Project Imbituba, Brazil

From sedimentation to solution

Master Project – Project Imbituba

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TU Delft Van Oord project imbituba

CIE 4061-09 Multidisciplinary Project – Project Imbituba
Delft University of Technology

Document title	Project Imbituba
Date	1st of December 2015

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Preface

This report has been written by Arno Kemper (Coastal Engineering, HE), Koen van Ekdom (Coastal Engineering, HE), Laurens Beulink (Hydraulic Structures, HE) and Marius Hendriks (Hydraulic Structures, SE). It contains a study concerning sedimentation in the Port of Imbituba, and possible long-term solutions to the sedimentary problem.

This report and the research study has been created and executed in light of the multidisciplinary project CIE 4061-09, which is an opportunity for master students to study abroad and pick up practical experience.

We want to thank our primary sponsor Van Oord for the financial support of the project as well as the TUDelft for giving us the opportunity to study abroad.

We also like to thank all the involved professors and personnel of the TUDelft, the Universidade Federal de Santa Catarina and CB&I.

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Barra da Lagoa, 23trd of October 2015

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Abstract

The Port of Imbituba, located in the state of Santa Catarina, Brazil, is a privately operated port in Brazil. In the past, the port has been upgraded in order to meet the future growth in the size and number of vessels. The main breakwater and the quay were elongated and the waterway was deepened. In the first six months of 2014, a large dredging operation took place in the port. Since the extension of the main breakwater, the port is facing difficulties regarding sedimentation. The port authority of Imbituba is eager to find a proper long-term solution that prevents the area of enormous amounts of sand accretion. Therefore, the goal of this research report can be formulated as follows:

Investigating the sediment transports and propose a suitable long-term solution for the sedimentation problems in the Port of Imbituba

In order to find the source of the sedimentation, a sediment budget model is constructed. The foundations of this model are the dataset of the bathymetry in the port area. Furthermore, the driving forces are analysed, the locations where sedimentation or erosion takes place are indicated and the fluxes are presented to show the likely origin of the sediment. One of the outcomes of this model is that the waves are the largest contributor of the sediment transport. Also the structures of the port have been determined to be the primary cause of the sedimentation issues. The main wave directions that cause the highest sediment transport rates towards the port are waves from the Northeast and Southeast. The port area is subdivided in three areas of highest interest, the access channel, the turning circle and the basin. It is found that the total amount of sedimentation, in these three areas together, is equal to 277000 [m^3/year]. The main source of this accretion is from an offshore location outside the bay.

With the input of the sediment budget model, four variants are proposed. Variant I consist of an extension of the primary breakwater in combination with the expansion of the groyne in the middle. Variant II combines a shore parallel breakwater at the former location of the three groynes with a sand trap in front of the primary breakwater. Variant III is more a soft solution, as a sediment bypass system with two jetties will be constructed, one in front of the primary breakwater and one at the former location of the groynes. Variant IV is a dredging operation including a long-term maintenance contract. Each variant contains a design and construction costs overview.

Based on the output of the sediment budget model, the four variants are analysed in the Delft3D programme. At first, a base case is developed with two out of twelve wind and wave conditions. These conditions stem from thirteen years of wind and wave data. The base cases form the foundation of comparing the effectiveness of the four variants regarding the sediment transport rates. Three aspects are compared, namely the significant wave height, the depth-averaged velocity and the mean total sediment transport. Based on the output of the Delft3D model, Variant I has the highest effectiveness regarding the sediment transport rate. Remark to this conclusion is that a properly operating sediment bypass system in the model is most likely not achieved.

To score the proposed variants, a multi criteria analysis is conducted. The analysis concludes that Variant IV seems to be the most optimal solution due to low initial costs and high functionality. Variant I also scores significantly on functionality, but initial costs are high and therefore weighs down the score.

1 Approach

The first stage of this report consists of a global analysis of the current situation. This includes an analysis of the location, the type of system that is being dealt with and what kind of physical processes occur.

The following phase consists primarily of the construction of a sediment budget model that is based on the input for this coastal system and the bathymetry datasets. With this model, output in the form of several maps can be generated. These maps can later be used to predict the effect of alternative solutions to the current dredging scheme.

Alternative “harder” solutions in the form of breakwaters or groynes are included in this report, but research will also go to softer and more natural solutions. Furthermore, the effects of these different alternative solutions are tested in Delft3D models. The results of these models, together with a cost and execution analysis, are evaluated for each alternative. The alternative solutions are weighed in a Multi Criteria Analysis (MCA) and a solution will be recommended to the reader. A week by week planning can be found in the Appendix J.

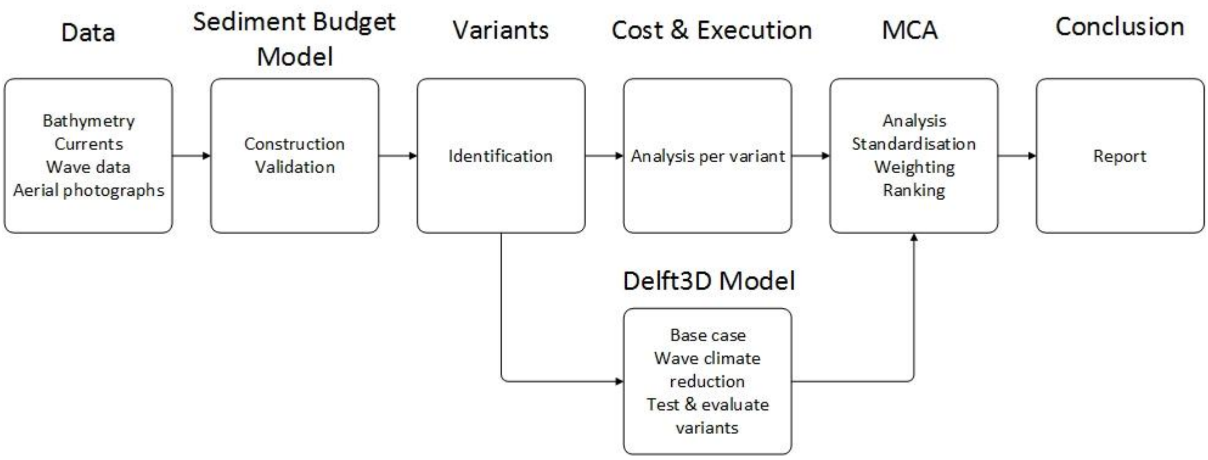

Figure 1-1 Methodology of Project Imbituba

2 Introduction

Imbituba is a small town situated at the coast in the province of Santa Catarina, in southern Brazil. It is located 90 kilometres South of Florianopolis, the capital of the province. The Port of Imbituba is a privately operated port in Brazil. In the past, the port has been upgraded in order to meet the future growth in the size and number of vessels. The main breakwater and the quay were elongated and the waterway was deepened.

Figure 2-1 Location of Imbituba (Menegaz)& (MAPA DAS CIDADES DIGITAIS - SANTA CATARINA)

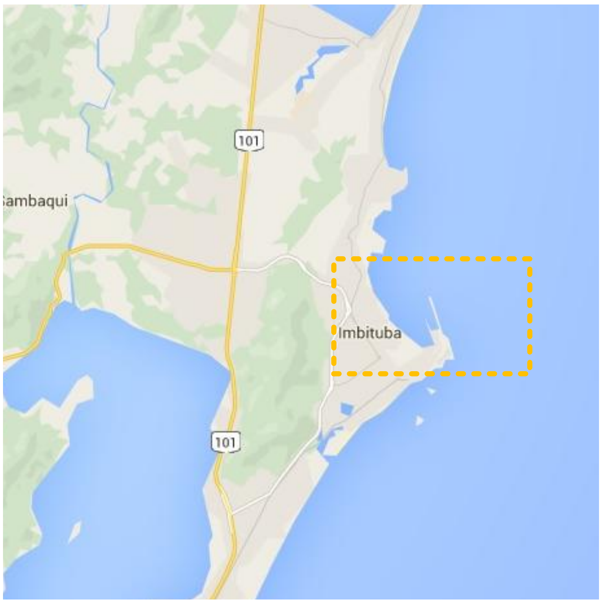

Figure 2-2 Location Port of Imbituba [-28.23˚, -48.65 ˚] (Google, 2015)

2.1 The port

Currently, the port of Imbituba moves a gross tonnage of 3 million tons of solid and liquid bulk, containers and general cargo a year (Porto de Imbituba, 2015). The port is relatively small compared to some other ports in Brazil. It is constructed on a headland and has only one breakwater. It has three berthing locations and one container terminal.

The primary breakwater was built on the tip of the headland and extends 850 [m] into the North-Northwest direction. The quay wall that has been constructed in the sheltered area of the port is 410 [m] long and runs parallel to the breakwater. To the Northwest of the port three groynes of roughly 80 [m] can be found that have been constructed several years ago, to reduce the amount of sedimentation.

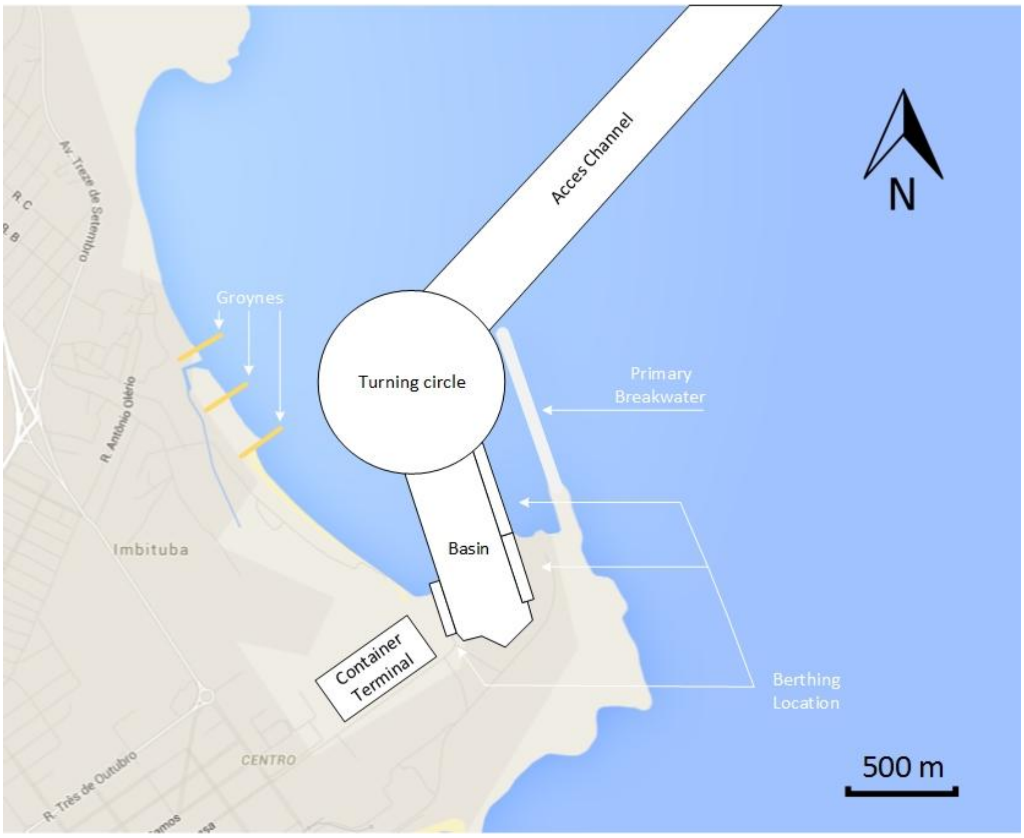

Figure 2-3 Current infrastructure of the port (Google, 2015)

To the North of the berthing locations a turning circle can be found. The average depth of the turning circle is 16 [m]. The access channel that connects the port to the Atlantic Ocean is 18 [m] deep and extends roughly 3500 [m] into the ocean.

2.2 Problem description

Since a large scale dredging program that started in the beginning of 2014, it has become evident that the port is attracting large amounts of sediment. The sedimentation is occurring at such a rapid pace that the port authority is now looking for a proper long-term solution. This report will focus on investigating the sediment transports and proposing a suitable long-term solution to the problems concerning the port of Imbituba.

2.3 History

The first step of this research will focus on finding the origin of the problem by analysing the port's history and search for any large changes that may have resulted in the increased rate of sedimentation.

2.3.1 Complete history

On the 3rd of November 1922, the Port of Imbituba was officially opened, with Alvaro Cato as the director of the Imbituba Port Authority.

In 1972 the construction of the primary breakwater started, which was finished in 1975. The port continued growing, leaving the breakwater to be extended up to 850 [m] only a few years later. This process took place between 1980 and 1982.

At the same time, three groynes were constructed at the beach at the West side of the bay, in order to stabilize the shape of the bay. For decades the port of Imbituba was relying heavily on coal mining and exports, reaching about 4 million tons of movement of that particular product in the 1980's.

The reduction of import tariffs and the removal of coal subsidies in 1990 led to the collapse of the Santa Catarina coal industry. In this new scenario, the Port of Imbituba was forced to change from a coal export terminal to a multi-purpose port with the handling of various types of goods.

After the collapse of both import and export, the port was left with much less movement than before. In the beginning of the 21st century, the cargo movers rediscovered the Port of Imbituba for its strategic location and favourable expansion conditions. In 2010, the primary quay was extended up to 410 [m] and from December 2013 to August 2014 the port, access channel and turning basin were dredged, increasing the maximum allowable draught to be 15 [m]. (Porto de Imbituba, 2015) (Bijl, 2015).

From the history of the port one can identify a few large interventions and adaptations that have taken place:

- Construction breakwater (1972-1975)
- Extension breakwater (1980-1982)
- Construction groynes (1980-1982)
- Large scale dredging scheme (2013-2014)

As the port authority did not report large amounts of sedimentation before these interventions, it can be concluded that either one of the adaptations and interventions or a combination has resulted in the current acceleration of sedimentation.

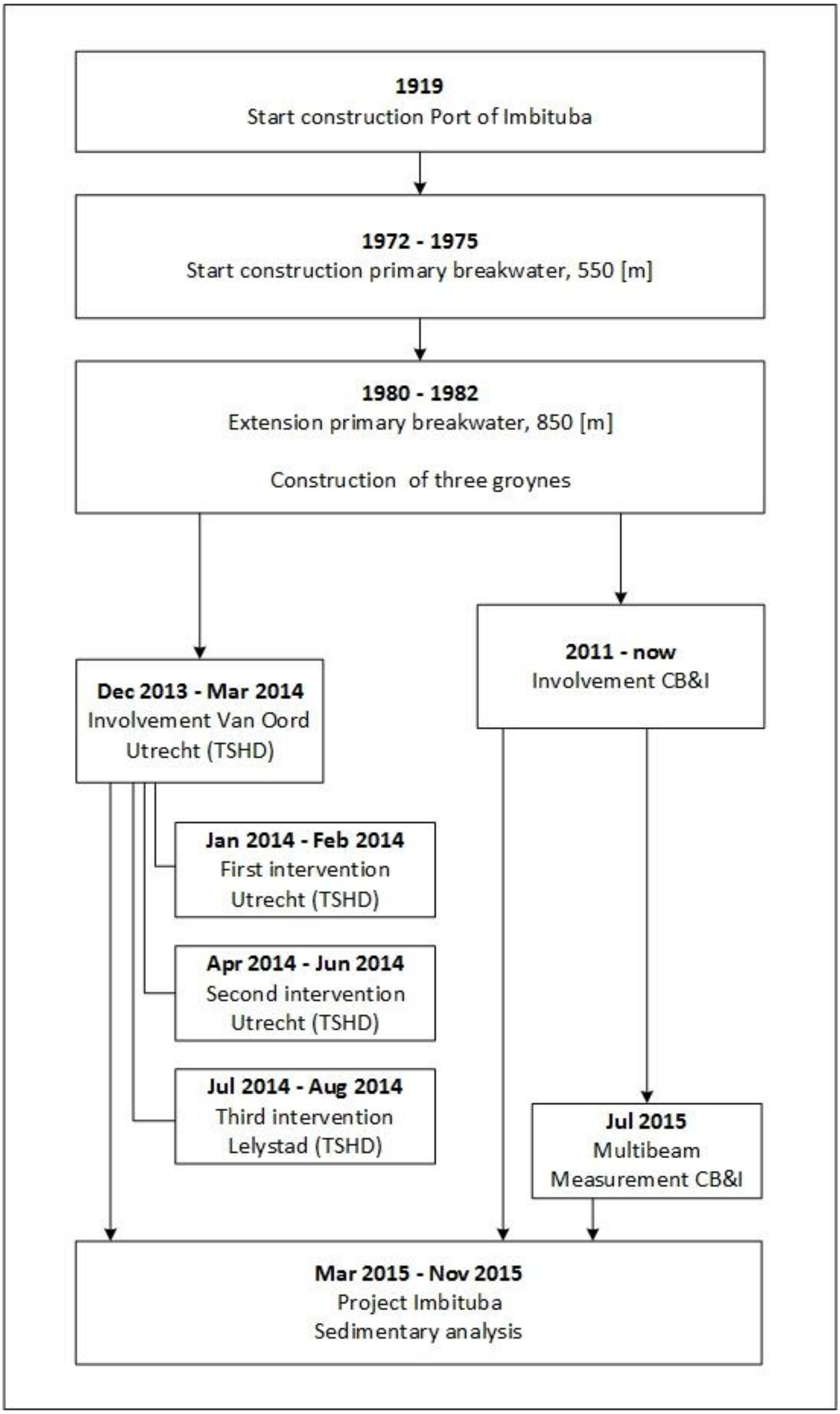

Figure 2-4 History of the Port of Imbituba

2.3.2 Evolution of bay since construction and elongation breakwater

Considering the current situation, one can observe a large scarp near the northern beach has formed. Due to erosion, the scarp has been reported to move land inward while gradually collapsing into the bay. It has an average height of 50 [m] and spans 700 [m] along the coast.

Furthermore, the beach in front of the scarp is popular amongst surfers for the large wave heights the area is famous for. This might be a source of the erosion, but heavy rainfall has also created several gullies on the slope that seem to be a strong contributor to the erosion problem. The scarp can be found in Figure 2-5, and is visual by the red-hatched zone.

South of the scarp, as mentioned before, three groynes are situated. From visual observations it can be seen that the coastline has already accreted roughly 40 [m] near groyne A. This can be observed in Figure 2-5 by the yellow lines. From this we can conclude that during the last 30 years the bay has gradually been rotating.

Figure 2-5 Current situation northern beach

Looking the evolution of the bay, it can clearly be seen that since the improvements in the 70's and 80's, the coastline has expanded dramatically in some areas and retreated in some other regions.

The shorelines from both 1978 and 2010 are compared to each other and are shown in (Figure 2-6). Out of these, it can be seen that the region towards the northern headland, has eroded 25 [m] on average, over a length of 700 [m]. This equals 0,8 [m] per year. It can be estimated that, on a yearly basis, 32.000 [m^3] of primarily sand and finer sediments erode from the scarp and are transported towards the bay. A detailed elaboration of the erosion of the scarp is presented in Appendix B.

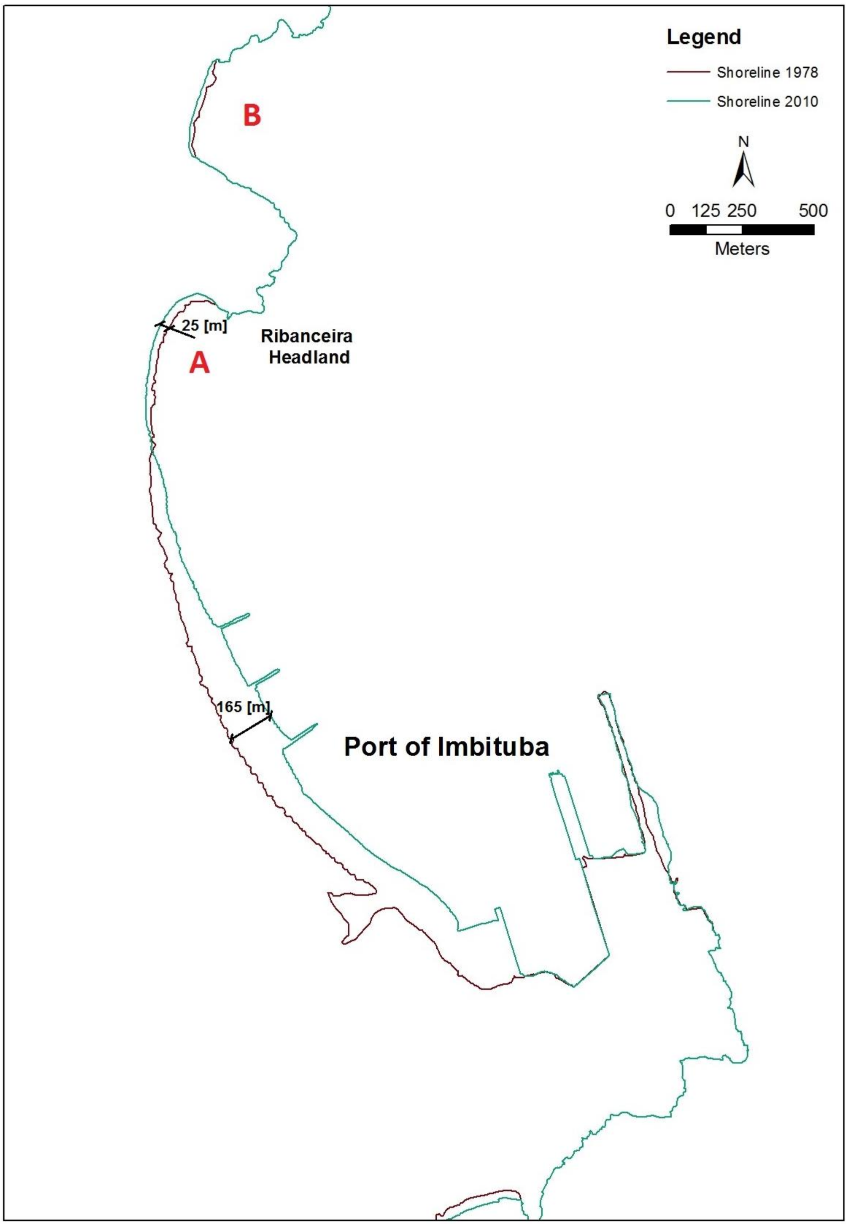

Figure 2-6 Shoreline changes between 1978 & 2010 (LOC)

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As was observed, the bay of Imbituba has been rotating counter clockwise for the last few decades. According to a study conducted by (Lausman, 2009), the construction and elongation of the primary breakwater caused an increase of sedimentation of the port. He concluded that the coastline location of different years confirmed a trend of erosion and retreat in the northern section of the bay and accretion in the southern parts of the bay. With the application of the parabolic bay shape equation (PBSE) he discovered that the breakwater had caused a disruption of the equilibrium state of the bay.

According to his findings, the northern part of the bay changed from a dynamic equilibrium to a static equilibrium, while the southern part of the bay was defined to be unstable.

He stated that the tendency of the sedimentation of the southern part of the bay could be explained by looking at the static equilibrium planform (SEP) belonging to the new up coast diffraction point at the tip of the breakwater: The seaward position of the SEP predicts a need for sediment in order for the bay to achieve a stable planform.

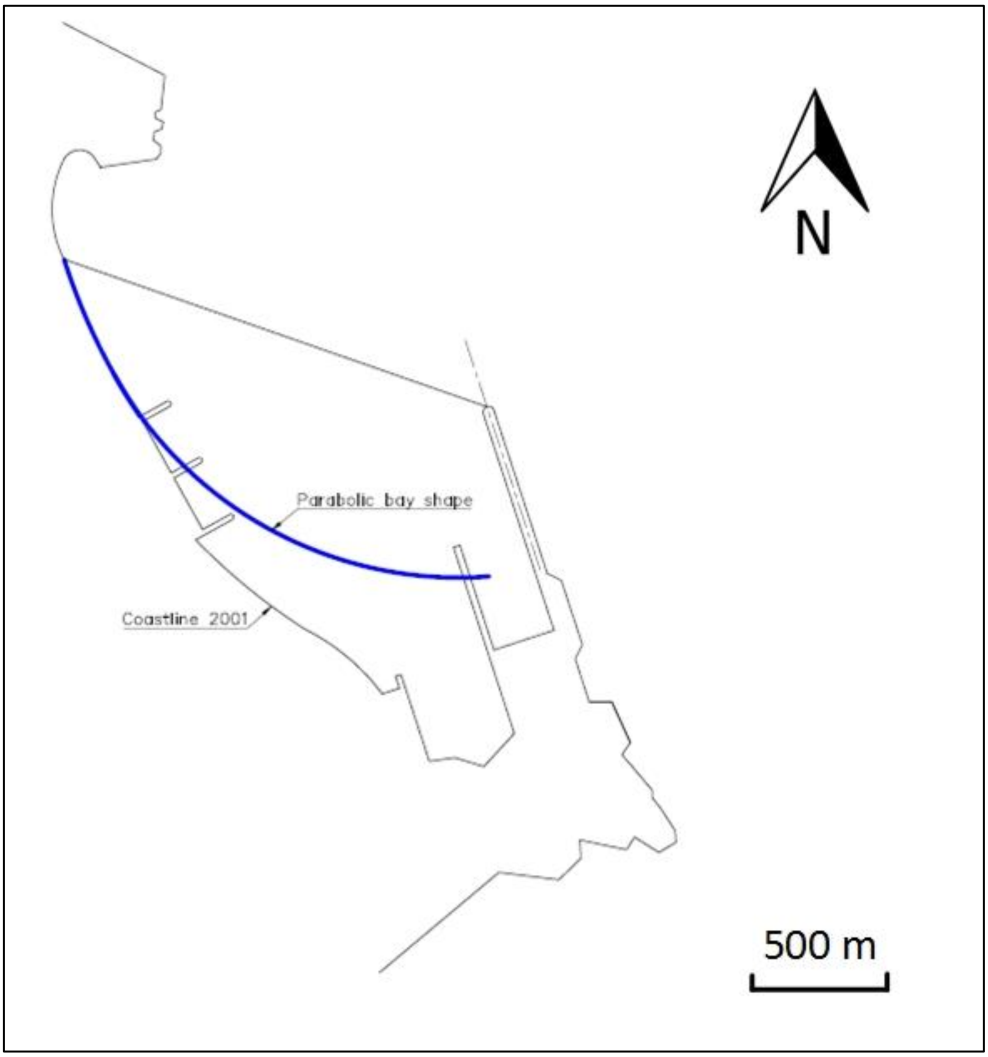

Figure 2-7 Desired equilibrium bay shape according to the PBSE (Lausman, 2009)

2.3.3 Evolution of the bay after dredging activity van Oord

In order to investigate the response of the port to the dredging activities, it is important to quantify the dredging activities Van Oord conducted during the period of December 2013 and August 2014. During this period, the engineering company CB&I preformed a multibeam survey in the port. With the bathymetry data provided by CB&I an accurate calculation can be made.

Using the software programme Matlab the datasets can be compared and a map with the difference between them can be generated (Figure 2-9). From this, the total volume change of the area can be calculated. The maps on which this difference map has been based can be found in Appendix C.

Table 2-1 presents the amount of volume change in three distinct sections: namely the basin, the turning circle and the access channel (Figure 2-3) is quantified. In the table a positive number corresponds to sedimentation while a negative number corresponds to erosion or dredging. During a period of eight months, from December 2013 until August 2014, this change of volume has taken place. The total sedimentation in this time period would be $+185{,}3\cdot 10^{3}$ [m^3] for the total area of the Port of Imbituba.

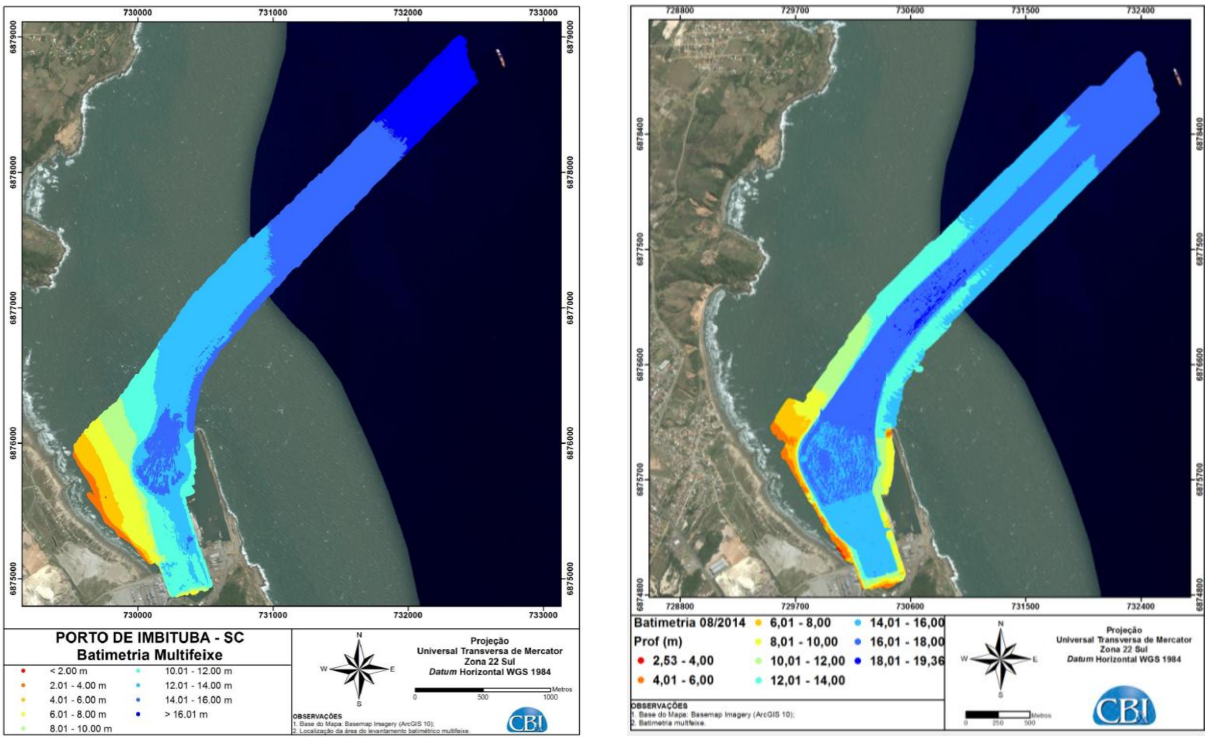

Figure 2-8 Bathymetry prior to dredging activity (left) & after dredging (right) (CB&I)

Even from the bathymetry maps visible in (Figure 2-8) it can be seen that the bathymetry has been significantly altered. The alteration may have resulted in a significant disturbance of the equilibrium that was present.

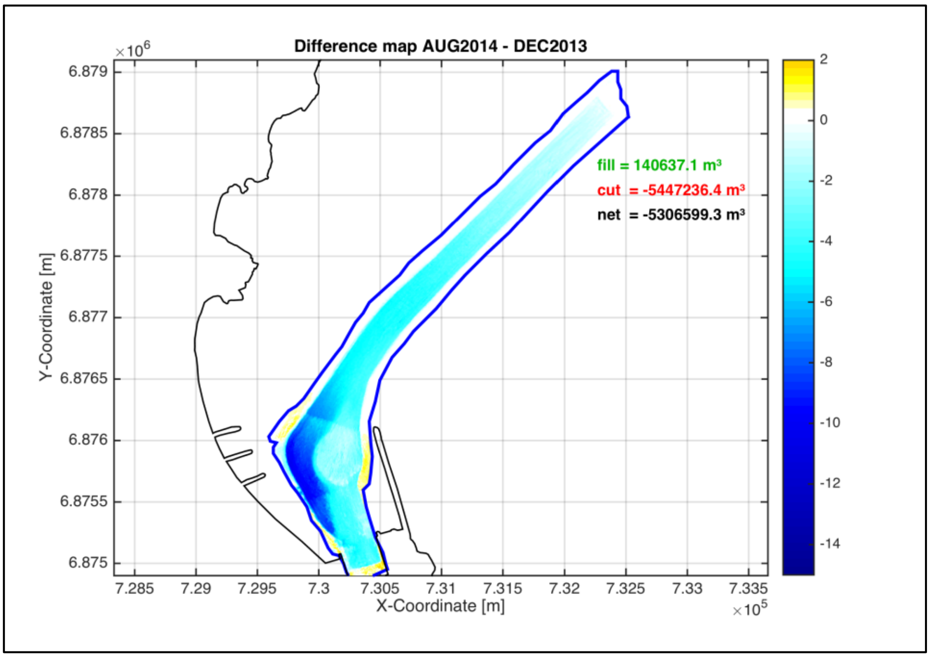

Figure 2-9 Bathymetry difference map (December 2013 - August 2014)

Table 2-1 Dredging activities (December 2013 – August 2014)

Section number	Section	Volume change [*10^3 m^3]	
1	Basin	-962,8	
2	Turning circle	-1654,5	
3	Access channel	-2689,3	
		-5306,6	*Net change Volume*
		185,3	*Amount of Sedimentation*
		-5492,1	*Total Volume Dredged*

Table 2-2 Dredging activities (August 2014 – July 2015)

Section number	Section	Volume change [*10^3 m^3]	
1	Basin	+30,2	
2	Turning circle	+120,4	
3	Access channel	+127,4	
		+278,0	*Amount of Sedimentation*

With an extensive measurement of the bathymetry in the port, eleven months after conducted dredging activities, the sedimentation during the given time period after can be computed. According to the bathymetry datasets visible in Figure 2-10 & 2-11, the total sedimentation in the entire port is 278.000 [m^3]. With most of the sedimentation taking place in the basin near the berthing locations (Figure 2-12), and also a large amount of sedimentation taking place in the turning circle and the South part of the access channel.

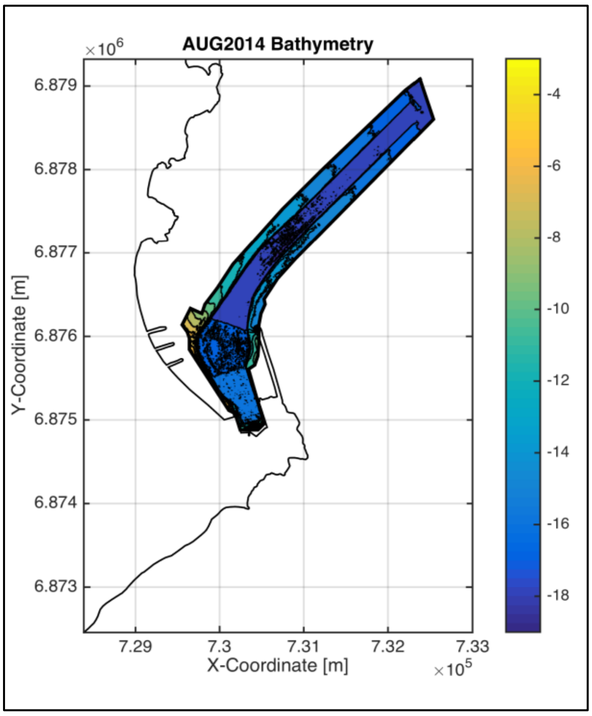

Figure 2-10 Bathymetry August 2014

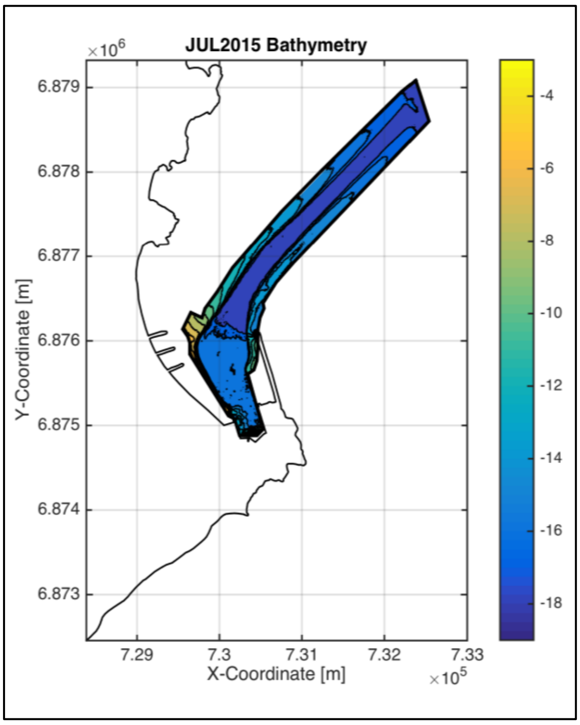

Figure 2-11 Bathymetry July 2015

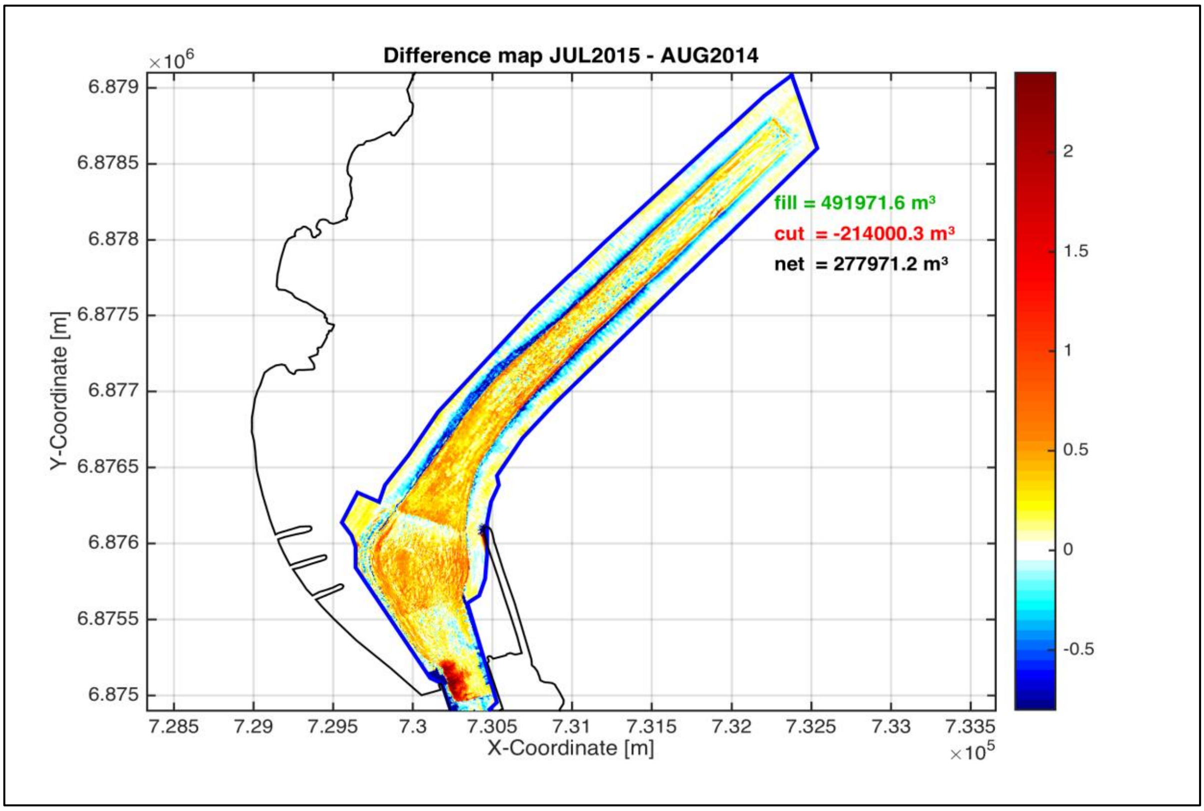

Figure 2-12 Bathymetry difference map (August 2014 - July 2015)

2.4 Wave and tidal environment

To come to a definitive conclusion, it is important to investigate local wave and tidal conditions. This chapter will provide an insight to the origin of the sediment as well as the distinct forcing mechanisms like wind, tides, waves and currents combined with their direction. Furthermore, the process of coastal evolution will be identified in more detail.

2.4.1 Temperature distribution

Wind and ocean currents develop as a consequence of uneven distribution of heat over the earth's surface. The main source for this is the uneven distribution of solar radiation, emitted by the sun, around the earth's surface. In time, the solar radiation leads to heating of the surface. Due to this uneven heat distribution around the earth's surface, heat will be transferred partly by air currents (60%) and partly by ocean currents (40%). For Brazil, which is located at the southern Hemisphere (SH), the isotherms bend towards the equator in January and vice versa in July.

2.4.2 Wind patterns

The Coriolis Effect, caused by the earth's rotation, causes the currents and atmospheric flows to deviate to the left at the southern Hemisphere. Due to this effect, the air around Imbituba at large altitude is flowing primarily from the West to the East (subtropical jet stream). Characteristic for this type of wind is that they are moderate but persistent throughout the year and occur mainly over the oceans. Due to the presence of landmasses, the situation is more complex. Large-scale pressure belts are subdivided in low- and high-pressure areas. This results in typical wind patterns, as can be seen in Table 2-3. For the Brazilian coast, the wind is primarily directed from the Northeast to the Southwest at moderate altitude (e.g. Southeast trade winds). However, this type of wind pattern is one of the most important contributors in supplying energy to the coastal system. The local impact of sediment transport induced by the wind is however relatively small.

2.4.3 Tidal characteristics

At the coast of Imbituba (28° South), a micro-tidal regime is present which include that the mean spring tide is less than two meter. Since the movement of the tide is deflected by the Coriolis effect and blocked by landmasses, rotational movements are created; these are the so-called Amphidromic systems. As can be seen in Figure 2-13 Tidal wave map, a node is present East of the investigated location. As the Amphidromic point is located in the southern Hemisphere, the Coriolis effect forces a clockwise rotation of tidal movements around it. From the node onwards, the South American landmass forms an obstruction for the propagation of the tide. Together with the counter clockwise circulation, caused by the Coriolis effect, the tide is forced to propagate northwards along the coast. From this reasoning, the sediment transport by the tide will be directed from the South to the North. However, due to the fact that the tide is small, tidal currents in the continental shelf and associated sediment transport is small in comparison with the sediment transport induced by waves.

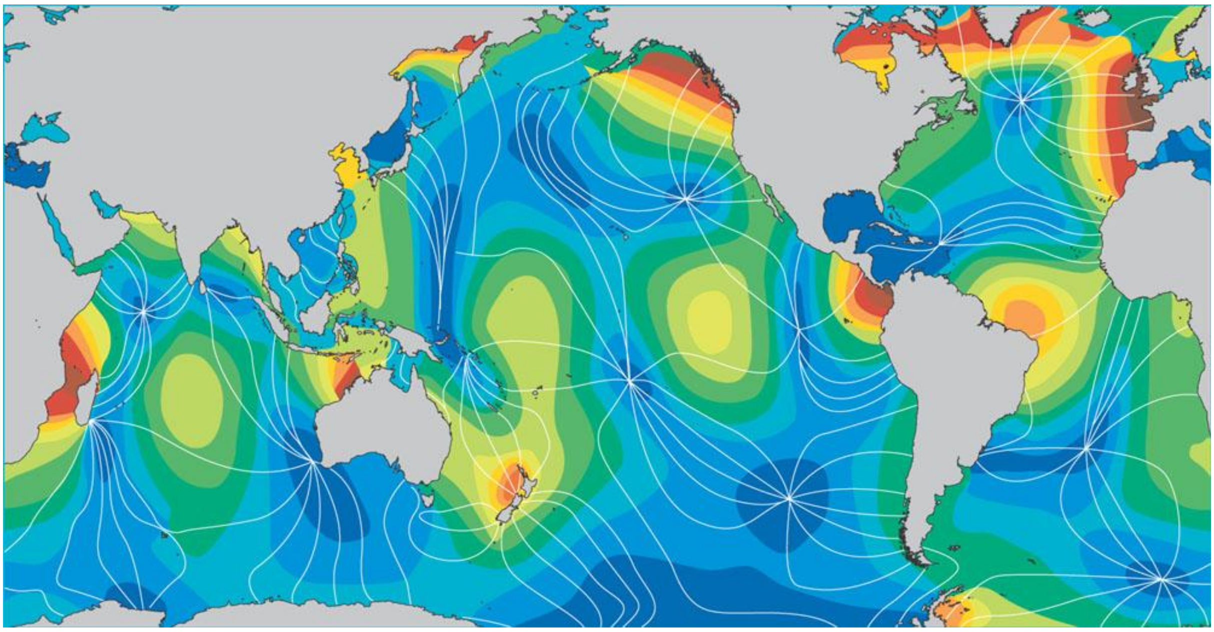

Figure 2-13 Tidal wave map (Thompson, 2015)

2.4.4 Oceanic Circulation

Apart from the wind patterns and temperature distribution, the oceanic circulation or "ocean conveyor belt" principle is of major importance as well. This type of circulation is driven by the difference in density. In a simplified model, the deep-water flow is moving from the North Atlantic Ocean towards Antarctica, is cooling down and flowing to the Pacific and Indian Ocean. From there, after upwelling, it returns as surface flow to the North Atlantic Ocean. In front of the coast of Brazil, the warm water is circulating in Southward direction.

2.4.5 Wave system

For the wave system, data provided by CB&I is analysed and categorized, resulting in twelve wave and wind conditions. NOAA (National Oceanic and Atmospheric Administration) obtained data over a period of 13 years along the coast of Imbituba. The conditions itself are generated by using Matlab. This programme clusters data that has similar values within certain boundaries. The consideration for making only twelve conditions out of 13 year of data is time related, as the conditions form the input for the modelling programme Delft3D. Each simulation takes a few hours computation time. Due to this limitation, only twelve conditions are considered.

As can be seen in (Figure 2-14) and (Table 2-3), the main deep water wave directions are from the Northeast, the East and the Southeast as these have the highest frequency. Waves directed to the North and Northwest are less important as their point of impact is outside the port area. Waves propagating from the East and Northeast occur 155 [days/year], which makes these directions the dominant wave directions for the port of Imbituba.

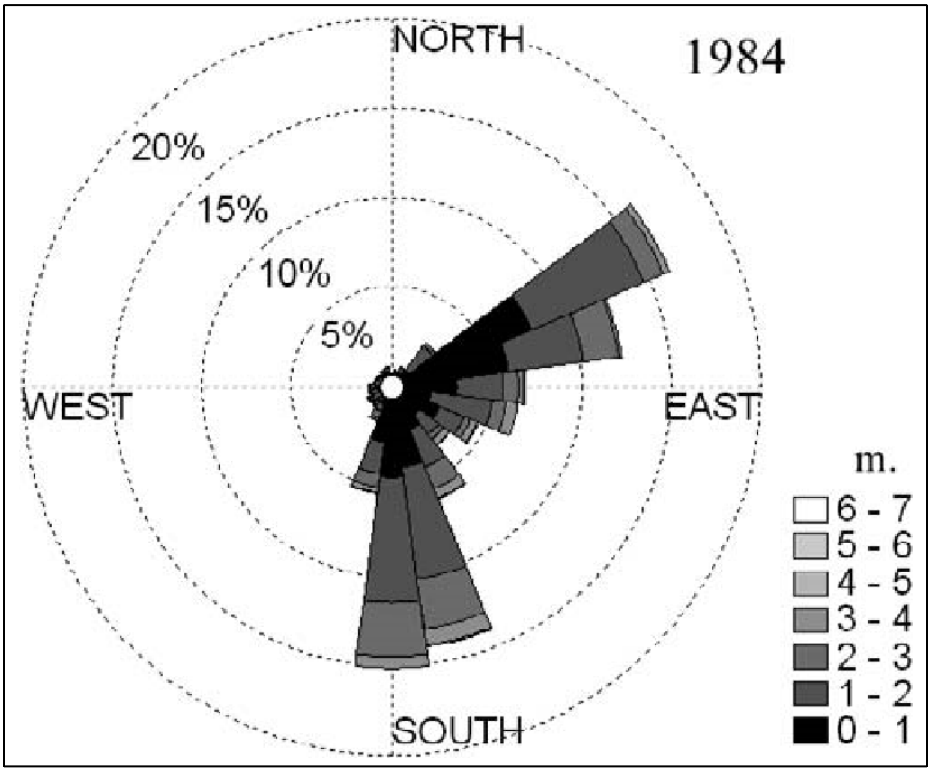

Figure 2-14 Wave direction Imbituba

Table 2-3 Wind & Wave conditions

Condition	Hs [m]	Tp [s]	Dir [deg.]	Freq.	[days/yr]	Wind [m/s]	Wind [deg.]	Cosine Power	Scale factor
1	1,4	6,0	54,7	0,1	34,6	4,6	16,5	4,0000	34,6
2	2,3	6,8	54,2	0,0	13,3	7,3	19,4	4,0000	13,3
3	3,7	8,0	56,6	0,0	0,4	11,5	26,2	5,0246	0,4
4	1,4	7,2	86,7	0,2	69,8	2,5	40,8	5,0824	69,8
5	2,3	8,0	88,5	0,1	29,4	4,2	54,6	4,0000	29,4
6	3,7	8,7	90,9	0,0	1,7	8,0	80,6	4,0000	1,7
7	1,6	8,4	134,0	0,1	51,3	2,3	67,1	7,0386	51,3
8	2,9	9,4	135,6	0,0	12,8	4,0	117,6	4,0000	12,8
9	5,0	10,4	133,9	0,0	0,4	10,6	164,0	4,0000	0,4
10	1,7	9,2	181,7	0,2	73,2	1,4	100,2	8,5693	73,2
11	2,7	10,2	184,1	0,1	49,3	3,4	163,8	5,4934	49,3
12	4,2	11,0	185,7	0,0	3,6	9,4	203,5	4,0000	3,6

2.5 Preliminary Conclusion

From the global analysis concerning that has taken place a few things can be concluded:

- Since the upgrade in the late 1970s and early 1980s the bay has been gradually rotating counter clockwise. The displacement of the diffraction point can be held responsible for this. An is now demanding the port to attract massive amounts of sedimentation (Lausman, 2009)

- The groynes that have constructed seem to have slowed the pace of rotation but have not been able to stop the process entirely.

- The scarp in the North has been eroding for over 30 years now, retreating roughly 25 [m] over a length of 700 [m]. The beaches South of the scarp have been expanded dramatically during the same period.

- The dredging activities seem to have accelerated the pace of sedimentation significantly, all areas are now importing large amounts of sediment, but especially near the quay wall in the basin area, an extreme amount of sedimentation is taking place. This might be the result of a combination of the rotation of the bay that was already taking place, in combination with the disturbance of the quasi equilibrium by the dredging activities.

From these conclusions it is evident that an investigation concerning the sedimentation caused by dredging activities is important to come to a closing argument. The investigation of the sedimentation that is currently taken place will start in the next chapter.

3 Sediment budget model

3.1 Introduction

This chapter provides a detailed overview of the method that is used to quantify the sediment transport rates in the port of Imbituba. The foundation of this analysis is based on the datasets provided by CB&I. As described in the previous chapter, the dredging company Van Oord finished the dredging work in August 2014; this implies that from that moment on the sedimentation became relevant again. To analyse this process, the bathymetry maps of August 2014 and July 2015 are therefore of importance.

3.2 Method

For the port of Imbituba, the following incremental approach is used:

1) An analysis of the driving forces for the sediment transport
2) The areas where sedimentation or erosion occurs are identified and quantified
3) Several areas are allocated with their corresponding fluxes, as far as is possible

A detailed explanation is given below:

1) In Chapter 2.4, an analysis is presented regarding the directions as well as the driving forces of the sediment transport in the discussed area. It was concluded that the waves are the largest contributor of the accretion process in the port. The reason for this is the micro-tidal regime that Imbituba experiences, resulting in small horizontal and vertical tide. The main direction of the tide is northwards oriented, due to the Coriolis force and the deflection on the Brazilian landmass. This has small impact on the sediment transport and its direction. The wind and ocean currents are also of minor importance to the sediment transport, as the impact on local scale is negligible. Concerning the waves, twelve wave conditions are composed out of thirteen years of data. The main deep water wave directions that are influencing the sediment rate in the area are: Northeast (NE), East (E), Southeast (SE) and South (S). The waves from the Northeast will transport the sediment into the sheltered area of the port (Figure 3-1). The waves from the East will not induce a large transportation of sediment alongshore the bay, as they are perpendicular oriented. However, due to the set-up gradient that is due to sheltering of the waves near the port, a transport of sediment is expected towards the sheltered area of the port (Figure 3-2). The waves from the Southeast and the South will transport the sediment towards the North. Only the Southeast waves will partly penetrate the bay of Imbituba when the waves diffract at tip of the breakwater. The set-up gradient due to the sheltering of the bay will cause sediment transport inside the bay (Figure 3-3).

   As described in the previous chapter, the port area is subdivided in three areas, namely: the access channel, the turning circle and the basin. The latter two are primarily influenced by the sheltering behaviour of the port. The channel is hardly influenced by this as its location is outside the sheltered area behind the breakwater. From this moment, it is considered that the channel area is outside the influence of the bay. As the channel has been deepened, its cross-sectional area is increased. This causes decreasing flow velocities in the channel, resulting in the accretion of sand. The location of this accretion depends on the dominant transport direction, caused by the wave and current direction.

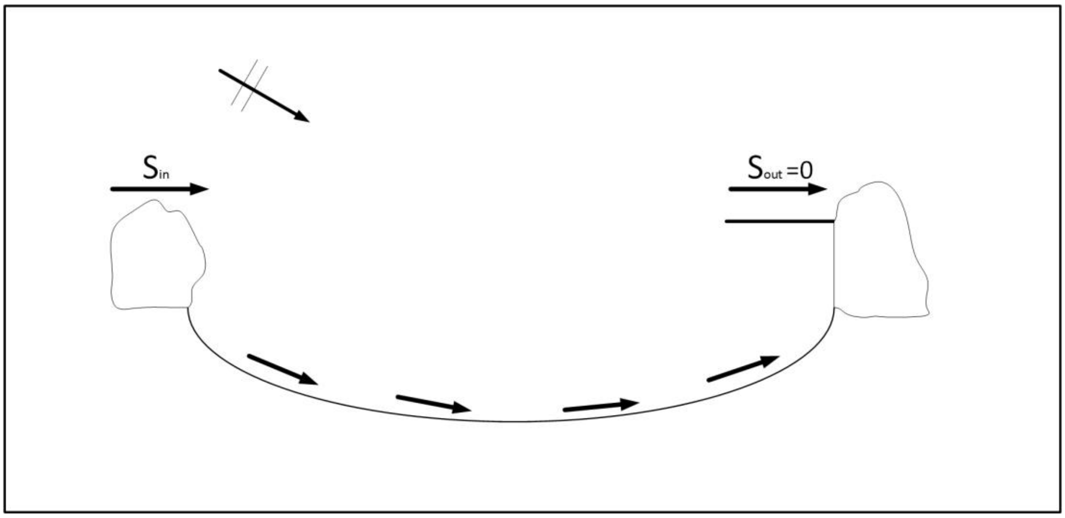

Figure 3-1 Sediment transport with waves from NE direction

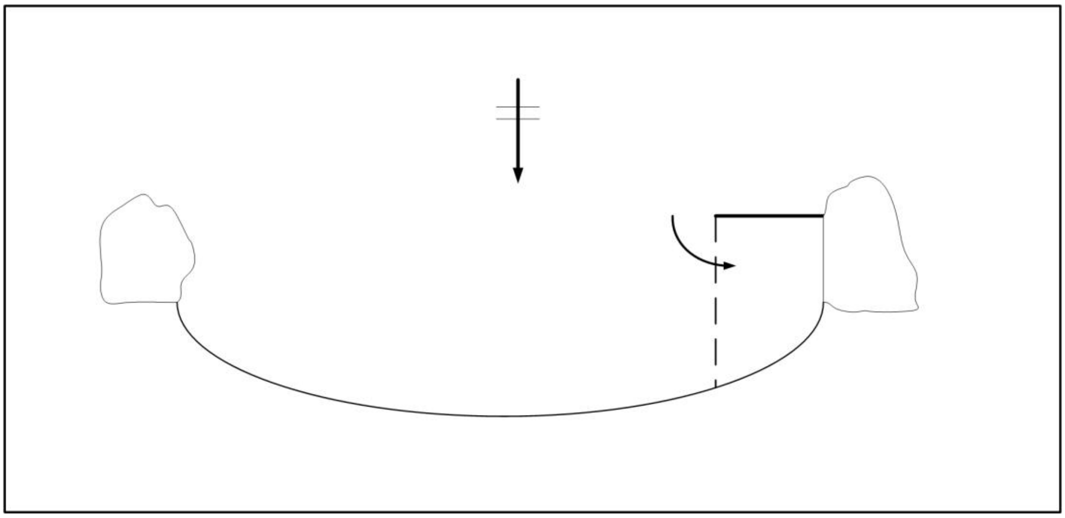

Figure 3-2 Sediment transport with waves from E direction

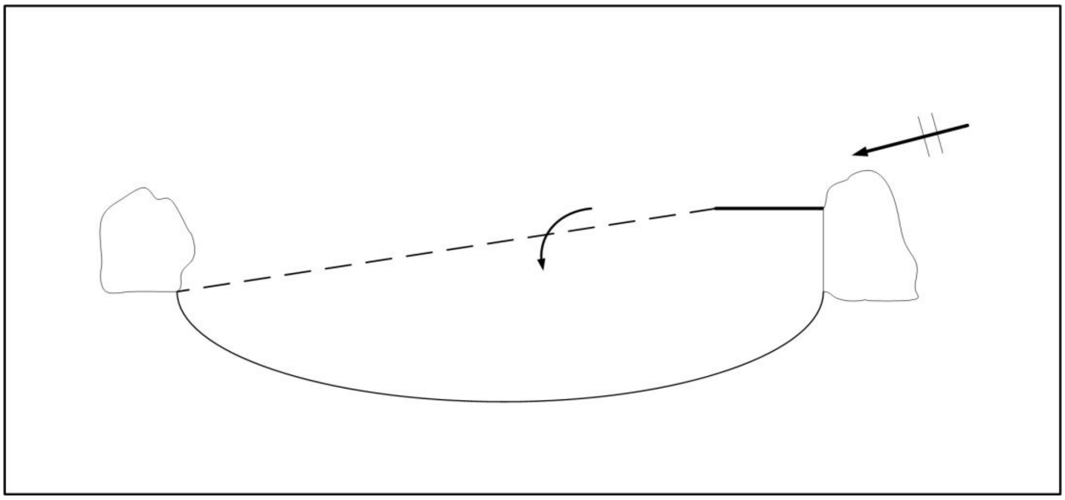

Figure 3-3 Sediment transport with waves from SE direction

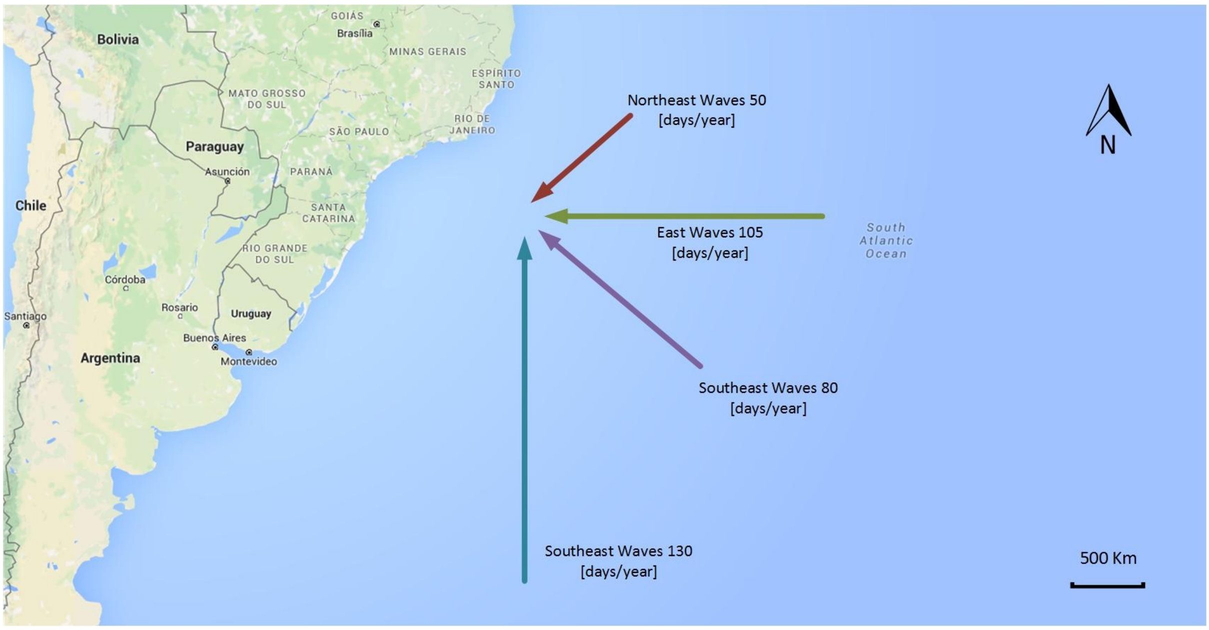

Figure 3-4 Occurrence of wave conditions (Google, 2015)

The following can be concluded concerning the sediment:

- Waves are the largest contributor of the sediment transport
- Three main wave directions transport sediment into the port area, either by alongshore transport (Northeast) or by set-up gradient induced transport (Eastern and Southeast)
- Sediment transport from the South to the North occurs 210 [days/year]
- Sediment transport, from the East and Northeast, inside the port occurs 155 [days/year]
- The structures at the port cause the gradients in sediment transport and wave set-up and in turn, the sedimentation

2) The Matlab script, that is used to obtain the bathymetry difference map for the two datasets, provides the input for the amount of sedimentation and erosion (Figure 2-12). This script can be found in Appendix C. In this script, the three areas (channel, turning circle and basin) are used to define the total amount of sedimentation or erosion during a period of one year. At the northern side of the bay, using the aerial photos of 1978 and 2010, changes in shoreline position are compared to estimate the erosion of the scarp.

   For the southern beach area, West of the basin, the amount of sedimentation is estimated by comparing the expansion of the coastline between the years 2003 and 2013. In the map, sedimentation is indicated by the + sign and erosion by the – sign. To summarize the amount of sedimentation and erosion, see Table 3-1 and Figure 3-5.

Table 3-1 Volume change rates

Area	Volume change*10^3 [m^3/yr]
Channel	+ 127
Turning circle	+ 120
Basin	+ 30
Northern side of bay	- 32
Southern side of bay	+ 20

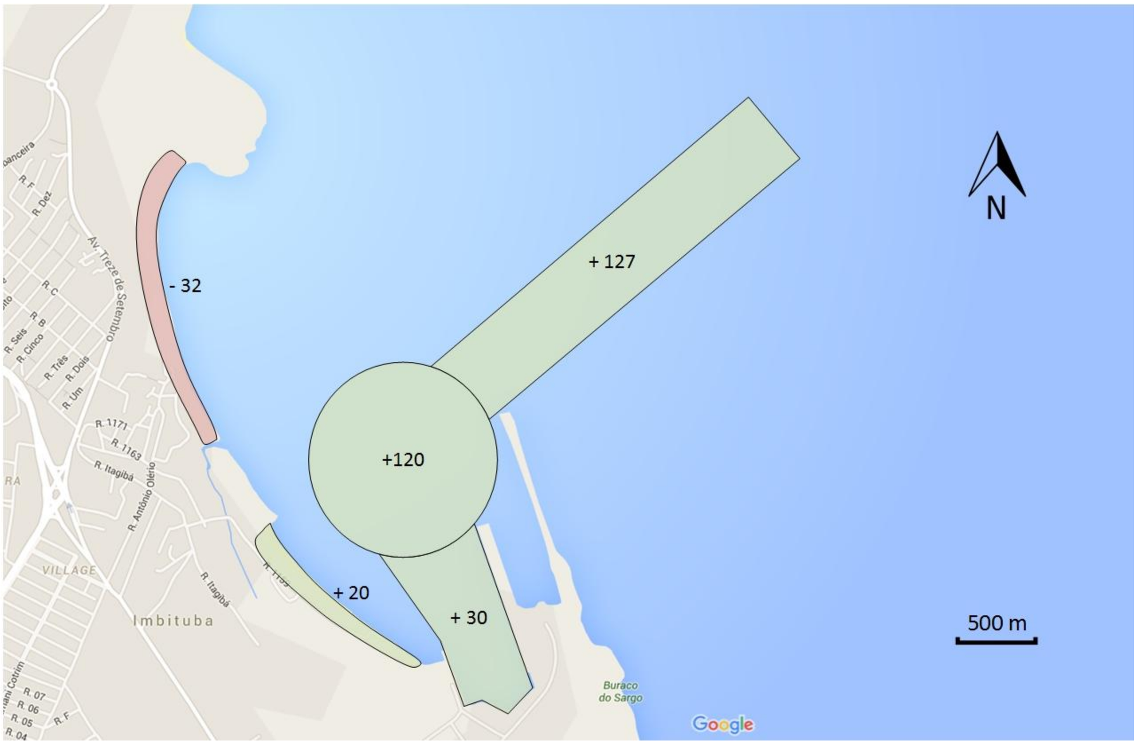

Figure 3-5 Accretion and erosion at investigated zones (numbers in [m^3/yr])

3) By analysing the area regarding the amount of sedimentation or erosion, the corresponding fluxes can be obtained (**Fout! Verwijzingsbron niet gevonden.**). This analysis consists of indicating the sediment transport directions, induced by external forces as well as elaborating a mass balance between the areas. For the mass balance, it is logical to start at the location where the minimum amounts of fluxes are possible, namely the basin. This area is partially surrounded by concrete structures on three sides. In this line of reasoning, it can be assumed that sediment would have to enter this area from either the turning circle or the adjacent beach. The southern beach accretion itself can only be possible by a sand supply from the North. The erosion that takes place at the northern side of the bay is due to the gradients of wave set-up in the bay. Furthermore, the two main areas of interest (the turning circle and the basin) are importing more sediment than there is erosion on the northern side of the bay. This mismatch regarding the amount of volume suggests that the sediment should come from outside the bay.

   By using the analysis of the sediment transport, it can be concluded that the sediment primarily comes alongshore from the North as well as from the tip of the breakwater, due to the difference in wave set-up gradients. Due to the deep water wave conditions, the primary direction of sediment transport is from the Southeast and East, so in this position it enters the bay. The direction and quantaties of the fluxes are determined as far as possible (**Fout! Verwijzingsbron niet gevonden.**).

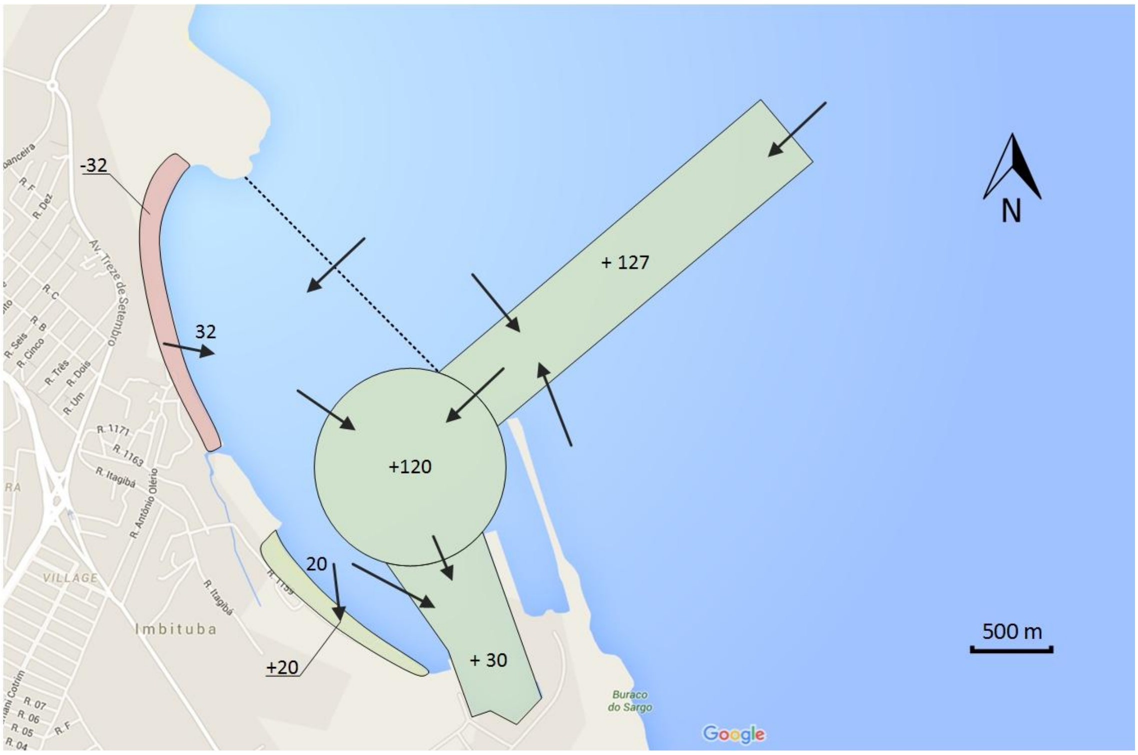

Figure 3-6 Sediment transport (indicated by black arrows)

4 List of possible measures

In this chapter, several possible measures that are taken into consideration are discussed. In appendix E these measures are evaluated with the input of the sediment budget model that has been elaborated in Chapter 3. Furthermore, possible locations for these measures are presented. In Chapter 5, four solutions (variants) are be proposed. These solutions are comprised of either one or more of the measures that are discussed in this chapter.

4.1 Adaptation primary breakwater

As the extension of the primary breakwater has caused the problems in the port in the first place, changing its shape and size may be an easy but effective solution. Depending on the source of the sediments the influx may be reduced sufficiently.

4.2 Secondary breakwater

A breakwater is a structure that is constructed to prevent waves from passing, but also have a tendency to hinder transport of sediment. The two possible alternatives are:

4.2.1 Shore normal

A shore normal breakwater is a solution to coastal problems that is often applied. As the problems in the bay of Imbituba started with the construction of a breakwater, constructing a secondary breakwater may mitigate the problem.

4.2.2 Shore parallel

A shore parallel breakwater is applied on many coasts around the world. These breakwaters are known to stabilize the coast and usually attract sediment behind it. In time a so-called “salient” or “tombolo” may develop. Shore parallel breakwaters can be emerged or submerged. The effect of submerged breakwaters is known to be a somewhat unreliable however.

4.3 Groyne

Groynes are applied in rivers and coastlines all over the world, to stabilize their shape. The Imbituba bay already has three groynes. The addition of one or several groynes somewhere in or around the bay may be a solution. Alternatively an adaptation of the current set of groynes may prove to help.

4.4 Sand bypass

A sand bypass system is a system that collects sediment and transports it to either land or adjacent bays. The system is experimental, but several systems already exist around the world with promising results. The correct placement of a sand bypass system may therefore be a very effective solution to the sedimentation problem.

4.5 Revetment/Scarp protection

As discussed before, the scarp seems to be a source of sediments to the bay. Improving the slopes of the scarp with geotextiles, or protecting the beach beneath it with a revetment, may reduce erosion and thereby the sedimentation of the bay.

4.6 Dredging

The final measure discussed is keep dredging the port. This is currently the strategy of the port authority. Definitely an effective solution but it may prove to be a costly permanent solution.

5 Proposed Variants

The following chapter contains four possible solutions to the sedimentation problem. As sedimentation is partially caused by the bay trying to rotate and partially by the disturbance caused by dredging activities in recent history, each variant will propose a measure for both problems. These variants will shift of focus from a purely hard to a more soft solution.

5.1 Variant I: Hard Intervention

Variant I focusses on a hard solution for both the rotation of the bay as the offshore and nearshore import of sediments by extending the middle groyne and the primary breakwater.

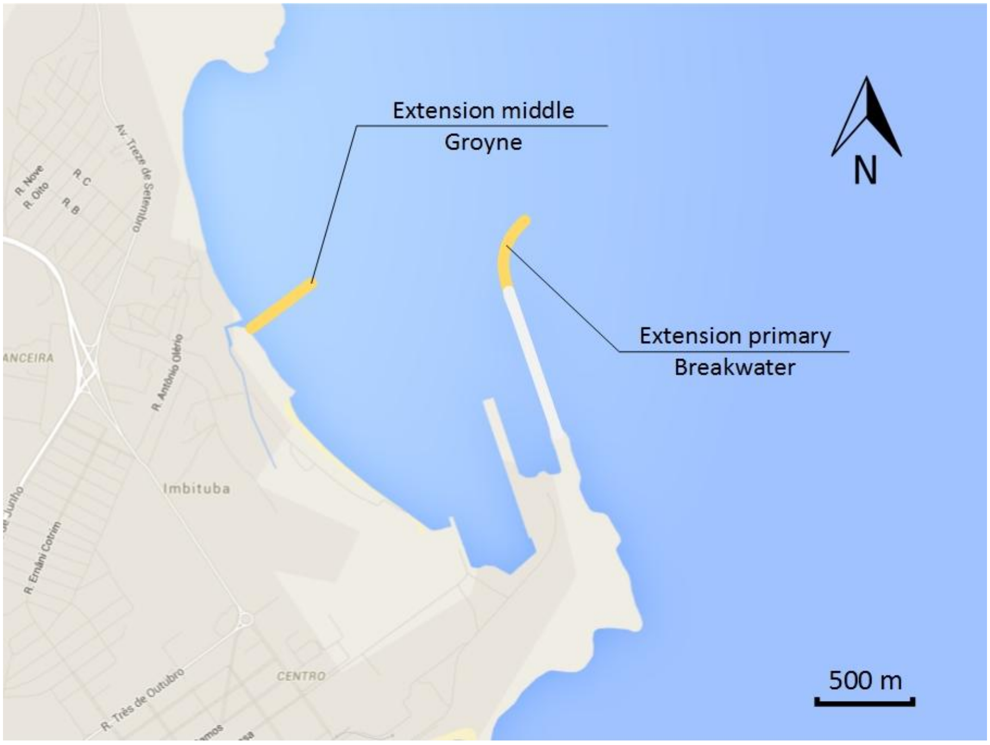

Figure 5-1 Variant I (yellow lines indicate changes)

5.1.1 Solution to rotation of bay

As the rotation of the bay is causing sedimentation in the berthing areas of the port, reducing it is important for the accessibility of the ports infrastructure. Two of the groynes present on the beach to the West are removed. The sediment present in the area between the groynes is removed via dredging to prevent further fill up of the berthing areas. The groyne in the centre is extended up to 350 [m]. By recycling the materials used for the other two groynes, costs can be reduced.

The extension of the groyne will allow the northern side of the bay to rotate without severely impacting the location of the beach and port basin South of the groyne. A design including the shape, dimensions and estimated stone size of the groyne has been made and can be found in Appendix H.

An impression of the cross section of this groyne can be found in Figure 5-2. A complete drawing of the design can be found in Appendix I.

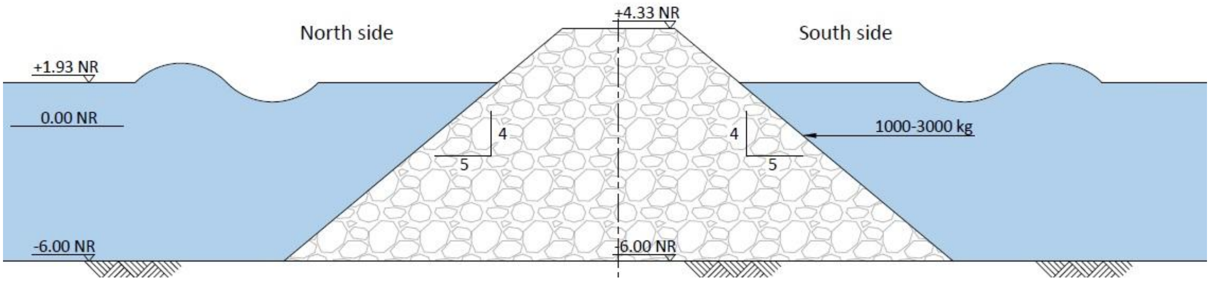

Figure 5-2 Cross section groyne

5.1.2 Solution to sediment import

The import from near shore sources is especially important to the sedimentation in the access channel and turning circle. An elongation of the primary breakwater of 400 [m] towards the East Northeast (Figure 5-1) seems to be a possible solution to prevent sediment coming from the South from entering the bay, as it is expected that this is the primary direction. Although sediment will inevitably pass the extension, some part of it may be trapped in the area North of the extended groyne, effectively trapping it in the North side of the bay and preventing it from entering the berthing area.

An impression of the cross section of this breakwater can be found in Figure 5-3. A complete drawing of the design can be found in Appendix I.

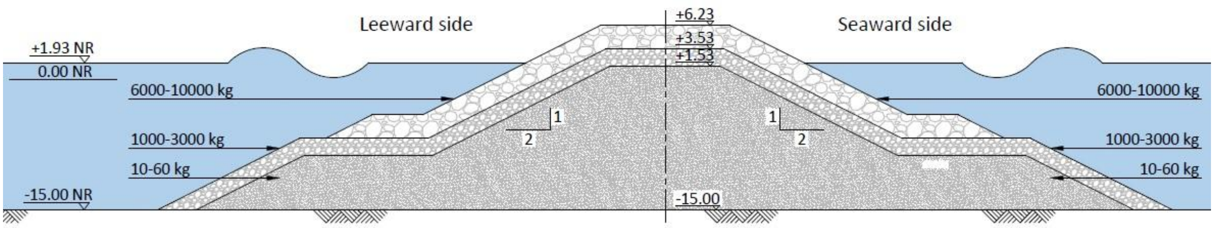

Figure 5-3 Cross section extended breakwater

5.1.3 Costs

The costs of Variant I are presented in Table 5-1. These costs include construction and maintenance of the extended breakwater & groyne and the removal of the other two groynes. Estimations are made using a unit price used for a stone breakwater elsewhere in Brazil (Bijl, 2015). The current exchange rate between the euro and the Brazilian real is 1:4,3 (October 16, 2015). Further specification of the costs can be found in Appendix F.

Table 5-1 Cost specification Variant I

Construction costs [€]	18.500.000
Maintenance costs [€/year]	100.000

5.1.4 Application of the parabolic bay shape equation

With the extension of the primary breakwater, it is important to investigate the new equilibrium shape the bay would want to achieve naturally. The program MEPBAY and the configurations as stated in (Bijl, 2015) and (Silveira, Klein, & Tessler, 2010) are used. (Figure 5-4) shows the initial situation, where the bays shape reaches up to the beginning of the quay wall. After the extension of the primary breakwater the equilibrium shape alters slightly by mitigating more towards the North (Figure 5-5).

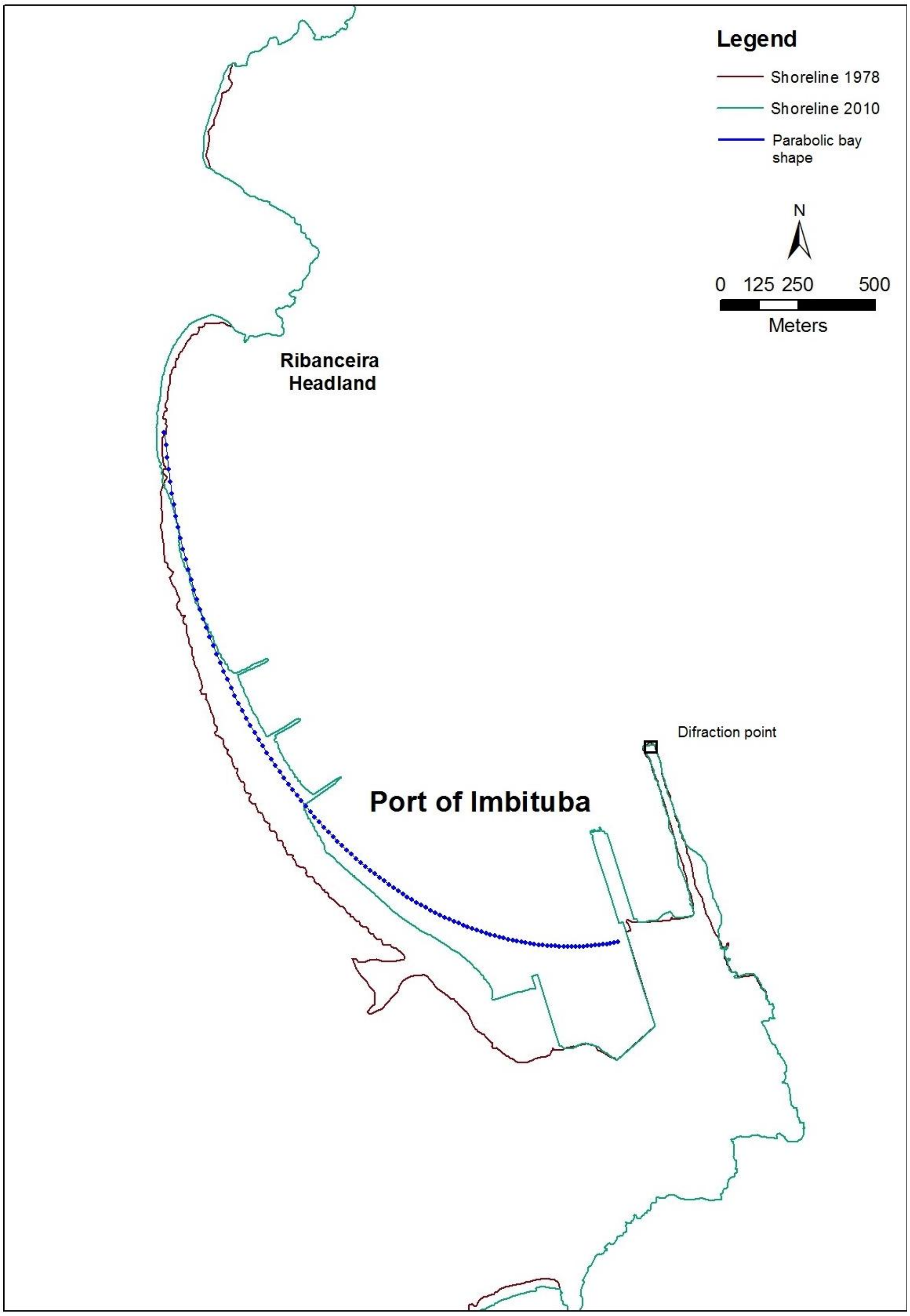

Figure 5-4 Parabolic bay shape before intervention

Naturally one can conclude that the bay would want to attract slightly more sediment from the extension of the breakwater. A definitive conclusion regarding the long-term effect of the extension cannot be given however, as the extension of the breakwaters primary function was to increase the chance of sediment being trapped North of the groyne.

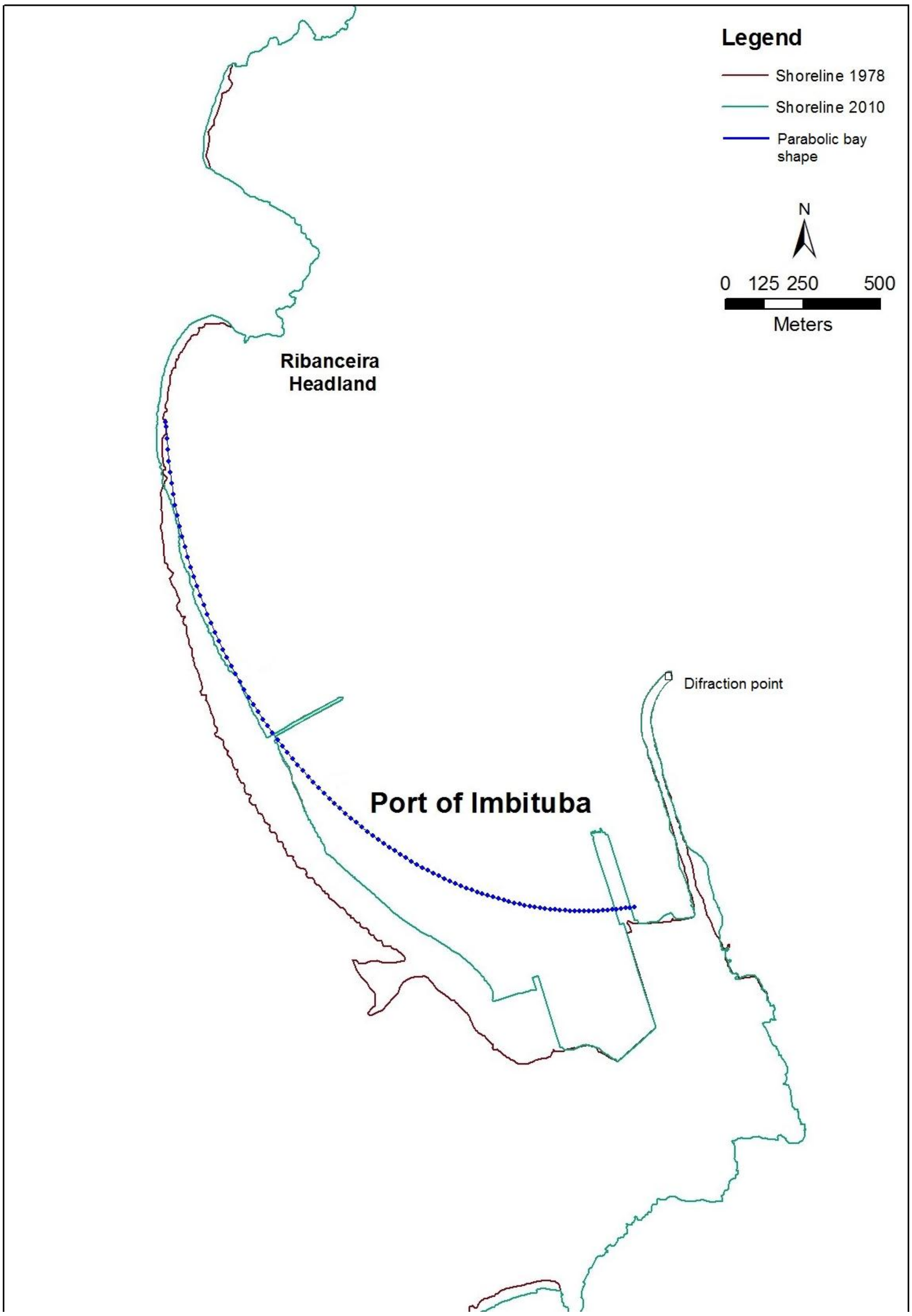

Figure 5-5 Parabolic bay shape after intervention

5.2 Variant II: Tombolo

Variant II focusses on a semi hard solution for the rotation of the bay and a much softer solution for the offshore and near shore import of sediments by building a sand trap and a shore parallel breakwater which will shape the beach in the form of a tombolo.

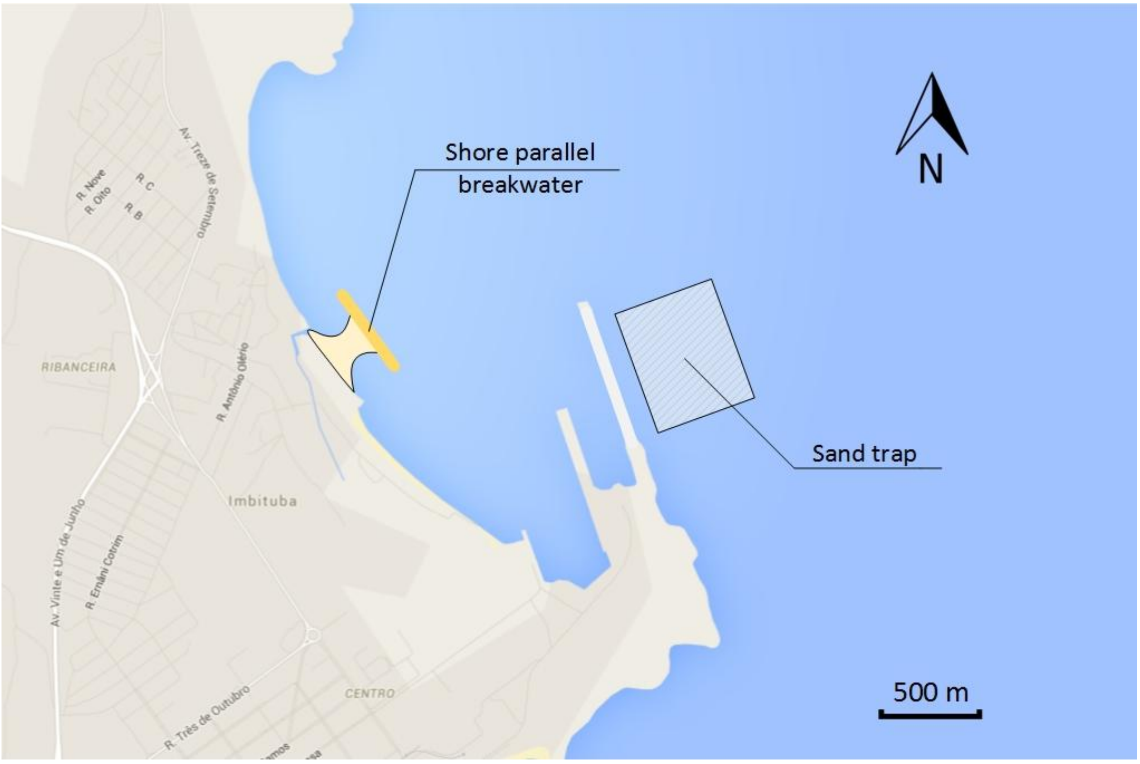

Figure 5-6 Variant II (yellow lines indicate changes)

5.2.1 Solution to rotation of bay

As the rotation of the bay is causing sedimentation in the berthing area of the port, reducing it is important for the accessibility of the port's infrastructure. The three groynes present on the beach to the West are removed. The sediment present in the groyne area is dredged to prevent further filling up of the port's berthing area. An offshore shore parallel breakwater is constructed. Important for this breakwater is that its width must be twice as large as the distance it is placed from the shoreline.

A distance of 200 [m] from the shore is chosen. The breakwater must therefore become at least 400 [m] wide. This will facilitate the formation of a tombolo behind it, allowing the northern beach to stabilize and obtain a new equilibrium with itself (Figure 5-6).

A design including the shape, dimensions and estimated stone size of the groyne has been made and can be found in Appendix H.

An impression of the cross section of this shore parallel breakwater can be found in (Figure 5-7). A complete drawing of the design can be found in Appendix I.

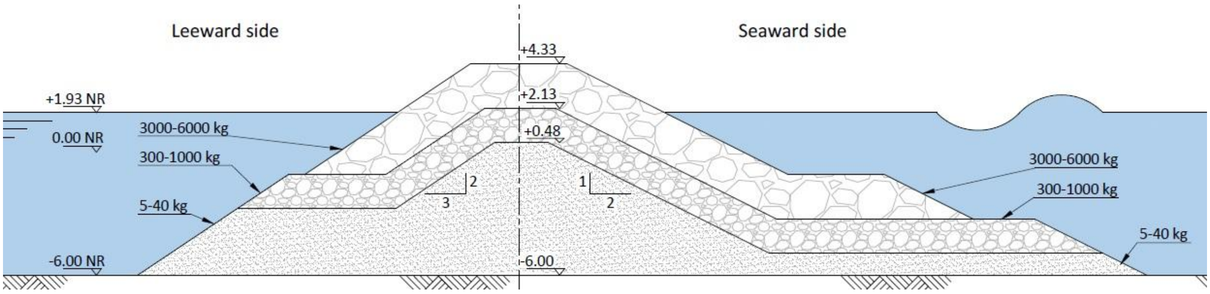

Figure 5-7 Cross section shore parallel breakwater

5.2.2 Solution to sediment import

As sediment import from near shore sources will still strongly contribute to the sedimentation in all areas, dredging a sand trap just Northeast of the primary breakwater may prove to be an adept solution. The sand trap will be 400 [m] * 400 [m] in surface area. This area will be deepened by 6 [m]. As the sand trap allows the accumulation of large amounts of sediments coming from the South, maintenance dredging in the port can be reduced to a minimum. The sand trap will probably have to be emptied once every four or five years, with sedimentation at current rates. This can be done together with the maintenance that will still be necessary for the port, once every few years.

5.2.3 Costs

The costs for Variant II are presented in Table 5-2. These costs include construction and maintenance of the new shore parallel breakwater, the sand trap and the removal of the groynes. Estimations are made using a unit price used for a stone breakwater elsewhere in Brazil (Bijl, 2015). The current exchange rate between the euro and the Brazilian real is 1:4,3 (October 16, 2015). Further specification of the costs can be found in Appendix F.

Table 5-2 Cost specification Variant II

Construction costs [€]	7.500.000
Maintenance costs [€/year]	350.000

5.3 Variant III: Building with nature

Variant III focuses on a semi-soft solution for both the rotation of the bay as well as the offshore and near shore transport of sediment. This is done while building with nature by improving the shoreline at the northern beach and constructing sediment bypass system at two locations.

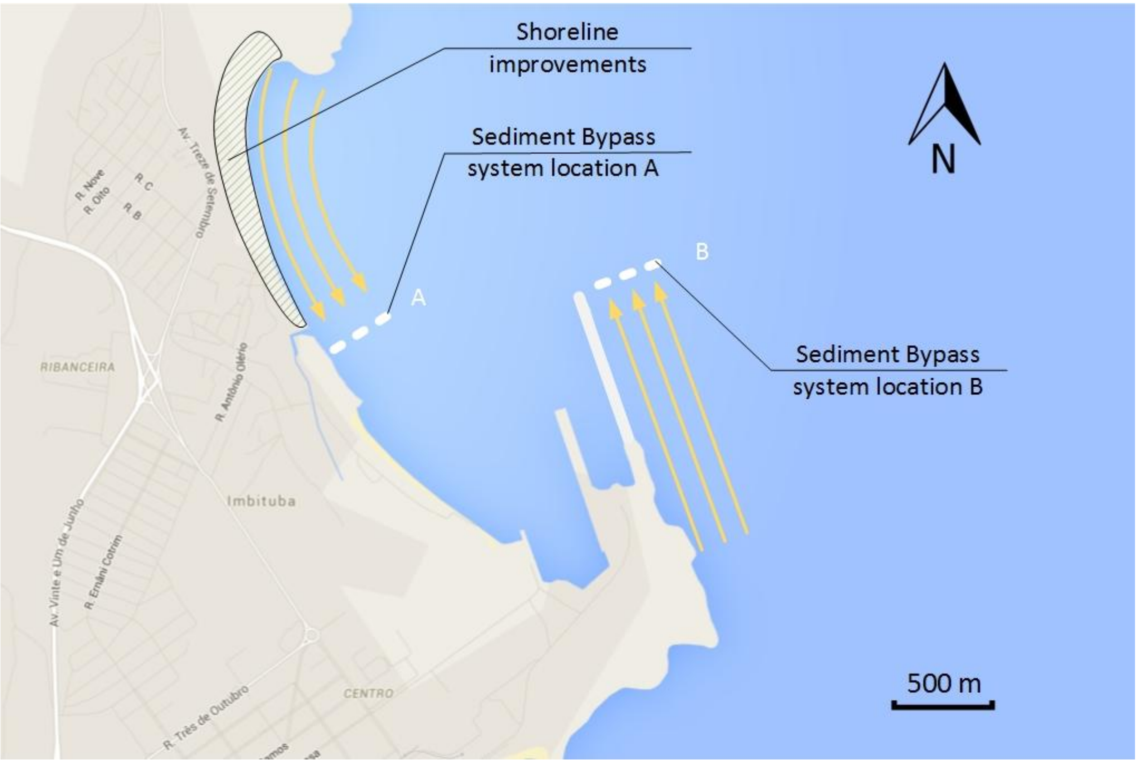

Figure 5-8 Variant III (yellow arrows indicate sediment transport direction)

5.3.1 Solution to rotation of the bay

To reduce the bay rotating, the scarp present at the northern beach can be protected from erosion in multiple ways. The beaches in front of the scarp can expanded thereby making them more dissipative. By doing this, the incoming waves will have less opportunity to reach the toe of the scarp, reducing the amount of erosion and reducing the areas role as a source of sediment. This could also be accomplished by strengthening the toe of the scarp with a geotextile, a stone bed protection or a combination of both.

Figure 5-9 An impression of the application of a geotextile shoreline improvement

The slopes of the gullies in the area to the North can be strengthened using (biodegradable) geotextiles, on which vegetation can be grown. Doing so, this will severely reduce the erosion caused by heavy rainfall. The sizes and yearly erosion of these gullies are estimated in Appendix B. The total area of the gullies that need strengthening by geotextile with vegetation amounts to approximately 150.000 [m^2].

5.3.2 Solution to sediment import

The offshore and near shore transport of sediment can be blocked using a sediment bypass system. With this system, sediment is collected from the seabed, transported through a series of pipes and placed in a storage area in the port. The sediment bypass system consists of two jetties, a system of pipes, a pump and a storage area. The tubes are positioned from the tip of the jetty towards the seabed. From here, sediment is pumped through the tube system.

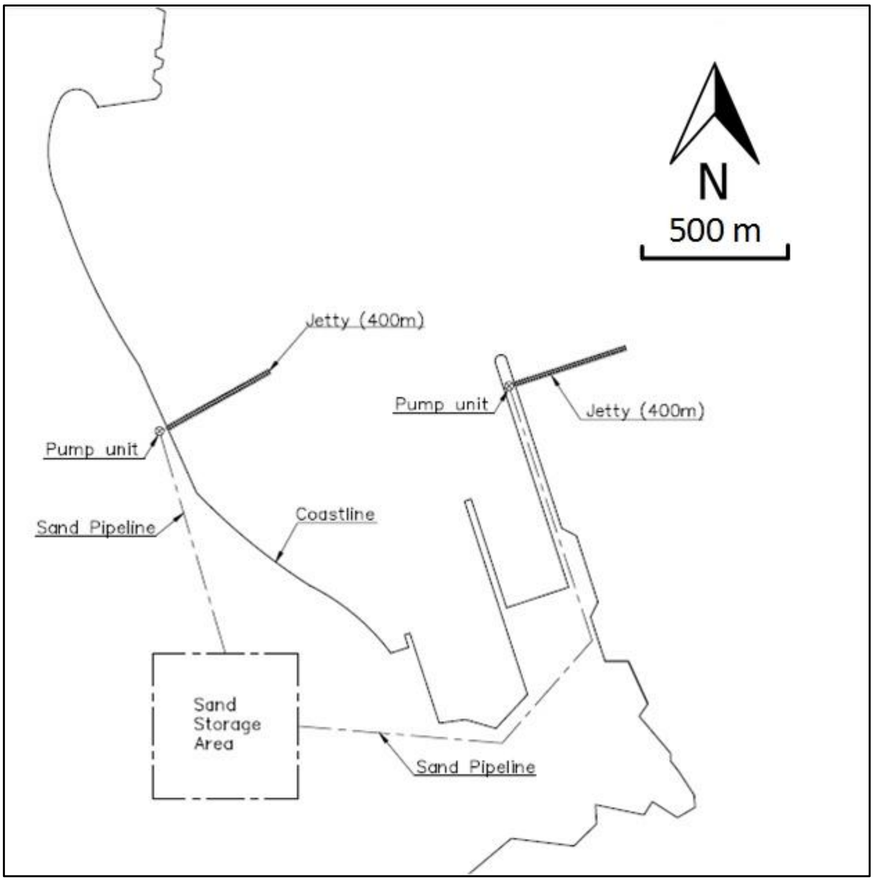

Figure 5-10 Sediment Bypass system in the port of Imbituba

5.3.3 Costs

The costs of a sand bypass system are estimated using the costs of the Tweed River Entrance Sand Bypassing System as reference (TRESBP, 2015). The Tweed River Entrance Sand Bypassing System has an estimated annual sediment transport of 500.000 [m^3]. The expected amount of sand transport in Imbituba is about half this estimation.

Figure 5-11 An Impression of the Tweed river sand bypass system jetty (TRESBP, 2015)

The total cost of the Tweed River Entrance Sand Bypassing System is presented below using an exchange rate between the Euro and the Australian Dollar of 1:1,56 (October 16, 2015)

Table 5-3 Cost of Tweed River Sand Bypassing System

Construction costs [€]	23.500.000
Operational costs [€/year]	4.300.000

Labour costs in Brazil are much lower than in Australia. Furthermore it is expected that the Imbituba system transports only half the amount of sediment than the Tweed bypass system does, leaving the total costs involved to be much lower as well. However, two jetties and two separate installations need to be constructed instead of one. It is therefore estimated that the construction of the system in Imbituba will be around 70% of the construction costs of the Tweed bypass system. The total costs concerning the Imbituba sediment bypass system are visible in Table 5-4.

Table 5-4 Cost of the Imbituba sediment bypass system

Construction costs [€]	16.310.000
Operational costs [€/year]	2.950.000

In addition to the costs of the sediment bypass system, the costs of the improvement and protection of the scarp and gullies at the northern beach are estimated:

Table 5-5 Costs improvement scarp and gullies

Construction costs [€]	500.000
Maintenance costs [€/year]	50.000

This makes that the total costs for Variant III will become:

Table 5-6 Total costs

Construction costs [€]	16.810.000
Maintenance costs [€/year]	3.000.000

5.4 Variant IV: Dredging

Variant IV focusses on a soft solution for both problems by maintaining the port with periodical dredging operations.

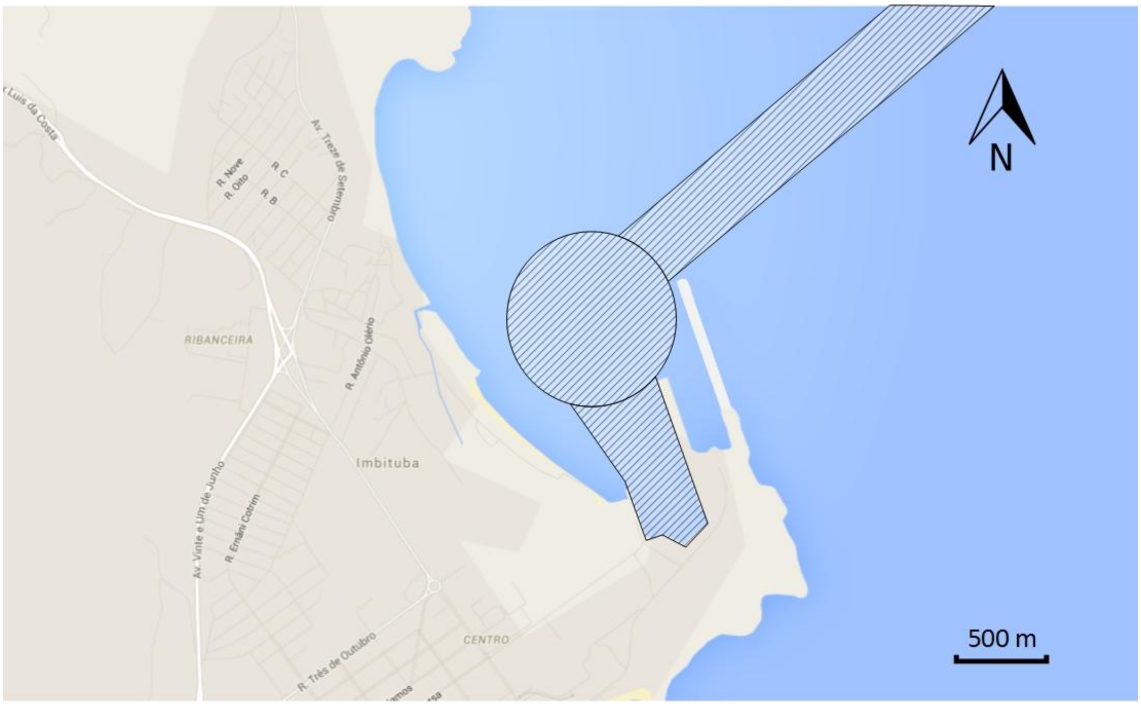

Figure 5-12 Dredging areas (hatched zone)

5.4.1 Solution to rotation of the bay

The rotation of the bay will not be stopped, but dredging will alleviate the negative effects. In case that no dredging will take place, the basin will face accretion up to 30.000 [m^3] each year, coming from the North. The scarp in the North will keep eroding but possibilities to reduce erosion might involve increasing the size of the beaches in front of the scarp with the dredged sediment, effectively reducing wave attack on the toe of the scarp.

5.4.2 Solution to sediment import

The offshore and near shore transport of sediment will continue, to maintain accessibility of the port it is also recommended to dredge the port regularly. This can be achieved by removing 120.000 [m^3] from the turning circle and 127.000 [m^3] of sediment from the access channel, for each year since the last dredging operation. The sediment can be transported offshore or it can be sold for construction purposes.

5.4.3 Costs

Estimating the port has to be dredged every 4 years, a cost estimation can be given from previous dredging operations. From a large scale dredging operation in the past conducted by Van Oord, the costs per year can be estimated if preference goes to a 20 year maintenance contract.

Table 5-7 Van Oord Dredging operation in Imbituba (2014)

Days of operation [days]	66
Removed volume [m^3]	5.492.000
Cycle production [m^3/day]	83.200

It is assumed that a Trailing Suction Hopper dredger with a capacity of about 18.000 [m^3] will be used for the maintenance operation. The weekly costs for such a dredger are estimated in Table 5-8 (Schrieck, 2014).

Table 5-8 Estimated weekly operational costs

Depreciation and interest [€]	300.000
Maintenance and repair [€]	100.000
Crew [€]	65.000
Fuel and lubricants [€]	75.000
Insurance [€]	45.000
Other expenses [€]	45.000
Total [€]	630.000

Assuming that the sedimentation rate continues, a removal of approximately 1.108.000 [m^3] of sediment is needed every 4 years. With a cycle production of 83.200 [m^3/day], this would amount a 14 days dredging operation once every 4 years. This results in a cost estimation of:

Table 5-9 Estimated Costs for single dredging operation

Required volume [m^3]	1.108.000
Cycle production [m^3/day]	83.200
Estimated operation time [days]	14
Estimated Costs [€]	1.260.000
Costs of mobilisation and demobilisation [€]	750.000
Total costs [€]	2.010.000
Total yearly costs [€/year]	502.500

6 Delft3D

6.1 Introduction

The programme Delft3D is a software package, developed by Deltares, to simulate 2D and 3D flow, sediment transport, waves, morphology and the interaction of them in time and space. The programme is built up in one single user interface that combines the different disciplines. The frequently used ones for modelling the port of Imbituba are the FLOW and WAVE modules. The Delft3D model can handle complex geometries as this can be seen in the Imbituba case.

The foundations for the Delft3D-FLOW module are the Navier-Stokes equations that hold for an incompressible fluid, under the shallow water and the Boussinesq assumptions. The set of partial differential equations in combination with an appropriate set of initial and boundary conditions is solved on a finite difference grid. The Delft3D-WAVE module uses the input of SWAN to simulate the evolution of random, short-crested waves.

6.2 Grid and bathymetry

For the port of Imbituba, a new curved-linear grid is constructed from scratch. The area of interest is located along the beach and in front of the breakwater. Under this assumption, a fine grid (with a high resolution) is used at this location. The reason for this is to prevent having a staircase grid at these locations that negatively influence the results of the sediment transport. Along with the finest grid, two regional grids are used. The larger grids are intended for the WAVE computation and the finest grid for the FLOW computation. A downside of a well-fitted grid at the target area, despite of the multiple splines that are used, is that outside this area the grid fits less and has a staircase pattern along the coast. It is assumed that this will hardly influence the area of interest. Moreover, regarding the computation time, applying the finest grid in the whole area would be too much time consuming.

The data of CB&I, regarding the depth, is used to setup the bathymetry. With this data, locations are indicated regarding their sediment availability. This entails that the area around the breakwater and locations where rocks are situated are indicated as locations of zero sediment availability. For the rest of the region, the sediment availability is set at ten meters to make sure that the available sediment is enough for transportation by flow.

6.3 Boundary conditions

The boundary conditions prescribe the limits of the model that is used. The boundaries at the northern side and southern side of the grid (cross shore) are prescribed by a Neumann time-serie with a small gradient on both sides in order to induce offshore currents. The other parameters are assumed to be zero. At the eastern side of the grid (alongshore boundary), a harmonic water level with a zero gradient is used, induced by four tidal components (M2, S2, K1 and O1). The obtained domain, in other words the grid, is small in relation to the tidal wave length. Furthermore, the tidal currents in open waters are relative low at the Brazilian coast. Under these conditions, it can be assumed that the start and end point of the tide at the water level boundary are equal.

6.4 Results

6.4.1 General

The Delft3D software is used to simulate, with the input of two out of twelve wave conditions, the effectiveness of the proposed interventions that are elaborated in Chapter 5. These conditions are obtained by using the Matlab software. In this programme, a script is built that clusters the data of thirteen years of wave and wind data in order to obtain the twelve conditions. Subsequently, the twelve conditions will all be evaluated in a base case, defined as the original situation as it is at the moment in Imbituba. The two conditions that have the highest sediment transport rates in the port will be used for evaluating the variants regarding their effectiveness to limit the amount of sedimentation. The reason for minimizing the amount of conditions is time related. In case that twelve conditions are evaluated against four variants makes that the end result equals 48 runs, where each run takes one-day of computation time. The conditions that have the highest impact regarding the sediment transport rates are listed in Table 6-1.

Table 6-1 Deep water wave conditions

Condition	H_s [m]	T_p [s]	Direction [degrees]	Days / year	Wind [m/s]	Wind [deg]	Cosine Power	Scale factor
2	2,3	6,8	54,2	13,3	7,3	19,4	4,0000	13,3
12	4,2	11,0	185,7	3,6	9,4	203,5	4,0000	3,6

6.4.2 Base case

The two base cases are based on the input as listed in Table 6-1. These base cases will be used to compare the variants with each other. For both of the two conditions, three aspects are compared regarding their influence. These three aspects are:

1) The wave height and direction
2) The depth-averaged velocity
3) The mean total transport

It must be kept in mind that the consideration of the conditions is done on mutual basis. In other words, the other ten conditions resulted in lower sediment transport rates in the areas that are of most interest. For both base cases, a detailed elaboration is provided below.

Condition 2

As mentioned above, for each condition, the wave height and direction, the depth-averaged velocity and the mean total transport are analysed in order to get a better insight in the sediment transport rates. Figure 6-1 shows the wave height and the corresponding direction of the propagating waves. The arrows indicate the direction of the waves that penetrate the bay perpendicular to the coast. At the tip of the breakwater, the waves diffract inside the basin area. As indicated by the colour bar, due to the decrease of the bed level and diffraction, wave energy is dissipated and the significant wave height decreases in the sheltered basin area.

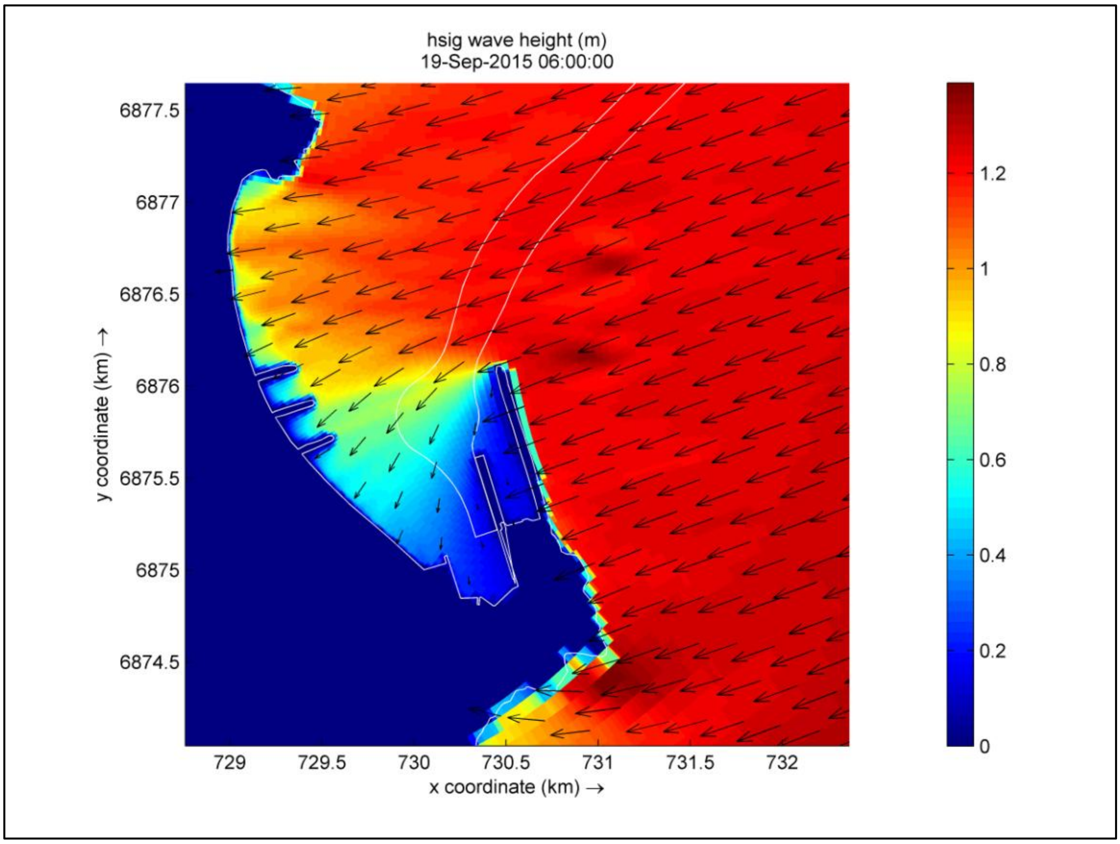

Figure 6-1 Significant wave height condition 2

The magnitude of the depth-averaged velocity, presented as Figure 6-2 shows that the offshore velocities (directed southward) slightly increase from the North to the South. In the model, the default viscosity is assumed. Furthermore, at the northern and the southern boundary of the grid a small gradient is applied in order to induce offshore currents, as mentioned in the previous paragraph. The areas of interest (the turning circle and the basin area) are hardly influenced by these velocities; however their presence cannot be neglected. A more detailed impression of this depth-averaged velocity is given in (Figure 6-3). Based on these figures, it can be said that accretion is likely to occur as result of decreasing velocities towards the port.

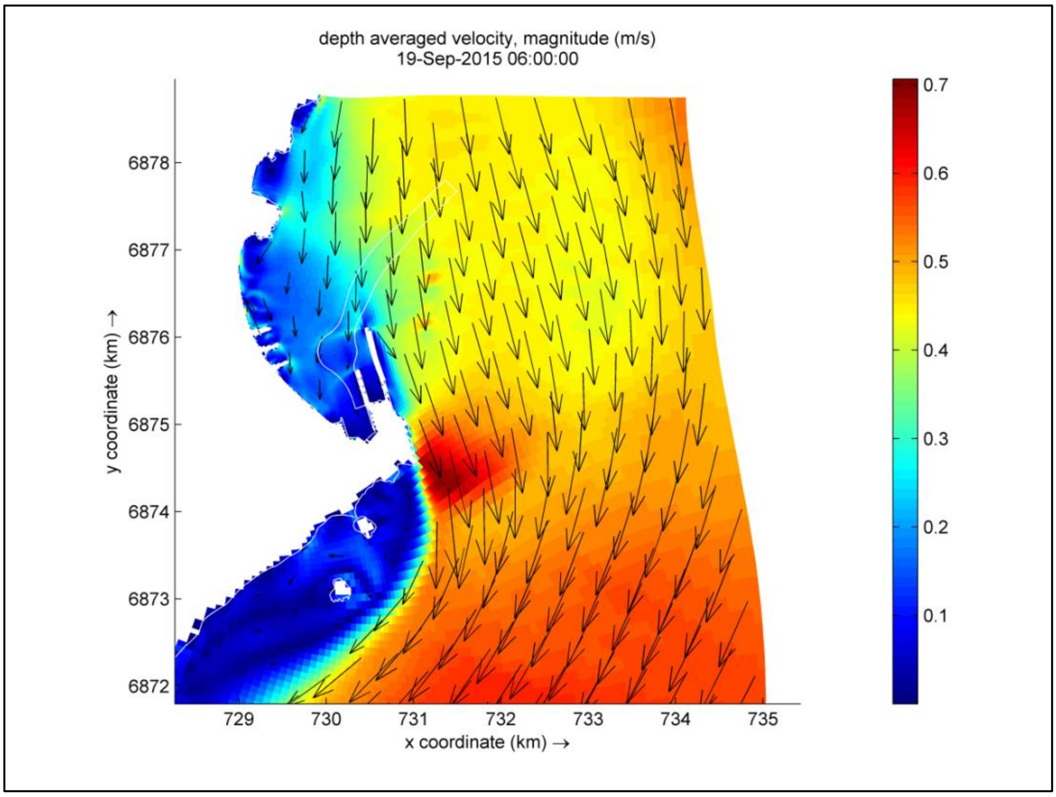

Figure 6-2 Depth-averaged velocity condition 2 (regional)

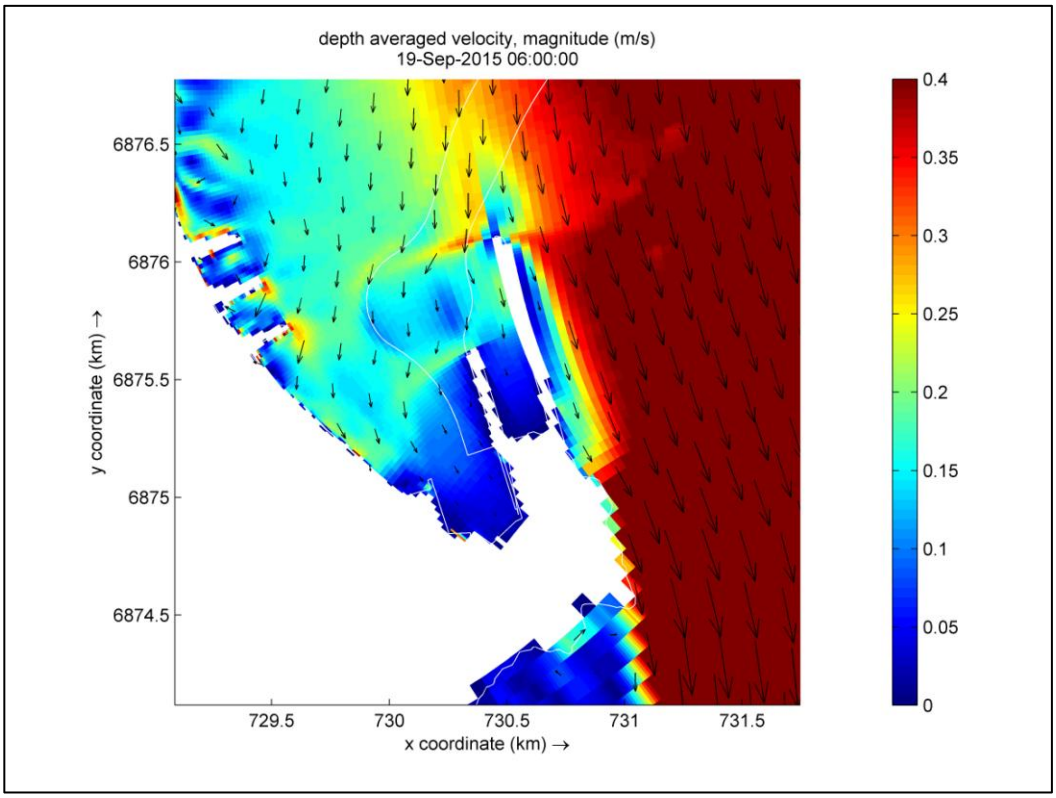

Figure 6-3 Depth-averaged velocity condition 2 (local)

The mean total transport is presented in (Figure 6-4Figure 6-2). On the bottom right-hand corner of this figure, there are large sediment transport rates present. However, as this area is outside the obtained domain, it is hardly influencing the sedimentation process of the port. It must be remarked that the groynes have a significant impact on the sediment bypassing. However the effectiveness of these structures is not as should be. During condition two, it can be seen that the channel and the turning circle have lower sediment transport rates than the surrounding areas (Figure 6-5 & Figure 6-6). This implies that, as the velocities decrease, accretion is likely to occur at these locations. For the basin area, the sediment transport rate is decreasing rapidly so accretion occurs there. At the northern part of the bay, a lot of sediment transport is taking place that is directed to the East and South.

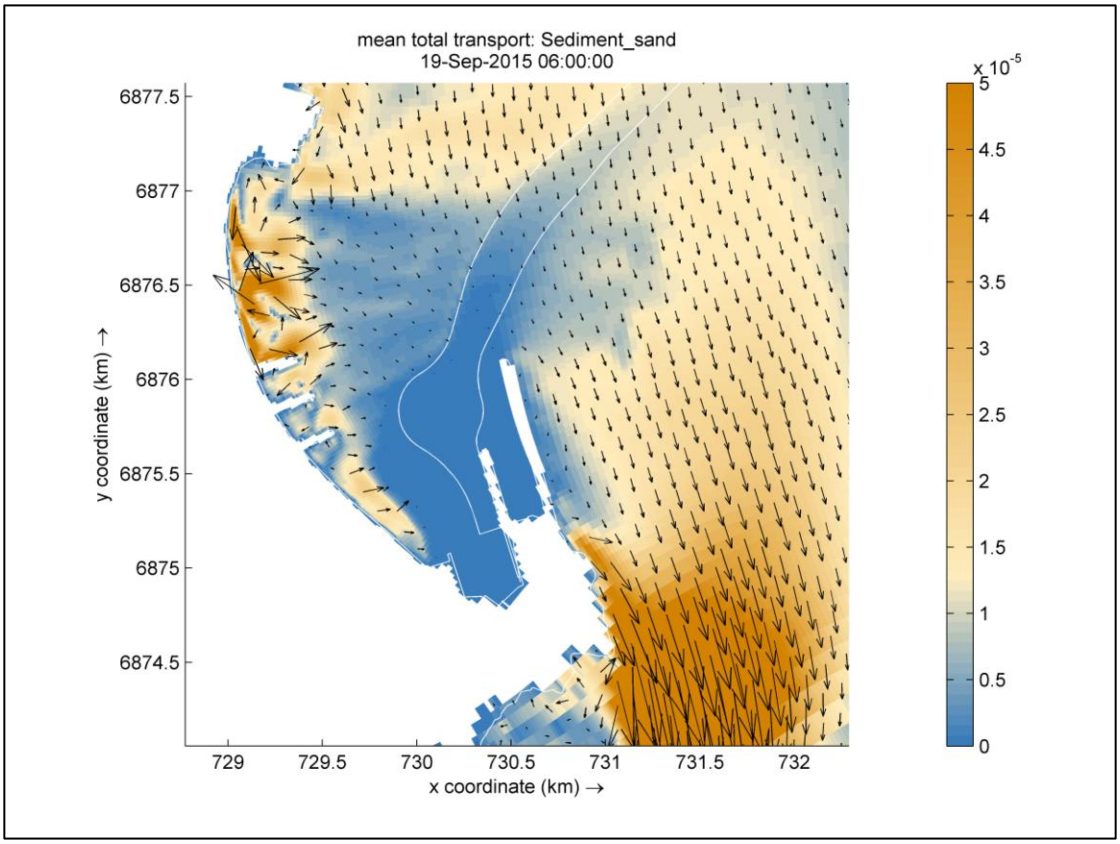

Figure 6-4 Mean total transport condition 2 (regional)

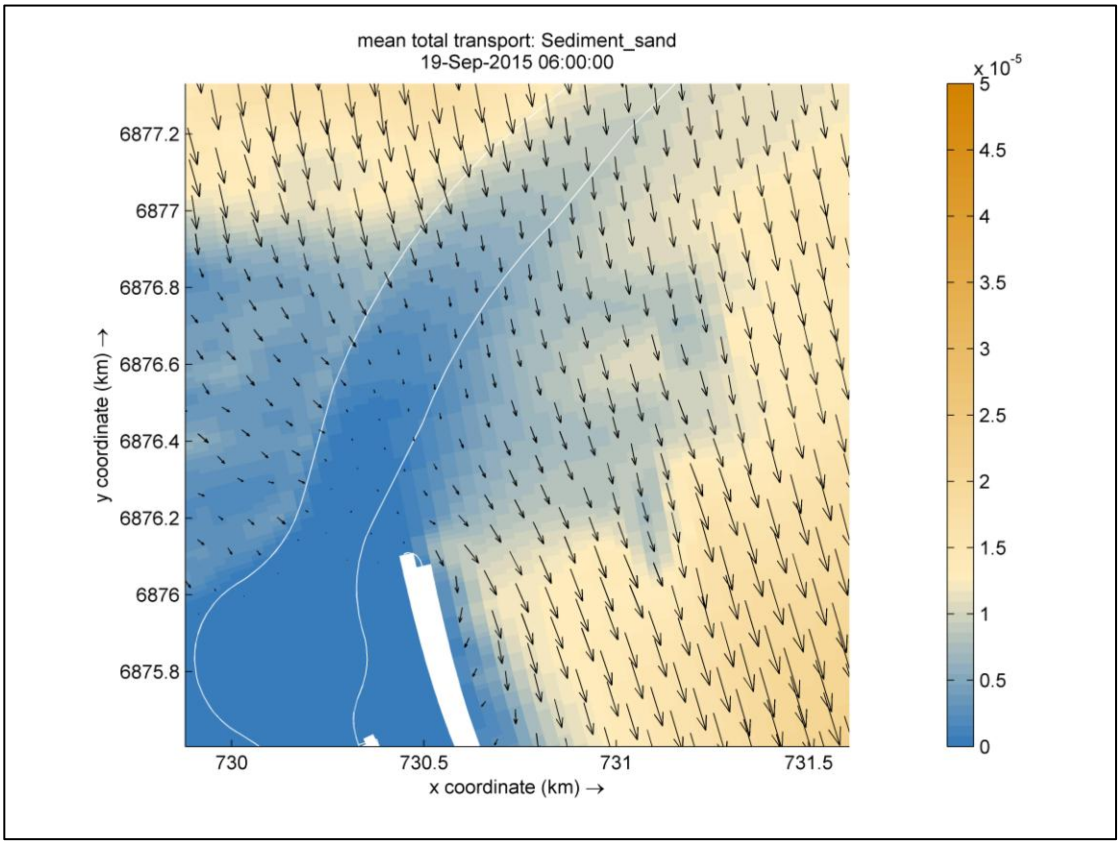

Figure 6-5 Mean total transport condition 2 (channel)

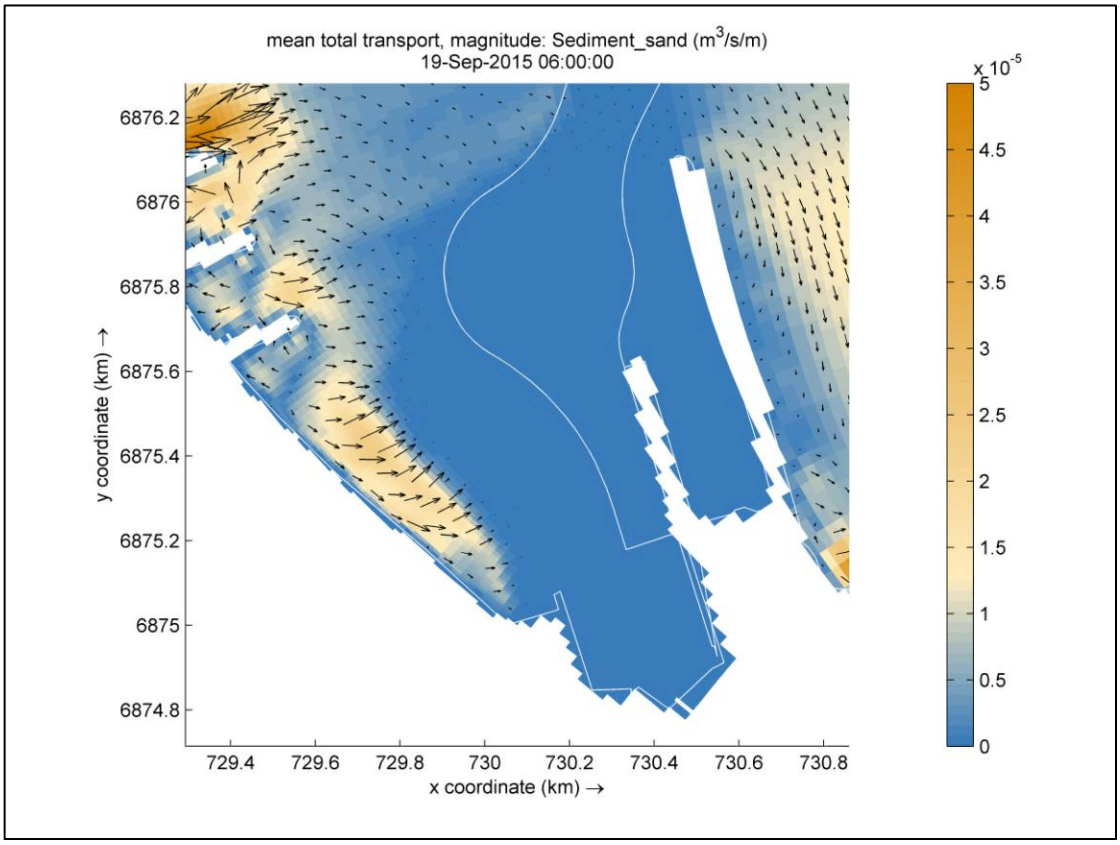

Figure 6-6 Mean total transport condition 2 (basin)

Condition 12

In order to compare the influences of different wave and wind characteristics, the same approach is used as is done for the previous condition. Figure 6-7 shows the main direction of the propagating waves, indicated by the black arrows. This condition, in comparison with number two, results in waves from the South to the North that has larger significant wave heights. The same principle holds for the diffraction at the tip of the breakwater. Due to energy dissipation, it leads to smaller wave heights at the northern side of the sheltered bay. In the basin area, the presence of waves is almost non-existent.

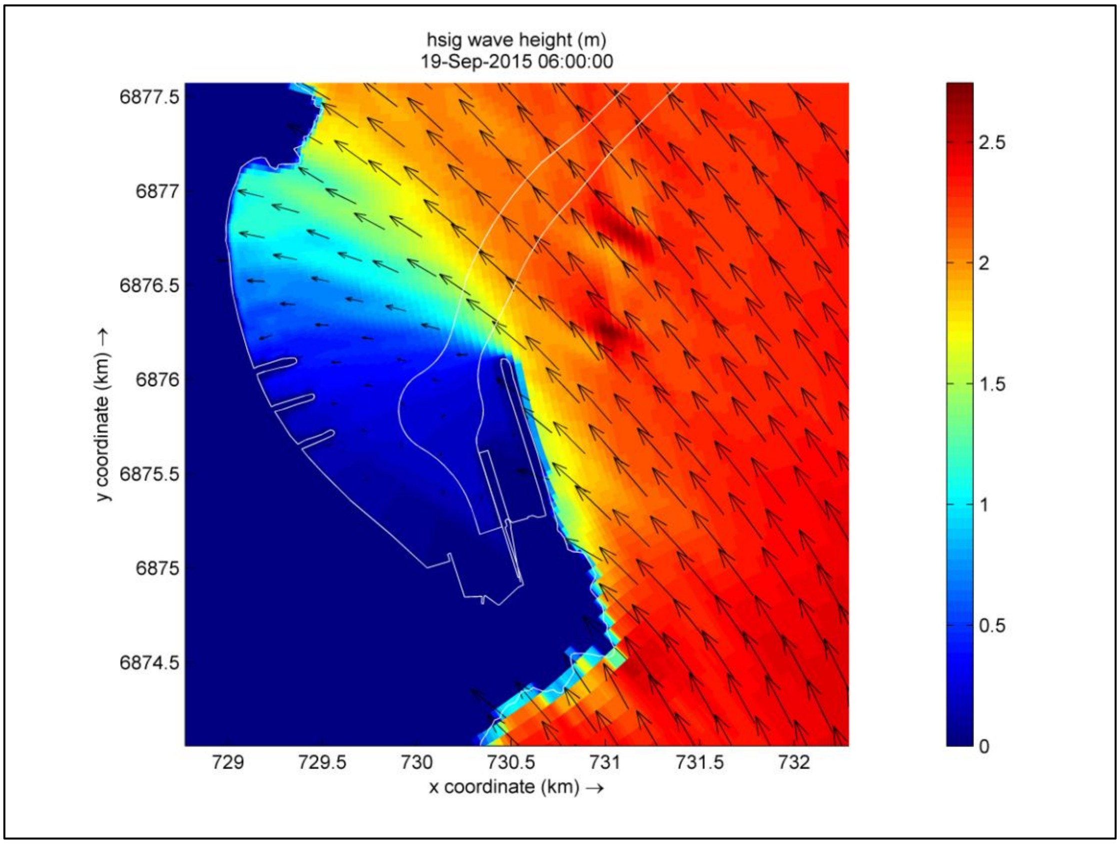

Figure 6-7 Significant wave height condition 12

The depth-averaged velocity (Figure 6-8) shows a decrease of velocity from the South to the North of the offshore currents. As it is done for condition two, the initial conditions of the Neumann boundaries at the northern and southern side of the grid are such that currents are present at the offshore area. The turning area and the basin are hardly influenced by these velocities as the breakwater shelters these areas. Moreover, these velocities are directed outwards in this sheltered area. A closer look is taken in the area of interest (Figure 6-9), it shows a relative high depth averaged velocity at the tip of the breakwater. The reason for this phenomenon is that at this location, where flow is directed to the East, the discharge is large resulting in large velocities (as water follows the path of least resistance).

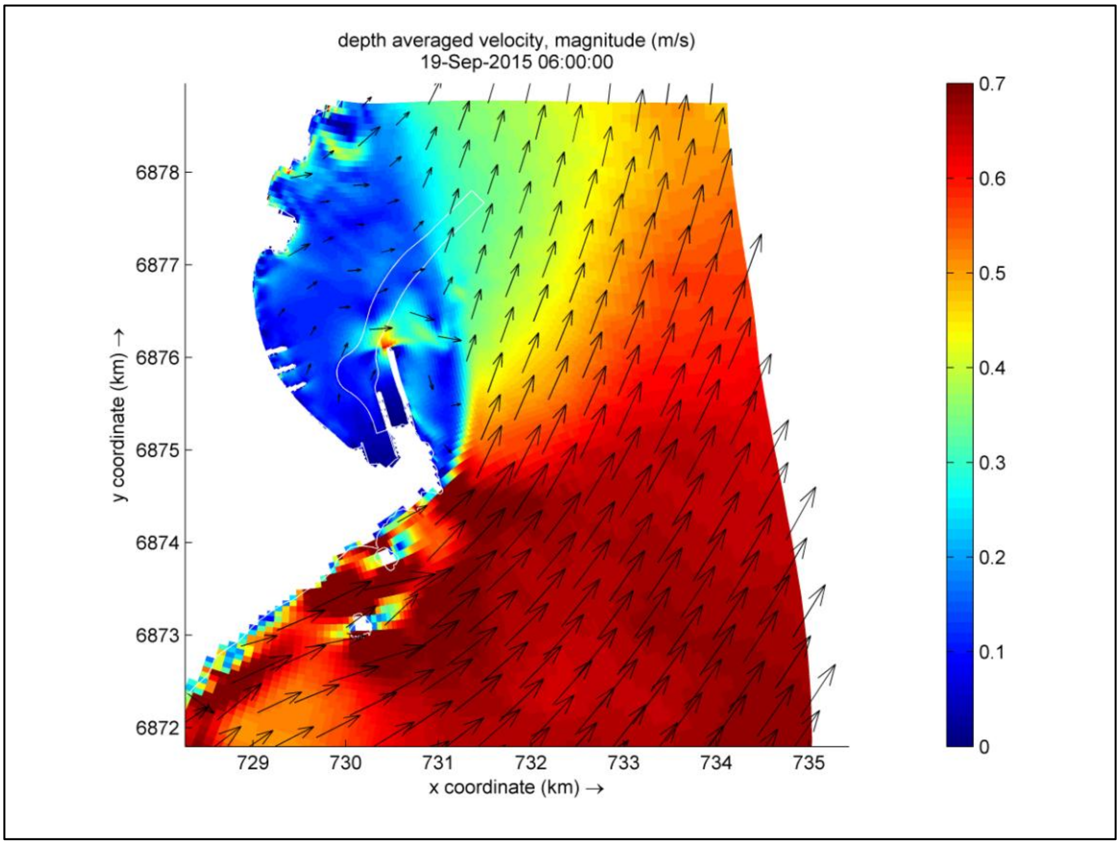

Figure 6-8 Depth-averaged velocity condition 12 (regional)

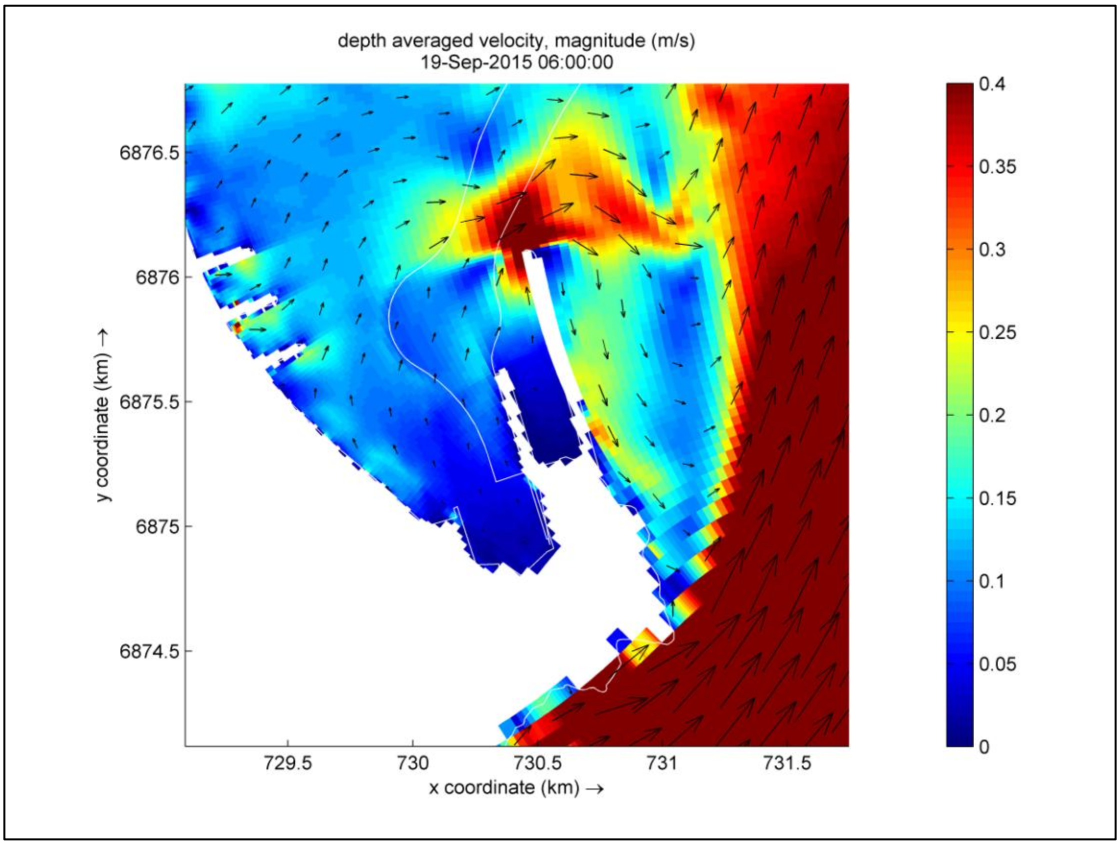

Figure 6-9 Depth-averaged velocity condition 12 (local)

The mean total transport is given in (Figure 6-10). With the input of the previous figures, it is proven that this condition has decreasing transport rates over the length of the channel. This phenomenon will result in accretion in the access channel. Considering the sheltered areas (e.g. the turning circle and the basin) the transport rates are nearly equal to zero, which implies that there will be not much accretion. At the northern part of the bay, there are large sediment transport rates present that can influence the obtained domain, depending on the variant that is proposed (Figure 6-11 & Figure 6-12).

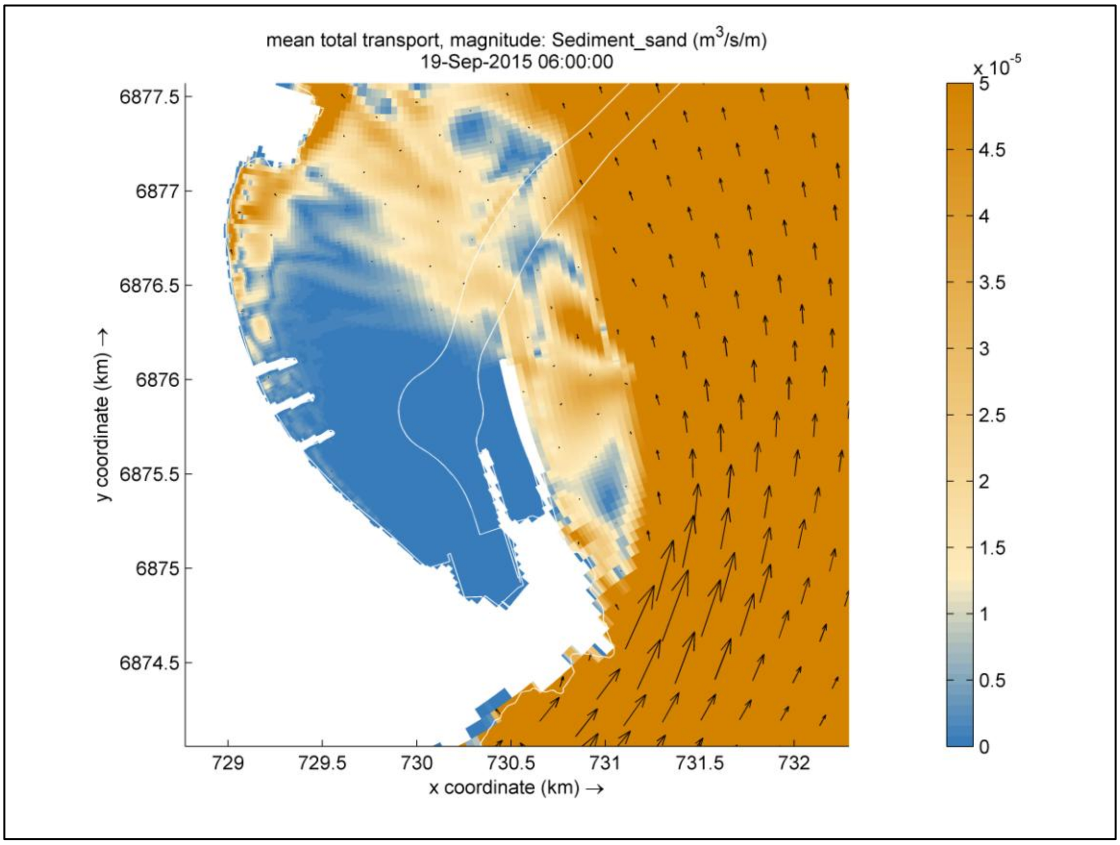

Figure 6-10 Mean total transport condition 12 (regional)

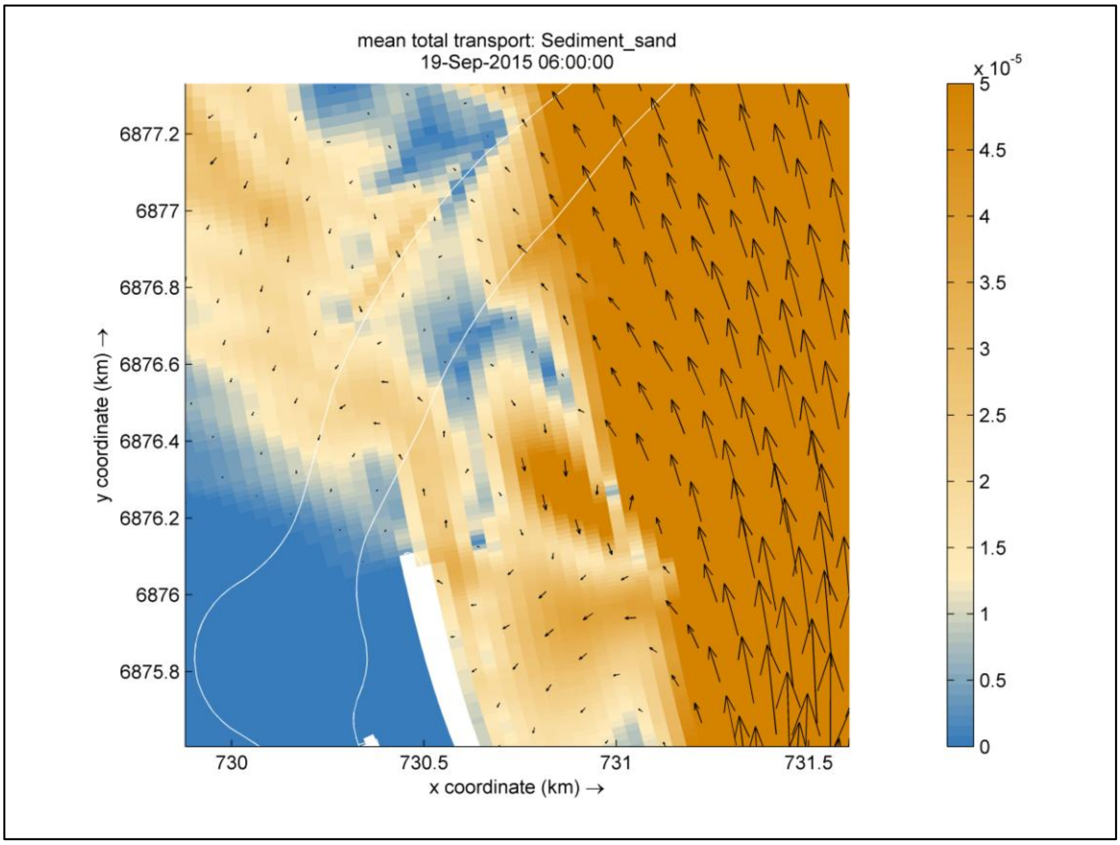

Figure 6-11 Mean total transport condition 12 (channel)

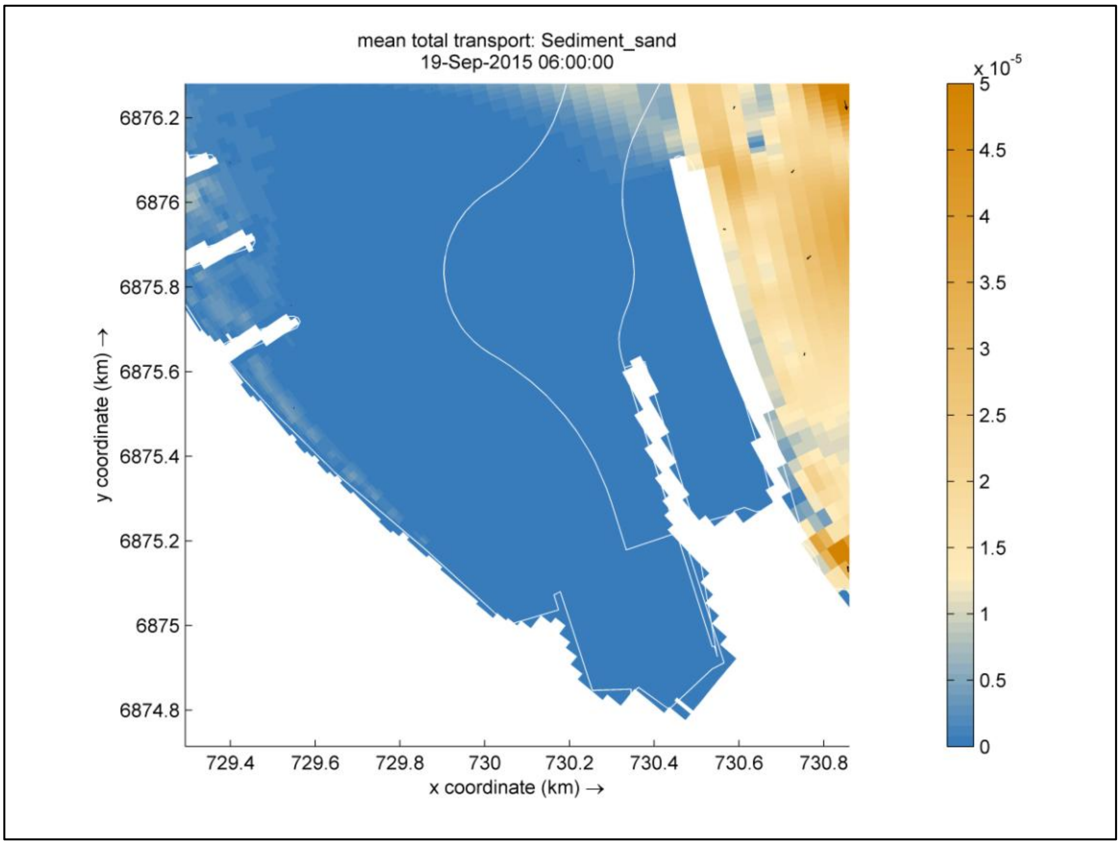

Figure 6-12 Mean total transport condition 12 (basin)

6.4.3 Conclusion Base case

Based on the two conditions that are elaborated in this chapter, the following things can be concluded:

- The significant wave height of condition twelve is twice as large as condition two, so for the outer channel the sediment transport rates and thereby the rate of accretion is larger for condition twelve. However the sediment transport rate and thereby the rate of accretion for the basin and turning circle is stronger for condition two.
- The groynes, especially during condition two, show that their effectiveness is not as it should be. This is probably due to the fact that they are already filled with sand.
- During condition twelve, there are high velocities at the tip of the breakwater. This should be taken into account for the design of the breakwater extension.

6.5 Variants

In Appendix D, all the four proposed variants are evaluated based on their effectiveness regarding the sediment transport rate. It turned out that the results of Delft3D on the third and fourth variant is not as expected. For variant one and two, the figures of the waves, the depth-averaged velocity and the mean total transport are presented on the next two pages. On the left side, condition two and on the right side condition twelve. Based on this output, the following is concluded:

Variant I: Hard intervention

- For both wave conditions variant I creates more sheltered area inside the bay. The bay is now experiencing **less** wave energy
- For both wave conditions in variant I, the depth-averaged velocities inside the bay will **decrease**. There is less flow velocity to transport the sediment
- The extended breakwater has a **large** impact on the wave and flow regime in the bay area.
- Variant I **considerably decreases** the sedimentation of the basin and the turning circle with respect to the base case
- Variant I **decreases** the sedimentation of a part of the channel with respect to the base case
- Variant I **considerably decreases** the erosion of the northern part of the bay with respect to the base case

Variant II: Tombolo

- The effects on the waves and the depth-averaged velocities of variant II are **local** instead of regional. There will be less sedimentation with respect to the base case
- The formation of the tombolo will block the sediment transport coming from the North. However, there will be still some **bypassing** of sediment
- Variant II **decreases** the sedimentation of the basin and the turning circle with respect to the base case
- Variant II **does not** decrease the sedimentation of the channel with respect to the base case
- Variant II **does not** decrease the erosion of the northern part of the bay with respect to the base case

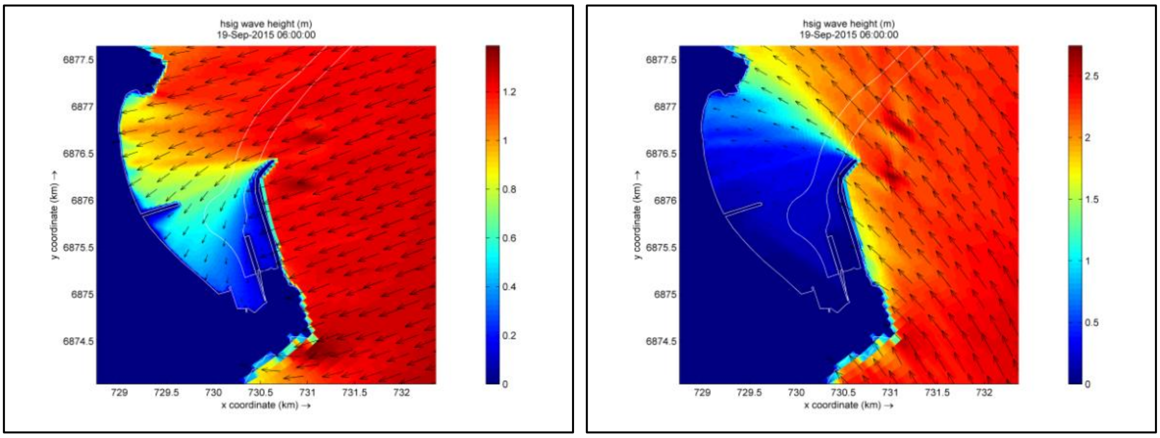

Figure 6-13 Significant wave height variant I (condition 2 (left) and 12 (right))

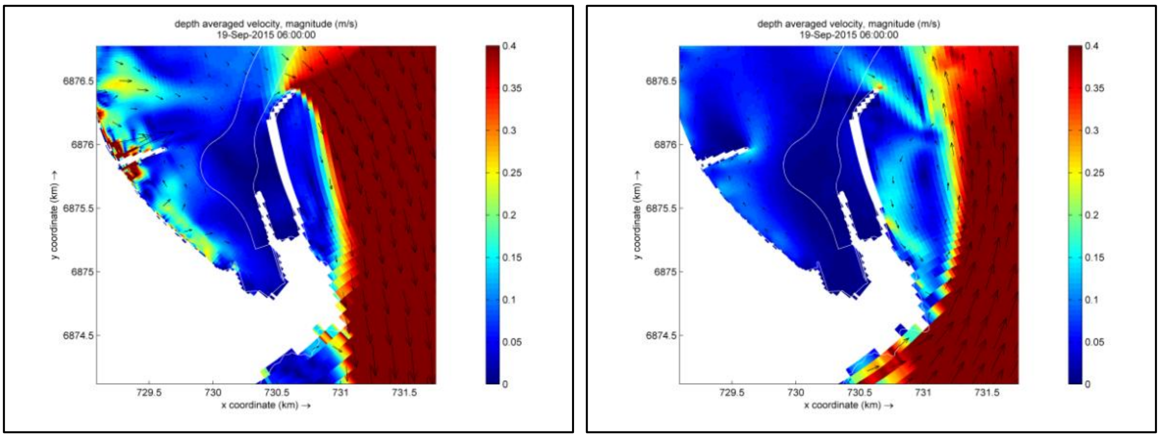

Figure 6-14 Depth-averaged velocity Variant I (condition 2 (left) and 12 (right))

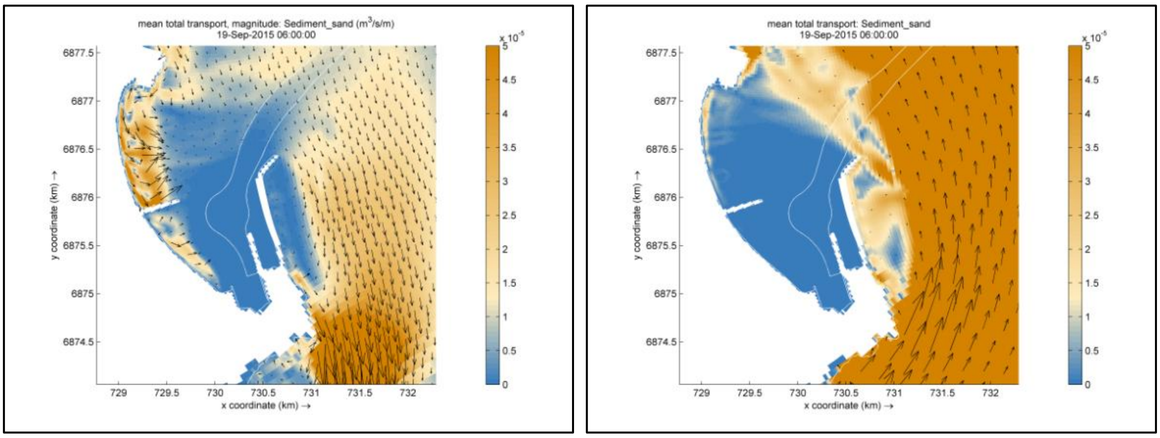

Figure 6-15 Mean total transport variant I (condition 2 (left) and 12 (right))

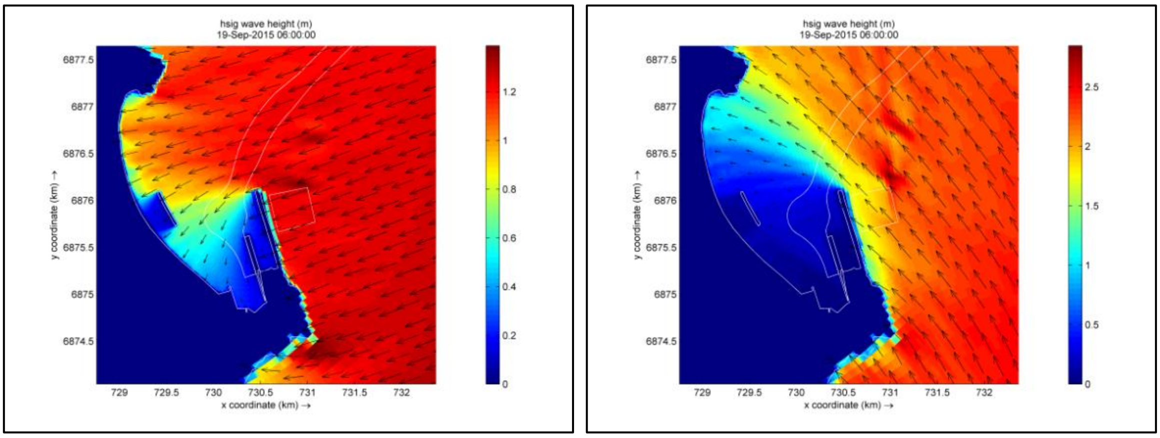

Figure 6-16 Significant wave height variant II (condition 2 (left) and 12 (right))

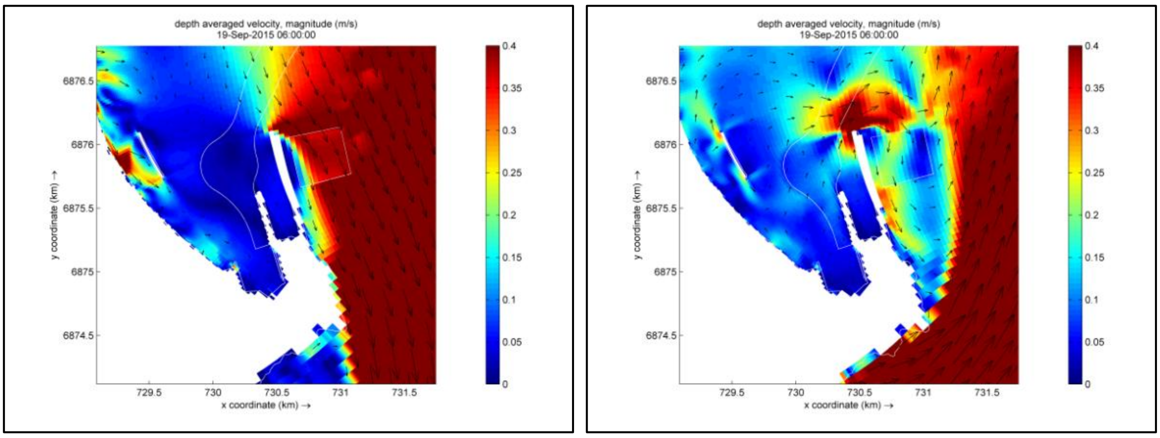

Figure 6-17 Depth-averaged velocity Variant II (condition 2 (left) and 12 (right))

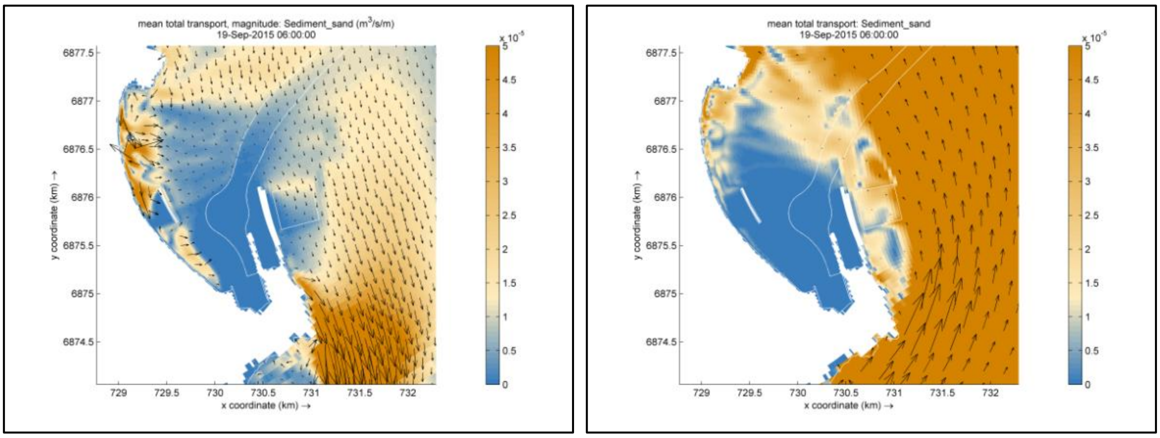

Figure 6-18 Mean total transport variant II (condition 2 (left) and 12 (right))

Variant III: Building with nature

- For both conditions, the significant wave height and the diffraction pattern is **equal** to the base case situation
- The depth-averaged velocity for both conditions is different, however it is **uncertain** if this is due to the presence of the sediment bypass system or due to the absence of the three groynes
- For both wave conditions, the sediment transport rate is **equal** to the base case situation.
- The actual working of the sediment bypass system, at least in the model, is **uncertain**. More research should be conducted to ensure the effectiveness of this alternative

Variant IV: Dredging

- The Delft3D model **does not** show significant differences for the waves, flow and transport compared to the base case
- Based on the Delft3D model it is expected there is **no difference** in sedimentation and erosion inside the bay
- The expectation is that the Delft3D model **does not** properly compute the effects of this variant

6.5.1 Conclusion variants

Based on the output of the Delft3D programme, Variant I "hard intervention" has the highest effectiveness in limiting the sediment transport rate in the port of Imbituba. In the following chapter, a Multi Criteria Analysis is performed where the variants are evaluated.

7 Multi Criteria Analysis

This chapter of the report focusses on a Multi Criteria Analysis regarding the proposed variants from Chapter 5. The variants are compared to each other on the following 12 criteria subdivided into four categories:

- Economical
  - Construction costs
  - Maintenance costs
  - Durability
- Functional criteria
  - Functionality
  - Feasibility
  - Uncertainty
  - Navigability
  - Sensitivity
- Environmental
  - Environmental risk
  - Greenhouse gas impact
- Social criteria
  - Human risk
  - Public acceptance

The criteria are weighted and a score for each variant is given. The entire process concerning normalisation of scores and determination of weight factors can be found in Appendix G. From the Multi Criteria analysis visible in Table 7-1, it can be seen that Variant IV including a long-term dredging scheme, seems to be the most effective solution.

Although Variant I scores best on the functionality regarding the mitigation of the sedimentation problem, Variant I scores relatively low due to high construction costs and uncertainty of the long-term effects the structures might have on the equilibrium of the bay. Variant IV scores best due to its durability, the absence of construction costs and little uncertainty.

Table 7-1 Multi Criteria Analysis and score

	weight	0	I	II	III	IV
1: Construction costs	**7,5**	1	0	0,6	0,1	1
2: Maintenance costs	**7,5**	1	1	0,9	0	0,8
3: Durability	**6**	-	0,6	0,7	0	1
4: Environmental risk	**6,5**	1	0,8	0,7	0	0,5
5: Carbon footprint	**4**	1	0,8	0,7	0	0,3
6: Functionality	**12**	0	1	0,5	0,4	0,9
7: Feasibility	**7,5**	-	0,6	1	0	0,8
8: Uncertainty	**6,5**	-	0,5	0,3	0	1
9: Navigability to the port	**8,5**	0	0,9	1	0,9	0,9
10: Sensitivity	**3,5**	-	0,8	0,7	0,3	0
11: Human risk	**1,5**	1	0,7	0,7	0	0,5
12: Public acceptance	**6**	0,6	0,5	1	0	0,4
Total scores variants		**30,6**	**53,75**	**30,6**	**14,25**	**58,05**

8 Conclusion

After an investigation of the port and its history, several interesting events are noted. The construction and elongation of the breakwater in the mid-seventies and early eighties caused the bay to start importing sediment due to the displacement of the diffraction point. Dredging operations conducted in 2014 also resulted in an acceleration of the sedimentation process, due to a large disturbance of the quasi equilibrium the port had reached.

A sediment budget model was constructed to quantify the sediment transport rates and their directions in the port of Imbituba. It is determined that the waves are the primary contributor of sediment transport, especially when they are directed from Northeast (alongshore transport) or offshore from the East. The structures of the port have been determined to be the primary cause of the sedimentation issues. Except for one location on the northern side of the bay that is facing erosion, all the other locations experience accretion. The areas that are facing sedimentation difficulties are the basin, the southern beach in the bay, the turning circle and the access channel. The main source of this accretion is from an offshore location outside the bay.

An analysis of the situation was conducted with input of Delft3D; two wave conditions, implemented with Matlab, formed the so-called “base cases”. The wave conditions were selected among twelve conditions for their significance regarding the location and sediment transport. Of these two wave conditions, condition “two” has waves from the Northeast and condition “twelve” has waves from the South. These “base cases” act as reference material for the four proposed variants. The Delft3D programme computed the significant wave height, the depth-averaged velocity and the mean total sediment transport in a predefined grid. Regarding the effectiveness of the sediment transport, it is found that “Variant I: Hard intervention” has the largest reduction of sedimentation in the areas of interest. Remark to this conclusion is that a properly operating sediment bypass system (Variant III) in the model is most likely not achieved.

The multi criteria analysis concluded that Variant IV, including a long term dredging contract, seems to be the most optimal solution due to low initial costs and low environmental impacts. Variant I also scores significantly on functionality, but initial costs are high and therefore weigh down the score. Variant II scores average on most criteria, but has limited effect on the sedimentation problems. Variant III is the worst scoring variant, scoring low on all criteria.

9 Recommendation

In order to improve the findings of this research project, the following topics should be considered:

Sediment budget model

- A more comprehensive elaboration should be done to quantify all sediment transport quantities and their corresponding directions.

Variants

- If the extension of the main breakwater (Variant I) is desirable, a more complete study should be conducted to determine the ideal shape, length and position. A possible combination with a dredging scheme may also be suggested.
- If Variant II is desirable, the sand trap can be left out as it does not seem to have any significant effect; This will reduce the costs of Variant II
- A comprehensive design for the breakwaters of Variant I and Variant II should be conducted.
- The costs of all Variants but especially Variant III could use further detailing.

Delft3D model

- The Delft3D model can be improved to a higher level of accuracy as more realistic boundary conditions are applied.
- Another improving parameter will be when off shore currents are imposed.
- Furthermore, applying multiple depth layers (a minimum of six) should give more realistic outcomes regarding the amount of sediment transport.
- The operations that are imposed in variant three and four, “dump and dredge” and the enforceability of a sediment bypass system, should be done more accurate.
- In order to calibrate this model, more input of measured data is required, primarily of offshore and near shore buoys.
- Validation can be done by applying the same model in different areas to check whether the outcomes are in line with the obtained output of this research.

Multi Criteria Analysis

- The weight factors for each criterion can be revaluated according to the stakeholders’ interests.
- Different criteria could be added or neglected if required by stakeholders.

List of Figures

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References

Bijl, A. (2015, 9 20). (A. Kemper, & K. van Ekdom, Interviewers)

Brazil, N. D. (1978). Aerial photographs 1978. Santa Caterina, Brazil.

CIRIA, CUR Building & Infrastructure, Cetmef. (2007). *The Rock Manual.* London.

D.H.N. Porto de Imbituba 1992. *D.H.N. map nr. 1908.* Diretoria de Hidrografia e Navegação, Imbituba.

Deltares. (2015, 10 1). Delft3D. Delft, Zuid Holland, The Nehterlands: Deltares.

EPA. (2015). *Climate Change Indicators in the United States: Sea Level .* EPA.

Google. (2015, 9 11). *Google Maps*. Retrieved from Google Maps: https://www.google.nl/maps

Lausman, R. (2009). *Uncertainty in the application of Bay Shape Equation.* Delft.

LOC. IMBITUBA_SHP. *1978_&_2010_IMBITUBA_SHP.* Laboratório de Oceanografia Costeira - Universidade Federal de Santa Catarina, Florianopolis.

MAPA DAS CIDADES DIGITAIS - SANTA CATARINA. rede cidade digital.

Marco A.R. Romeu, J. A. (2015). *Typical Scenarios of Wave Regimes off Rio Grande do Sul, Southern Brazil.* Coastal Education and Research Foundation.

Mathwork Inc. (2014). Matlab. *Matlab2014b*. Natick, Massschusetts , United States of America: Mathwork Inc.

Menegaz. *Brazil Blank Map.* Wikipedia.

Porto de Imbituba. (2015). *Porto de Imbituba*. Retrieved 09 10, 2015, from http://www.portodeimbituba.com.br

Romeu, F. M. (2015). *Typical Scenarios of Wave Regimes off Rio Grande do Sul, Southern Brazil.* Coastal Education and Research Foundation.

Schrieck, G. v. (2014). *Dreding Technology .* Aerdenhout: GLM van der Schrieck BV.

Secretary of State for Economic Development, D. o. (2010, 4 1). DHRI / Mapping Coordination - CC. Aerial photographs. *Aerial photographs*. Santa Caterina, Brazil.

Silveira, L. F., Klein, A. H., & Tessler, M. G. (2010). Headland-bay beach planform stability of Santa Catarina State and of the NOrthern Cost of São Paulo State. *Brazilian Journal of Oceanograhhy*.

Thompson, B. C. (2015, 10 1). *Kennesaw state University*. Retrieved from http://science.kennesaw.edu/~jdirnber/oceanography/LecuturesOceanogr/LecTides/1116.jpg

TRESBP. (2015, 10 1). *Tweed River Entrance Sand Bypassing Project*. Retrieved from http://www.tweedsandbypass.nsw.gov.au/

Verhagen, H. J., d'Angremond, K., & van Roode, F. (2009). *Breakwaters and Closure Dams.* Delft: VSSD.