

Multi-criteria approach to the infrastructural problems of San Pedro de la Paz

From an urbanistic and hydraulic perspective

Preface

This is the report of the multi-disciplinary project, *Project Chile 2015*, a master project from the faculty of Civil Engineering of Delft University of Technology and carried out at the Universidad Católica de la Santísima Concepción.

The project team covers two disciplines; Structural Engineering and Hydraulic engineering, with different specializations within these disciplines. These specialisations are used in the scope of the project.

This report is the final result of the 8 weeks during research into the congestion problem of San Pedro de la Paz, where several solutions to this problem are analysed from an urban and hydraulic perspective.

First of all we would like to thank all the people involved in this project. First of all we would like to thank Dr. Ir. R. Aránguiz, Dr. Ir. D. Caamaño, Ir. S. Loyer and Ir. M. T. Rodrigues Tastets, for supervising and guiding us through this project. They made sure we understood the complexity of the problem, but also that we got to know more about the Chilean culture.

Special thanks to Ir. L. Urra for her help with the NEOWAVE modelling, which was unknown territory for us. Also a thank you for the students of the lab, helping us with a survey among the students.

Lastly, we would like to thank Ir. H.J. Verhagen for bringing us in contact with Dr. Ir. R. Aránguiz and supervising our project.

We hope you read this report with pleasure.

Kind Regards,

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Abstract

Part I concerns the analysis of the infrastructural problems at hand in San Pedro de la Paz. To get insight into the problems first an analysis of the location is made. This analysis involves the geographical characteristics of the city, historical development, land use, infrastructure etc. Based on this analysis a problem description is made. The major problem is the congestion of Ruta 160 and Pedro Aguirre Cerda. This problem has different causes: the inter-communal traffic flows, trucks, public transport deficiency, connectivity of the secondary roads and organisational problems. To solve the congestion on Ruta 160 and Pedro Aguirre Cerda several solutions have been proposed by different parties. These proposed solutions are elaborated upon with figures of the road profiles and tables containing the road characteristics and combined into variants by the research team. The most promising variants are filtered using a set of constraints and demands. Finally in Part 1 the criteria that are used in the Multi-criteria analysis (MCA) of Part 4 are introduced and explained. These criteria are: time, costs, environmental impact, social impact, safety, comfort and co-benefits.

Part II considers the Biobío River and the Los Batros wetlands north of the Ruta 160 Bridge. The influence of the infrastructure variants Costanera Sur, Puente Industrial and Ruta Humedal on this inland water system is analysed. For this analysis two existing 1D HEC-RAS models of the Biobío River and Los Batros are modified to meet the current and proposed situations. The design conditions that are used for both models are discharges with a return period of 100 years. Also other discharges are used in order to evaluate the effects of the infrastructure for different situations. The results show that the water level in the Biobío River increases with a maximum of 10 centimetres due to the presence of Puente Industrial and Costanera Sur. The water level in (Estero) Los Batros experiences a negligible increase due to the presence of Ruta Humedal. The resulting water levels and LiDAR topography data are also used to create an inundation map for San Pedro de la Paz and the Biobío River. It can be concluded that in the present situation no mentionable floods occur along the southern bank of the Biobío River. This is also the case for the Costanera Sur situation since the riverbanks are heightened. For the design condition flooding occurs for parts of Los Batros. Ruta Humedal does not increase the flooded area in Los Batros but protects a part of the farmland located in that area from flooding.

Several roads are also analysed on the tsunami impact with the NEOWAVE model. These roads consist of Ruta Costa (elevated coastal highway), Costanera Sur (elevated road along the riverbank) and Ruta Humedal (through the wetlands). They are combined into three different combinations: (I) Costanera Sur and Ruta Humedal, (II) Costanera Sur and Ruta Costa and (III) Costanera Sur, Ruta Humedal and Ruta Costa. To assess these combinations properly, first the generation of a tsunami by an earthquake is explained. Then an earthquake scenario has to be devised in order to come up with a worst case tsunami scenario. This scenario is derived from multiple major earthquakes that generated tsunamis that affected the coastal area around San Pedro de la Paz over the last centuries. This has led to a scenario M_w 8.9 and M_w 9.0, which both show inundation of the coastal area of San Pedro de la Paz but in different amounts. Since the amount of inundation of M_w 8.9 is not significant enough for a detailed analysis, only the results of M_w 9.0 are used. This scenario overtops the dunes and inundates the coastal neighbourhoods. In the case combination (II) and (III) this coastal inundation is completely prevented, only Los Batros has a small amount of inundation. Combination (I) does not prevent coastal inundation and seems to increase the amount of

inundation in Los Batros. However, this increase of inundation in Los Batros could be due to deviations in the model itself and needs more research.

Part IV starts with the analysis of the different solutions based on the criteria as defined in Part 1. The analysis is followed by the MCA. The MCA consists of three different steps. The first step is the weighting of the criteria. In this step the relative importance of the criteria is determined. This is done using pairwise combination of criteria. The pairwise combination of the criteria is presented in a survey to the research team and students of the UCSC. The weights of the different criteria as determined by both the students and the research team are used in the MCA. The results show major difference in what the students think are important criteria and what the research team thinks are in important criteria. The students view safety, time and costs as most important criteria. But the members of the research prioritize safety, environmental impact and social impact. Step 2 concerns the scoring of the different proposed solutions and the variants. The solutions are given a score for every criterion as defined in Part 1. This scoring is done by the research team and based on the analysis as done in Part 4. The absolute scores from Part 2 show significant difference on solution level. The two proposed solutions with the highest scores are Ruta Costa and Ruta 160. The improvement of Pedro Aguirre Cerda scores relatively low. On variant level the differences are much smaller. The variants that have the highest scores are variant 1A and 1B. Step 3 of the MCA takes into account the info from the previous both steps by multiplying the absolute scores of step 2 with the weight of the criteria as determined in step 1. This multiplication results in the so-called relative weighted score. By taking into account the relative weights of the criteria the ranking of the variants changes significantly. When using the weights as defined by the students, variant 1A scores the highest. When taking into account the weights of the criteria as defined by the research variant 1B comes out on top.

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Introduction

The master tracks of Civil Engineering of Delft University of Technology offer students a chance to do a multidisciplinary project abroad. Doing a project like this is a good opportunity to test the knowledge you gained in the lecture halls. It contains a civil engineering problem to be solved with a multidisciplinary team. This report contains the results found by the multi-disciplinary team *Project Chile 2015*. The team analysed the congestion problem of San Pedro de la Paz from an urbanistic and hydraulic point of view. These are also the different disciplines within the team.

The main congestion problem in San Pedro de la Paz is that of the Ruta 160 and Pedro Aguirre Cerda. However, this congestion is caused by several smaller problems. There are already some suggested solutions for this rising problem and all of them have some opponents.

The aim of the project is therefore to analyse already proposed solutions to the problem not only on a time/costs basis, but also on more criteria. The urbanistic view includes criteria as safety, comfort, environmental impact, social impact and travel time. The hydraulic point of view covers a tsunami analysis, as well as a river flooding analysis of the proposed solutions.

All these results and criteria are analysed for the different for the proposed solutions and concluded together into a multi-criteria analysis. The weight factors in this analysis are based on the opinion of students from and south of San Pedro de la Paz. This is to include the opinion of the people that are affected by the congestion of Ruta 160 and Pedro Aguirre Cerda.

It has to be noted that this MCA is merely to show how the different proposed solutions score, based on what the locals consider most important. Since the project has a limited amount of time, only students were used. In a full scale MCA however, more people (not only students) would be questioned and the different criteria would be assessed in more detail, which could affect the final outcome.

Outline of Report

As mentioned before, the problem is assessed on three different topics. They also form the three sub-teams of the multi-disciplinary team; urban, river and tsunami. Since these topics are all assessed in equal amounts, the report is divided in different parts to cover all the conducted research.

- In Part I the infrastructural problems in San Pedro de la Paz are analysed. This is followed by an introduction to the criteria that are used in the Multi-Criteria analysis (MCA) of part IV.
- In Part II the river research of the Biobío River and the Los Batros wetlands is presented. The models that are used and that are adjusted to the proposed infrastructure are explained. The effects of the infrastructure on the hydraulics of the rivers and flooding of San Pedro de la Paz are analysed.
- In Part III the conducted tsunami research can be found. It explains the physics behind the generation of a tsunami, what earthquake scenario is used and why. It will also cover the results of how the different proposed solutions affect the inundation of San Pedro de la Paz.
- Part IV is the final part of the report. It consists of an analysis where all the proposed solutions are graded on the chosen criteria.

Research question

The aim of this project is to analyse different solutions to the congestion problem of San Pedro de la Paz. This analysis will not be done only on the aspects of time and costs, as is done now, but will also include other aspects, viewed from an urbanistic and hydraulic point of view. These aspects include among others: safety, environmental impact, tsunami and river flood risk.

Main research question

The main research question of this report is as follows:

How do the different proposed solutions for the congestion problem affect the current situation of San Pedro de la Paz and which solutions scores the best in an MCA?

Sub questions are formulated per part.

Sub questions part I

1. What is causing the congestion of the roads in San Pedro de la Paz?
2. What are the proposed solutions to this congestion problem?
3. What are the important criteria that will be used in the MCA analysis?

Sub questions part II

1. What are the hydraulic conditions used for the river analysis?
2. What is the effect of the different variants to the hydraulic behaviour of the Biobío and Estero Los Batros?
3. What is the effect of the different variants to flooding of the Biobío and Los Batros?

Sub questions part III

1. Which variants can affect the region of San Pedro de la Paz in case of a tsunami?
2. What is the most relevant earthquake scenario to use in answering the main question?
3. How do the selected variants affect the region of San Pedro de la Paz, compared to the reference situation?

Sub questions part IV

1. How do the different proposed solutions score on the selected criteria?
2. How is the weight factor for the MCA determined?
3. How do the different proposed solutions score in a MCA?

Part I

Problem analysis & MCA criteria

Part I concerns the analysis of the infrastructural problems at hand in San Pedro de la Paz. This is followed by an introduction to the criteria that are used in the multi-criteria analysis (MCA) of part IV.

To get familiar with the city of San Pedro de la Paz and gain insight into the current situation an analysis of the location is done. This kind of location analysis is of great importance to get to the source of the existing problems. The different aspects that cause the current problems are presented in the problem description.

Next the proposed solutions for the infrastructural problems are introduced and elaborated upon. These solutions are combined into variants and the five most promising variants are analysed in further detail.

Finally, in the last chapter, the criteria that will be used in the multi-criteria analysis are introduced and explained.

1 Location analysis

This section covers the analysis of the study area (San Pedro de la Paz) that is done to get familiar with the location and identify the different aspects that lead to the main problem. In the analysis is focussed on the geographical characteristics of the location, the urban development and the socio-demographic properties of San Pedro de la Paz, land-use, environmental characterization, infrastructure and facilities.

1.1 Geographical characteristics

As a commune of Greater Concepción San Pedro de la Paz is located in central/southern Chile. Greater Concepción is a conurbation that includes the municipalities of Concepción, Talcahuano, Penco, San Pedro de la Paz, Chiguayante and Hualpén.

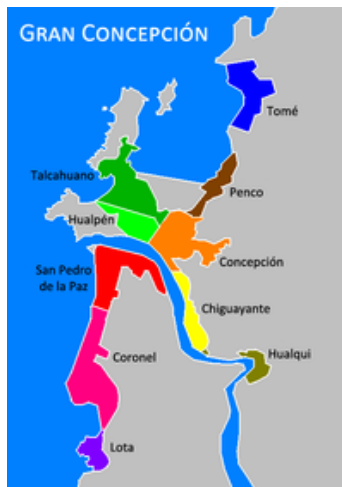


Figure I - 1: Communes of Greater Concepción¹

The construction of industry in the 1950s boosted the expansion of the urban area in Concepción. The city saw itself forced to expand in satellite cities, one of which was San Pedro de la Paz. San Pedro de la Paz experienced such a growth in inhabitants that it became a municipality itself.²

The coastal commune of San Pedro de la Paz is situated between the Pacific Ocean and the mouth of the Biobío River as can be seen in Figure I - 1.

The communal territory of San Pedro de La Paz covers an area of 11,250 ha.³ It is a coastal commune that extends in the north from the Biobío River to the bordering town of Coronel in the south. In east-west direction it is closed in by the Pacific Ocean and the Biobío River.

1.2 Urban development

Figure I - 2 shows the historical development of San Pedro de la Paz. The development started in 1889 with the construction of the Railroad Bridge over the Biobío River. The bridge was funded by industrials that owned important coalmines in Coronel. To be able to transport coal to the ports in the north they constructed this train bridge. The first development of San Pedro de la Paz started in

¹ Wikipedia. Área metropolitana de Chile.

² (Almuna, Alonso, & Maríquez, 2012)

³ (SECTRA, Mejoramiento interconexión vial, San Pedro de la Paz., 2013)

the vicinity of this train bridge. Near the entrance of the bridge some factories were build and later some houses followed.

In 1942 the Biobío Bridge was build with private money from the people living in San Pedro de la Paz. This improved the connectivity between San Pedro de la Paz and Concepción. As a result the area between the two bridges developed into an urban area. At the same time a fishing village was established near the coast.

Parallel to this development the government focussed on the agricultural development of San Pedro de la Paz. They assigned parts of San Pedro de la Paz as farmlands. They also build houses with large gardens. The idea was that the inhabitants would use these large gardens to grow crops.

The industrialization started in the fifties. During this period, Concepción and Talcahuano were thought to be an important industrial development centre due to presence of two important features; a protected bay suitable for port activity and large navigable river. These new industries caused a demand for labour force, which had to find housing in the vicinity of the industry. This boosted the expansion of the urban area and as a consequence there was a shortage of land for development. As mentioned before, this forced the cities to grow in other locations. This is how in 1958 San Pedro Village was founded. San Pedro Village became a dormitory town in which the employees of the industrial sector established themselves.

In 1970 a third bridge was build, called Juan Pablo II. This bridge was constructed to increase the connectivity between the communes south of the Biobío River and the new Carriel Sur Airport.

In the 80s the government developed large social housing plans. This resulted in the construction of large neighbourhoods like Boca Sur and Michaihue. Under the regime in the 80s poor people were relocated from the city centre to these areas. Because of this Boca Sur and Michaihue became low-income areas. Figure I - 2 shows the class division within San Pedro de la Paz.

In 1990 some new houses were build by private companies near San Pedro village. Then with the construction of the Llacolen Bridge in 2000 the connectivity improved even more. Because of this improvement, private companies developed the areas in the hills into urban areas for the upper class. Parallel to this private housing concept for the upper class also private housing was established for lower classes along Ruta 160.⁴

San Pedro de la Paz was at one point the fastest growing city in the entire country.⁵ This growth still continues today as becomes clear from the large amount of new urban development projects.

1.3 Socio-demographic properties

Currently San Pedro de la Paz has 80,477 inhabitants of which 48% is male and 52% is female. Taking into account the growth of the last years the expected amount of inhabitants for 2020 will be around 106,266. Taking into account a number of 3.7 residents per house this corresponds with 381 extra hectares necessary for residential areas by 2020.⁶ Figure I - 2 shows the future development of San Pedro de la Paz. The blue coloured areas represent the areas that are being developed into residential areas.⁷

⁴ (Tastets, 2015)

⁵ (Almuna, Alonso, & Maríquez, 2012)

⁶ (SECTRA, Mejoramiento interconexión vial, San Pedro de la Paz. , 2013)

⁷ (Municipality)

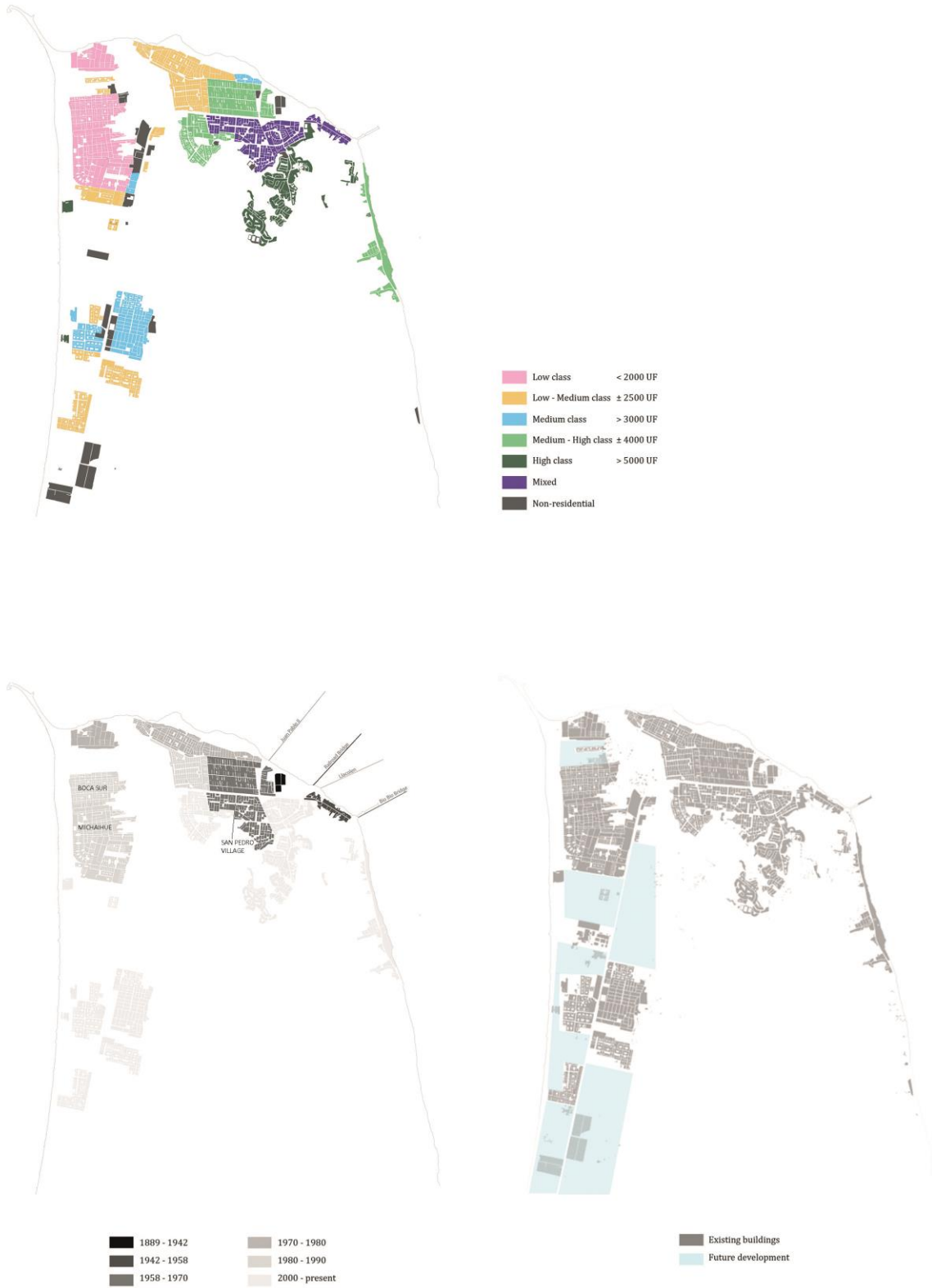


Figure 1 - 2: LRTB: Historical development, class division, future development

1.4 Land-use

In Figure I - 3 below the different types of land-use in San Pedro de la Paz are indicated. The location comprises a great percentage of natural landscape like forest and lakes. Especially compared to man made landscape (residential areas). Another remarkable usage is “no use”, which refers to wasteland. Other noticeable categories are sports, public space and farmland.

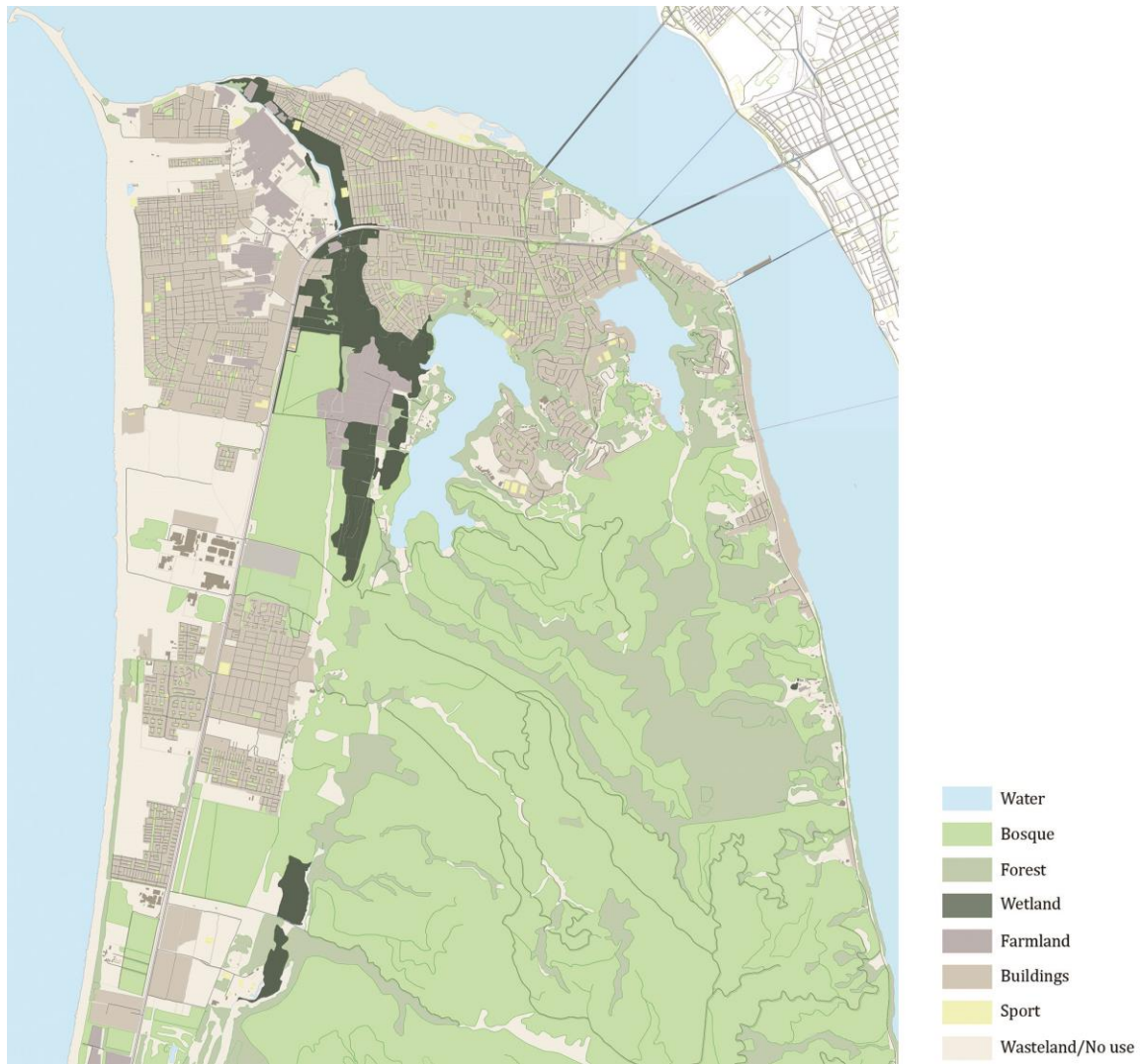


Figure I - 3: Land-use San Pedro de la Paz

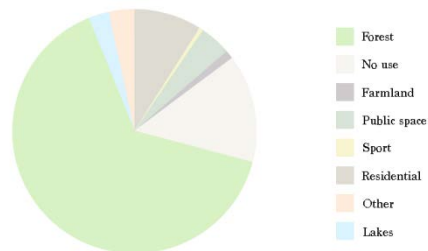


Figure I - 4: Land use diagram

1.5 Environmental characterization

San Pedro de la Paz is located near the mouth of the Biobío River and thus mainly consists of low-level land. Due to the high sediment load of the Biobío River these lands have been become filled in by sediments. These obstruct the flow of the water and can cause floods. This has given rise to the creation of ponds, meadows and wetlands in this area. In the area of San Pedro de la Paz four distinct different ecosystems can be classified: Lagunas, Wetlands, Dunes and Native forest. The natural ecosystems are gradually being altered and degraded by humans. Because of this erosion has increased and during heavy storms the drainage of water becomes a serious problem causing floods.⁸

1.6 Infrastructure

The analysis of the infrastructure is subdivided into four aspects. These aspects are: main roads, secondary roads, public transport and bicycles.

1.6.1 Main Roads

As seen in Figure I - 5 there is only one traffic axis that provides a direct connection between the commune of Coronel in the South and the communes of San Pedro de la Paz and Concepción in the North. The axis is formed by the combination of Ruta 160 and Pedro Aguirre Cerda. The fastest option to cross the river is by using these roads. The only other option would be to use Ruta 156 in combination with Ruta O-852 to travel from Coronel to Concepcion. This is a curvy road through the hills and using this alternative takes significantly more time. On top of that this road is used by approximately 100 trucks per day.⁹

1.6.2 Secondary Roads

From Figure I - 5 becomes clear that the amount of secondary roads transversal to Ruta 160 is limited. Furthermore these roads often have no continuity and no mutual connection. This counteracts the fluidity in the traffic flows through the different neighbourhoods.

1.6.3 Public Transport

From Figure I - 5 can be concluded that the busses mainly use Ruta 160 and Pedro Aguirre Cerda. In the city centre the busses not only use Pedro Aguirre Cerda, they use the secondary roads as well and go into the city centre. This creates a good connectivity for the centre of San Pedro de la Paz and the other neighbourhoods surrounding Pedro Aguirre Cerda. Outside the city centre the situation is different. The busses leave Ruta 160 to access Boca Sur and Michahue. The problem is that the frequency is too low to meet the demand for public transport in Boca Sur and Michahue. The problem in Lomas Colorados is that only a limited amount of busses actually leave Ruta 160 and enter this part of San Pedro de la Paz.

The other form of public transport is the train. The railway runs parallel to Ruta 160 and Pedro Aguirre Cerda as can be seen from Figure I - 5. There are train stations situated along both roads creating a decent access to the train for all the neighbourhoods. These are indicated in Figure I - 6.

⁸ (SECTRA, Mejoramiento interconexión vial, San Pedro de la Paz. , 2013)

⁹ (SECTRA, Presentatie, 2015)

1.6.4 Bicycles

As can be seen in Figure I - 5 there are almost no bicycle lanes. It is possible to travel from San Pedro de la Paz to Concepcion using the Llacolen Bridge. But apart from this route the only possibility to use a bicycle is using the public roads. These roads have no separate bicycle lanes creating dangerous situations for both cyclists and vehicles.

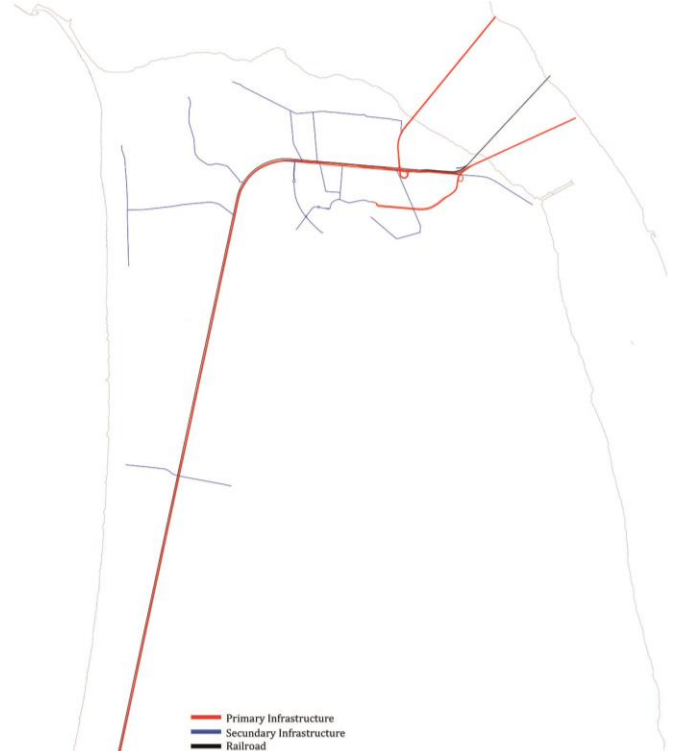


Figure I - 5: LRTB: Infrastructure large scale, Infrastructure San Pedro de la Paz, Bike lane network¹⁰, Bus routes

¹⁰ (SECTRA, Presentatie, 2015)

1.7 Facilities

The facilities within San Pedro de la Paz that are analysed are divided into four different categories. These categories are: medical, educational, retail and train stops.

1.7.1 Medical facilities

As can be seen in the Figure I - 6 there are only two medical facilities in San Pedro de la Paz. These two are both general practitioners and not large hospitals. For serious cases the inhabitants need to visit the major hospitals in Concepcion.¹¹

1.7.2 Educational facilities

There are a lot of educational facilities in San Pedro de la Paz. This is due to the fact that a lot of schools have in the recent years relocated from Concepcion to the higher-class areas in San Pedro de la Paz. Most of the educational institutes are located near the city centre of San Pedro de la Paz. But none of these are universities, these are all located in Concepcion.

1.7.3 Train stops

San Pedro de la Paz has access to five different train stops. All of them are located along Ruta 160.

1.7.4 Retail points

The retail points in San Pedro de la Paz mainly consist of medium sized supermarkets. Just like the train stops they are all located along Ruta 160. The larger retail points, for example the large malls are all located in Concepcion.

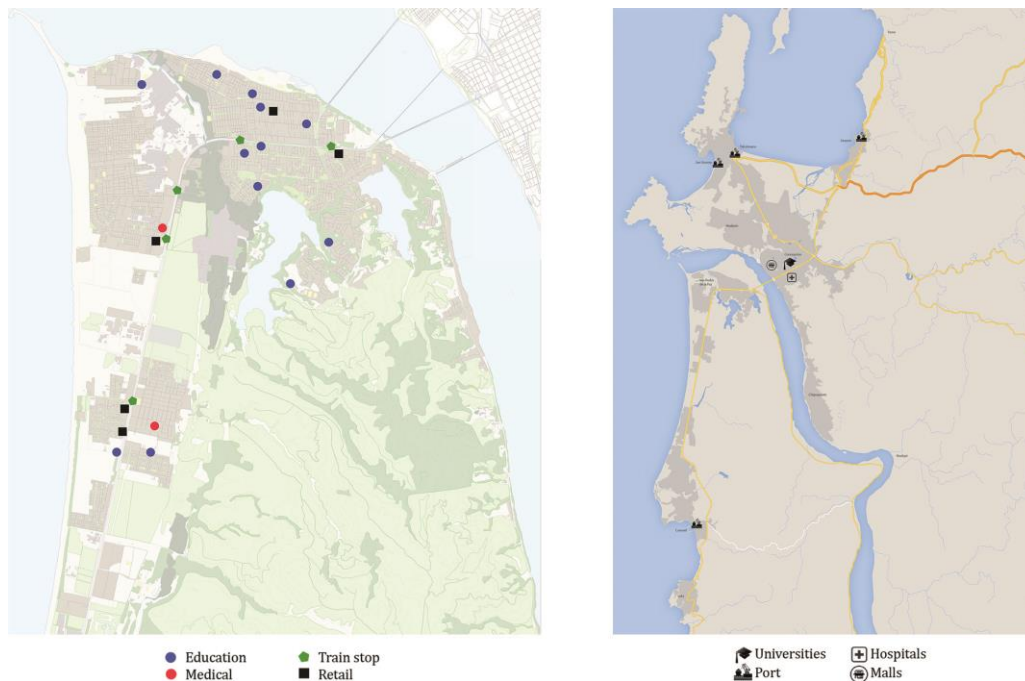


Figure I - 6: LR: Facilities San Pedro de la Paz, Facilities large scale

Figure I - 6 shows some important facilities that contribute greatly to the usage of the road network through San Pedro de la Paz.

¹¹ (Tastets, 2015)

2 Problem description

The main problem in San Pedro de la Paz is the congestion of Ruta 160 and Pedro Aguirre Cerda, which causes major traffic jams. There are several smaller problems leading up to this major congestion. These are schematised in Figure I - 7 and will be described in this section.

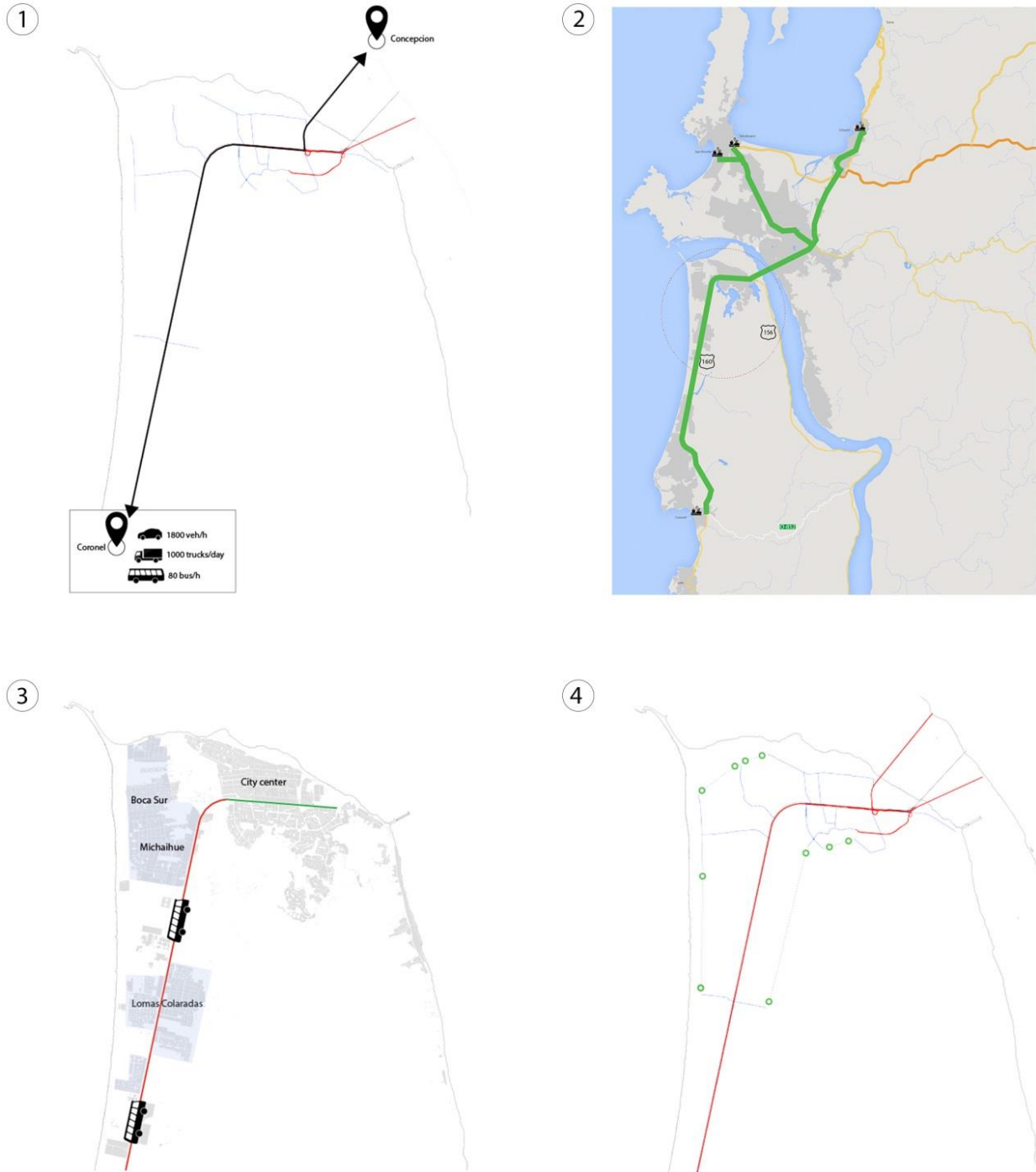


Figure I - 7: LRTB: 1. Inter-communal traffic, 2. Trucks, 3. Public transport deficiency, 4. Connectivity

2.1 Inter-communal traffic (1)

Ruta 160 and Pedro Aguirre Cerda are not only used by the locals from San Pedro de la Paz but they also form the connection between the other communes of Greater Concepcion in the North and South. This is because these roads are the only ones connecting the different communes. There is especially a lot of traffic between the communes of Concepción and Coronel. This is illustrated in Figure I - 7. The flow from Coronel to Concepción is estimated to be 1800 vehicles/hour, not including trucks or busses. This traffic flow between the communes in the North and South almost fully utilizes the total capacity of Ruta 160 and Pedro Aguirre Cerda. Meaning that without considering the traffic demand of the inhabitants of San Pedro de la Paz itself, the roads are already almost used to their full capacity. So the current capacity of roughly 2400 vehicles/hour only barely sustains the inter-communal flow, especially during the morning rush hours.¹²

2.2 Trucks (2)

The second issue is the usage of Ruta 160 and Pedro Aguirre Cerda by trucks. Greater Concepcion is home to four ports, which generate a lot of transport by trucks (Figure I - 7). Trucks are not the largest contributor to the congestion but they can slow down the traffic flow significantly. The solution for this extra traffic demand by trucks would be Ruta 156. This is a separate road that was created for trucks so that they would bypass Ruta 160 and Pedro Aguirre Cerda. The problem is that the trucks still prefer to use Ruta 160. The reason for this is that choosing the alternative of Ruta 156 generates a much longer travel time for the trucks. Ruta 156 also runs through the mountains, making it a hazardous road with a lot of accidents. The preferred usage of Ruta 160 and Pedro Aguirre Cerda by trucks adds approximately 1000 trucks/day to the already congested roads. While only 100 trucks/day use Ruta 156.¹³

2.3 Public transport deficiency (3)

The bad access to public transport of some neighbourhoods further contributes to the need of the inhabitants to make use of their car. The city centre has a good access to the public transport with a frequent arrival of busses. The neighbourhoods of Boca Sur and Michuahue also have a good access to the public transport. But what causes problems here is the frequency of the busses. The frequency is too low to meet the demands. The neighbourhood of Lomas Colaradas has overall a very poor connection to the public transport system. Both the access to the busses and the frequency is not sufficient. This forces the inhabitants of these neighbourhoods to use their car, adding to the traffic demand of San Pedro de la Paz.¹⁴ In Figure I - 7 the blue coloured areas indicate areas that experience a deficiency in public transport availability.

2.4 Connectivity (4)

One more issue adding to the congestion is the lack of connection between the different secondary roads running through the neighbourhoods of San Pedro de la Paz. The different neighbourhoods have a direct connection to Ruta 160 and Pedro Aguirre Cerda but are not connected to each other. This is schematised in Figure I - 7. Because of this there is no road network enabling the inhabitants to travel from one neighbourhood to the other using the secondary roads. This means that traffic flows between the neighbourhoods of San Pedro de la Paz also have to access Ruta 160 and Pedro Aguirre Cerda. This contributes greatly to the traffic demand of San Pedro de la Paz to Ruta 160 and

¹² (SECTRA, Presentatie, 2015)

¹³ (SECTRA, Presentatie, 2015)

¹⁴ (SECTRA, Presentatie, 2015)

Pedro Aguirre Cerda. Furthermore there is also the railway parallel to Ruta 160. Because all existing vehicle crossings are on street level, the existence of this railway even further complicates the intersections and lowers the connectivity.

2.5 Conclusion

So not taking into consideration the traffic demand from San Pedro de la Paz itself the roads are almost running at full capacity already due to the inter-communal traffic. When the traffic demand of San Pedro de La Paz is added to the inter-communal traffic demand the road becomes congested due to under capacity. This is illustrated in Figure I - 8. It can be observed that the congestion starts at the first connection between Ruta 160 and the residential areas of San Pedro de la Paz. The congestion of Ruta 160 results in queues for cars that want to access Ruta 160 from the adjacent neighbourhoods. This results in large traffic jams on Ruta 160 and Pedro Aguirre Cerda. Secondly the inhabitants from San Pedro de la Paz have to wait in line to enter the Ruta 160 and Pedro Aguirre Cerda.

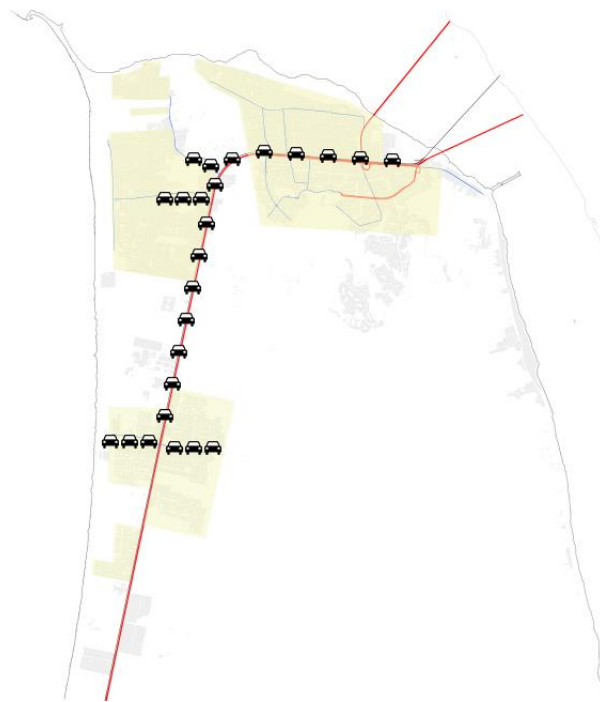


Figure I - 8: Traffic demand San Pedro de la Paz

With the current traffic demand from San Pedro de la Paz the road is already congested. The problem is that the traffic demand is only going to increase. First of all due to the issues as described above: the public transport deficiency and the bad connectivity. Secondly the plans for more urban areas in the vicinity of Ruta 160 will cause a major increase in traffic demand. Taking this into account the under capacity of the road is only going to get larger. Resulting in even longer traffic jams and delays.¹⁵

¹⁵ (SECTRA, Presentatie, 2015)

2.6 Decision-making

Besides the physical problem there is also an organisational problem. As seen in Figure I - 9 below there are a lot of governmental institutions involved in the decision-making and design of both transport and infrastructure. Due to this decentralisation every institution is only responsible for a part of the project.

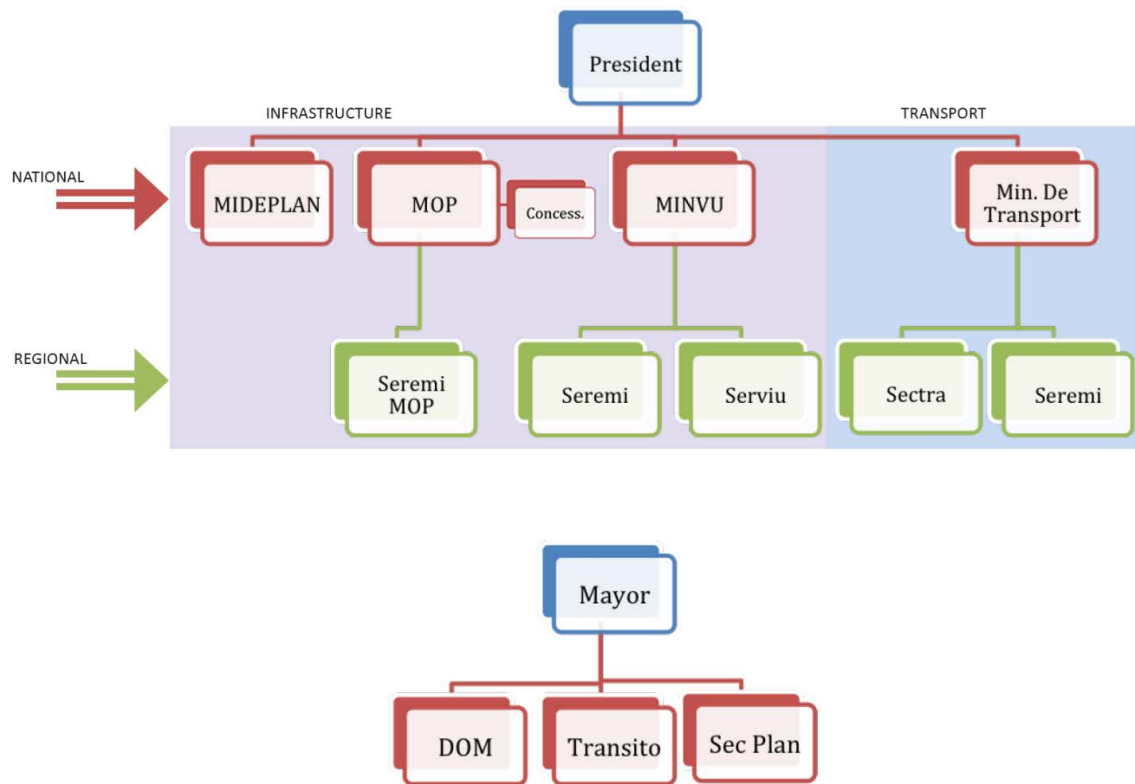


Figure I - 9: Governmental institutions involved in design and decision making of transport and infrastructure

This system would be able to function if the different institutions would communicate better. In practice however it is almost impossible to get all the different parties together. In Chilean culture they are not accustomed to sharing their information. Because of this important data and ideas are not exchanged between the different institutions. Due to this lack of communication, projects experience major delays.

Another drawback is that some of the institutions that make important decisions and do important research are located in Santiago. MOP is a good example of this. These organisations that have no personal connection to the area are put in charge of important research. They are not familiar with the locals which is why the important input of these people is often not taken into account.

Something else that is important to point out is that the mayor and the other institutes on a communal level, as seen in Figure I - 9, have no influence on the decision-making. The funds and with that the power to decide which projects are going to be constructed are situated in Santiago. The only thing that can be done by the mayor is to oppose a project that can possibly be harmful to his community.¹⁶

¹⁶ (Loyer, 2015)

3 Proposed Solutions

In this chapter the future Puente Industrial and seven proposed solutions are presented and are depicted in Figure I - 10. Six of these are known by SECTRA and previously analysed. Pedro Aguirre Cerda and Ruta 160 concern improvements of existing roads. For these two solutions both the existing and the improved situation will be treated. The other solutions are new roads that connect existing roads or completely new roads. For these solutions only the characteristics of the new design will be presented. The different stages that the development of a solution goes through before it is completed are: feasibility studies, engineering phase and construction. For every solution also this phase of the process is indicated.

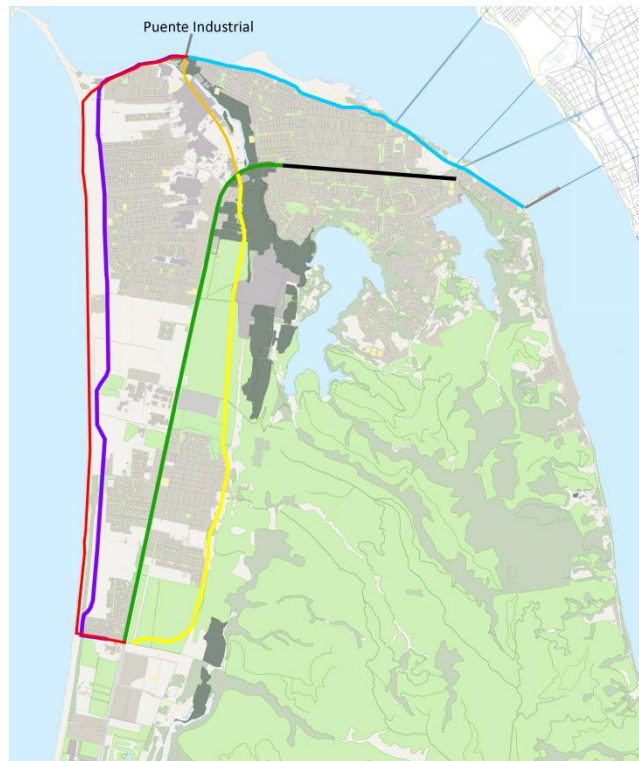


Figure I - 10: Map containing all proposed solutions

3.1 Puente industrial

Puente industrial or Industrial Bridge is going to be the fourth bridge over the Biobío River. The design, construction and maintenance are being executed by a private company. Puente industrial forms a connection between the Avenida Costanera in the commune of Hualpén and San Pedro de la Paz. As it is a private road, a toll fee has to be paid to enter the bridge. The main idea behind the construction of the bridge is that it improves the connection between the communes north and south of the Biobío River, especially the connectivity between two important ports. These are the ports of Coronel and Talcahuano. Usage of this new bridge will result in a lower traffic density on the other bridges. Puente Industrial will have a total length of 6.5 km and provide two lanes in each direction.¹⁷

¹⁷ (S.A., 2015)

3.2 Pedro Aguirre Cerda

Pedro Aguirre Cerda is schematised as the black line in Figure I - 11. The road runs through the centre of San Pedro de la Paz. It forms a connection between Ruta 160 coming from the South and the bridges to the North. The proposed solution for the Aguirre Cerda is to improve the existing situation. In Figure I - 11 below both the road profiles are presented. The upper profile is the previous situation, and the bottom profile is the design of the improved situation. The improvement of the Pedro Aguirre Cerda is through the entire development stage and has already been completed. The characteristics of the road profiles are given in Table I - 1 below.



Figure I - 11: LRTB: Location of Pedro Aguirre Cerda, Existing road profile³, Improved road profile design³

Table I - 1: Road profiles characteristics of Pedro Aguirre Cerda

| Characteristics | Existing | Improved |
|--------------------------------------|----------|----------|
| Length | 20.7 km | 2.07 km |
| Total width | 35.6 m | 35.6 m |
| Number of vehicle lanes | 4 | 4 |
| Number of exclusive bus lanes | 2 | 2 |
| Number of bicycle lanes | 1 | 0 |
| Maximum speed | Unknown | Unknown |

The width of Pedro Aguirre Cerda maintains the same. The bus lanes move to the centre of the road. The amount of vehicle lanes remains the same, from improved road profile design presented in Figure I - 11 it follows that the bicycle lane is removed.³ However, Figure I - 5 shows that there is an existing bike lane running parallel Pedro Aguirre Cerda. In the remainder of the report we assume there is actually a bike lane at Pedro Aguirre Cerda.

3.3 Ruta 160

Ruta 160 is schematised as the green line in Figure I - 12. It is the main traffic axis that connects the commune of Coronel in the South with the Communes of San Pedro de la Paz and Concepción in the North. The proposed solution for Ruta 160 is to improve the existing situation. In Figure I - 12. The upper profile is the existing situation, and the bottom profile is the design of the improved situation. Ruta 160 is in the feasibility stage of the development. The characteristics of the road profiles are given in the Table I - 2 below.



Figure I - 12: LRTB: Location of Ruta 160, Existing road profile³, Improved road profile design³

Table I - 2: Road profile characteristics of Ruta 160

| Characteristics | Existing | Improved |
|--------------------------------------|----------|----------|
| Length | 13.5 km | 13.5 km |
| Total width | 27.8 m | 30 m |
| Number of vehicle lanes | 4 | 6 |
| Number of exclusive bus lanes | Unknown | Unknown |
| Number of bicycle lanes | 0 | 1 |
| Maximum speed | 80 km/h | 80 km/h |

The improvement of Ruta 160 concerns the addition of one vehicle lane in each direction. The width of the central strip separating the transverse directions is significantly reduced. This allows adding a bicycle lane on one side of the road.¹⁸

¹⁸ (SECTRA, Mejoramiento interconexión vial, San Pedro de la Paz, 2013)

3.4 Costanera Sur

Costanera Sur is schematised as the blue line in Figure I - 13. The road runs along the southern bank of the Biobío River. It forms a connection between the industrial bridge and Ruta 156. It also provides a connection to the Chacabuco Bridge. The design of the road profile can be seen in Figure I - 13. For the stretch between Puente Industrial and Costanera Mar, the feasibility studies are done and the project is ready to go into the engineering phase (after funds are collected). For the remainder of Costanera Sur the project is considered in the first phase of the study (preliminary alternative analysis). The characteristics of this design are presented in Table I - 3.

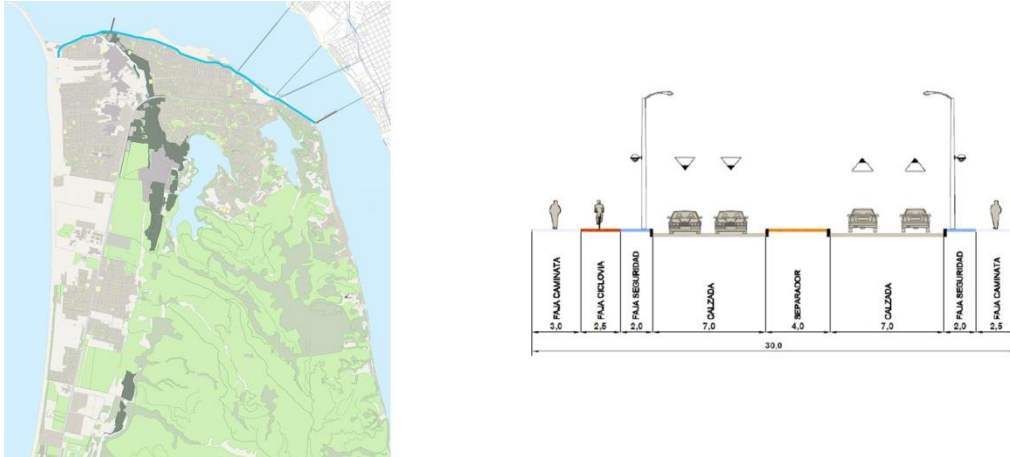


Figure I - 13: LR: Location of Costanera Sur, Road profile design³

Table I - 3: Road profile characteristics of Costanera Sur

| Characteristic | Value |
|--------------------------------------|---------|
| Length | 7.5 km |
| Total width | 30 m |
| Number of vehicle lanes | 4 |
| Number of exclusive bus lanes | 0 |
| Number of bicycle lanes | 1 |
| Maximum speed | 70 km/h |

3.5 Ruta Pie de Monte

Ruta Pie de Monte is schematised as the yellow line in Figure I - 14. The route will be constructed in a natural area that is not urbanized (yet). The natural areas mainly consist of forest and wetlands. The design of the road profile can be seen in Figure I - 14. Ruta Pie de Monte is a private road that is being developed by a private party. At the moment they still have to start the feasibility studies. The characteristics of this design are presented in Table I - 4.

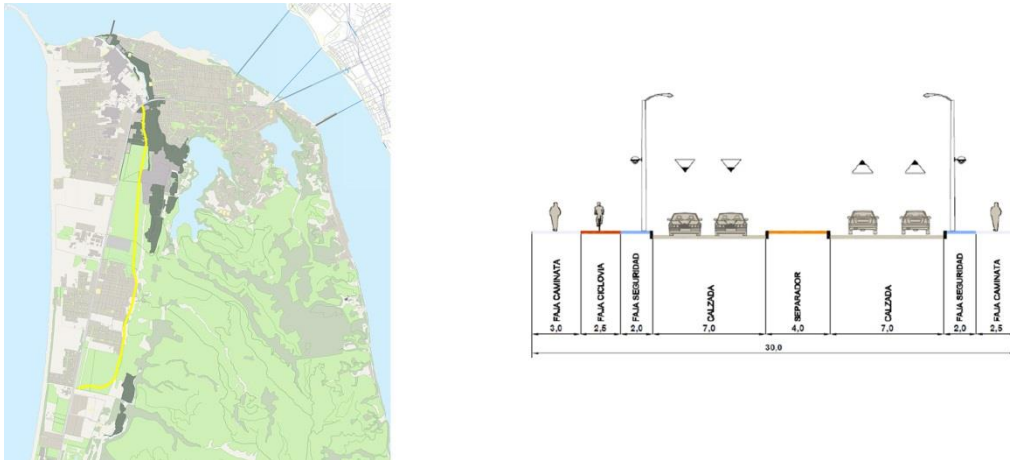


Figure I - 14: LR: Location of Ruta Pie de Monte, Road profile design³

Table I - 4: Road profile characteristics of Ruta Pie de Monte

| Characteristic | Value |
|--------------------------------------|---------|
| Length | 9 km |
| Total width | 30 m |
| Number of vehicle lanes | 4 |
| Number of exclusive bus lanes | 0 |
| Number of bicycle lanes | 1 |
| Maximum speed | 70 km/h |

3.6 Costanera Mar

Costanera Mar is schematised as the purple line in Figure I - 15. The proposed solution of the Costanera Mar is a special case. Parts of this road are already constructed. The problem is that these parts are not connected. The idea for this solution is to connect these loose parts and improve them. By doing this a new road is created called Costanera Mar. The design of the road profile can be seen in Figure I - 15. Costanera Mar is already through the feasibility studies phase of the development and ready for the engineering stage. The only thing that has to be done is gathering the funds to start the engineering stage. The characteristics of this design are presented in Table I - 5.

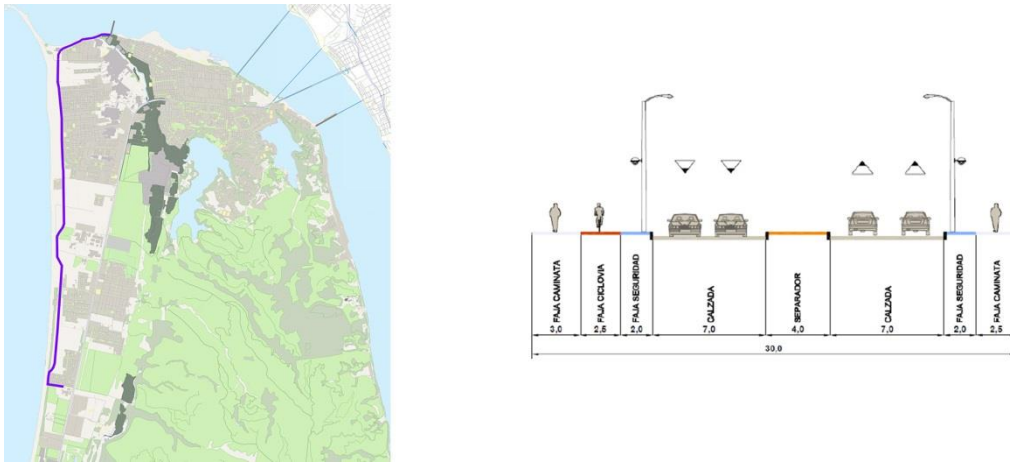


Figure I - 15: LR: Location of Costanera Mar, Road profile design³

Table I - 5: Road profile characteristics of Costanera Mar

| Characteristic | Value |
|--------------------------------------|---------|
| Length | 7.4 km |
| Total width | 30 m |
| Number of vehicle lanes | 4 |
| Number of exclusive bus lanes | 0 |
| Number of bicycle lanes | 1 |
| Maximum speed | 70 km/h |

3.7 Ruta Costa

Ruta Costa is schematised as the red line in Figure I - 16. The road is no official proposed solution that was researched by SECTRA. This road is a solution that is added to the research to investigate it as an alternative for Ruta Pie de Monte and the Costanera Mar. Because this road might have a mitigating effect on tsunamis.

This is a solution that is not investigated by SECTRA. Because of that there is no information available about the design of this road. Ruta Costa is assumed to be a 7.5 high elevated road, existing of 4 lanes designed for cars. There is also a bike lane running along the road on the opposite side of the coast. Ruta Costa is directly connected to Costanera Sur and Ruta 160. Since Ruta Costa is an elevated road it is not easy to connect to the current road network, so it is assumed there are no crossings along the entire road. This results in a road without traffic lights or other interfering elements. The maximum speed is assumed to be 80 km/h. The assumed characteristics of the road profile are presented in Table I - 6.



Figure I - 16: LR: Location of Ruta Costa, Assumed road profile design

Table I - 6: Road profile characteristics of Ruta Costa

| Characteristic | Value |
|--------------------------------------|---------|
| Length | 7.4 km |
| Total width | 24.5 m |
| Number of vehicle lanes | 4 |
| Number of exclusive bus lanes | 0 |
| Number of bicycle lanes | 1 |
| Maximum speed | 80 km/h |

3.8 Ruta Humedal

Ruta Humedal is schematised as the orange line in Figure I - 17. This road is not included in the research done by SECTRA. This is because Ruta Humedal is a private project. SECTRA does not have access to information regarding projects in the private domain.

Because of that there is no information available about the design of this road. To be able to present a complete analysis it is assumed the road has the same design as Ruta Pie de Monte, since these two roads are directly connected in line. The design of the road profile can be seen in Figure I - 17. Due to protests from the local community the development of Ruta Humedal is on hold. The feasibility studies for Ruta Humedal have already been done and it is ready to go into the engineering phase. The characteristics of this design are presented in Table I - 7.

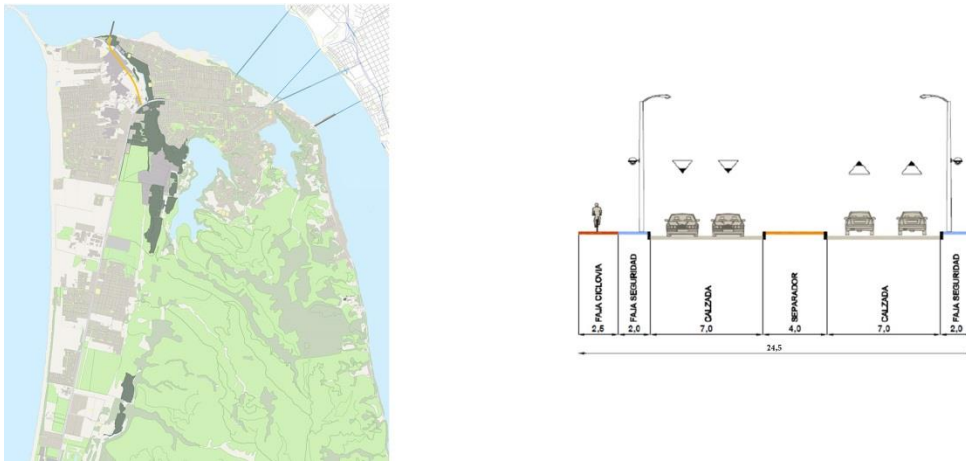


Figure I - 17: LR: Location of Ruta Humedal, Assumed road profile design³

Table I - 7: Road profile characteristics of Ruta Humedal

| Characteristic | Value |
|--------------------------------------|---------|
| Length | ≈ 2 km |
| Total width | 24.5 |
| Number of vehicle lanes | 4 |
| Number of exclusive bus lanes | 0 |
| Number of bicycle lanes | 1 |
| Maximum speed | 70 km/h |

4 Variants

This section covers an explanation of the different variants that will be analysed part IV of this report. First is described how these variants were created and selected.

4.1 Constraints

Each of the solutions as proposed in the previous chapter only solves a specific part of the problem. To be able to get rid of the congestion on Ruta 160 and Pedro Aguirre Cerda the particular solution need to be combined into a complete variant. The combination of all the separate projects in different ways results in 30 different variants. In order to eliminate variants that contain illogical combinations, the following constraints are applied to the variants:

- The improvement Pedro Aguirre Cerda is already realised. Which means that this improvement should always be taken into account. So it is only logical that the improvement of Pedro Aguirre Cerda is implemented in every combination. Ruta 160 and Pedro Aguirre Cerda are intertwined roads. So the first constraint is that Ruta 160 is always improved in combination with the improvement of Pedro Aguirre Cerda and vice versa.
- Ruta Pie de Monte is always constructed in combination with Ruta Humedal and vice versa. This is because Ruta Humedal forms the connection between the Industrial Bridge and the Ruta Pie de Monte. If only one of them is constructed the roads lose their purpose.
- Construction of both Ruta Costa and the Costanera Mar in one variant is no option. Both of these roads have the same function; they create a bypass for the inter-communal traffic. Building two roads with exactly the same function very close to each other is considered an obvious flaw in the design.
- The industrial bridge is constructed in all variants without exception.

By applying the constraints the amount of variants is reduced to 11 different options. Not all of these 11 variants make it to the analysis phase of the research. A variant will only be analysed if it meets the following three demands.

- The variant should, apart from the existing roads, contain an exclusive alternative for trucks.
- The variant should contain a bypass that improves the inter-communal connectivity.
- The variant should lower the traffic density on Ruta 160 and Aguirre Cerda so that the inhabitants of San Pedro de la Paz can enter and use these roads again without waiting and delays.

By applying these demands only four of the 11 variants remain. The elimination process is visualised in Appendix I-A.

One extra variant is added to these four. This is the variant that the local municipality of San Pedro de la Paz suggests to construct to solve the congestion. This variant does not meet the demand of having an alternative exclusively for the trucks. It also fails to meet the constraint of always combining Ruta Humedal with Ruta Pie de Monte. It is analysed anyways because the local municipality of San Pedro de La Paz has expressed a lot of interest in the outcome of the research regarding their solution.

These five variants will be described in the following sections.

4.2 Variant description

In this section the five final variants are presented. Also the functioning of the different variants are explained.

4.2.1 Variant 1

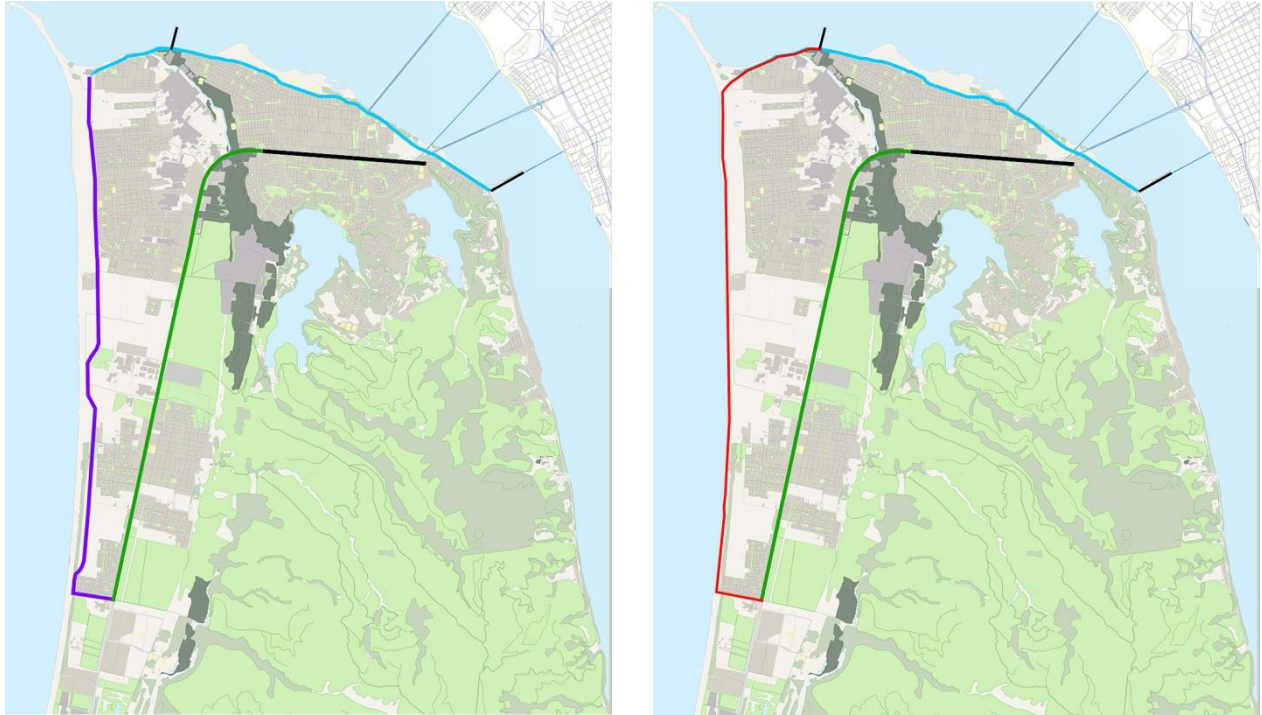


Figure I - 18: LR: Variant 1A, Variant 1B

4.2.1.1 Variant 1A

The left map in Figure I - 18 shows variant 1A. This variant combines an improvement of Ruta 160 (green line) and Pedro Aguirre Cerda (black line) with the construction of Costanera Sur (blue line) and Costanera Mar (purple line).

The idea behind this variant is that Costanera Mar forms a bypass to the inter-communal traffic. People travelling from Coronel to Concepción and vice versa will use this road. By using Costanera Mar and the Industrial Bridge the inter-communal traffic flow will bypass San Pedro de la Paz.

With the creation of this bypass the traffic density on Ruta 160 and Pedro Aguirre Cerda decreases significantly. As seen before the inter-communal traffic was responsible for almost 50 per cent of the total traffic demand of Ruta 160 and Pedro Aguirre Cerda. This enables the inhabitants of San Pedro de la Paz to fully utilize these roads again. Inhabitants of San Pedro de la Paz that want to travel to either Coronel or Concepción can choose between both Costanera Mar and Ruta 160.

The construction of Costanera Sur forms a connection between Ruta 156 and the industrial bridge. Ruta 156 was originally constructed for trucks so that they would avoid Ruta 160. In reality this never worked out as planned. By building a connection between the industrial bridge and Ruta 156 this becomes again a more attractive option for the trucks to choose. By giving the trucks an alternative for Ruta 160 and Costanera Mar the traffic flows on these roads can improve.

4.2.1.2 Variant 1B

The right map in Figure I - 18 shows variant 1B. This variant combines an improvement of Ruta 160 (green line) and Pedro Aguirre Cerda (black line) with the construction of Costanera Sur (blue line) and Ruta Costa (red line).

The idea behind this variant is in exactly the same as variant 1A. The only difference is that now, instead of Costanera Mar, Ruta Costa is constructed to function as a bypass.

4.2.2 Variant 2

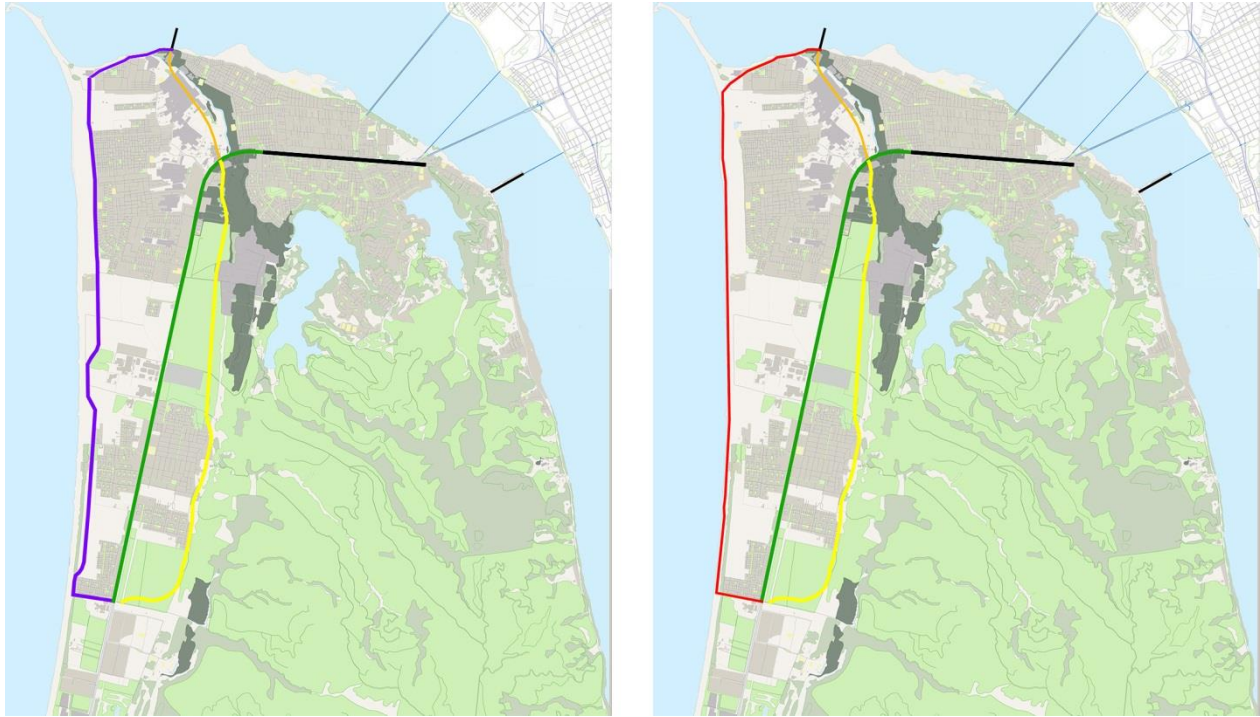


Figure I - 19: LR: Variant 2A, Variant 2B

4.2.2.1 Variant 2A

The left map in Figure I - 19 shows variant 2A. This variant combines an improvement of Ruta 160 (green line) and Pedro Aguirre Cerda (black line) with the construction of Costanera Mar (purple line), Ruta Pie de Monte (yellow line) and Ruta Humedal (orange line).

The idea behind this variant is, that just like in variant 1A, Costanera Mar functions as a bypass for the inter-communal traffic. To in this way, decrease the traffic demand for Ruta 160 and Pedro Aguirre Cerda

Also just like in the previous two variants, Ruta 160 and Pedro Aguirre Cerda will be mainly used by the locals of San Pedro de la Paz itself.

The big difference with the previous variants is that now is chosen to construct Ruta de Pie Monte and Ruta Humedal instead of Costanera Sur. Ruta Pie de Monte and Ruta Humedal will both be private roads. Meaning that vehicles have to pay a toll fee to enter the road. The construction of Ruta Humedal creates a connection between Ruta Pie de Monte and the Industrial Bridge. By constructing these two roads an interesting alternative route for trucks comes into existence.

4.2.2.2 Variant 2B

The right map in Figure I - 19 shows variant 2B. This variant combines an improvement of Ruta 160 (green line) and Pedro Aguirre Cerda (black line) with the construction Ruta Costa (red line), Ruta Pie de Monte (yellow line) and Ruta Humedal (orange line).

The idea behind this variant is the same as the idea behind variant 2A. The only difference is the construction of Ruta Costa, instead of Costanera Mar, to function as a bypass.

4.2.3 Variant 3

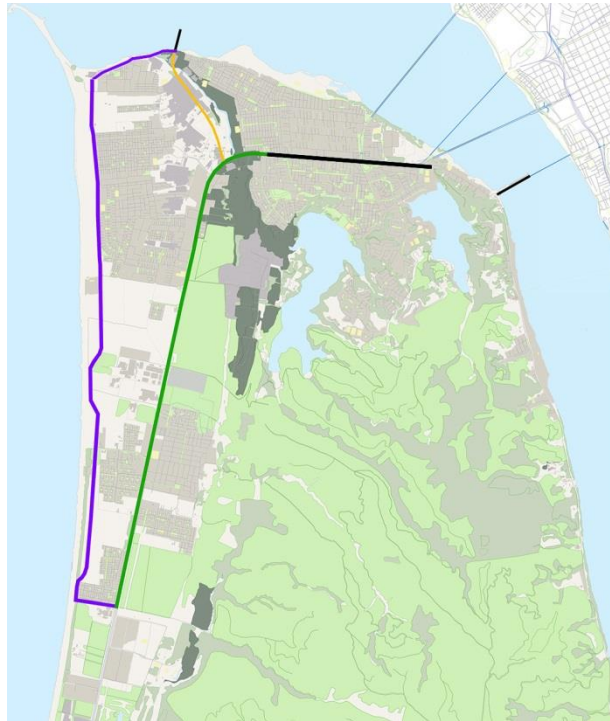


Figure I - 20: Variant 3

Figure I - 20 shows variant 3. This variant is suggested by the local municipality of San Pedro de la Paz as the solution for the congestion on Ruta 160. Variant 3 combines the improvement of Ruta 160 (green line) and Pedro Aguirre Cerda (black line) with the construction of Costanera Mar (purple line) and Ruta Humedal (orange line).

Just like in the previous variants the Costanera Mar functions as a bypass around San Pedro de la Paz. This will result in a decreased traffic density on Ruta 160 and Pedro Aguirre Cerda, by which it becomes possible for the local inhabitants to use these roads in a comfortable way again.

The construction of Ruta Humedal creates a connection between the Industrial Bridge and Ruta 160. A difference with other variants is the missing connection between Ruta Humedal and Ruta Pie de Monte, as Ruta Pie de Monte is not constructed in this variant.

Another difference with the previous variants is that this variant does not offer an exclusive alternative for trucks. Trucks have the options to take either Ruta 160 or Ruta 156, which already exist in the current situation. Another option for the trucks would be to make use of the constructed bypass. But since this road is intentionally constructed for inter-communal traffic, this is not preferable.

5 Criteria

The first step in the MCA process concerns the identification and definition of the criteria that are used in the MCA. In this section the criteria that are used in the MCA are presented and a definition is given. Each criterion is divided into several sub-criteria.

5.1 Time

Time represents the time that is necessary to travel from A to B. The sub-criteria that make up the total time are: accessibility time and travel time.

5.1.1 Accessibility time

This is the time that is needed to access a road. If there are a lot of access points to the road this accessibility time is low. Complicated access point due to railway crossings, stop signs and traffic lights have a negative influence on the accessibility time.

5.1.2 Travel time

The travel time is a combination of the time spent actually moving and the extra time due to delays. The potential number of stops and the maximum allowed speed influences the travel time

5.2 Costs

This criterion concerns costs that the user of the road experiences due to usage of the road. This criterion is subdivided into 3 sub criteria: fuel costs, operational costs and toll fee.

5.2.1 Fuel costs

Fuel costs are the costs that are made because of fuel usage. The fuel usage is based on the amount of stops. This is done because San Pedro de la Paz is an urban area with a lot of stops. The fuel usage of a vehicle is also the largest in the accelerating phase after a stop.

5.2.2 Operational costs

The operational costs are costs that are related to the usage of a vehicle. An example is the wearing down of brakes and tires. This is also directly related to the number of stops.

5.2.3 Toll fee

To make use of a private road a toll fee has to be paid. If as user decides to use a private road, this toll fee has to be added to the costs.

5.3 Environmental impact

The environmental impact is the impact of the different solutions on the area they intersect. The environmental impact is divided into three sub-criteria: ecological impact, river hydrodynamics and tsunami inundation.

5.3.1 Ecological impact

The ecological impact concerns the impact of a solution on the flora and fauna in that area. Due to the construction of a road the habitat of flora and fauna can get lost. A road can also form a barrier in an area, preventing animals to travel from one place to another.

5.3.2 River hydrodynamics

Some of the solutions can possibly influence the hydrodynamics of the river. This influence can both be positive and negative. The solution could function as a road and simultaneously as a flood barrier

for example. It is also possible that the road can increase the chance on flooding by acting as a bottleneck for example.

5.3.3 Tsunami Inundation

Some of the solutions can potentially influence the inundation caused by tsunamis. This influence can both be positive and negative.

5.4 Social impact

The social impact is the effect that a particular solution has on the inhabitants of the area that the solution runs through or runs along. The social impact is made up by two sub criteria, these are: evacuation routes and zone disturbance.

5.4.1 Evacuation routes

This section analyses the possible impact of a particular solution on the evacuation routes. In case of a tsunami or a river flooding inhabitants have to flee to certain higher places in the vicinity to be safe. In some cases a proposed solutions can have a negative impact regarding evacuation routes, if it for instance, forms a barrier. The impact can also be positive, if the density on the road decreases, or crossings improve, it becomes easier to access the road.

5.4.2 Zone disturbance

This section focuses on the zones that the proposed solutions intersect. Constructing a road through an urban area might be harmful to the people living in that area. The road can become an inconvenience due to noise or pollution from the road or it can ruin the view people have. Constructing a road through the wetlands or the farmlands might be harmful to the natural environment due to air pollution or disturbance in ecological systems for example.

5.5 Safety

This criterion treats the safety of the different solutions. This is done by looking into the following five sub criteria:

5.5.1 Complexity

The sub criterion complexity concerns the different transportation modes that use the road and their influence on the complexity of the crossings.

5.5.2 Signposting

The sub criterion signposting concerns the presence and effects of signs on the road. To prevent chaos signs are necessary. If there are no signs the users have to start to think for them self and have to be very alert or they will miss the exit. This leaves less attention to focus on the road and other users, which can lead to unsafe situations.

5.5.3 Speeding

The sub criterion speeding concerns the possibility for users to drive at high speeds due to a lack of interventions like crossings, intersections, stop signs etc. Too much speeding can lead to accidents.

5.5.4 Area

The sub criterion area concerns the areas that a solution intersects. If a solution for examples runs through a dangerous neighbourhood it can cause unsafe situations for the road users.

5.6 Comfort

This criterion revolves around the comfort the users of a road experience while driving this road. The comfort analysis revolves around four sub criteria, these are: drivability, bike lanes, bus stops and surroundings.

5.6.1 Drivability

The drivability is the possibility to make a trip on a road without too many disturbances. Disturbances can be stops due to traffic lights or pedestrian crossings for example. But also the reduction in speed because of the presence of trucks and busses can be seen as a disturbance. The more disturbances on a road the less drivable the road becomes. This reduces the comfort that the users experience.

5.6.2 Bike lanes

The availability of bike lanes next to a road increases the comfort the users experience from a road. It gives the people an alternative to public transport or the car. It is important that the bike lane is safe and provides a decent connection to other bike lanes. The user should be able to reach his destination by bike without any dangerous crossing with other transportation modes.

5.6.3 Bus stops

The presence of bus stops in a solution also increases the comfort for the users. It presents the people with an alternative for using their car. It is important that the distance to the bus stops is not too large.

5.6.4 Surroundings

This sub criterion concerns the location of the solution. Roads can for example run along a coastal area or the river. Roads like this offer a comfortable ride with nice views to the users. A road through a busy city centre will offer far less attractive surroundings. Causing a less comfortable experience for the user.

5.7 Co-benefits

Another important criterion that is used to test the variants is the so-called co-benefit. A co-benefit is defined as an extra benefit that can be gained from constructing a solution. What this means is that the variant solves another problem besides the infrastructural problem at hand in San Pedro de la Paz.

6 Conclusion

From part I it can be concluded that there are several problems that cause the traffic congestion on Ruta 160. To gain insight into the effect of the different proposed solutions and variants on the congestion of Ruta 160, a MCA is done in part IV. The criteria that are used in this MCA are presented in Part I. To be able to score the proposed solutions in the MCA an analysis of the solutions is required regarding the different criteria. The analysis of the criterion river hydrodynamics is done part II. The criterion tsunami inundation is analysed in part III. The analysis of the other criteria is done in part IV.

7 Recommendations

Based on the discussion of the results the recommendations are listed below.

- The analysis done in Part I is solely qualitative. Meaning that no quantitative data is used about traffic flows and density. Also not available were origin-destination studies. To improve the analysis and gain a better understanding of the problem this data should be taken into consideration. This will provide the analysis besides the qualitative basis also with quantitative data. In this way the analysis becomes more detailed and reliable.
- Due to the limited time span the research team has, not all proposed solutions that are researched by SECTRA in (SECTRA, Mejoramiento interconexión vial, San Pedro de la Paz. , 2013) are taking into consideration in the analysis presented in this report. The amount of proposed solutions is cut down to 7 in total, from which 6 are researched by SECTRA and 1 alternative solution proposed by the team.
- To gain a better insight into the density and the direction of the flows traffic models should be used.
- In the process of creating the variants some constraints and demand were made. These constraints and demand were set up using assumptions from the research team. But to be able to create even better variants these constraints and demands should be researched more and elaborated on by experts.

Part II

River Analysis

1 Introduction

The focus of this second part of the report is the impact of the new infrastructure developments on the inland water systems of San Pedro de la Paz. These systems consist of the Biobío River, the Estero Los Batros, the wetlands of Los Batros and the two lagoons (Laguna Grande and Laguna Chica) that are connected to them. The road variants that may influence this system are Costanera Sur and Ruta Humedal, as described in Part I of this report.

Part II of the study starts with a problem definition for the River Analysis in chapter 2. In chapter three the goals of the analysis are stated. In the analysis two existing river models are used, which are described in chapter four. The changes that are made to the models are listed in chapter five. Hydraulic data that is used as input for the two models is described in chapter six. Then the process of the model calibration is explained in chapter seven. In chapter eight the model results are given and explained. Finally chapter nine presents the conclusions in relation to the goals of the River Analysis and recommendations are made.

2 Problem definition

Chapter two describes the elements that are studied in this part of the study. Also the infrastructural variants that affect the river system are explained.

2.1 Description of the study area

Figure II - 1 shows an overview of the study area and the relevant water bodies. The Biobío River is the northern limit of the city of San Pedro de la Paz. It is one of the largest rivers in Chile, with a catchment area of 24,264 km² and average discharges of 200 m³/s to 2000 m³/s (at the river mouth) depending on the season (Ministerio de Obras Públicas)



Figure II - 1: Plan view of important locations.

The sediment transported by the river is medium to coarse sand (González, 2013). There is an elongated and very dynamic sand bar that blocks part of the river mouth and a big bar with dense vegetation that is rarely flooded and characterizes the southern bank of the river at San Pedro. Four bridges cross the Biobío between San Pedro and Concepción, three road bridges (Juan Pablo II, Llacolén and Chacabuco; from east to west) and a railroad bridge (Puente Ferroviario).

The other relevant system is the combination of the lagoons of San Pedro (Laguna Grande and Laguna Chica) with the wetlands and stream of Los Batros. Both lagoons are interconnected with a pipeline (Baecheler, Romero Bravo, & Alcayaga Saldias, 2007) and collect the rainfall run-off from the hills at the center of the Comuna. Laguna Grande discharges to the wetlands of Los Batros through a natural weir when the water level of the lagoon increases.

Los Batros connects the lagoon system with the Biobío River through approximately 4.3 km of stream, the so-called Estero Los Batros. Throughout this distance, the stream also collects water from the urban drainage system of San Pedro and from rainfall run-off. The terrain is really flat and the average slope of the streambed is only 0.6‰ which, combined with the presence of vegetation in the floodplains leads to very small flow velocities and the category of wetlands area. Because of these characteristics Los Batros has developed a rich ecosystem.

Ruta 160 crosses Los Batros with narrow bridges (three road bridges and a railroad bridge) and restrains the flow of the Estero, defining two distinct areas. Between Ruta 160 and Laguna Grande the bed slope is 0.4‰ and the flow is spread over a big surface. From Ruta 160 to the mouth at the Biobío the stream was deepened and fixed to a width of 30 m after the flood of 2006, for which the streambed slope increased to 0.8‰ (Baecheler, Romero Bravo, & Alcayaga Saldias, 2007)

The concentration time of this system (lagoons and wetlands) is very short, and strong rainfall events are followed by a rapid increase in discharge. The new urban developments in the catchment area of the lagoons have also reduced the water retention capacity of the land and this combination has caused several floods in the recent past.

2.2 New infrastructure that can affect the water systems

The road variants that may influence the hydraulic systems defined in the previous section are Costanera Sur and Ruta Humedal. Costanera Sur is the road located on the southern bank of the Biobío River, connecting the road bridges with the future Costanera Mar. This road also crosses the mouth of Los Batros and will eventually be connected with the new Puente Industrial across the Biobío. The preliminary design of Costanera Sur considers occupying approximately 30m of the southern riverbank, which may alter the hydrodynamic behaviour of the river.

Ruta Humedal connects the future Puente Industrial with Ruta 160 through Los Batros. It is positioned in the middle of the wetlands and also crosses the Estero near the mouth of the stream. The road will be built on embankments except for the crossing of the Estero and the connection to Ruta 160 that will be built on piles.

3 Goals

The following aspects are the goals of part II of the study:

1. Create an inundation map of the present situation (year 2015) for 100 years return period (of both the Biobío and Los Batros discharge).
2. Assess the impact of Costanera Sur on the hydraulic behaviour of the Biobío River.
3. Assess the effect of Costanera Sur on flood prevention.
4. Assess the impact of Puente Industrial on the hydraulic behaviour of the Biobío River.
5. Assess the impact of Ruta Humedal on the hydraulic behaviour of Los Batros.
6. Assess the effect of Ruta Humedal on the flooded area for extreme scenarios.

4 Existing models

In order to predict the behaviour of the river and the wetlands under the different circumstances described in the goals section, some numerical models need to be developed. During the past years, and especially after the big floods of 2006, there has already been a significant effort to develop such numerical models. In particular, 1D models for both the Biobío River and Los Batros were available and are used as starting point for the present study.

Both models are made with the freely available software HEC-RAS, developed by the US Army Corps of Engineers. For convenience the same software (in its version 4.1) will be used in this project. An overview of the extension of both models is depicted in Figure II - 2, which shows all the cross-sections that are used for the computations.

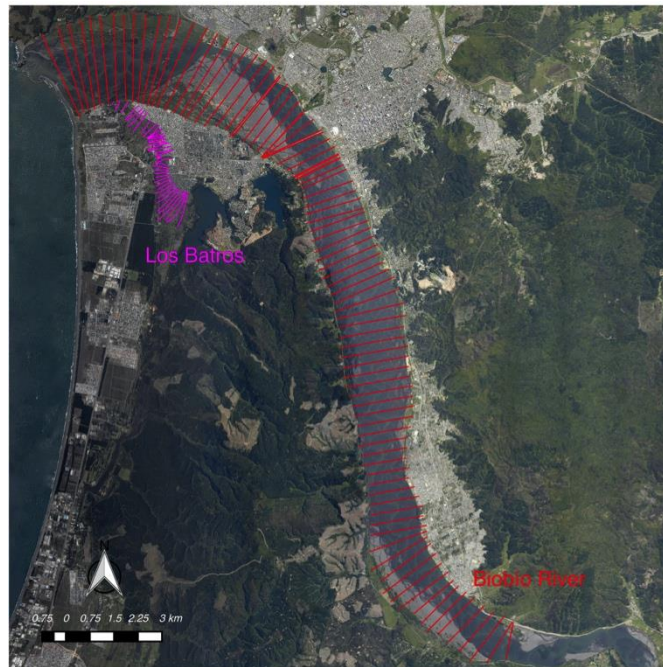


Figure II - 2: Overview of cross-sections for both models.

4.1 Model of the Biobío River

The 1D HEC-RAS model of the Biobío River was made by a previous group of students from Delft University of Technology in 2012 (Weller, van Heemst, van Verseveld, & Willems, 2012).

The extents of the model are the lowest 26.5 km of the river, from Chiguayante to the river mouth. The width of the river decreases in upstream direction with a maximum width of 2800 m at the mouth and 1100 m at Chiguayante.

The modelled section of the river includes two bends. The anticlockwise bend at the lower 5 km from the mouth, between the cities of Concepción and San Pedro de la Paz, is a sharp bend and has a clear distinction between channel and flood plains. At the flood plains extensive vegetation is present, which influences the roughness of the bed and is therefore important for the inundation analysis.

The bathymetry data for the model originates from measurements by private contractors, commissioned by the Chilean Ministry of Public Works (MOP). The lower 11 km of the river were surveyed in 2010 and the remaining 15 km in 2012. The model consists of 92 cross-sections in total.

The model also includes 4 bridges: Puente Juan Pablo II between cross-sections 23 and 24; Puente Ferroviario between cross-section 28 and 29; Puente Llacolén between cross-sections 31 and 32 and Puente Viejo between cross-sections 37 and 38. This last bridge collapsed during the earthquake in 2010 and is now replaced by Puente Chacabuco and the provisional Puente Mecano.

This HEC-RAS model was calibrated using rating curves from the DGA gauging station named “Biobío desembocadura”.

4.2 Model of the Estero Los Batros

The model for Los Batros was developed by Centro EULA (Baecheler, Romero Bravo, & Alcayaga Saldias, 2007) in 2007 to assess the impact of the expansion of the Bayona District, which was finally build in 2008. The topography data is based on multiple surveys made before 2007. In 2006 the channel of the reach downstream of the Ruta 160 bridge was dredged and it is also reflected in the topography used.

The model consists of 43 cross-sections, from the outflow of Laguna Grande to the mouth of the Estero at the Biobío River. Most of the cross-sections extend horizontally until a height of 5 m above sea level at both sides. This makes a total stream length of 4.3 km and a surface area of 2.5 km².

5 Changes to existing models

The existing models of the Biobío River and Los Batros described in Chapter 4 are updated to the current situation. To analyse the effects of the proposed new roads; Costanera Sur, Puente Industrial and Ruta Humedal are added. These changes are described in this chapter.

5.1 Georeferencing

To analyse the results of the models a precision LiDAR digital elevation model (DEM) was provided by Eng. R. Aránguiz. Aerial orthophotos of the region were also obtained from SEREMI MINVU. Both of them are georeferenced using the datum WGS84 and projected in UTM 18S coordinates (the standard in the region). In order to properly work with such information a GIS software is required. The freely available and open-source software QGIS is chosen.

Because of the availability of such georeferenced information it is very useful to also have the hydraulic models georeferenced in the same reference system. For Los Batros, the HEC-RAS model is already geolocated using UTM 18S coordinates and the cross-sections can be exported to QGIS directly. However, the model for the Biobío River is not georeferenced. Different information is available for the bathymetric profiles used in the model since they were produced in different years (see Chapter 4.1). In both cases the cross-sections are drawn in a CAD file using a local reference system.

Biobío model, 2010 bathymetry

For this case, no information regarding the local coordinate system is provided. The cross-sections are exported from the AutoCAD file to QGIS and are manually adjusted to fit the aerial picture. The cross-sections are first scaled so that their length is the same as in the HEC-RAS model. They are then moved and slightly rotated. The 4 bridges are used as reference to fit all the cross-sections to the aerial picture.

Biobío model, 2012 bathymetry

For the 2012 bathymetry several Local Coordinate Systems (PTL for its acronym in Spanish) are provided, with their respective locations in UTM coordinates. Different profiles refer to different PTL stations (physical points in the ground with known coordinates), but there is no information on which PTL corresponded to which profile. For this reason the PTL CC8 (the one located more to the south) is used to geolocate profiles 92 to 57 and the PTL CC3 is used for profiles 56 to 45. Using these two PTL's the cross-sections fit correctly to the aerial picture used as background.

However, the last cross-section of the 2012 bathymetry intersected the first one from 2010. For consistency of the algorithm HEC-RAS requires all the cross-sections to not intersect with each other. A few meters of error in the precise location of the cross-sections is negligible on the scale of the river and for this reason sections 46 and 45 were slightly rotated manually.

5.2 Vegetation

During the last years vegetation has grown at the southern bank of the Biobío River, especially west of Puente Juan Pablo II as indicated in Figure II - 3. Nowadays a significant part of this vegetation can be considered as permanent and will not be washed out in case of flooding of the riverbank. This aspect was not considered in the original HEC-RAS model (from 2012) and is now implemented.



Figure II - 3: Area with increased vegetation. Image from Google Earth.

The most recent aerial images available in Google Earth (29/06/2015), Figure II - 3, have been used to estimate the area covered by this vegetation. Images from the LANDSAT 8 satellite, captured on 31/08/2015 (high water) and 11/05/2015 (low water) are also useful because the sensors on this satellite capture different infrared wavelengths as well as visible light. Since vegetation reflects infrared light it is possible to identify from these images where vegetation is denser in the riverbank (reflected infrared light is shown as red in Figure II - 4).



Figure II - 4: False colour satellite images of the mouth of the Biobío River. Dense vegetation (high infrared light reflection) is depicted in bright red. Images from LANDSAT 8 captured a) on the 31/08/2015 and b) on the 11/05/2015.

In the HEC-RAS model, part of the cross-sections from 10 to 24 contain permanent vegetation and are assigned a default manning coefficient of $n=0.04$. The uncertainty related to this coefficient is discussed in Paragraph 7.1 with a sensitivity analysis.

5.3 Puente Chacabuco

The original HEC-RAS model of the Biobío River includes Puente Viejo. This bridge collapsed during the 2010 earthquake and all the other road bridges were damaged as well. To replace Puente Viejo a new bridge was planned; the twin Puente Chacabuco consisting of two identical and parallel bridges with two lanes each. However, the construction of the new bridges would take too long and a

temporary steel bridge was built; Puente Mecano. This small bridge is constructed on pile foundations that will be the permanent foundations for one of the Chacabuco bridges, the upstream one. Right now the downstream bridge is finished (Figure II - 5) and the next step will be to replace Puente Mecano for the definitive bridge.

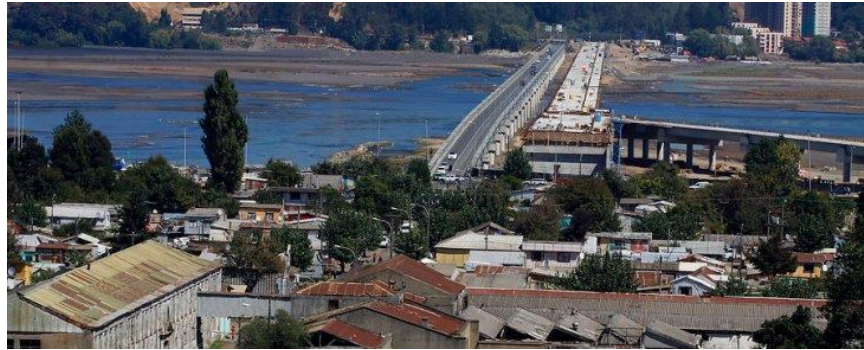


Figure II - 5: Picture of Puente Mecano (left) and the downstream Puente Chacabuco under construction(right) from the north bank of the Biobío River. Image credit: Victor Salazar, biobiochile.cl (Biobio)

In order to analyse the river for the current situation, Puente Viejo (located between cross-sections 37 and 38) is removed and Puente Chacabuco is added to the Biobío model between cross-sections 35 and 36.

Because both bridges are located very close to each other they are introduced in the model as a single, hydraulically-equivalent bridge. Puente Chacabuco is modelled with a length of 1,550 m, the bottom of the bridge deck at a height of 10.0 m and the top at 10.7 m with respect to the reference level. Both bridges have 33 groups of piers with a spacing of 39.8 m. Each pier consists of 3 cylindrical piles of 1.2 m diameter joined together with a 1.4 m thick beam at the upper 2 m. Since the piers of both bridges are aligned area is not decreased. For the abutment of the bridge the same dimensions as for Puente Mecano are used, which are estimated using satellite imagery from Google Earth.

5.4 Costanera Sur

From the different alternatives considered in this project, the most important impact on the river, from a hydraulic point of view, will be the construction of the road Costanera Sur along the San Pedro de la Paz riverbank.

The available information for this riverside road mostly comes from (CIPRES Ingeniera, 2013). The Costanera Sur project is considered in the first phase of that study (preliminary alternatives analysis), but is not studied in more detail in the second phase (project draft and economic evaluation). For this reason the Costanera Sur route is only described as a preliminary design, which contains a general description of the road, its cross-section, a plan-view design and the solutions proposed for crossings with existing roads and bridges. However, an elevation profile is not provided and has been estimated, as described in the following sections.

The width of the road is 30.0 m, which includes 4 car lanes, a bike lane and 2 sidewalks. The central axis of the road is imported into QGIS and is used to modify the cross-sections in HEC-RAS.

A similar project (Ministerio de Obras Públicas) constructed in the northern bank of the Biobío has been used to define the slope of the embankments. At the riverside there is a rock revetment with a

slope of 1:2. For the HEC-RAS model a roughness coefficient of $n=0.07$ is assumed for this revetment. If the slope of the terrain at the riverbank is lower than 1:2, the existing topography is maintained.

5.4.1 Bridging rivers and roads

Costanera Sur will cross Puente Juan Pablo II, Puente Ferroviario and Puente Llacolén. The road will be built over the existing bridges according to SECTRA's study. This leads to high elevations with respect to the ground level when the road needs to cross such infrastructures. The top of the asphalt above Puente Juan Pablo II is assumed to be at 15.32 m. This value is derived from the LiDAR data at the bridge location (11.02 m) + 4 m of clearance + 0.3 m for the thickness of Puente Costanera Sur. The top of the asphalt above Puente Ferroviario and Puente Llacolén is assumed to be at 16.26 m. This value is derived from the highest value of the LiDAR data (11.96 m) plus the same additions as for Puente San Pablo II. The connection with Puente Chacabuco is at ground level and. At the mouth of Los Batros, Costanera Sur will be at ground level crossing below Puente Industrial.

According to the study the sloping road close to the bridges is built on an embankment that is enclosed by vertical walls.

5.4.2 Height profile

In order to implement Costanera Sur in the HEC-RAS model of the Biobío River, height information is needed. Since there is no information available for this an estimation has been made. Terrain elevation is extracted from the LiDAR data along the road axis. Since the topography in the cross-section of the road is highly variable two height profiles are made, one on the northern boundary (riverside) and one on the southern boundary (landside) of the road. These profiles function as a base for the estimation of the height of Costanera Sur since the road will be built as much as possible at the existing ground level. A design rule, as found in (Ministerio de Obras Públicas) is that the minimum elevation of the embankment is of 1 m above the maximum water level for a return period of 100 years. This water level is approximated by the flood event in 2006. In the estimation of the longitudinal elevation profile the maximum slope for the road is taken as 2%. With these boundary conditions and the assumed heights of the road at the cross overs, a height profile for Costanera Sur is made. The Costanera Sur height profile is depicted in Figure II - 6.

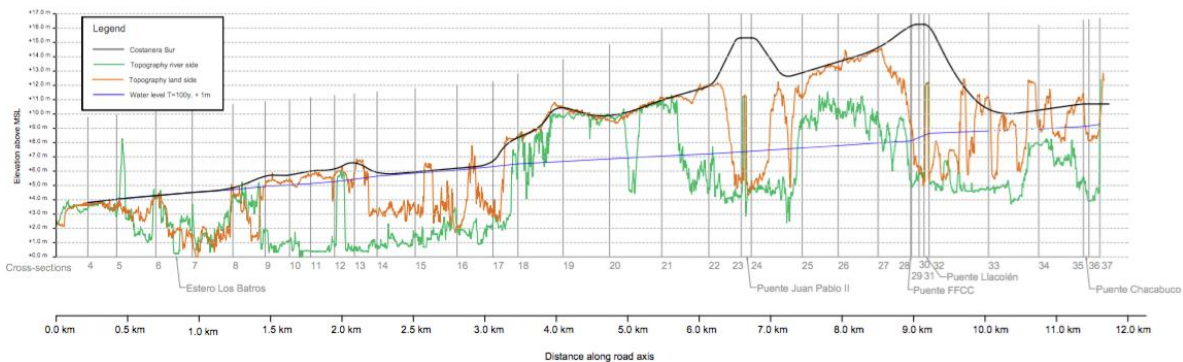


Figure II - 6: Assumed height profile of Costanera Sur.

In Figure II - 7 an example of an updated cross-section in HEC-RAS is depicted.

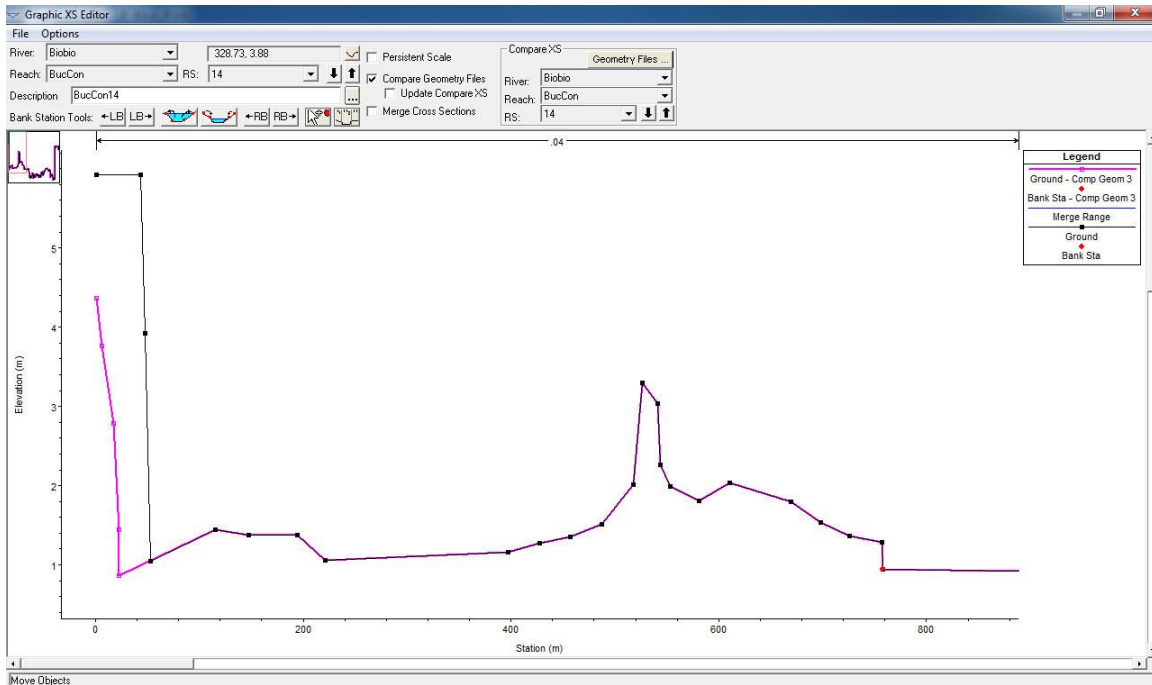


Figure II - 7: Cross-section with original situation and Costanera Sur profile in HEC-RAS.

5.5 Puente Industrial

Puente Industrial is a bridge that will be built in the next coming years. The bridge will connect San Pedro de la Paz with Hualpén. Its piles will have an effect on the water flow in the Biobío River as well as on the wetlands, since Ruta Humedal (the connection between the bridge and Ruta 160) will be built there.

5.5.1 Bridge

Puente Industrial is modelled in between cross-sections 9 and 10. The bottom of the bridge deck is taken at 9.5 m and the top at 10.7 m. According to information by the contractor that will build the bridge (Un Puente Una Poblacion y la Ciudad de Concepcion), the length is 2,520 m. This however would lead to an embankment crossing the floodplain on the northern side of the river, which is a non-desirable situation from the hydraulic point of view. Since different parties present different information on this aspect, the bridge will be modelled with piers on the entire flood plain. The bridge will be built on 64 piers that will have a diameter of 2.5 m and a spacing of 45 m. Since cross-sections in HEC-RAS have to be perpendicular to the flow and the bridge has to be located between two cross-sections, the bridge is rotated in the model. In order for the resistance on the flow due to the piers to be equal to the situation with the normal bridge position, the same number of piers is used but with a smaller spacing. The bridge is rotated over an angle of 19.4 degrees; this leads to a spacing of 42.4 m and a total length of 1,792 m (within the boundaries of the cross-section). The embankments of the bridge are located outside of the cross-sections.

5.5.2 Ruta Humedal

Ruta Humedal, that functions as a connection between Puente Industrial and Ruta 160, will be built through the wetlands. The road crosses over Ruta 160, Estero Los Batros and Costanera Sur. It is built on an embankment from the southern end to the crossing of Estero Los Batros. From there up to its connection with Puente Industrial the road is built on piles so that Estero Los Batros remains

connected to the Biobío River. This connection is depicted in Figure II - 8. In this figure the roads, bridges and embankment are shown.



Figure II - 8: Detailed view of connection between Costanera Sur, Puente Industrial and Ruta Humedal

Similar to Costanera Sur, the location of Ruta Humedal is known but not its elevation profile. Again this information has to be estimated. The height at the northern end of the road is the same as the level of the top of Puente Industrial deck, 10.7 m. From there a drop in height is assumed, crossing Estero Los Batros, until the beginning of the embankment. According to the study by SECTRA an embankment height of 3.6 m above ground can be assumed, with lateral slopes of 1:2. Using the LiDAR topography data the longitudinal elevation profile of the road is determined. The road is assumed to have a constant slope until the ramp to cross Ruta 160. The southern end of the road, at the crossover of Ruta 160, is estimated at 9.0 m. This value is derived from the height of Ruta 160 (4.7 m) + a clearance of 4 m between the road and the bottom of the bridge deck + a deck height of 0.3 m.

The road height increases at the start of the embankment (after crossing Estero Los Batros) from 4.9 to 6.3 m over a length of 1,416 m. Then, to meet the level of the bridge over Ruta 160, it rises from 6.3 to 9.0 m over a length of 52 m.

With this information a scheme of the elevation profile of Ruta Humedal is made, see Figure II - 9. This road profile is then used to update the cross-sections of the Los Batros model. The part of the road that is built on piles is not included into the model since it will have a negligible effect on the flow in Estero Los Batros.

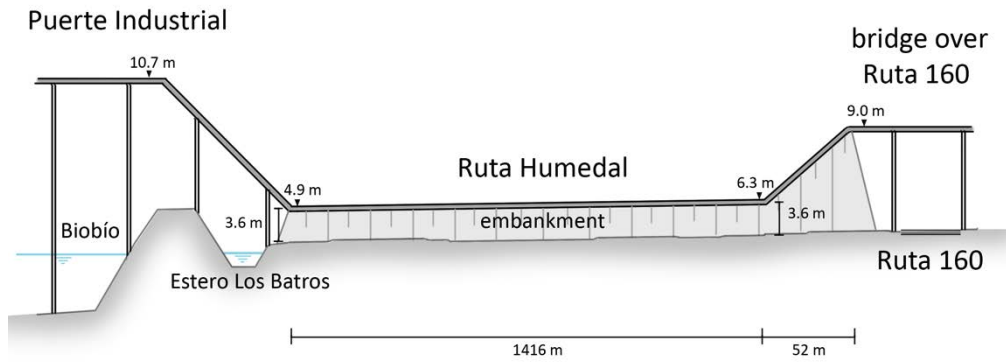


Figure II - 9: Sketch of the Ruta Humedal profile (not on scale).

5.5.3 Mouth of Estero Los Batros

The mouth of Estero Los Batros will be crossed over by Costanera Sur. According to the study by SECTRA the span of the bridge (70 m) will be much larger than the width of the stream. At this point the flow in Los Batros is not driven by friction but determined by the Biobío River water level. For this reason this bridge does not affect the hydraulic behaviour of the stream and therefore Costanera Sur bridge over the mouth is not taken into account in the model.

6 Hydraulic data

This chapter will describe the hydraulic boundary conditions used in the Biobío and Los Batros models.

6.1 Biobío model

The 1D Biobío model uses one upstream boundary condition, a known discharge, and one downstream boundary condition, a known water level.

6.1.1 Discharge

The hydraulic design criterion for structures in Chile is an event with a return period of 100 years. As found in this report (Baecheler, Romero Bravo, & Alcayaga Saldias, 2007), the value for the discharge with a return period of 100 years is 19,028.40 m³/s. This value is the result of fitting a Gumbel distribution curve to measurement data from the DGA gauging station “Biobío Desembocadura”. The peak discharge during the 2006 flood event is known from data of the same station, 16,261.28 m³/s. Additionally, a low discharge of 1,500.00 m³/s is used for low water conditions, which corresponds to a return period of approximately 1 year.

6.1.2 Sea level

For the sea level, tidal elevation and wind setup are used. The values are taken from (Weller, van Heemst, van Verseveld, & Willems, 2012). Tidal elevations are only measured in Talcahuano (10 km North of the Biobío mouth) and Coronel (20 km South). The Talcahuano data is used since it is closer to the project area. The highest astronomical tide is 1.09 m + MSL. The set-up of the water level due to a storm surge is about 0.50 m for a storm with a return period of 100 years. The design water level that is used as a boundary condition for the Biobío model is therefore 1.59 m. This value is on the safe side since the chance of a storm and river discharge both with a return period of 100 years and high tide is small.

6.2 Los Batros model

Los Batros model uses as downstream boundary condition the water level of the Biobío at the Estero Los Batros mouth. It uses multiple discharge boundary conditions in the form of inflows along the stream. Also, different combinations of values of the boundary conditions are used in order to analyse the effects of different scenarios.

6.2.1 Discharges

In a hydrologic and hydraulic study (Baecheler, Romero Bravo, & Alcayaga Saldias, 2007), the run-off of rainwater into the Los Batros wetlands has been defined. These results are already incorporated into the model. They are discharges for specific return periods at specific locations along the stream. For this study the discharges with return periods of 2 and 100 years are used, so that the minimum and maximum known discharges are taken into account.

An overview of the different discharges per location in Los Batros can be found in Appendix II-A.

6.2.2 Biobío water level

The water level of the Biobío River at the location of the Los Batros mouth functions as a boundary condition for Los Batros model. The output of the Biobío model is therefore input for Los Batros model. The used water levels are for return periods of 1 and 100 years at cross-section 7 of the Biobío River Model.

6.2.3 Combinations

Since the water level of the Biobío is input for the Los Batros model, many different combinations of boundary conditions can occur. Since floods and the effect of the proposed infrastructure on floods are a central aspect of this chapter, the following scenarios are studied:

Table II - 1: Combinations of return periods of Los Batros and Biobío discharges

| Scenario | T_{Los Batros} [yr] | T_{Biobío} [yr] |
|-----------------|------------------------------------|--------------------------------|
| I | 2 | 100 |
| II | 100 | 100 |
| III | 100 | 1 |

With these scenarios the effects of high and low discharge (and thus water level) of the Biobío River and high and low rainfall run-off in Los Batros can be studied.

7 Calibration

In this chapter the calibration processes of the Biobío and Los Batros model are described.

7.1 Biobío model

In the time frame of this project it has not been possible to obtain measurements from the river to properly calibrate the model of the Biobío River. The information that is available from the flood event in 2006 cannot be used to calibrate the model for the present situation because of the increase in vegetation (see paragraph 5.2) and the replacement of the Puente Viejo by the new Puente Chacabuco since that event. Instead a sensitivity analysis is performed. This sensitivity analysis focuses on the effect of the roughness coefficient for vegetation on the riverbank west of Puente Juan Pablo II, as depicted in Figure II - 10.

Since the model is 1D the entire width of the riverbanks at each cross-section is modelled with one averaged value for the Manning coefficient. The value of the coefficient for vegetation originally used in the model is $n=0.04$, and for the sensitivity analysis it has been increased and lowered by 5% and 12.5%, giving the values of 0.035, 0.038, 0.042 and 0.045.



Figure II - 10: Plan view of vegetation on riverbank near Biobío mouth. Background image from Google Earth.

The maximum Biobío discharge during the flood in 2006 was $16,261.28 \text{ m}^3/\text{s}$, as measured by the DGA gauging station "Biobío de Desembocadura". To account for the uncertainty in the measurement results two additional discharges are considered; a lower discharge of $16,000 \text{ m}^3/\text{s}$ and a higher discharge of $16,500 \text{ m}^3/\text{s}$.

The model is run again for each combination of roughness and discharge and the new water levels are compared with each other.

Figure II - 11 shows the effect of changing the roughness coefficient while maintaining the same discharge. An increase of the roughness coefficient ($n = 0.042$ and $n = 0.045$) causes an increase in water level and vice-versa (for $n = 0.038$ and $n = 0.035$ the water level decreases). It is important to notice how the effect of these changes propagates further upstream from the region where the

coefficient is modified, as can be seen in Figure II - 11 (backwater effect). This is the characteristic behaviour of subcritical flow, as is the case for the Biobío. The magnitude of these changes is of the order of cm with maximums of:

- +0.060 m for $n = 0.045$
- +0.025 m for $n = 0.042$
- -0.023 m for $n = 0.038$
- -0.071 m for $n = 0.035$

For the different discharges the results are the same (variations only on the order of mm), meaning that variations of the water levels due to changes in the Manning coefficient are independent of the discharge for the range of discharges considered in this analysis.

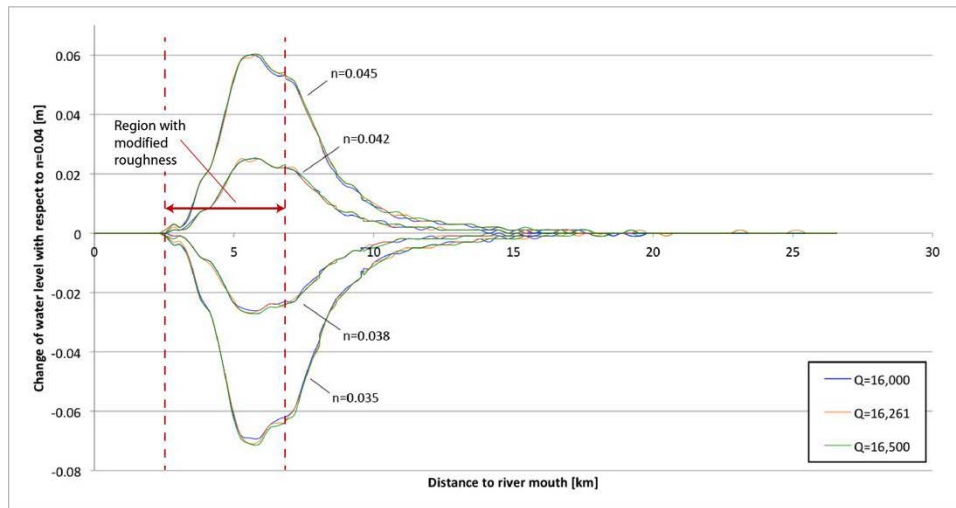


Figure II - 11: Change in water level caused by changes in roughness coefficient. The different combinations of roughness and discharge are compared to the case $n = 0.04$ for the same discharge.

Also the effect of increasing the discharge is studied. For each value of the Manning coefficient, as described above, the discharges are varied. Figure II - 12 compares the water level for the different values of Q with respect to the case $Q = 16,000 \text{ m}^3/\text{s}$. Similar to the previous case, the changes in water level seem independent of the choice of roughness coefficient. An increase of the discharge results in increasing differences in water level for increasing distance to the mouth of the Biobío. This is in line with the expectations since the area near the mouth is dependant on the boundary condition at the river mouth. Further upstream the equilibrium depth is more dependant of the discharge and so the differences in water level are higher there.

The maximum differences in water level are observed at the upstream part of the model (the last 5km). The maximum differences are 0.049 m for $Q = 16,261 \text{ m}^3/\text{s}$ and 0.049 m for $Q = 16,500 \text{ m}^3/\text{s}$ with respect to $Q = 16,000 \text{ m}^3/\text{s}$. This is roughly $\pm 5 \text{ cm}$ deviation if $16,261 \text{ m}^3/\text{s}$ is used as discharge in the model.

However, if only the study area is considered, i.e. San Pedro de la Paz, the differences in water level here reduce to 0.039 m for $Q = 16,261 \text{ m}^3/\text{s}$ and 0.074 for $Q = 16,500 \text{ m}^3/\text{s}$. Again taking into account the study area the water level deviation is about $\pm 4 \text{ cm}$ if $16,261 \text{ m}^3/\text{s}$ is used as discharge in the model.

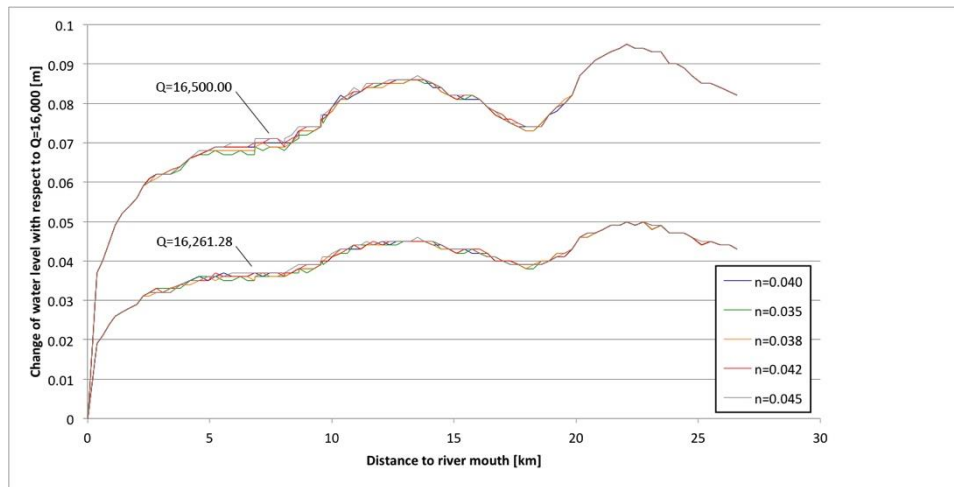


Figure II - 12: Change in water level caused by changes in discharge. The different combinations of roughness and discharge are compared to the case with lower discharge ($Q = 16,000 \text{ m}^3/\text{s}$) and the same roughness coefficient.

Since the effect of both changes, in roughness coefficient and discharge, can be considered independent, the uncertainties can be added together. This gives a final maximum uncertainty of $\pm 0.11 \text{ m}$ in the study area.

Considering that the elevation of Costanera Sur was set to at least +1 m above the maximum water level for the 2006 flood the above uncertainty is reasonable and will not affect the validity of the model.

7.2 Los Batros model

For the calibration of Los Batros model an aerial picture of the Biobío flood in July 2006 is used. The river flood also caused a flood of Los Batros wetlands. The maximum Biobío discharge during the flood was $16,261.28 \text{ m}^3/\text{s}$ and the discharges due to rainfall run-off during this event are estimated to have a return period of 100 years.

The maximum water level in the Biobío at Los Batros mouth was, as calculated with the Biobío model, 3.60 m. The length of the backwater curve in the lower reach is very long and therefore the water surface is very close to horizontal, as can be seen in Figure II - 13 for different water levels in the Biobío River. Because of this the LiDAR data can be used to identify the locations in Los Batros where the topography is lower than 3.60 m and where they are connected to Estero Los Batros. These locations are thus flooded.

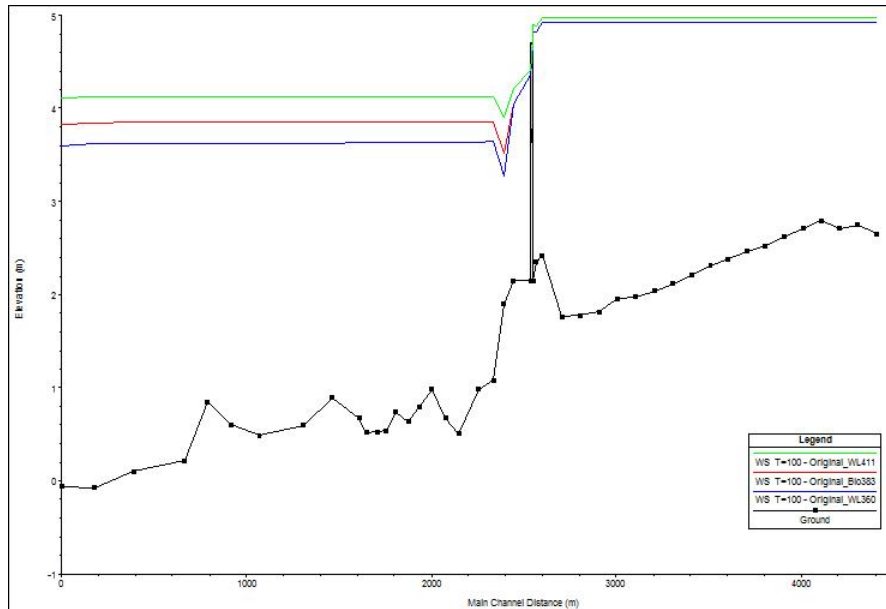


Figure II - 13: Water level profile of Los Batros for the 2006 flood, calculated with HEC-RAS.

The above leads to an inundation map for the 2006 flood, which is compared to the aerial picture of Los Batros. The inundation map and the waterline in the pictures are remarkably similar, so it can be concluded that the lower reach of Los Batros is correctly modelled. For the comparison see the small pictures below. Larger pictures can be found in Appendix II-B.



Figure II - 14: Inundation map from model results (left) and aerial photograph (right) from 2006 flood.

Upstream of Ruta 160 bridge the rainfall run-off is not known precisely for the 2006 flood situation and there is not enough data on the inundation height for that episode. For this reason the model cannot be calibrated in the upstream reach. The flow restriction of Ruta 160 bridge acts as a control point and separates Los Batros in two independent systems, as can be seen in Paragraph 8.1.2. This means that it is not necessary to properly calibrate the upstream reach in order to obtain reliable results for the downstream reach, where Ruta Humedal is located.

8 Results

This chapter describes the results from the Biobío and Los Batros model. With these results the inundation maps are made.

8.1 Model results

The model results are separated in results of the Biobío and the Los Batros models. Only water levels are considered since these are used for the analysis of the effect of the infrastructural changes. Since the models are 1D, local effects (velocity changes, scouring, etc.) of the infrastructural changes cannot be analysed.

8.1.1 Biobío model

As described in Paragraph 6.1 the model is run for two different scenarios, as depicted in Table II - 2. The downstream boundary condition is a water level of 1.59 m in both cases.

Table II - 2: Upstream boundary conditions for the Biobío model.

| Return period [yr] | Discharge [m ³ /s] |
|--------------------|-------------------------------|
| 1 | 1,500.00 |
| 100 | 19,028.40 |

In order to analyse the effects of the infrastructural changes to the river the model is run with 4 different geometries. Those are:

1. Current situation (2015)
2. Current situation + Costanera Sur
3. Current situation + Puente Industrial
4. Current situation + Costanera Sur and Puente Industrial

The resulting water levels for $T = 100$ for these geometries are depicted in Figure II - 15. The differences in geometry cause differences in water level. But as can be seen in the figure the differences are very small.

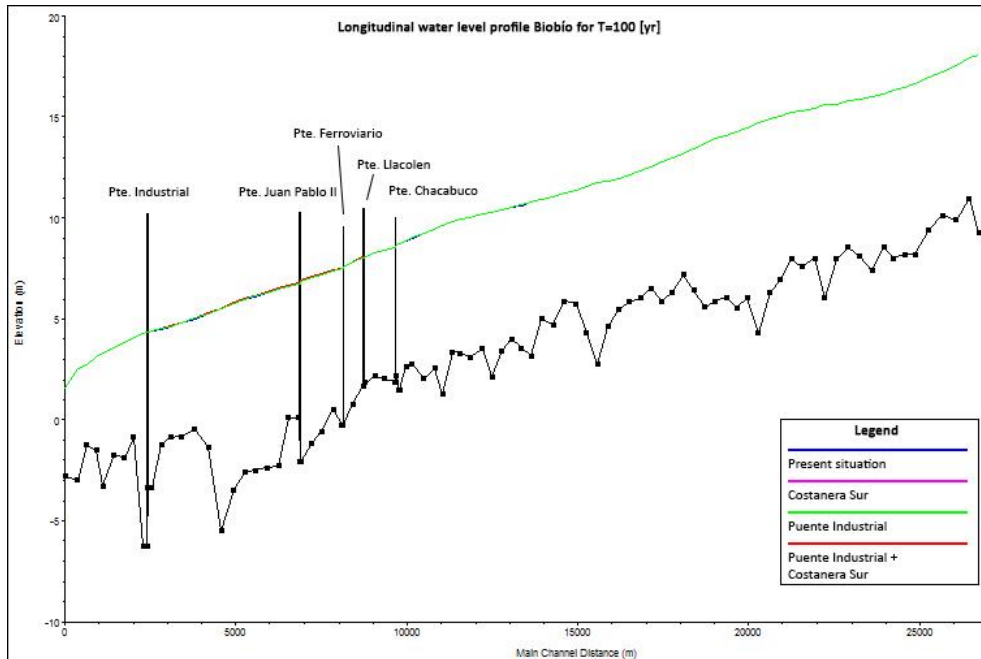


Figure II - 15: Longitudinal water level profile Biobío for T=100 [yr].

Figure II - 16 to Figure II - 18 depict the water level for the respective geometry and the water level of the current situation. The difference between these levels is plotted in green.

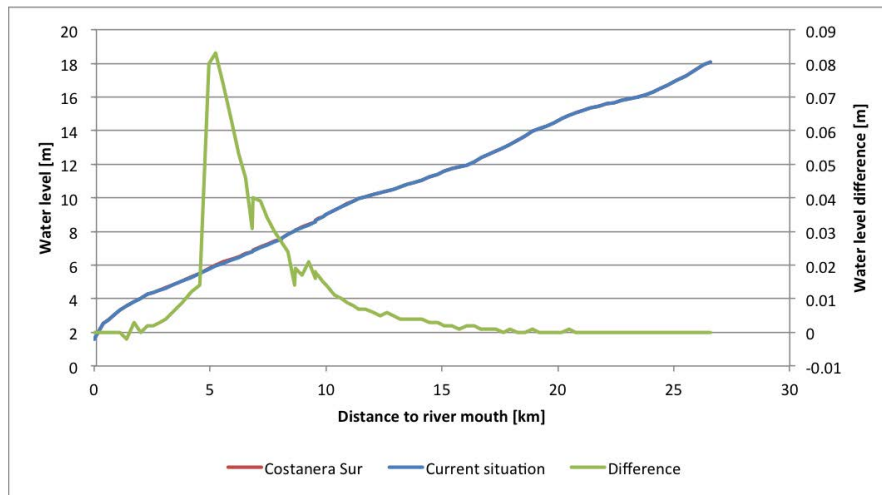


Figure II - 16: Water level changes for the situation with Costanera Sur.

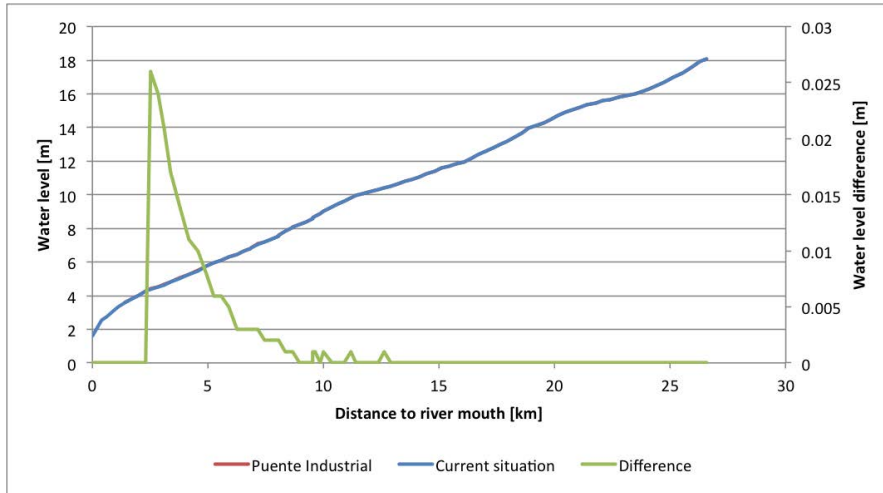


Figure II - 17: Water level changes for the situation with Puente Industrial.

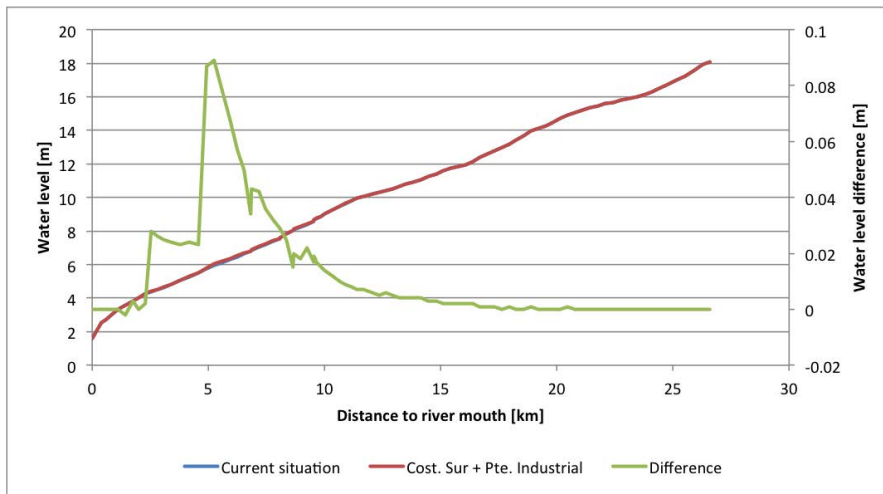


Figure II - 18: Water level changes for the situation with Costanera Sur and Puente Industrial.

As can be seen in the pictures above the water level differences occur upstream of Puente Industrial and along Costanera Sur. The cross-sections where these differences are the largest are located at 100 meter upstream of Puente Industrial (point A at 2534.84 km from the mouth) and 1600 meter downstream of Puente Juan Pablo II (point B at 5235.33 km from the mouth), as indicated in Figure II - 19. The largest differences with respect to the current situation are listed in Table II - 3.

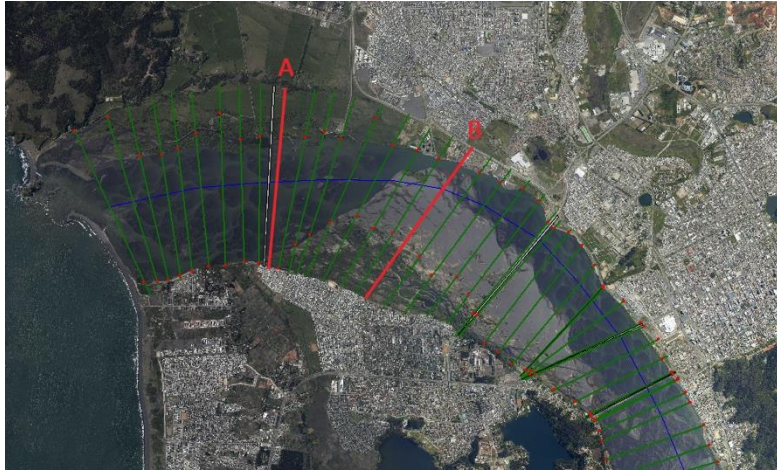


Figure II - 19: Locations with largest difference in water level.

Table II - 3: Differences in water level of the scenarios compared to current situation.

| Point | Water level Current situation [m] | Difference in water level with respect to current situation | | |
|-------|-----------------------------------|---|----------------------------|--|
| | | With Costanera Sur [m] | With Puente Industrial [m] | With Costanera Sur + Puente Industrial [m] |
| A | 4.39 | 0.00 | 0.03 | 0.03 |
| B | 5.94 | 0.09 | 0.01 | 0.09 |

The water level differences in point A occur because of a backwater effect of Puente Industrial. This effect is however negligible. The water level differences at point B are also due to a backwater effect that originates from Costanera Sur. From 2.3 to 5.2 km from the mouth (cross-sections 9 to 18) Costanera Sur is positioned in the flood plain of the river, and thus influences the hydraulics of the Biobío. For an overview see Figure II - 20.



Figure II - 20: Plan view of the part of Costanera Sur that is positioned on the flood plain.

Results summary

Along the entire Southern riverbank of the considered reach of the Biobío the water level is lower than the levee height for the current situation. Since the changes in water level are small for the different scenarios the Biobío will not flood for a discharge with return period of 100 years. This has been checked for each cross-section using the model results and the LiDAR data. Only at the mouth

of the Biobío a small area will be flooded. This will be further elaborated in paragraph 8.2 with the use of flood maps.

8.1.2 Los Batros model

As described in Paragraph 6.2 the model is run for three different scenarios, as depicted in Table II - 4. The water levels of the Biobío for return periods of 1 and 100 years are taken from the Biobío model output, at the cross-section 7.

Table II - 4: Boundary conditions for the Los Batros model.

| Scenario | Upstream | Downstream | |
|----------|------------------------------|--------------------------|--------------------------|
| | $T_{\text{Los Batros}}$ [yr] | $T_{\text{Biobío}}$ [yr] | Water level at mouth [m] |
| I | 2 | 100 | 3.83 |
| II | 100 | 100 | 3.83 |
| III | 100 | 1 | 1.64 |

For all scenarios the differences in water level between the current situation (without Ruta Humedal) and the situation with Ruta Humedal are very small. This can be seen in Figure II - 21 and Figure II - 22, and is explained for each scenario below.

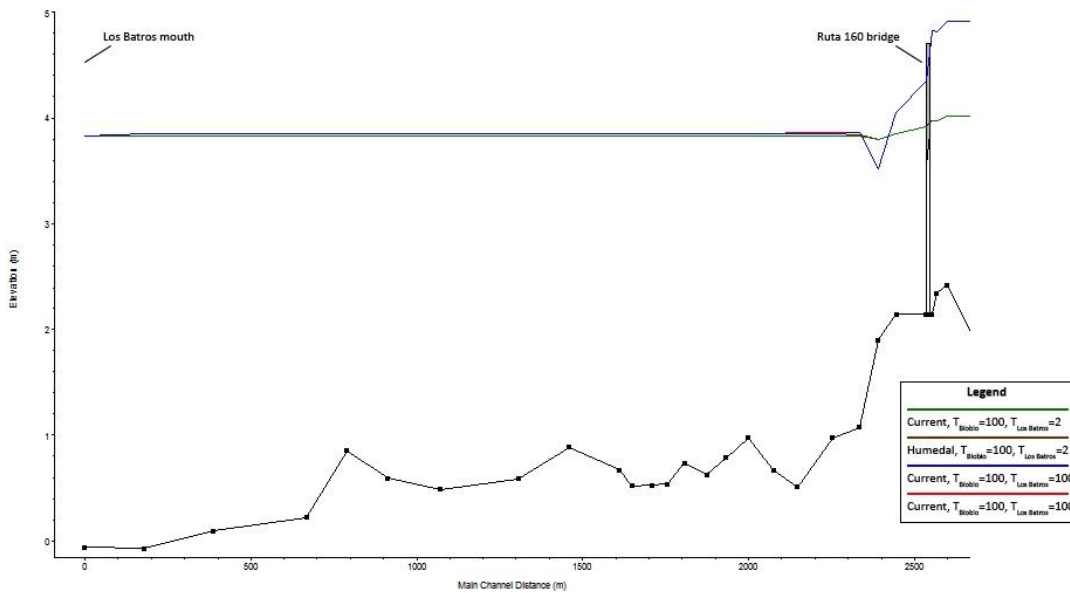


Figure II - 21: Water levels for scenarios I and II for the current situation and Ruta Humedal situation

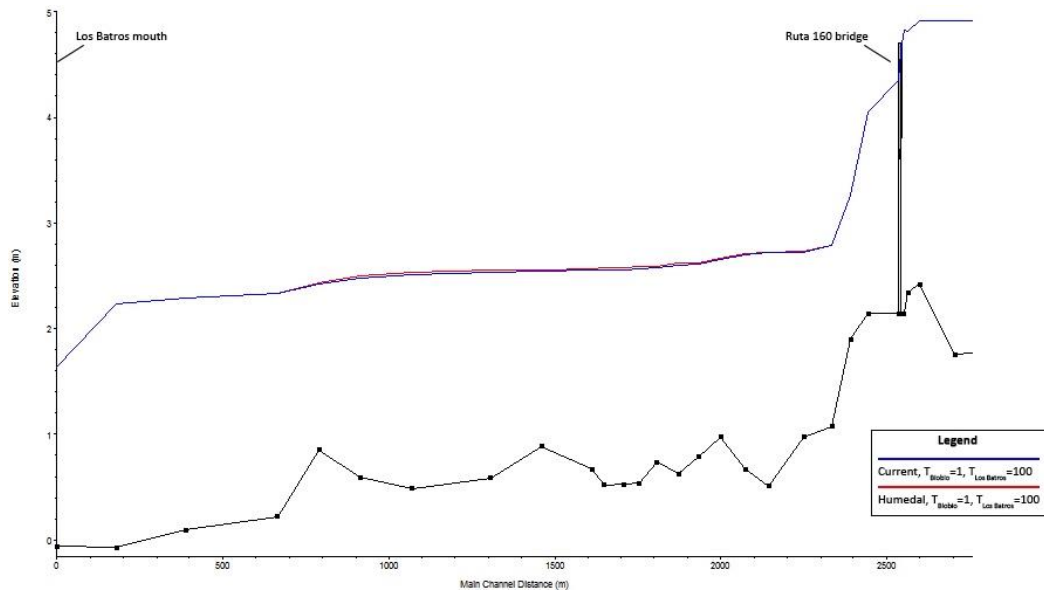


Figure II - 22: Water levels for scenario III for the current and Ruta Humedal situation

Scenario I: Low rainfall in Los Batros and high water level at the Biobío

In this scenario the water level of the Biobío induces a backwater curve in Los Batros that is very close to horizontal. The water level downstream of Ruta 160 bridge is thus equal to the water level in the Biobío. The presence of Ruta Humedal in Los Batros does not make a difference since the water level is mostly dependant on the downstream boundary condition and friction is not dominant any more. The reach upstream of the bridge is in the same way dependant on the control point of the bridge. A value of the water level cannot be given with certainty since this part is not calibrated.

Scenario II: High rainfall in Los Batros and high water level at the Biobío

Scenario II presents the same characteristics as scenario I. The backwater curve in Los Batros is almost horizontal and determined by the water level of the Biobío River. The water level increases in upstream direction with 2 cm compared to scenario I, this is due to the increase in rainfall run-off upstream of Los Batros. Upstream of the Ruta 160 bridge the water level increased around 1 m while staying horizontal compared to scenario I. The bridge functions as a bottleneck for the water in the upstream reach of Los Batros.

Scenario III: High rainfall in Los Batros and low water level at the Biobío

In scenario III the water level is more dependent on friction. The downstream reach of Los Batros does not act as a basin anymore and changes in the topography affects water levels. However, changes in water level between the current and Ruta Humedal situations are very small, with a maximum difference of only 2 cm, as can be seen in Figure II - 22. This is because in this scenario the water only reaches the toe of the Ruta Humedal embankment and the decrease in cross-section volume is therefore very small. Water level is always more than 2.5 meter below the road level of Ruta Humedal, as can be seen in an example of a cross-section in Figure II - 23.

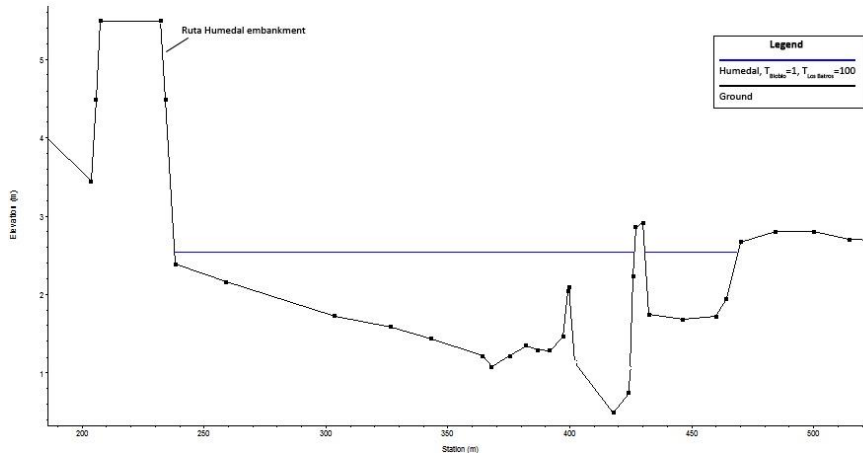


Figure II - 23: Water level for scenario III at cross-section 37

Velocity changes

Ruta Humedal decreases the flow area of Estero Los Batros from about 900 m from the mouth until the end of the Ruta Humedal embankment. This leads to higher flow velocities in this section. The velocity profiles for scenario I and II for the original geometry and the Ruta Humedal situation are depicted in Figure II - 24. The difference is large but the velocities themselves are small. Scour may occur; this should be investigated in a more detailed analysis.

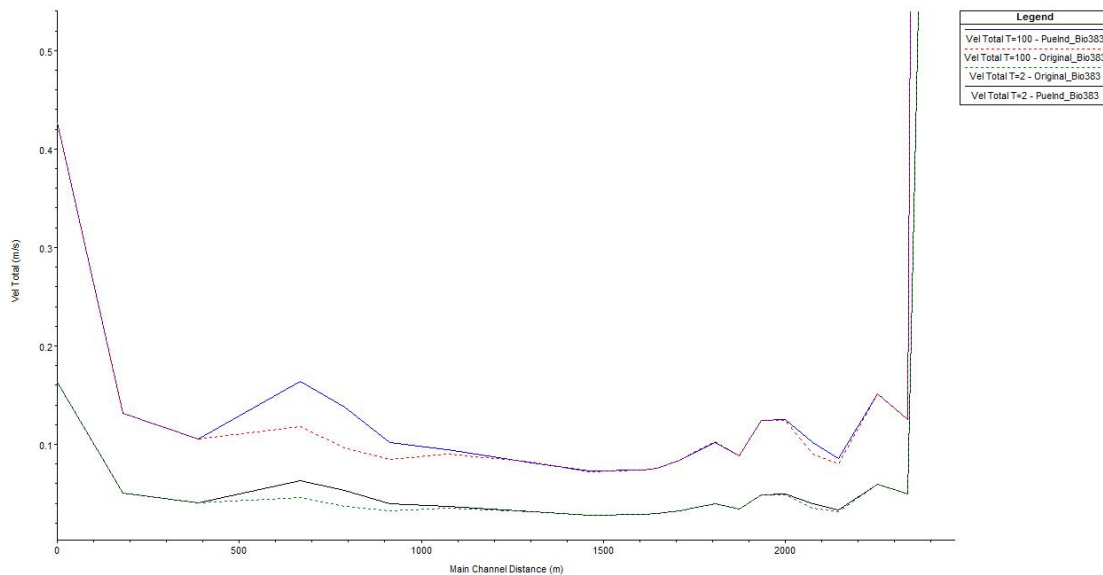


Figure II - 24: Flow velocities in Los Batros for scenarios I and II with original and Ruta Humedal geometry.

Results summary

For scenarios I and II the water level in the downstream reach is at a similar level, regardless of the presence of Ruta Humedal. This level exceeds the boundaries of Los Batros at some places and thus causes floods, this is further elaborated in paragraph 8.2. Upstream of the Ruta 160 bridge floods will occur because of the bottleneck effect of the bridge. Values can however not be given since this part of the model is not calibrated. The water level for Scenario III does not exceed the boundaries of Los Batros and thus does not cause floods.

8.2 Inundation map

The process for determining the inundation maps is described in the first place. Then, the flooded areas are described as well as the effect of Costanera Sur and Ruta Humedal.

8.2.1 Creation of inundation maps

In order to get a good view on the effects of a flood event of the Biobío River an inundation map is made for the 100 years return period scenario for both the Biobío River and Los Batros (Scenario II). Since the Biobío and Los Batros are modelled separately, inundation maps are made for both models and are then combined together. Since both models are 1D, each cross-section has one water level. In order to know the water level outside of the model area the cross-sections of the models are extended so that the same water level reaches a larger area. The extended cross-sections are depicted in Figure II - 25.

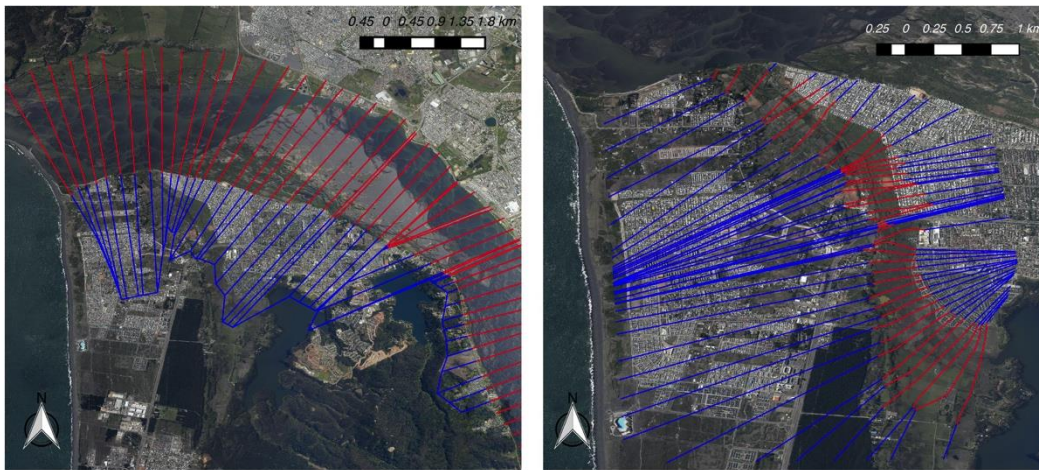


Figure II - 25: Computed- (in red) and extended (in blue) cross-sections of the Biobío (left) and Los Batros (right) models.

With the use of RAS-Mapper extension of HEC-RAS, the extended cross-sections and the LiDAR data the flooded areas are determined. The downside to this approach is that HEC-RAS, not being a 2D flow model, is not able to simulate the effect of water flowing over the riverbanks. For this reason some areas are incorrectly marked as flooded. For example some areas are marked as flooded while they are not directly connected to the water in the Biobío or Los Batros. All the flooded areas are manually checked for whether they can be realistically flooded. Both maps are then merged into one inundation map. This map is shown in Figure II - 26. More detailed pictures can be found in Appendix II-C.



Figure II - 26: Inundation map for T = 100 (Scenario II).

8.2.2 Flooded areas

In this paragraph the flooded areas are listed and the effects of the infrastructure on these areas is described.

Along the southern riverbank of the Biobío River there are no significant areas flooded. At some places, however, the water comes close to houses. This can be seen in Figure II - 27 and at the detailed figures in Appendix II-C.

At the lowest part of the Biobío river and at Los batros more areas are flooded, as can be seen in Figure II - 27. At section A of the same figure Ruta Humedal is built on piles so this area can still be flooded. At section B farm lands and a residential area is flooded. Also in section C a larger residential area is flooded up to Ruta 160. There is a possibility that section D is protected from flooding if Ruta Humedal is built, as it could cut off the connection to Estero Los Batros. Water may however be able to flow underneath the bridge of Ruta Humedal over Ruta 160 to section D. Section E, which consists of farmland, is protected from flooding if Ruta Humedal is built. Section F on the other hand will still be flooded since Ruta Humedal only cuts off Estero Los Batros on the East side but not the North side. Section G is flooded but no urbanization or properties are found on that location. Costanera Sur cuts off a small part of the flooded area here.

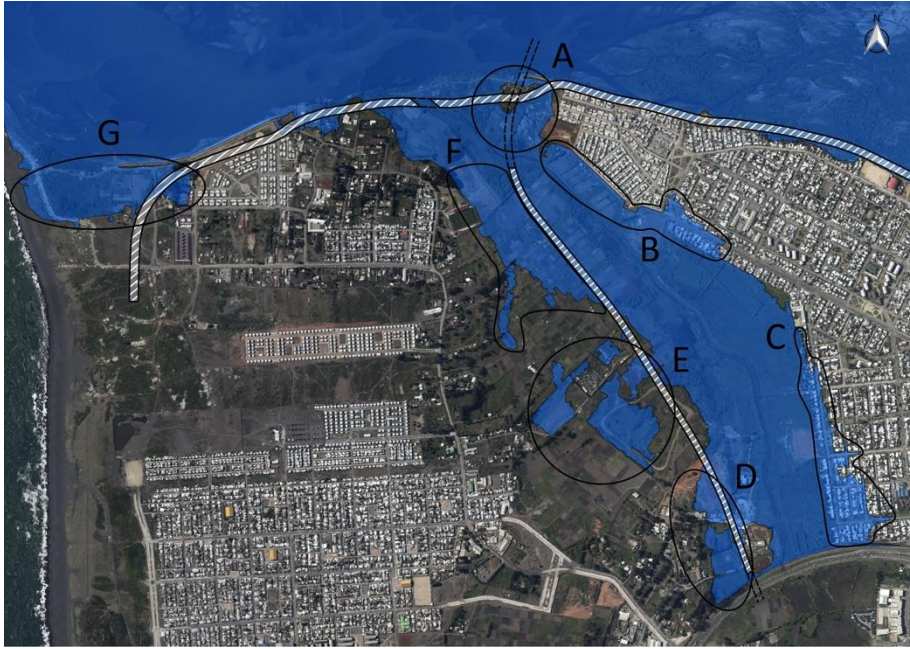


Figure II - 27: Inundation map for T = 100 zoomed in at Biobío mouth and Los Batros.

9 Conclusions

The goal of the river study is to analyse the effects of Costanera Sur and Ruta Humedal with respect to flooding of San Pedro de la Paz. The conclusions of this Part II of the report are given in the same order as the goals listed in Paragraph 3. Some other aspects not directly related to the main goals are also given. Finally recommendations based on the conclusions are provided.

9.1 Inundation map for the present situation

The development of this inundation map is described in Paragraph 8.2 and the map itself can be found in Appendix II-C.

For the 100 years return period scenario the Biobío river does not flood the city of San Pedro de la Paz between Puente Chacabuco and the future Puente Industrial. Over this entire reach the maximum water levels do not exceed the elevation of the terrain at the southern bank of the river. In isolated cases water can reach close to existing buildings but not overflow to larger areas.

In the case of the Estero Los Batros the terrain is lower than the maximum water level of the Biobío River. This maximum water level for the 100 years return period is calculated as 3.8 m above mean sea level. A large area is flooded between the mouth of the Estero and the Ruta 160 bridge over the wetlands.

In case of high rainfall in the catchment area of the lagoon and wetlands system of San Pedro the reach of Los batros upstream of the Ruta 160 bridge will also be flooded. However it has not been possible to analyse the consequences of this in this study.

At the mouth of the Biobío River there is an area of about 11.3 ha that will be flooded above Boca Sur. However, this area is not urbanized and the Master Plan (Plan Regulador Comunal) of San Pedro de la Paz (Municipality) marks this area as “coastal risk” or “recreation area” and therefore the consequences of flooding are low.

9.2 Impact of Costanera Sur on the hydraulic behaviour of the Biobío River

Costanera Sur extends 30 m into the river floodplains at the southern bank of the Biobío. The reduction in cross-sectional area available for the flow is not significant in comparison with the total width of the river (between 1.3 and 2.5 km) and the maximum differences observed in the model are of a few centimetres only.

9.3 Effect of Costanera Sur on Flood Prevention

The construction of Costanera Sur does not have a significant effect on flood protection. On the one hand between Puente Chacabuco and Puente Industrial there are no important flooded areas. Costanera Sur would protect the first lane of houses from minor inundations but this would not justify the costs of the road.

On the other hand, Costanera Sur does not protect Los Batros against floods because it crosses the Estero over a bridge. Water from the Biobío River can flow through this bridge and flood the wetlands area.

A small part of the flooded area above Boca Sur would be protected by the connection between Costanera Sur and Costanera Mar, but the value of this area is not significant to justify this infrastructure as flood protection.

9.4 Impact of Puente Industrial on the hydraulic behaviour of the Biobío River

The construction of Puente Industrial does not affect significantly the hydraulic behaviour of the river. Assuming a pile diameter and distribution similar to that of Puente Juan Pablo II and the

information available about the bridge, the reduction in cross-section is negligible and thus the water level changes are also negligible.

9.5 Impact of Ruta Humedal on the hydraulic behaviour of Estero Los Batros

Ruta Humedal reduces significantly the available floodplain area downstream of Ruta 160 but does not affect significantly the hydraulic behaviour of Los Batros under the different scenarios analysed.

For low discharges in Los Batros (low rainfall) and low water level at the mouth (normal conditions), water does not reach the embankment of Ruta Humedal and therefore the flow of the stream is not affected.

For high discharges in Los Batros (high rainfall) and low water level at the mouth (scenario III), water can reach the embankment of Ruta Humedal but the maximum increase of the water level according to the model is very small, of the order of 2cm.

For high water levels at the mouth (high discharge of the Biobío river), and regardless of the discharge at Los Batros (scenarios I and II), downstream of Ruta 160 bridge the water flow is controlled by the downstream boundary condition (river water level) and friction is not dominant any more. In this case the construction of Ruta Humedal does not affect the water surface elevation.

9.6 Effect of Ruta Humedal on inundation area

Ruta Humedal does not prevent the lower reach of Los Batros from being inundated under high water conditions for the Biobío River. This is because Ruta Humedal is build over piles over the Estero and until its connection with Puente Industrial and therefore it cannot prevent inundation due to high water at the river. Only some farmland areas located at the west side of Ruta Humedal and more than 1 km away from the Biobío River would be protected from floods.

9.7 Other aspects to consider

Effects on the northern bank of the Biobío River

In relation with Paragraphs 1.2 and 1.3, the construction of Costanera Sur on the southern bank of the Biobío River could cause an increase of the water levels on the northern bank. During the 2006 flood event there were severe floods on that side of the river (Hualpén), which could be increased with the construction of this road. Further studies are required as this project only considers effects at the Comuna of San Pedro, and given the 2D nature of the river bend at this location.

Local scour at Puente Industrial

As stated in Paragraph 1.4 the construction of Puente Industrial does not have an effect on the global behaviour of the river. However, local scour around the piles of the bridge can be an important issue that needs to be considered.

Ruta 160 bridges over Los Batros

The bridges of Ruta 160 over the wetlands are an important control point for the lagoons-wetlands system that is determinant for the inundation extents in case of high discharges. However, these structures are not designed for the hydraulic regulation of the system and therefore are not reliable. The bridges have an insufficient hydraulic capacity; high flow velocities are expected there, which can produce important scour processes. In case of overflow (water flowing over the roadway) the bridge can also collapse.

Rainfall runoff at Los Batros

The construction of Ruta Humedal does not have an effect on the stream (Estero) itself, but will block rainfall runoff from the farmlands into the stream. This can generate flooding at the farmland zone in case of high rainfall events, and reduce the discharge of the Estero as most of its discharge comes from direct rainfall runoff.

10 Recommendations

The density of vegetation north of San Pedro de la Paz increased over the last years. This results in a higher roughness. In order to obtain more accurate results of the model field measurements should be used to calibrate the model.

The Los Batros model should also be calibrated with field measurement data. This leads to more accurate results and to the ability to use the upstream reach of the Ruta 160 bridge to assess the flood risk. Also the bottleneck effect of the bridge can be studied in more detail.

The run-off into Los Batros from the west is partially blocked by Ruta Humedal. This is not taken into account in this study. When this is taken into account more accurate discharges can be used.

The models used for this study are 1D models. More accurate results are obtained when 2D models are used. These kinds of models are especially useful for the river bends, flow through floodplains and studies of local phenomenon (such as local scour). Also the inundation maps can be made more reliable since instead of extending the water level at each cross-section the flow is modelled.

Part III

Tsunami analysis

In this chapter three variants, consisting of different combinations of solutions, will be evaluated on how they are affected in case of a tsunami in the region of San Pedro de la Paz. As mentioned before, the project evaluated several suggested partial solutions for the traffic problem. To compare the variants and show the differences on various aspects a multi-criteria analysis is used. In this chapter the hydrological aspects (in the form of tsunami impact) are assessed.

It is unknown how the variants will be affected by a tsunami event. Only the roads that can have an influence on the inundation are considered. These will be tested with the earthquake and tsunami scenarios. The simulations will be done using the NEOWAVE model. With the use of this model inundation maps of the projected area can be made.

In order to do this properly, first some information about tsunamis is presented to gain some insight into the phenomenon itself; what they are, how they are generated and how they are modelled. This can be found in the paragraphs below. Then the results of the modelling with and an analysis follow. A conclusion, discussion and recommendation can be found at the end of this chapter.

1 Introduction into tsunami's

This paragraph covers the information about the source of a tsunami and the theory behind the tsunami wave.

1.1 Earthquakes

Tsunamis are closely related to tectonic movements. On the borders between tectonic plates, converging or diverging movements of the plates generate an enormous amount of energy. Below the water surface these movements can result in tsunamis. Big (submerged or emerged) landslides, generated by the released energy of an earthquake can also result in a tsunami.

The magnitude of the earthquake determines the size of the tsunami. This magnitude depends on multiple factors; the length and width of the fault plane, displacement of this plane, the depth at which this occurs and more. These factors will be addressed below.

1.1.1 Plate tectonics

Chile is located close to the border of the Nazca- and South American tectonic plate, as can be seen in Figure III - 1. Because of this, there is a lot of seismic activity in this area.

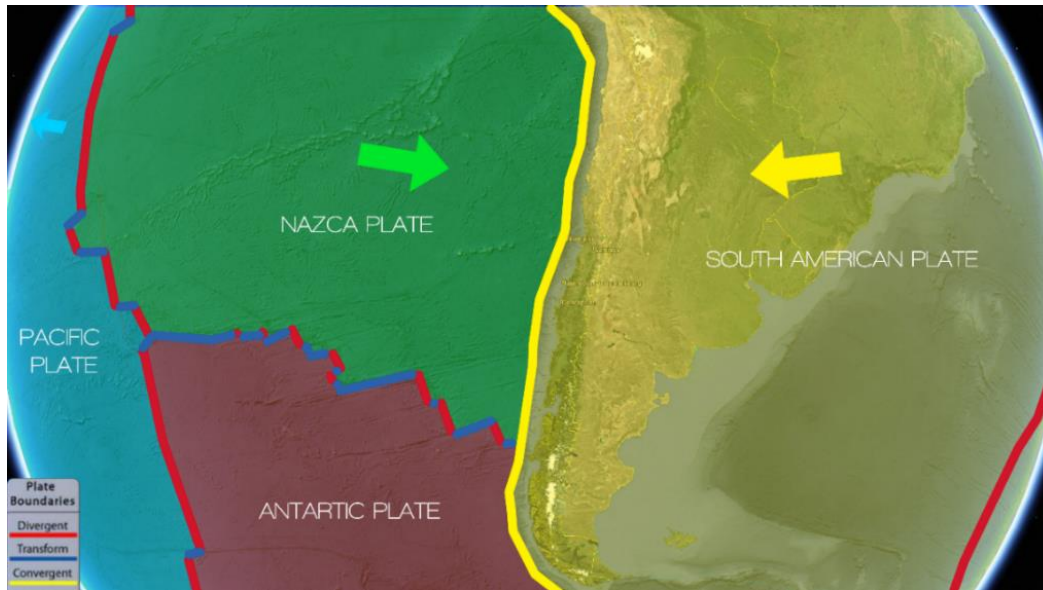


Figure III - 1: Tectonic plates affecting Chile.

The Nazca and South American plates are converging. The Nazca plate is subducting the South American plate. This is not a smooth linear movement but a slow process. Where the two plates meet, friction prevents further movement. This causes the upper plate to bulge as can be seen in Figure III - 2(b), which locally causes subsidence and uplift. A lot of energy is stored during this process until a maximum is reached.

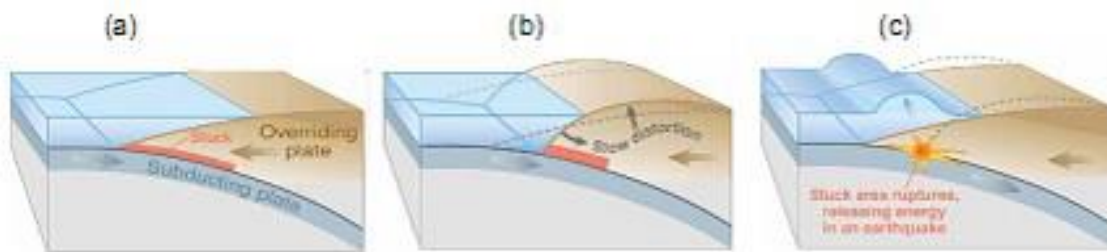


Figure III - 2: (a) subduction and overriding planes interact. (b) Friction between the two plates prevents further movement, the upper plate starts to bulge and energy is stored. (c) The build-up strain exceeds the friction and the upper plate is released.

At this moment the fault area ruptures and the upper plate slips over the lower plate. The stored energy is released and causes an earthquake as can be seen in Figure III - 2(c). Earthquakes that occur at a subduction zone on the plate boundary are referred to as megathrust earthquakes.

1.1.2 Seismic gap

As said above, the process of building up towards an earthquake is a slow process. It could take decades for enough energy is being stored for a major earthquake to occur. This time gap is referred to as a seismic gap, more precisely the inter-seismic gap. It has to be noted that smaller earthquakes can occur in between two major events. These smaller earthquakes reduce the accumulated strain and therefore reduce the seismic potential.

1.1.3 Basic calculation of earthquake moment magnitude (M_w)

The moment magnitude of an earthquake determines the effects it has and the size of the tsunami it generates. In order to calculate this magnitude M_w , the seismic moment M_0 has to be calculated. This is done using formula (III.1) and it depends on the length, width and displacement of the fault plane. The magnitude is then calculated using a log formula, as can be seen in formula (III.2). The variables are visualised in Figure III - 3.

$$M_0 = \mu LWD \quad \text{III. 1}$$

$$M_w = \frac{2}{3} (\log(M_0) - 9.1) \quad \text{III. 2}$$

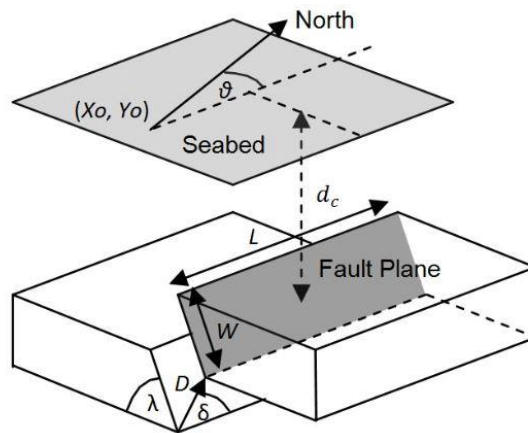


Figure III - 3: Fault plane and variables.

Where:

M_0 = Seismic moment [N*m]

μ = Shear modulus of the rocks involved in the earthquake [N/m²]

L = Length of the fault plane [m]

W = Width of the fault plane [m]

D = Displacement of the fault plane [m]

M_w = Moment magnitude [-]

ϑ = Strike angle [degree]

δ = Rake angle [degree]

λ = Dip angle [degree]

d_c = Focal depth [m]

1.2 Tsunamis

A tsunami (Japanese for 'harbour wave') is a long wave generated by a sudden release of energy caused by for example an earthquake or a landslide. In the case of the subducting Nazca plate the sea bottom and the water column above will be uplifted. The sea surface will displace in the same order as the sea bottom resulting in a long wave with a wave period in the order of 10 - 90 minutes.

1.2.1 Propagation of a tsunami wave

This wave has a wave length in the order of 100 km. The water depth over wave length is therefore very small ($d/L < 0.05$) which explains its typical shallow-water wave non-dispersive behaviour. The propagation speed can then be calculated using the following equation;

$$c = \sqrt{gd} \quad \text{III. 3}$$

Where:

c = propagation speed [m/s]

g = gravitational constant: 9.81 [m/s²]

d = water depth [m]

The propagation of a tsunami wave can be influenced by several processes. The most important for the NEOWAVE model are shoaling, refraction, diffraction and reflection. Shoaling is the process of increasing wave heights due to decreasing water depth in shallow water. The change of propagation direction due to changing bathymetry is referred to as refraction. Diffraction is the change of propagation direction due to the presence of obstacles (e.g. islands, rocks, peninsulas or structures). The wave reflection due to interaction with obstacles is referred to as reflection.

1.2.2 Propagation of a tsunami wave

Tsunamis are often quantified with the run-up. This is the highest contour line which indicates the inundation area, often marked with a clearly visible line of debris. The flow depth here is zero. The flow depth is obtained by subtracting the topography from the wave height as shown in Figure III - 4.

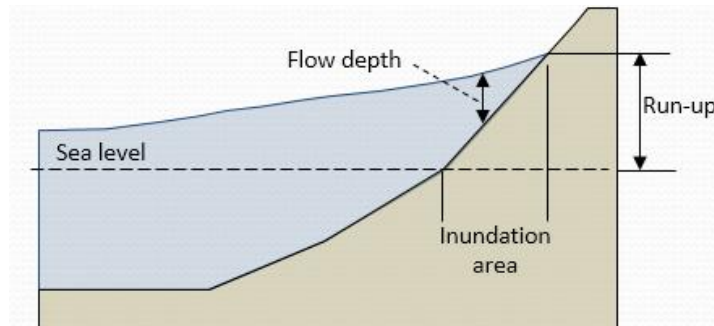


Figure III - 4: Explanation of flow depth, inundation area and run-up.

2 Earthquake scenario

The region of Concepción has experienced several major earthquakes. Since there is only information available up to 1500 AD, there are only 7 major earthquakes described¹⁹. These are;

Table III - 1: Information about 7 major earthquakes around the region of Concepción¹.

| Year | Magnitude | Length of fault plane [km] | Description |
|------|--------------------|----------------------------|--|
| 1570 | 8 | 140 | Concepcion, then located at present day Penco, was highly affected, complete inundation. No information was available about the tsunami waves and the tide. However, it is estimated that the maximum wave height was 4 meters estimation above sea level. |
| 1657 | 8 or slightly less | 120 | Tsunami may have started with ebb. 3 large waves (at least), out of which the first was the largest. Estimation; 4 meters maximum above sea level. |
| 1751 | 8.5 | 260 | 4 waves were seen, of which the 3rd one was the biggest. 3.5 m inundation, but less in other areas. After this tsunami they moved the city to current location, away from Penco. The epicenter of the earthquake was close to Concepción. |
| 1835 | 8.25 | 210 | 12.5 meters tsunami in the bay of Concepcion. The water receded, a small wave occurred, the water receded again after which there was inundation. This was seen as 1 wave, but should be taken as 2 waves. In total 4 waves, of which the 4th wave was the biggest. Talcahuano had 8 m inundation and more. |
| 1928 | 8.4 Richter | 150 | 1906-1928 can be seen as a 2-stage rupture. It was felt from Antofagasta to Puerto Montt. No information about a tsunami in Concepción. |
| 1960 | 8.3-9.6 | 1,000 | An earthquake of around 8 on the Richter scale at Concepción, but if the total region is regarded, it generated an earthquake of 9.5. Maximum rise in water was 25 m in all of Chile, but it highly depended on shape of bays. It caused 3 m inundation in Talcahuano, but there is no information of what happened in San Pedro de la Paz. |
| 2010 | 8.8 | 550 | Various run-ups, maximum of 29 m. However, at the mouth of the Biobío this was below 2 m run-up, therefore the dunes stopped most of the inundation in San Pedro de la Paz. Before the earthquake, the magnitude of a possible event was estimated to be 8.0 – 8.5 M_w in a conservative manner, which is significant less than the 8.8 that occurred. |

¹⁹ Based on (Soloviev & Go, 1975), (Lomnitz, 2004) and (SERVICIO HIDROGRÁFICO Y OCEANOGRÁFICO DE LA ARMADA, sd), (Aránguiz, 2014)

Before the 2010 earthquake in Chile, a pre-estimation of a potential earthquake was made in a conservative manner. This resulted in an estimation of $8.0 < M_w < 8.5$ based on the seismic gap of 175 years²⁰. However the 2010 earthquake turned out to be larger than this conservative estimation.

In 2011 a similar situation happened in the Honshu area in Japan, where the earthquake had a magnitude of 9.0 instead of the expected 8.5. An earthquake with magnitude of 9.0 normally requires a relatively long and straight fault line. Because in this area this was not the case, the maximum expected earthquake was 8.5. In 2001 a big 1/1,000 years earthquake was reckoned to occur somewhere in the near future based on sedimentary data.²¹

From this it can be concluded that even in a conservative calculation a potential earthquake can be quite underestimated. As can be seen in Table III - 1, there is only data of 500 years, of which a big earthquake happens roughly every 100 years in Chile. It is therefore hard to estimate when there will be a bigger 1/1,000 years event in the region of Concepcion. Based on this, several scenarios will be used in this project: an earthquake of M_w 8.9 and one of M_w 9.0 both during mean sea level.

The region of Concepcion was not affected by the 1960 earthquake, which had a 1000 km fault region starting from just south of Concepcion. The tsunami generated by this earthquake did not inundate the city of San Pedro de la Paz. Therefore, this area will not be part of the simulated fault area. That will be an area around the Biobío river, the same fault area as the 2010 earthquake.

For the simulations of the M_w 8.9 and M_w 9.0 earthquake scenarios the following parameters are used:

Table III - 2: Overview of the 2010 reference scenario and the two other scenarios based on the paragraph Earthquake scenario.

| Variables | Units | Scenario 0 Reference 2010 | Scenario 1 | Scenario 2 |
|----------------------|---------------------|---------------------------------|----------------------|----------------------|
| ϑ | [degree] | 18 | 18 | 18 |
| δ | [degree] | 110 | 110 | 110 |
| λ | [degree] | 18 | 18 | 18 |
| μ | [N/m ²] | $3 \cdot 10^{10}$ | $3 \cdot 10^{10}$ | $3 \cdot 10^{10}$ |
| L | [m] | 450,000 | 510,000 | 600,000 |
| W | [m] | 150,000 | 150,000 | 150,000 |
| D | [m] | 10 | 12 | 15 |
| M₀ | [Nm] | $2.03 \cdot 10^{22}$ | $2.75 \cdot 10^{22}$ | $4.05 \cdot 10^{22}$ |
| M_w | [-] | 8.8 | 8.9 | 9.0 |
| d_c | [cm] | $3.00 \cdot 10^6$ | $3.00 \cdot 10^6$ | $3.00 \cdot 10^6$ |

²⁰ (Fritz, et al., 2011)

²¹ (Maugh, 2011)

Table III - 2 gives the overview of the final values of the variables of the different scenarios. Below, a short explanation per variable can be found.

- Scenario (0) describes the scenario for the earthquake of 2010, as modelled by (Aránguiz, Analysis of Tsunami Propagation in Coastal Areas, 2014). The average fault length L for the other 2 scenarios is calculated in the same way as in this research, namely by the formula of Papazachos.

$$L = 10^{0.55M_W - 2.19} \quad \text{III. 4}$$

- The width W of the fault plane of the 2010 earthquake is 150,000 m. The solid state of the earth's crust in Chile is however limited to approximately 150,000 m. More downwards, the crust is actually melting and therefore not contributing to the earthquake. Therefore, the width of the fault plane of the other scenarios is also limited to this maximum of 150,000 m.
- The shear stress μ equals 30 GPa and is standardly used for earthquake modelling in Chile.
- Since the moment magnitude of the scenarios was already defined, the displacement D could be calculated using Formula 1.1 and Formula 1.2 and the values of L , W and μ .
- The rake, strike and dip are the same for all the scenarios, since it regards the same section of the fault line in front of Chile.
- The focal depth d_c depends on the total width of the fault plane. In the NEOWAVE program, this depth is located in the middle of the fault width. Therefore it is the same for all scenarios.



Figure III - 5: Overview of the reference scenario 0 and the two other scenarios 1 and 2. In the lower corner the start coordinates for all scenarios is given (37.6 S, 74.86 W).

3 Introduction into the NEOWAVE model²²

In order to calculate the propagation of tsunamis and their inundations, they are modelled with the NEOWAVE model (Non-hydrostatic Evolution of Ocean WAVE). This model calculates the tsunami propagation and the inundation, based on the proposed earthquake scenario and the bathymetry, in a spherical coordinate system. These results will later be further analysed with Matlab and Google-Earth.

The NEOWAVE model uses formulas based on the non-linear shallow-water equations with the Manning expression for the friction term²³; these are depth-integrated, non-hydrostatic equations. Because of this, wave dispersion and refraction are taken into account.

3.1 Nesting grids

The model consists of several layers of grids, that range from coarse to fine, or respectively from A to D. A fifth finer grid is possible, but further on it will be explained why it is not taken into account in this report. These grid layers overlap each other as shown in Figure III - 6.

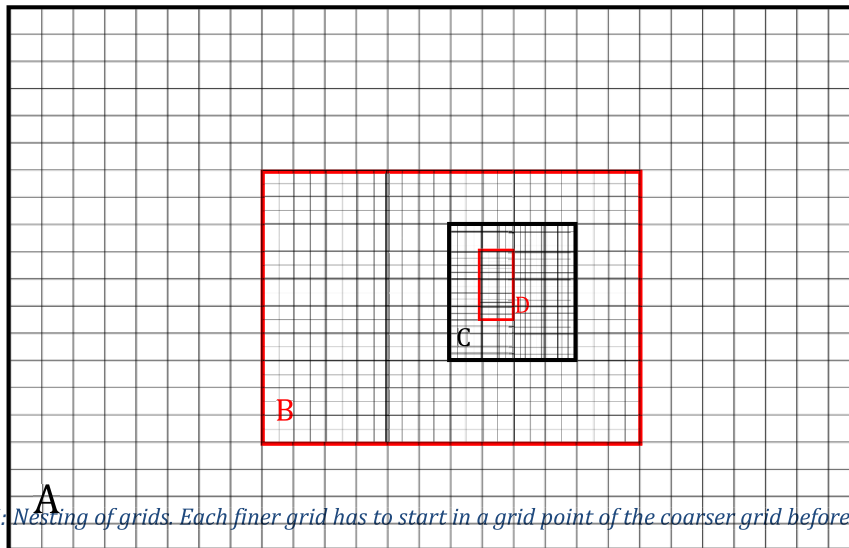


Figure III - 6: Nesting of grids. Each finer grid has to start in a grid point of the coarser grid before it.

The model is based on a semi-implicit finite difference model, with a momentum conserved advection scheme. This is implemented by using two-way grid-nesting. This means that the model will calculate for 1 time step, the solution for the outer grid A. Then by linear interpolation of velocity, surface elevation and non-hydrostatic pressure (both in time and space), the input boundary conditions for grid B are calculated. This goes on until the finest grid D. After the first time step is completed, the outer grids are updated with the average value from the overlapping inner grids.

²² (Yamazaki, Cheung, & Kowalik, 2010)

²³ This Manning coefficient is $n = 0.025$, as explained in (Aránguiz, Shibayama, & Yamazaki, Tsunamis from the Arica-Tocopilla source region and their effects on ports of Central Chile, 2013)

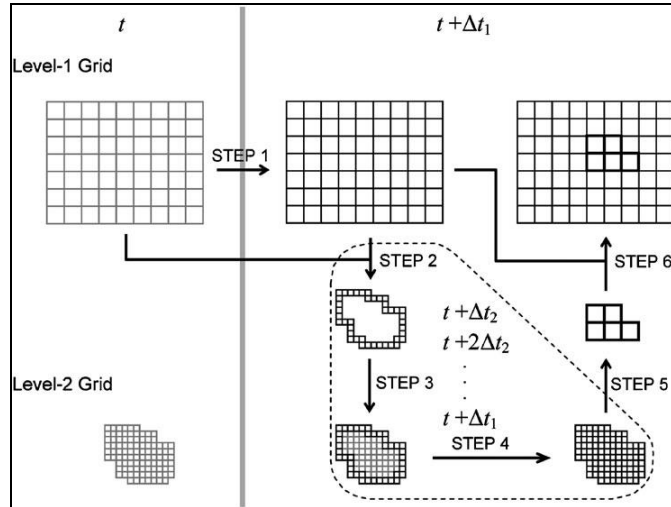


Figure III - 7: Two-way grid nesting and time integration scheme.

3.2 Courant number

In order to be able to run the model smoothly, the model has to meet the CFL condition. This condition is as follows:

$$Cr = \frac{u\Delta t}{\Delta x} < 1 \quad \text{III. 5}$$

Where;

u = Wave celerity [m/s]

Δt = Timestep [s]

Δx = Grid size [m]

Some NEOWAVE models show that the best results are acquired if the Courant number lies between the values 0.1 and 0.3, but this can change for each different case.

4 Model validation

After defining the model, the model needs to be validated. This can be done by comparing the results of scenario 0, with measured results of a tide gauge. However, this is already done by (Aránguiz, Analysis of Tsunami Propagation in Coastal Areas, 2014) so another validation is not necessary. Because it is still important to know how data from the field is obtained, the following paragraph will describe how this is done after the 8.3 M_w earthquake on 16-9-2015.

4.1 Inundation and run-up data

Because of this M_w 8.3 earthquake on 16-9-2015, a tsunami hit the coast of central Chile. This caused severe damage in several regions. One of this regions was the area around Coquimbo. Since this occurred during this project, it was a perfect opportunity to see how data is acquired in the field. Due to the presence of an elevated road along the beach, it was also a good reference to the suggestion of an elevated road in San Pedro de la Paz. One should keep in mind however, that this suggestion is located on top of some dunes, not on the lower beach.

4.1.1 Measurements

To obtain this data, it is required to go into the field with some GPS equipment. This consists of a fixed GPS (reference point) and some free GPS that are fixed on a pole for easy manoeuvring. The fixed and the free GPS are in contact with each other, to be able to determine the ground elevation at the different locations.



Figure III - 8: Fixed GPS on a tripod and a free GPS on a pole.

When this setup is completed, the search for good watermarks begins. A watermark is a clear line on an object (building, trees, etc.). The maximum inundation is therefore the highest line possible, as the lower lines will represent the lower Tsunami waves that occurred after the maximum water level. At some steeper inclinations, a run-up can be observed. Again, the end of the run-up is clearly marked by a waterline. When the free GPS cannot connect well with the fixed GPS, it is necessary to move it several meters from the watermark location. This is however not a big problem, since a few meters error is very small on the length scale of a tsunami (several kilometres) and on the length scale of the grid size (30 meters). With these locations, flow depths and inundation levels, a model can be validated.



Figure III - 9: Left; waterline (marked red) on object. Right; end of run-up on a slope (marked red).

4.1.2 Reference to our project

The road along the beach in Coquimbo is somewhat of a reference to what could happen to an elevated road in San Pedro de la Paz during a tsunami. However, it must be kept in mind that the road in Coquimbo consists of several bridges that cross small rivers, which will cause a different impact than just a continuous road/dike. Also, the road is built on top of the beach, instead of on top of the dunes, as would be the case in San Pedro de la Paz.

In Figure III - 10 and Figure III - 11 below, the following can be seen. Figure III - 10 shows a higher part of the road (and one of the bridges), where the revetment is mostly intact. There is less damage on both sides of the road. Where the road is lower, there is more damage on both sides; parts of the road are actually completely destroyed. This can be seen in Figure III - 11. Over wash by the wave probably caused damage on both sides of the road, and the return flow caused extra severe damage to the sea side. It was strong enough to move real heavy objects (massive blocks, complete trees, cars) all the way to the beach and the sea.

So why is there such a difference in damage between the two sections? It could have something to do with the difference in road elevation, difference in inundation height, but it can also depend on the construction itself. At the location where the revetment collapsed, the armour layer of the protection was only 20-30 centimetres big. No extra layers or filter layers were found on top of the sand core. Therefore it could be the case that the construction of the road differs from the construction of the bridge, explaining the difference in damage.



Figure III - 10: Road with bridge, minor damage (still usable road and revetment).



Figure III - 11: Taken right next to figure (III - 10), both the revetment and road are destroyed.

5 The model

The model uses four nested grids with a maximum resolution of 30 meters. This is accurate enough to estimate inundation areas and flow velocities. A fifth with an even smaller resolution is not used, due to generation of discontinuities in the model. The computation covers 4 hours of elapsed time, with an output time interval of 1 minute.

5.1 Grids

The four nested grids are shown in Figure III - 12. This figure also shows the coordinates of the corners of these grids. Table III - 3 gives an overview of the resolution per grid, both in arc seconds/minutes and in meters.



Figure III - 12: The four nested grids, where A has the largest grid size and D the smallest.

Table III - 3: Resolution for the different grids.

| Grid | Resolution [arcsec] | Resolution [m] |
|----------|---------------------|----------------|
| A | 120 | 3,600 |
| B | 30 | 900 |
| C | 6 | 180 |
| D | 1 | 30 |

5.2 Courant number

The magnitude of the time steps of the different grids are determined by trial and error. The model for San Pedro de la Paz runs smoothly if the time steps as shown in Table III - 4 are used.

Table III - 4: Maximum depth, maximum wave celerity, time step and courant number for the different grids.

| Grid | Maximum depth [m] | Maximum wave celerity [m/s] | time step [s] | Courant number [-] |
|----------|-------------------|-----------------------------|---------------|--------------------|
| A | 6,471 | 254.4 | 1 | 0.07 |
| B | 5,193 | 227.9 | 0.5 | 0.1254 |
| C | 1,826 | 135.1 | 0.125 | 0.0928 |
| D | 415 | 64.5 | 0.03125 | 0.0665 |

5.3 Modelling of the earthquake

The model will use a Uniform Fault Plane (UFP), with a static deformation. This means every location in the fault plane will experience the same amount of slip. (Aránguiz, Analysis of Tsunami Propagation in Coastal Areas, 2014) shows that using a UFP gives good results that are in comparison with the results from the field.

5.4 Overview variants, combination of roads and earthquake scenarios

In San Pedro several road combinations are proposed, as defined in Part I. Not all of these have an influence on the inundation maps of the area. The roads that could have an influence on this are:

- the elevated coastal road; Ruta Costa (yellow in Figure III - 13)
- the road along the river; Costanera Sur (blue in Figure III - 13)
- the road through the wetland; Ruta Humedal (green in Figure III - 13)

Combinations of these roads are investigated in this paragraph.

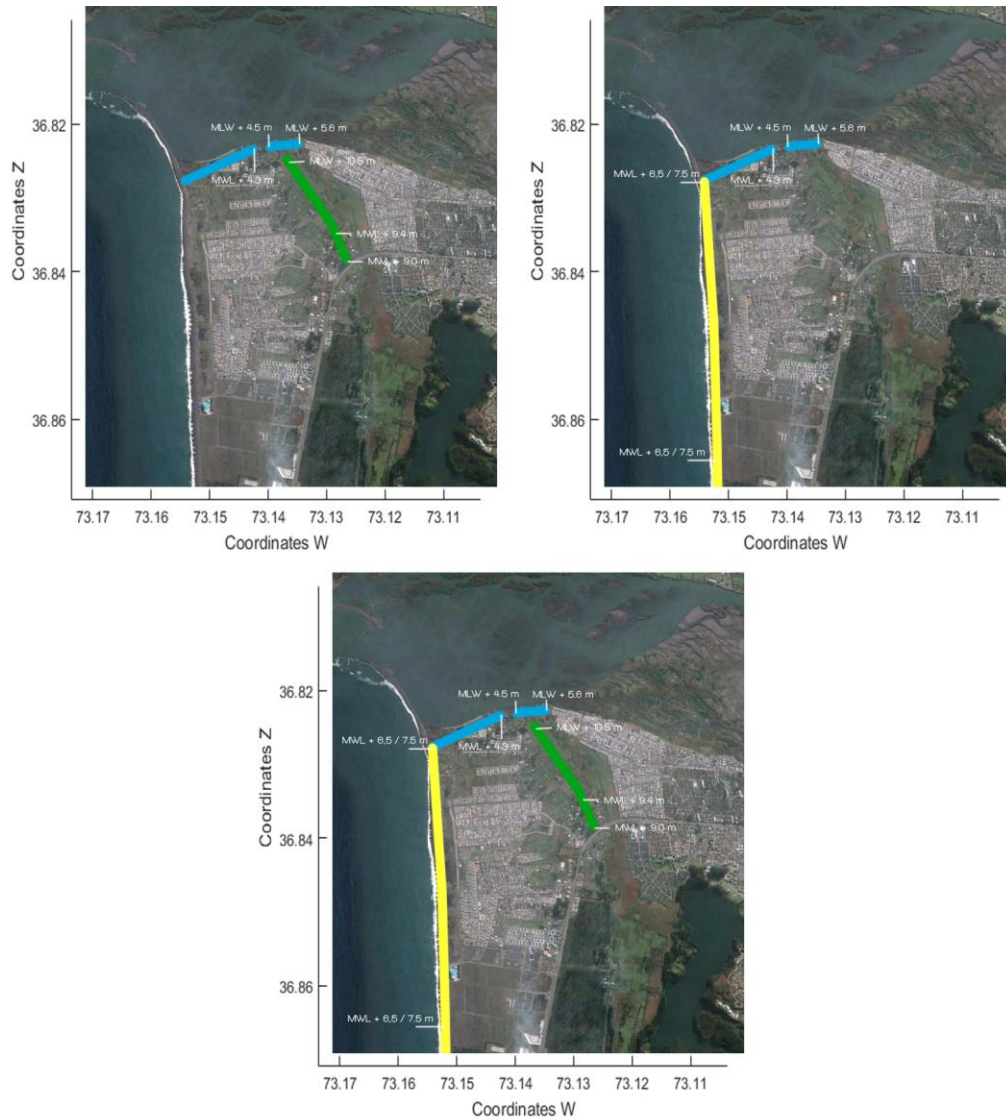


Figure III - 13: LRTB road combinations I, II and III.

The different road combinations are being defined by changing the bathymetry in MATLAB (i.e. elevating lines, representing roads, on the existing bathymetry). An example of this can be found in Appendix III-C. They will be assessed with two earthquake tsunami simulations (M_w 8.9 and M_w 9.0) for the present situation. Eventually 10 simulations with different road combinations will be done and analysed.

The first combination (see Figure III - 13) consists of the elevated road along the river (blue) and elevated road in Los Batros (green). The gap in the road along the river represents a bridge, under which a river from the wetland crosses to the river. The gap between the wetland road (green) and the river road (blue) is also a bridge on piles. It is assumed that water can flow freely in and out the wetland zone in case of a flooding and these (bridge) locations are therefore not changed in the bathymetry. The second variant consists of the same road along the river (blue) and the elevated road along the coast (yellow). The existing dunes have an elevation between MWL + 4.5 m and MWL + 6.5 m. The elevated coastal road, projected on these dunes will be tested with an elevation of 6.5 m and 7.5 m.

The third variant is the variant which consists of all the elevated roads. Also this variant will be tested with two elevations of the coastal road. So eventually there will be two sets of five simulations analysed (five with an M_w 8.9 event and five with an M_w 9.0 event), as is shown in Table III - 5.

Table III - 5: Overview of simulations with their changed bathymetry and tsunami events.

| Simulation # | Combination | Roads | Event |
|--------------|-------------|------------------------------------|-----------|
| 1 | I | Costanera Sur | M_w 8.9 |
| 2 | | Ruta Humedal | M_w 9.0 |
| 3 | IIa | Ruta Costa (6.5 m) | M_w 8.9 |
| 4 | | Costanera Sur | M_w 9.0 |
| 5 | IIb | Ruta Costa (7.5 m) | M_w 8.9 |
| 6 | | Costanera Sur | M_w 9.0 |
| 7 | IIIa | Ruta Costa (6.5 m) | M_w 8.9 |
| 8 | | Costanera Sur Ruta Humedal | M_w 9.0 |
| 9 | IIIb | Ruta Costa (7.5m) Costanera Sur | M_w 8.9 |
| 10 | | Ruta Humedal | M_w 9.0 |

6 Results

This paragraph shows the most relevant results of the simulations. The remaining results can be found in the Appendix III-B. The simulations with M_w 8.9 (all even simulation numbers) have a minor influence on the area. Only a small, uncultivated area nearby the river mouth inundates (see simulation #0 of 8.9 in Appendix III-B), the elevated coastal road stopped this inundation and all other simulations containing the same road gave similar results (which stopped the inundation). Because of this, these results will not be considered further in the assessment of the different combinations. Only those figures that are of importance of the analysis are shown here:

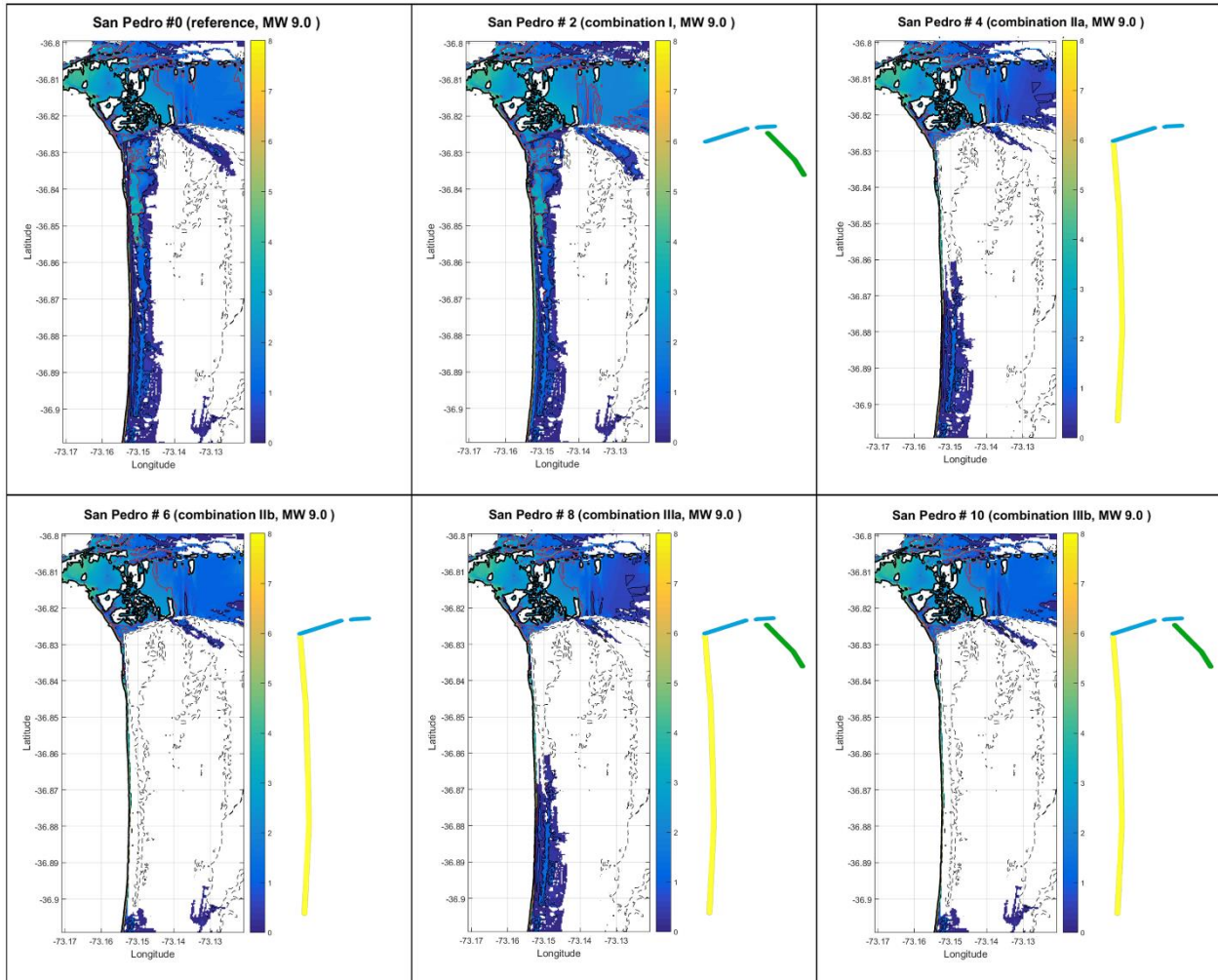


Figure III - 14: Overview of all simulations with a MW 9.0.

7 Analysis

This paragraph analyses the results of the effects of the M_w 9.0 tsunami event. The maximum wave height recorded in three locations can be seen in Figure III - 15. These show a maximum wave height of 5.44 m after 30 minutes, as can be seen in Figure III - 16. In the south of the Biobío river mouth, the tsunami waves propagate in a South East direction, analogous the tsunami waves travel in North East direction north of the river mouth.



Figure III - 15: Locations of water level stations R1 (river mouth), B1 (mouth Estero Los Batros) and M1.

By combining the results and comparing the effects, the influences of the separate roads on the inundation in San Pedro de la Paz is found. These influences are explained in the next subparagraphs.

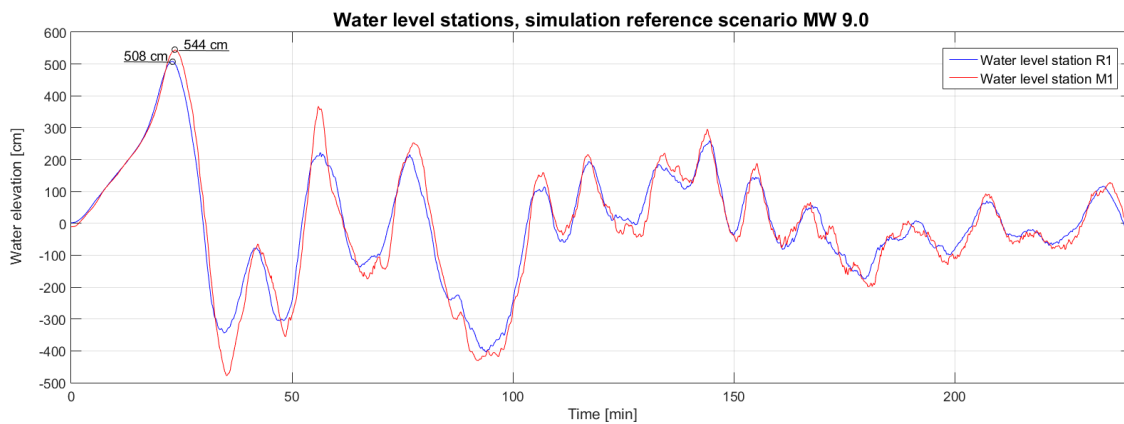


Figure III - 16: Results of water level stations R1 and M1, for reference scenario with MW 9.0.

7.1 Ruta Costa

By comparing the results of simulation #4 and #6, the influence of the difference in road elevation can be seen. In the case where Ruta Costa in total is elevated to MWL + 6.5 m (simulation #4) the southern part of the road is overtopped by the tsunami wave. An elevation of MWL + 7.5 m (simulation #6) is sufficient to stop this overtopping. The fact that only the southern part of Ruta Costa in simulation #4 is overtopped could be due to the presence of the Biobío canyon as explained in (Aranguiz & Shibayama, 2013). This research showed the influence of the canyon on the tsunami wave height, which is lower in the canyon and river mouth, compared to its adjacent coastline. This can also be seen when water level stations R1 and M1 are compared; over a distance of 2.9 kilometres, the wave already increases by 36 centimetres.

7.2 Costanera Sur

The inundation of the wetland is different for #2, #6 and #0 (reference), after comparing the results of these simulations. It seems that in simulation #2 (without elevated coastal road) more water is flowing into the river and wetlands than in simulation #0 or #6.

A possible explanation of this effect could be that the Costanera Sur creates a sort funnel, where the water is guided from the coast towards the mouth of Estero Los Batros. In simulation #6, this water is blocked by the Ruta Costa, causing a lower water level than in the reference simulation and simulation #2.

Another explanation could be that the difference is caused by the model itself. The area of the wetlands is relatively flat. Therefore, when the inundation is generated, it could be that the model inundates too much of the flat area.

7.3 Ruta Humedal

By comparing the results of simulation #6 and #10 (with and without Ruta Humedal) the influence of the Ruta Humedal becomes clear; there is not a significant to no difference in inundation.

8 Conclusion & Discussion

This paragraph concludes the information given in this chapter. The observations from the analysis are concluded and the experiences from Coquimbo are taken into account.

- Building an elevated road along the coast, or at least a barrier, will mitigate the inundation of the lower area of San Pedro de la Paz. However;
 - It has to be at least 7.5 meters high for a M_w 9.0 tsunami (and 6.5 meters for a M_w 8.9 tsunami).
 - It should be built as a proper breakwater, with armour on the landward side to avoid road collapse, in case of overtopping.
- An elevated road as the Costanera Sur, has no negative influences, if (and only if) it is built together with a coastal barrier. When it is built without a coastal barrier, it has no effect on the inundation area and could even cause extra inundation in the wetland. However, it is unsure if this an effect caused by the Costanera Sur, or a discrepancy of the model itself.
- The Ruta Humedal has no visible effects on the inundation of the wetlands, since the bridge will allow water to flow around it.

As explained before, the NEOWAVE model uses the shallow water equations with a numerical scheme. However, in the model of this research, some assumptions are made that could affect the model and cause some errors.

- The presence of the canyon has a negative influence on the model, since it limits the maximum allowable courant number. Due to this, only four grids can be used, which cannot show the inundation in detail.
- NEOWAVE uses the bathymetry without any buildings, since a resolution of 30 meters is too big to take them into account. If these objects would be included, they would cause less space to be available for the water to flow, and therefore cause a bigger inundation area.
- Both the area on the landward side of the dunes, as well as Los Batros, are relatively flat areas. Because of this, the model inundates a relatively large area that is not realistic. A fifth grid with a smaller grid size could positively influence this, since more details about these areas can be added.

9 Recommendations

The recommendations are based on the conclusion and discussion of the results and are listed below.

- An earthquake with M_w 9.0 is an extreme worst case scenario. Whether this will happen in the next 100 years is unknown, however, as shown in paragraph 2, it could be a 1/1000 years earthquake as the 2011 Japan earthquake. More research into these extreme earthquakes could lead to a better estimation of a worst case scenario.
- Only four grids have been used for modelling the inundation of San Pedro de la Paz. This is because the presence of the canyon influences the maximum allowable courant number, which was too small for a smooth run of a fifth grid. A fifth finer grid can show more detailed information and is therefore better for analysing the effects of the tsunami. Therefore, it is recommended to research if there is still a way to implement a fifth grid.
- The used grid is coarse in the wetland resulting in a relatively shallow and flat wetland areas. These areas are instantaneously equally inundated, which is not realistic. Therefore they are at the limits of the model. To get better results the 1-D HECRAS model of the wetland as used in Part III, could be used in combination with an input as a certain water depth in the mouth of Estero Los Batros generated with the NEOWAVE model.
- To reduce the costs of a coastal barrier or elevated highway, it could be better investigated which areas are allowed to have a lower elevation and if so, what this elevation should be.
- The simulations do not include the tidal differences, only a mean water level has been assessed. The NEOWAVE model cannot include this tidal difference automatically; the bathymetry has to be elevated or lowered with the value of this tidal range. It is recommended to implement his tidal difference, so evaluate what difference it makes on the amount of inundation.
- An elevated barrier is effective in protection San Pedro de la Paz. However, for completion it is recommended to research if this barrier can be extended all the way to Coronel, to improve the protection of the entire region and not just one city.

Part IV

Solution analysis & MCA

1 Introduction

The final part of this report consists of two distinct processes. The first process is the analysis of the different solutions based on the criteria as defined in part I. The second process is the so-called Multi-Criteria Analysis (MCA). The analysis of the solutions forms the basis for scoring the different solutions in the MCA.

To solve the infrastructural problems in San Pedro de La Paz there is a large selection of variants, each with their own pros and cons. Besides that there are also a lot of stakeholders, complicating the decision-making process. The MCA is an evaluation method that offers a rational basis for making a decision between different variants based on multiple criteria. What the MCA does is that it transforms a complex decision-making situation with a lot of variables into a clear and comprehensible result.

Presently there are only two important criteria that are decisive in the decision making process in Chile. These criteria are costs and time saving. The environmental impact is studied but not made into an integral part of the decision making. This MCA is going to introduce new important criteria like social impact, environmental impact, comfort, safety and co-benefits into the decision making process. If these are not included in the analysis from the start, the impact of the solutions on these neglected criteria can cause unexpected problems. This can lead to additional costs and unsatisfied users.^{24,25}

The MCA consists of three steps:

1. Assign relative weight factors to the different criteria.
2. Judge how the different variants score on the selection of criteria based on the analysis of the different solutions. (Scoring)
3. Calculate the relative weight score for each variant by multiplying the absolute scores with the weight factors.

The advantages that the MCA offers in complex decision making situations are:

- A framework in which different criteria, effects and their relative importance can be made explicit.
- A certain amount of objectivity by using a mathematical approach despite the subjective character of the scoring itself.
- A toolkit with methods to analyse large amounts of information.
- A stepwise and traceable process.

²⁴ (TNO)

²⁵ (Wikipedia, Multicriteria-analyse , 2015)

2 Solution analysis

This chapter analyses the different solutions based on time, cost, environmental impact, social impact, safety, comfort and co-benefits.

2.1 Time

In this section the different aspects that contribute to the time that is necessary to travel from A to B is analysed. This is done for all the different solutions. The aspects that make up the total time are: accessibility time and travel time.

2.1.1 Pedro Aguirre Cerda

2.1.1.1 Accessibility time

Table IV - 1: Access- and exit-point characteristics of Pedro Aguirre Cerda

| Access- and exit-point characteristics | Amount |
|--|--------|
| Total amount of access- and exit-points | 16 |
| Intersected by a railroad | 4 |
| Controlled by traffic lights | 9 |
| Containing stop signs | 1 |
| No interference | 2 |

In the new design all of the intersections are still on street level. This leads to access- and exit-points with a lot of traffic lights, stop signs and intersections by railways. In general the accessibility to the Pedro Aguirre Cerda is good due to the large number of access points. The problem is that at a lot of crossings access is possible from both sides but exiting the road is only possible from one side. This leads to detours for the traffic flow that wants to exit the Pedro Aguirre Cerda. The connection to the Puente Llacolen is an example of this. For one side of the road there is a direct connection between Pedro Aguirre Cerda and the Puente Llacolen. The other side has to make a detour using another road to access the Puente Llacolen.

2.1.1.2 Travel time

Table IV - 2: Potential interferences at Pedro Aguirre Cerda

| Type of interference | Amount |
|-------------------------------------|---------|
| Traffic lights | 9 |
| Pedestrian crossings | 1 |
| Public transport (bus) stops | 0 |
| Maximum speed | unknown |

The total amount of potential stops on Pedro Aguirre Cerda is 10. This is a relatively large number of potential stops compared to the other solutions.

2.1.2 Ruta 160

2.1.2.1 Accessibility time

Table IV - 3: Access- and exit-point characteristics of Ruta 160

| Access- and exit-point characteristics | Amount |
|--|--------|
| Total amount of access- and exit-points | 10 |
| Intersected by a railroad | 0 |
| Controlled by traffic lights | 0 |
| Containing stop signs | 3 |
| No interference | 7 |

In the new design two of the intersections are not on street level anymore. This increases the amount of access points without interference greatly. Because there are no more complicated crossings with railways and/or traffic lights. Ruta 160 can be accessed directly from Costanera Mar, Pedro Aguirre Cerda and Ruta Humedal. Ruta 160 can only be accessed from Ruta Pie de Monte at one location despite a second intersection of the roads.

At the elevated crossings it is possible to access Ruta 160 from both sides of the road. But at the street level crossings it is only possible to access the road from one side.

2.1.2.2 Travel time

Table IV - 4: Potential interferences at Ruta 160

| Type of interference | Amount |
|-------------------------------------|---------|
| Traffic lights | 0 |
| Pedestrian crossings | 0 |
| Public transport (bus) stops | 0 |
| Maximum speed | 80 km/h |

The new design of Ruta 160 eliminates street level crossings and traffic lights. Because of this there are no more elements that can cause potential stops in this solution. This leads to a fluent traffic flow.

2.1.3 Costanera Sur

2.1.3.1 Accessibility time

Table IV - 5: Access- and exit-point characteristics of Costanera Sur

| Access- and exit-point characteristics | Amount |
|--|--------|
| Total amount of access- and exit-points | 8 |
| Intersected by a railroad | 0 |
| Controlled by traffic lights | 1 |
| Containing stop signs | 7 |
| No interference | 1 |

The accessibility is limited to one direction of the traffic flow. Vehicles travelling towards the East have a relatively large number of access points and exit points. The problem is that the opposite traffic has only two access points along the entire Costanera Sur. On top of that also the connection to Puente Industrial for this direction is absent.

2.1.3.2 Travel time

Table IV - 6: Potential interferences at Costanera Sur

| Type of interference | Amount |
|-------------------------------------|---------|
| Traffic lights | 0 |
| Pedestrian crossings | 0 |
| Public transport (bus) stops | Unknown |
| Maximum speed | 70 km/h |

The design of Costanera Sur does not contain any elements that can cause potential stops. This solution provides a fluent traffic experience for the users.

2.1.4 Ruta Pie de Monte

2.1.4.1 Accessibility time

Table IV - 7: Access- and exit-point characteristics of Ruta Pie de Monte

| Access- and exit-point characteristics | Amount |
|--|--------|
| Total amount of access- and exit-points | 14 |
| Intersected by a railroad | 0 |
| Controlled by traffic lights | 0 |
| Containing stop signs | 11 |
| No interference | 3 |

Ruta Pie de Monte is a private road. Despite that there are many access points to other primary and secondary public roads. The Pie de Monte can be accessed from Ruta 160, Ruta Humedal and the Costanera Mar. Again the connection to Ruta 160 is made at only one location despite the fact that the roads intersect twice. At all the crossings it is possible to exit and access the road from both sides.

2.1.4.2 Travel time

Table IV - 8: Potential interferences at Ruta Pie de Monte

| Type of interference | Amount |
|-------------------------------------|---------|
| Traffic lights | 0 |
| Pedestrian crossings | 0 |
| Public transport (bus) stops | 0 |
| Maximum speed | 70 km/h |

In the design of Ruta Pie de Monte there is only one potential element that can cause a potential stop. This is a pedestrian crossing area at the end of the road. The remainder of the road provides a fluent traffic flow.

2.1.5 Costanera Mar

2.1.5.1 Accessibility time

Table IV - 9: Access- and exit-point characteristics of Costanera Mar

| Access- and exit-point characteristics | Amount |
|--|--------|
| Total amount of access- and exit-points | 17 |
| Intersected by a railroad | 0 |
| Controlled by traffic lights | 1 |
| Containing stop signs | 15 |
| No interference | 2 |

Costanera Mar has a direct connection to Ruta Pie de Monte, Costanera Sur and Ruta 160. At the majority of the crossings it is possible to access and enter the road in both directions. But at three crossing it is only possible to access and exit the road from one direction.

2.1.5.2 Travel time

Table IV - 10: Potential interferences at Costanera Mar

| Type of interference | Amount |
|-------------------------------------|---------|
| Traffic lights | 1 |
| Pedestrian crossings | 0 |
| Public transport (bus) stops | Unknown |
| Stop signs | 1 |
| Maximum speed | 70 km/h |

The Costanera Mar functions as a bypass for the traffic from the communes in the South. There are only 2 sources for potential stops in this solution. This low number of stops was expected because if there were a lot of stops this would greatly decrease the efficiency of the bypass

2.1.6 Ruta Costa

2.1.6.1 Accessibility time

Table IV - 11: Access- and exit-point characteristics of Ruta Costa

| Access- and exit-point characteristics | Amount |
|--|--------|
| Total amount of access- and exit-points | 4 |
| Intersected by a railroad | 0 |
| Controlled by traffic lights | 0 |
| Containing stop signs | 0 |
| No interference | 4 |

Ruta Costa is connected to Ruta 160 and Costanera Sur. Access- and exit-points are free from interfering elements. This has a positive effect on the accessibility time.

2.1.6.2 Travel time

Table IV - 12: Potential interferences at Ruta Costa

| Type of interference | Amount |
|-------------------------------------|---------|
| Traffic lights | 0 |
| Pedestrian crossings | 0 |
| Public transport (bus) stops | 0 |
| Maximum speed | 70 km/h |

There are no crossings along the road and busses and pedestrians are not using the road, so also no possible delays.

2.1.7 Ruta Humedal

2.1.7.1 Accessibility time

Table IV - 13: Access- and exit-point characteristics of Ruta Humedal

| Access- and exit-point characteristics | Amount |
|--|--------|
| Total amount of access- and exit-points | 7 |
| Intersected by a railroad | 0 |
| Controlled by traffic lights | 0 |
| Containing stop signs | 0 |
| No interference | 7 |

Ruta Humedal can be accessed directly from the Industrial Bridge, Pedro Aguirre Cerda, Ruta 160 and Ruta Pie de Monte. The road forms thus an excellent connection between these roads and the Industrial Bridge.

2.1.7.2 Travel time

Table IV - 14: Potential interferences at Ruta Humedal

| Type of interference | Amount |
|-------------------------------------|---------|
| Traffic lights | 0 |
| Pedestrian crossings | 0 |
| Public transport (bus) stops | 0 |
| Maximum speed | 70 km/h |

There are no crossings along the road and busses and pedestrians are not using the road, so also no potential delays.

2.2 Costs

In this section the costs are analysed for the different solutions. This criterion concerns costs that the user of the road experiences due to usage of the road. This criterion is subdivided into three sub criteria; fuel costs, operational costs and toll fees.

In the travel time analysis already an overview was made of the amount of potential stops for every solution. This is used in this analysis again. Both sub categories are treated at once as they are both related to the number of stops.

2.2.1 Pedro Aguirre Cerda

2.2.1.1 *Fuel costs and Operational costs*

The total amount of potential stops on Pedro Aguirre Cerda sums up to 10. This is a relative large amount of stops that could greatly increase the fuel usage and the operational costs for the users

2.2.2 Ruta 160

2.2.2.1 *Fuel costs and Operational costs*

In the new design there are no more elements that can cause potential stops, which could increase the fuel usage or the operational costs for the users

2.2.3 Costanera Sur

2.2.3.1 *Fuel costs and Operational costs*

The Costanera Sur supports fluent traffic flow. On this road there are no elements that can cause potential stops and thus increase the fuel usage or operational costs for the users.

2.2.4 Ruta Pie de Monte

2.2.4.1 *Fuel costs and Operational costs*

The design of Ruta Pie de Monte does not contain any elements that can cause potential stops.

2.2.4.2 *Toll fee*

To make use of this road a toll fee has to be paid.

2.2.5 Costanera Mar

2.2.5.1 *Fuel costs and Operational costs.*

In the design of the Costanera Mar there are two possible elements that can lead to potential stops. These stops could increase the fuel usage on this road and the operational costs for the users.

2.2.6 Ruta Costa

2.2.6.1 *Fuel costs and operational costs*

Since there are no possible stops along this road, using this road does not cause extra fuel or operational costs.

2.2.7 Ruta Humedal

2.2.7.1 *Fuel costs and operational costs*

Since there are no possible stops along this road, using this road does not cause extra fuel or operational costs.

2.2.7.2 *Toll fee*

To make use of this road a toll fee has to be paid.

2.3 Environmental impact

In this section the environmental impact on of the different solutions is studied. This is done by looking at three different aspects of the environmental impact; ecological impact, river hydrodynamics based on Part II and tsunami inundation based on Part III.

2.3.1 Pedro Aguirre Cerda

2.3.1.1 Ecological impact

As seen in the map the Pedro Aguirre Cerda is situated in the city centre of San Pedro de la Paz. The improvement of the Pedro Aguirre Cerda runs only along urban areas and will thus not influence any flora or fauna.

2.3.2 Ruta 160

2.3.2.1 Ecological impact

A major part of Ruta 160 runs along residential, industrial and retail areas. This part has no mentionable impact on the environment. But at the northern end Ruta 160 crosses the wetlands. For this crossing a bridge has been built. To improve the capacity of Ruta 160 another bridge is built parallel to the existing one. The wetlands are seen as an important habitat for local flora and fauna. Because of the construction of the bridge part of the living area of the flora and fauna will be disturbed. The bridge will also form a barrier for the animals as it divides the wetlands in two parts and animals will have to cross the road.

2.3.2.2 River hydrodynamics

The bridges of Ruta 160 that cross the wetlands are an important control point for the lake-wetland system. They can strongly influence the extend of the flooded areas. The problem is that these bridges are designed based solely on their infrastructural function and not on their hydraulic function. Because of that the hydraulic capacity of these bridges is not sufficient. This can cause the wetlands to flood.

2.3.3 Costanera Sur

2.3.3.1 Ecological impact

The construction of the Costanera Sur will have a large impact on the flora and fauna in the area. First of all a lot of green areas near the bank of the river are lost due to the construction of the road. Secondly the road will form a barrier in the natural transition from river to land. Because of this barrier the animals will not be able to cross anymore from the river to the land. To do this they have to cross the road, which will result in a loss of animal live.

2.3.3.2 River hydrodynamics

The construction of the Costanera Sur does not have an effect on flood protection. This is because the riverbank was already high enough between the Puente Chacabuco and the Industrial Bridge. Secondly the Costanera Sur crosses the wetlands with a bridge. Meaning that in case of high water levels the wetlands are still flooded despite the construction of the Costanera Sur.

The Costanera Sur extends 30 meter into the river. This creates a reduction in the cross sectional area but it has no significant influence on the flow conditions in the river. The increase in water level is only a few centimetres.

2.3.3.3 Tsunami inundation

An elevated road as the Costanera Sur has no negative influences, if (and only if) it is built together with Ruta Costa. When it is built without Ruta Costa, it has no effect on the inundation area. In worst case it could even cause extra inundation in the wetland.

2.3.4 Ruta Pie de Monte

2.3.4.1 Ecological impact

As seen in the map the Ruta Pie de Monte crosses for a major part through natural forest. To be able to construct the road a major part of the forest has to be cut down. This leads to the destruction of the natural habit of the flora and fauna living here. Secondly the last part of Route Pie de Monte also runs through the wetlands. The construction of the road here will also mean that a great part of the wetlands gets lost. Finally the road runs through an area with a lot of hills. This means that certain parts of the hills have to be excavated to make room for the road.

2.3.5 Costanera Mar

2.3.5.1 Ecological impact

The Costanera Mar runs mainly through a wasteland between the dunes and the residential areas. The dunes are littered with garbage due to activities by the people living next to them. Almost no mentionable flora and fauna is present in this area. The construction of this road will thus have a minor ecological impact.

2.3.6 Ruta Costa

2.3.6.1 Ecological impact

The impact of the coastal highway on the environment is limited. The road will be built on top of the existing dunes. These dunes form a barren landscape with almost no important flora or fauna. The dunes are also littered with garbage due to activities by the people living next to them.

2.3.6.2 Tsunami inundation

Building an elevated road along the coast, or at least a barrier, will mitigate the inundation of the lower area of San Pedro de la Paz. However;

- It has to be at least 7.5 meters high for a 9.0 MW tsunami (and 6.5 meters for a 8.9 MW tsunami).
- It should be built as a proper breakwater, with armour on the landward side in case of overtopping, to avoid road collapse.

2.3.7 Ruta Humedal

2.3.7.1 Ecological impact

Ruta Humedal runs on the border between the farmlands and the wetlands. It does not run through the wetlands directly but the construction of the road can cause a lot of disturbance for the wetland area. Because of this it can have some impact on the local flora and fauna living here.

2.3.7.2 River hydrodynamics

The construction of Ruta Humedal through the wetlands and the farmlands reduces the cross sectional area significantly of the floodplains along the wetlands. But despite the reduction in cross sectional area the hydraulic behaviour of the stream in the wetlands is not influenced, since the water does not reach the embankment of Ruta Humedal in normal situations. Also, Ruta Humedal does not have any effect on the flooded area in case a flooding occurs, since the water level in the

lower reach of the wetlands has the same value as the water level in the Biobío River at the mouth of the wetlands, regardless of the presence of Ruta Humedal.

As described above the construction of Ruta Humedal does not have any effect on the stream itself. It can however block the rainfall run-off from the farmlands into the stream. This can generate flooding in the farmland zone in case of high rainfall events.

2.3.7.3 Tsunami inundation

Ruta Humedal has no visible effects on the inundation of the wetlands, since the bridge over Estero Los Batros will allow water to flow around it.

2.4 Social impact

In this section is the impact of the proposed solutions on the people living in San Pedro de la Paz is analysed on two aspects: evacuation routes and zone disturbance. The evacuation routes proposed by the municipality are indicated in Figure IV - 1 below. It is advised by the municipality to evacuate by foot. But it is rather common that people take their car. Although, this depends on the situation. It is determined by the distance and the amount of time they have to flee. This is something that should be taken into account in the analysis. In part I a map about class division is presented in Figure I - 2. This map is used in the analysis of the zone disturbance. It is convenient to know which area of a certain income class the solution will cross. People with a low income have a different opinion than people with a higher income. It is more likely to expect a protest from the upper class, because people with a low income give priority to the basic needs in life.

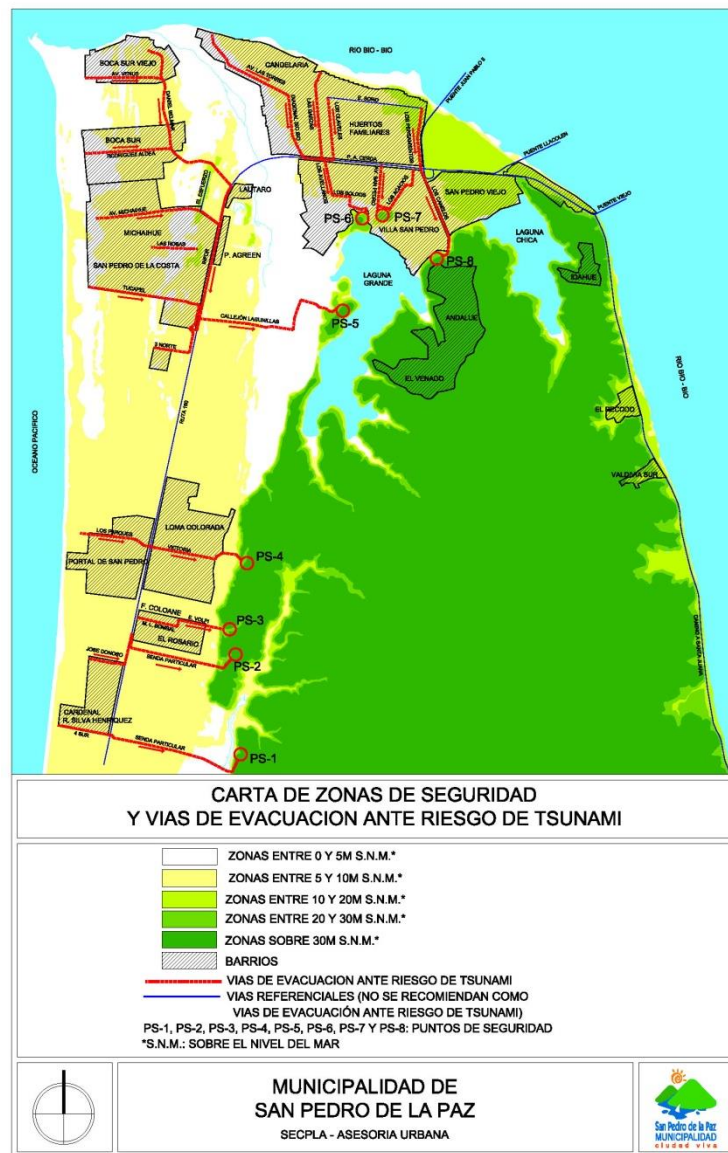


Figure IV - 1: Recommended tsunami evacuation routes

2.4.1 Pedro Aguirre Cerda

2.4.1.1 Evacuation routes

As can be seen from Figure IV - 1 Pedro Aguirre Cerda forms a barrier to the people who live in the area between the Biobío River and Pedro Aguirre Cerda. At the moment the traffic density at the Pedro Aguirre Cerda is high. If the quality of the road improves, this will attract more traffic and the density will rise even more. Because of this it becomes even harder to cross the road, so Pedro Aguirre Cerda becomes an even bigger barrier. This implies a negative impact related to the evacuation routes.

2.4.1.2 Zone disturbance

Pedro Aguirre Cerda is located in the city centre of San Pedro de la Paz. This road crosses a residential area with houses directly adjacent to the road. People living in this area belong to the low-medium income class and medium-high income class. The class division within San Pedro de la Paz can be seen in Figure I - 2. At the present the road is already part of the primary infrastructure. An improvement of this road will not actually add any harm. It might even improve the current satisfaction of the people living near the road because the road might become easier to access due to the improvements. On the other hand, if the capacity of the road increases, the traffic density increases as well and consequently the noise increases.

2.4.2 Ruta 160

2.4.2.1 Evacuation routes

Ruta 160 is an important road in case of evacuation. A lot of people have to cross this road. Currently the road is used to its full capacity. This might complicate things, because it is hard to access the road and people might not be able to cross the road if they are forced to flee. Building a road parallel to Ruta 160 results in a decreased traffic density at Ruta 160, which implies a positive impact regarding the evacuation routes. Improving Ruta 160 results in a higher density, but also improves crossings, which actually makes it easier to access to road.

2.4.2.2 Zone disturbance

This road crosses different zones. Adjacent to the road some residential areas can be found, industrial areas, equipment areas, retail areas, forest and a cemetery. Residential areas consist of low-medium and medium-high class houses. Plans for the near future are to increase the amount of retail areas adjacent to the road.²⁶ Behind these retail areas, everything will be packed with houses. If these plans are completed, no forest will be left adjacent to the road. Improvement of the road will not harm the people in these residential areas. Again, it might even improve the current satisfaction of the people living in the vicinity. As the quality of the intersections will improve significantly, it becomes easier to access the road, which improves the connectivity to the city centre of San Pedro de la Paz. For retail it is actually convenient to be situated next to such an important traffic access.

2.4.3 Costanera Sur

2.4.3.1 Evacuation routes

The Costanera Sur has no mentionable impact on the evacuation routes.

2.4.3.2 Zone disturbance

Costanera Sur runs along the south bank of the Biobío River, along some residential areas, industrial areas and the wetlands. This road is built in extension of Ruta 156 and can provide an excellent

²⁶ (Municipality)

connection to the bridges that cross the Biobío River. Because of this Costanera Sur is an attractive alternative for trucks, as they avoid going through the centre of San Pedro de la Paz by taking this road. The residential areas that Costanera Sur passes by mainly belong to the low-medium income class with currently a wonderful view on the Biobío River. The road crosses a minor part over the wetlands. This can cause damage to the natural environment. This is already explained in the section environmental impact.

2.4.4 Ruta Pie de Monte

2.4.4.1 *Evacuation routes*

Ruta Pie de Monte is a major barrier regarding the evacuation routes. The road blocks evacuation routes for multiple residential areas. When taking into account the construction plans for even more residential areas in the vicinity of this road, the negative impact becomes even bigger. On top of that the road will be constructed as a private road. An important aspect of private roads is that it is in most cases surrounded by fences. If this is the case for Ruta de Pie de Monte then it will block the evacuation routes for a lot of people.

2.4.4.2 *Zone disturbance*

This road crosses through the wetlands, the cemetery and a forest. According to the master plan of the local municipality this forest will be transformed into residential areas. The road is supposed to be mainly used by trucks. The density of the trucks is currently 1000 trucks/day. Ruta Pie de Monte consists of four lanes, and a maximum speed of 70 km/h is allowed. This may be harmful to the people living in these residential areas. Trucks are very noisy and a road mainly occupied by trucks is definitely not something people wish to have in their backyard. Constructing Ruta Pie de Monte may be harmful to the value of the houses within the residential areas adjacent to the road. Furthermore, the road crossing through the wetlands causes severe damage to the natural environment as explained in the section environmental impact.

2.4.5 Costanera Mar

2.4.5.1 *Evacuation routes*

Costanera Mar is no barrier. As said before, building a road parallel to Ruta 160 results in a decreased traffic density on Ruta 160, which implies a positive impact regarding the evacuation routes because the road becomes easier to access or cross.

2.4.5.2 *Zone disturbance*

The Costanera Mar is situated parallel to Ruta Costa. The road is currently only partly built and crosses several residential areas. The road is used by locals of the low- and medium-income class residential areas. If the different sections of this road will be connected, the number of lanes will increase and consequently the amount of traffic on the road. This might hamper the accessibility to the road for the locals. Since this is something that actually is important to them a protest can be expected.

2.4.6 Ruta Costa

2.4.6.1 *Evacuation routes*

Ruta Costa functions the same as Costanera Mar. It is no barrier and even has a positive impact regarding the evacuation routes.

2.4.6.2 Zone disturbance

This road is constructed on top of the dunes along the coast and does not cross any residential areas directly. The closest residential areas consist of houses from different classes. At the low class residential area the road runs through a wasteland. The people living here are so busy with work and facilitating their basic needs that they do not have the time or possibility to enjoy their proximity to the beach. This becomes apparent from the large amount of garbage that is dumped here. They probably do not mind the fact that the Ruta Costa hinders their access to the beach for instance. Ruta Costa also crosses some high income residential areas. A protest from the people that live here can be expected because they currently have a wonderful view at the beach and the sea.

2.4.7 Ruta Humedal

2.4.7.1 Evacuation routes

The Ruta Humedal has no mentionable impact on the evacuation routes.

2.4.7.2 Zone disturbance

Ruta Humedal crosses farmlands, wetlands and equipment areas. The impact on the farm- and wetlands is already described in the previous section. Equipment areas will not experience disturbances due to the construction of this road.

2.5 Safety

In this section the safety analysis of the proposed solutions is presented.

2.5.1 Pedro Aguirre Cerda

2.5.1.1 Complexity

Transportation modes:

- Cars
- Busses
- Pedestrians
- Trucks
- Railway
- Bicycles

The design of Pedro Aguirre Cerda contains all the different types of transportation. The presence of exclusive bus lanes in the middle of the road creates order, as the traffic flows are no longer intertwined. This leads to a decreased complexity. Furthermore the crossings are dominated by traffic lights. This contributes greatly to the safety of this road. However, all crossings are at street level. Four crossings even include a railroad. These crossings have a negative impact on the safety of this road. First, there is a traffic light at the turn. Then, between the traffic light and the railroad, there is a stop sign. Users of the road have to look for themselves if a train is approaching, while waiting on a slope. There are no bars or lights that stop a road user from crossing the railroad if a train passes.

2.5.1.2 Signposting

In the design there is a shortage in signs indicating an approaching exit point. Signs warning for pedestrian crossings are implemented in the design.

2.5.1.3 Speeding

Most of the access points/crossings at Pedro Aguirre Cerda are controlled by traffic lights. This means that the traffic has to stop a lot and will not be able to continue speeding. This contributes to the safety of the road.

2.5.1.4 Area

The road runs along the city centre of San Pedro de la Paz. This is a crowded area. From this it can be concluded that the road runs through a safe area.

2.5.2 Ruta 160

2.5.2.1 Complexity

Transportation modes:

- Cars
- Busses
- Pedestrians
- Trucks
- Railway
- Bicycles

Since crossings are not at street level anymore, different traffic flows can continue without interfering each other. At access-, and exit-points an extra lane is added to the road. Traffic continuing driving straight on does not encounter any interference at all.

The design of Ruta 160 is still in the feasibility stage. These studies are not completed yet. So the amount of exclusive bus lanes included in the design is not decided yet. As there also is no information available about the bus stops. But it is safe to assume that there will be exclusive bus lanes implanted into the design.

The design of Ruta 160 includes a bike lane on one side of the road and space for pedestrians on both sides of the road. Two major crossings/access points are below street level. At these particular crossings it is possible to leave the road to both sides for bikers and pedestrians.

2.5.2.2 Signposting

Signs that provide information about approaching exit lanes and possible destinations are available at only two locations. On top of that the placing of the signs is again to close to the actual exit.

2.5.2.3 Speed

It is possible to drive the road without any interference at all, since crossings are not at street level anymore, and there are no traffic lights along the road. So it is easy to accelerate to a high speed. The maximum allowed speed is 80 km/h.

2.5.2.4 Area

Ruta 160 does not cross any dangerous/unsafe neighbourhoods.

2.5.3 Costanera Sur

2.5.3.1 Complexity

Transportation modes:

- Cars
- Busses
- Pedestrians
- Trucks
- Railway
- Bicycles

The design of Costanera Sur focuses on four out of the six transportation modes. A bike lane is included on one side of the road and there are pedestrian sidewalks on both sides of the road. The design of the road does not include exclusive bus lanes, but there are also no bus stops along the road. From this we can assume that busses will not use the road. Crossings are not being complicated by a railway, since there is no railway crossing the road. This contributes to the safety of the road.

Access and exit points are on street level. There are no traffic lights that control the crossings. The road can be left via an exclusive exit lane, straight on going traffic can continue without interference. Connections with Puente Industrial and Puente Juan Pablo II are above street level. At the point where Costanera Sur approaches Puente Chacabuco the users of the road encounter a complex crossing. Costanera Sur meets three other roads at this crossing: Puente Chacabuco, Ruta 156 and Pedro Aguirre Cerda. This crossing is dominated by stop signs, priority signs and includes a traffic light. Along the road there are multiple access and exit points. At all these crossings/exit/access points no thought is given to bikes or pedestrians. The bike lane is situated at the opposite side of the road. If cyclists approach the complex crossing at the Puente Chacabuco, the bike lane just stops. There are no pedestrian crossings along Costanera Sur.

2.5.3.2 Signposting

Only at the exit points to Puente Llacolen, Puente Juan Pablo II and Puente Industrial signposting is present on one side of the road. These signs are not introduced until the exit starts. For the other side of the road no directional information is available.

2.5.3.3 Speeding

The design of Costanera Sur allows users to speed up. There are no traffic lights along the road, and straight on traveling traffic can continue without interference along the entire road.

2.5.3.4 Area

Costanera Sur runs along the south bank of the Biobío river and does not cross any dangerous neighbourhoods.

2.5.4 Ruta Pie de Monte

2.5.4.1 Complexity

Transportation modes:

- Cars
- Busses
- Pedestrians
- Trucks
- Railway
- Bicycles

The design of Ruta Pie de Monte focuses on the same transportation modes as Costanera Sur. The design includes a bike lane on one side of the road, and pedestrian sidewalks on both sides. There are no exclusive bus lanes and no bus stops along the road. Access- and exit points and the road itself do not encounter a railway track. Furthermore the design of every crossing is the same. This consistency contributes to the safety of the road because the users know what to expect. The design of the crossings does not include the possibility for bikers and pedestrians to cross to the opposite side of the road. This results in less complex crossings, but it is not convenient for bikers and pedestrians that use the road. This can result in unsafe situations if bikers and pedestrians cross the road anyway.

2.5.4.2 Signposting

Signposting is present at only one point of the road. That is where the road connects to Ruta 160 and Costanera Mar. There is no signposting containing information about approaching exit lanes and destinations along the entire road and also no signposting at the point where the road connects to Ruta Humedal.

2.5.4.3 Speed

Since there are no traffic lights at crossings and the road contains separate lanes for vehicles that exit the road, it is possible to speed up without any disturbances. Vehicles that enter the road have to wait until the road becomes clear to enter.

2.5.4.4 Area

Ruta Pie de Monte runs through hills and passes through residential areas and wetlands. These are all safe areas.

2.5.5 Costanera Mar

2.5.5.1 Complexity

Transportation modes:

- Cars
- Busses
- Pedestrians
- Trucks
- Railway
- Bicycles

The design of Costanera Mar focuses on the same four transportation modes as Ruta Pie de Monte and Costanera Sur. The design includes a bike lane on one side of the road and pedestrian sidewalks on both sides. There are no exclusive bus lanes and no bus stops along the road. Access- and exit points and the road itself do not encounter a railroad track.

Crossings are designed simple. It is easy to access or exit the road. Through going traffic can continue without interference. Traffic exits the road via separate exit lanes. Traffic that accesses the road has to give priority to the traffic already using the road. Again, the design of the crossings does not include the possibility for bikers and pedestrians to cross to the opposite side of the road. This results in less complex crossings, but it is inconvenient for bikers and pedestrians that use the road. This can result in unsafe situations if bikers and pedestrians cross the road anyway.

2.5.5.2 Signposting

The signposting is limited to the location where you access the Costanera Mar from Ruta 160. For the remainder of the road there are no signs at all until the access point to the Industrial Bridge.

2.5.5.3 Speed

It is again possible to speed up without any interference. There are no traffic lights at crossings, the road contains separate lanes for vehicles that exit the road, and vehicles accessing the road have to give priority to vehicles that are already using the road.

2.5.5.4 Area

Costanera Mar runs through dunes and crosses some low-income areas. Entering these areas can cause unsafe situations.

2.5.6 Ruta Costa

2.5.6.1 Complexity

Transportation modes:

- Cars
- Busses
- Pedestrians
- Trucks
- Railway
- Bicycles

The design of Ruta Costa includes four vehicle lanes to be used by mixed transportation modes. The road can only be accessed or exited at the connection to Costanera Sur and the connection to Ruta 160. Since the road is elevated and located at a distance of 200 m from residential areas it is not

convenient to have bus stops along this road. From this it can be assumed the amount of busses on the road is negligible. The design includes one bike lane, located at the side opposite to the coast, this way there is no need for cyclist to cross the road at any time. Besides that, there are no crossings along the entire road. The connections to Costanera Sur and Ruta 160 have a simple design. Vehicles that access or exit the road make use of an exclusive lane. These connections are free from interfering elements.

2.5.6.2 Signposting

There is no information available about the signposting along Ruta Costa. Since there are no crossings, it is only needed to place signs in time before approaching of exit lanes.

2.5.6.3 Speeding

Traffic on Ruta Costa can continue without any interference, so it is again possible to speed up. The maximum allowed speed on this road is assumed to be 80 km/h.

2.5.6.4 Area

Ruta Costa is an elevated road along the coast of the Pacific Ocean. The road runs parallel to Costanera Mar, but is located 200 m further towards the coast. Costanera Mar passes through unsafe areas. Because of the fact that Ruta Costa is elevated to 7,5 m and because the road is located a significant distance from these unsafe areas, this does not hold for Ruta Costa. The area that the road runs through is considered to be safe.

2.5.7 Ruta Humedal

2.5.7.1 Complexity

Transportation modes:

- Cars
- Busses
- Pedestrians
- Trucks
- Railway
- Bicycles

The design of Ruta Humedal is assumed to be the same as the design of Ruta Pie de Monte except for the pedestrian sidewalks. The road has four lanes available for cars or trucks, and a bike lane on one side of the road. The road is easy to access and along the road there are no crossings. This contributes to the safety of the road.

2.5.7.2 Signposting

There is no information available about the signposting along Ruta Humedal. Since there are no crossings, it is only needed to place signs in front of exit lanes.

2.5.7.3 Speeding

It is again possible to speed up without any interference. The maximum allowed speed on this road is assumed to be 70 km/h.

2.5.7.4 Area

Ruta Humedal runs through the wetlands. And passes through farmland. These are both safe areas.

2.6 Comfort

In this section the analysis on comfort is done.

2.6.1 Pedro Aguirre Cerda

2.6.1.1 *Drivability*

The drivability on the Pedro Aguirre Cerda is limited due to the presence of nine crossings dominated by traffic lights. The busses use exclusive bus lanes. This improves the fluency of the traffic flow and with that the drivability. Signs that indicate an approaching exit lane are almost not present. On top of that they are placed right at the start of the exit lane or even at the end of the exit lane. This increases the difficulty to get into the right lane. Especially for people not familiar with the area

2.6.1.2 *Bike lanes*

The design of Pedro Aguirre Cerda contains a bike lane. The design of this bike lane is not available in the information received from SECTRA. Because there are many traffic lights at Pedro Aguirre Cerda it is assumed there are plenty of possibilities to cross the road, which contributes to the comfort experienced by cyclists.

2.6.1.3 *Bus stops*

Pedro Aguirre Cerda is currently the only road containing exclusive bus lanes. Meaning that the busses can drive without interference from other transportation modes.

2.6.1.4 *Surroundings*

Pedro Aguirre Cerda runs through the city centre of San Pedro de la Paz. These surroundings do not contribute to a comfortable and relaxing drive.

2.6.2 Ruta 160

2.6.2.1 *Drivability*

The drivability on Ruta 160 is excellent because the crossings are elevated and not on street level anymore. This leads to a driving experience without any disturbances like traffic lights or pedestrian crossings. The design of Ruta 160 is still in the feasibility stage. These studies are not completed yet. So the amount of exclusive bus lanes included in the design it is not decided yet.

2.6.2.2 *Bike lanes*

The design of Ruta 160 contains a bike lane at one side of the road. The only comfortable points to access or exit the bike lane is at the two elevated crossing. At other locations it is also possible to access or exit Ruta 160. However, it is not comfortable to exit the road at these locations, because a railroad has to be crossed and the bike lane does not continue. On top of that it is impossible to access the bike lane from the other side of the road.

2.6.2.3 *Bus stops*

Since there is no information available on the decisions regarding the busses on Ruta 160 yet, nothing can be concluded about the amount and locations of bus stops.

2.6.2.4 *Surroundings*

Ruta 160 is located between two urban areas. Retail points and equipment storage dominate the area right next to the road. Also parallel to the road runs the railway. These surroundings do not provide the users with attractive sights.

2.6.3 Costanera Sur

2.6.3.1 *Drivability*

There are no traffic lights that can influence the drivability on Costanera Sur. There are separate lanes to exit the road and users accessing the road have to give priority to the on going traffic. Also the connections to Puente Industrial and Juan Pablo II are elevated and not on street level. This creates an excellent drivability for Costanera Sur. Because Costanera Sur is designed as a bypass for vehicles, the amount of access- and exit-points is limited. Besides, there are no pedestrian crossings along the road. Because of this it is inconvenient to have bus stops along this road. Adding bus stops to Costanera Sur would significantly decrease the drivability of the road.

2.6.3.2 *Bike lanes*

In the design there is a bike lane present on one side of the road. The only two points to exit or access the bike lane are at the connection to Puente Industrial and Enrique Soro. It is impossible to access or exit the bike lane at any other point. The bike lane runs along the entire Costanera Sur and has a direct connection to the bike lane of Costanera Mar. On the opposite end of the road the bike lane users are faced with a complex crossing and the bike lane suddenly ends.

2.6.3.3 *Bus stops*

This road is not used by public transport because of that there are no bus stops along Costanera Sur.

2.6.3.4 *Surroundings*

The road runs along the water and offers an attractive view on the Biobío River creating a comfortable ride.

2.6.4 Ruta Pie de Monte

2.6.4.1 *Drivability*

All the crossings on Ruta Pie de Monte are designed in exactly the same way. The crossings are on street level but they do not contain any traffic lights. This is because the exiting traffic has an exclusive lane and the accessing traffic has to give priority to the on going traffic. The consistency in the design of the crossings and the undisturbed traffic flow together create an excellent drivability. Ruta Pie de Monte is a private road without any public transport improving the drivability even more.

2.6.4.2 *Bike lanes*

Although Ruta Pie de Monte is a private road there is a bike lane present on one side of the road in the design. Just like for Ruta 160 it is only possible to access or exit the bike lane from side of the road. The only two comfortable locations to exit or access the bike lane are found at the end and the beginning of the road. At the end it connects with Ruta Humedal and in the beginning it connects to Ruta 160 and Costanera Mar. In between these two locations the possibility to exit or access is limited. On top of that it is impossible to cross the road by bike along entire Ruta Pie de Monte.

2.6.4.3 *Bus stops*

There are no bus stops along Ruta Pie de Monte.

2.6.4.4 *Surroundings*

The road runs through areas with hills and forest. This offers nice views and creates a comfortable ride.

2.6.5 Costanera Mar

2.6.5.1 *Drivability*

Despite all crossings on Costanera Mar are on street level, only one of the crossings has a traffic light. Traffic exiting the road is provided with an exclusive lane and accessing traffic has to give priority to the on going traffic. This results in a good drivability on Costanera Mar. It is not known yet if Costanera Mar will be used by public transport. The current design of the road does not contain exclusive bus lanes or bus stops along the road. So it is assumed this road will not be used by public transport.

2.6.5.2 *Bike lanes*

In the design of Costanera Mar there is one bike lane at the ocean side of the road. It is easy to access the road from the Ruta Pie de Monte, Costanera Sur and Ruta 160. But in between the end and the start of the road there is no possibility at all to cross the Costanera Mar by bike. This creates an uncomfortable situation, as the users have to be prepared to travel a large distance if they want to use this road.

2.6.5.3 *Bus stops*

There are no bus stops along Costanera Mar.

2.6.5.4 *Surroundings*

Costanera Mar is situated between urban areas on one side and wasteland on the other side. This wasteland is littered with trash from the inhabitants of the urban areas. This does not contribute to the comfort of the road.

2.6.6 Ruta Costa

2.6.6.1 *Drivability*

The drivability of Ruta Costa is excellent since there are no crossings along the road. The access- and exit-points are free from traffic lights or other possible interferences. It is expected that the traffic flows continuously along the entire road.

2.6.6.2 *Bike lanes*

Ruta Costa contains a bike lane along one side of the road. This bike lane runs along the opposite side of the coast and continues onto the connected roads. It is not possible to exit Ruta Costa at another point. Since Ruta Costa is an elevated road, it is not easy to implement some exit points into the design to connect this bike lane to the existing network of bike lanes.

2.6.6.3 *Bus stops*

Ruta Costa will not be used by busses, equivalently there are no bus stops along the road.

2.6.6.4 *Surrounding*

Ruta Costa is an elevated road along the coast of the Pacific Ocean. This offers a nice view to the users of the road, which contributes to a comfortable ride.

2.6.7 Ruta Humedal

2.6.7.1 *Drivability*

The drivability of Ruta Humedal is excellent since there are no crossings along the road. The access- and exit-points are free from traffic lights or other possible interferences. It is expected that the traffic flow can continue along the entire road. Delays can be caused by the presence of trucks at the

road. Since this road can be seen as an extension of Ruta Pie de Monte, it can be expected that a lot of trucks use the road.

2.6.7.2 Bike lanes

Ruta Humedal contains a bike lane along one side of the road. This bike lane continues onto the connected roads. It is not possible to exit Ruta Humedal at another point, simply because there are no other crossings.

2.6.7.3 Bus stops

There are no bus stops along Ruta Humedal.

2.6.7.4 Surroundings

Ruta Humedal runs through wetlands and farmland. This is a quiet area. Driving this road might be a restful experience.

2.7 Co-benefits

2.7.1 Pedro Aguirre Cerda

The improvement of the Aguirre Cerda does not provide any mentionable co-benefits.

2.7.2 Ruta 160

From the development plans for San Pedro de la Paz it becomes clear that in the future, the open spaces now surrounding Ruta 160 will be used as retail areas. For retail areas it is important that they have a good access to the main road. The improvement of Ruta 160 can increase the access to these retail areas.

2.7.3 Costanera Sur

Costanera Sur runs along the riverbank. Due to its location along the riverbank the road could have a multifunctional purpose. It could both be a road and a river flooding barrier. To be able to function as a flood barrier the road should have an elevation as described in Part II.

2.7.4 Ruta Pie de Monte

The construction of Ruta Pie de Monte does not provide any co-benefits.

2.7.5 Costanera Mar

The area that the Costanera Mar runs through and the dunes behind it are littered with garbage. This waste is dumped here by the locals living in the low-income areas of Boca Sur. The construction of the road could prevent the use of this land as a garbage dump. First of all people are less likely to dump garbage on a functioning road. Secondly the road will form a kind of barrier between the urban areas and the dunes.

2.7.6 Ruta Costa

The construction of the Coastal Highway provides the co-benefit to function as a tsunami barrier. The road is constructed along the coast of San Pedro de la Paz. Due to its elevation the road functions as a road and at the same time as a barrier in case of an incoming tsunami.

2.7.7 Ruta Humedal

The construction of Ruta Humedal does not provide any co-benefits.

3 MCA Step 1: Weighting criteria

In Part I the criteria were identified and described. The next step is to indicate the importance of the different criteria. This process is called the ‘weighting’ of the criteria. By doing this, the relative importance of the criteria becomes clear. The end result of the weighting of the criteria is a quantitative score for every criterion.

Determining the weight of the different criteria is done by so called pairwise comparison. This means that two criteria are compared and that it is decided which one is more important or that they are equally important. This is done for all possible pairs of criteria.

In practice this weighting is done by either experts on the different criteria or by the people who make the final decision about the project. In the timeframe of this research there was no possibility to contact either experts or the people responsible for the final decision. Because of that the pairwise comparison was presented in a survey to the students of the UCSC in Concepcion. The results of these surveys are used to determine the relative weight of the different criteria. An example of the survey can be found in the Appendix IV-A.

The survey is completed by 31 students of the UCSC in Concepcion. The students that took part in the survey were either from San Pedro de La Paz or Coronel. The results of the survey can be found in Appendix IV-A.

To prevent a subjective view on the weighting of the criteria, the members of the multidisciplinary team also participated the survey.

3.1 Relative weights criteria 1

Based on the result of the survey as filled in by the students, the relative weights are determined. This is visualised in

Table IV - 15.

| <i>Scaled importance (2=more 1=equal 0=less)</i> | Costs | Time | Environmental impact | Social impact | Safety | Comfort | Co- Benefits |
|--|------------|------------|-------------------------|------------------|------------|------------|-----------------|
| Costs | X | 1 | 0 | 0 | 2 | 0 | 0 |
| Time | 1 | X | 0 | 0 | 1 | 0 | 0 |
| Env. Impact | 2 | 2 | X | 1 | 2 | 1 | 0 |
| Social impact | 2 | 2 | 1 | X | 2 | 2 | 2 |
| Safety | 0 | 1 | 0 | 0 | X | 0 | 0 |
| Comfort | 2 | 2 | 1 | 0 | 2 | X | 0 |
| Co-benefits | 2 | 2 | 2 | 0 | 2 | 2 | X |
| Total | 9 | 10 | 4 | 1 | 11 | 5 | 2 |
| Scaled total | 1.3 | 1.4 | 0.6 | 0.1 | 1.6 | 0.7 | 0.3 |

Scoring system:

0: the criterion is less important than the criterion that it is compared with.

1: the criterion is equally important as the criterion it is compared with

2: the criterion is more important than the criterion it is compared with

The scores (0, 1 or 2) are summed per criterion to find the total score per criterion. This total score is then divided by 7 (the amount of criteria) to come up with the scaled total. These scaled totals represent the relative weight of the different criteria.

Table IV - 15: Relative weight criteria based on survey presented to students

| <i>Scaled importance (2=more 1=equal 0=less)</i> | Costs | Time | Environmental impact | Social impact | Safety | Comfort | Co- Benefits |
|--|------------|------------|-------------------------|------------------|------------|------------|-----------------|
| Costs | X | 1 | 0 | 0 | 2 | 0 | 0 |
| Time | 1 | X | 0 | 0 | 1 | 0 | 0 |
| Env. Impact | 2 | 2 | X | 1 | 2 | 1 | 0 |
| Social impact | 2 | 2 | 1 | X | 2 | 2 | 2 |
| Safety | 0 | 1 | 0 | 0 | X | 0 | 0 |
| Comfort | 2 | 2 | 1 | 0 | 2 | X | 0 |
| Co-benefits | 2 | 2 | 2 | 0 | 2 | 2 | X |
| Total | 9 | 10 | 4 | 1 | 11 | 5 | 2 |
| Scaled total | 1.3 | 1.4 | 0.6 | 0.1 | 1.6 | 0.7 | 0.3 |

Next the relative weights are determined based on the same survey. But in this case the multidisciplinary team itself did the survey. This is to check whether the weight the research team gives to the criteria differs from the weight the students assign to the criteria. These results are given in Table IV - 16 below.

Table IV - 16: Relative weight criteria based on survey presented to research team

| <i>Scaled importance (2=more 1=equal 0=less)</i> | Costs | Time | Environmental impact | Social impact | Safety | Comfort | Co- Benefits |
|--|------------|------------|-------------------------|------------------|------------|------------|-----------------|
| Costs | X | 2 | 1 | 2 | 2 | 0 | 1 |
| Time | 0 | X | 1 | 2 | 2 | 2 | 0 |
| Env. Impact | 1 | 1 | X | 2 | 2 | 0 | 0 |
| Social impact | 0 | 0 | 0 | X | 2 | 0 | 0 |
| Safety | 0 | 0 | 0 | 0 | X | 0 | 0 |
| Comfort | 2 | 0 | 2 | 2 | 2 | X | 2 |
| Co-benefits | 1 | 2 | 2 | 2 | 2 | 0 | X |
| Total | 4 | 5 | 6 | 10 | 12 | 2 | 3 |
| Scaled total | 0.6 | 0.7 | 0.9 | 1.4 | 1.7 | 0.3 | 0.4 |

3.2 Results

First the results from the survey are presented as done by the students. They are ranked from most important to least important. The results are based on the values in

Table IV - 15.

| <i>Scaled importance (2=more 1=equal 0=less)</i> | Costs | Time | Environmental impact | Social impact | Safety | Comfort | Co- Benefits |
|--|------------|------------|-------------------------|------------------|------------|------------|-----------------|
| Costs | X | 1 | 0 | 0 | 2 | 0 | 0 |
| Time | 1 | X | 0 | 0 | 1 | 0 | 0 |
| Env. Impact | 2 | 2 | X | 1 | 2 | 1 | 0 |
| Social impact | 2 | 2 | 1 | X | 2 | 2 | 2 |
| Safety | 0 | 1 | 0 | 0 | X | 0 | 0 |
| Comfort | 2 | 2 | 1 | 0 | 2 | X | 0 |
| Co-benefits | 2 | 2 | 2 | 0 | 2 | 2 | X |
| Total | 9 | 10 | 4 | 1 | 11 | 5 | 2 |
| Scaled total | 1.3 | 1.4 | 0.6 | 0.1 | 1.6 | 0.7 | 0.3 |

1. Safety
2. Time

3. Costs
4. Comfort
5. Environmental impact
6. Co-benefits
7. Social impact

Secondly the results from the survey as done by the research team are presented. Again they are ranked from most to least important based on the values in Table IV - 16.

1. Safety
2. Social impact
3. Environmental impact
4. Time
5. Costs
6. Co-benefits
7. Comfort

4 MCA Step 2: Scoring of the variants

The next step in the MCA-process is to judge how the different variants score on the previously defined criteria. This step in the MCA process is called the “scoring” of the variants. Each variant is assigned a qualitative score (1-5) per criteria. Unlike the weighting that was done in the previous chapter, these scores are absolute scores. The scores are based on the analysis that is done per solution on the different criteria and sub criteria.

4.1 Absolute scoring process

The first step is executing the scoring on solution level. Meaning that for every solution a score is given ranging from 1 to 5 for the different sub-criteria that make up a criterion. The result of this scoring process is presented in Table IV - B1 in Appendix IV-B.

To create an understandable basis for the scores and provide more insight into the scoring process, the scores are elaborated on. This is done by explaining per sub-criterion what a score of 1 to 5 exactly represents. The elaboration on the scores can be found in Appendix IV-C.

The second step is combining the scores for the sub-criteria into one score for a complete criterion. This is done by summing up the scores of the different sub-criteria that make up a criterion and take the average. The results are given in Table IV - 17 below.

Table IV - 17: Absolute score on solution level

| Absolute score (1-5) | Time | Costs | Environmental impact | Social Impact | Safety | Comfort | Co-benefits | Total |
|----------------------------|------|-------|----------------------|---------------|--------|---------|-------------|-------------|
| Pedro Aguirre Cerda | 1.5 | 3.0 | 3.7 | 1.5 | 3.5 | 3.8 | 1.0 | 18.0 |
| Ruta 160 | 4.5 | 5.0 | 2.3 | 3.5 | 2.8 | 4.3 | 5.0 | 27.4 |
| Costanera Sur | 3.0 | 5.0 | 1.7 | 4.0 | 2.8 | 3.5 | 1.0 | 21.0 |
| Ruta Pie de Monte | 4.5 | 3.0 | 2.3 | 2.0 | 2.8 | 3.5 | 1.0 | 19.1 |
| Costanera Mar | 2.5 | 3.0 | 3.3 | 4.0 | 1.8 | 2.5 | 5.0 | 22.1 |
| Ruta Costa | 4.0 | 5.0 | 4.0 | 3.0 | 3.5 | 3.5 | 5.0 | 28.0 |
| Ruta Humedal | 5.0 | 3.0 | 1.7 | 5.0 | 4.0 | 3.5 | 1.0 | 23.2 |

The final step is to combine the score of the different solutions into a score per criterion on a variant level. To do this the scores of the different solutions that together form a variant are summed and after that the average is taken. The results of this third step are presented in Table IV - 18.

Table IV - 18: Absolute score on variant level

| Absolute score (1-5) | Time | Costs | Environmental impact | Social impact | Safety | Comfort | Co-Benefits | Total |
|----------------------|------|-------|----------------------|---------------|--------|---------|-------------|-------------|
| Variant 1A | 2.9 | 4.0 | 2.8 | 4.3 | 2.7 | 3.4 | 3.0 | 23.1 |
| Variant 1B | 3.3 | 4.5 | 2.9 | 3.0 | 3.1 | 3.8 | 3.0 | 23.6 |
| Variant 2A | 3.6 | 3.4 | 2.7 | 3.2 | 3.0 | 3.4 | 2.6 | 21.9 |
| Variant 2B | 3.9 | 3.8 | 2.8 | 3.0 | 3.3 | 3.7 | 2.6 | 23.1 |
| Variant 3 | 3.8 | 3.5 | 2.7 | 3.5 | 3.0 | 3.4 | 3.0 | 22.9 |

4.2 Results

Below a ranking is given ranging from the highest absolute score to the lowest absolute score for the different solution, based on the values in Table IV-17

1. Ruta Costa (28.0)
2. Ruta 160 (27.4)
3. Ruta Humedal (23.2)
4. Costanera Mar (22.1)
5. Costanera Sur (21.0)
6. Ruta Pie de Monte (19.1)
7. Pedro Aguirre Cerda (18.0)

Below a ranking is given ranging from the highest absolute score to the lowest absolute score for the different variants. Based on the values in Table IV-18.

1. Variant 1B (23.6)
2. Variant 1A (23.1)
3. Variant 2B (23.1)
4. Variant 3 (22.9)
5. Variant 2A (21.9)

5 MCA Step 3: Relative weighted scores.

The final step of the MCA process is determining the relative weighted scores. This combines both the absolute scores based on the analysis and the relative weights of the criteria based on the surveys

5.1 2.1 Relative weighted scores

Calculating the relative weighted score for the criteria is achieved by multiplying the absolute scores of a criterion with its relative weight. This is done for all the criteria and the results are presented in the tables below. Table IV - 19 represents the relative weighted scores based on the weights assigned to the criteria as determined by the students. Table IV - 20 represents the relative weighted scores based on the criteria as weighted by the multidisciplinary team.

Table IV - 19: Relative weighted scores variant level (students)

| Relative weighted score | Costs | Travel time | Environmental impact | Social impact | Safety | Comfort | Co-Benefits | Total |
|-------------------------|-------|-------------|----------------------|---------------|--------|---------|-------------|-------------|
| Variant 1A | 3.7 | 6.0 | 1.6 | 0.6 | 4.2 | 2.4 | 0.9 | 19.5 |
| Variant 1B | 4.2 | 6.4 | 1.7 | 0.4 | 4.9 | 2.7 | 0.9 | 21.2 |
| Variant 2A | 4.6 | 5.1 | 1.5 | 0.5 | 4.7 | 2.4 | 0.7 | 19.7 |
| Variant 2B | 5.0 | 5.4 | 1.6 | 0.4 | 5.2 | 2.6 | 0.7 | 21.0 |
| Variant 3 | 4.9 | 5.4 | 1.5 | 0.5 | 4.7 | 2.4 | 0.9 | 20.4 |

Table IV - 20: Relative weighted scores variant level (research team)

| Relative weighted score | Costs | Travel time | Environmental impact | Social impact | Safety | Comfort | Co-Benefits | Total |
|-------------------------|-------|-------------|----------------------|---------------|--------|---------|-------------|-------------|
| Variant 1A | 1.7 | 3.0 | 2.5 | 6.0 | 4.6 | 1.0 | 1.2 | 20.1 |
| Variant 1B | 2.0 | 3.2 | 2.6 | 4.2 | 5.3 | 1.1 | 1.2 | 19.6 |
| Variant 2A | 2.2 | 2.5 | 2.4 | 4.5 | 5.1 | 1.0 | 1.0 | 18.8 |
| Variant 2B | 2.3 | 2.7 | 2.5 | 4.2 | 5.6 | 1.1 | 1.0 | 19.5 |
| Variant 3 | 2.3 | 2.7 | 2.4 | 4.9 | 5.1 | 1.0 | 1.2 | 19.6 |

5.2 Results

Below a ranking is presented, ranging from the highest to the lowest relative weighted score based on Table IV - 19.

1. Variant 1B (21.2)
2. Variant 2B (21.0)
3. Variant 3 (20.4)
4. Variant 2A (19.7)
5. Variant 1A (19.5)

Below the ranking is given of the relative weighted scores as based on Table IV - 20.

1. Variant 1A (20.1)
2. Variant 1B/Variant 3 (19.6)
3. Variant 2B (19.5)
4. Variant 2A (18.8)

6 Conclusions

This chapter will list the conclusions based on the information from Part IV.

- There is a large difference between the relative weights of the criteria as determined by the students of the UCSC and the multidisciplinary team. Both of the groups value the safety criterion as the most important of all the criteria. But while the student experience time and costs as relative important criteria, the multidisciplinary team attaches more value to social impact and environmental impact. A similarity between the two groups is that they both assign little importance to the criterion co-benefits.
- The fact that the students attach less value to the social impact and environmental impact can be influenced by the large number of surveys that were filled in by students from Coronel. It is possible that because these students are not from San Pedro de la Paz they do not care about the environmental impact and social impact in another commune.
- The scores of the different proposed solutions show quite some difference. Ruta Costa and Ruta 160 have a relative high absolute score compared to the other solutions. The improvement of Pedro Aguirre Cerda and the construction of Ruta Pie de Monte have, relative to the other solutions, a rather low score. The other solutions score more or less the same.
- On variant level the differences in absolute scores between the different options are much smaller. All of the variants have a comparable score with exception of variant 1B and 2A. Variant 1B scores relatively high. This is because this variant contains both Ruta 160 and Ruta Costa, the two highest scoring solutions. Variant 2A contains both Pedro Aguirre Cerda and Ruta Pie de Monte. These are the two lowest scoring solutions. That is why its score is relatively low.
- It can be concluded that taking into account the relative importance of the different criteria changes the ranking of the different variants significantly compared to the ranking of the absolute scores. This was the case for both the weights as determined by the students of the UCSC and the research team. Using both the absolute scores and the relative weights can thus definitely influence the final decision making.

7 Recommendations

This chapter gives an overview of the recommendations of Part IV.

- The analysis of the different criteria has to be improved. The specialisation of the multidisciplinary team revolves around hydraulic engineering and structural engineering. These aspects make up just a minor part of the analysis on the criteria. The analysis of the other criteria has to be done by experts in this field. This results in a more accurate scoring process.
- The relative weights of the criteria were defined using the results of a survey. First of all the survey was completed by only 31 students. This is not enough to get representative results. Besides that most of the students were from Coronel and not from San Pedro de la Paz. Finally students only represent one group of the society and one generation.
- Experts in the field of MCA's should be in charge of determining the relative weights of the criteria. There should also be input from the final decision makers of the project concerning the relative importance of the criteria.
- The reliability of the solutions should be added as a criterion in the MCA.
- All the proposed solutions have been taken into account in this research. In reality some of these solutions are already in the engineering phase while other are still concepts. Taking this into account while analysing the variants can change the outcome of the research.

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