



FINAL RAPPORT

12/12/2011

Recife

Coastal Protection Plan

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General notice to the reader:

In the academic programme for Hydraulic Engineering we have in the 4th year (i.e. in the first year of the Master Programme) the requirement that students should do in a group of four to six persons a so-called "groupwork". It is also called "Master Project". During this groupwork they should make a full design of something. The work should be integral, starting with terms of reference, and ending with the real design. This can be a structure, but also it can be a harbour lay-out, a policy plan design, etc. The total time available for the project is in the order of two months and will provide 10 European Credits. It has to be practical and applied.

It is certainly not an M.Sc. thesis assignment (the thesis work is individual, 6 months and more focussed on research or advanced design work on details). But it is also not an apprenticeship, internship or traineeship where the student has to work together with a group of experienced people. For this groupwork they have to solve the problem on their own (of course with guidance).

This report is the result of such a Master Project. This report has been assessed by staff of TU Delft. It has been provided with a passing mark (i.e. a mark between 6 and 10 on a scale of 10), and consequently considered sufficient for publication.

However, this work has not been fully corrected by TU Delft staff and therefore should be considered as a product made in the framework of education, and not as a consultancy report made by TU Delft.

The opinions presented in this report are neither the opinions of TU Delft, neither of the other sponsoring organisations.

Department of Hydraulic Engineering Delft University of Technology





Preface

This project has been put together as part of the course Multidisciplinary Master Project (MMP). The MMP is a course of the Master Civil Engineering at the Delft University of Technology (DUT) in the Netherlands. The main purpose of this course is to:

- Solve an actual and recent civil engineering problem in a multidisciplinary team
- Integrate several studies and designs into a coherent project, based on knowledge, understanding and skills acquired in the preceding years.

The project typically takes two months (earns 10 ECTS) and takes place abroad. It is important that the subject is fitting for the students. Typical subject for the master project are small projects where there is a client with a problem and the students come up with a possible solution to the problem. It is not the intention that the students carry sole responsibility for the project. The students only make recommendation based upon their research after which further action can be taken.

The students participating in this project all have a common hydraulic background. So it is only logical that the project is a hydraulic subject. Brazil, as part of the BRIC nations, is a country of great economic growth and a huge growth in construction projects in the area of civil engineering. Brazil is also the common interest of the participants, and thus a fitting subject in Brazil is sought.

The coasts in the metropolitan area of Recife have been experiencing many problems and changes need to be made in the coming years. In this report these problems are analyzed and solutions are developed.

This report was intended to act as a preliminary design. It was written with the policy makers as target group in the backs of our minds. We hope you enjoy reading this report!

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Acknowledgement

The opportunity to do a coastal protection project in Recife came up after an appointment with ir.J.Van Overeem of the Delft University of Technology (DUT). He has been most helpful from this point on with the organization of this project. Also with his years of experience, he was been able to help us with all technical aspects of the project. So without exaggerating, we can state that this project wouldn't be possible without the help of our guiding professor ir. Jan van Overeem and we thank him for the time and effort he has put into this project.

Once the contact with the Universidade Federal de Pernambuco (UFPE) was set, the project started to take shape. Our guiding teachers from the UFPE, Prof. Tereza Araújo and Prof. Dr. Pedro de Souza Pereira have helped us a lot with a whole variety of things, from practical things like arranging accommodation, to more technical things like information about local conditions. During the project, they were always available to answer questions regarding problems. Again can be stated that without our professors from the UFPE, this project wouldn't be possible and we thank them for their time and effort.

Furthermore we would like to thank the our sponsors with their aid in making for master project in Brazil feasible.:

Van Oord (main sponsor):

- Mark Lindo
- Dennis van der Weijden
- Jurge van Nieuwenhoven

Arcadis BAM infra IV infra Royal Haskoning





Nomenclature

Revetment

A revetment is a structure of stone, concrete or anything ceramic material built at and parallel to the toe of a bluff, embankment or scarp. It can also be built at the front of a beach to protect the slope against wave or current-induced erosion. Revetments are often used in place of bulkheads in areas with moderate to severe wave energy.

Groin

A groin is a structure built generally perpendicular or under a slight angel on the shore, extending into the water like a finger pointing to the ocean. Groins are used to build up or widen a beach or to protect and stabilize a beach by diminishing erosion. This function is performed by trapping and holding sediment (littoral drift) passing through the area in which they are deployed. Groins can be used singly or in groups. Two or more are called groin fields. Groins can be permeable or impermeable, dependent on the amount of littoral drift trapping desired.

Breakwaters

A breakwater is a structure constructed either offshore from or connected to an eroding shoreline extending out into the water to protect the shore from wave action and/or to provide calm water for maritime navigational purposes. Offshore breakwaters are usually built parallel to the shore, but can be aligned at a slight angel to the shore to meet specific bottom or wave conditions. Breakwaters provide erosion control by dissipating and reflecting wave energy and creating a shadow zone of calm water.

Lee

The leeward side of the breakwater is the side facing the shore. The leeward side is protected against the direct excitation of oceanic waves.

Jetty

A jetty is any of a variety of structures used in river, dock and maritime works that are generally carried out in pairs from river banks. Jetties may also be used as a continuation of river channels at their outlets into deeper water. The forms and construction of these jetties are as varied as their uses (directing currents or accommodating sea vessels).

Landward side

The landward side of the structure is the side facing the shore.

Seaward side

The side of the structure is the side facing the sea.

Tombolo

Local accretion of the beach behind a structure, that reaches the structure itself.

Salient

Local accretion of the beach behind a structure, that does not reach the structure itself.

Reverse salient

A Salient at the breakwater side instead at the coast.





sygyzy

The term "syzygy" is used in astronomy to describe a situation in which three or more astronomical bodies are aligned in a roughly straight line. People most commonly use this term to talk about the relationship among the Sun, Moon, and Earth; syzygy affects the tides on Earth, and in extreme cases, it can also cause eclipses.





Abstract

Over the past decades the north-eastern coast of Brazil has been degrading due to erosion. This degradation has both natural- and men-made causes.

Brazil has no specific laws and acts which relate to coastal protection and management up to this date. Beaches in the metropolitan area of Recife show variety in beach width according to the seasons. However the local factors play such a significant role in this, that it is not possible to establish a direct link between the seasons and beach width.

Since the beginning of the 20th century, men has built structures all along this coast without proper guidelines. Wrong implementation of the structures has ,most probable, made matters worse. Another aspect is that men built structures (1970) on the backshore creating less back buffer which resulted in relative erosion.

This paper entails the study of the coast of metropolitan Recife which is 45 km long. The goal of this study is to assess the area: to create solutions for their problems. The paper consist of two parts, part A and part B. Part A consists of a study of the entire coast of metropolitan Recife. Part B focuses on Boa Viagem, an area of 2.78 km within the metropolitan area of Recife.

In order to assess the entire area more sufficient, the area has been split up into 7 parts, from north to south: Janga, Casa Caiada, Bairro Novo, Fortim, Boa Viagem, Piedade and Candeias. All these areas have been studied in order to find the cause of erosion, and possible solution. This has been done by preliminary assessment, where the current structures are observed; a problem assessment, this study emphasizes each area's problem and probable causes; and finally a solution assessment where possible solutions are represented.

The total area of the coast of metropolitan Recife consists of men-made hard structures such as groynes, breakwaters and revetment. But has also natural breakwaters such as reefs. The presence of the latter makes study of this coast highly complex.

The area has one major and one minor source of sediment. The major is the sediment that is transported in the littoral drift. The minor source is sediment being discharged by the rivers in the area. The sediment is fine to medium size sand.

The current level of "protection" is highly ineffective and has made matters worse in many cases such as Casa Caiada. The level of protection can be classified as poor. Initially, the area was thought be a flood risk, however, closer inspection has revealed that coastal flooding is a non-issue in the metropolitan area of Recife.

The amount of erosion cannot be limited but only displaced if hard measures are deployed. If sediment is trapped in one area, another area will be adversely affected. The only solution to sediment deficiency is introducing additional sediment in the area.





Part B focusses on Boa Viagem, an area of 2.78 km long with probably the most economic value. The coast of Boa Viagem has healthy beaches but also shows signs of erosion. The area consist mostly of reefs, but also has revetments and a harbor.

Different solutions for Boa Viagem have been presented, via a Multi Criteria Analysis one has concluded that a solution of only nourishment will be applied.

The nourishment will be dredged by a hopper, 10 km off the coast. The hopper transports the sand with the aid of a pumping system through a 2.5 km piping system to the beach. The nourishment will be spread by a bulldozer and a scraper. In order to maintain the beach, re-nourishment will be done every 5 years. The total amount of initial nourishment is 1.2 million m³ sand. And for re-nourishment 0.5 million m³ sand has been calculated.

The whole operation cost R\$ 143 mln (€ 60 mln) during a period of 50 years, this includes: initial nourishment, re-nourishments and interest etc.





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PART A

The metropolitan area of Recife





1. Introduction

Recife is a major city in the upcoming economic power that Brazil is. The appeal of Recife is however not only an economic one; the city is renowned for its beautiful city beaches, culture and colonial buildings. In recent years the beautiful city beaches have shown erosion and some beaches have disappeared due to the erosion. The entire appeal of the city would change if the beaches were to disappear. Thanks to the pleasant climate which dominates almost the whole year, it's not just the tourists who love to use the beaches, but also the residents. Specifically looking at the metropolitan area of Recife, it can be noticed that where the beaches are healthy they are used in abundance. In the early morning people use the beach to play volleyball and to jog; in the afternoon people like to recreate and during the night the youth comes to the beach to enjoy their self.

Work has been done to protect the beaches. However some of these works do not act as expected and in some areas they have speed up the erosion process. The implementation of coastal protection works is a very complex one as many aspects play a role in the morphology. A careful study will have to be done in order to assess the structures and point them on their flaws.

In this report the coastline of the metropolitan area of Recife will be studied. The metropolitan area of Recife consists of the following municipalities: Jaboatão dos Guararapes, Recife, Olinda and Paulista. It is vital that these municipalities will work together in order to come up with an integral solution for the area.

This paper has been divided in 2 parts, Part A and Part B. Part A studies the entire area of metropolitan Recife and part B focuses on one particular area(Boa Viagem). At the end of this report, recommendations and conclusions are presented.





2. Problem description

The coast of the metropolitan area of Recife is suffering from several problems amongst others coastal erosion. Recife's center figures in many reports as the most vulnerable regions along the Brazilian coast, due to its physical characteristics and various problems related to coastal erosion. The erosion of the shoreline is a direct danger to the buildings close to the shore. The destruction of the beach also damages tourists' activities and decreases the land value.

The coast of metropolitan Recife has many coastal structures to counter this erosion and the sediment transport processes. However when looking at the coastline it is clear that not all of these structures are very effective and many mistakes have been made with the design and construction of the structures.

¹ Vulnerability and impacts related to the rising sea level in the Metropolitan Center of Recife, Northeast Brazil, 2010, http://www.panamjas.org/pdf_artigos/PANAMJAS_5(2)_341-349.pdf





3. Objectives

The ultimate objective of the project is to make recommendations on and improve the safety of the coast of metropolitan Recife. In order to achieve this goal the following 2 main questions of the project, with each having a group of sub questions, are defined:

- What design and constructional mistakes have been made with the coastal structures that are supposed to protect the beaches and coast of the metropolitan area of Recife
 - a. What are the different kinds of sources of sediment and which characteristics does the sediment have?
 - b. What are the governing wave and current conditions within the system boundaries?
 - c. What beach states can one expect in those conditions and what characteristics does the coast have?
 - d. What are the design guide lines in Brazil or Recife specifically (i.e. what regulations, requirements etc.)?
 - e. How does the reef influence the total system?
 - f. What is the current level of protection, e.g. which structures are built and what are the characteristics of these structures?
 - g. For what purpose are the structures built, i.e. what are the desired goals of each structure?
 - h. To what degree do these structures fulfill their functional requirements, e.g. are these structures over/under-dimensioned?
- 2. What are possibilities for improving the situation so that the coast can restore/maintain all of the former/current function and values (economical, safety, recreational, cultural etc.)?
 - i. What are possible solutions to limit the amount of erosion?
 - j. What improvements can be made to these structures so that one can maintain a healthy beach?
 - k. Which areas have high economical potential?
 - I. Is it worth the money to invest in the improvement of the coastal structures?





4. System boundaries

To understand the coastal morphology of the environment, the system boundaries are very important. The total system should be considered for an accurate understanding of the coastal dynamics. Not only does one have to take into account the coastal morphology, it is also important to account for economic interests. A high valued economic area will be worthwhile protecting and therefore be more interesting. The recommendation made in the project will have a higher chance of being implemented, if the economic value is sufficient.

In Figure 1 one can see the system boundaries for this project: the system stretches from the mouth of the river of the Rio Timbó (the green dot) to the mouth of the river Rio Jaboatão (the pink dot). The length of the coast to be assessed is approximately 45 km. The project assesses the piece of coast that is exactly the agglomeration of the city of Recife. From north to south, the system boundaries include the cities of Paulista, Olinda, Recife and Jaboatão dos Guararapes.

The project boundaries have been deliberately chosen very large. A large system boundary will allow giving a full insight on how the full morphology of the total system works. However it is not feasible to assess the whole coast prescribed by the system boundary in detail given the duration of the project. The areas with high economic value/potential are more likely to be assessed in more details. These 'high potential' locations will be determined during the project.

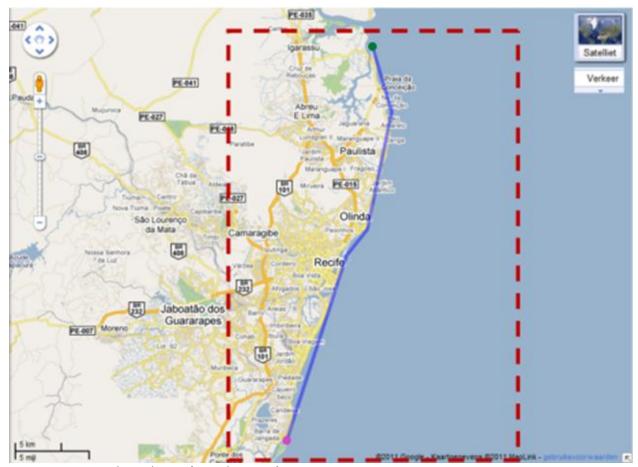


Figure 1: Project boundaries (Google Maps)





5. Stakeholders analysis

The different stakeholders that might have involvement to coastal projects are mentioned here, with their interests; position against such a project, their influence on the project and the relation between these stakeholders. Note that the values in

Food	Agriculture (i.e. owners of coconut fields)	Water inflow into acres Loss of land	Maintaining/expanding their fields No erosion in current coastline	Very low
	Fisheries	Destruction of ecology leading to less marine life	Maintaining/expanding fishing places Preserving ecological value in the ocean	Very low

Table 1 and Figure 2 are based on guesses since it is nearly impossible to quantify these values based upon hard proof. The goal is to get an overview of the different actors involved and their possible influence and interests. The different stakeholders are divided into different groups depending on their role in society. Furthermore it is recommended to do a more extensive stakeholder analysis in order to come up more reliable results. This could be done with for example public surveys.

Group	Stakeholder	Possible consequences	Interest	Influence
Government	Government of Brazil	Loss of land Risk of area flooding	Increased safety for people Minimal costs Fixed coastline National prestige	Very high
	State of Pernambuco	Loss of land Risk of area flooding Loss of land value	Increased safety for people Minimal costs Fixed coastline Regional prestige	Very high
	Metropolitan Municipality of Recife	Loss of land Loss of land value Risk of flooding	High investment in area Regional prestige Safety of people Minimal costs	Very High
	Municipality of Paulista	Loss of land Loss of land value Risk of flooding	Increased investment in area Safety Minimal costs	High
	Municipality of Olinda	Loss of land Loss of land value Risk of flooding	Increased investment in area Safety Minimal costs	High
	Municipality of Recife	Loss of land Loss of land value Risk of flooding	Increased investment in area Safety Minimal costs	High





	Municipality of Jabatao de Guararapes	Loss of land Loss of land value Risk of flooding	Increased investment in area Safety Minimal costs	High
	Ministry of Transport	Increased construction/maintenance of roads Traffic jams Less space available	Providing safe roads and good traffic accessibility Preserving space for roads	High
	Ministry of Defense and Safety (i.e. Naval Base, Naval School)	Less space	Preserving function	High
	Ports and harbors	Decrease of safety of harbor Sedimentation/erosion of harbor area	Increased port use Increase of economic activity	Normal
Public service	Water company	Increased salinity in drinking water Decrease in water quality	Maintaining/improving water quality	Low
Social	Residents	Loss of valuable land Loss of landscape values Risk of flooding	High land value Safety against floods and erosion Availability of services, shops etc. High quality of landscape/environment High quality/quantity facilities/services Minimal disturbance from construction works	Medium
	Recreation and tourists	Loss of space Pollution Construction Risk of flooding	High quantity/quality facilities/services High quality of landscape/environment	Medium
Economic	Industry (i.e. factories)	Safety of harbor Loss of land	High productivity Easy transportation options Safety	High
	Commercial services (hotels, restaurants, shops etc.)	Loss of land value Loss of land Risk of flooding	Lots of residents and tourists Safety	Low
	Businesses	Loss of land value Loss of land	High land value High economic productivity	High





			Easy transportation options	
Public	Commuters	Increase in traffic jams Accidents	Fast and comfortable trip	Low
Construction	Engineering firm, designer, constructor, maintenance company	cm, designer, Company prestige constructor, aintenance		Very high
	Workers	Increased amount of jobs Decrease in workers' rights due to work pressure	More jobs High payment Preserving workers' rights	Very low
Food	Agriculture (i.e. owners of coconut fields)	Water inflow into acres Loss of land	Maintaining/expanding their fields No erosion in current coastline	Very low
	Fisheries	Destruction of ecology leading to less marine life	Maintaining/expanding fishing places Preserving ecological value in the ocean	Very low

Table 1: Stakeholders and their characteristics





Stakeholders influence/position

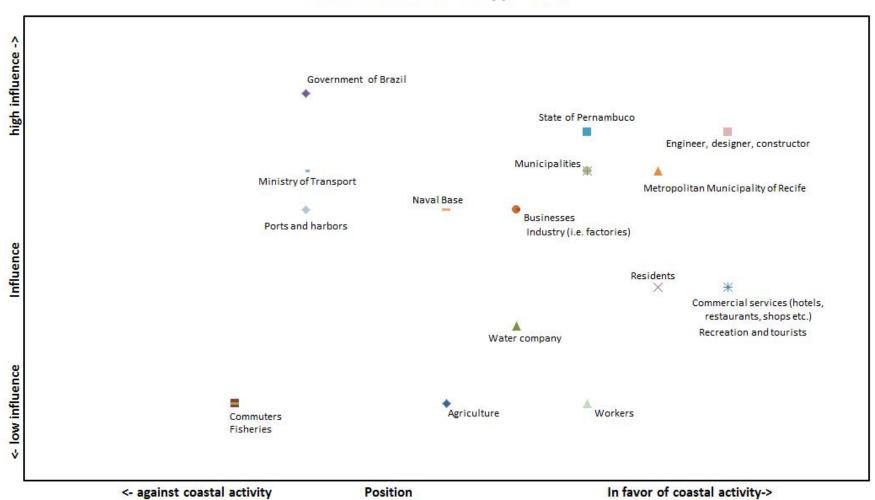


Figure 2: Stakeholders influence/position diagram





6. Hydraulics and morphology

The coastal morphology and Hydraulics is often not well understood because of its complex system. The morphological system involves various aspects, such as wind, wave and tide conditions but physical features are a part of the morphology as well.

The metropolitan area of Recife can be classified as a medium wave energy environment because the significant wave heights generally occur in the general vicinity of 0.6 m and 1.5 meters (MAI, 2009; CPE, 2011). However classification based upon significant wave heights is not the only way to classify a coast, there are several methods. The coast can be classified using criteria such as continental features and dominant beach shaping processes. The metropolitan coast of Recife can be classified as a trailing edge coast (but with a narrow continental shelf) according to the classification based upon continental features. According to the classification based upon dominant beach shaping process the coast of metropolitan Recife can be classified as a wave dominated coast. For more information on coastal classification of metropolitan area of Recife see *Appendix A: Morphology*.

The coast of metropolitan Recife is characterized by the presence of a reef and many hydraulic structures. There are three types of reefs present, barrier, fringing and sandbar types of reef, for more information about the reefs see *Appendix A: Morphology*. The reefs and hydraulic structures contribute to the complex morphology of the coast, as does the presence of several river mouths. The rivers in the metropolitan area of Recife do not carry much sediments (which can be used as beach material), causing the coast to be deprived of a big sediment source. The general transport direction of sediment for the entire area is likely towards the North-East because the strongest currents are directed towards the North-East as well.

6.1 Conclusion

The morphology of the metropolitan area of Recife is very complex. The coast of Recife is a unique one because of the presence of the reef. There are different types of reefs present and there are at some places three reef lines distinguishable. The rivers in the area contribute to this complexity. The morphology does not solely depend on a single factor, but on multiple factors and their interaction with each other. The wind and wave conditions show seasonality, the rivers at the northern and southern boundary of the system, the presence of the many reef lines and the many structures, the complex bathymetry and human interventions all contribute to the complexity of the problem.

The shoreline has not developed uniformly. Some parts have shown erosion; meanwhile other parts have shown accretion. Most of the accretion is very local and due to the presence of structures, reefs and rivers. Adjacent coasts have shown extra erosion. The metropolitan area of Recife has a segmented coast, where each part shows different characteristics.

More detailed information on the hydraulics and morphology such as wind, wave and tide conditions as well as physical features can be found in appendix A morphology, appendix B winds, appendix C currents, appendix D bathymetry, appendix E long time scale variation of the coast and appendix F material characteristics.





7. Metropolitan Area of Recife

The coastal characteristics of the metropolitan area of Recife differ along the coastline. But some parts have some certain structural features and characteristics in common. In order to assess more efficient, distinctions have been made between certain areas based upon the characteristics of the coast and the hydraulic structures that are present. A global overview of the coastal areas of the metropolitan area of Recife is shown in Figure 3. The following areas, south to north, are defined within the system boundaries:

- 1. Janga
- 2. Casa Caiada
- 3. Bairro Novo
- 4. Fortim
- 5. Boa Viagem
- 6. Piedade
- 7. Candeias







Figure 3: Overview of the sub-areas (Source: Google Earth)





8. Candeias

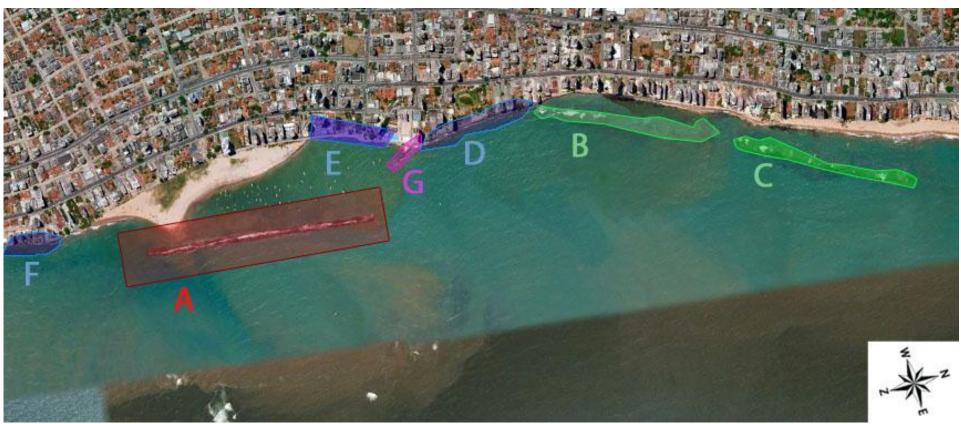


Figure 4: Overview Candeias (Source: Google Earth) (red:breakwaters green: distinctive reefs, blue: revetments, purple: groynes)

Part A Candeias 22





8.1 Introduction

Candeias is the most southern area in the system boundary, south of Piedade. The structure that characterizes the area is the huge breakwater A in front of the coast. The northern boundary of the area is north of reef C where the beach of Piedade ends. The southern boundary is at the ending of revetment F.

The total length of the area is 2657 m and contains one large breakwater (A), 2 distinctive reefs (B-C), 3 revetments (D-F) and 1 groyne (G).

8.2 **Problem Assessment**

To completely understand the system would be nearly impossible since its complexity due to the influence of the (natural) structures; however there are some brief justifications that can be made based upon the structures' function. As the reef can be seen as a submerged breakwater, one e.g. would expect an accretion along the coastline near the two barrier reefs (B and C). In Figure 5, which shows the erosion/sedimentation pattern after a period of 5 years, this theory has been fortified.

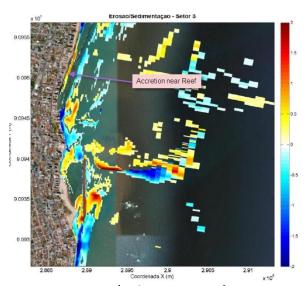


Figure 5: Erosion/sedimentation after a 5 year period (CPE, 2011).

Figure 6 shows among others, the annual sediment transport at Candeais. The main direction of the sediment transport is directed north. Cross shore wise, there are relative many differences in the sediment transport direction. At the northern and southern area of Candeais the greatest part of sediment transport is directed on shore, but near the breakwater, sediment is transported out of the system.

When assessing the sediment transport of this part of the coastline, obvious is the amount of sediment that goes offshore, sink, this could be due to the presence of the breakwater which seems to play a part for the blockage of sediments going north and due to a small canyon (gap) on the bottom.





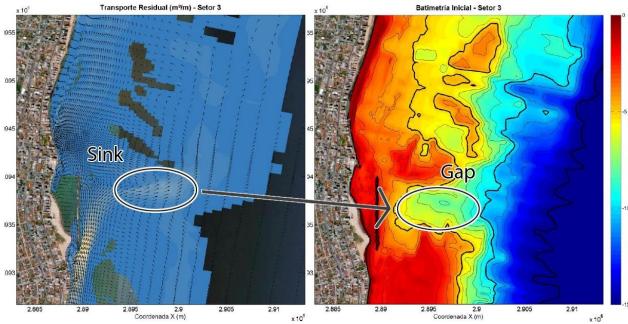


Figure 6: Annualized Sediment transport Cassa Caiada (left) Bathymetry Cassa Caida (right) (CPE, 2011)

Breakwater

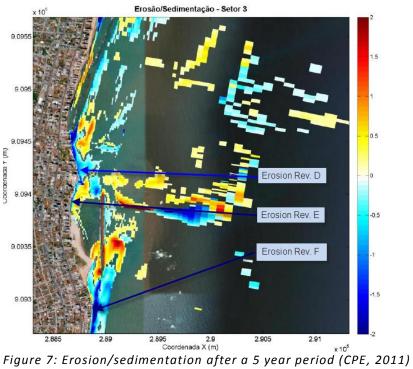
The large breakwater in Candeais was probably built in order to preserve a beach. When assessing Figure 4 it can be seen that there is a relatively small beach in front of a relatively large breakwater. One would expect a larger beach from such a breakwater. Next to the breakwater there are also some revetments present. Since it is not very clear what the true purpose of the breakwater was with respect to the size of the beach, it is assumed that there would be a beach present between structures F to G (Figure 4Error! Reference source not found.). Note that the assessment will be based on this preassumption.

Revetment

Revetment E was built to stop the degradation of the coastline; the goal went from preserving a beach to protecting the coastline. In the next 5 years the coastline is expected to erode (Figure 7), this will thus endanger the stability of revetment E. Revetment F and D are solely built to protect the coastline, since there is no beach expected here. Also for these revetments erosion is expected and could thus endanger the revetment, especially revetment F, where strong relative erosion is anticipated (Figure 7).







It is not clear what the purpose of Jetty G is. Perhaps it was made in order to preserve a relatively very small beach; even then, erosion processes are expected to dissipate the beach as can be seen in Figure 7.





8.2.1 Model versus Obervations

In this part the model results will be compared to pictures from Google earth. Figure 8 shows the local sediment transport near the breakwaters, the red arrows have been added for clarification and the orange arrow refers to the sink transport. One can see that there is a circulation on the north part of the breakwater; this is probably due to diffraction (this phenomenon is clearly visible in Figure 9Jan 26, 2007). On the right side of Figure 8 a prediction of the amount of erosion/accretion after 1 year is shown. One can see erosion on the south side of the salient, on the top of the salient and north of the salient a small stroke of erosion along the coast. Thus, in time, flattening of the top of the salient is expected.

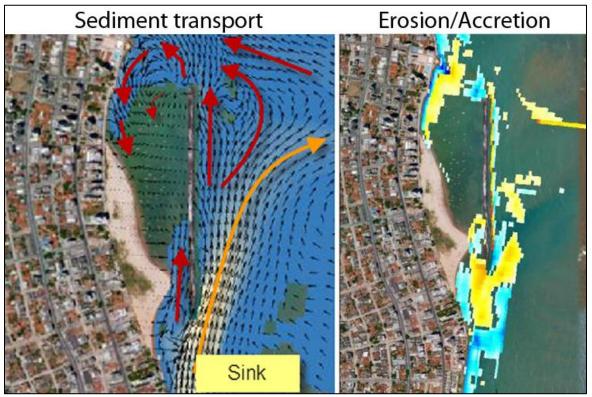


Figure 8: Annualized Sediment transport (left) and Erosion/Accretion after 1 year (right) (CPE, 2011)

Theories have been used to predict, model and calculate the sediment transport. Figure 9 shows the coastline in 2007, 2009 and 2010. It is assumed that all pictures were made during high tide taking the breakwater overtopping as reference: in Figure 9 there is overtopping, meanwhile in Figure 10 there is no overtopping at all (low tide). There is a clear change in beach profile during progression in time. Firstly, there is clear evidence of accretion in the middle part of the salient. Secondly, the south side of the salient is clearly eroding. Thirdly, from 2009 to 2010, one can see flattening of the top of the salient. Fourthly, the northern part of the salient is slightly eroding; this is clearly the effect between the years of 2007-2010.







Figure 9: Progression of the coastline Candeias (Google Earth, 2010)



Figure 10: Candeias during low tide

Although the CPE report was published in April of 2011, the resulted beach profile changes on the google earth pictures could for the bigger part also be found in the 1 year model such as: 1) erosion of the top of the salient, erosion of the south side of the salient and slight erosion north of the salient. What was not found in the model was the accretion in the middle of the salient; this is clearly between 2007-2009 and slightly visible between 2009-2010.

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8.2.2 Conclusion of the problem assessment

Candeias has several coastal features which could become a problem in the near future. Despite the main purpose of the breakwater, it has created some beach. However, it has failed to create a full beach and according to the models (CPE, 2011) the beach will get smaller than it is at the present do to the occurrence of erosion. Another result of erosion is the weakening of the revetment.

Other features are the reefs which cause accretion at the landward side of the reefs and not to forget the amount of sediment that is transported offshore, sink.

From the comparison of the 1 year model vs Google earth, could be concluded that the model was evidently in phase with the Google earth pictures.

The main problems in this area can be summed up as follows:

- 1. Breakwater A has been improperly designed given the situation, because there is no wide and full beach and there is erosion on the coast north and south of the breakwater
- 2. The area doesn't have enough residual sediment transport which doesn't allow for the formation of wide and full beaches along the entire coastline.





8.3 General Solutions

The solutions for the problems in Candeias will mean modification on the already built 'hard measure', i.e. the breakwater. Not only will hard measures be used soft measures, i.e. nourishment will be used as well.

Sediment transport

The main sediment transport direction is from south to north. At the south, where the breakwater starts, there is a huge loss of sediment. This is one of the reasons for the low inflow of sediment in Candeias. If the sand lost at the sink could be kept inside the system, this could partly compensate for the erosion problems.

What can be seen in Figure 11 is that the sediment is transported along the shore, nearly parallel to it. On the landwardside of breakwater A there is a large salient which blocks the sediment transport, which forces the sediment to flow towards ocean. This is the sink explained in the problem assessment. With the aid of structures, this loss could to some degree be reduced.

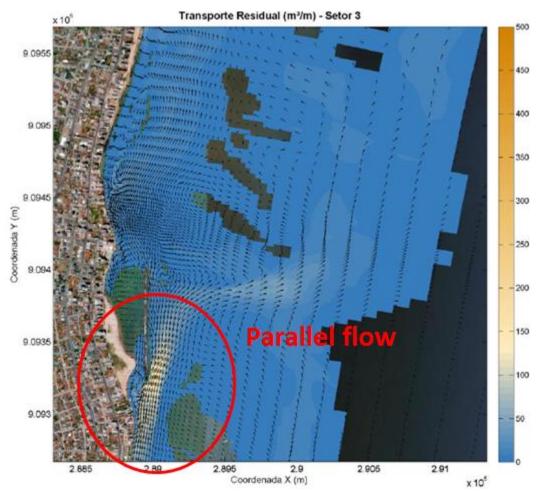


Figure 11: Sediment transport direction (CPE, 2011)

Breakwater A

The dimensions of breakwater A are a striking appearance in the Candeias area. The goal of the breakwater is to create a sheltered area in front of the coast. As can be seen in the assessment of the





area, there is no beach in the northern part of the breakwater A, even revetments are needed. This is because at the north and south, adjacent to the breakwater, erosion has occurred. Thus, the overall effect that the breakwater has on the area is larger than simply creating a beach. It can be concluded that the existing breakwater is not designed properly.

According to the guidelines as can be seen in *Appendix G: Design Guidelines*, a tombolo can be expected near the breakwater. This is a clear indication that the breakwater is either too large, or too close to the shore, i.e. there is no balance between length and distance. From the observations (Figure 11) can be concluded that the tombolo has not yet formed, however during low tide the salient almost reaches the breakwater. The erosion can also be explained as a consequence of the current balance between length and distance.

Groyne G

Why groyne G is built is hard to say, most likely it is built to preserve a small piece of beach. It can be concluded that the design of the groyne is inadequate. The groyne fails in creating a beach because it's too short and due to its orientation with respect to the beach.

Beach nourishment

The beach needs to be restored in order for the structures to work properly. For any solution a primary nourishment is needed, i.e. a nourishment process that is applied once in the beginning to restore the system. After this, the beach has to be nourished after some years in order to restore the structural erosion that happens within those years. For example, at some coast in the Netherlands, this structural nourishment happens every 5 years to account for the erosion that took place.

Structural nourishment

As long as there are no major system changes, the structural erosion remains the same. The amount of structural nourishment that is needed is thus the same for every solution.

The yearly structural erosion is 13.2 m3 sand per meter coast (MAI, 2009). Even though this number is likely to differ along the coast, it is a safe assumption to make. To account for this yearly loss of sediment, the structural nourishment will need to be applied. Using the annual erosion rate together with the total length of Candeias (about 2500 m), leads to a total loss of sediment of 33000 m3/year. The nourishment will be done every 5 years, so about 200.000 m3 of sand will need to be nourished (including the loss during nourishment) to maintain the beaches.

Primary beach nourishment

Beach nourishment will be applied on the coast, making the beach at its widest spot about 130 meters. The breakwaters will be parallel to the new coastline and create a wider beach along the coast. The old revetments will no longer be needed in the new system. However, removing them adds to the total costs and seems rather meaningless. Therefore the choice is made to leave revetment and simply nourish on top of them.

From the (CPE, 2011) can be determined that the amount of sand that needs to be nourished to restore the beaches and create a desired coastline that is similar to the one proposed in the alternatives. This number is based upon the equilibrium profile in Bruun's Rule and the amount of sand is approximately 780.000 m3.







Figure 12: Indication of the desired coastline and required nourishment





8.3.1 Alternatives

For the problems sketched above, different solutions are conceived. The first alternative uses only breakwaters to solve the problem while the second alternative makes use of a combination of groynes and breakwaters.

Alternative 1

Instead of one big breakwater, divide breakwater A up and place several smaller once and add more breakwaters to protect the entire coast. This is the main idea of this alternative. Some of breakwaters can be created by simply tearing down the current large breakwater. These breakwaters will be supplemented by additional breakwaters in front of the current location of the revetments.

Breakwaters

According to the guidelines a salient will form when the ratio between length and distance offshore is between 0.8 and 1.3, for this report a ratio of $\frac{L}{D} = 1.00$ has been chosen.

The proper distance offshore for a breakwater has to be within the range of 80 to 230 meters (Stive & Bosboom, 2011). Combined with the current distance of breakwater A, the lengths of the new breakwaters are determined (see *Table 2* and *Figure 13*).

The same process is done for determining the ratio between the gap length (Lgap) and the length of the breakwater. If this ratio is $\frac{L_{gap}}{L} < 1$, most probably no erosion will occur (Stive & Bosboom, 2011).

Breakwater	Length [m]	Distance offshore [m]	L/D ratio	Distance Lgap [m]	Lgap L
A	150	150	1.00	100	0.7
В	150	150	1.00	100	0.7
С	150	150	1.00	100	0.7
D	150	150	1.00	100	0.7
E	150	150	1.00	100	0.7
F	150	150	1.00	100	0.7
G	150	150	1.00	100	0.7
Н	150	150	1.00	100	0.7
I	150	150	1.00	100	0.7

Table 2: New breakwaters in Candeias

From Table 2 can be concluded that the new breakwater will be 150 m long and at a distance of 150 meter offshore and that the gaps between the breakwaters will be 100 m.







Figure 13: Alternative 1 with the 'hard' and 'soft' measures

As can be seen in Figure 14, there is the possibility to build another breakwater to the north of the new breakwater A to ensure that the sediment will accrete on the beaches. With the construction of this breakwater, the system will become similar to Casa Caiada in its current state. In Casa Caiada the system is clogged by breakwaters and reefs which are blocking sediment transport.

The gap between breakwater A and reef C (Figure 4) is currently about 300 meters, which most probably will allow the sediment to be transported to the north. But if an additional breakwater will be built, the future gap will become 100 meter and then it will be doubtful whether there will be enough sediment transport to the northern area. Because of this, the choice is made to leave out this additional breakwater.



Figure 14: Indication of the gap between the new breakwater and reef C in Candeias





Alternative 2

In Alternative 2, breakwater A will be divided in several smaller breakwaters. The main difference with Alternative 1 is that instead of breakwaters, groynes will be built in front of revetment D and F.

The choice to keep the breakwater is based upon economic reasons as well as practical. Another reason for simply adjusting breakwater A is the desired purpose of the coast. It is generally accepted that by using groynes, one creates a beach that is not really fit for recreational purposes, due to the saw-tooth shape and the transversal block along the beach. Further in the north at the revetment, the relatively cheaper option of groynes is favorable and will be applied.

Currently, on the coast at breakwater A, the desired beach should be wide and full. This can be best achieved with breakwaters.

The beaches will need to be maintained by 'hard measures', i.e. structures. The current breakwater A will be adjusted and supplemented with additional structures in order to perform this function.

The guidelines will be applied to calculate the new lengths of the separated breakwaters (see Table 3).

Breakwater	L/D ratio	Distance offshore [m]	Length [m]	Distance to successive groyne, Lgap [m]	lgap L
A	1.00	170	170	125	0.7
В	1.00	150	150	123	0.82
С	1.00	116	116	-	-

Table 3: Specifications of the new breakwaters in Candeias

It must be emphasized that there will be no new constructions of breakwaters, but they will be created by tearing down large parts of old breakwater A. This alternative surely poses a more economical (therefore more feasible) solution.

Breakwater A is the main reason for the appearance of erosion at the coast. This erosion is located near the revetments and poses a threat to the stability of the revetments and the buildings directly behind it. In order to restore these pieces of coast, nourishment will be used. The erosion is expected to be less with the changes to breakwater A. However, in order to minimize the erosion, groynes will be applied at these locations to hold the long shore sediment transport. In Table 4 one can find the dimensions of the new groynes in Candeais, the groynes dimensions and placement have been designed using the design guidelines see *Appendix G: Design Guidelines*. Note that Groyne I has been reduced in size due to groyne tapering.

Groyne	Length of surf zone [m]	Length of the Groynes [m]	Distance to next groyne [m]
E	110	66	198
F	110	66	198
G	110	66	198
Н	110	51	198
I	90	54	162





J	90	54	162
K	90	54	162
L	90	54	162

Table 4: Specifications of the new groynes in Candeias

In between groynes, there is still the choice between permeable groynes and impermeable groynes. Permeable groynes have the disadvantage that they do not slow down the erosion as much as impermeable groynes do. Combined with the low sediment transport into the area, the use of impermeable groynes is more favorable.

The height of the groyne should be about +1 MSL (mean sea level) to allow for enough sediment bypassing during storms and high tide conditions (Stive & Bosboom, 2011). Another reason is that high crest levels are generally unattractive if the beach will be used for recreation.

After a construction of a compartment it will take a relative long time to fill the compartment to its capacity due to the low transport rates in the area. It is therefore advised to fill the cell compartments to their capacity to avoid large amounts of erosion at the down drift side of the groyne field. T or L head groynes can be used to increase the effectiveness of the groynes. T and L head groynes are used at very exposed eroding coasts to reduce the wave energy in the compartment (van Rijn 2010). Because of the limited wave action in the Bairro Novo area T or L head groynes

A sketch of the situation with the new 'hard' and 'soft' measure is displayed in Figure 15. Here the relative location of the breakwater and groynes to each other is visible. Figure 15 is merely an indication of the proposed alternative.



Figure 15: Candeias with the 'hard' and 'soft' measures

8.3.2 Feedback on Piedade

The solution for Candeais will have an effect on the northern Piedade area. Alternative 1 uses breakwaters along the entire coast. This alternative ensures that less sediment will go offshore near the current sink. The expected main flow of the sediment is indicated in *Figure 16*.







Figure 16: Expected main flow of the sediment with Alternative 2

It can be seen that the sediment will move along the coast (accreting in the meanwhile), and it's plausible that some of this sediment will reach the beaches in Piedade. This assumption is enforced by the solution (see Figure 17) and models (see Figure 18) of the (CPE, 2011). Alternative 2 in particular presents a similar solution as the (CPE, 2011). The expected sediment transport is also similar to the one presented above (see Figure 16). Thus can be said that it is plausible that some sediment continues to Piedade.



Figure 17: Solutions by the (CPE, 2011)

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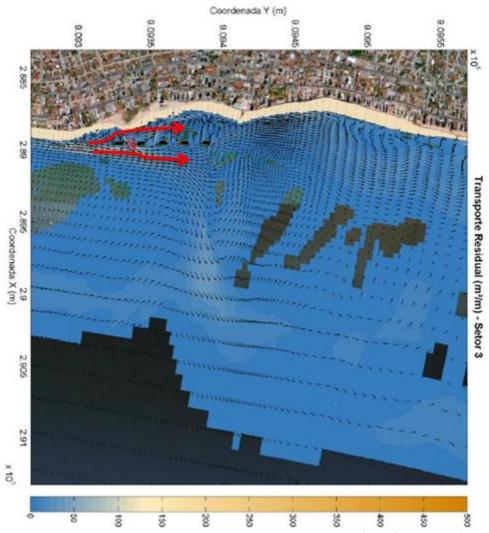


Figure 18: Modeled sediment transport with the solutions of the (CPE, 2011) and the main transport

It is likely to assume that this flow of sediment into Piedade will be beneficial for the beaches in Piedade. Even though it's possible that the additional incoming sediment is carried forward with the littoral drift, is it plausible that it will contribute to the overall health of the beaches. This will be beneficial for the beaches in Piedade. Adding the beach nourishment, so more sediment, into the system well contribute to this effect.

Because of the good beach conditions in Piedade and thanks to the above mentioned effects, the Piedade beach probably will remain healthy.

In Alternative 2 the southern groynes stop some of the sediment transport to create a beach locally. How much sediment will go offshore is hard to predict in this stage. The (CPE, 2011)-models however are almost similar to this alternative. Like concluded above, it is plausible to assume that the sediment does reach Piedade. The current beaches of Piedade are healthy and there is no expected process in Candeias that could lead to a worsening of these beaches.





8.4 Conclusion

The system in Candeias seems to be heavily influenced by the large breakwater A (see Figure 4). This breakwater is the reason for most of the erosion in the area. Linked to this problem is the low sediment transport into the system. A large portion of the sediment supply simply moves towards the ocean due to the sink near breakwater A.

The solutions for this area mainly aim to limit the problems and create a healthy beach at the location of the current salient. In any solution therefore can be seen that breakwater A is simply too large and needs to be partly demolished. A second returning aspect for the different alternatives is the extension of the protection along other parts of the Candeias coast. Finally, all solutions require beach nourishment, both primary nourishment (applied once) and structural nourishment (generally applied every 5 years to account for the structural erosion).

The two proposed alternatives differ mainly in terms of type of structure. Alternative 1 uses only breakwaters along the coast while Alternative 2 uses a combination of breakwaters and groynes. The use of groynes over breakwater poses some advantages (more economic, no visual block at the ocean) but has also disadvantages (limits travel along beach, less applicable for fine sand). The choice between the two also depends on the type of beach that is preferred at the location.

Both the alternatives pose a solution for the assessed problems in the area. Making a choice between the two requires more information and further analysis into aspects like costs, constructability, created value etc.





9. Piedade



Figure 19: Overview Piedade beach (Google Earth)

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9.1 Introduction

The northern boundary of the area of Piedade is at the southern boundary of Boa Viagem, so at the end of the revetments. This area is in total 3733 meter long and contains virtually no structures. It seems that some revetments have been built in the past that have meters of beach in front of it. There are also no large reefs in front of this coast.





9.2 **Problem Assessment**

9.2.1 Problem description

The area doesn't appear to have been subject to any measures because it seems to be a healthy beach. The beach may be a bit narrow; however, it's comparatively healthy.

A possible threat in this area is that now that there is accretion along the coast, people will continue to build towards the coast. This way, the beach cannot follow its natural process and the buildings will be once again in danger, forcing the government to build safety measures. This has been the case for pretty much the entire coast of metropolitan Recife.

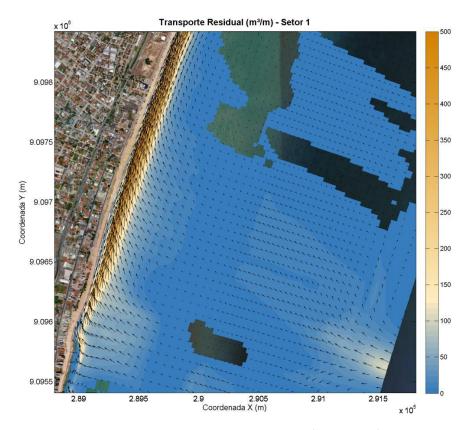


Figure 20: Transport rates and direction Piedade (CPE, 2011)

In (CPE, 2011) the problem was examined more closely and erosion is expected to occur in Piedade in a narrow strip along the shoreline. (See Figure 21) This is similar to what happens in the neighboring area of Boa Viagem. There doesn't appear to be any problems with Piedade currently; however, in the near future erosion can become an increasingly large problem





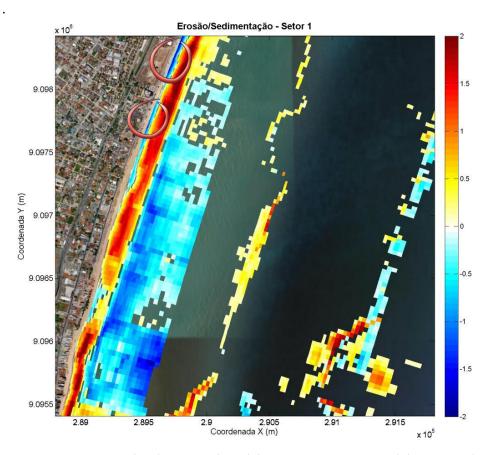


Figure 21: Accretion (red) Erosion (blue) (Scenario 5 years later) (CPE, 2011)





9.3 **General Solutions**

Alternative 0: do nothing

If no action is taken the shoreline may slightly retract in the north of Piedade, however, the majority of the area is accreting (see Figure 22).

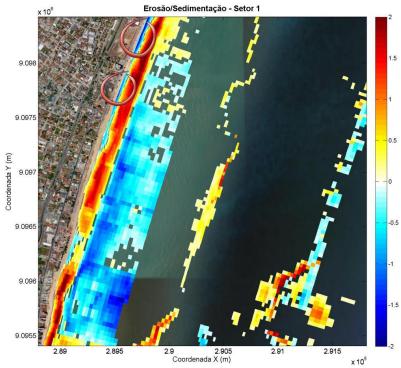


Figure 22: accretion (red), erosion (blue)





Alternative 1: Beach nourishment



Figure 23: The quick and easy solution for Piedade (only the northern area requires some nourishment)

There is no need to consider measures for Piedade because in the current situation there are no problems. However, delft3D model results published in (CPE, 2011) have predicted some erosion in the more northern area of Piedade (Figure 21).

Beach Nourishment

Beach nourishment seems like a clear cut solution for the area. The sector slightly upstream in Boa Viagem requires beach nourishment as well. It is therefore recommended to nourish the area in a single stretch. The amount of nourishment required has been calculated in (CPE, 2011). The equilibrium profile was compared with the current profile and from both a construction profile was determined. The deficit of sand to attain the construction profile is the amount that will need to be deposited. The amount required is displayed in Table 5. The profiles that will be nourished are BV1 to BV5 (See Figure 24)

Volume required for Beach nourishment	86000 m3
Volume required for Fore shore Nourishment	144000 m3

Table 5: Amount of beach nourishment required Piedade – Fore shore nourishment has a net loss of approximately 40 % of the deposited sediment Erosion (blue) (5 years later) (CPE, 2011)







Figure 24: Beach profiles in Piedade (Only profile BV01 to BV05 are in Piedade – The remainder are in Boa Viagem





10. Boa Viagem

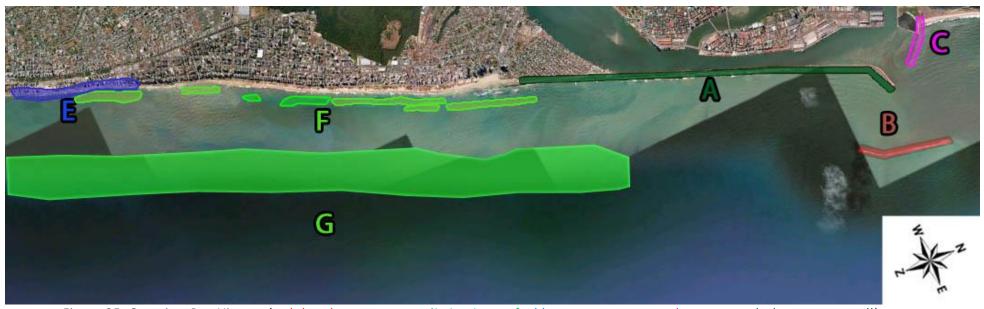


Figure 25: Overview Boa Viagem (red: breakwaters green: distinctive reefs, blue: revetments, purple: groynes, dark green: seawall) (Google Earth)





10.1 Introduction

Boa Viagem is the richest and most prosperous area of Recife (*HDI, 2008*). It houses most of the major touristic commercial establishments such as hotels. It also houses many companies. The beach of Boa Viagem seems to be in good shape for the most part. The areas behind the reef (Figure 25), which enjoy the reef's protection (F), have the richest beaches in the region.

Boa Viagem is the part of coast that stretches over 12 km and is the longest area in the metropolitan area. The coast can be divided into three parts, namely one long stretch of seawall in front the harbor, a part with healthy beaches and lastly a part with revetments without a beach.

While there is a long beach, the area with large population densities also shows long revetments without any beach in front of this. An important aspect that has been observed is that overtopping occurs at revetment E during high tide that could be an indication of a future failure, but more about this in the Problem Assessment.

10.2 Problem Assessment

10.2.1 Problem definition

Structures A, B and C (see Figure 25) are built to stabilize the harbor mouth and to protect the harbor. Seawall A is built partially on top of an existing reef and follows the orientation of the reef. At the end of seawall A, the reef still continues until the start of the beach. At this part the fringed reef acts as a natural revetment.

Construction in Boa Viagem has had a large influence on the northern beaches of Olinda and Paulista. Beaches north of Boa Viagem (Olinda, Paulista) have shown progressive degradation. Observations of the beaches have shown that the progressive degradation began after the constructions in front of the harbor in 1970. (Luci Cajueiro Carneiro Pereira et al 2004)².

Overall, there is a transport of sediment from the south to the north (see Figure 26 and Figure 27). This regular pattern can be observed along the entire coast except for some local features. The regular pattern is due to the straight line the coast makes and the very few curves the coastline makes. In front the entire Boa Viagem area there is a submerged barrier reef. In between the reef and the coast there is a channel of approximately 7 meters depth. The surf zone is located close to the shore; resulting in a narrow and high sediment transport (see Figure 27).

There are two revetments present in the Boa Viagem area. The goal of the revetments is to prevent regression of the shoreline. The revetments will have to be stable in order to fulfill their goal. One can see that directly in front of revetment E erosion takes place. This would mean that the stability of the revetment could be in danger. However data from *Appendix J: Boa Viagem* shows that In front of revetment E not everywhere erosion took place; there are even places that have accreted. If these sedimentation patterns would continue, the data from Figure 26 (model) differs from the data from *Appendix J: Boa Viagem* (observations). Observations (MAI, 2009) give a more accurate representation than models, which have many uncertainties. The sedimentation pattern at revetment E will likely show the pattern as observed.

http://www.sciencedirect.com/science/article/pii/S0964569104000031





Another problem revetment E faces is the overtopping of the water during high tide. These observations have been made during the Preliminary Assessment of the structures. Overtopping of revetment E could endanger its stability by forming a scour hole behind the revetment. Because this process has been seen along the entire length of the structure, the entire revetment is in danger.

The residual transport behind revetment E varies. Some areas have significant amounts of transport and other areas have complex and poor sediment transport. (See Figure 26) The area behind revetment E seems to have a narrow channel directly adjacent to the coastline where erosion is occurring. (See Figure 26)

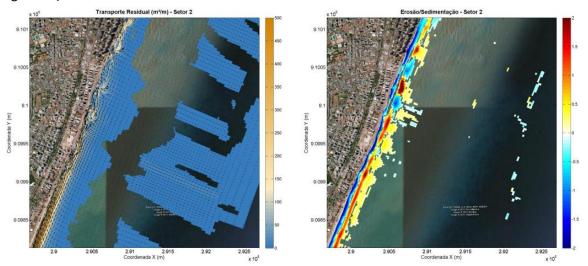


Figure 26: Residual annual transport (left) and accretion/erosion for the southern Boa Viagem area (at revetment E) (CPE volume 6, 2011).

In front of seawall A there is a huge flow (order of magnitudes of 250 m³/m/y) of sediment towards the north and one can find erosion as well as accretion (see Figure 27). The revetments in the Boa Viagem area suffer from accretion and erosion. For the parts that erode the stability of the revetment could become an issue.

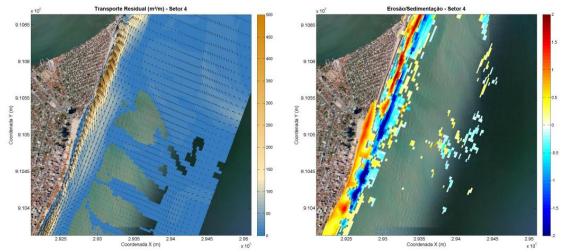


Figure 27: Residual annual transport (left) and accretion/erosion for middle Boa Viagem area (at seawall A) (CPE volume 6, 2011).





Not all parts in Boa Viagem have a large beach in front of its coast like in the middle part (Figure 28). The southern part of the coast has very small beaches (Figure 29).

This observation can be explained with the use of the models (CPE, 2011). The middle part of Boa Viagem has a lot of accretion on its coast (Figure 27). This is largely related to the presence of the reef in front of the coast.

In the south (see Figure 26) there is a very thin line of erosion on the coast. It is likely that this process has contributed to the small beach in the south.

The dominant sediment transport direction is south to north so the sediment that is not being trapped in the south ends up in the middle part. If more sediment was being trapped in the south, this would of course have direct influence on the beaches in the middle part.



Figure 28: Middle part of Boa Viagem (Google Earth, 2009)



Figure 29: Southern part of Boa Viagem (Google Earth, 2009)





10.2.2 Desired Situation

From the problem assessment and the wishes of all the stakeholders can be derived how the area is supposed to be and what changes need be done to the area in order to create this desired situation. The main goal is that the coast is protected and that there is available beach for mainly recreational purposes.

The main factor adding to the desired situation will be the presence of a beach in front of revetment E. This stretch of coast is almost 2 km long with only revetments. The situation is so bad that even the revetments are in danger because of the overtopping. North of revetment E, the beach is too narrow to fulfill it's at some parts and will need to be expanded.

Once a beach is created at revetment E, the beach along the coast of Boa Viagem will need to be maintained. So the two things main goals for this area are:

- 1. Creation of beach along the entire coast
- 2. Protection against erosion

The first goal incorporates the wish to maintain the current beaches. The second goal hopes to create new beaches and expand the narrow beaches that are present.

10.2.3 Conclusion

There are not many coastal deviations in the straight coastal line of Boa Viagem. This leads to a somewhat regular sediment transport direction from the south to the north.

The beaches in the middle part of Boa Viagem are large and according to the models of (CPE, 2011) there will be even more accretion. The complex influence of the reefs G and F plays some role in this. The opposite is true for the beaches in the south. They are small and there will be even more erosion here. Revetment E is placed here to limit this process. Since the sediment transport direction is from the south to the north, the southern and middle part of Boa Viagem is linked to each other.

The area has several major problems

- 1. The beach in the area is narrow in some places and policy makers wish for a wider beach.
- 2. Revetment E is subjected to structural erosion in some parts. There is also rather heavy wave action present due to absence of reef F which provides protection. This combination of factors will cause failure of revetment E in some parts. Some parts are already displaying signs of failure. However, no major failures have been observed yet (see *Appendix J: Boa Viagem*)
- 3. Revetment E (see Figure 25) has probably been constructed to protect against structural erosion, however, revetments not useful to perform this function.





10.3 General Solutions

10.3.1 Beach nourishment

Beach nourishment is a possible solution for the problems posed here. There are different types of nourishments methods possible, like foreshore nourishment and beach nourishment. While considering the different methods an important aspect is the practical application of the method. Because of the reef, it is impossible for the dredging ships to perform the activities. More about the advantages and disadvantages are explained in *Appendix J: Boa Viagem*

10.3.2 Alternatives

The northern area of Boa Viagem, involving structure A, B and C and D seems to be fine and will probably require no changes. This area seems quite stable and will require no additional measures. Moreover, the area behind seawall D is actually accreting. In the evaluation of the alternatives use has been made of the design guidelines (see *Appendix G: Design Guidelines*).

• Alternative 0: Do nothing

The first alternative assumes no changes to the current situation. What happens when this alternative is applied is explained further down.

It should be noted again that Alternative 0 can't possibly be seen as a possible option. The alternative doesn't solve any of the problems and this choice poses a threat for the problems that can occur. For this alternative, the additional costs of mitigation and the huge risk management are not taken into direct account if only a cost-benefit analysis is performed. Like stated, the alternative is only considered as a reference to make judgments about Alternative 1 & 2.

• Alternative 1: Nourish the area at revetment E

Sand deposition across the entire beach will counteract the naturally occurring erosional process to which the entire area is rather susceptible. The beach would need to be nourished along the entire stretch of revetment E. Because of the dominant sediment transport is from south to north the nourished sediments will also be transported to the north. It is therefore chosen to nourish at revetment E which will in time benefit the entire coast upstream. Revetment E will be protected from wave action as there will be a beach in front of it, the beach will eliminate the need for repairs of revetment E. However for esthetic arguments the revetment can be repaired.

• <u>Alternative 2: nourish area at revetment E and construct breakwaters offshore of revetment E</u> This solution will not only allow for everything solution 1 offers, it will also allow for a wide and calm beach to be created at the most prosperous area in Recife. However, this solution will require costly breakwaters offshore of revetment E.





Alternative 0



Figure 30: Effects of the zero Alternative (source image: GeoEye, 2011)

If nothing is done there will be no beach in front of revetment E, which is preferred. If no action is taken, sections of revetment E are prone to fail eventually (See Figure 34). These sections are exposed to a narrow strip of heavy structural erosion which will endanger their stability. In the area behind the reef there are still pockets of erosion which will continue to cause degradation of the shoreline in some sections (see Figure 31).

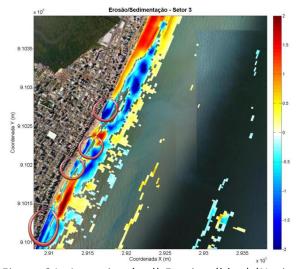


Figure 31: Accretion (red) Erosion (blue) (Notice that the area behind the reef experiences pockets of erosion along the shore (scenario 5 years later) (CPE, 2011)





Alternative 1

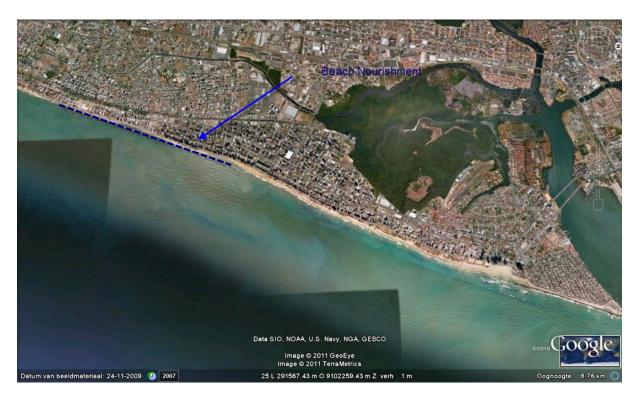


Figure 32: Alternative 1 Boa Viagem (beach nourishment behind revetment E) (source image: GeoEye, 2011)

The primary characteristic of this solution is beach nourishment. There are no hard measures and this usually means little adverse effects to upstream sediment balances.

Beach Nourishment

Nourishment of the area at revetment E (see Figure 33) will be beneficial because the area has a narrow beach and nourishment can widen the beach. In (CPE, 2011) an identical solution was conjured and the amount of sediment required to satisfy the equilibrium profile of the area to be nourished was determined. The area begins at approximately BV06 and ends at approximately BV17 (see Appendix Boa Viagem). The amount of sand required for a shoreline protraction is 693,000 m3. The expected growth of the beach is between 25 and 40 m according to (CPE, 2011)

The amount of nourishment required can be calculated by considering the equilibrium profile and nourishing the sand deficit. Afterwards the area can be injected with an amount of sediment dependent on the occurring erosion repeatedly. In (CPE, 2011) which used DELFT3D results were also conjured up which showed that area directly next to the revetment (see Figure 33 and Figure 34) is eroding in a narrow strip (the blue line next to the shore). The erosion is primarily concentrated at a narrow strip adjacent to the shoreline and nourishment can easily be used to counteract this erosion problem and increase the shoreline.

The amount of structural erosion that will occur yearly is difficult to predict and should be determined after the nourishment and construction of the breakwaters have been implemented. The nourishment





and breakwaters will affect the amount of structural erosion therefore; the erosion occurring now might not be the erosion that will transpire post-implementation of these measures.

Nourishment required for beach nourishment	693000m3
Nourishment required for Fore shore nourishment	1150000 m3

Table 6: Amount of nourishment required Boa Viagem (remember that fore shore nourishment requires approximately 40% more sediment) (CPE, 2010)

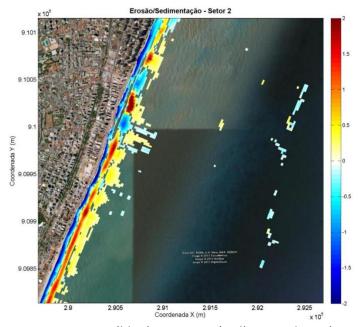


Figure 33: Erosion (blue) Accretion (red) 1 year later (CPE, 2011)

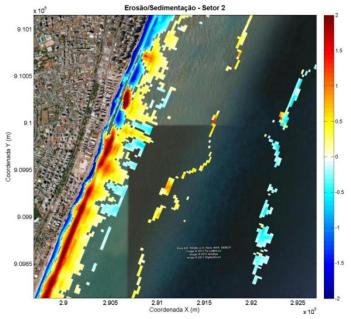


Figure 34: Erosion (blue) Accretion (red) 5 years later (CPE, 2011)





Alternative 2

Alternative 2 consists of the nourishment of the area at revetment E and the constructing of breakwaters offshore of revetment E.



Figure 35 Overview of the Boa Viagem area in alternative 2

The area at revetment E is used as a leisure area; there is a theater, football cage etc. A healthy beach in the area could enhance the attractiveness of the area drastically. This alternative entails nourishment combined with breakwaters. Breakwaters could reduce the frequency of nourishment which could become favorably in the end, e.g. costs.

What clearly can be seen in this alternative is that the breakwater continues the line of the existing reef. The area at revetment E will get nourished to create a healthy and attractive beach. The created beach at revetment E will be protected by the breakwaters. It is expected that the breakwaters will behave almost the same as the reef. It is expected that the breakwaters will induce erosion on the down drift side, this is however a complex phenomenon and the consequences are therefore hard to predict.

Nourishment

The area will be nourished at revetment E identical to solution 1.

Breakwaters

Approximately 5 breakwaters, of which the dimensions are given in Table 7, will be required to shield the area of revetment E from the waves (see Figure 36). Dimensions of designed breakwaters have been chosen in such a specific manner that tombolo formation will not occur according to design guidelines given in (COASTAL DYNAMICS, 2011). Total obstruction of the along shore transport will have devastating effects upstream. It's critical that this doesn't occur. The dimensions of the breakwaters which will supposedly create a wider beach at revetment E can be seen in Table 7. The gaps have also been chosen with the right dimensions to prevent erosion opposite the gaps between the breakwaters according to (COASTAL DYNAMICS, 2011). The expected beach formations behind the breakwaters have been drawn in Figure 36. For this beach formation to take place there must be enough sediment available. The residual transport rate behind the breakwaters is quite substantial (see *Appendix J: Boa Viagem*), which enforces the hypothesis that the formation will occur as depicted in Figure 35, as there is enough sediment available. The salient will provide for enough sediment bypasses so to minimize the down drift erosion. However one should keep in mind that there will always be down drift erosion but a





salient will minimize the effect compared to a tombolo. The area down drift of breakwater A1 (the most down drift breakwater) will be nourished as well as can be seen in Figure 36.

Breakwater	L (m)	Lg (m)	D (m)	D/L	Lgap/L
A1	110	-	130	1.18 (Salient)	-
A2	115	95	130	1.18 (Salient)	0.82 (No erosion)
A3	115	90	130	1.18 (Salient)	0.78 (No erosion)
A4	110	90	130	1.18 (Salient)	0.81 (No erosion)
A5	125	100	130	1.04 (Salient)	0.80 (No erosion)

Table 7: Dimensions breakwaters offshore of revetment E



Figure 36 Overview area with breakwaters

First global dimensions will be estimated taking into account reference projects. When looked at the bathometry (*Appendix J: Boa Viagem*) and location (*Appendix D: Bathemetry*), one could estimate a depth of approximately 5 meter. The top height has been estimated as 2 meters above mean sea level, this has been based upon the significant wave height and tide changes.

A natural slope of 1:3 should be sufficient (Schipper, 1992). The cross-section of the breakwaters can be seen in Figure 37. Note that the breakwater is relative simple dimensioned, because the main goal is only to have a global estimation of the cost.

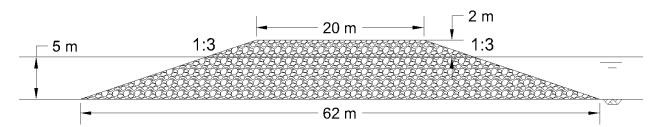


Figure 37: Cross section breakwater



11. Fortim



Figure 38: Overview Fortim (red: breakwaters, blue: revetments, purple: groynes, pink: jetty)(Google Earth)

Part A Fortim 57





11.1 Introduction

Fortim, south of Bairro Novo, stretches from the southern boundary of Bairro Novo at the most southern groyne to the start of jetty H (Figure 38). This part of coast is 3880 meters long and can be characterized by a few breakwaters at the start that overlap each other and the long stretched narrow beach. There are 3 breakwaters (A-C), 3 revetments (F-D) a jetty (H) and some scattered small reefs (I-K).

11.2 Problem Assessment

Reef I has a large influence on the total system and adds much to the complexity of the sediment flows (see Figure 40). The direction of the sediment transport in the south is predominantly from north to south at the coast further offshore it is from south to north. The water circulates anti-clockwise around the red circle (see Figure 39) in the water body which is very close to breakwater C. This is causing a lot of the high speed flows and a lot of erosion on the seaward side of breakwater C.

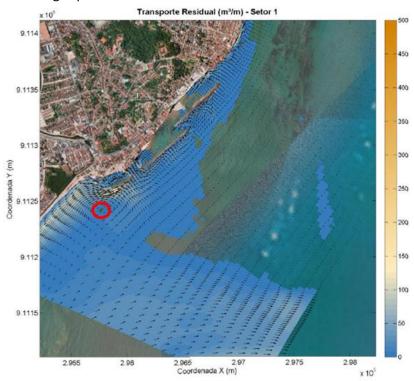


Figure 39: Circulation of the water body

At the relatively long beach in the south the circulation leads to a flow from north to south with high velocity that causes much turbulence due to interaction with the coast. In the end this leads to much erosion of the beach, which seems to be healthy at the moment.

In the south, at the mouth of the river, jetty H guides the outflow of water towards the ocean. Here one can find a huge outflow of water out of the system towards the ocean (see Figure 40). Due to jetty H and breakwater B (in Boa Viagem area) only a small part of the sediment is transported to the Fortim area, while the majority of the sediment goes towards the ocean. This lost sediment could be well used in contributing to the buildup of the beaches.





On the north of Fortim there is a high velocity flow coming from Bairro Novo. Also in front of this coast there are some reefs of barrier types, like reef K, I and J, but these reefs do not dissipate much wave energy (Figure 43). These two aspects are the main causes that lead to much local erosion north in Fortim.

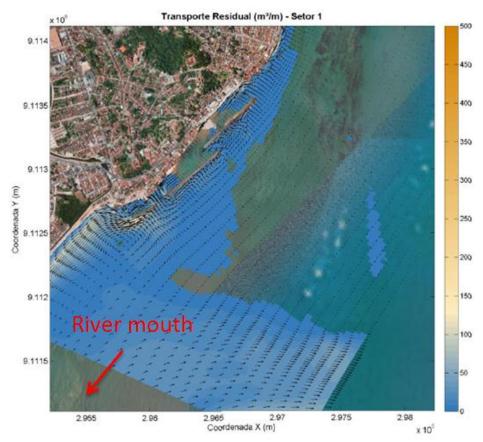


Figure 40: Sediment transport direction in Fortim (CPE 2011)

Both the water flow and sediment transport direction encircles around breakwater C (see Figure 40). At the seaward side of breakwater C this leads in combination with the anti-clockwise flow further south to relatively high velocities. At this side a lot of erosion can be seen from the models of the Figure 42 (CPE, 2011). The water flows in between the gap of breakwater B and C, and then hits the coast, causing much erosion locally. The water then spreads north and south of this place leading to sedimentation at both sides (see Figure 41).







Figure 41: Indication of sedimentation and erosion in Fortim (Google Earth, 2009)

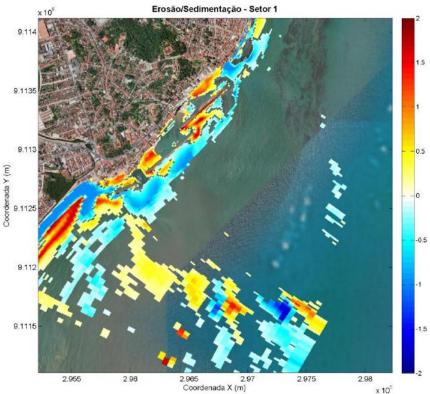


Figure 42: Sedimentation/erosion in Fortim after 5 years (CPE, 2011)





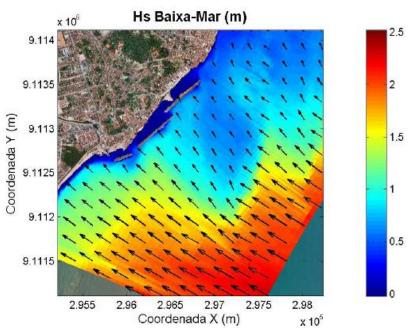


Figure 43: Significant wave heights Hs (CPE, 2011)





11.2.1 Conclusion of problem assessment



Figure 44: Overview influences of erosion

In this area there is one obvious problem, which is erosion of the beaches near the breakwaters. There are several factors that influence this process of erosion which have been denoted in Figure 44:

- 1. The sediment supply from the river is blocked by jetty H, this causes the sediment to go offshore (sink) and could instead be used for the supply of the Fortim beaches.
- 2. Despite the northern reefs, there still seems to be enough wave activity responsible for erosion, which indicates that the reefs don't dissipate wave energy that well.
- 3. There is a strong current, near the breakwaters north of Fortim, going from north to south.
- 4. Due to continuous erosion, revetments are endangered.
- 5. The breakwaters itself are not well constructed, i.e. not parallel to the coast and perhaps not with the appropriate distances off the coast, note that the distances also differs per breakwater.
- 6. The beach that looks healthy for now is eroding away.

The system of Fortim is complex because of the reef in front it, the different breakwaters that are not parallel to the coast, differences in size and distances offshore. From the models and observation can be said that there are many problems in this area that need to be solved.

The breakwaters are not functioning as they are intended. Only a steep narrow beach can be observed that is slowly turning into a tombolo. On the landward side of the other breakwaters there are hardly any beaches. Finally, from the models (CPE, 2011) can be derived that the southern beach that seems to be healthy, is actually subject to a lot of erosion.





11.3 General Solutions

In order to guide the sediments, originating from the harbor, to the area of Fortim and not to the sink, one could remove jetty (1). However, the jetty protects the harbor from wave activity, so removing this jetty will not be an option. A possibility is to reconstruct the jetty so the sediments are not lost to the sink. However changing the jetty in such a way is not straightforward and there is no assurance for the sediments to reach the Fortim area, this should be kept in mind when changing the jetty. Note that the sediment, originating from the harbor, is not necessarily suitable as nourishment.

The strong current going from north to south (3) can be strongly reduced with the aid of a groyne or breakwater. The groyne/breakwater will reduce the currents' energy and therefore diminishes the process of long shore erosion hence the littoral drift in the surf zone. Note that with structural changes, other aspects will have to be taken into account such as structural erosion and change in long shore sediment transport. Furthermore, it is possible that the groynes do not allow for enough sediment bypass so that the beaches on the south side of Fortim starve.

The reef doesn't dissipate waves/current energy as much as desired and the breakwaters' orientation and position are not well enough to dissipate the wave energy. The breakwaters have to be orientated parallel to the coast and as a tombolo is not wished for, as it blocks sediment transport going to the southern area of Fortim, the breakwaters have to be distanced more than its length to create a salient (CONSIENCE, 2010). It is also possible to replace the breakwaters with groynes since it seems that the main erosion cause is the strong, along shore directed current.

11.3.1 Alternatives

This chapter presents possible solutions (alternatives) that attack the problems in this area. The first alternative consists only of groynes, which would be continuation of the groynes in Bairro Novo. The second alternative entails breakwaters.

Alternative 1

From the chapter of Bairro Novo, it became clear that there are two decisive parameters for constructing groynes which are the groynes length and the distance between two successive groynes. Since this alternative only involves groynes, the breakwaters will be demolished. This would likely have a large impact on the residual sediment transport. Information about the residual sediment transport is needed to determine the length and the distance between the groynes.

For groynes, the same dimensions have been taken from Bairro novo; a length of 70 m and a mutual distance of 220 m between the groynes. The groynes of Fortim can be seen as the continuation of the groynes Bairro Novo; in Figure 45 this has been visually shown. Note that the most southern groyne has been made shorter. This is because the bulge (Figure 46) is already functioning as a small groyne: creating the same length of groyne for this part would due to the residual sediment transport direction, which is from north to south (although this could change without the presence of breakwaters), result in a relatively large (structural) erosion at the bulge and may haps even further downside (Figure 46). This solution requires therefore more often nourishments at the healthy beach part.







Figure 45: Alternative 1 groynes



Figure 46: Structural Erosion

From (CPE, 2011) it follows that along the stretch of 1300 m, an amount of approximately 1.6 million m³ of nourishment is necessary, which creates an average beach width of 30 m (Figure 47.)



Figure 47: Nourishments along the stretch of Fortim

Due to waves and currents, the beach fill sand will distribute in alongshore and crosshore directions. Background erosion may persist; this may lead to large losses of sediment from the shore. As a result, maintenance nourishments should be done after the initial nourishment. This especially holds for the healthy beaches (6, Figure 44) where there is no initial placement of sediment to preserve a beach.





Alternative 2

Alternative 2 consists of only breakwaters. The current breakwaters can be handled two different ways:

- 1. One could adjust the present breakwaters; this would be more practically since the breakwaters are already present;
- 2. Or one could design new breakwaters taking into account that the current breakwater should be demolished and that the current and sediment transport would change drastically (this one is out of scope for the general solution due to its complexity, and thus will not be further elaborated). Thus in this alternative, the current breakwaters will be altered.

As can be seen in (Figure 48), not all breakwaters are parallel to the shore Breakwater A is for a large part parallel to the shore in the new design. The aim is to maintain this feature of breakwater A. Basic rules of thumb can be applied to breakwater A to come up with new dimensions (*Appendix H: Candeias*).

It is found that the breakwater distanced 100 m should have a length of 100 m and a gap length of 60 meters: this resulted in breakwaters 5' and 6' (Figure 49).

The most southern part of breakwater A is not parallel to the shore and it was therefore the choice is made to demolish this part. The rule of thumb has been applied to breakwater B and it resulted in breakwaters 2', 3' and 4' (Figure 49). The respective lengths of breakwaters 2', 3' and 4' differ because their distance to the shore differs as well.

The design of breakwater 1' (Figure 49) is crucial, as it is the most down drift breakwater. Breakwater 1' should trap enough sediment so the nourished sediments do not wash away easily. On the other hand it should allow for enough sediment bypassing, so it does not starve the down drift beaches.

It is desirable that there is a salient instead of a tombolo present on the landward side of the breakwater. However, this salient should be larger than the other salients in the area, to lessen the nourishment frequency. Information about the breakwaters (length, distance, gap length etc...) can be found in Table 8.



Figure 48: Current breakwaters







Figure 49: Alternative 2

Breakwaters	Length [m]	Distance Offshore [m]	L/D ratio	Distance Lgap[m]	Lgap/L
A'	64	80	0.8		0.7
				140	
B'	80	80	1		0.7
				80	
C'	110	110	1		0.7
				90	
D'	140	140	1		0.7
				120	
E'	100	100	1		0.7
				60	
F'	100	100	1		0.7

Table 8: Breakwaters

Like in Alternative 1, nourishments must be done in order to preserve a beach first; it is assumed that the amount of nourishment is the same (1.6 million m³). Also for this alternative it holds that the healthy beach south of Fortim continues eroding and thus needs nourishment maintenance.







Figure 50: bypass phenomena of sediment transport in the Candeias area

11.3.2 Feedback on Bairro Novo & Boa Viagem

For Alternative 1 groynes have been used in the Fortim area. It has already been mentioned that the groynes in the Fortim area could be seen as an elongation of the groynes of Bairro novo. The future situation of alternative 1 would therefor unify both these areas. With the assumption that the local current direction is directed North-South, one would expect little or no changes in the area North of Fortim (Bairro Novo). However, due to the demolishing of the breakwaters, the local current pattern could change direction which might impact Bairro Novo. Though, occurrence of erosion/accretion due to the change of the current is hard to predict without numerical simulations. Evidently, due to the unification of the areas the groyne field of the general solution of Fortim and Bairro Novo is designed as one groyne field, not as two separate ones. Due to the jetty south of Fortim (and North of Boa Viagem), there is little interaction between Fortim and Boa Viagem.

Alternative 2 consists of breakwaters. According to the solutions, the "new" breakwaters should only form salients. This formation would likely block some sediment transport; again, this has no or little impact on the area North of Fortim (Bairro Novo), due to the local current direction. Even if a tombolo is formed, where one would expect a great decrease in sediment by-pass, there is little or no impact on Bairro Novo. The presence of the jetty South of Fortim results in little interaction between Boa Viagem and Fortim.

11.3.3 Conclusion

The Fortim area has some longshore drift related problems. To attack these problems, two alternatives have been presented, one of which only consists of groynes and the other one consists of only breakwaters.

It is more realistic to adjust the current breakwaters, due to e.g. economical factors. The combination of breakwaters with groynes will probably be most effective to elongate the nourishment period. Originally





Alternative 2 was designed to contain a combination of groynes and breakwaters, however due to the probability of some processes (e.g. sediment bypass on the wrong side of the breakwater) the groynes where left out of this alternative. On the other hand in the (CPE, 2011) a solution was presented which entails a combination of groynes and breakwaters. As the CPE used numerical models one can conclude that the unwanted phenomena would not occur. The best solution would be to use a combination of groynes and breakwaters.





12. Bairro Novo



Figure 51: Overview Bairro Novo (green: distinctive reefs, blue/purple: revetments+groynes, purple: groynes) (Google Eart)

Part A Bairro Novo 69





12.1 Introduction

The coastline of Bairro Novo consists of groynes, structures perpendicular to the coastline, which protect the coastline and preserve the beach; revetments and reefs. This area adjoins with area 2, Casa Caiada, in the north, at groyne D. In the south the area adjoins with area 4, Fortim. Over a total length of 1860 meter, 32 groynes have been observed. The structures which are used in this area can be distinguished as follows: a mix between revetments and groynes (A-C), groyne (D) and reefs (E-H) (see Figure 51).

For a more complete preliminary assessment see Appendix L: Bairro Novo.

12.2 Problem Assessment

12.2.1 Introduction

The (continuous) erosion problems of Olinda started reportedly after the expansion of Recife's Harbour in 1909, destroying even houses and streets (Quebra-mar 1976). At first in 1962 only three groynes were built in the south of Bairro Novo. After the construction the city continued to grow further northwards, forcing the construction of another 29 new similar groynes. The structures changed the hydrodynamics in front of Olinda (Pereira, 2006). The coastal structures to protect the coast of Olinda have been reorganized during 1996-1999 (CPRH, 1999). Since this reorganization, 10-15 years have passed by, which is a reasonable time to assess the coastal processes.

12.2.2 Problem description

The system

The buildings in Bairro Novo are close to the coastline, down to 15 meters at some locations, including a road in between the buildings and the coast. The reason that the buildings are relatively close could be either that they were initially built close to the coast, or that the coast has degraded the last decades. Most likely it is a combination of the two.

The area has two large reefs in front of it (reef E and F). These reefs have great influence on the sediment transport direction in front of the coast and make it much more complex (CPE, 2011). The sediment transport direction of Bairro Novo can be seen in Figure 52.





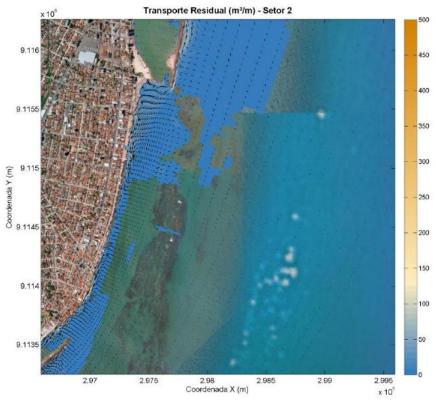


Figure 52: Sediment transport direction (CPE, 2011)

From the sediment transport direction – model, it follows that between reef E and F, there is a relatively large gap (Figure 53) in which there is an exchange of sediment. Sediment activity can also be perceived from the erosion/accretion - model at this gap (see Figure 54).





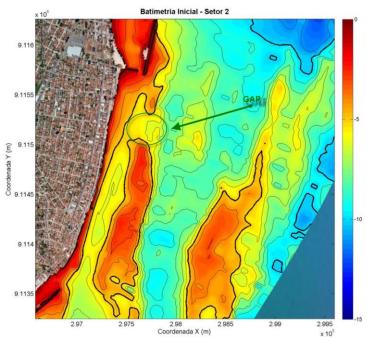
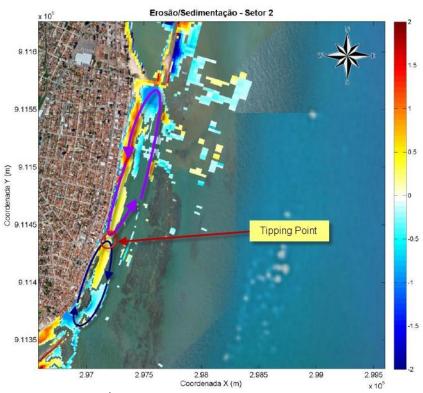


Figure 53: Bathymetry of Bairro Novo

Figure 54 shows the outcome of the CPE which describes the erosion/accretion after 5 year. Besides the erosion/accretion, it also shows a simplified version of the sediment transport direction (the arrows) based upon Figure 52. In order to describe the sedimentation transport of this system, Figure 54 will be assesed.







Coordenada X (m) $\times 10^5$ Figure 54: Erosion/accretion according to the 5 years model and sediment transport direction (CPE, 2011)





In the northern part of Bairro Novo, the sediment transport direction is directed anti-clockwise (the purple arrows, see Figure 54). This might explain the erosion just south of groyne D (3) as well as the sedimentation at groyne D (2) and further down south of the groyne D (1) see Figure 55.

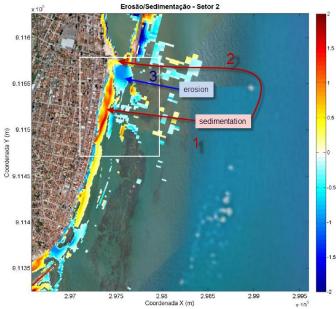


Figure 55: Sedimentation/Erosion of the northern part of Bairro Nova

In the southern part of Bairro Novo, the sediment transport direction is directed clockwise (the blue arrows, see Figure 54). This might explain the erosion in the southern part of Bairro Novo (1) and the sedimentation along the northern direction of the coast (Figure 56).

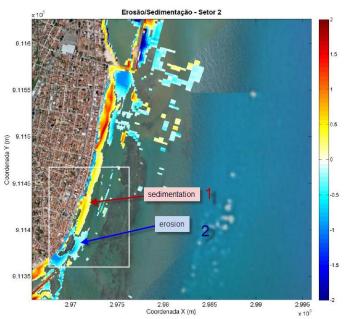


Figure 56: Erosion/Sedimentation at the southern part of Bairro Novo





Between the northern part and the southern part, lies a tipping point (Figure 54). This is the point where the clockwise sediment transport direction from the southern part and the anti-clockwise transport direction from the northern part, meet. One would expect a relatively large amount of sediment at the tipping point, however this could not be perceived from the model.

What stands out is that even though there are two relatively large reefs, one would expect an amount of energydissipation of the waves/current. However when assessing Figure 54 one can see relatively much sediment transport. This would suggest that either the reef doesn't dissipate the waves as much as expected or the wind influence on the currents might play a bigger role (wind induced waves).

Groynes

The general purpose of a groyne is to trap sediment from long shore drift in order to craft and maintain a beach. These structures absorb energy from the sea on the shore and reduce the impact of the energy on the coast. The short groynes in Bairro Novo, groynes A, B and C (Figure 51) are likely built with the same goals. However there is little beach during low tide and no beach at all during high tide (see Figure 57). Especially where there are lots of revetments, there is no beach, not even during low tide (see Figure 58). The reason for this might be that there is a lot of erosion very near in front of the groynes according to the CPE Model (see Figure 54, the thin blue line in front of the coast).



Figure 57: Beach states during low tide (left side) and during high tide (right side). (Google Earth, 2009)







Figure 58: Beach state during low tide and lots of revetments. (Google Earth, 2009)

The purpose of groyne D (Figure 51) is not very clear. One of the possibilities is that Groyne D was built in order to build breakwater L (Casa Caiada). Another one is that this relatively large groyne was built in order to create a beach. From Figure 54 it follows that there is relatively much accretion at this groyne, probably due to its length. This could pose problems for the area north (Casa Caiada) of Bairro Nova, due to a shortage of sediment inflow.

Revetment

Further degradation of the coast would put the buildings close to the coast in immediate danger. Revetments are generally built to protect the coastline and fix the location of the coast. The revetments in Bairro Novo are likely built to stop further degradation in order to protect the coastline and the buildings.

As stated before, there is continuous erosion along the coastline. This could have a negative impact on the stability of the revetments, due to the formation of scour holes in front of the revetments.

Evaluation

The revetments and groynes were built simultaneously. It is therefore unclear what the real purpose of the mix of these structures was. Was the primary goal to craft and maintain a beach (groynes) or was the primary goal to protect the coastline (revetments). In other words: did they want to create a beach or not?

From Figure 57 and Figure 58 can be perceived that crafting/maintaining of qualitative beaches has failed. Also from Figure 58 one can imply that the groynes cannot maintain the beaches, due to continuous erosion.

The revetments along the coast have met their purpose, this follows from the CPE report. In this report the shoreline shifts of the last 30 years have been evaluated; the conclusion was that the shoreline was stable (CPE, 2011).





The prior goal of the mix of these structures was probably protecting the coastline and as secondary goal crafting a beach (CPRH, 1999).

12.2.3 Conclusion

The groynes have up till now failed in creating and maintaining a beach in front of Bairro Novo. The influence of the groynes on the system is hardly visible in models (CPE, 2011). The energy dissipation due to the groynes is not nearly enough for the sediment to settle there. This is an indication that adjustments are necessary for the structures to function.

The revetments have up till now succeeded in fixing the coastline, however this may be a problem later due the continuous erosion along the revetments that could cause instability due to scour holes.

The erosion in the upper south of Bairro Novo contributes to large local problems. There is hardly any beach there and models predict continuous erosion (CPE, 2011).

At the south side of groyne D there is some sedimentation and a beach is visible here. Whether this is a problem depends on the system in Casa Caiada, north of Bairro Novo. The sediment is trapped by groyne D, so there is less inflow of sediment and this could pose problems for the beaches in Casa Caiada.





12.3 General Solutions

12.3.1 Introduction

The problem assessment has shown that the structures currently present are successful in protecting the coastline but not in creating a beach. The goal therefore is to create a beach meanwhile assure that the safety of the coastline is maintained. To meet this goal, different alternative (possible solutions) are presented and evaluated.

12.3.2 Alternatives

Alterative 1: Groynes

For construction and financial aspects it is beneficial to incorporate structures already present in an area. As the area of Bairro Novo has groynes implemented, the first solution contains improvement/implementation of groynes.

Groynes should only be constructed along coasts with recession rates exceeding 2 m/year and dominant long shore transport processes; groynes cannot stop erosion, but only reduce erosion; groynes are most effective at coarse-grained beaches (0.3 to 1 mm) along swell-dominated coasts (van Rijn 2010).

The recession rate at Bairro Novo exceeds 2 m/year (MAI 2009), the long shore process is dominant (in front of the revetments there is no worthy beach), and the material consists of medium coarse sediments. Using a groyne field in the Bairro Novo area is an effective solution. One should however be aware of the fact that groynes do not stop the erosion, they only reduce the erosion rate, and once the compartments are filled to their capacity. Another (negative) aspect is that groynes might have a negative effect on downdrift beachs, also called downdrift erosion.

It is clear that the current groynes are too short and too closely placed to each other in order to work properly.

The solution of Alternative 1 has been visually shown in Figure 59. It can be seen that there is now a total of 10 groynes, each with a length of 70 meter and a mutual distance of 220 meter. Note that because of the limited wave action in the Bairro Novo area, T or L head groynes are not used. For the calculation of the dimensions of/between groynes, one is referred to *Appendix G: Design Guidelines*.







Figure 59: solution Alternative 1

Alternative 2: Breakwaters

Offshore breakwaters can be used as an alternative to the groynes. Offshore breakwaters work by sheltering an area from wave action so the long shore sediment transport decreases and thus accumulation will take place behind the breakwater. The currents in Bairro Novo are created by a combination of the complex bathymetry, wave action and wind inducement. The breakwater will not shelter the coast from all these current sources and thus a breakwater in the Bairro Novo area will be less effective than groynes. A groyne interferes with the long shore current no matter what the source of the current is, thus a groyne will be more effective than a breakwater in the Bairro Novo area.

Alternative 3: Nourishment

Beach nourishment is another alternative. The safety of the coast is already safeguarded by the revetments and with beach nourishment one will create a beach. It is mandatory to conduct long term structural beach nourishment as the area suffers from erosion; in time the amount of nourished beach will erode. In order to assess the viability of the nourishment the repetition time and the amount of nourishment will have to be determined.

The coast of Bairro Nova is approximately 2240 meters long. From *Appendix L: Bairro Novo* follows that the amount needed for nourishment is equal to 1.6 million m³ and for re-nourishment 5400 m³. These amounts seems of outrageous magnitude but possible.

Alernative 4: Groynes & Nourishment

Beach nourishment can also be combined with groynes (Alternative 1&3). If only beach nourishment is used the first nourishment would be exceptionally large. When using the groynes it was recommended to fill the compartments to their capacity, this is already a combination of hard and soft measures. If the compartments would be filled naturally (so not using nourishment) it would take a long time to fill the compartments due to the small net total sediment transport in the area, leading to maximization of the lee side erosion. The combination of nourishment and groynes would remove the necessity of





exceptionally large first nourishment. The groynes would also increase the repetition time of the nourishment, making it more viable.

The solution of using a groyne field and nourishment will have the biggest impact on Casa Caiada. Shortening groyne D can be also be used in the solution of Casa Caiada and the nourishment will cause the dimensions of the structures of Casa Caiada to be smaller. Both are positive consequences.

12.3.3 Conclusion

To fully understand the effect of breakwaters, models will have to be used which are beyond the scope of this study at this point. However the use of breakwaters as hard structures is not recommended as the complex flow patterns in the area will likely cause the breakwater to be less efficient.

The combination of beach nourishment and groynes seems to be the best solution. Groynes do not stop erosion they only delay it, making it perfect in combination with beach nourishment as the repeat time will be increased. It has been proven that groynes in combination with long term structural nourishment can solve an erosion problem (van Rijn 2010).

12.3.4 Feedback on Casa Caiada

The solution in the Bairro Novo area will have an effect on the Casa Caiada area. If the groyne field will be implemented the large groyne D (see Figure 51) in the north will be made significantly shorter. Shortening groyne D it will cause for more sediment bypass and thus reduction of down drift erosion. The Casa Caiada area will experience a more energetic wave condition as it is not sheltered as good as before. From the solutions of Casa Caiada it follows that it is wished that the Casa Caiada area will be made more open (less sheltered), the shortening of groyne D could be used well for the solution in both areas (Bairro Novo and Casa Caiada). In general on the down drift side of a groyne field erosion will take place. Groyne D is very long shortening it will cause for more sediment bypass and thus reduction of down drift erosion.

The impact of beach nourishment in Bairro Novo on Casa Caiada is the available sediment supply. This would mean that the solutions in the Casa Caiada area can be dimensioned smaller as more sediment supply can be expected.





13. Casa Caiada



Figure 60: Overview Casa Caiada (red: breakwaters, green: distinctive reefs, blue: revetments, purple: groynes) (Google Earth)





13.1 Introduction

The erosion problems of Olinda started reportedly after the expansion of Recife's Harbour in 1909, destroying even houses and streets (Quebra-mar 1976). The construction of five breakwaters in this area was done during 1970s and 1980s. After some years, it turned out that the erosion problems were shifted towards the north of Casa Caiada. In response to this, two more breakwaters were built there, adding up to the current total 7 breakwaters (Pereira, 2006).

Casa Caiada, south of Janga, can be characterized by the non-parallel breakwaters offshore (Figure 60). The total length of this area is 5.3 km. The northern adjacent area is area one: Janga. The southern boundary of the area is taken at groyne L. This area has in total 7 breakwaters (A-G), 1 important reef location (M) and 2 revetments (H-I).

The most northern breakwater A in this area is connected to jetty K at the mouth of the river. Another aspect that can be seen is that there is a lot of sedimentation both the northern and the southern side of the jetty.

Striking aspects are that all the breakwaters in this area overlap the previous/following breakwater, and that they are not all placed parallel to the coast. They are placed behind each another and are not next to each other like it is the case in Janga. Another feature that can be observed is that all breakwaters have sediment on the landward side of breakwater, i.e. reverse salients are forming on the landward side of the breakwaters.

13.2 Problem Assessment

Over the whole Casa Caiada area there are breakwaters present. The breakwaters have been built to create a healthy beach. However not everywhere in the Casa Caiada area there is a healthy beach, at some places even revetments are needed to protect the shore. The design of the breakwaters and other structures will have to be altered in order to create a healthy beach for the whole Casa Caiada area. An indication of the bad design is the accumulation of the sediment on the landward side of the breakwater. It is desirable if this sediment could be a part of the beach. At breakwater F the accumulation of the sediments can be seen very clearly. The waters enclosed by breakwater A and jetty K experience little circulation. As a result the quality of the water decreases and sediments are deposited in the area.



Figure 61: Overview Casa Caiada (Source: Google Earth) (red: breakwaters green: distinctive reefs, blue: revetments, purple: groynes) Elementary Information





Reef M is of the Barrier type, it dissipates some of the wave energy. Because the Casa Caida area is only partly protected by such a reef, one can expect a more energetic wave condition than the adjacent beaches. Some small line-reefs formations can be found at the northern boundary of the area. These reefs do not have a very big impact on the bathymetry; some of the breakwaters have been built on top of these reefs.

Between reef M and the reefs formations more to the south there is a gap see the white box in Figure 62. The gap with a width of 3.5 km characterizes the Casa Caiada area. Results from the (CPE 2010 volume 7) shows that the sediment transport is towards this gap (see Figure 63). The sediments are thus transported offshore; the gap is there for considered to be a sink. Because of the gap one would expect to find a diffraction pattern. However due to the size of the gap and the existence of a small reef formation in the middle of the gap (see Figure 62) the diffraction pattern is not as one would expect.

Because of the dimensions and orientation of the breakwaters the residual sediment transport at every gap is directed inside of the waters enclosed by the breakwaters. Only at the gap between breakwaters G and F the residual sediment transport is directed outwards. The sediment transport between breakwaters A and B (see Figure 63) illustrates the circulation problem of the area enclosed by breakwater A and jetty K.

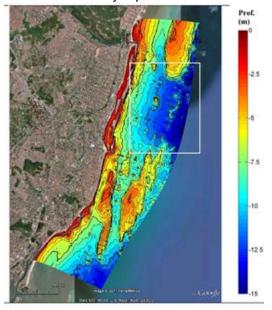


Figure 62: Bathymetry of the Casa Caiada area (CPE volume 7 2010)





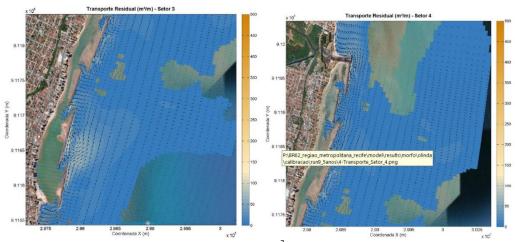


Figure 63: Annualized residual transport in m^3/m /year left the southern part, right the Northen part of the Casa Caiada area.

Causes of erosion

In theory breakwaters works by interrupting the long shore sediment transport. By sheltering an area the sediment transports stops and starts again past the sheltered area. In the area where the sediment transport stops accumulation will occur, this is a very coarse explanation of the way breakwaters work. In the Casa Caiada area there is no significant long shore sediment transport close to the shore present. The long shore sediment transport of the Casa Caiada area is blocked from the south by groyne L. The breakwaters prevent that the long shore transport starts up again. In the north the area is closed off by jetty K. The combination of these structures ensures that the sediment supply of the area is dependent on the small gaps in between the structures. Due to alignment of the gaps and diffraction of waves at the gaps, the sediment transport has a different direction at each gap. The direction of sediment at each gap can contribute to a sediment import or export in the area. See Figure 64 for an example of the diffraction pattern at one of gaps.

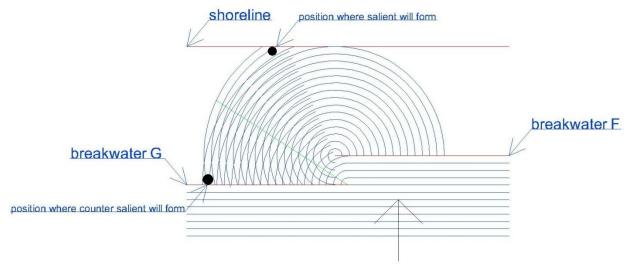


Figure 64: schematically view of the diffraction pattern at breakwaters G and F.





The diffraction pattern will also cause for set up differences in the water level. This set up difference leads to a current pattern which in it turns leads to a sedimentation and erosion pattern see Figure 70. The salient and reverse salient at breakwater F is a perfect example of this see Figure 66.

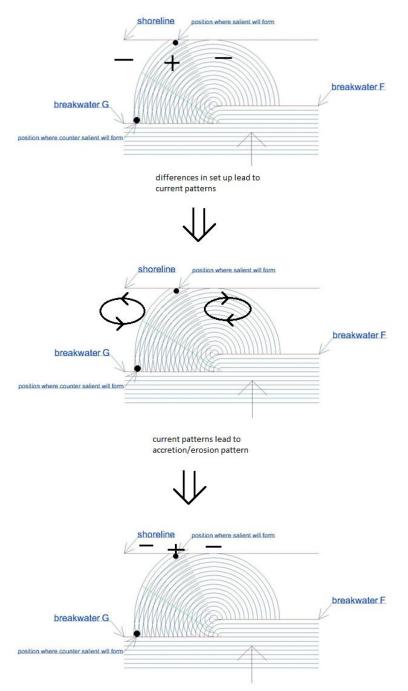


Figure 65: a schematical view of the water level setup, current and sedimentation/erosion pattern

After the waves have deposited their sediments at the salients they have lost their sediments. However not all the wave action has dissipated, as the wave continues, erosion will take place. The sediments that erode at salient F are transported to groyne L where they are trapped and thus accrete.

In the above the assumption was made that the waves propagated perpendicular to the breakwaters. However the waves come from all different angles resulting in the sediment transport as can be seen in Figure 63. For different wave angles certain gaps will be sheltered. These gaps will experience wave with little energy due to the big refraction angle the waves will be forced to make to enter the gap. Other gaps however will have relative much energy available. The diffraction pattern will look similar to that of Figure 64. One of the differences is however that the energy on the green line will be bigger.







Figure 66: Salients at breakwater F.

Other problems

It appears that many problems at the coast of Casa Caiada are not only related to coastal engineering, but also to many socio-ecological problems. With the construction of the breakwaters, sheltered zones were created. With less water circulation, the water temperature increased resulting in a worsening of the water quality and biodiversity (Pereira, 2006). Another example in the area is for example the discharge of illegal sewage and waste water in the area increasing the water pollution.

Before the construction of the breakwaters, there were healthy coral organisms in the area parallel to the coast. But first due to the construction of the breakwaters on top of the reef, and later by the worsening water quality, this reef has degraded (Pereira and others, 2004), resulting in a dead reef. Many of the people who live very close to the beach refuse to go inside the waters because of the very shallow depth and the fear to get ill because of the pollution. The overall perception of beaches in the area can be called bad (Pereira and others, 2004).

13.2.1 Conclusion of the Problem Assessment

The Casa Caiada area is characterized by the small openings in between the structures in which all sediment import and export will have to take place. At Casa Caiada one can see the erosion at some parts of the beaches. At some places even revetments are needed to protect the shore line. One could get to the hasty conclusion that the area suffers from erosion. However not all the beaches at the Casa Caiada area suffer from this erosion, some beaches experience accretion. There is more annual residual sediment transport inside the area enclosed by the breakwaters. This sediment is however not evenly spread over the area, causing some parts to erode and some parts to accrete. The locations, alignment and size of the gaps and breakwaters determine the locations of erosion and accretion. The main problems are:

- Erosion on some parts of the beaches
- Accretion at the wrong side of the coast i.e. on the landward side of the breakwaters
- No beaches at the coast
- Bad water quality





• Some parts of the area is clogged with sediments





13.3 General Solutions

As can be concluded from the assessment of Casa Caiada, changes are needed in order to create a sustainable solution for the coastal problems and to create a healthy beach in front of Casa Caiada. Possible solutions for the area are:

- Increase the distance between the breakwaters
- Change the orientation of the breakwaters
- Shorten the breakwaters
- Change the offshore distance of the breakwaters
- Shorten / remove groyne L
- Shorten / remove jetty K

All these possible solutions are discussed further and to what degree they are applicable. First the goals of the changes and adjustment will be elaborated, i.e. what is the desired condition of the coast to be?

13.3.1 Desired situation

The goal of the breakwaters is to create a sheltered area in front of the coast, protecting it from the high Atlantic waves. Apart from this, the breakwaters also create beaches on the coast by holding sediment from the long shore transport. There is sediment present in the area, but it is located at the wrong place. This sediment needs to be at the correct location, i.e. on the coast forming a beach. This beach is needed along the entire coast in Casa Caiada. In order to do this, the dimensions of the breakwaters will need to be modified, as well as groyne L and jetty K.

Creating an open system

Because the system is almost closed, sediment gets trapped, clogging up the coast along Casa Caiada. As mentioned in the assessment of the problems, this causes among others a worsening of water quality. The system acts more like a lagoon, a closed system with only a few inlets/outlets through which all sediment and water must flow.

The first step towards a healthier coast would be to shorten groyne L or completely remove it. By doing this, one creates a flow of water and sediment from the south. This sediment can then be used to prevent erosion and to build up beaches. To make sure that there is also an outflow of the system, either breakwater A must be shortened/removed or jetty K needs to be shortened. Jetty K is used for the purpose of stabilizing the river mouth, so removing it will endanger this function. However, keeping it connected to breakwater A would cause problems in the area of Janga, due to low sediment inflow. This problem will be dealt with in the generated alternatives. Numerical models can be a handy tool in determining on what needs to be done.

With the removal/shortening of the outer groyne and jetty, the system once again acts as an open coast instead of a lagoon. The sediment that enters can then be used in order to create beaches using the breakwaters that are already present.

Distance offshore of the breakwater

According to the rule of thumb of tombolo formation (see *Appendix G: Design Guidelines*), it can be predicted that a tombolo will form near every breakwater (see *Appendix M: Casa Caiada*). This is in accordance with the prior thought that the system will just clog up in the current situation. This is a clear indication that the breakwaters are either too large, or too close to the shore, i.e. there is no balance





between length and distance. This ratio is intended for breakwaters next to each other with some gap length in between each other. The Casa Caiada area works as a lagoon and not as an open coast. This is why the guidelines are not applicable for this area. In this situation the gap length is practically zero while the breakwaters are not next to each other. These influences will stimulate the tombolo formation and the clogging up of the system.

Distance in between the breakwaters

The combination of groyne L, jetty K and the too closely placed breakwaters cause the system to clog up. Opening up some space between the breakwaters, would stimulate the circulation of water in the system. Due to the overlapping and close proximity to each other, there is a difference in the diffraction pattern, as is described in the problem assessment. This is why there are no salients at the coast this is also the main reason for the formation of salients opposite to the coast. Instead of sedimentation, there is erosion at the coast which explains the placements of the revetments. The solution for this is to increase the gap between the breakwaters, by removing parts of the breakwater.

The orientation of the breakwaters relative to each other is another important aspect. In the current situation the breakwaters have different distances offshore and they overlap each other. Because of this, the incoming waves at breakwater G form only one-sided diffraction patterns at area A, so there is almost no diffraction patters at area B (see Figure 67). This is also explained in the assessment of the problem. The solution for this is to place the breakwaters next to each other instead of altering the distances offshore.



Figure 67 Diffraction patterns at breakwater F and G

Orientation of the breakwaters

It is unknown for what reason the breakwaters are placed under such an angle to the coast. The most likely reason would be that at the time, they were parallel to the coast, but due to changes in the coastline, this changed. The difference in angle is especially visible at breakwaters C and D. For breakwaters to shelter the largest area, they need to be parallel to the coast. This oblique orientation thus works less effective.





13.3.2 Alternatives

Different solutions are possible in order to solve the problems posed above. Here, these solutions are explained with their benefits as well as downsides.

Alternative 0

This alternative presumes no changes to the current situation. The consequences of this alternative can be seen in the problem assessment of Casa Caiada. This option is actually only feasible for the areas where not much is wrong.

Alternative 1

Since the breakwaters are already placed, it's more economical to shorten them rather than to move them further offshore. This alternative makes use of the current structures to improve them so that they will function as desired. It is highly likely that this solution is the most economical one; however the solution will not be most optimal one, since it starts with the shortcomings of the current structures.

Breakwater adjustments

The most economic, and thus most feasible solution, would be a re-arrangement of the current structures. How this rearrangement needs to take place will be looked upon here. The general proposed changes to the breakwaters are:

- further distance offshore
- change in orientation
- creating more gap length in between the breakwaters

The influence of the reef is like a submerged breakwater. In some cases, a submerged breakwater may even lead to structural erosion at the coast. Because of the presence of the reef near breakwater A, B and C, large portions of these breakwaters can be removed.

The lengths of the breakwaters can be determined using the rule of thumb for salients. A salient forms when $0.5 < \frac{L}{D} < 1.3$ (see *Appendix G: Design Guidelines*). A value of 1.0 is chosen to determine the length of the breakwaters. For this value a distinctive salient will be seen while at the same time no tombolo will form. These lengths are only indicative since they don't take complex influences of the reef. But overall can be said that there is a huge reduction of the lengths of the breakwaters.

New Breakwater	L/D ratio	Distance offshore [m]	Length [m]
Α	1.00	285	285
В	1.00	108	108
С	1.00	213	213
D	1.00	240	240
E	1.00	96	96
F	1.00	143	143
G	1.00	249	249

Table 9: Lengths of the new breakwaters for alternative 1





Using the guidelines it is clear that all of the breakwaters need to be shortened.

Groyne L and jetty K

Groyne L will need to be shortened or completely removed in order to create an open system. Jetty K is needed for stabilizing the river mouth, but can be shortened to increase the sediment flow out of the system. Quantifying this shortening goes beyond the reach of this analysis, but should be in the order of 10-40% of the original size. The gap created with this shortening will allow sediment to flow into the system forming beaches.

Revetments

Currently at the location of the revetments, there is some erosion. In the CPE models this erosion is not predicted (CPE, 2010). As there are breakwaters in front the revetments, this erosion would indeed seem strange. With the above mentioned adjustments to the system, these revetments would be unnecessary. However, removing them seems rather unnecessary as they are already built. So no adjustments are needed for the revetments.

Beach nourishment

The current situation is that there are very small beaches and a lot of sedimentation at the wrong places. After the adjustments, a lot of nourishment will be needed to restore the beach profile. With the proposed adjustments, the inflow and outflow of this sediment will be in constant balance, meaning that this nourished sand will not just simply wash away but the beaches will be maintained. The deposition of sand will be primarily on the dry beach that is already present.

A rough estimate of the sediment amount will be made to get an idea. In Casa Caiada, about 3500 m of coast will need beach nourishment. With information from the bathymetry can be calculated that the amount of nourishment needed is approximately 600.000 cubic meters of sand, about 170 cubic meters/m sand.



Figure 68: Sketch of alternative 1, breakwater lengths not on scale





Alternative 2

Another solution is not to use the current structures as a base for the solution. This can be justified easily, since the current structures are the main cause of the current problems. So another way of dealing with this problem is to remove all the structures, restore the beaches along the coastline, then build structures to protect and maintain these beaches. The adjustment to the groyne, jetty and the revetments will be the same as in alternative 1. The same beach nourishment will be used

Breakwaters

As mentioned some of the current breakwaters will be removed. These are breakwaters B, D, E, F. Some of the breakwaters are only partially removed. These are breakwaters A, C, D and G.



Figure 69 a sketch is made of the proposed changes for alternative 2. Note that the breakwaters in this figure are not to scale and the length are not representative, the image just shows the idea of alternative 2. The exact dimensions cannot be determined with the current information. Only an indication of the lengths will be given with the use of rules of thumb.

New Breakwater	L/D ratio	Distance offshore [m]	Length [m]
A	1.00	180	180
В	1.00	180	180
С	1.00	180	180
D	1.00	180	180
E	1.00	180	180
F	1.00	180	180
G	1.00	180	180

Table 10: Lengths of the new breakwaters for alternative 2







Figure 69: Sketch of alternative 2, breakwater lengths not on scale

13.3.3 Feedback on Janga

On the boundary between the two areas there is currently a jetty (jetty K) that stabilizes the river mouth. North of this jetty, in Janga, there is a small stretch of beach of 650 meters. On south side of this jetty, in Casa Caiada, there is the blockage of sediment due to the connection between breakwater A and jetty K.

Both alternatives in Casa Caiada create a similar system near the boundary, i.e. breakwater A is partly demolished and jetty K is shortened thus creating a large gap at that location.

As mentioned in the solutions for Janga, part the main problem is the low sediment transport into the system of Janga. The shortening of jetty K in combination with the placement of the new breakwater A creates a relatively large gap that allows for sediment to flow towards Janga. This increased sediment inflow (see *Figure 70*) might have a positive effect on Janga. In other words, a solution for Janga may lie in the changes done in Casa Caiada.







Figure 70: Sediment transport out of Casa Caiada

The sediment flow (see *Figure 71*) in Janga adds to its development and could lead to faster formation of the undeveloped tombolos.

Another possible consequence is that beach south in Janga starts accreting more due to the increased sediment input (see *Figure 71*).

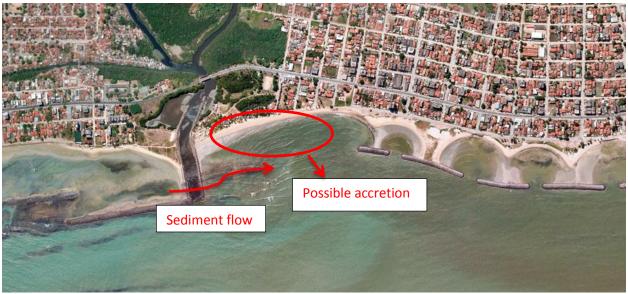


Figure 71: Sediment transport into Janga

13.3.4 Conclusion

The dimensions, orientation, distance offshore and the distances between the breakwaters are all aspects that need to be adjusted. The combination of the closed off system and the locations of the reef have caused the coast to erode and accrete on the opposite side of the coast, i.e. at the breakwaters.

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The coastal protection strategy that will be used here is to protect the coast against the problems since retreating is not an option.

To solve this system and create a safe coast, there are no simple measures that can be taken. The damage done by the structures on the coast is far too great for this. The solution must be a combination of 'hard' and 'soft' measures.

The first thing to do would be to restore this damage. This is done with the beach nourishment. After this, the system will be changed with the proposed adjustments. These adjustments will keep the beaches healthy and create a safe coastline. Which alternative will give an optimum solution depends on many other factors like costs, effectiveness, economic potential of the area and subjective factors like which one has less visual intrusion etc.



14. Janga



Figure 72: Overview of Janga (red: breakwaters green: distinctive reefs, blue: revetments, purple: Jetty) (Google Earth)

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14.1 Introduction

Janga is the most northern area of metropolitan Recife. The northern boundary of the area is at the end of the northern revetments (See *Figure 72*). The southern boundary of the area is at the jetty near the mouth of a river in the south which separates the areas of Janga and Casa Caiada. The total length of this area is 4.3 km.

In this area one can observe a series of 9 breakwaters (A till I), 4 distinctive reefs and 2 revetments that are built to protect the coast. All the structures in the area are named from A to P by type of structure and from north to south.

Striking characteristics in the coastline of Janga are the formation of a tombolo and several salients behind the breakwaters (see Figure 72). Also in the area several revetments along the coast can be seen as well as the presence of many reefs, close to the breakwaters and further offshore. For the details of these structures see *Appendix N: Janga*.

The coastline of Janga is full of beaches and overall looks pretty healthy. Some problems however must be pointed out. The locally formed tombolo at breakwater H blocks the local long shore sediment transport. Another point of issue is behind breakwater A, the longest one. Besides the two salients, the coast behind this breakwater is fully eroded and the revetments prevent any further land loss. Another issue that must be looked upon is further north. Here, a huge revetment has been placed and the area doesn't have a healthy beach. The breakwaters in the south of the area could be the cause of this and further analysis is needed here.

14.2 Problem assessment

14.2.1 Introduction

At first sight, Janga appears to be a healthy beach. However, when one observes the area immaculately several problems do appear. The beach of Janga has two major problems. The breakwaters (*Figure 73*) have failed to protect the shoreline and create a healthy beach because they allowed for the accretion of tombolos which negatively affected the long shore transport in an area with poor residual transport. Secondly, an inordinately large revetment had to be constructed in the Northern area to fix the shoreline in position because the beach was eroding. The area has reefs, breakwaters, revetments and even a jetty. To understand the problem, an analysis of these structures and their part in the problem will be performed.







Figure 73: The Janga area (Image Source: GeoEye 2011 – Image date 24-11-09)

14.2.2 Elementary information about Janga

Elementary information about Janga	
Wave direction	154° Az
significant wave height	0.29 m
significant wave period	5.12 sec
Sediment direction	Generally North in some areas – In other areas nowhere in particular
Sediment sinks	Some small channels behind breakwater (C and D) and A
Tidal range	1.76 m

Table 11: Elementary information about Janga(MAI, 2009)

More information concerning the wave and tidal conditions can be found in *Appendix A: Morphology*.

14.2.3 Problem description

Bathymetry

In (CPE, 2011) the bathymetry of the area was mapped along with the sediment transport. The Janga area was divided into 3 sectors (Figure 74). DEFLT3D was used and the area was mapped for a total duration of 5 years. Understanding the bathymetry is vital to understand the Janga area.





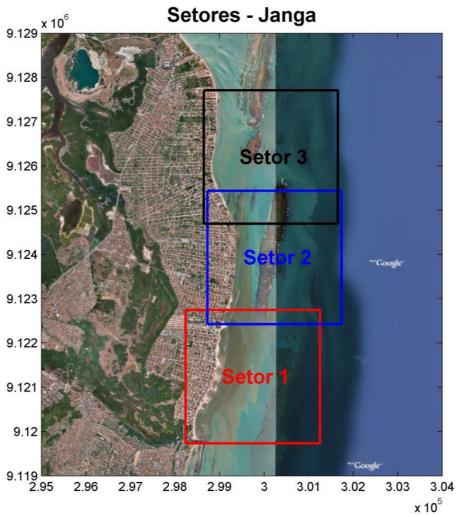


Figure 74: Division of the Janga Beach into more sectors (CPE, 2011)





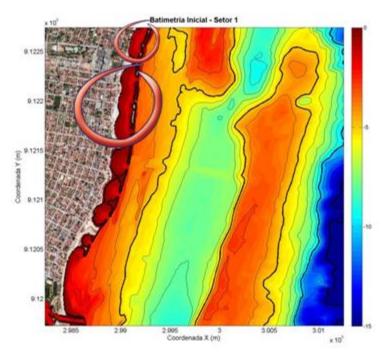


Figure 75: Bathymetry Janga sector 1(The marked area is the location of a deep channel, this channel probably had some influence on the formation of salient and tombolos behind the breakwaters) (current scenario) (CPE, 2011)

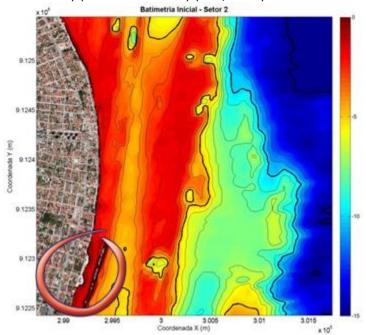


Figure 76: Bathymetry Janga sector 2 (The marked area is the location of a deep channel, this channel probably had some influence on the formation of salient and tombolos behind the breakwaters) (current scenario) (current scenario) (CPE, 2011)





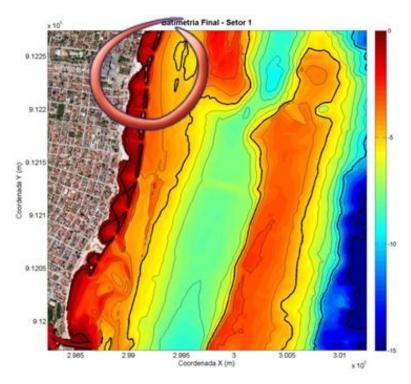


Figure 77: Bathymetry Janga Sector 1(The marked area is the location of a deep channel - The channel seems to be getting smaller according to the DELFT3D model analysis) (current scenario) (5 years later) (CPE, 2011)

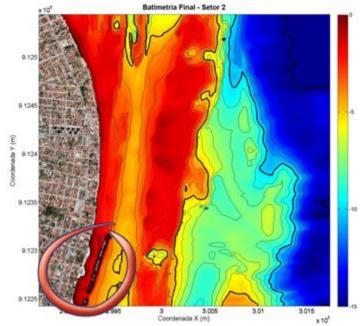


Figure 78: Bathymetry Janga Sector 2(The marked area is the location of a deep channel – The channel seems to be closing slightly) (current scenario) (5 years later) (CPE, 2011)





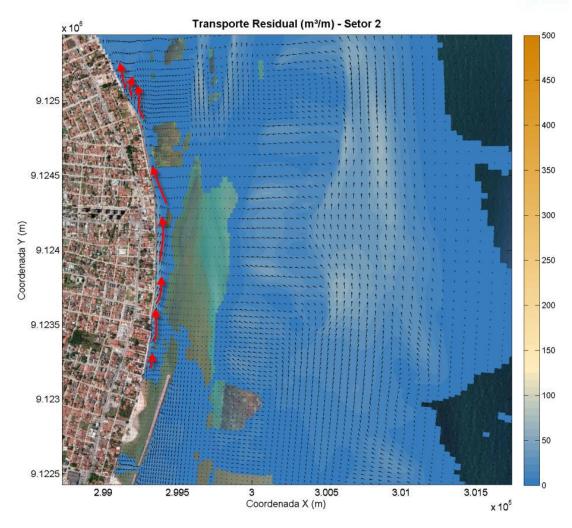


Figure 79: Transport rates sector 2 Janga (CPE, 2011)

Tidal Influence

The majority of the formations between the breakwaters are formed during high tide because the area behind the breakwaters is drained for a large part during low tide. (See Figure 80) The majority of the erosion and accretion process must therefore occur during high tide for the more southern areas. An interesting phenomenon which stems from the satellite images is that there are two rather deep channels in the area which can prevent or diminish an accretion process. This can be seen in Figure 80. The entire southern area is drained but these parts are completely submerged. This indicates a deep channel.

This is also confirmed in the bathymetry of the area which reveals two deep channels. One channel is behind breakwater C and D and another is behind breakwater A. The date of formation of these channels is unknown. In (CPE, 2011) the bathymetry of the area was modeled for a total duration of 5 years for which they used DELFT3D. If one compares the channels of the present (Figure 75 and Figure 76) with those 5 years later (Figure 77and Figure 78) the channels appear to be accreting and can be classified as sediment sinks.







Figure 80: Low tide (left) high tide (right) (notice the majority of the areas behind the southern areas are drained during low tide) (source image (left): GeoEye, 2011- date image: 3-10-2010) (Source image (right): GeoEye, 2011 date image: 16-11-2010)

Reefs

There are three reefs in tandem formed in front of the coastline of Janga. The reefs act primarily as submerged breakwater and dissipate and reflect significant amounts of wave energy. In (PROCOSTA,2010) data analysis resulted in an average wave heights of 0,27 m to 1,28 in outer measuring stations of the coast of the Boa Viagem and the inner average wave heights were 0,15 m to 0,58 m. It is clear that the reef performs a vital role.

There are two very large reefs (L and K - Figure 73) which are classified as a barrier reefs. Field observations have revealed that waves can shoal and break on this reef. The depth below the wave is drastically lower than the ocean bed while above a reef and shoaling and breaking can occur There are also a reefs M and J. However this reef is very small and no particularities due to the reef can be witnessed from satellite imagery alone. These reefs, considering its proximity to the shoreline as size probably behave as immovable sand bars.





On a very large scale the protection of the reef can be seen. In Figure 81 one can see the effects of reefs on a very large scale. Every location which has a large barrier reef in front of the coastline bulges forward and the small gap where there is no reef present, it bulges backward. The shapes of the "bulges" are quite similar to those of a salient, which is the expected shape behind artificial breakwaters.

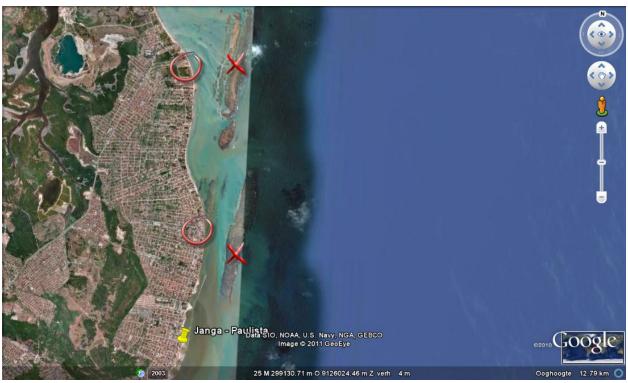


Figure 81: Shaping of the coastline by reefs (notice the bulges behind the large and shallow reefs – This is likely not coincidence)(Image Source: GeoEye, 2011 – Image date: 24-11-09)





Revetments

An interesting aspect about the breakwaters is the need of revetments behind the breakwaters which seems peculiar (revetments O) *Figure 73*. The breakwaters have failed to protect the coast if revetments are required as well at a later date. This indicates that the engineers weren't completely aware of the coastal processes that occur after the construction of a breakwater.

It can also be seen that the problem was never expected to happen because in 2003 and 2007 there were no revetments and no indications that any were under construction, but in 2009 they started appearing behind several breakwaters. This can be examined from Figure 83 and Figure 84. The most logical reason for their construction is fixation of the coastline because it eroded.



Figure 82: Formation of a Tombolo behind breakwater H (2003 left) (2007 right) (Image source: GeoEye, 2011)

What can be seen is that a tombolo was formed on the southern end. Satellite images suggest that this must have occurred between 2003 and 2007 (see Figure 82) and this perhaps influenced the long shore transport of sediment. The decrease in transport rates from the southern probably adversely affected the balance of sediment in the area.

However, in (CPE, 2011) which used DELFT3D it was found that hardly any residual sediment transport is occurring through the system of breakwaters at the coast (see Figure 86 and *Figure 73*). The sediment already present on the shoreline could have also been moved by the diffracted incoming waves to areas behind the breakwaters, basically reorganizing the scarce sediment on the beach.







Figure 83: Janga (2003 left) (2007 right) (No revetments) (GeoEye, 2011) (Image source: GeoEye, 2011)



Figure 84: Janga 2009 (The red dots indicate where revetments were constructed) (Image source: GeoEye, 2011)

There is also a revetment N in place just north of the series of breakwaters at the Janga coastline. There are many large properties here and fixing the coastline is crucial (Figure 85). Furthermore, the tombolos which formed at some of the breakwaters just south of this region may have had an adverse effect on the long shore transport and without this revetment, retraction of the coastline would occur. This theory is enforced by the fact that in 2003 parts of revetment were already constructed. Revetment N had been extended in 2007. This can be observed in satellite imagery. In 2003 satellite images (See





Figure 85) showed approximately 1 km of revetment but in 2007 this revetment was increased to approximately 1, 8 km.

Length of revetments constructed in 2003	993,3 m
Length of revetment constructed in 2007	1785,3 m



Figure 85: Revetments in the North (2003 left - small revetment) (2007 - Enormous revetment) (the extension of the revetment has been marked in red) (Image Source: GeoEye, 2011)

Breakwaters

The wave activity behind the breakwaters is influential to the shape of the shore. Diffraction plays an important role in for the way the shoreline is shaped. The guidelines of (COASTAL DYNAMICS, 2010) can predict the formation of a tombolo or salient behind a breakwater based on the dimensions of the breakwater and its distance to the shore. The predictions according to (COASTAL DYNAMICS, 2010) can be seen in Table 12





Breakwater	L (m)	Lg(m)	D (m)	D/L
Α	640,00	-	150,00	0,23 Tombolo
В	270,00	44,00	130,00	0,48 Tombolo
С	180,00	40,00	192,00	1,07 Salient
D	240,00	36,00	210,00	0,88 Salient
E	310,00	40,00	180,00	0,58 Tombolo
F	240,00	46,00	170,00	0,71 Tombolo
G	204,00	45,00	172,00	0,84 Salient
Н	250,00	48,00	148,00	0,59 Tombolo
I	127,00	49,00	143,00	1,13 Salient

Table 12: Predicted Formation behind a breakwater according to (COASTAI DYNAMICS, 2010)

A tombolo hasn't formed behind breakwater I because this one is still subjected to incident waves from the Atlantic ocean and the wave height behind this one is still relatively high. The waves directly penetrate behind breakwater I due to their incoming angle. The breakwater is unable to shield the area behind it and the formation of a tombolo is difficult. Moreover, it can be seen than the guidelines of coastal dynamics (Table 11) suggest that its dimensions aren't proper for the formation of a tombolo.

The breakwaters F and G have been unable to form a tombolo. The argument for the inability of the tombolo to form is sediment deficiency in the system. According to the design guidelines by (COASTAL DYNAMICS, 2010) a tombolo should form behind breakwater F but this hasn't occurred. This can probably be attributed to lack of residual sediment transport in the area.





Sediment transport

Many of the occurrences seen at the Janga beach can be attributed to the sediment transportation in the area.

Figure 23 in Appendix E: long time scale cariation of the coast displays long time scale variations of the shoreline. The big spike in this figure, the purple line (in the most southern part) corresponds with the first breakwaters in the south of the Janga area.

This spike is larger than the spike to the first breakwaters to the north of Janga, thus indicating that the dominant sediment transport direction is from south to north. There may also be secondary sediment transport from north to south. The secondary sediment transport may not be the dominant but it probably has some influence on the beach morphology.

One can conclude that the dominant sediment transport takes place from south to north. In the (CPE 2010) the beach profiles have been monitored for about one year. From these beach profiles it is possible to calculate the amount of sediments lost or gained. This beach has suffered an averaged erosion of 3 m³/m/month (MAI volume 1 2009).

The sediment transport rates found in (CPE, 2010) using DELFT3D of the area further enforce the hypothesis of almost no sediment coming in. There is almost no long shore transport coming in and hardly anything happens behind the breakwaters anymore. The situation looks balanced.

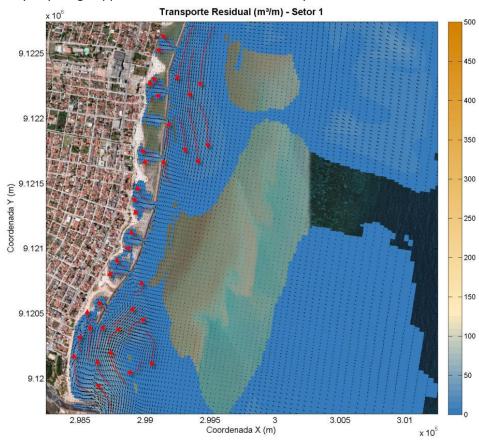


Figure 86: Transport rates sector 1 Janga (CPE, 2011)





In the section on morphology, it was reported that there aren't any major sources of sediment in the area due to absence of major sediment transporting rivers. Despite of little residual sediment transportation activity in the area, the area has clearly changed, which is evident in Figure 83 and Figure 84. The question to be posed is, "how did this change occur?"

Hypothesis 1

The source of the sediment for the formation of the tombolos and salients is peculiar. The author theorizes that the sources of the sediment for the tombolos, almost tombolos and salients have been the beach itself.

The breakwater reorganized the entire beach and tombolos drained sediment from adjancent areas. The revetments have been marked in red and the tombolos and almost tombolos are formed by sediment transported (indicated by the arrows) from these adjacent areas.

The lack of sediment in the area is probably also the contributing factor to the absence of much larger accretion behind the large breakwater A.

There can be no formation of tombolos if there is no sediment. The lack of sediment is probably also a reason why tombolos haven't been fully formed yet.



Figure 87: Reorganization of the shoreline due to breakwaters (Image Source: GeoEye, 2011) (The arrows indicate where sediment was moved from to form the tombolos) (The red dots indicate where revetments were built) (notice that the areas where sediment was taken from to form tombolos and where revetments have been built coincide? This is probably not coincidence)





Hypothesis 2

The tombolos blocked the incoming sediment transport north like a groyne would do and adversely affected the sediment balance upstream. This is probably the most likely explanation but is somewhat unclear due to the lack of residual sediment transport in the area. However, Hypothesis 1 may hold some merit and shouldn't be dismissed yet. Hypothesis 1 does fail to explain the additional erosion that occurred at the location of revetment N (*Figure 73*).

Hypothesis 3

Perhaps both hypothesis 1 and 2 occurred. This is most probable considering hypothesis 2 doesn't completely explain the erosion upstream at revetment N and hypothesis 1 fails to consider transportation of sediment in the area (which is very low). Strictly taken these hypotheses' doesn't conflict with each other and in combination probably explains the area in the most comprehensive manner.

The order in which everything probably occurred is listed below;

- Before the transport rates were blocked by the tombolo behind breakwater H there was no accretion or erosion in the system as a whole because the sediment transport rate was unaffected.
- Secondary current patterns, due to set up differences cause a transportation of sediment into the shadow zone. The wave diffraction also caused the waves to approach the beach at an angle and the beach changed its orientating fitting the incoming wave angle. This caused the formation of tombolos in areas exposed to little wave energy
- Eventually the formation of the tombolos on the coastline blocked the sediment transport from reaching the north.
- Other tombolos in formation such as those behind breakwater B and breakwater E were reduced in their formation speed or may have stopped forming completely
- Due to the reduced transport of sediment northward due to the blockage at breakwater H. Revetment N was also experiencing erosion.
- The municipality witnessed this erosion and responded by building revetments along the shore of the heavily affected areas. The municipality also responded by extending revetment N.





Jetties

The jetty P (Figure 73) appears to be fixating a river mouth in position. Satellite Imagery of the jetty can be seen in

The outer banks appear to have the shape of a small delta. Historical analysis showed almost no change of the shape and size of this mini delta. There does not appear to be any erosional problems here and the jetty was likely constructed to keep the river mouth in place.



Figure 88: Jetty P (2007 left) (2003 right)

14.2.4 Conclusion

The major problem in the area is probably the local construction of the series of breakwaters (*Figure 73*) with the aim to protect the beach against erosion.

The breakwaters reduce the wave height and maintain sediment in its shadow zone. Erosion occurred after a tombolo was formed due to reorganization of sediment deposited on the beach. Behind certain breakwaters which meet the dimension criteria for tomobolos, tombolos were even prevented from forming due to insufficient sediment available in the system.

The erosion lead to rapid responses by building revetments in heavily struck areas (Figure 83 and Figure 84). These revetments are relics of failed engineering experiments with breakwaters by not considering coastal processes and the complexities of it.

The formation of tombolos may have also had a far-field effect and that's the additional erosion caused to the north (revetment N - Figure 73). The revetment was suddenly lengthened by a huge distance in the same timeframe as revetments (revetment O - Figure 73) were constructed.

In closing, the source of all the problems is that the breakwaters were built too near the shore and allowed for the formation of tombolos and overly large salient and no sand was nourished to meet the sediment deficit the system has.





14.3 General solutions

The series of breakwaters at Janga beach were constructed to create a healthy and wider beach according to (CPE, 2010). (See Figure 89) Many aspects of coastal processes were likely overlooked during the design of these breakwaters. Aspects such as diffraction patterns, resulting in very reduced wave energy directly in the shadow of the breakwaters (side of the breakwater which faces the coast), were not considered. Little wave energy behind the breakwaters can result in the formation of tombolos, sub sequentially blocking the sediment transport in the area, resulting in transport imbalances in an area with already poor residual sediment transport.

Furthermore, breakwaters without beach nourishment is only effective in creating and sustaining a relatively wider and healthier beach if there is enough sediment supply in the area. (COASTAL DYNAMICS, 2011)

The Metropolitan coast of Recife by default has little sediment influx from rivers and is exposed to relatively stronger wave action due to its narrow continental shelf. The relatively stronger excitation combined with fine sand of trailing edge coasts leads to susceptibility to erosion (*Appendix A: Morphology*).

Janga beach was quite narrow and probably slightly eroding. The policy makers wanted a wider beach and this led to the construction of a series of breakwaters. (marked in red – see Figure 89)



Figure 89: Overview of Janga (GeoEye, 2011) (red:breakwaters green: distinctive reefs, blue: revetments, purple: Jetty)





A problem that the area faces is lack of sediment. This can only be remedied with beach nourishment. The area has two major fundamental problems:

- 1. The area has a sediment deficit which doesn't allow for the formation of a healthy and wider beach.
- 2. The breakwaters have been improperly designed under the circumstances, because the dimensions allowed for the formation of tombolos which blocked the sediment transport; further amplifying sediment deficit problem. The second problem stems from the first and isn't an issue that stands on its own because, if there was enough sediment being transported in the area, the formation of a tombolo isn't a problem.

The problems can be addressed with a series of well-designed breakwaters combined with beach nourishment

14.3.1 Solutions

There are a plethora of coastal zone management strategies (CZM). Aside from protect, which involves taking measures, accommodation and retreat are also possible. Accommodation involves adaptation of the coastal zone infrastructure and retreat involves moving all assets from the coastal zone into a safer area. It's important to define proper CZM strategy by considering the functions and value of coastal zone (social, economic and culture) in relation to coastal protection. (COASTAL DYNAMICS, 2011) For the metropolitan area of Recife, accommodation and retreatment are probably completely out of reach because the strategies that have been explored in previous reports such (MAI, 2009) and (CPE, 2010) considered neither retreatment nor accommodation. (MAI, 2009) and (CPE, 2010) were supported by the government. It can be concluded that local decision makers will support neither retreatment nor accommodation. Therefore the strategies retreatment and accommodation are dismissed without prejudice.

There are two basic approaches possible. One approach is solving the cause of the erosion problem but this isn't an option and the second approach is mitigation of the negative effects. Mitigation can be performed with soft measures, which involves beach and foreshore nourishment. The hard measures involve coastal infrastructure. In the past, a significant amount of hard measures were taken at Janga beach. It started with the construction of breakwaters which failed due to not considering coastal processes. The adverse effects caused by the breakwaters were mitigated by constructing revetments. Ironically, structural erosion cannot be solved with revetments but merely delays the inevitable.





The Janga region has breakwaters in place approximately 150 meters from shore which makes direct nourishment on the beach only possible if pipelines are used. The area also seems rather shallow on satellite images. (See Figure 90) Shore face nourishment seems to be the only option, given the situation.



Figure 90: Janga Beach - Area seems too shallow for the draught of the hopper - Shoreface nourishment seems like the only alternative (image: GeoEye, 2011)

The only feasible option is placing the nourishment on the shore face. Larger volumes of sand are required for shore face nourishment because only 30 % to 50 % (COASTAL DYNAMICS, 2010) will reach the beach zone. The costs per m3 for shore face nourishment are 50% to 70% less (COASTAL DYNAMICS, 2010) which does make it an attractive measure due to cost balance.

14.3.2 Alternatives

Two alternatives are considered to address the problems of Janga Beach.

1. Nourish the area

This solution will stimulate the growth of a wider beach. The tombolos which were in stages of formation would probably completely form. This measure doesn't stop the erosional problems experienced at revetment N (see Figure 89) because the long shore transport will be permanently and more rigorously obstructed.

The allowance for sediment bypass will diminish the erosional problems faced at the location of revetment N. Revetment N was also extended between 2007 and 2009. This extension can also possibly be removed and the area can be a sandy and healthy beach again, enjoying mostly the protection from





the offshore submerged reefs. This solution exists of both hard and soft measures. The hard measures were already taken with the construction of a series of breakwaters (see Figure 89) and the soft measures are added to the equation. The advantage of this solution is absence of major construction works in the area.

2. Adjust the dimensions of the breakwaters and nourish the area.

The breakwaters had the right dimensions for the formation of tombolos, which is undesired because it obstructs the long shore sediment transport. Changing of the dimensions of the breakwaters to more efficient measurements can allow for a healthier and wider beach. However, the lack of sediment in the area will never allow for a wide beach to form behind the breakwaters, therefore some nourishment is also necessary. The beach will be nourished behind the breakwaters and also upstream of the series of breakwaters at revetment N.





Alternative 1

The hypothesis is that the entire source of the problem at Janga beach is the lack of sediment in the area which is enforced by findings in historical satellite images.. Lack of sediment in the area was further amplified by the formation of a tombolo behind breakwater H (see Figure 89).

Hard measures can further improve the situation; but it's very likely that they aren't required because the situation was fine in 2003 and 2007. In 2009 the erosion problems heavily and suddenly struck. Somewhere in 2007-2008 a permanent tombolo was formed behind breakwater H. Correlation doesn't necessarily mean causation but one cannot help but think that the formation of this tombolo played a vital role in the cause of increased downstream erosion at the location where revetment N was extended.

Design guidelines for breakwaters can be found in *Appendix G: Design Guidelines* These guidelines have been applied to the existing breakwaters on the Janga beach and their responses behind the structure has been reported in Table 13. (For the dimensions of the breakwaters and their distance to the shore see *Appendix N: Janga*). The predicted formations behind that breakwater may differ from those found in satellite images because of the sediment deficit or failure of the guidelines to predict the area. Some responses which should have happened but never did due to sediment shortage. A major tombolo never formed behind breakwater A (see *Figure 73*).

Breakwater	L (m)	Lg(m)	D (m)	D/L	L/D	Is	Lgap/L
Α	640	-	150	0.23	4,27	0.97	NA
				Tombolo		Permanent Tombolo	
В	270	44	130	0.48	2,08	2.38	0.16
				Tombolo		Periodic Tombolo	
С	180	40	192	1.07	0,94	3.80	0.22
				Salient		Not full developed Salient	
D	240	36	210	0.88	1,14	3.50	0.15
				Salient		Not full developed salient	
E	310	40	180	0.58	1,72	2.76	0.13
				Tombolo		Fully Developed salient	
F	240	46	170	0.71	1,41	3.13	0.19
				Tombolo		Fully developed salient	
G	204	45	172	0.84	1,19	3.43	0.22
				Salient		Fully developed saleitn	
Н	250	48	148	0.59	1,69	2.79	0.19
				Tombolo		Fully developed salient	
I	127	49	143	1.13	0,89	3.88	0.39
				Salient		Not fully developed salient	

Table 13: Responses according to the various guidelines of breakwater design | D is the distance to the shoreline | L is the length of the breakwater | Lg is the distance between gaps of two aligned breakwaters | For details see Appendix G: Design Guidelines

InTable 13, there appears to be some differences in the prediction on what should form behind the breakwaters. (Ahrens, 1990) seems to disagree with the formation of a tombolo at location H, which is the location of the largest tombolo that was formed in the system.

Another difference is that prediction with the method of (COASTAL DYNAMICS, 2011) predicts the formation of a tombolo behind F but no such prediction can be deduced from (Ahrens, 1990). There also doesn't seem to be any indication that a tombolo should form judging from the diffraction patterns





found in *Appendix N: Janga*. However, it's quite close to the limit which is 0, 8 (see design guidelines above) from which salients start to form.



Figure 91: Prediction of what the shoreline should look like if there were no sediment deficit - The size of the Tombolo behind breakwater A is debatable but It will definitely be large (image: GeoEye, 2011)

If one addresses the problem of sediment deficit by nourishing the area, a healthy and wider beach can be created and the problems that suddenly occurred between 2007 and 2009 at revetment N can be considered solved with nourishment.

Beach Nourishment

The only measure which will be taken in solution one is beach nourishment. Nourishment will take place in three stages

- Deposit the amount of beach nourishment that the equilibrium profile requires on the beach.
 This must be deposited behind the breakwaters, which will naturally shape the salient and tombolos.
- 2. The beach at revetment N suffered significant erosion since the tombolo was formed behind breakwater H, between 2007 and 2009. This stretch of beach must be restored. Enough sand must be deposited in the area where revetment N was extended
- 3. The beach must be nourished periodically depending on how much sediment leaves and enters the system.





In (CPE, 2010) Volume 8 – Alternative 2 - a similar solution was proposed, however, (CPE, 2010) adjusted the dimensions of the breakwaters in combination with beach nourishment. The author doesn't believe that adjustment of the dimensions of totally essential because the core of the problem is really a sediment deficit which beach nourishment can solve. The amount of beach nourishment required will probably also be in the same order of magnitude. The amount of sand required has been summarized in Table 14.

It was found in (CPE, 2010) that the amount of volume needed for the area behind the breakwaters is 0, 9 Mm m3. The solutions differ marginally and the area will probably require a volume of sand in the same order of magnitude.

The area upstream of the breakwaters according to (CPE, 2010), in the region of revetment N (see figure 12), will require 0, 66 Mm3 of sand. The measures which the author proposes and which (CPE, 2010) proposes for this area are identical and it can be concluded that the amount of sediment required will be similar.

The amount of structural erosion that will occur yearly is difficult to predict and should be determined after the measures have been implemented. The measures themselves will affect the amount of structural erosion therefore; the erosion occurring now might not be the erosion that will occur post-implementation of these measures. Approximately 40% of sediment placed on the beach will be lost during the process of natural spreading of the sand through natural forces

Required volume of sand behind breakwaters	1.5 M m3
Required volume of sand at the area of revetment N	1.1M m3

Table 14: Required volumes for beach nourishment - Take into account that approximately 40% of the volume will be lost from the system due to spreading of the sand post-placement. 40% is an overestimation. Appendix N: Janga.





Alternative 2

In this solution the dimensions of the structures will be adjusted. The smaller breakwaters will still allow for the formation of tombolos and salient. Reduction of the length of breakwater A (see Figure 89) into several smaller units will allow for the formation of several salients behind this breakwater and this will improve the overall quality of the beach.

Breakwaters B, E and H will maintain the dimensions for the formation of tombolos and the rest will be given dimensions for the formation of salients. The tombolos can stay because they allow for a very wide beach in some areas. This gives the beach more recreational value (for example, it's a good spot to play beach volleyball on). The overall more consistent pattern will form a healthier beach environment. Adjustment of the breakwaters will occur with the three prior mentioned design guidelines. Breakwaters will be reduced in length and attention must be paid to the size of the gap compared to the size of the breakwater, because erosion can occur opposite to the gaps (on the shore), which is undesired. The salients and tombolos behind the breakwaters will be designed by considering the design guidelines of (COASTAL DYNAMICS, 2010) because these guidelines have been quite successful for the area. Some breakwaters are unnecessarily large which adversely affects the view on the ocean. Reduction of

Some breakwaters are unnecessarily large which adversely affects the view on the ocean. Reduction of the overly large breakwaters will improve the view in the area dramatically. Furthermore circulation of water in the area will also improve, though these were never really core problems of the area, they are desired for a healthy and lively beach environment.

В	R(m)	Lg(m)	Y(m)	D/L	Ls/Y	Is	Lgap/L
A1	130	-	150	1.15	0.86	3.91	-
				Salient		Poorly developed salient	
A2	130	125	150	1.15	0.86	3.91	0.96
				Salient		Poorly developed salient	
А3	130	125	150	1.15	0.86	3.91	0.96
				Salient		Poorly developed salient	
В	190	124	130	0.68	1.46	3.06	0.65
				Tombolo		Well developed salient	
С	120	116	192	1.6	0.62	4.32	0.96
				Salient		Poorly developed salient	
D	140	120	210	1.5	0.66	4.24	0.85
				Salient		Poorly developed salient	
E	240	180	180	0.75	1.33	3.23	0.75
				Tombolo		Well developed salient	
F	150	136	170	1.13	0.88	3.88	0.90
				Salient		Poorly developed salient	
G	134	115	172	1.28	0.78	4.05	0.85
				Salient		Poorly developed salient	
Н	200	98	148	0.74	1.35	3.20	0.49
				Tombolo		Well developed salient	
I	60	49	143	2.38	0.41	4.70	0.81
				No formation		No sinosity	

Table 15: Responses according to the various guidelines of breakwater design after making the breakwaters smaller and the gaps larger. | D is the distance to the shoreline | L is the length of the breakwater | Lg is the distance between gaps of two aligned breakwaters | For details see Appendix G: Design Guidelines

The breakwaters have been adjusted with different dimensions in Table 15. According to the guidelines of (COASTAL DYNAMICS, 2011), a tombolo will form behind breakwaters B, E and H. However, (Ahrens,





1990) predicts no such phenomenon. Behind the areas where a tombolo is expected to form according to (COASTAL DYNAMICS, 2010) a fully developed salient is expected to form according to (Ahrens, 1990). (Ahrens, 1990) seems quite conservative in its predictions of tombolo formation and probably fails to predict the area with sufficient accuracy or it could be overly conservative in general. In any case, the guidelines of (COASTAL DYNAMICS, 2010) seem to fit the area.

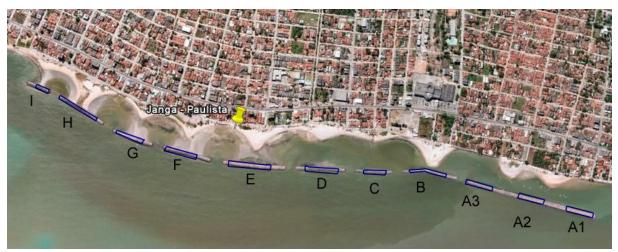


Figure 92: Breakwaters with adjusted lengths and gap sizes

Table 15 displays the dimensions of the breakwaters that have been adjusted. The new dimensions of the breakwaters are marked in blue. The exact dimensions are reported in table 2. Adjusting the breakwaters to these new dimensions will require significant amounts of rock removal from the existing structures. The benefits will be marginal because the core problem was never the dimensions of the breakwater but the lack of sediment transport in the area. However, these new dimensions will improve the improved circulation and the view on the ocean. If the breakwaters were designed with these dimensions initially they would have been cheaper and better.

The gaps have also been chosen as large as possible while keeping an eye on the size criterion for erosion opposite the gaps. The dimensions of the breakwaters B, E and H have been chosen such that a tombolo forms behind them according to (COASTAL DYNAMICS, 2010). The tombolos can stay because they allow for a very wide beach in some areas.

The remainder of the breakwaters, with the exception of breakwater I, has been chosen to have the proper dimensions which allow the formation of salients according to the design guidelines. Breakwater I will not allow for the formation of anything due to the heavy wave energy concentrating in this area because it's directly exposed due to the incoming wave angle. Choosing a large dimension here is not necessary because its primary function is shielding the southern side of breakwater H.





Beach nourishment will be essential, despite these adjustments because tombolos will still obstruct the sediment transport. Without nourishment the area at revetment N (see *Figure 73*) will still experience erosion. The areas behind the breakwaters further north will also experience erosion due to fully formed tombolos behind breakwaters B, E and H. (See Figure 93) It can be seen that reducing breakwater A in several segments will provide more useful beach property. The quality of the experience will increase due to the improvement of the view on the water behind breakwater A

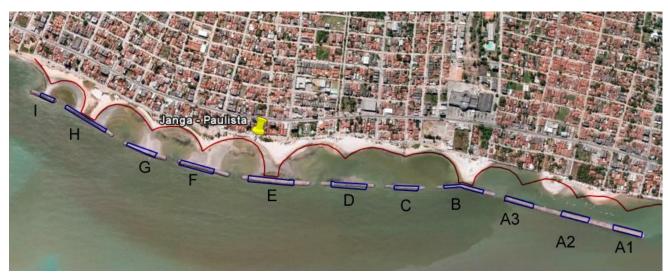


Figure 93: Expected Pattern behind breakwaters post-modification according to guidelines from (COASTAL Dynamics, 2010)

Beach Nourishment

Nourishment will take place in three stages

- 1. Deposit the amount of beach nourishment that the equilibrium profile requires on the beach. This must be deposited behind the breakwaters, which will naturally shape the salient and tombolos.
- 2. The beach at revetment N suffered significant erosion since the tombolo was formed behind breakwater H, between 2007 and 2009. This stretch of beach must be restored. Enough sand must be deposited in the area where revetment N was extended
- 3. The beach must be nourished periodically depending on how much sand leaves and enters the system.

In (CPE, 2010) a similar solution was suggested, (Alternative 2 in Volume 8). The solutions are exactly the same aside from the dimensions of the breakwaters. However, in order of magnitude, the dimensions of the breakwaters are also similar. The amount of sand required has been summarized in Table 16. It was found that the amount of volume needed for the area behind the breakwaters is 0,9 Mm3. The solutions differ marginally and the area will probably require a volume of sand in the same order of magnitude.





The area upstream of the breakwaters, in the region of revetment N (see Figure 89) will require 0,66 Mm3 of sand. The measures in this area are similar and will probably require close to similar amount of sand.

The amount of structural erosion that will occur yearly is difficult to predict and should be determined after the measures have been implemented. The measures themselves will affect the amount of structural erosion therefore; the erosion occurring now might not be the erosion that will occur post-implementation of these measures.

Required	Required volume of sand behind breakwaters							1.5 Mm3
Required	Required volume of sand at the area					area	of	1.1 Mm3
revetme	revetment N							

Table 16: Required volumes for beach nourishment - Take into account that approximately 40% of the volume will be lost from the system due to spreading of the sand post-placement. 40% is an overestimation. Appendix N: Janga





PART B:

Boa Viagem





15. Introduction

All the areas considered in the project have interesting characteristics. Due to the time span of the project only one area can be examined in more detail. Boa Viagem is interesting because it has healthy beaches as well as areas which have shown erosion. Boa Viagem does not have many structures as some of the other areas and is relatively healthy. If wrongly implemented structures where to be built in Boa Viagem they would have a large impact on the area as it is relatively healthy (there are some parts that erode). A solution of Boa Viagem is less clear and has a high probability of causing larger problems, as there are healthy beaches present in the area. Other areas already have wrongly implemented structures, a solution in these areas is clearer and have a smaller probability of causing larger problems, as there are virtually no healthy beaches present. The Boa Viagem area has a lot to lose and thus should be assessed well.





16. Cost-benefit analysis

16.1 Introduction

Cost-benefit analysis seeks to value the expected impacts of an alternative in monetary terms. This analysis is based upon the economic principle of willingness-to-pay or to accept. The valuations are based on the willingness to pay of the potential gainers for the benefits they will receive as a result of the chosen alternative and the willingness of potential losers to accept compensation for the losses they will incur. Basically, a project is desired when the benefits (i.e. value) of the project exceed the losses. Ultimately, the choice between the alternatives in Boa Viagem will be based upon the value/costs-ratio. This ratio ensures that the best value is created for that specific amount of costs, and thus chooses the alternative that turns costs into value most efficiently.

The benefit will be determined using a multi criteria analysis (MCA), which is explained below. After the MCA, the costs for the different alternatives will be estimated based upon key figures. For the costs, the Netto Product Value (NPV) analysis will be used. This method, explained later, provides a rough estimation of the costs of the alternatives relative to one another.

With both the values and cost per alternative, a value/cost-ratio can be calculated, which will form the end of the cost-benefit analysis.





17. Multi Criteria Analysis

17.1 Introduction

A *Multi Criteria Analysis* (MCA) will be used to determine the value of the different alternatives. An MCA is a scientific method to evaluate the value of different alternatives in a rational and objective way. The objectives of an MCA are organizing, increasing the transparency of decision making and supporting decision makers in their choice.

The analysis is based upon different criteria, which are determined based upon the stakeholders analysis and value-variables. A detailed explanation of the chosen criteria is given in *Appendix O: MCA*. These criteria have unequal importance and thus have a different influence on the total project. This factor is called the weight factor and is determined with a *Weight Matrix*. This has been determined as follows (example): the criteria *visual obstruction* of an alternative is not really important for the builders nor for the government, but it is really important to the people who use the beach and live near it. So, depending on their potential influence on the entire project, one can judge whether this criteria is being this is important or not. Like this, all criteria are assessed, of which the results can be found *Appendix O: MCA*.

17.2 MCA

Based upon the criteria and their weight factor, the created value for the different alternatives will now be determined. This will be done for each alternative with a grade, ranging from 1 to 5, where 1 is worst and 5 is best. The judgments done here are largely based on the objective that is described in the problem assessment and the wishes of the stakeholders.

The different alternatives with their main characteristics are:

Alternative 0: Making no changes to the current situation

Alternative 1: Nourishment at E (see Figure 32)

Alternative 2: Nourishment at revetment E + breakwater at revetment E (see Figure 35)

It should be noted again that Alternative 0 can't possibly be seen as a possible option. The alternative doesn't solve any of the problems and this choice poses a threat for the problems that can occur. For this alternative, the additional costs of mitigation and the huge risk management are not taken into direct account if only a cost-benefit analysis is performed. Like stated, the alternative is only considered as a reference to make judgments about Alternative 1 & 2.

In Figure 94 the results of the MCA can be seen.





	Values			Weight factor	Scaled values		
Criterion	Alternative 0	Alternative 1	Alternative 2		Alternative 0	Alternative 1	Alternative 2
Construction time	5	2	1	6%	0,32	0,13	0,06
Constructability	5	4	3	8%	0,38	0,31	0,23
Defense against storms and tides	2	3	4	14%	0,28	0,42	0,56
Defense against structural erosion	1	3	4	15%	0,15	0,46	0,62
Beach quality	1	3	3	13%	0,13	0,38	0,38
Durability	1	3	4	9%	0,09	0,27	0,36
Sustainability	4	4	4	8%	0,31	0,31	0,31
Esthetics	4	4	3	1%	0,05	0,05	0,04
Visual obstruction	5	5	2	4%	0,19	0,19	0,08
Physical obstruction	5	5	3	1%	0,06	0,06	0,04
Recreational value	1	3	3	9%	0,09	0,27	0,27
Ecology	2	3	2	3%	0,05	0,08	0,05
Safety feeling	2	3	4	9%	0,18	0,27	0,36
Total scaled value	38	45	40		2,29	3,21	3,36

Figure 94: Multi Criteria Analysis

On the left of the MCA can see the values that are appointed to each alternative for the specific criteria. On the right the values are multiplied by the scale factor determined from the Weight Matrix. These scaled values are what the alternatives are really worth, scaled by the Weight factor. In the end, all values are summed up. The effect of the Weight Matrix becomes immediately visible. If looked upon the normal values, it seems that Alternative 1 creates the most value. However, when scaled, it's clear that Alternative 2 creates more value.

The values are defined relative to each other, one gaining far more points if that alternative does so much better than the other one.

From Figure 94 one can conclude that Alternative 2, nourishment near revetment E and the construction of a breakwater offshore of E, has the most value. This could be expected, since this solution offers the most extensive defense, using a combination of hard and soft measurements to solve the problems. However, the real question is whether this alternative created so much more value to compensate for the extra amount of costs (analyzed after this).

As expected, Alternative 0 i.e. doing nothing, has the least value. The problems remain the same and this alternative therefore scores badly for the important criteria such as defense and beach quality.





18. Net Present Value analysis (NPV)

18.1 Introduction

The Net Present Value analysis (NPV) is used to compare the different alternatives based upon costs. In finance, a NPV is used to is defined as the sum of the present values of the individual cash flows of the same entity. In terms of coastal engineering projects it should be noted that one cannot make an in- and outflow model like many other civil engineering projects. This is mainly because there are no clear revenues that can be expressed in terms of money. Coastal engineering projects are mainly projects that create public good, which are projects that are not decided by the individual consumer, but the society as a whole and which is financed by taxation.

The costs of the different alternatives will be estimated here based upon key figures. Note that the estimations are relatively rough, but can be helpful for a quick comparable global overview of the cost for each alternative.

In Appendix Q: Exped. Model Alternatives. the complete NPV-analysis can be found. Here are also all terms explained like time-preference value, the pricing date and the time horizon will be explained. The costs are plotted for variable time-preference rates, to see the influence of a changing economy. However, the global value of 2,5% is chosen to base the selection on. The project duration is chosen 50 years and the start-date is chosen to be 1 January 2015. For more information and elaboration of these values, see Appendix Q.





18.2 Costs alternatives

18.2.1 Costs Alternative 0:

Alternative 0 is based upon leaving the situation as it is now. The current situation will create no extra value and will also cost nothing, however like explained in the Introduction of the MCA, it will not be considered further.

18.2.2 Costs Alternative 1:

- Initial costs

- Recurrent costs

R\$ 32.500.000

R\$ 18.000.000 R\$ 14.500.000

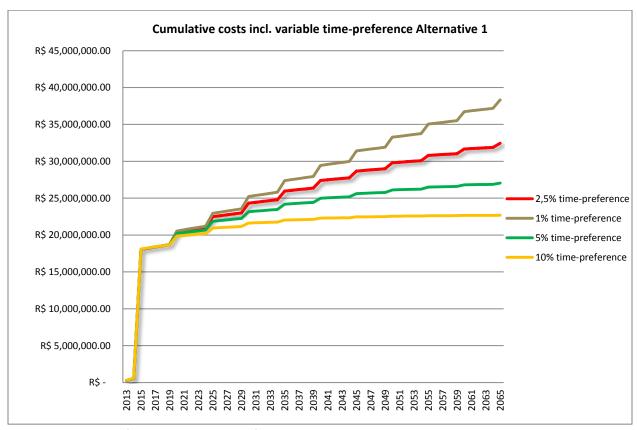


Figure 95: Graph of costs development for Alternative 1

What is interesting to see is the initial bump representing the initial costs. Other than that the recurrent nourishments are visible in the form of small bumps in the graph along time.





18.2.3 Costs Alternative 2

Initial costs

- Recurrent costs

R\$ 56.500.000 *R\$ 44.500.000*

R\$ 12.500.000

For Alternative 2 the recurrent costs are the largest part of the costs. This somewhat expectable, due to the high costs for design and maintenance because more structures need to be designed. In Figure 96 the development of the costs has been given over time.

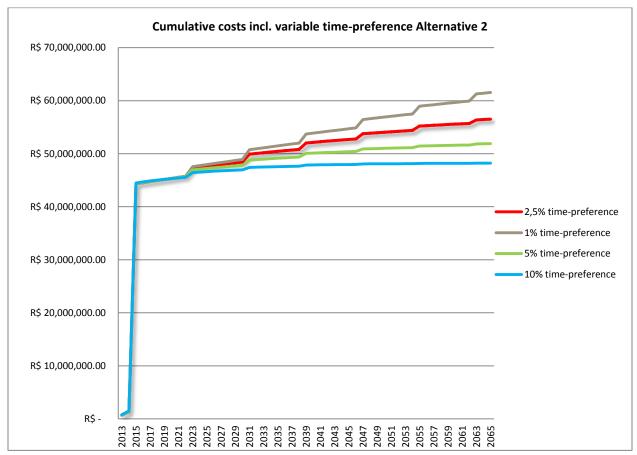


Figure 96 Graph of costs development for Alternative 2

What is interesting to see is the initial bump representing the initial costs. Other than that the recurrent nourishments are visible in the form of small bumps in the graph along time.





18.2.4 Summary

In Table 17 the costs for the different alternatives are put together.

alternative	Costs
Alternative 1	R\$ 32.500.000
Alternative 2	R\$ 56.500.000

Table 17 Costs incl. time-preference for the alternatives for the given time horizon

Clearly is visible that Alternative 0 is the most economic option, where nothing is done. The most expensive one is Alternative 2.

The high costs of Alternative 2 can be appointed mainly to the high initial costs. One would expect that even though this alternative has high initial costs, this would even out and even be more economical in comparison to Alternative 1. Alternative 1 makes use of more recurrent nourishments, costing a lot of money especially given the total of the project. However, one factor that is not regarded in this way of thinking is the influence of time-preference rate on the project.

In comparison with the costs of Alternative 1 can be said that the costs line of Alternative 1 is much steeper. This means that at some point in time, Alternative 2 will become a cheaper solution.

An extra analysis will be made to calculate to answer the following question that might arise based upon the result: Is there a time in the future where ultimately Alternative 2 will be the more economical solution?

For this analysis, we extend the time duration of the project to a much longer period of 148 years (till 2160) to see the changes. The changes in costs are portrayed in Figure 97. One would expect that in time Alternative 2 would become more economic; however this is not visible in the graphs. This can be explained by the time-preference rate. It dampens out the jumps (in the graphs) caused by the recurrent nourishments. The longer the time in the future, the more this dampening is visible. This is why Alternative 1, even for very long periods, will be the more economical solution.





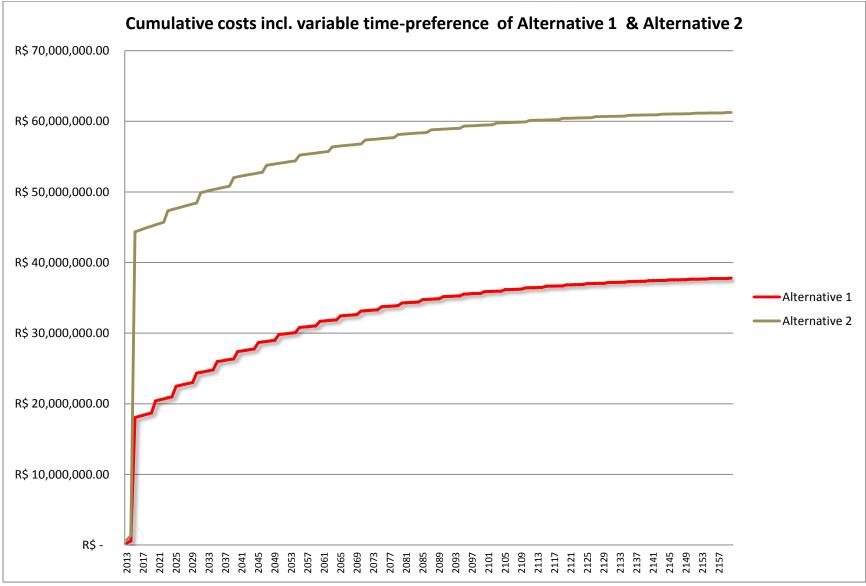


Figure 97 Costs graph with longer project duration





19. Selection

In previous chapters both the values and costs of each alternative have been determined. When assessing projects it is not only about costs, it is also about the total benefits of a project. In this paper the Value/Cost-ratio will be used (Table 18) to determine the best alternative. The alternative with the highest value/cost ratio will be most preferred, since this alternative utilizes the costs most efficiently into value.

Note that the Value/Cost ratio have been multiplied by 1E10 due to relative small quantities.

Alternative	Value	Cost [R\$]	Value/Cost Ratio [value point/\$R]
1	3.21	R\$ 32.500.000	987
2	3.36	R\$ 56.500.000	595

Table 18: Value/Cost ratio for the different alternatives

According the value-cost ratio, Alternative 1 is most preferred and this alternative will be further elaborated in more detail.





20. Beach Nourishment

20.1 Introduction

The area will be nourished can be seen in Figure 98. The amount of sand that will be required has already been determined in (CPE, 2011). In this section the focus will be on the process of dredging the material required for the beach nourishment. There are several ways to dredge, so a selection will need to be made on which method and sub sequentially which equipment will be used. Some assumptions must also be made about the project parameters because important critical data isn't available. In the actual projects these parameters are subject to change.

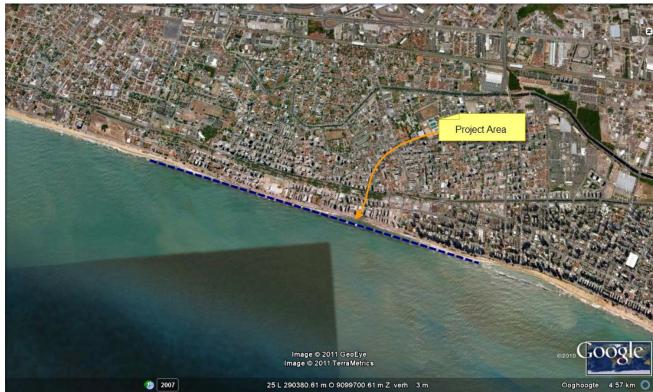


Figure 98: Location of the nourishment project on the Boa Viagem beach (CPE, 2011)

The stretch of beach that will be nourished in the project area is approximately 2,78 km long and the expected gain of beach is around 25 to 40 m according to (CPE, 2011).

Project area	
Length of the project area	2,78 km
Expected increase in width post-	25-40 m
nourishment	





20.2 Engineering brief, assumptions and desires

20.2.1 Engineering brief

- 1. The dredging must occur with maritime vessels.
- 2. The volume of sand that will be deposited must be 1, 15 million cubic meters.
- 3. The sediment must be of the same grading of that of the native beach.
- 4. The sand should be spread equally throughout the nourished section
- 5. The increase in shoreline must be at least 25 meters.
- 6. The increase in shoreline must be maintained no less than the 25 m mark
- 7. Replenishment should occur every 5 years.
- 8. The public must be well informed on what they should expect from the nourishment project

20.2.2 Assumptions

- 1. The borrow pit is 10 km from the shoreline.
- 2. The depth of the borrow pit is 30 m
- 3. The borrow pit contains sand of equivalent grading to that of the native beach profile.
- 4. The minimum distance that the vessels need to maintain from the coast is 2,5 km due to depth restrictions and presence of the reef.

20.2.3 Desires

- 1. The operations will require closing the beach in certain sections. The operations should occur as quickly as possible.
- 2. As little annoyance and obstruction must be presented to pedestrians and other beach visitors.





20.3 Beach nourishment requirements

The beach nourishment process requires the following items:

- 1. A borrow pit with sand equal to that of the native sand on the beach
- 2. A methodology to nourish the profile
- 3. Dredging vessels
- 4. Delivery system
- 5. Bulldozer and other heavy land based equipment to spread out deposited sand on the beach
- 6. Surveying equipment to monitor the progress of the nourishment

20.3.1 Borrow pit

The construction of a beach nourishment project inherently requires the search for sources of sediment that meet the criteria for the location that will be nourished. The farmed sediment is preferably identical to the sediment of the to-be nourished beach. The search for viable sediment should occur early in the project planning because it eventually will control the cost and viability of the project. Over the past decades sand has been primarily farmed from the continental shelf in case offshore sources were used. Offshore borrow sites have a tendency to fill in with fine-grained material that is ill-suited for beach fill. It is therefore very unlikely that deep water borrow sites will yield the right quality sand. Tidal inlets, specifically those used for navigation are generally very good sources of sediment as well. Another interesting source of sediment is the littoral drift. Accretional downdrift beaches have served as sources of sand for beach nourishment projects through "backpassing". An analogous method to "backpassing" is bypassing. Bypassing of sand blocked by construction of jetties or breakwaters is a special case of using a beach subjected to accretion as a sediment source. Aside from the before mentioned "offshore" sources there are also various inland sources.

The size of the sediment plays a crucial role. Finer sediment tend to form more gentle slopes and some researchers have assumed that finer sediment leads to more erosion, however, it is not clearly known whether finer sediment merely appear to have more loss due to their more gentle slope or if more sediment is actually lost in the littoral drift. The metropolitan area of Recife is currently trying to locate a sand source. Word of mouth and hearsay have implicated several locations of unknown sediment size. This sediment should be larger or at least equally large to the sediment on the Boa Viagem beach.

Currently, nothing is known about the borrow pit and its dimensions. It is <u>assumed</u> that the pit will be quite distant offshore and therefore relatively deep. The assumed depth is 35-40 m and the average distance to the project area is approximately 10 km. According to (beach nourishment and protection, 1995) the economical sailing distance for US vessels is around 10 km for dredging projects. See Table 19 for characteristics borrow pit.

Characteristics borrow pit	
Depth borrow pit	35-40 m
Distance to project area	Approximately 10 km

Table 19: The borrow pit data





20.3.2 The Nourishment methodology

Initial nourishment

The area which will require beach nourishment stretches 2,78 km long. The objective of the project is to create a wider beach and sustain it. The amount of sand which will be required was already calculated in (CPE, 2011). The total amount of sand which will be required is reported in Table 20. (CPE, 2011) determined a construction profile from beach profile measurements (See *Figure* 99). Immaculate attention to placement on the beach isn't necessary because the incoming waves would reshape the nourishment material.

Nourishment required for beach nourishment	693118 m3
Nourishment required for beach nourishment	1155196 m3
while taking 40 per cent loss into account	

Table 20: Sediment required for beach nourishment

Replenishment

Post-widening of the beach, erosion will take its toll and the beach will start to retract and replenishment will be required. For replenishment the Netherlands Method (or *Dutch Method*) will be used. In (Verhagen, 1990) a nourishment design method was described. The Netherlands Method, employed in the Netherlands, which, rather than relying on the results of numerical models places substantial reliance on historical data and makes a few design assumptions.

The Netherlands method

- 1. Perform coastal measurements (for at least 10 years)
- 2. Calculate the loss of sand in cubic meters per year per coastal sections
- 3. Add 40 per cent to account for losses
- 4. Multiply this quantity with a convenient lifetime
- 5. Put this quantity somewhere on the beach between the low-water minus-1-m and the dune foot.

Verhagen addresses difficulties with this method, including approaches to use if detailed monitoring results aren't available and the implicit assumption is that the beach will erode at the similar rate as before the nourishment (Beach Nourishment and Protection, 1995). The explanation for the 40 per cent volume is the recognition of end losses and the loss of finer particles during placement operations on the beach. Verhagen proposes that the subsequent "renourishment" has to be derived from the monitoring results of the earlier nourishments. Similar to the initial nourishment, immaculate attention to placement on the beach isn't necessary because the incoming waves would reshape the nourishment material. Verhagen indicates that sediment has to be placed in the area where it is least costly. The only restriction is that the sediment has to be placed within the near shore zone of active wave breaking.





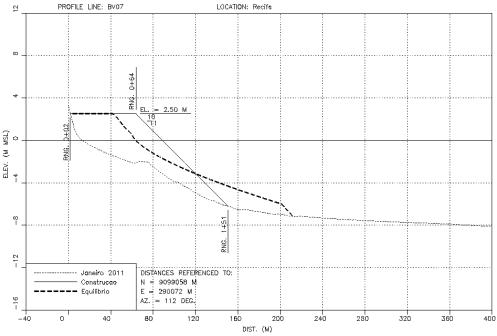


Figure 99: Beach Nourishment (CPE, 2011)

Step 1: Making measurements

The measurements of the coastline have already been done and can be found in (MAI, 2009).

Step 2: Netherlands method: losses in cubic meter per coastal section

Measurements have shown that the area under consideration for beach nourishment is accreting (MAI 2009 & CPE vol.2 2011). This would mean that in time a beach will form at the area. However another source which used numerical models to predict erosion/accretion showed that the area will erode (CPE 2011 volume 6) at the waterline but the sand is deposited right behind it, however, the total profile volume remains unchanged. The beach nourishment can be used to speed up this process and assist the formation of a wider beach. The rate of erosion is 29,16 m3/year/m and $405,000 \frac{m^3}{5 \ years}$ will be required for each iteration of nourishment. More information can be found in *Appendix J: Boa Viagem*.

Step 5: Placement on the beach

According to (Verhagen, 1992) there is not much preference where the sand is deposited on the stretch of beach. Placement outside the breaker zone can be attractive and very economical. The first minor storm will rearrange the sand fitting the wave climate. The placement by incoming waves will probably be superior to bulldozers and scrapers (Verhagen, 1992). In the Netherlands, years of experience has indicated that profile nourishment doesn't significantly affect the erosion rate. The discharge pipes are placed onshore just out of reach from the waves and the slope is formed by freely flowing sand. There is no need for support structures such as bunds.





20.3.3 Dredging vessels

There are two major pieces of equipment to choose from. A trailing suction hopper dredge or a cutter suction dredge. The decision to utilize which equipment is dependent on the available equipment in the area. It is known that Van Oord with their -suction dredger Hercules and trailing-hopper-suction dredge HAM 309 can easily operate in the area.

The physical dimensions of the borrow pit also play a key role. The equipment must be able to operate close enough to the beach given the draft constraints and the power of the suction dredge pump must be enough to transport the material to the beach. Another key consideration is whether or not the dredge can excavate the depths required by the borrow pit dimensions.

A <u>Trailing-suction-hopper</u> dredge (TSHD) will be used because of its wide array of applicability and the possibility to easily operate at a depth of approximately 30 meters which is the <u>assumption</u> that was made earlier for the depth of the borrow pit. For details see *Appendix J: Boa Viagem*.

20.3.4 Duration

When all aspects are combined, including setting up the equipment, removing the equipment, dredging the sand, sailing back and forth between the pump out station and borrow pit. The project is estimated to last approximately 2 months. For details see *Appendix J: Boa Viagem*.

20.3.5 Delivery system

Depth waters and navigational options





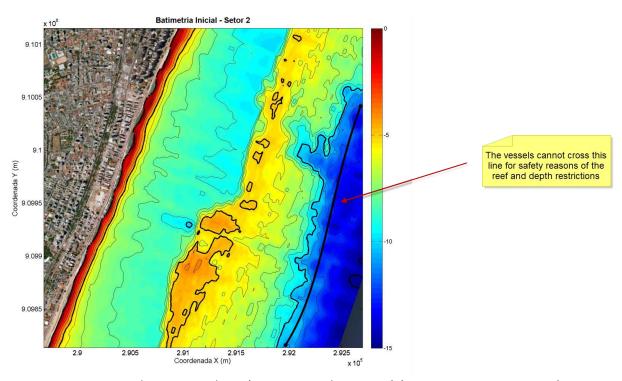


Figure 100: Minimum distance to shore (approximately 2500 m) (Image source: CPE, 2011)

The hopper vessel can move anywhere beyond the black line in Figure 100. The distance is approximately 2500 m. At least 2500 m of pipeline to reach the coastline will be required. The reefs present a major obstruction to regular dredging operations (see Figure 101). Any possibility of using a rainbow method to get the sand to shore with a hopper vessel is defaulted considering these conditions. However it is possible that the reef can be crossed with smaller vessels and ships can get relatively close to shore but it is <u>assumed</u> that this is impossible, since this seems unpractical considering the amount of nourishment needed.

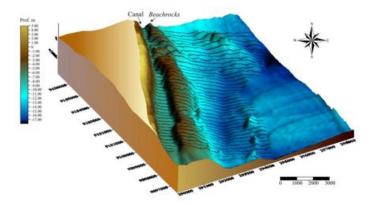


Figure 101: Terrain model of the coast Recife (Neves, 2010)

Pipe System offshore





Nourishment will be done with a piping system. Like mentioned before, it is assumed that 10 km offshore, a borrow pit is available.

For transport, several options are available: one could create a pipeline that reaches the pit, which would then be at the least 10 km long. Another option is create a pumping station nearer to the coast and reclaim through a piping system. For practical reasons a pumping station will be used, located approximately 2.5 km offshore. For more information about the pumping station see *Appendix J: Boa Viagem* This is the closest location to allow for enough draught for a hopper (Figure 102).(*Appendix D: Bathymetry*).

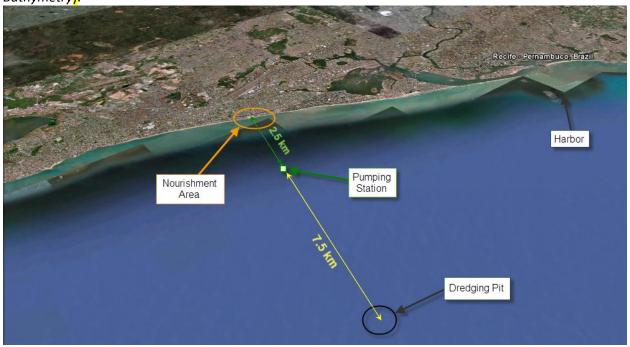


Figure 102: Overview locations

The piping system can be floating, emerged, or a mix of both. In order to shorten the length of the pipeline it would be most convenient to use a floating system. An example of a floating pipeline system can be seen in Figure 103. More information on the piping system can be found in appendix piping system.

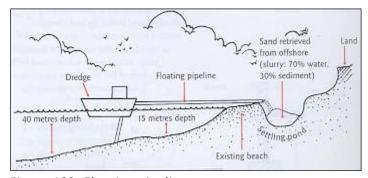


Figure 103: Floating pipeline system





Pipe system to the beach

Beach nourishment can be performed by pumping the sand trough pipes on to the beach. The sand will have to be worked by bulldozers and scrapers. The sand source is from an offshore supply. Thanks to the pump-station the water slurry can be transported through the floating pipelines to the beach. At the beach the sand will be deposited and the water will drained.



Figure 104: Pipe system on the beach

As can be seen in Figure 104 the area of Boa Viagem will be nourished by pipes on the shore. The green spot stand for an additional pump. This to ensure that the amount of sands can be delivered on the beaches. The pipes will be stored on the beach and used whenever the beach nourishment continues, thus extending the length of the pipe. In this way the whole nourishment area can be reached.

The sand will be deposited on the beach and water will be drained away. It is recommended that this operation will be done when the weather and sea conditions are calm, otherwise there can be more loss of sand.

To find out how many meters of pipe have to be laid every day, an easy calculation can be made. From the cross section *Figure* 99 an amount of volume sand needed is estimated per meter and is equal to 400 m2. If looked to the cycle time for the hopper it can be noticed that the hopper can dredge 4400 m³ every 160 min. Assumed that a work day is 24 hours a day, 8 cycles can be completed every day, resulting in a maximum 88 meters of pipe to lay per day. The maximum amount of pipe needed is 2.78 km.





$$\frac{4400}{400} = \frac{11m}{cycle} \qquad \rightarrow \qquad 11 \times 8 = 88 \frac{m}{each \, day}$$

After the sand has been deposited on the beach bulldozers and scrapers are needed to spread the sand evenly over the beach. The beach will have to be monitored after the nourishment in order to check the effectiveness of the nourishment. See *Appendix J: Boa Viagem* for more information about monitoring





Beach nourishment schematic

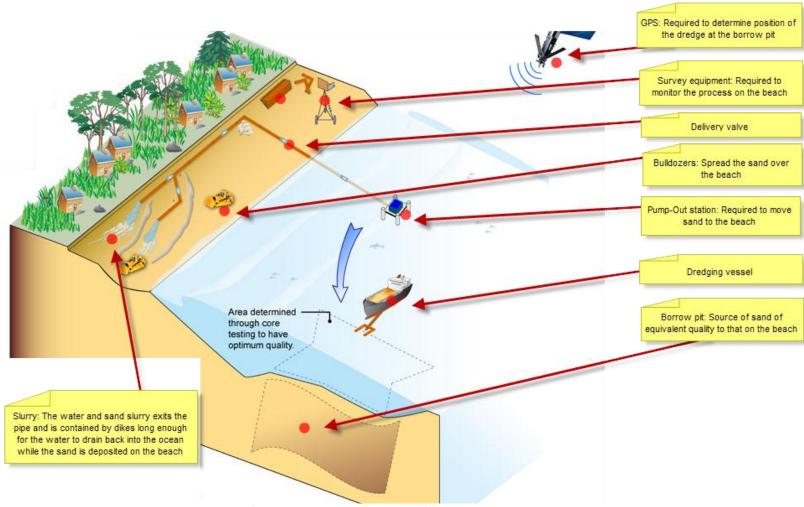


Figure 105: The beach nourishment process (Image source: USACE, 2011)





20.4 Secondary Considerations

20.4.1 Public Access

If dredged material is placed on the dry beach the beach will be inaccessible for a while. This will undoubtedly cause aggravation of the commercial exploiters of the beach environment. The primary stakeholders are the owners of the shops, hotels and restaurants near the beach. There is no clear solution to this problem other than working as quickly as possible. Nourishing the foreshore is common in the Netherlands to avoid this problem. The scheduling requirement needs to restrict nourishing in the high season to reduce the negative impact during the nourishment.

20.4.2 Public opinion

When beach nourishment has been done recently a wide stretch of dry beach has been added to the beach zone. The wide stretch is under a rather steep slow and will be reshaped by the waves into a profile fitting the wave conditions and part of the dry beach will eventually be submerged. Sediment deposition on the dry beach, especially a beach primarily used for recreational purposes can have adverse effects on public's perspective of the effectiveness and efficiency of beach nourishment. Beach nourishment hasn't been tried on the Boa Viagem beach before and public opinion of its success can influence the project. Beach Nourishment doesn't solve the erosional problems and needs to be repeated after some period of time. If the public determines that the nourishment has failed, it could endanger the longevity of the project. It is the opinion of the author that the public is thoroughly informed about what beach nourishment is actually supposed to achieve.

20.5 Recommendations

It is also possible to create a perched beach. The use of a perched beach could reduce the cost of the project. However the effectiveness of such a beach will have to be assessed. See *Appendix J: Boa Viagem* for more information on the perched beach.





21. Planning

An efficient construction plan is of critical importance to the feasibility of the project. Therefore an analysis is made of the different construction activities, the time required to realize these, and the place in time they will be executed. An overview of the building method can be found in Figure 103.

The planning has been divided into 3 sections:

- 1. Preparation
- 2. Execution
- 3. Finalizing

It is assumed that in the weekends work will be done and a workday is 12 hours. The project will be initialized in the winter to minimize the disturbance in the area.

The assumed exact start date is Monday 4/22/2015 and the end date is Wednesday 8/28/2015, approximately 4 months.

One can see the total planning in *Appendix P Planning*. Note that this planning is only the planning of the initial nourishment; re-nourishment has not been included (it would be likely the same, only a smaller amount of nourishment).





22. Detailed Costs

The costs are further elaborated and calculated with more precision. The calculation can be divided into the initial costs that need to be spent at the start of the building phase and the recurrent costs, i.e. the re-nourishments that need to be done in the exploitation phase. For the full detailed version of the Expenditures Model, see *Appendix R Expenditures Model Detailed*.

The assumptions, time-preference rate, time-horizon and pricing date are all explained in Appendix R Expenditures Model Detailed Costs. These values are:

Time-preference rate: 2,5% Time-horizon: 50 years

Pricing date: January 1th, 2015

Adding up all the detailed costs, the total initial costs are **R\$ 30.600.000**. This means that the price per cubic meter of nourishment is about R\$ 27. This price is comparable with the R\$ 25 /cubic meter posed in the CPE (*CPE*, 2011).

The difference in price can be explained as follows: the CPE uses different key figures and does not have an extensive construction method planned. The complex building method could be the difference in pricing that the CPE possibly didn't account for.

The recurrent costs add up to **R\$ 20.600.000** per re-nourishment. This means that the price per cubic meter of nourishment is about R\$ 51. This is much higher than the R\$ 27/cubic meter and way higher than the price in the CPE (*CPE, 2011*). This number is heavily influenced by the high mobilization costs for the hopper dredge. Since this cost is the same, yet the amount of re-nourishment is less, is cubic meter price goes up. The price per cubic meter nourishment is too high to make this feasible; it is therefore recommended that the re-nourishment is done with larger nourishment amounts, for example by re-nourishing the other areas of the metropolitan area.





Conclusions & Recommendation





23. Final conclusions and recommendations for the area

23.1 Conclusions

- The most important conclusion that the project has yielded is, that there is insufficient sediment in the system. Hard measures were taken without considering this deficit and the results have not been satisfactory. The only method to counteract the sediment deficiency is by adding more sediment to the system.
- 2) The presence of the reefs makes this area a very complex hydrodynamic environment. The reefs act as submerged breakwaters and influence not only the wave heights in their lee but they influence the sediment transport as well.
- 3) The wave heights for areas sheltered by the reefs are relatively small, contrary to the wave heights of areas not sheltered by the reefs. The reef on this coast in plays a vital role in wave height reduction. The wave heights in the exposed areas are also higher than usual due to the narrow continental shelf.
- 4) The most important conclusion from the general solutions is that the hard structures were constructed without thorough consideration of coastal processes and the real problem which is a sediment deficit.
- 5) Certain hard structures didn't have the effect the designers likely predicted because they accelerated erosion in some areas, though they did cause some accretion effects in some areas.
- 6) Certain structures were heavily overdesigned such as the very large breakwater in the Candeias area. The breakwater is too high according to standards of economical design.

23.2 Recommendations

- Addressing the problems of the area should be done in an as integral approach as possible; this
 involves addressing the problems of all seven areas in a single solution. On a larger scale, the
 problem could also be addressed in cooperation with neighboring provinces should they face similar
 challenges.
- 2) The reefs play a vital role in shoreline protection and some are in state of decay. Through time wear and tear will eventually destroy these affected reefs and the consequences of which should be thoroughly researched.
- 3) Because of the sediment deficit it is recommended to use structural beach nourishment. It is recommended to fight an optimal contract form for this long term nourishment.
- 4) Hard measures are discouraged and only beach nourishment should be performed to improve the beach because beach nourishment is a proven formula without any significant adverse effects on beach morphology in the upstream area.
- 5) Nothing is known about the source where sediment can be found. Assumptions about the location were made in this project but in order to have a project ready for tendering an actual location must be established. Sources must not only be located for the initial nourishment but the authors also recommend that the responsible authorities consider future nourishment and replenishment of the area as well.
- 6) A single organization responsible for coastal protection and aiding in drafting legislation and all other processes in regards to coastal protection would be very beneficial to Pernambuco or even





Brazil in general. Similar organizations are the USACE in the United States and Rijkswaterstaat in the Netherlands.

7) The stakeholder analysis and the Multi Criteria Analysis are done based upon value judgments. To come with more reliable values, one should do an extensive analysis beforehand. These can be done with for example public surveys, questionnaires etc.





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