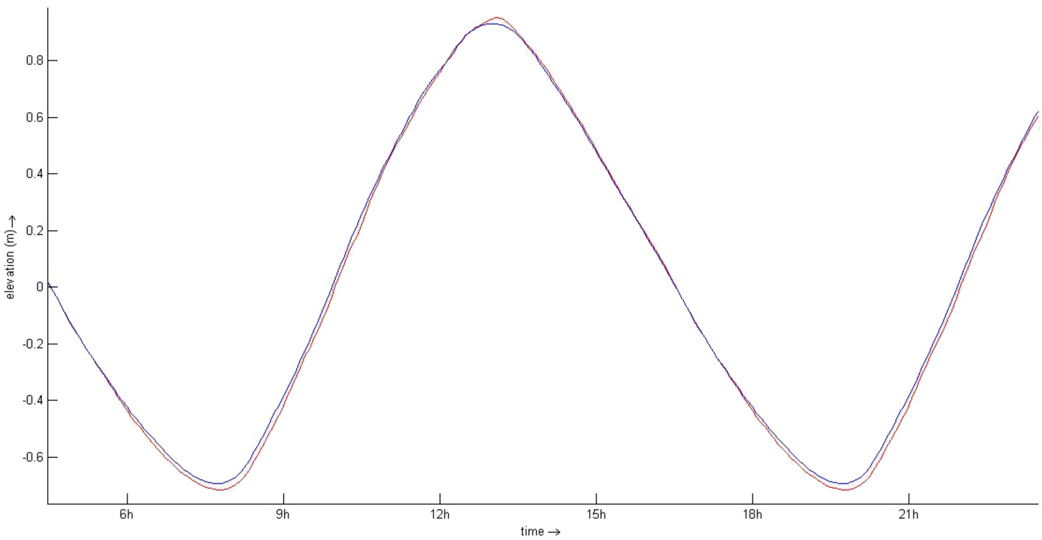

Figure C.23: Water levels during tidal cycle and low discharge at both ends of the Cau Cau river. Cruces river (red) and Calle Calle river (blue) (Own work)

D. Social costs and benefits analysis

D.1 Growth factors

The future of the transport of wood chips from Valdivia depends on different driving forces with a uncertain future development. These include for example the development of the global economy, domestic economy, technology, globalisation, relative costs, and so on (Romijn et al., 2016). The growth is mainly dependent on the growing performance of Chile's principal trading partners China, the United States and Latin American countries (OECD, 2017).

In 2016, the transport of wood chips was 982,425 ton. The expectation for 2017 is a transport of 1,015,523 ton (Port of Corral, 2017b). This is an expected growth of 3.4% relative to 2016. This matches with the expected growth of the economy of Chile as a whole, which growth potential is up to 3.5% (OECD, 2017) (Financial Tribune, 2017) (Trading Economics, 2017).

A distinction is made between three growth scenarios for the zero alternative and project alternative. The low scenario contains a growth of 1% in the future. This percentage indicates a stagnation. The middle scenario contains a growth factor of 3.5%, based on the expectations mentioned above. The growth factor of the high scenario is based on the average annual growth factor of the export at the port of Corral between 2011 and 2016 (Port of Corral, 2017b), which was 7.6% per year (Calculations can be find in `Excel`). The zero point in the analysis will be the amount of transport of wood chips from the port of Corral in 2016.

D.2 Costs

D.2.1 Investment costs

This section describes a calculation for the investment cost of the alternative project. The investment costs comprise only the costs for the dredging works that are necessary to reach a minimum water depth of 10 meters in the considered river section between the ports of Las Mulatas and Corral.

Reference project
In 2013, dredging activities were started to dredge the Valdivia river to a minimum depth of 4.5 meters (Bracho, 2017). The dredging company Dragatec was in charge of the execution. According to the Ministry, the total amount of dredged material comprised around 150,000 cubic meters of material (Direccion de Obras Portuarias, 2017). An execution period of 2 years was assumed for this dredging work. Although the real execution turned out the be different in terms of time and amount of material, the planned figures by the Ministry will be used as a reference in this cost calculation. The two-year dredging activities have cost 4.5 million US dollar.

Area analysis
The area to be considered is the river section between the port of Las Mulatas and Corral. It is assumed that the same horizontal dimensions remain for the future channel. That means that the dredging area is the area between the channelling structures from Port Mulatas to Corral. This area comprises 3.83 square kilometres.

Currently, the channel is being maintained on a minimum of 4.5 meters depth which will be taken as reference depth. This minimum value holds for the sedimentation points 1, 2, 3, and 4 (see Figure 5.6.1). These points are all located within the considered river section. According to Navionics, the water level difference between the sedimentation spots and the rest of the channel section is on average 10 meters (Navionics, 2017). Therefore, it is assumed that only the 4 identified sedimentation spots are needed to be dredged to 10m in order to reach a total minimum depth of 10 meters within the navigation channel.

The total area of the four sedimentation spots is 60.4 hectares (Direccion de Obras Portuarias, 2017).

With respect to the reference depth, these areas need an increase of 5.5 meters in depth. This results in a total dredging volume of 3.32 million cubic metres, see Figure D.1.

Port analysis
During the previous dredging works, the cargo traffic was not hindered by the dredging activities. Assuming that during the dredging activities, the amount of cargo traffic does not change, it is assumed that the dredging activities do not cause any downtime of the port activities (Mundo Maritimo, 2013).

Equipment
The equipment necessary for the dredging activities depends on the available space at the dredging site, the required accuracy, and the material that needs to be dredged. The bed of the Valdivia river consists of fine material (see Section 5.6). Therefore, the soil to be dredged is assumed to consist of fine sand and silt. High values of accuracy are not required in this case. According to this information, a trailing suction hopper dredger is suitable for the dredging work.

Currently, the dredger Ernesto Pinto is the only dredging vessel in Chile (La Tercera, 2016). This vessel is a trailing suction hopper dredger (TSHD). A TSHD is effective for dredging large amounts of material, but it lacks accuracy. Since the Ernesto Pinto is the only available vessel in Chile, it will also be used for this calculation. However, the possibility must remain that other vessels can be rent to speed up the dredging works and make the operation more cost effective. This is important to keep in mind, because the Ernesto Pinto is an old vessel (1978) which is frequently under maintenance.

The characteristics of the Ernesto Pinto are summarised below:

Table D.1: Specifications Ernesto Pinto dredger (Barrera-Gana, 2013)

Name	Ernesto Pinto
Type	Trailing suction hopper dredger
Length [m]	56
Width [m]	12
Max. draught [m]	4
Sailing speed [km/h]	15
Capacity [m^3]	640
Production [m^3/h]	1,000
Max. dredging depth [m]	18
Costs [$/week]	45,000
Operational hours [OH/week]	100

The vessel specifications are taken from (Barrera-Gana, 2013). The sailing speed was estimated based on similar TSHD vessels. The costs are an uncertainty. To make a rough estimation, the previous dredging activities were taken as a reference. The two-year execution has cost 4.5 million US dollar. Assuming 50 weeks of execution per year (including holidays and downtime), this amounts to a weekly cost of 45 thousand US dollar. The operational hours are estimated on 100 hours per week. This includes downtime due to holidays and maintenance.

Disposal site
Due to the large area that needs to be maintained, it is important to choose a disposal site with a central position in order to keep the cycle time as low as possible. This can either be a disposal site in the water but also on land. With a TSHD the most convenient will be a disposal site in the water. Then the unloading time is lowest.

Currently, the sand is disposed in the sea at six nautical miles from Corral (Plata Forma Urbana, 2015). Since this is ideal for a TSHD, this current disposal site is also chosen for the future dredging activities.

Cost calculation
The total estimated costs of the dredging work are calculated by determining the cycle time of the dredger. This cycle time comprises the filling, sailing time, dumping, and sailing back to the dredging

location. Since the amount of dredged material is known, the total necessary number of cycles are known as well, based on the dredger capacity. Based on the operational hours per week, the total number of cycles per week can be calculated. From this, the total number of weeks for the dredging work are calculated.

The calculation shows a monetary value of 7.36 million US dollar and an execution duration of 126 weeks (see Figure D.2).

Dredging depth				
Reference depth [m]	4,5			
Desired depth [m]	10			
Difference [m]	5,5	(5.5 for investment costs, 0.5 for maintenance costs)		
Area and dredging volume				
Sedimentation spot	Area [m2]	% of total	Dredged volume [m3]	Distance to disposal [km]
1	115000	19,04	632500	12
2	241000	39,90	1325500	14,5
3	137000	22,68	753500	18,5
4	111000	18,38	610500	23,5
Total	**604000**		**3322000**	
Average distance to disposal [m]				**16,6**

Figure D.1: Dredging volumes and sailing distances (Own work)

Equipment		
Name	Ernesto Pinto	
Type	TSHD	
Sailing speed [km/h]	15	
Length [m]	56	
Width [m]	12	
Max. draught [m]	4	
Max. dredging depth [m]	18	
Capacity [m3]	640	
Production [m3/hour]	1000	
Costs [$/wk]	45000	
Op. Hours [OH/wk]	100	
Scenario 1		
Loading time [hours]	0,64	
Dumping time [hours]	0,3	including stopping time and turning around
Sailing time [hours]	2,21	taking the average distance to the disposal site
Cycle time [hours]	3,15	
Cycles/week	31,73	
Total necessary nr. of cycles	5191	
Duration [weeks]	164	
Costs [$]	$ 7.360.907,81	

Figure D.2: Dredging investment costs (Own work)

D.2.2 Maintenance costs

When the channel has been dredged to the desired depth, the maintenance stage begins. Currently, approximately each 15 years a soil layer of 15 cm is dredged from the sedimentation areas (1 t/m 4). Taking into account the larger reference depth in the new situation, the sedimentation rates are likely to be higher, as described in Section 7.5.2. Two types of maintenance have to be considered:

- Frequent, small dredging activities
- Long term, large dredging activities

Rough estimations are made regarding the sedimentation rates. In the current situation, the sedimentation rate is assumed at 1 cm per year. This is based on dredging volumes from the reference situation and taking into account that the previous dredging activity was 15 years earlier, thus 15 cm divided by

15 years (Direccion de Obras Portuarias, 2017). With a twice as large depth and an exponential relation between depth and sedimentation rate an estimation for the new sedimentation rate can be made. This is estimated on 5 cm per year.

This sedimentation rate seems negligible for yearly maintenance. The costs would be 70,000 US dollar and the execution time almost 2 weeks each year. However, a dredging vessel like the Ernesto Pinto is not capable of dredging with an accuracy of 5 cm. Therefore, long term dredging activities are desired. Every 10 years, a layer of 50 cm will develop. Dredging will take 16 weeks and costs about 670,000 US dollar.

D.2.3 Uncertainties

Because of the long execution time, it is obvious that new sediment deposits at the dredging areas during execution. Therefore, the total amount of dredged material is probably much higher. However, this is not taken into account.

D.3 Benefits

D.3.1 Current vessels in Port of Corral

Table B.6 in Section B.2.2 shows that all vessels between Valdivia and Corral belongs to the smaller vessel types. The handysize vessels can not use the Valdivia river. The port of Corral allows maximum the Panamax Vessels with a draught of 12.5 meters. For all vessels larger than a draught of 4.5 meter, the Valdivia river is not deep enough. Table D.2 shows all vessels that have used the port of Corral in 2016. The share is calculated by the total amount in DWT by the DWT depending on the draught.

Table D.2: Vessels port of Corral in 2016; share in DWT (Port of Corral, 2017a) (Traffic, 2017)

Name Vessel	Load (DWT)	Draught (m)	Share %	Share %
SURABAYA EXPRESS	70,100	7.60	6.45	
SURABAYA EXPRESS	70,100	7.60	6.45	
NANJING EXPRESS	70,475	7.80	6.49	
Kalimantan Express	70,401	7.80	6.48	25.88
CROSSANDRA	64,486	8.00	5.94	
MILKY WAY II	50,766	8.20	4.67	
HACHINOHE MARU	62,806	8.20	5.78	
MILKY WAY II	50,766	8.20	4.67	
MILKY WAY II	50,766	8.20	4.67	
SHANGHAI EXPRESS	70,417	8.30	6.48	
PRINCESS ROYAL	57,053	8.60	5.25	
PRINCESS ROYAL	57,053	8.60	5.25	42.73
Green Sapphire	63,883	9.10	5.88	5.88
CRIMSON SATURN	49,997	10.50	4.60	4.60
C. S. BRIGHT	63,291	11.40	5.83	
WORLD SWAN II	49,603	11.50	4.57	
Hokuetsu Bright	49,692	11.60	4.57	14.97
CRYSTAL PIONEER	64,510	12.20	5.94	5.94

D.3.2 Travel time

To calculate the reduction of the travel time, which will result in a reduction of transport costs, firstly the number of vessels is calculated that use the Valdivia river in the zero alternative. In the base year 2016, 982,425 tonnage was transported from Valdivia, in vessels (Comau) with 1,042 DWT (Port of Corral, 2017b). So, 982,425 ton / 1,042 ton = 943 vessels per year have used the Valdivia river. After deepening, four ships of 70,100 DWT (Section D.3.1 can go through the river and reach the Valdivia port. So, only 982,425 ton - 280,400 ton = 702,025 ton has to be transported by the smaller vessels. Which is 982,425 ton / 1,042 ton = 674 ships per year. This will lead to a reduction of 265 vessels per year to transport the same amount of ton. Assumed is that the vessels arrive empty and will depart loaded. The growth factors 1% and 3.5% only will lead to more Comau ships. By a growth factor of 7.6%, the growth is more than 70,100 ton, which is the size of one Surabaya. There will be one Surabaya vessel more in this scenario, and this will replace the smaller ships. In Table D.3 the number of vessels are shown.

Table D.3: Number of vessels (Own work)

	DWT by Comau	DWT by Surabaya	Number of vessels by Comau	Number of vessels by Surabaya
Zero alternative				
2016	982,425	0	943	0
1%	992,249	0	953	0
3.5%	1,016,810	0	976	0
7.6%	1,057,089	0	1,015	0
Project alternative				
2016	702,025	280,400	674	4
1%	711,849	280,400	684	4
3.5%	736,410	280,400	707	4
7.6%	706,589	350,500	679	5

The costs of transport over the Valdivia river will decrease when there are less vessels needed. The use of key figures makes it possible to estimate the effects (der Meulen et al., 2009). It is assumed that the Comau belongs to the DVS ship classification of a M5. The costs of a M5 are given in the Table D.4. There are no key figures about the Surabaya, because this boat is not an inland vessel. For the Surabaya, the costs are calculated by taking the DVS classification ships Bii-4 and Bii-6b. The costs per extra ton are calculated by these ships, and are added to the Surabaya vessel. The calculations can be found in the SCBA model.

Table D.4: Average cost of dry bulk per vessel type (der Meulen et al., 2009)

DVS-classification	Costs of general waiting ($/hour)	Costs of waiting for freight ($/hour)	Costs of loaded transport ($/km)	Costs of unloaded transport ($/km)
Comau (M5)	86.75	79.43	12.96	9.30
Surabaya	1,213.06	1,213.06	109.48	67.81

To calculate the costs of the vessels only the waiting time and the distance are needed. The calculation of the waiting time is explained in D.3.3. The distance from Las Mulatas to Port Corral is 15.5 kilometres for one way. So, the costs of loaded and unloaded transport is multiplied by 31 kilometers. For example the costs of loaded transport for the Comau are 12.96 US dollar * 31 kilometers = 401,71 US dollar. The total costs for one vessel are shown in Table D.5.

Table D.5: Total cost of dry bulk per vessel type (der Meulen et al., 2009)

	Comau (M5)		Surabaya	
Costs of general waiting	8.07 hours	$700,09	59.28 hours	$71,910.40
Costs of waiting for freight	5 hours	$397,16	5 hours	$6,065.32
Costs of loaded transport	31 km	$401.71	31 km	$3,393.90
Costs of unloaded transport	31 km	$288.25	31 km	$2,102.14
Total costs		$1.787,22		$83,471.76

The number of vessels is multiplied by the total costs of one ship. The reduction of transport costs is calculated by taking the number of vessels per year in the zero alternative and compare this with the number of vessels per year in the project alternative. The difference is the reduction of transport costs. For example in the project alternative with a growing factor of 3.5% there is a reduction of transport costs per year of $1,744,324 - $1,597,450 = $146,874. This can be seen in Table D.6 below. When there is a growing factor of 7.6%, there is a reduction of transport costs per year of $1814,025 - $1,630,879 = $183,146.

Table D.6: Effect of transport costs scenario (Own work)

	Number of ships	Total costs [USD]
Zero alternative		
2016	943	1,685,346
1%	953	1,703,218
3.5%	976	1,744,324
7.6%	1,015	1,814,025
Project alternative		
2016	678	1,538,471
1%	688	1,556,344
3.5%	711	1,597,450
7.6%	684	1,630,879

For new load of the waterways, the rule of half should be applied. This is a calculation method to calculate the benefits for new cargo. Because on average, a new user has half as much benefit from an improvement of the infrastructure as compared to a vessel that already uses the infrastructure in the zero alternative (Mouter et al., n.d.). In this case, there is no new cargo, because the same growth factor is used for the zero and project alternative. It is likely that the port of Las Mulatas will grow when the river is deeper. This cargo is new and should therefore be calculated by the rule of half.

D.3.3 Reduction in waiting time

The deepening of the river will cause a reduction in waiting time. The waiting time consists of the general waiting time, the waiting time for freight and the time for loading. The general waiting time depends on the transshipment time plus 1,5 hour of waiting time assumed in general. The waiting time for freight is put on 5 hours, based on the report 'Kostenkengetallen binnenvaart 2008' (der Meulen et al., 2009).

The reduction in waiting time is subdivided in a reduction in transshipment time and loading time.

Transshipment time
It is assumed that the transshipment time at the port of Corral depends on the descarga (unloading capacity) and the embarque (capacity of shipment) (Port of Corral, 2017b). The transshipment time per ton is calculated by dividing the capacity of unloading and loading with the number of seconds in a day. After that, the transshipment time for a Comau vessel is calculated by multiplying the transshipment time per ton with the DWT of a Comau vessel. This data is shown in table D.7. For the calculations, see the SCBA model.

Table D.7: Transshipment capacity and time (Port of Corral, 2017b)

Transshipment Capacity	Ton/ day	Seconds/ ton	Hours/ Comau vessel
Descarga	11,125	7.8	2.2
Embarque	8,000	10.8	3.1
Total		18.6	5.4

Loading time
The loading capacity at Las Mulatas is 29,629 TM per day (Table D.8). This means a loading time of

50.6 minutes for a Comau vessel with a DWT of 1,042 and 3,406 minutes for a Surabaya vessel with a DWT of 70,100, see table D.9. For the loading time, it is important to include the mooring time. For the Comau and Surabaya vessel the mooring time is set at 20 minutes and 60 minutes respectively. These values are estimated and just to indicate that mooring a bigger vessel costs more time, because the coordination is harder. The calculations can be found in the SCBA model.

Table D.8: Capacity port of Corral (Port of Corral, 2017b)

Production [t/day]	Loading [t/day]	Fluvial transport [t/day]	Unloading [t/day]	Shipment [t/day]
4,500	29,629	3,913 - 5,137	11,125	8,000

Table D.9: Loading time (Port of Corral, 2017b)

Vessel	DWT	Loading time minutes	Mooring time minutes	Total time minutes
Comau	1,042	50.6	20	70.6
Surabaya	70,100	4306.9	60	3466.9

D.3.4 Air quality and climate

The use of vessels effect the air quality and climate. These effects needs to be monetised. In order to do this, there should be a calculation of the emissions in both alternatives. Four parameters of air quality will be taken into account. These are carbon dioxide (CO_2), nitrogen oxides (NO_x), suspended particles (PM_{10}) and sulfur dioxide (SO_2).

The Comau vessel and Surabaya express both have different rates of emission for these parameters, because of the difference in vessel size. Given the fact that the distance between Las Mulatas and Corral is 15.5 kilometres (see Figure 7.1), the total emission rates for one loaded movement from Las Mulatas to Corral and one unloaded movement back to Las Mulatas are displayed in Table D.10.

Table D.10: Emission rates per vessel (den Boer et al., 2008)

Vessel	$CO_2[kg]$	$NO_x[kg]$	$PM_{10}[kg]$	$SO_2[kg]$
Comau	1,674	37.2	2.79	20.46
Surabaya	8,463	248.0	19.53	132.37

The emissions have different effects on the air quality. Carbon dioxide will have an impact on the climate and the other parameters will have an influence on the viability of the area. Therefore, the emissions will be monetised with different values.

For the viability outside urban areas, emissions for suspended particles in the air, sulfur dioxide and nitrogen oxides are monetised at the following values: 104.18 US dollar per kilogram PM_{10}, 5.96 US dollar per kilogram SO_2 and 10.41 US dollar per kilogram NO_x (Ruijgrok & Sluis, 2011). For climatological reasons the emission of carbon dioxide is monetised at 73.96 US dollar per ton CO_2. Per kilogram this is an amount of 0.074 US dollar (Ruijgrok & Sluis, 2011). Per vessel that navigates a total of 31 kilometres this will in total lead to the costs shown in Table D.11.

Table D.11: Costs per vessel for 31 kilometres (Ruijgrok & Sluis, 2011)

Vessel	CO_2[$]	NO_x[$]	PM_{10}[$]	SO_2[$]	Total costs[$]
Comau	124.25	387.32	290.65	121.90	924.12
Surabaya	628.13	2,582.12	2,034.57	788.67	6,033.48

As can be seen in Table D.11, the total costs per Comau vessel are 924.12 US dollar. These include 799.87 US dollar for viability reasons and 124.25 US dollar for climatological reasons. The total costs per Surabaya vessel are 6,033.48 US dollar, where the total viability costs are 5,405.35 US dollar and the total climate costs are 628.13 US dollar. For every scenario within the alternatives there is a different fleet mix. This is described in Section 7.6.1. With this total in costs per vessel and the amount of vessels according to the fleet mix, the total costs can be calculated. With this information, the costs per year can be calculated. This is displayed in Table D.12.

Table D.12: Effect of air quality per scenario (Own work)

	Number of vessels	Total costs [USD]
Zero alternative		
2016	943	871,443
1%	953	880,684
3.5%	976	901,939
7.6%	1,015	937,979
Project alternative		
2016	678	646,738
1%	688	655,451
3.5%	711	677,233
7.6%	684	657,643

D.4 Sensitivity analysis

D.4.1 Input of sensitivity analysis

- **Discount rate**
  The basic SCBA is based on a 10% discount rate. This has been used to show the future uncertainty. There is uncertainty about the future of project effects and the lifespan of a project (Rijkswaterstaat: Ministerie van Mileu en Infrastructuren, 2016). Therefore, it was decided to apply a higher and lower discount rate in the sensitivity analysis. If the discount rate is lower, the NPV will be more positive and when the discount rate is higher, the NPV will be more negative. The sensitivity analysis also shows this, as can be seen in Figures D.3 and D.4.

- **Travel time**
  The travel time gains are in the basic SCBA for the Comau $1.8 million US dollar and for the Surabaya $0.8 million US dollar. The travel time gains are calculated on the basis of waiting and navigating. Some of the waiting times have been assumed, by taking the waiting times of a similar vessel. However, it is uncertain whether the port in Valdivia has the same waiting time as these similar vessels. Besides that, the transport costs of the Surabaya and Comau had to be based on Dutch sources, and are not the exact costs of these vessels. This leads to a very big uncertainty. For this the transport costs are changed to a value 25% higher and 25% lower in the sensitivity analysis. If the shipping costs will be higher, there is a bigger difference between the prices per vessel. This should turn out to be a more positive NPV. The sensitivity analysis also shows this, as can be seen in Figures D.3 and D.4.

- **Dredging costs**
  The costs of dredging include the investment costs and maintenance costs. Regarding to Section D.2.1, the investment costs are unreliable. It is uncertain where exactly the dredging is needed, how many dredging vessels can be used and what the costs of a dredging vessel are. Besides this, regarding to Section D.2.2, the costs of maintenance are unreliable as well. The sedimentation rate is rough estimated and the total amount of material that needs to be dredged is uncertain.

  Because of this large amount of uncertainties, the investment and maintenance costs are changed to a value 25% higher and lower to test their impact. If the costs are lower, the NPV has to be more positive, because the ratio of benefits compared to the costs will increase. If the costs are higher, the NPV has to be more negative. This is in line with the calculations shown in Figures D.3 and D.4.

- **Air quality and climate costs**
  Assuming the base SCBA, the costs of the emission of NOx, PM10, SO2 and CO2 are $942 US dollar and $6,022 US dollar for the Comau and Surabaya vessels respectively. These values are uncertain, because the amount of emissions and the costs of these emissions are based on Dutch resources (Ruijgrok & Sluis, 2011) (den Boer et al., 2008). Therefore, the impact of air quality and climate costs is tested in the sensitivity analysis by reducing and increasing these costs with 10%. If the emission costs are lower, the NPV will be more negative, because the benefits of reducing the amount of emissions by using less vessels in the project alternative will be less. This is also showed in Figures D.3 and D.4.

- **Growth factor**
  The growth factor of the transport already has been taken into account with three different values in the scenarios of the zero alternative and project alternative. Therefore, the growth factor is only used in the sensitvity analysis to analyse the impact of a negative growth factor with values of -1% and -7.6%. If the transport decreases with -1%, there are less vessels using the river in zero and project alternative. There is not a change in the amount of Surabaya vessels. So, the reduction costs and air quality will not change. If the transport decreases with -7.6%, the amount of Surabaya vessels will decrease to 3. This means that the NPV will be lower, as showed in Figure D.4.

- **Transport costs of Surabaya**
  The average transport costs of the Surabaya are calculated in Section D.3.2. The calculations are uncertain, because the Surabaya is not an inland vessel. Therefore, the costs of the Surabaya are changed to a value 25% higher and a value 25% lower. In this sensitivity analyse, the costs are shown separately in transport costs and waiting costs. In the base SCBA the effect on transport costs are negative, but the effect on waiting time is positive. This is possible and explained by the fact that sea vessels travel great distances. E.g. from Chile to Japan it is 17 thousand kilometers, for these distances a big vessels will be much cheaper in comparison with small vessels. If the costs of the Surabaya are 25% higher, the NPV will be more negative. When the costs are 25% lower, the NPV will be more positive. The model responds as expected, the results can be seen in Figure D.5. The reduction of transport costs is positive in the last scenario, because the costs of transporting 1 ton in US dollar is for the handy size vessel cheaper than for the smaller vessel.

- Fleetmix change
  Assumed in the base scenario is that the 74% of smaller vessels in the project alternative do not change to handy size vessels (7.6.1). In this analysis, the 74% is also changed to a handy size vessel. The NPV is $-2.24 million US dollar, which corresponds to the expectation that the NPV will be more positive. The total overview of the effects can be seen in Figure D.4. It is improbable that all vessels will change to Surabaya vessels. Besides that, it is not known whether the current vessels want to change into other vessels, and what kind of vessels that would be.

- Change of depth and fleetmix change
  A change from 4.5 meters depth to 10 meters depth is very big. When analysing the depth, it will more realistic to dredge to a depth of 6 meters (Figure C.5). This is also more in line with the bathymetry in the Delft3D model. Also with a depth of 6 meters the current small vessels can be replaced by bigger size vessels, even though they are smaller than handysize vessels. With the change of depth, the dredging costs will be cheaper. The investment costs for a depth of 10 meter is $7.36 million US dollar and for 6 meter it is only $2 million US dollar. The maintenance costs will be cheaper as well. It is assumed that the sedimentation amount will be smaller. Every ten year, only 20 centimeters will be added instead of 50 centimeters D.2.2. The maintenance costs for a depth of 10 meter are $670,000 US dollar and for 6 meter $270,000 US dollar. In this scenario it is assumed that all current Comau vessels are replaced by a DVS ship classification C4 (der Meulen et al., 2009). These vessels can handle a DWT of 8,000. The reduction in transport costs is now $9.8 million US dollar instead of $1.3 million US dollar. In this alternative, the NPV is positive with a value of $8.2 million US dollar.

D.4.2 Results of sensitivity analysis

1,00%		Discount rate		Transport costs		Dredgingcosts		Air quality + Climate	
		Positive	Negative	Positive	Negative	Positive	Negative	Positive	Negative
		8%	12%	25%	-25%	-25%	25%	10%	-10%
Investmentcosts									
	Deepening Valivia river	-$7.360.907,81	-$7.360.907,81	-$7.360.907,81	-$7.360.907,81	-$5.520.680,86	-$9.201.134,77	-$7.360.907,81	-$7.360.907,81
Maintenance costs									
	Maintenance costs	-$622.989,43	-$355.888,13	-$461.776,14	-$461.776,14	-$346.332,10	-$577.220,17	-$461.776,14	-$461.776,14
Direct effects									
	Travel time	$1.699.033,60	$1.092.798,92	$1.668.880,51	$1.001.328,31	$1.335.104,41	$1.335.104,41	$1.335.104,41	$1.335.104,41
Indirect effects	Air quality (PO10, SO2 + NOx)	$335.835,94	$216.005,82	$263.900,63	$263.900,63	$263.900,63	$263.900,63	$290.290,70	$237.510,57
	Climate (CO2)	$53.633,94	$34.496,73	$42.145,67	$42.145,67	$42.145,67	$42.145,67	$46.360,23	$37.931,10
	Recreation	Neutral	Neutral	Neutral	Neutral	Neutral	Neutral	Neutral	Neutral
	Noise	Postive	Postive	Postive	Postive	Postive	Postive	Postive	Postive
	Ecology	Negative	Negative	Negative	Negative	Negative	Negative	Negative	Negative
Results									
	Total costs	-$7.983.897,24	-$7.716.795,94	-$7.822.683,95	-$7.822.683,95	-$5.867.012,96	-$9.778.354,94	-$7.822.683,95	-$7.822.683,95
	Total benefits	$2.088.503,47	$1.343.301,48	$1.974.926,81	$1.307.374,61	$1.641.150,71	$1.641.150,71	$1.671.755,34	$1.610.546,08
	NPV (Net Present Value)	**-$5.895.393,77**	**-$6.373.494,46**	**-$5.847.757,14**	**-$6.515.309,34**	**-$4.225.862,25**	**-$8.137.204,23**	**-$6.150.928,61**	**-$6.212.137,87**

3,50%		Discount rate		Transport costs		Dredgingcosts		Air quality + Climate	
		Positive	Negative	Positive	Negative	Positive	Negative	Positive	Negative
		8%	12%	25%	-25%	-25%	25%	10%	-10%
Investmentcosts									
	Deepening Valivia river	-$7.360.907,81	-$7.360.907,81	-$7.360.907,81	-$7.360.907,81	-$5.520.680,86	-$9.201.134,77	-$7.360.907,81	-$7.360.907,81
Maintenance costs									
	Maintenance costs	-$622.989,43	-$355.888,13	-$461.776,14	-$461.776,14	-$346.332,10	-$577.220,17	-$461.776,14	-$461.776,14
Direct effects									
	Travel time	$1.699.033,60	$1.092.798,92	$1.668.880,51	$1.001.328,31	$1.335.104,41	$1.335.104,41	$1.335.104,41	$1.335.104,41
Indirect effects	Air quality (PO10, SO2 + NOx)	$335.835,94	$216.005,82	$263.900,63	$263.900,63	$263.900,63	$263.900,63	$290.290,70	$237.510,57
	Climate (CO2)	$53.633,94	$34.496,73	$42.145,67	$42.145,67	$42.145,67	$42.145,67	$46.360,23	$37.931,10
	Recreation	Neutral	Neutral	Neutral	Neutral	Neutral	Neutral	Neutral	Neutral
	Noise	Postive	Postive	Postive	Postive	Postive	Postive	Postive	Postive
	Ecology	Negative	Negative	Negative	Negative	Negative	Negative	Negative	Negative
Results									
	Total costs	-$7.983.897,24	-$7.716.795,94	-$7.822.683,95	-$7.822.683,95	-$5.867.012,96	-$9.778.354,94	-$7.822.683,95	-$7.822.683,95
	Total benefits	$2.088.503,47	$1.343.301,48	$1.974.926,81	$1.307.374,61	$1.641.150,71	$1.641.150,71	$1.671.755,34	$1.610.546,08
	NPV (Net Present Value)	**-$5.895.393,77**	**-$6.373.494,46**	**-$5.847.757,14**	**-$6.515.309,34**	**-$4.225.862,25**	**-$8.137.204,23**	**-$6.150.928,61**	**-$6.212.137,87**

Figure D.3: Sensitivity analyses 1% and 3.5% (Own work)

7.6%		Discount rate		Transport costs		Dredgingcosts		Air quality + Climate	
		Positive	Negative	Positive	Negative	Positive	Negative	Positive	Negative
		8%	12%	25%	-25%	-25%	25%	10%	-10%
Investmentcosts									
	Deepening Valivia river	-$7.360.907,81	-$7.360.907,81	-$7.360.907,81	-$7.360.907,81	-$5.520.680,86	-$9.201.134,77	-$7.360.907,81	-$7.360.907,81
Maintenance costs									
	Maintenance costs	-$622.989,43	-$355.888,13	-$461.776,14	-$461.776,14	-$346.332,10	-$577.220,17	-$461.776,14	-$461.776,14
Direct effects									
	Travel time	$2.118.623,39	$1.362.674,27	$2.081.023,76	$1.248.614,26	$1.664.819,01	$1.664.819,01	$1.664.819,01	$1.664.819,01
Indirect effects	Air quality (PO10, SO2 + NOx)	$419.447,94	$269.784,11	$329.603,13	$329.603,13	$329.603,13	$329.603,13	$362.563,45	$296.642,82
	Climate (CO2)	$66.988,52	$43.086,25	$52.639,73	$52.639,73	$52.639,73	$52.639,73	$57.903,70	$47.375,76
	Recreation	Neutral	Neutral	Neutral	Neutral	Neutral	Neutral	Neutral	Neutral
	Noise	Postive	Postive	Postive	Postive	Postive	Postive	Postive	Postive
	Ecology	Negative	Negative	Negative	Negative	Negative	Negative	Negative	Negative
Results									
	Total costs	-$7.983.897,24	-$7.716.795,94	-$7.822.683,95	-$7.822.683,95	-$5.867.012,96	-$9.778.354,94	-$7.822.683,95	-$7.822.683,95
	Total benefits	$2.605.059,86	$1.675.544,62	$2.463.266,63	$1.630.857,12	$2.047.061,88	$2.047.061,88	$2.085.286,16	$2.008.837,59
	NPV (Net Present Value)	**-$5.378.837,39**	**-$6.041.251,32**	**-$5.359.417,32**	**-$6.191.826,83**	**-$3.819.951,09**	**-$7.731.293,06**	**-$5.737.397,79**	**-$5.813.846,36**

		Growth factor	Growth factor	Fleetmix	Depth
					6 meters
		-1%	-7,6%	100% Handy size	100% C4 vessels
Investmentcosts					
	Deepening Valivia river	-$7.360.907,81	-$7.360.907,81	-$7.360.907,81	-$2.007.520,31
Maintenance costs					
	Maintenance costs	-$461.776,14	-$461.776,14	-$461.776,14	$184.710,45
Direct effects					
	Travel time	$1.335.104,41	$1.005.389,81	$4.474.584,96	$9.880.158,69
Indirect effects	Air quality (PO10, SO2 + NOx)	$263.900,63	$198.198,14	$953.908,96	$121.066,38
	Climate (CO2)	$42.145,67	$31.651,60	$152.498,04	$55.717,36
	Recreation	Neutral	Neutral	Neutral	Neutral
	Noise	Postive	Postive	Postive	Postive
	Ecology	Negative	Negative	Negative	Negative
Results					
	Total costs	-$7.822.683,95	-$7.822.683,95	-$7.822.683,95	-$1.822.809,86
	Total benefits	$1.641.150,71	$1.235.239,55	$5.580.991,97	$10.056.942,44
	NPV (Net Present Value)	**-$6.181.533,24**	**-$6.587.444,40**	**-$2.241.691,98**	**$8.234.132,58**

Figure D.4: Sensitivity analyses 7.6%, growth factor -1% and -7.6%, fleetmix, depth (Own work)

		Transportcosts Surabaya	Transportcosts Surabaya	Transportcosts Surabaya
		$83.471,76	25%	-25%
Investmentcosts				
	Deepening Valivia river	$ -7.360.907,81	$ -7.360.907,81	$ -7.360.907,81
Maintenance costs				
	Maintenance costs	$ -461.776,14	$ -461.776,14	$ -461.776,14
Direct effects	Reduction transport costs	$ -152.173,31	$ -860.981,24	$ 556.634,63
	Reduction waiting time	$ 1.487.277,72	$ 1.437.318,09	$ 1.537.237,34
Indirect effects				
	Air quality (PO10, SO2 + NOx)	$ 263.900,63	$ 263.900,63	$ 263.900,63
	Climate (CO2)	$ 42.145,67	$ 42.145,67	$ 42.145,67
	Recreation	Neutral	Neutral	Neutral
	Noise	Postive	Postive	Postive
	Ecology	Negative	Negative	Negative
Results				
	Total costs	$ -7.974.857,26	$ -8.683.665,19	$ -7.266.049,32
	Total effects	$ 1.793.324,02	$ 1.743.364,39	$ 1.843.283,64
	NPV (Net Present Value)	**$ -6.181.533,24**	**$ -6.940.300,80**	**$ -5.422.765,68**

Figure D.5: Sensitivity analyses Transportcosts (Own work)

D.4.3 Recommendations

Since the result of the scenario in the sensitivity analysis in which the depth of dredging is 6 meters is positive, it might be useful to further research scenarios like this in detail. Although less than 10 meters deepening means that the handy size vessels can not go through from the port of Corral to Las Mulatas, the Comau vessels can be replaced by other vessels having a larger load capacity, which might reduce costs and makes it still possible to increase the cargo transport.

The port of Las Mulatas is private. It is not clear whether this port is willing to adapt to be able to receive and make use of bigger vessels and increase their transshipment capacity. It is useful to research what the interest of this port and the surrounding companies in Valdivia is related to a possible growth in the demand and transport of wood chips.

In order to find out what the growth of cargo transport will be by implementing such a project alternative, more information is needed about the market share of Corral and Las Mulatas. In the report the market share of Corral has remained the same for both the zero and project alternative.

E. Data

The content of this appendix supports the tables in Chapter 8. The classification of data that was used in the Delft3D and SCBA models is explained per data subject.

E.1 Delft3D

Bathymetry
The bathymetry in the model is based on nautical charts from 1990. These maps are old an probably not representative for the current situation. Digitising the map comes with inaccuracy causing that the level of detail decreases. Furthermore, a nautical map does not include bed irregularities so a smooth surface is used. The bathymetry is therefore quite reliable but not accurate.

Discharges
The data from the river discharges is either for just one year (from September 2016 until August 2017) or from 2000 until 2013. Therefore, not the same time frames are used, so some data is not accurate because it is from just one year and some data might be outdated. On top of that, the measuring stations were located in a way that the drainage area at the measuring station were not equal to the total river catchment. Therefore, the actual river discharges could be higher than the data that was found. Since the data is extracted from governmental sources, it is assumed that the data is reliable.

Tidal signal
The tidal signal was measured at a measuring station in Corral. This signal is assumed to be correct and was used to clarify the behaviour of the estuary system with theoretical knowledge. The tidal movement in the system was the only information which could be used to calibrate the model because of earlier research containing exact water level measurements. However, this research was done in 1990 and showed a significant lower tidal range than currently present. Also, the moment of the measurement (high or low river discharge) is unknown and the daily inequality, which is present in the actual tidal signal, is not included.

Roughness
The Chezy roughness factor is used as a fine-tuning parameter. The roughness of the river bed is calculated with the calibration of the tide. It is not based on the actual present bed irregularities and sediment information. Therefore the roughness factor is not reliable. However, the obtained roughness factor refers to sediment sizes which are in the range of the actual present sediment sizes which is positive for the accuracy.

E.2 SCBA

Dredging costs
The dredging costs are totally based on estimations. Dredging is not common in Chile and therefore the methods that are used in the Netherlands are not applicable.

The value for the amount of material that has to be dredged is reliable. It is based on the reference project. However, the sedimentation rates are unknown which causes uncertainties in the maintenance costs and thus incompleteness. This is a factor of high priority.

The operational costs comprise the weekly equipment costs and the execution time. The equipment costs are unreliable and inapplicable because of a lack of information about the dredger. The execution time is reliable because the technical specifications of the dredger are known and the operational hours are based on reference project. However, these reference projects are Dutch, so not applicable for Chile. The operational costs have the most impact on the total investment costs and are therefore more important than the actual amount of material to be dredged.

Travel time

- Vessel specifications The data about vessel specifications is coming from three sources, the Dutch Ministry of Infrastructure & Environment, the Port of Corral and the Marine Traffic website. The reliability of this data is very high. The accuracy is low, because for a large part it is based on Dutch data which is not applicable for this situation. Besides that, the completeness is low, because the Dutch data is about inland vessels and not about seagoing vessels. So, costs of handy size vessels are based on the costs of inland vessels. The priority is high, because it has a big influence on the result.
- General waiting time For the general waiting time the data from the port of Corral is used which is a reliable source. Because the data is coming from this port, it is very accurate. The completeness is sufficient enough for this research. As can be seen in the SCBA, the influence is high so the priority of this data is high.
- Waiting time for freight The source is reliable, because it is coming from the Dutch Ministry of Infrastructure & Environment. It is unknown if the data is accurate, the waiting time for freight is totally based on the Dutch source. Because, it is unknown if the Dutch situation is comparable for this port. The data is complete. The priority is very low, because it is a very small part of the total travel time.

Emission costs

The source is reliable, the resources are coming from CE-Delft and Witteveen+Bos, these are key figures. It is unknown if this is accurate data, because it is unknown what the emission is of these vessels in this particular situation. All the factors are included, so the completeness is very high. Although, the priority is low, this can be seen in the total benefits in the SCBA.